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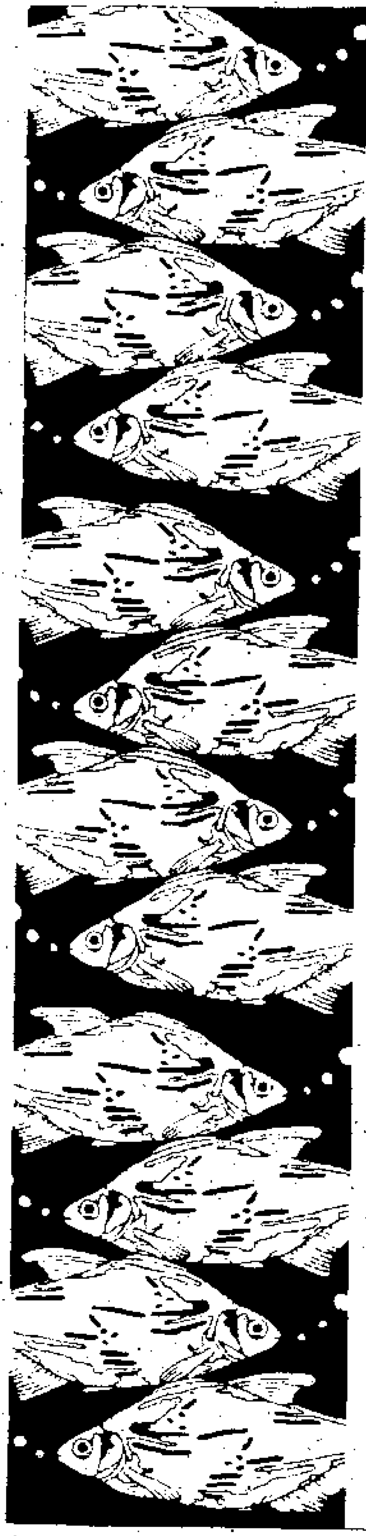

APPLICATION OF MATHEMATICAL MODELS IN THE ENVIRONMENTAL REGULATION OF NET-PEN AQUACULTURE

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Final Report Submitted to the
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EXECUTIVE SUMMARY

Considerable effort is presently being invested in making measurements of hydrodynamic, water-quality, and benthic parameters in an effort to control and identify the environmental impacts of net-pen aquaculture. However, discrete measurements over limited time periods at specific sites do not give a truly representative overall picture; they cannot address spatial variations within lease sites or the cumulative effects of several operations within a coastal embayment. In addition, field measurements are expensive and time-consuming. To overcome these difficulties, mathematical computer models are developed in this study to simulate tidal and wind-driven currents, waves, and the resulting dispersion of fish food/fecal matter. These models are considerably more comprehensive than previous modeling methods used in the prediction of net-pen waste distribution. Cobscook Bay and Toothacher Bay in Maine were chosen for this study. Field data were obtained to force, calibrate, and verify the various models. We find that a systematic site-specific step-by-step modeling strategy that involves the use of numerical models to simulate the overall hydrodynamic environment (viz. tidal and wind-driven flows and wave-induced velocities) in combination with a waste-particle transport model can be an extremely powerful method of determining *a priori* whether commercial-scale operations will cause high rates of net-pen waste accumulation at a particular site. The examples considered here demonstrate that the models can provide more comprehensive information on the hydrodynamic environment, without which it is difficult to make sound regulatory decisions. The data needed for these models are relatively easy to obtain, and additionally, they can examine such characteristics at several sites within a bay simultaneously. Therefore, the use of these models, if accepted by regulatory agencies, can result in significant cost savings to the industry.

ACKNOWLEDGMENTS

This report is the result of a study sponsored by the National Marine Fisheries Service (NOAA) under the Saltonstall-Kennedy Program. We are grateful to the University of Maine and to the Great Eastern Mussel Farms, Inc. for providing various facilities to carry out this research. We would like to thank Ms. Eloise Kleban of the University of Maine Computer Center for her expert assistance and the Swans Island Salmon Corporation and Connors Brothers, Limited for boat assistance and the use of their data. Dr. Robert Findlay was very kind in sharing his data and experience with us. It is a pleasure to thank Ms. Ellen Manzo of the University of Maine Civil Engineering Department for her cheerful assistance throughout the project.

1. INTRODUCTION

The last few years have seen an exponential growth in salmonid net-pen culture in Maine. According to the Maine Department of Marine Resources (DMR), there are 511 net-pens in the state. The 1990 landings from over 30 lease sites were estimated at 5,000 metric tons (Bettencourt and Anderson, 1990), and involved over 200 full-time and 70 part-time jobs; the value of the landings was second only to the lobster industry. While regulatory agencies (DMR, US Army Corps of Engineers (USACOE), Maine Department of Environmental Protection (DEP), National Marine Fisheries Service, US Fish and Wildlife Service, etc.) are under increasing pressure to regulate the expansion and limit the environmental impacts of these operations, the industry has identified delays in permitting and increasing costs of site monitoring as a major constraint to expansion and profitability. Indeed Bettencourt and Anderson (1990) state: "the future growth of the salmonid net-pen culture production in northeastern US will depend in large part on the regulatory constraints faced by the industry". There is still confusion between various agencies concerning the types of net-pens, and their effects. since the cumulative impacts of several pens within a given site have not been systematically addressed. Meanwhile, the state of Maine has identified in its Aquaculture Development Strategy (Ferland et al. 1990) the need for a coordinated development strategy for aquaculture and traditional fisheries, and has noted that the high cost of meeting regulatory requirements (estimated to be as much as $100,000 to obtain a lease and all necessary permits and several thousand dollars for annual monitoring) form a significant barrier to the future entry of local fishermen into the net-pen aquaculture business.

A significant component of the regulatory process deals with the interaction of the fish-farms with the hydrodynamics and the resulting environmental impact. The ability of the area to accommodate aquaculture operations without adverse impact has to be examined. Fish farm wastes, composed primarily of fish feed and fecal pellets, often adversely affect water quality and the benthic community; for instance, enhanced concentrations of ammonia, lowered dissolved oxygen, or bacteria mats are found at some sites. (Deterioration of the environmental conditions can in turn affect the viability of the farm also.) Factors influencing the sedimentation and accumulation of organic material in the vicinity of salmonid net-pen operations in the marine environment have been the subject of numerous studies and reviews (e.g. Ennel and Lof, 1983; Gowen and Bradbury, 1987; Fox, 1988; Ackerfors and Ennel, 1989; Hall et al. 1990; Gowen et al., 1989a,b; Gowen and Edwards, 1990; Hansen et al. 1991; Pillay, 1992; Silvert, 1992). Rates of deposition rely on several factors such as the settling rates of feed, the biomass of fish and their metabolic rates, the settling rates of fecal pellets, rates of feeding and amount of excess (waste) feed, hydrodynamic parameters like the current speeds, local bathymetry, and wave conditions at the site, the distance from the pens to the sea floor and their effect on the currents at the site, the consumption of waste feed by other species (crabs, fish, etc.), the rate of decay of organic particles on the bottom, including grazing by the benthos and bacterial decomposition, and resuspension of organic particles by currents and waves, which may vary seasonally and with differences in particle adhesion or "stickiness".

The regulatory process should be governed by the degree of environmental deterioration wrought by one or more net-pen operations in a region; however this is not easily ascertained, since a given amount of waste loading is influenced by tidal flushing, resuspension by waves, and decay. While the assimilative capacity of the benthos is generally poorly known, regulators have generally used guidelines based on a minimum current speed and water depth, in the hope that the particulate wastes are dispersed sufficiently away from the pens. For example, Parametrix Inc. (1990) have recently examined regulations, monitoring requirements, etc. for fish-farming in several regions of the world. Their report to the Maine Department of Marine Resources recommends that the minimum separation between the bottom of the pen and the sea- floor be between 10 and 60 feet (depending on water depth) and the mean current velocities halfway between the sea floor and the bottom of the pens be greater than 0.1 knots. Specific recommendations of how and where measurements must be made are given. For instance, water velocities are to be measured at the site by current meters and drogues. The recommended guidelines (see the report by Parametrix Inc. to DMR) state: "Characterizing the current velocities and directions is necessary for applying depth/current siting guidelines and for predicting the dilution and dispersion of excess feed and fecal matter. At the center of the farm, measurements should be made six feet below the surface and three feet above the bottom. Ten evenly spaced measurements should be taken throughout one tidal cycle during a periods of average tides (neither neap nor spring)".

In addition to velocities and elevations, water quality and benthic data are also required as part of the leasing/monitoring process. Benthic data in a 1000 foot radius from the farm are required, with sampling stations being chosen on the basis of the prevailing currents, and the anticipated drift of waste material. (The recommendations by Parametrix Inc. (1990) give guidance on the horizontal spacing of these stations.) Water-quality samples also should be taken at 0.1m and 1m above the sediment and at the bottom of the nets, at 5 plan locations: one up-current of the pens, one directly within the pens, and three down-current of the pens. In addition, the leasing program requires drogue tracking to estimate the fate of particulate matter and the potential for excess feed and feces to get trapped in eddies. The drogues should be tracked for at least eight hours, and should be reset if they are transported beyond a practical tracking range.

Considerable effort is therefore being invested by the Maine salmonid net-pen industry in making measurements of hydrodynamic, water quality, and benthic parameters, and although they are immensely useful, there are several difficulties:

1) It is not clear how regulations can be developed using these measurements alone. For instance, does requiring certain minimum velocity at the pen ensure that excess feed/fecal matter concentrations in some region will remain below tolerable levels? Flow patterns in many coastal regions (such as Cobscook Bay in Maine) are complex, and it would be difficult to predict the required dilution and dispersion of this matter. A more detailed description than a "blanket" minimum velocity or depth is needed. Also, water quality samples are to be taken from up-current and down-current locations etc. For this too, one needs a more detailed velocity field, since even the prevailing current direction itself is often difficult to establish.
2) The concentration of particulate matter is not governed only by currents, but also by dispersion, settling, and resuspension. For this, depth-varying velocity profiles may be needed, not just beneath the pens, but in the overall vicinity.
3) Current measurements are made on a certain day, and do not represent the variations due to winds (i.e. wind-driven currents and wave activity) and different tidal conditions (spring, neap).
4) Water quality or benthic sampling locations may not be truly representative, since currents, dispersion, settling, interaction with boundaries (i.e. bathymetric features), and other mechanisms influence the concentration levels of particulate matter.
5) Measurements for leasing and monitoring are expensive and time-consuming.
6) A considerable degree of arbitrariness accompanies the criteria discussed in the above paragraphs (e.g. blanket minimum velocity, etc.) and even the specified measurement locations. For instance, are they adequate for sites with several pens? Several researchers have emphasized, not surprisingly, that the environmental impacts are "site-specific" and depend also on husbandry techniques which dictate waste output.

Project Goals and Objectives

As described above, discrete measurements on their own cannot give a complete representative picture that can assist in developing guidelines. In fact, some fish-farmers have informed us that it is difficult to make much sense of isolated measurements. In such conditions, computer modeling, in conjunction with some field measurements, represents an eminently rational and powerful tool to investigate the hydrodynamics and dispersion of fecal and waste feed pellets at pen culture sites. Indeed, the report by Parametrix Inc. (1990) to DMR recommends the use of this approach to assess the effect of the farm on the surrounding waters. A rigorous effort was therefore undertaken to model the overall hydrodynamic and other aspects that influence net-pen waste distribution. Two sites in Maine (Toothacher Bay and Cobscook Bay) were selected for this study (Fig. 1.1). These sites were also the focus of the investigations of Dr. R. Findlay, Dr. L. Watling, and Dr. R. Blake of the University of Maine.

Computer modeling techniques for estimating the environmental impacts of aquaculture have been devised in recent years. Pioneering work in this area was done by Gowen et.al. (1989a) who constructed a "simple" modeling technique for the dispersion of net-pen wastes. This involves simply tracking the horizontal and vertical motion of the wastes, and determining where they settle (Fig. 1.2). This type of model was used to quantify environmental impacts under two separate net-pens in Puget Sound, Washington (Weston and Gowen, 1988). Essentially the same procedure was applied by Fox (1988) at these sites, emphasizing the configuration, the orientation, and the density of the net-pens to determine how they influenced the predicted deposition rates. These studies have shown the potential of such models for determining the spatial extent of the net-pen waste distribution and for site-selection from an environmental viewpoint. However, waste-distribution in these models is assumed to be governed by horizontal velocity data (C_v) from only one location only; these data do not describe the spatial variation in velocities. If one wished to do this, a large number of current meters would be required. Also the bottom topography in the area of interest is not taken into account. In a discussion of these models, Fox (1988) states: " _ _ _ a very detailed field investigation of the spatial distribution of currents near each site would be required _ _ _ ". In addition, some of these models do not account for post-depositional processes. All models ignore wave activity (resuspension) and suspension of fish wastes in the vertical column, which are noted as "valuable future research topics" by Fox (1988).

A simple analytical model for controlling the possible impacts has recently been proposed by Silvert (1992) using first principles. He combined the mean current velocity V with a "diffusion term" η and determined that the area affected is $4\eta(V+\eta)Z^2/S^2$, where S = the settling velocity, and Z = vertical fall distance. The ability of the bottom in this area to handle the waste loading depends on both the grazing rate of the benthos and the rate at which bottom currents remove the particulates. These two effects were combined to form the "assimilative capacity" (B) expressed in $g/m^2/d$. If the waste output of a fish farm is assumed to be proportional to its annual production Y (through a constant proportionality p), the total waste loading from the net-pen should be less than the pollution threshold, i.e. $pY < 4B\eta(V+\eta)Z^2/S^2$, in order to keep the area unpolluted. Using this equation, Silvert (1992) obtained the results presented in Fig. 1.3. Although the model is quite elegant, it is difficult to apply generally, since the parameter B cannot be determined easily. It depends on the hydrodynamics as well as the time-varying waste load on the bottom. As such, it is site-specific. A more general model is, therefore, required.

The goal of this study was to systematically investigate, in a "pilot study" at two contrasting sites (Toothacher Bay and Cobscook Bay), the use of computer models to simulate the flushing characteristics and dispersion of the fecal pellets and excess feed. The specific objective was to develop and use models that eliminate the deficiencies noted above. In particular, a systematic attempt to model all of the relevant hydrodynamic aspects was made, e.g. spatial variations in the currents, resulting from both winds and tides, and waves were modeled as appropriate. Field data were also gathered during this project and were used with data gathered by other researchers and aquaculturists to force, calibrate, or verify the models. Our case studies may provide regulators with a reasonably comprehensive modeling strategy that is more systematic than the guidelines described earlier.

In Chapter 2, we describe the overall modeling methodology for simulating tidal/wind-driven currents, dispersion of contaminants, including resuspension of settled wastes, and the effect of wave activity. In Chapter 3, we describe our efforts to obtain the relevant field data that are needed to adequately force and calibrate the models. Applications of these models to Cobscook Bay and Toothacher Bay are described in Chapters 4 and 5 respectively. Our findings are summarized in Chapter 6.

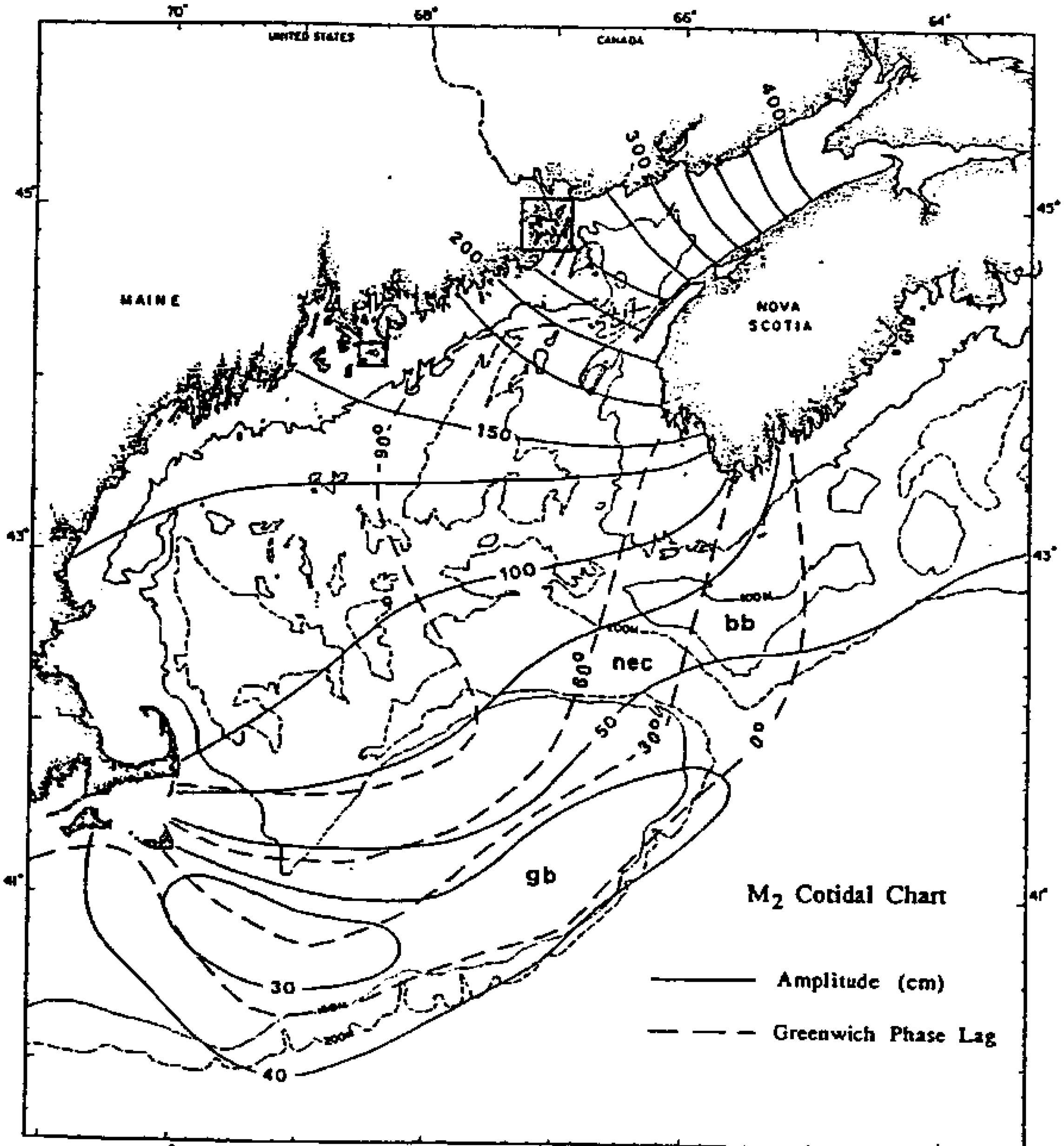


Fig. 1.1 The Gulf of Maine (after Brooks &Churchill,1991);
For detail of the study areas shown in the boxes, see Fig.4.1 & Fig.5.1

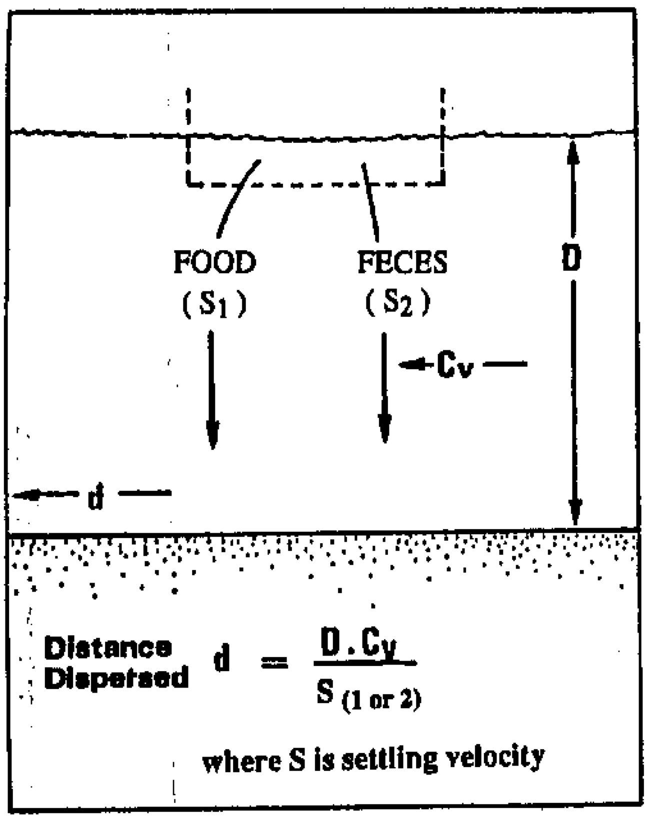


Fig. 1.2 Diagrammatic representation of the horizontal and vertical motion of the net-pen wastes (from Gowen et al, 1989a)

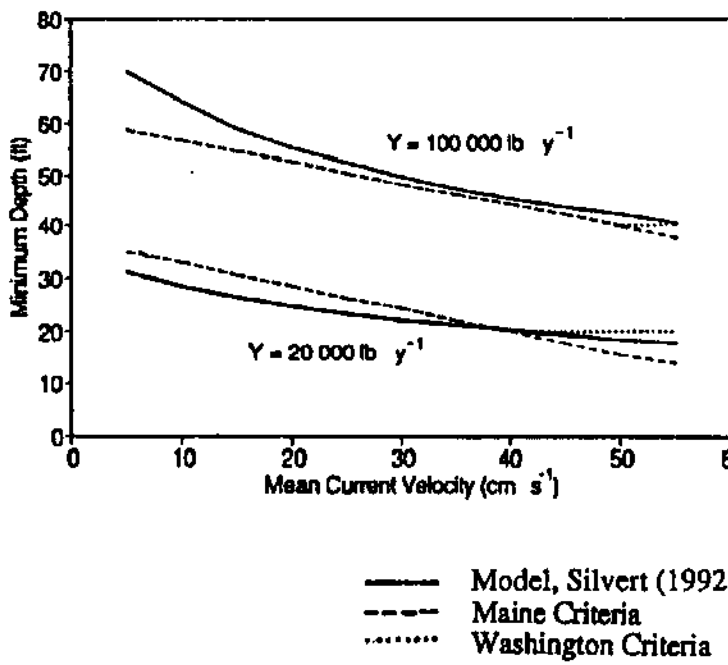


Fig. 1.3 Relationship of the Silvert (1992) criteria to the Maine and Washington State criteria

2. MODELING METHODOLOGY

For studies dealing with the environmental impacts of aquaculture, it is necessary to first simulate the tidal and wind-driven currents and/or the wave field that is responsible for transporting the net-pen wastes. Once the water velocities are obtained, waste particle motion is simulated by a transport model to determine their eventual dispersion characteristics.

2.1 Modeling the flow velocities

Numerical models to compute the tidal or wind-driven currents are developed from the 3-d hydrodynamic equations which provide complete spatial and temporal information on the currents for the entire computational domain. However, 3-d schemes require intensive computer resources, especially when the computational domain is large. In our study, for example, it is extremely difficult to run a 3-d model for Cobscook Bay, which has an area of approximately 200 km^2. Although not impossible, we feel that the high level of effort required to run a 3-d model is not warranted for the task at hand. A reasonable alternative is to use the 2-d model obtained by vertically averaging the 3-d equations; such a model yields the depth-averaged components of velocity. The computational resources required in this approach are far less than in the 3-d approach. However, the information provided by 2-d models is not sufficient in some cases, e.g. when the surface or bottom velocities differ considerably from the depth-averaged velocity. Such variations are likely to affect the dispersion of wastes, since it is the bottom velocities that cause resuspension of settled wastes.

An intermediate approach developed by Lardner & Cekirge (1988) relies on a "vertical/horizontal splitting" of the 3-d equations. The basic procedure of this method is to first use the 2-d schemes to compute the surface elevations and the depth-averaged velocity components (i.e. variations in the horizontal only). These values are then used as input to a simple (Ekman-type) scheme to calculate the vertical variations at a given (x, y) location. Compared with a 3-d model, this procedure requires much less computational effort, since the velocity profile can be calculated only where required rather than in the entire domain. Lardner & Cekirge (1988) have shown that this approach compares very favorably with the full 3-d model for many applications, and Lardner and Das (1991) have applied it in the Arabian Gulf. A variation of this approach has also been used in the Gulf of Maine by Tee (1979, 1982). In this study, therefore, we used this intermediate approach. We feel that this method is sufficiently practical and reliable for use by regulatory agencies. The details of the 2-d vertically-averaged flow model and the vertical variation model are discussed below.

2.1.1 2-d Flow Model

This model is based on the two-dimensional shallow water equations which allow us to calculate the surface elevation and depth-averaged velocities. These variables are functions of the horizontal coordinates (x, y) and time (t). The model equations are:

$$\frac{\partial \eta}{\partial t} + \frac{\partial[(H+\eta)U]}{\partial x} + \frac{\partial[(H+\eta)V]}{\partial y} = 0 \tag{2-1}$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - CV = -g\frac{\partial \eta}{\partial x} - \frac{fU\sqrt{U^2+V^2}}{H+\eta} + \frac{\partial(N_h(\frac{\partial U}{\partial x}))}{\partial x} + \frac{\partial(N_h(\frac{\partial U}{\partial y}))}{\partial y} + \tau_x^w \tag{2-2}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + CU = -g\frac{\partial \eta}{\partial y} - \frac{fV\sqrt{U^2+V^2}}{H+\eta} + \frac{\partial(N_h(\frac{\partial V}{\partial x}))}{\partial x} + \frac{\partial(N_h(\frac{\partial V}{\partial y}))}{\partial y} + \tau_y^w \tag{2-3}$$

where
- g = gravitational acceleration
- C = Coriolis coefficient
- H = depth from mean sea level to the bottom
- η = deviation of the free surface from mean sea level
- f = bottom friction coefficient
- N_h = horizontal eddy viscosity
- U = depth-integrated velocity in x-direction
- V = depth-integrated velocity in y-direction
- τ_x^w = wind shear on the water surface in the x-direction
- τ_y^w = wind shear on the water surface in the y-direction

This model may be forced by tides (specified at the open boundaries of the domain) and/or surface wind (specified over some or all grids in the domain). The surface wind stress is specified as:

$$\tau_x^w = \rho_a C_d |W| W_x$$
$$\tau_y^w = \rho_a C_d |W| W_y \tag{2-4}$$

where ρ_a = the mass density of air, W = wind velocity (with components W_x and W_y), and C_d = drag coefficient, which can be parameterized as a function of the 10-meter windspeed (e.g. Demirbilek et al. 1993).

Equations 2-1, 2-2, and 2-3 are solved by numerical methods on a discretized grid. An Alternating Direction Implicit (ADI) finite-difference model developed by Booij (1989) at the Technical University Delft (Holland) was used in this study. This model, called DUCHESS, has been used by us for other fisheries-related applications in coastal Maine (e.g. Newell, 1991). The model is very sophisticated, with options such as unsteady boundary conditions, nested grids, and the flooding/drying of shallow regions. The bathymetry of the computational domain is required as input to the model. In regions where the water level goes down and the calculated depth is smaller than the input depth (i.e. the depth becomes negative), points are taken out of the computational domain and are considered to be dry. When the water level increases, these points become flooded and are included in the computation. These features are particularly applicable to our study sites.

2.1.2 Modeling the vertical variation of velocities

Following Lardner and Cekirge (1988), we use the following linear momentum equations to model the vertically-varying currents:

$$\frac{\partial u}{\partial t} - \frac{\partial (N \frac{\partial u}{\partial z})}{\partial z} - C v = -g \frac{\partial \eta}{\partial x} \tag{2-5}$$

$$\frac{\partial v}{\partial t} - \frac{\partial (N \frac{\partial v}{\partial z})}{\partial z} + C u = -g \frac{\partial \eta}{\partial y} \tag{2-6}$$

where $u(z,t)$, $v(z,t)$ = horizontal velocities at a given location (x,y) of the 2-d model

$N(z)$ = vertical eddy viscosity

C = Coriolis parameter

$g\frac{\partial\eta}{\partial x}, g\frac{\partial\eta}{\partial y}$ = presure force per unit mass due to x and y directed surface slopes from 2-d flow model

These equations may be solved at any (x, y) location for the velocities $u(z, t)$ and $v(z, t)$. They are forced by the surface slopes calculated in the 2-d model and/or by wind stress (described later).

Eq. 2-5 and 2-6 may be written in complex form as

$$q_t - (Nq_z)_z + i\,C\,q = -\left(g\frac{\partial\eta}{\partial x} + i\,g\frac{\partial\eta}{\partial y} \right) \qquad (2\text{-}7)$$

where $q(z,t) = u + i\,v$ and $i = (-1)^{0.5}$. A program based on the following Crank-Nicolson finite-difference scheme (with a grid spacing = dz) was used to solve eq. 2-7:

$$- N_0 q_{j-1}^{t+1} + \left(N_1 + \frac{2dz^2}{dt} + i\,C\,dz^2 \right) q_j^{t+1} - N_2 q_{j+1}^{t+1}$$

$$= 2\,dz^2 \left(- g\frac{\partial\eta}{\partial x} - i\,g\frac{\partial\eta}{\partial y} \right) + N_0 q_{j-1}^{t} + \left(- N_1 + \frac{2dz^2}{dt} - i\,C\,dz^2 \right) q_j^{t} + N_2 q_{j+1}^{t+1} \qquad (2\text{-}8)$$

where

$N_0 = 0.5\,(N_{j-1} + N_j)$, $N_1 = 0.5\,(N_{j-1} + 2N_j + N_{j+1})$, and $N_2 = 0.5\,(N_j + N_{j+1})$.

Vertical eddy viscosity

Much uncertainty surrounds the values of the vertical eddy viscosity N. Although Panchang and Richardson (1993) have developed inverse modeling strategies for estimating this parameter, they rely on the availability of at least some data. In addition, application of such strategies was beyond the scope of this project. We therefore used empirical estimates of the eddy viscosity.

Bowden and Fairbairn (1952) and Bowden et al. (1959) indicated that N has a maximum value near mid-depth; they estimate the maximum value N_m as:

$$N_m = 2.5 * 10^{-3} U_m D \tag{2-9}$$

where U_m is the amplitude of the depth-mean tidal current. Using eq. 2-9, Tee (1982) constructed four profiles:

1) N(z) is constant , i.e. $N(z) = N_m$.

2) N(z) is a parabolic profile, given by

$$N(z) = N_m (R_1 + 4 (R_1 - 1) \eta + 4 (R_1 - 1) \eta^2)$$

where $\eta = z/D$, N_m = maximum vertical eddy viscosity at $\eta = 0.5$, and $R_1 = N_{surface} / N_m$

3) N(z) increases rapidly in a thin laminar sublayer from the bottom to a uniform value N_m in the turbulent layer, i.e.

$$N(z) = \nu_0 (1 + R_2 D (\eta + 1))^2 , \quad \eta \le \eta_z$$

$$N(z) = N_m = \nu_0 (1 + R_2 \delta_z)^2 , \quad \eta \ge \eta_z$$

where ν_0 = molecular eddy viscosity ($1.4 * 10^{-6}$ m^2/s), $\eta_z = \delta_z/D - 1$, and R_2 and δ_z are two parameters to be adjusted to provide the best match with field data.

4) N(z) is a combination of (2) and (3), i.e. N(z) is described by (2) for $\eta > \eta_z$ and by (3) for $\eta < \eta_z$.

These profiles, shown in Fig. 2.1, were selected for our study.

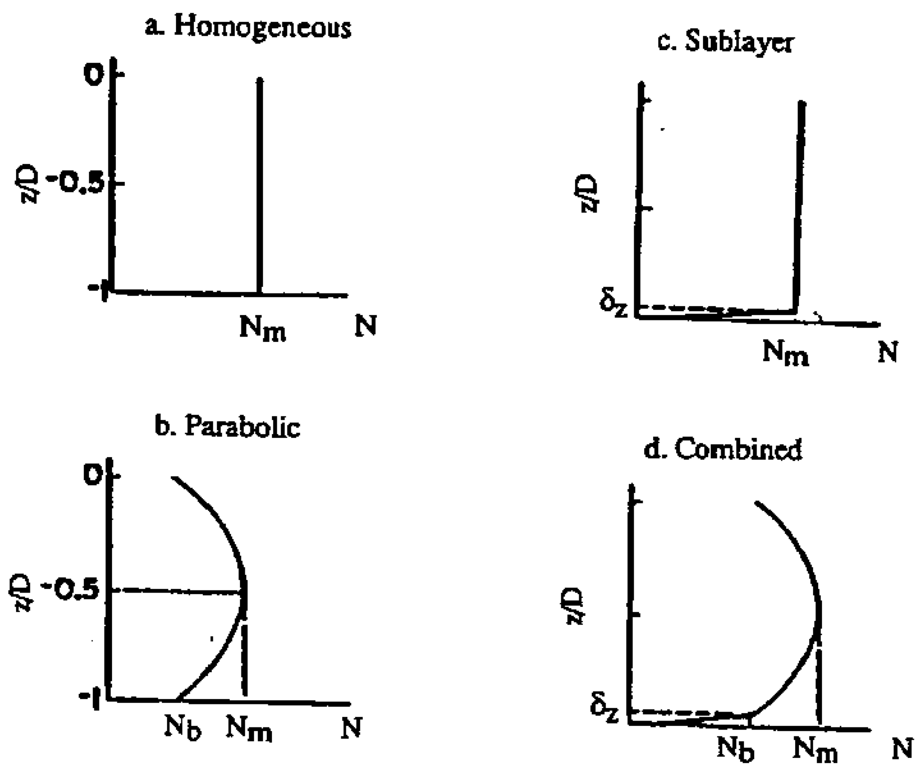


Fig. 2.1 Vertical eddy viscosity profiles (from Tee, 1982)

Boundary conditions for Eq. 2-5 & 2-6

Wind shear at the surface of the water influences the solution of eq. 2-5 and 2-6. The boundary condition at the surface may be stated as:

$$\rho N u_z = \tau_x^w ; \ \rho N v_z = \tau_y^w \tag{2-10}$$

where the right hand sides, representing the x- and y- components of the wind shear stress, may be related to the wind speed as in eq. 2-4.

The bottom boundary conditions can be specified in two ways: one could require that the velocities produced by eq. 2-5 and 2-6 have the same average as that obtained in the 2-d model (Lardner and Cekirge, 1988), in which case the bottom shear stress is the same as that calculated in the 2-d flow model; or, the shear stress at the bottom may be specified (through a friction coefficient) in terms of the local bottom velocity. These procedures are described below.

Method 1:

Three sets of velocity values at the bottom (grid point j = 1) are selected as:

$$u_1^{(1)} = 1,\ v_1^{(1)} = 0;\ u_1^{(2)} = 0,\ v_1^{(2)} = 1;\quad u_1^{(3)} = 0,\ v_1^{(3)} = 0 \tag{2-11}$$

Three model runs using the Crank-Nicolson scheme (eq. 2-8) with the above three bottom velocity combinations are made to obtain the dummy vertical profiles $u_j^{(p)}$, $u_j^{(p)}$ (p = 1, 2, 3). Let the ultimate velocity profile be related to these three profiles through the relation:

$$u_j = \alpha_1 u_j^{(1)} + \alpha_2 u_j^{(2)} + \alpha_3 u_j^{(3)} \tag{2-12}$$

$$v_j = \alpha_1 v_j^{(1)} + \alpha_2 v_j^{(2)} + \alpha_3 v_j^{(3)} \tag{2-13}$$

The constants α_1, α_2, and α_3 may be obtained from the following relationships:

$$\alpha_1 + \alpha_2 + \alpha_3 = 1 \tag{2-14}$$

$$\alpha_1 U^{(1)} + \alpha_2 U^{(2)} + \alpha_3 U^{(3)} = U \tag{2-15}$$

$$\alpha_1 V^{(1)} + \alpha_2 V^{(2)} + \alpha_3 V^{(3)} = V \tag{2-16}$$

where eq. 2-14 is a result of the linearity of the governing eq. 2-7, and eqs. 2-15 & 2-16 result from the requirement that the average of the velocity profile be equal to that obtained in the 2-D model. ($U^{(p)}$ and $V^{(p)}$ represent the vertical averages of the three dummy profiles).

Method 2:

The bottom shear stress may be specified as follows:

$$\rho N u_z = \tau_x^b \; ; \; \rho N u_z = \tau_x^b \qquad (2\text{-}17)$$

For linear friction $$(\tau_x^b, \tau_y^b) = \kappa_1 \rho (u, v)_{z=-h} \qquad (2\text{-}18)$$

For quadratic friction $$(\tau_x^b, \tau_y^b) = \kappa_2 \rho (u^2 + v^2)^{1/2} (u, v)_{z=-h} \qquad (2\text{-}19)$$

u_j and v_j can be solved by substituting eqs. 2-17, 2-18, and 2-19 in the finite-difference form of the governing equation (i.e. eq. 2-8) at the lowest grid point.

Although Method 2 is easier to implement, we have found its solutions in earlier studies in the Gulf of Maine to be unsatisfactory. In particular, it was unable to reproduce opposing flows in the surface and bottom layers (observed, for example, by Tee, 1979). The average velocity of the profile also is not the same as that obtained in the 2-d flow model. Furthermore, this method introduce additional parameters κ_1 and κ_2 (to describe the bottom friction) in addition to f. While methods are available to eliminate some of these limitations (Lardner & Cekirge, 1988; Jin and Kranenburg, 1993), they neutralize the advantages of the interim approach. In our studies, therefore, we have chosen to rely on Method 1, which was also used by Tee (1979) in the Gulf of Maine.

2.2 Modeling net-pen waste movement

The flow velocities calculated by the above models are used as input to a contaminant transport model which calculates the transport of the uneaten fish food and fecal pellets and determines their concentration levels on the bottom. We use a simple particle tracking model, without a "random walk component", since the particles are mostly advected by the flow and practically no diffusion takes place. The basic procedure is that the waste particles are horizontally advected at the local current velocity, and move downwards at the settling velocity. The new position of a particle at the end of a discrete time step is then determined. The number of particles that accumulate at a location is a measure of the contamination, and can be converted to a concentration. A model is developed according to the following equations:

$$x(t+1) = x(t) + u(x, y, z, t)\Delta t$$
$$y(t+1) = y(t) + v(x, y, z, t)\Delta t$$
$$z(t+1) = z(t) + s_{(1 \text{ or } 2)}\Delta t \qquad (2\text{-}20)$$

where $s_{(1 \text{ or } 2)}$ represents the settling velocity for uneaten fish food or fecal pellets, u and v are the spatial and time-varying flow velocities, and x, y, and z represent the position of particle at every time step. The relationship is illustrated in Fig. 1.2.

The entire model domain is divided into grids with the same mesh size as that of the 2-d flow model. The velocities (which vary in time) and the bottom bathymetry for each grid point are stored in a file. For each tracking time step, the required current velocity at the location of the particle is obtained by interpolating from the four horizontal adjacent grid points. Interpolation in time is also performed if the time-step for the transport model is different from that for the flow models. This model can account for both constant or varying velocity profiles in the vertical (as needed; see Chapter 4). Settling velocities for fish food particles and fecal pellets were estimated experimentally (as discussed in Chapter 3).

Our transport modeling studies examined two scenarios. The first scenario allows the particle to be transported in the horizontal and vertical till it settles down on the bottom. The concentration levels can then be calculated. The second scenario deals with the resuspension problem, i.e. settled particles may be picked up into the water again and moved around when the current velocity is higher than some threshold velocity. Resuspension of material on the bottom is extremely difficult to model; it depends on the amount of waste material already present, their composition and adhesive properties, type of bottom, etc. Models for the transport of even uniform sediments in the coastal or riverine environment are fraught with a large number of unknown parameters, such as the critical shear stress at which material is resuspended and the amount that is resuspended. Modeling the resuspension of net-pen wastes is compounded by the fact that the bottom contains a mixture of the foreign material (i.e. net-pen wastes) and the native material; not only is no information available on the resuspension and subsequent transport when the bottom is composed of only organic net-pen wastes, but the motion of the native material creates the possibility of the submergence of net-pen wastes by the native material. In view of these difficulties, we made the assumption that when the bottom currents exceed a certain threshold, settled net-pen wastes are resuspended and advected by the currents. When the currents are below this threshold velocity, the particles remain on the bottom. The uncertainties and assumptions associated with a more rigorous sediment transport type model justify the use of this assumption for the present investigation. The threshold velocities were of course unknown, and hence treated as a parameter in the modeling exercises; a range of values was considered based on the advice of divers who made observations. For most cases, resuspension occurs only periodically, mostly as a result of wind-driven and/or wave-generated velocities, and results in a redistribution of settled sediments, including the possibility that most of the wastes are flushed out of the embayment. A particle tracking model of the kind used here has the advantage (over finite-difference or finite-element models) of being able to provide the tracks of the particles (i.e. to see if they eventually leave the bay).

2.3 Estimating Decay of Settled Wastes

We assume the net pen wastes are completely organic and that they decay exponentially. The combination of new wastes (S) and the decay of existing wastes yields:

$$\frac{\partial C}{\partial t} = -K\,C + S$$

where C = concentration level (g/m^2) at time t, S is the loading rate (g/m^2/time), and k is the decay coefficient ($time^{-1}$). The concentration level at time t is obtained by integrating eq. 2-21:

$$C(t) = C_0 e^{-kt} + \frac{S}{k}(1 - e^{-kt}) \qquad (2\text{-}22)$$

When the decomposition rate matches the loading rate, a steady state is reached. From eq. 2-22, the maximum steady state value (at time goes to infinity) is:

$$C_{(t=\infty)} = \frac{S}{k} \qquad (2\text{-}23)$$

2.4 Modeling wave-induced velocities

Surface waves cause motion of the water on short time scales, and wave-induced velocities near the bottom can cause resuspension of settled wastes. Ocean waves can experience energy input from the wind, inter-frequency energy exchange, and energy loss by dissipation and wave breaking. In addition, they are influenced by bathymetric variations that can cause refraction, diffraction, reflection, etc. and by currents that can cause refraction. It is not appropriate to give detailed descriptions here of the many wave models that simulate these various complex mechanisms. We refer the reader to Ge et al. (1990) for a review of some coastal wave transformation models and to Bondzie & Panchang (1993) for a discussion of other models. In many cases, these models require a very high level of computational effort and wave/wind data to force and calibrate them. Such data are lacking in the Gulf of Maine. Our objective is not to accurately simulate the wave climate in a bay (as needed for coastal engineering applications), but only to determine if wave conditions strong enough to cause resuspension can occur, and if so, with what frequency. For this goal, then, it is adequate to use a reasonably simple model to estimate the wave conditions from the somewhat limited wind data available. We have used the US Army Engineers model (SPM, 1984) as contained in the Automated Coastal Engineering System Package (ACES, 1992). These models, though not very sophisticated, are convenient to apply and have been verified recently in Lake Balaton (Hungary) by Luettich and Harlemann (1990). The actual application depends on fetch and wind information and is described further in Chapter 5. The estimated wave heights (H) and periods (T) were then used with Airy theory to estimate the wave-induced velocity u_{wave} as follows:

$$u_{wave} = \frac{\pi H}{T} \frac{\cosh(k(z+d))}{\sinh(kd)} \cos(kx - \omega t) \tag{2-24}$$

where d is the total water depth, z is the vertical distance (z = 0 at the surface and z = - d at the bottom), ω is the wave frequency, and k is the wave number determined from the wave dispersion relationship ($\omega^2 = g\, k \tanh(kd)$).

3. FIELD MEASUREMENTS

Considering the importance of water flow on environmental impacts, the use of site-specific (embayment) mathematical computer models in conjunction with field measurements represents a rational and powerful tool to investigate the hydrodynamics and dispersion of waste fecal and feed pellets at pen culture sites. In this investigation, we attempted to demonstrate the usefulness of computer models in the environmental evaluation of salmon net-pen aquaculture in coastal embayments. In this chapter, we describe field measurements made at commercial net-pen sites in Cobscook Bay and Toothacher Bay which were used to calibrate and validate flow and particle-tracking computer models. Data were obtained on current speed and direction, current variation with depth, tidal phase variations within embayments, wind and wave conditions, settling rates of feed and fecal pellets, and rates of fecal pellet production.

Current measurements

Field measurements were made using an Interocean S4 electromagnetic current-meter with sampling frequency varying from 0.5 seconds (profiling and burst sampling for waves) to 30 seconds (tidal-cycle measurements). The S4 meter measured current speed, current direction, and water depth. The current-meter was factory-calibrated prior to deployment, and has about 0.1 cm/s accuracy. Periods of deployment ranged from 30-minute sequences of velocity profiles off the edges of the net-pens to 4-5 day periods at the major study sites, Broad Cove and Toothacher Bay.

A summary of the data collected with the current-meter is presented below:

Device	Period	Location	sec	Depth m
S4 current meter	7/7/92	Broad Cove	0.5	15 Profiles
S4 current meter	7/7-7/11/92	Broad Cove	60/600	17 Tidal Cycle
S4 current meter	8/27/92	Broad Cove	0.5	17 Profiles
S4 current meter	12/16-12/18/92	Swan's Island	0.5	16 Burst
S4 current meter	12/18-12/23/92	Swan's Island	60/600	16 Tidal Cycle

During the sampling periods, the S4 was moored 4m off the bottom at Broad Cove (7/7-7/11/92) and 3m off the bottom in Toothacher Bay (12/16-12/23/92). Profiles made on July 8, 1992 are summarized in Table 3.1; see also Chapter 4. The current-meter was lowered off a boom 2 meters from the platform of the net-pen (Connors Bros. 6400; Fig. 4.14 and 4.15) in the middle of a pen array of 20 cages at the mouth of Broad Cove. There were about 1 million fish in grow-out at the site investigated. The meter was slowly raised and lowered to the bottom for replicate profiles at each time sampled. The total time for replicate profiles ranged between 3 and 5 minutes. Measurements of current speeds, current directions, and water depths were plotted using S4 application software (e.g. Fig. 4.13). As discussed in Chapter 4, these data were influenced by the presence of the net-pen (e.g. Fig. 4.13b). On August 27, 1992, a boat was moored with 2 anchors and current profiles (e.g. Figure 4.13a) were made in a region of Broad Cove outside of the net pens.

Table 3.1. Files and sample limits of vertical profiles off pen array 6400 in Broad Cove on July 8, 1992.

File	Profile	Limits	(1/2 second samples)
Broad 2	1	150-750	edge of net pen
	2	815-1400	edge of net pen
	3	1450-2050	edge of net pen
	4	2100-2900	edge of net pen
Broad 3	2	470-820	flow parallel to pen
	4	2070-2600	middle of pen array
	5	2900-3260	edge of net pen

On December 16, the current meter was set to burst sampling current speeds, current directions, and water depths at a 1-second frequency for 60 seconds every hour in Toothacher Bay. Direct measurements of wave height and period (e.g. Fig. 5.12) were used to compare with model calculations of wave velocities. On December 18, the current-meter was reset to longer period sampling for tidal cycle variations at the edge of the net-pen and was also used to investigate the effects of wind on current speeds and directions in Toothacher Cove. The locations of these measurements are shown in Fig. 5.2.

Tide Gauges

Four VEMCO tide gauges moored at the bottom were used to calibrate the DUCHESS flow model in Cobscook Bay and Toothacher Bay.

Device	Period	Location	Period (sec)	Depth (m)
Gauges	6/17-7/7/92	Cobscook Bay	120	35, 25, 25, 15
	12/18-12/23/92	Toothacher Bay	120	18, 16, 9

In Cobscook Bay, tide gauges were located near Eastport, Goose Island, Denbow Point, and South Bay (Fig. 4.3). As noted earlier, in Toothacher Bay the gauges were located off Irish Point, in Toothacher Cove, near the salmon lease site, and at the head of Toothacher Cove (Figure 5.2). The tide gauge data were examined for time lag between water elevations of grid locations within the model. In Cobscook Bay, elevations from the 1992 Maine Tide Calendar (with time and height comparisons of 5 Maine substations within Cobscook Bay) were also used to compare model output with observed time lags.

Particle Settling Rates

Measurements of the settling rates of fecal pellets and food were made in July and August, 1992. In cooperation with Dr. Kling of the Department of Animal, Veterinary and Aquatic Sciences of the University of Maine, the bio-deposits of 746 salmon smolts fed on a commercial dried feed were collected and used for settling experiments. During this time, fecal pellets were also collected by gently siphoning and resuspending in a graduated cylinder. Settling rates of 50 observations resulted in a mean settling rate of 3.2 cm per second (Fig. 3.1) with 70% of the observations between 2 and 4 cm per second.

During the fieldwork involving the current-meter and tide gauges, samples of commercial salmon feed were also examined for settling rates with graduated cylinders and a stopwatch. Settling rates of feed were found to be 10 cm/s, which compares favorably with measurements by other workers (e.g. Findlay and Watling, 1993; Warren-Hansen, 1982).

Rates of Fecal Production

The rate of fecal production was studied in a recirculating system with 1/4 lb. salmon smolts at the University of Maine with 23.5 kg of fish in each system (A and B) with 373 fish in each. The fish were fed Moore-Clark dried feed over a 3.2 day period at 10.1 to 10.7 degrees C, and the bio-deposits were collected in a settling tank. From a 3.7 liter (system A) and 6.0 liter (system B) samples obtained as a wet slurry, 200 ml sub-samples were spun down with a centrifuge, dried, weighed, and sub-sampled for determinations of carbon, protein, fat, and ash. The results are given in Table 3.2.

Table 3.2. Bio-deposits from salmon smolts over 3.2 days in a recirculating system.

Bio-deposit attribute	System A	System B
Grams dry wt. kg^{-1} day^{-1}	1.7	2.1
Grams carbon kg^{-1} day^{-1}	0.47	0.58
Percent carbon (dry wt.)	27.9	34.8
Percent protein	30.9	25.3
Percent fat	8.6	3.8
Percent ash	32.9	40.4

Husbandry Practices

Industry interviews were made with commercial growers in the Cobscook Bay region to investigate fish stocking rates and feeding rates (which are based on fish size and seawater temperature), with 20% added for satiation feeding. Feeding rates were obtained from tables of the percent body weight per day for different fish sizes over a range of water temperatures. Except at cold temperatures, fish consumed about 1-4% of their body weight per day using moist fish pellets of 5-12 mm diameter (Fig. 3.2, courtesy of Connors Bros. Limited Aquaculture Division). The maximum consumption was by small fish during the warmest water temperatures.

Typical net-pen dimensions and stocking rates were:

Stocking density	10 kg m^{-3}	Year 1
	15 kg m^{-3}	Year 2
Cage size	15m x 15m x 7m deep	
Cage volume	1400 m^3	
Number of fish per cage	10,000	Year 1
	5,000	Year 2

Pellet sizes depend on fish sizes, with usually 2 sizes being fed to the different (year 1 and year 2) year classes. Feed wastage varies with site-specific husbandry, but with hand (demand) feeding, rates of 1.4% have been observed (Thorpe et al. 1990) and values of 2.5% have been mentioned by the industry as a typical wastage factor. The levels are one order of magnitude below early published values (e.g. Gowen and Bradbury, 1987).

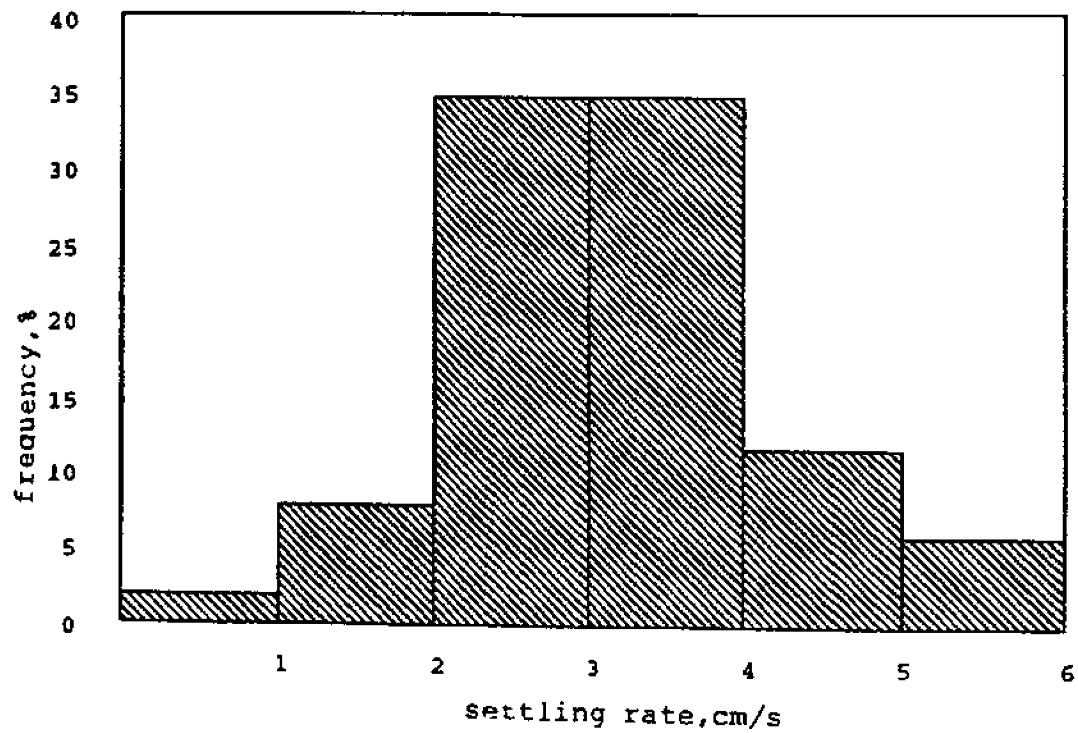


Fig. 3.1 Fecal pellet settling rate

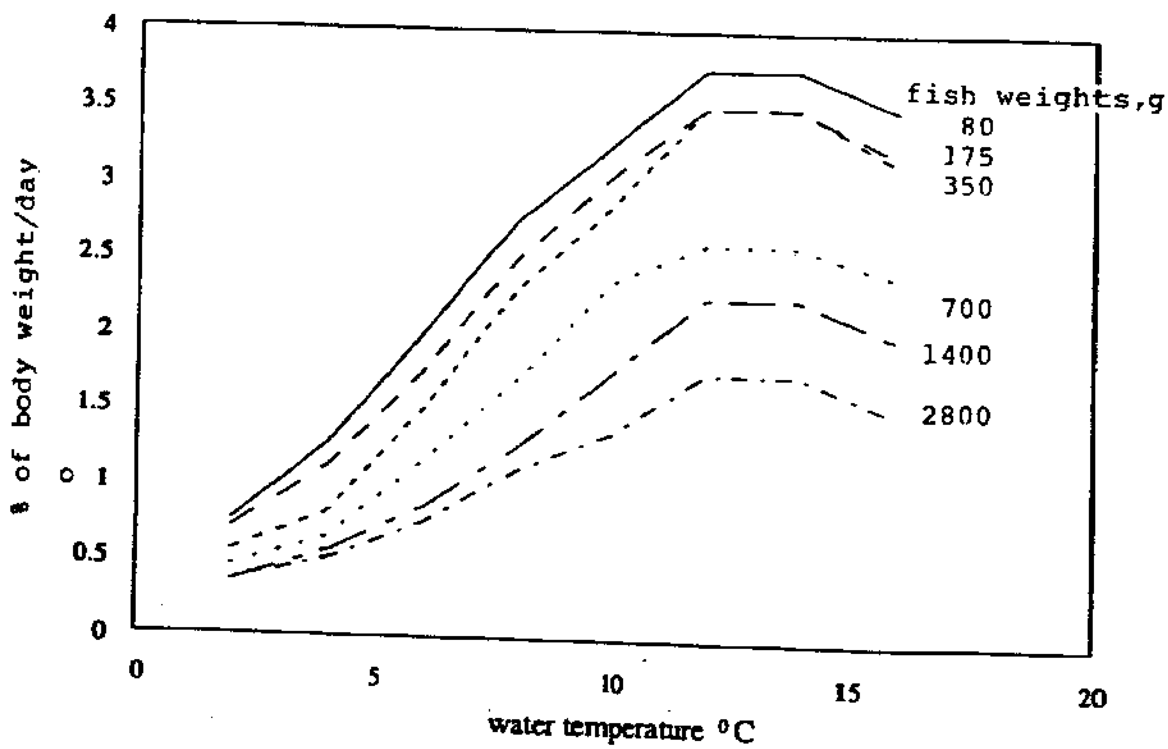


Fig. 3.2 Salmon feeding rates

4. AQUACULTURE WASTE-DISTRIBUTION IN COBSCOOK BAY

Cobscook Bay is located in the northern part of the Gulf of Maine, adjoining Passamaquoddy Bay and the mouth of the Bay of Fundy. It lies to the east of the international border separating the state of Maine, USA, from the Province of New Brunswick, Canada (Fig. 4.1). This region is well-known for its resonant tidal activity, with a tidal range greater than 15 m at the head of the Bay of Fundy during the spring tide. For the lunar semi-diurnal constituent (M_2), the mean tidal range in this area is about 5.5 m (Fig. 1.1). Cobscook Bay is a relatively closed region with an opening between Eastport and Lubec. The water depth is greater than 30 m in the main channel; the western part of the bay is much shallower. Tidal exchange between Cobscook Bay and the Gulf of Maine occurs through the confined and shallow Lubec Narrows, where tidal speeds can reach 4 to 5 m/s (Brooks and Churchill, 1991). The bathymetry in Cobscook Bay at low tide is shown in Fig. 4.2.

On account of the large tidal range, the northern Gulf of Maine has for long been considered to have the potential for the tidal power development. This has led to several numerical modeling studies (to examine possible impacts of tidal dams), but they have mostly dealt with the overall Gulf of Maine system (e.g. Greenberg, 1979; Sucsy et al. 1993). The scale of these studies was too coarse for their results to be directly applicable to the estimation of the environmental impacts of aquaculture in Cobscook Bay. A recent study by Brooks & Churchill (1991) was the first to model Cobscook Bay specifically. They used a hydrodynamic model called MECCA (Hess, 1989), with 10 vertical levels and a horizontal resolution of 225 m. Although the modeled tidal movement is generally consistent with many of the known aspects of the tidal regime in the bay, there was no detailed validation with data. Also, the resolution used was too coarse to simulate certain features like eddies, etc. which are known to exist and which can influence the dispersion of aquaculture wastes. Indeed, Brooks and Churchill (1991) noted that a study on a finer scale (with grid sizes approaching 100 m) is necessary for such simulation.

Because of its high current velocities and low temperature, fish-farming in Cobscook Bay is widespread with net-pens located in Broad Cove, Comstock Point, Deep Cove, Goose Island, Sheep Cove and elsewhere (see Fig. 4.3). Of these, three sites, viz. Broad Cove, Comstock Point, and Deep Cove were examined in detail in this study.

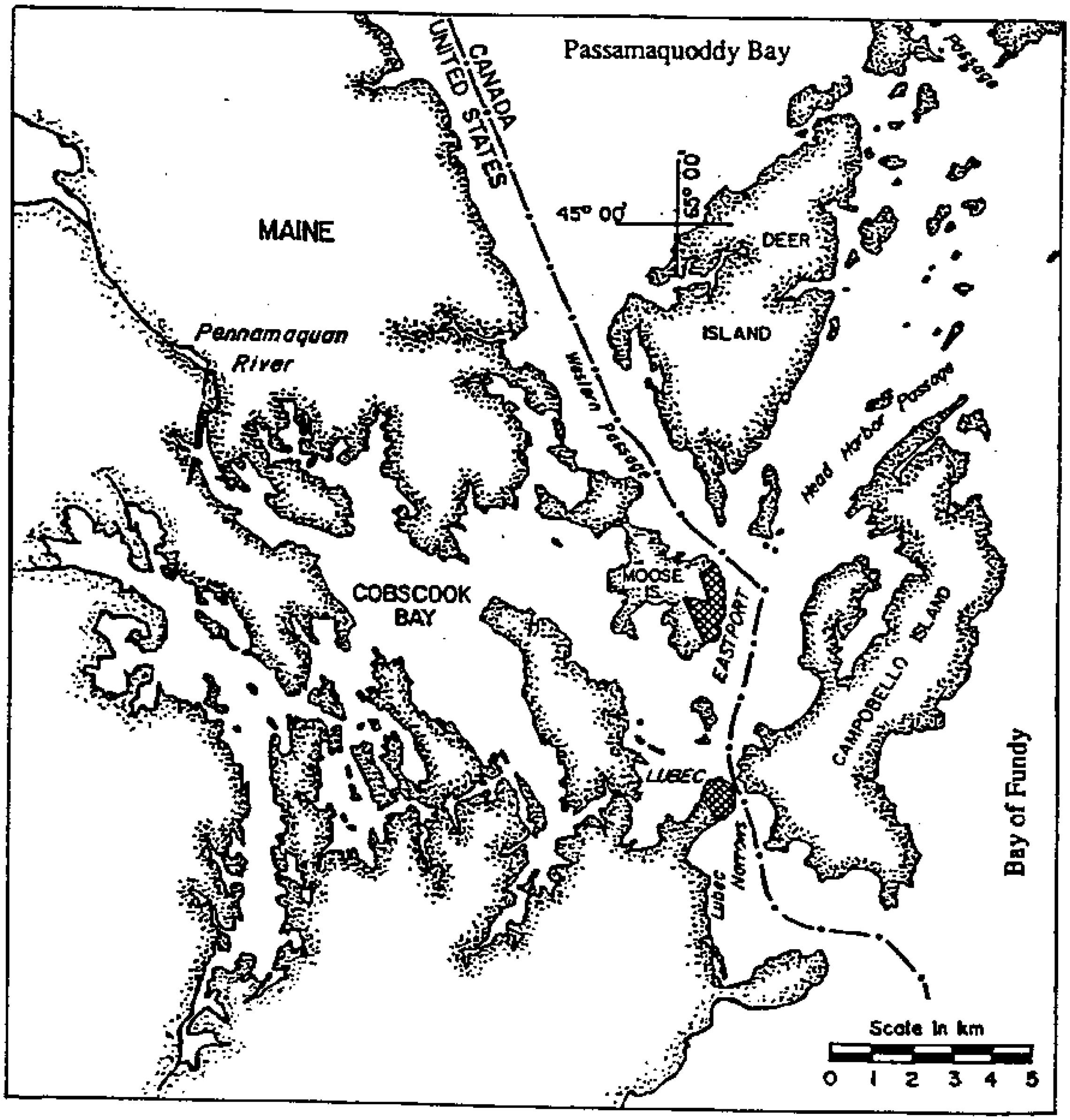


Fig. 4.1 Cobscook Bay (after Brooks & Churchill, 1991)

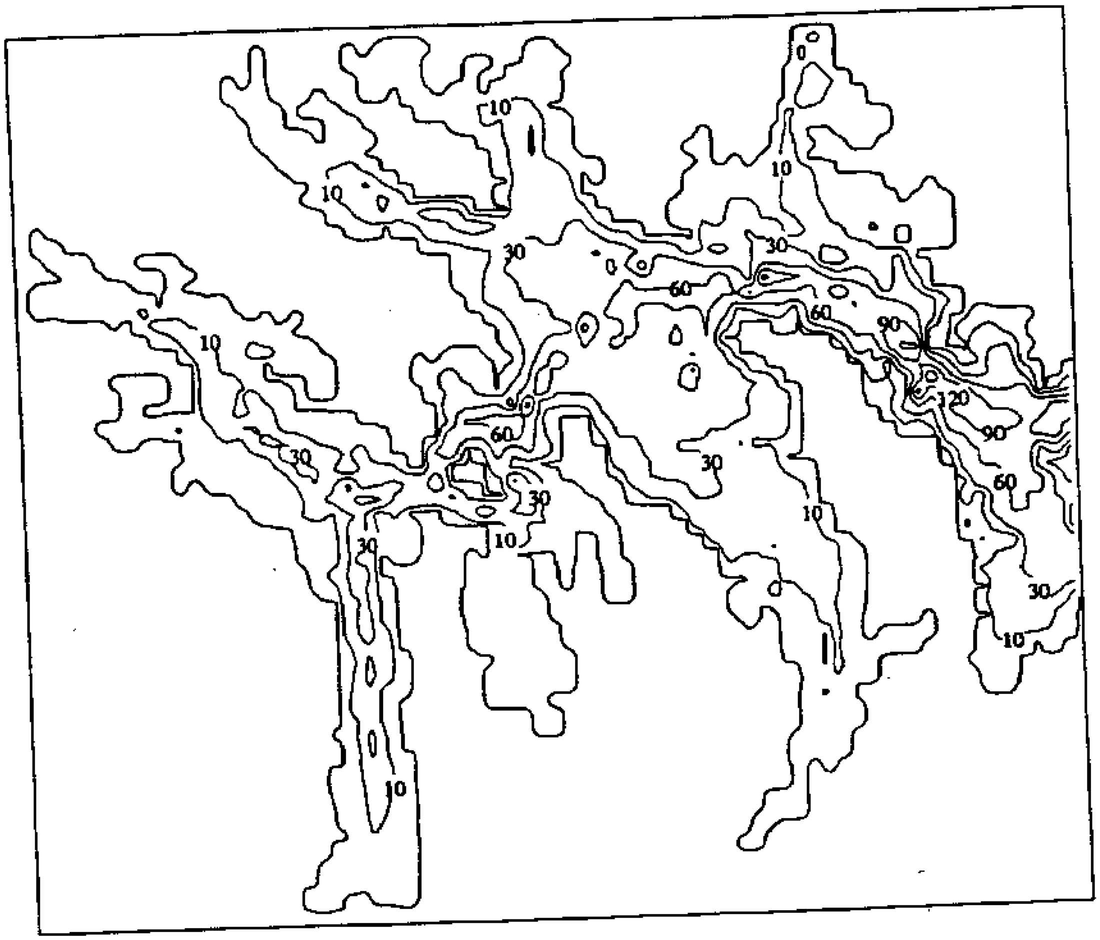
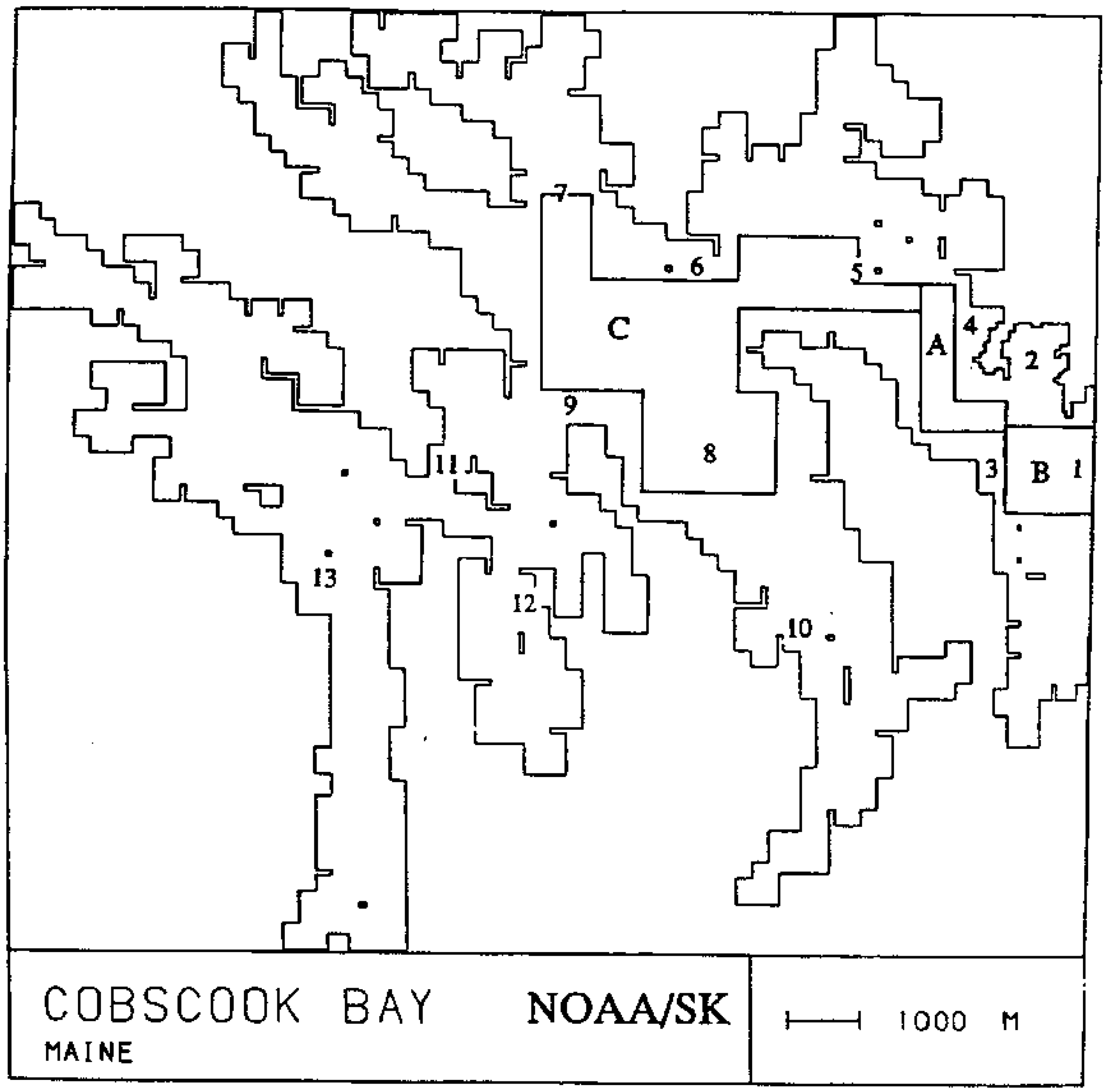


Fig. 4.2 Bathymetry in Cobscook Bay, in feet



		Region	Friction Coefficient
1 Eastport	8 South Bay	A	0.0008
2 Broad Cove	9 Denbow Point	B	0.008
3 Comstock Point	10 Horan Head	C	0.001
4 Deep Cove	11 Reversing Fall	elsewhere	0.03
5 Goose Island	12 Coffins Point		
6 Sheep Cove	13 Birch Island		
7 East Bay			

Fig. 4.3 Model domain in Cobscook Bay

4.1 2-d Flow Model Application

A bottom topography file containing depths digitized from NOAA Chart 13328 was provided to us by Dr. David Brooks of Texas A&M University. This file contained a total of 70x60 grids with a grid size of 225 m. Since this resolution was too coarse for our purposes (as discussed above), these data were interpolated onto a 75 m grid. Thus our study enhanced the resolution by a factor of 9 and used a total of about 208 x 178 = 37,024 grids. The coastal boundary was taken as the high-water land-sea interface (as done by Brooks and Churchill, 1991). The open boundary was taken on the eastern edge of the domain near Eastport. The overall model domain is about 15.5 x 13.7 km.

The 2-d model DUCHESS was forced by the M-2 semi-diurnal tide along the open boundary near Eastport. The amplitude was specified as 3.54 m (spring tide) and assumed to be uniform along the boundary. A maximum time step of 40 seconds was used to meet the stability criterion of the model (for a grid size of 75 m). The computation takes about 1.2 hours of CPU time on the University of Maine IBM 3090 for each tidal cycle, and model spin-up required about two to three tidal cycles (i.e. about 3 hours of CPU time). As anticipated by Brooks and Churchill (1991), modeling Cobscook Bay on this scale is extremely computer-intensive, even with a 2-d model. Flooding and drying were not included for the simulation initially, since this feature necessitates an adjustment of the available bathymetry file from mean low water to mean sea level or to mean high water. This was therefore done for later runs on smaller subdomains only.

Model Validation and Results

There are two parameters in the 2-d flow model that can be used for tuning: the horizontal eddy viscosity (N_h) and the bottom friction coefficient (f). Lacking the benefit of experience of other modeling studies in Cobscook Bay, we initially used a constant N_h of 10 m^2/s. Subsequent runs were made to determine the sensitivity of the results to this parameter and to obtain results that matched data. We found that model results were quite insensitive to the eddy viscosities. When N_h was varied over a range between 10 m^2/s to 100 m^2/s, the maximum modeled velocity differences were of the order of only 5%. A value of 100 m^2/s was therefore used for the subsequent runs.

On the other hand, the modeling exercise was considerably influenced by the value of the bottom friction. With a constant bottom friction of 0.03, we were unable to obtain successful model runs. Difficulties were encountered near the model boundaries where the depths change rapidly or are small. Lower friction factors, in the range of 0.0008-0.001, were therefore assigned to the central deeper parts of the bay. The higher values in this range generally produced lower velocities in the central channel. In general, the friction factor is spatially quite non-uniform (and possibly even time-dependent). It is influenced by the depths as well as the geometry of the domain. Tuning such a large model with too many degrees of freedom is extremely cumbersome. Ultimately, after several runs with different values of friction, it was found that a combination of friction factors as shown in Fig. 4.3 gave reasonably good simulations of observed data.

The results are shown in Fig. 4.4(a-d) in the form of 4 velocity vector plots for the entire domain for one tidal cycle at intervals of about three hours.

Comparison of Model Output with Data

Table 4-1 gives a comparison of modeled amplitudes and phases of the water surface elevation with observed data at 12 locations. The phases at these locations are all calculated relative to Eastport. Our tidal data from 4 locations (Eastport, Goose Island, Denbow Point, and South Bay) showed the influence of tidal constituents other than the M_2 (as well as that of possible wind-driven effects). The modeling study on the other hand was restricted to the M_2 tide only (since this is adequate for the task at hand). Thus for comparison, only those data cycles were selected for which the tidal amplitude was approximately 3.54 m at Eastport (e.g. July 2, 1992). In addition, tidal data for the same date at five other substations (Deep Cove, Horan Head, East Bay, Coffin Point, and Birch Island) were obtained from NOAA Tide Tables. These are also presented in Table 4.1. The comparison shows that the model produces very satisfactory simulations of the tidal behavior.

As seen in Table 4.1, the phase differences between the various locations range from several minutes to almost one hour, depending not only on the distance but also on the bottom topography and geometry. The phase differences are apparent in Fig. 4.4 as well. The Reversing Falls region is an excellent example of this. This region, which consists of a narrow passage, is characterized by a visually discernible water surface slope that reverses direction with the tide. High velocities in this region, of the order of 4m/s, have been reported by Brooks & Churchill (1991). Our calculations result in a maximum velocity of the order of 2.5 m/s. The differences in the tidal amplitudes and phases before

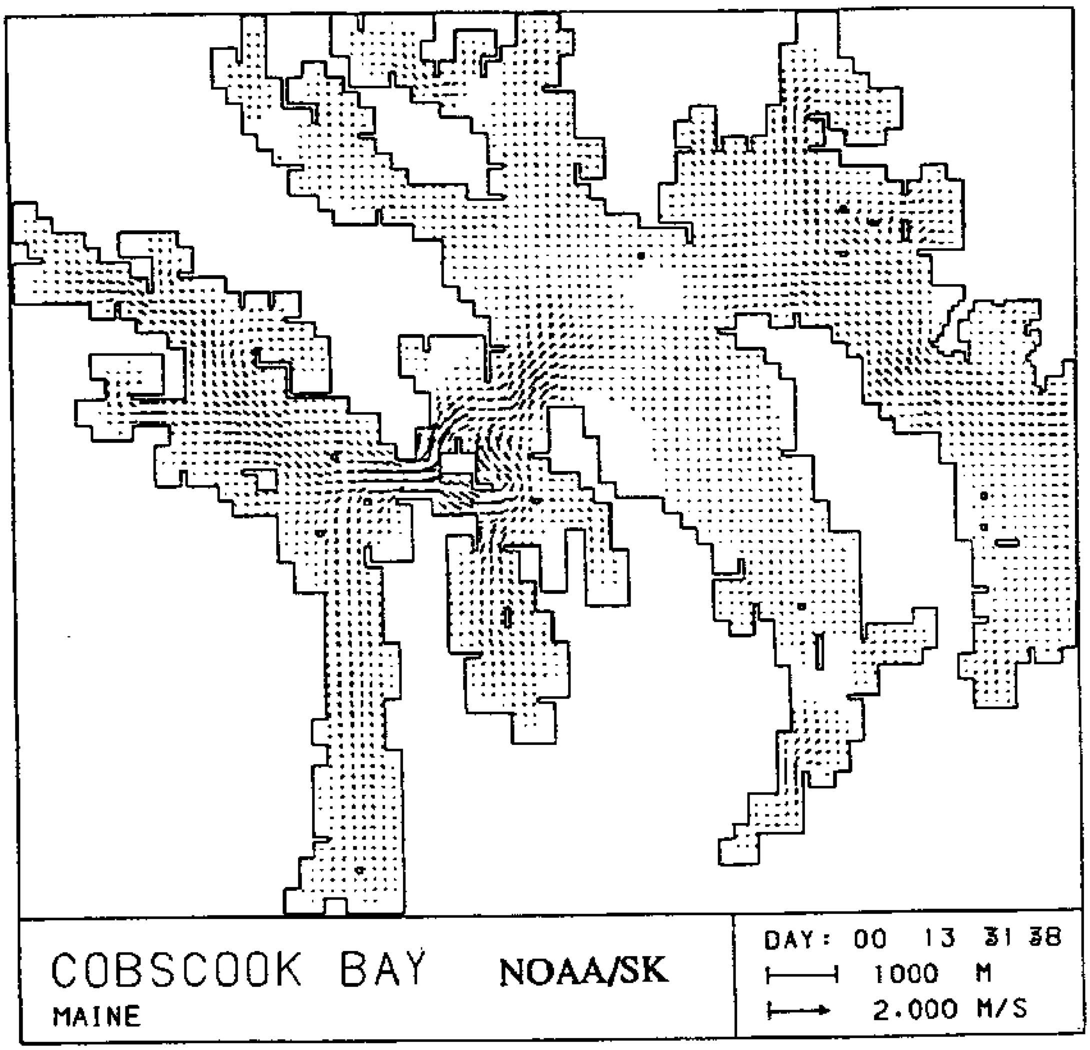


Fig. 4.4a Modeled velocities in Cobscook Bay (t = T, low tide)

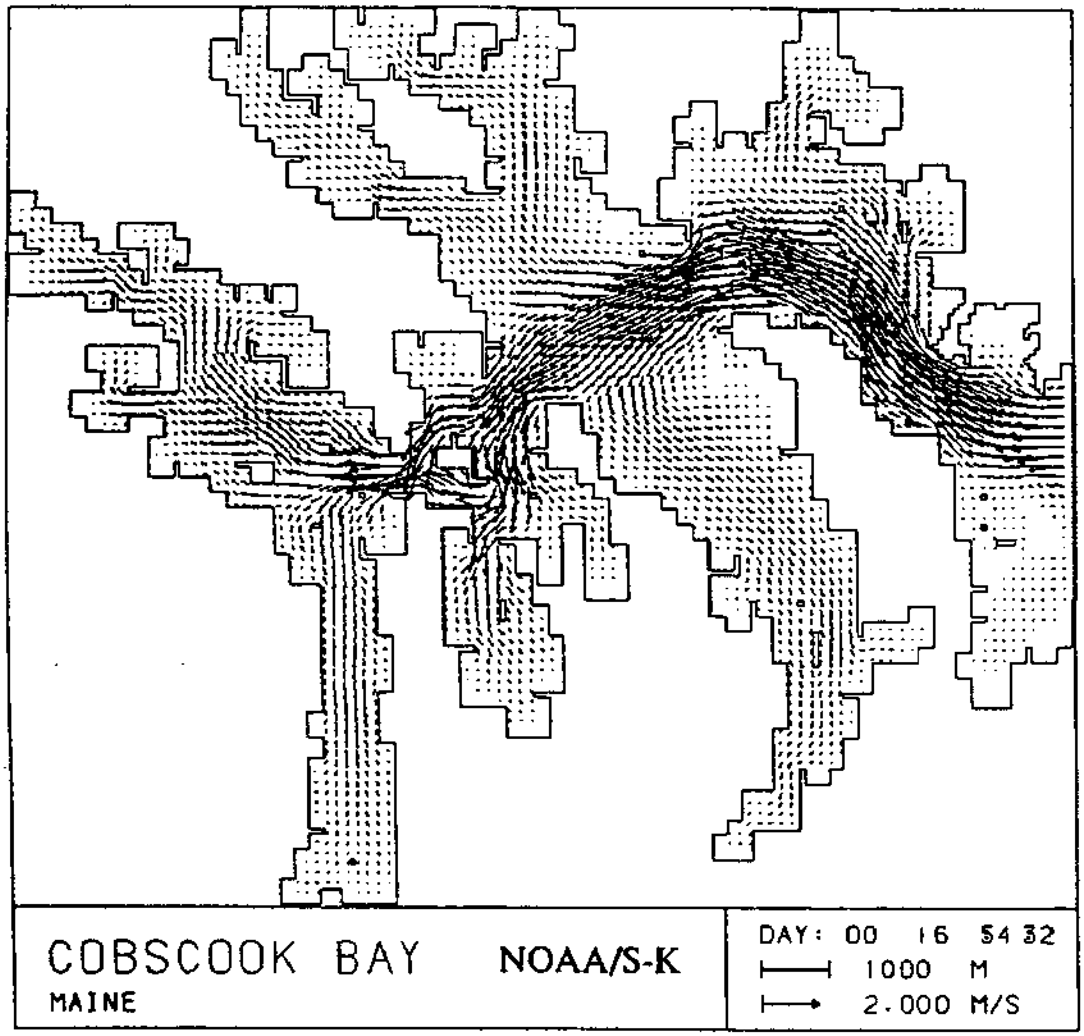


Fig. 4.4b Modeled velocities in Cobscook Bay (t = T+3hrs, mid-tide, flooding)

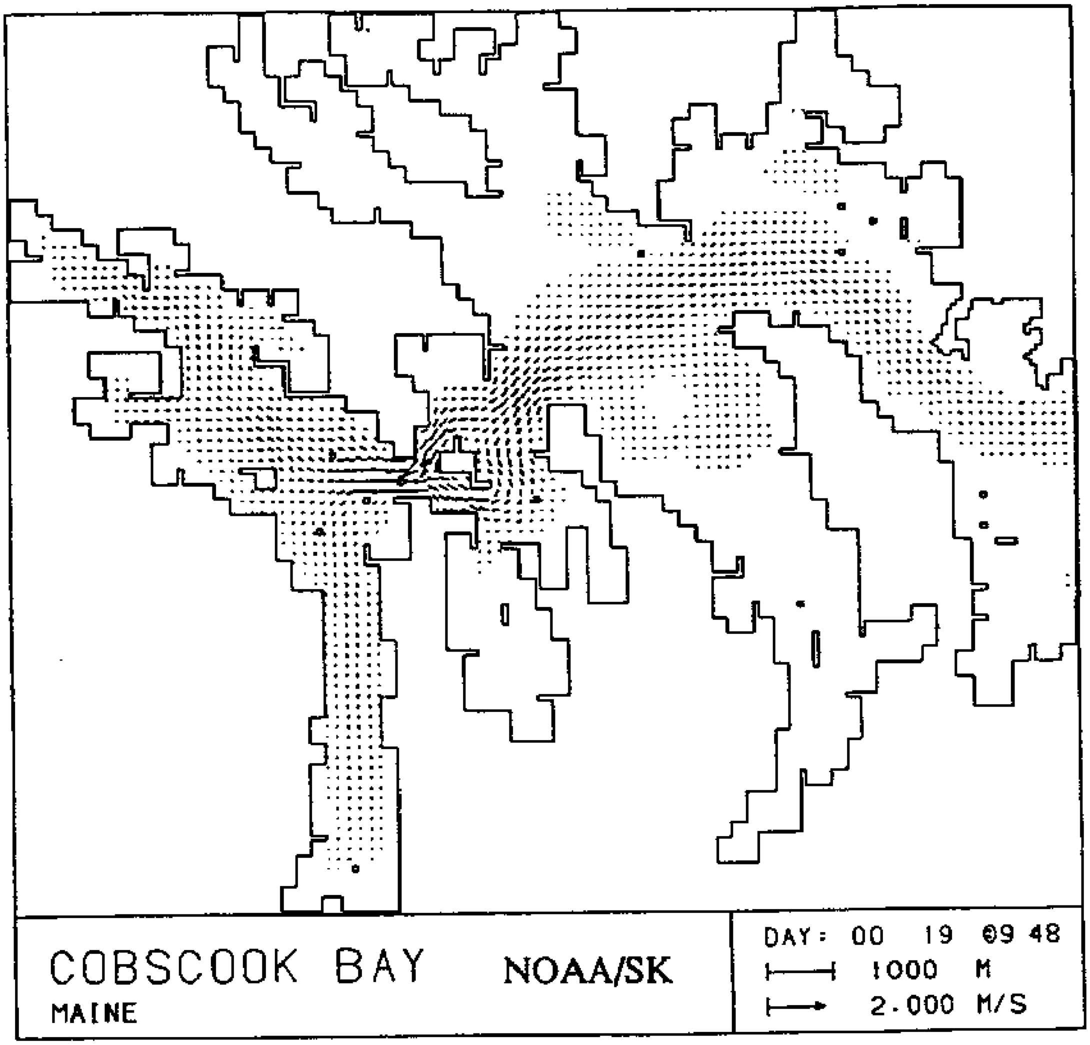


Fig. 4.4c Modeled velocities in Cobscook Bay (t = T+6hrs, high tide)

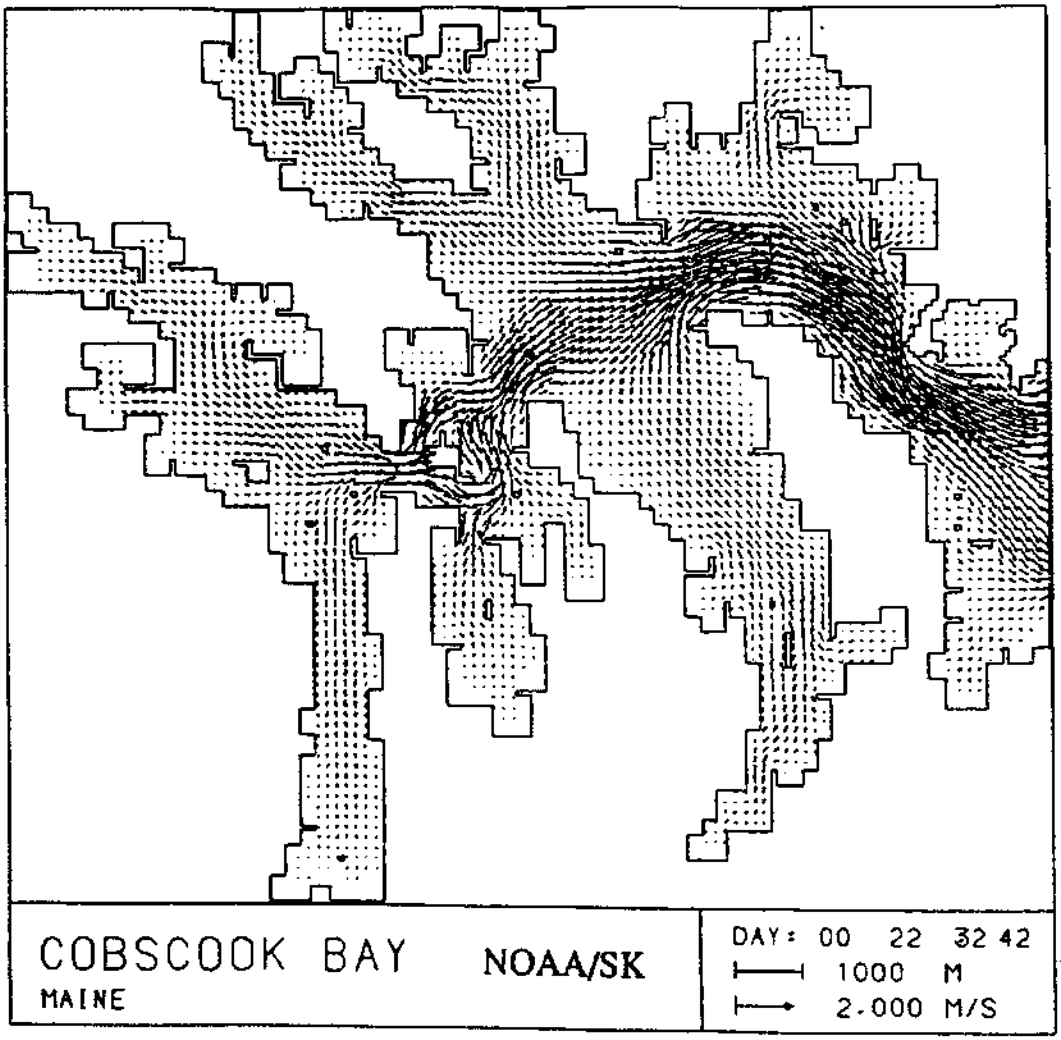


Fig. 4.4d Modeled velocities in Cobscook Bay (t = T+9hrs, mid-tide, ebbing)

Table 4.1 Tidal data comparison

Location		East Port	Goose Id	Denbow Pt	South Bay	Deep Cove	Horan Head	East Bay	Coffin Pt	Birch Id	Sheep Cove	Before Falls	After Falls
Model output	Phase-min	0	14	20	20	10	20	23	33	60	17	27	56
	Tidal range -m	7.1	7.0	7.0	7.0	7.2	7.0	7.0	6.5	6.2	7.0	6.8	6.2
Field data	Phase-min	0	0	--	15	8	18	14	33	65	--	--	--
	Tidal range -m	7.2	6.9	7.0	7.2	6.7	6.9	6.8	6.5	6.3	--	--	--
(July 2,1992)						*	*	*	*	*			

* Data from NOAA Tide Tables 1992, East Coast of North and South America

and after the Falls are substantial (Table 4.1). This creates an elevation difference of about 1 m over a relatively short distance of about 300 m.

Fig. 4.5 shows a comparison of the modeled velocities with our measurements in Broad Cove. Both components of the modeled velocities match the data very well. Additional comparisons are made with field data obtained previously by Brooks & Churchill (1991) in Sheep Cove. However, it is difficult to obtain a proper comparison with these data, because the exact location of these data is not certain, and the modeled velocities show considerable spatial variations due to the complex nature of the bathymetry and geometry in this region. In addition, the small island (Red Island) in Sheep Cove is not properly represented in the model with the resolution used. Modeled data from two grids in the vicinity of the measured data are presented in Fig. 4.6; model results from the study of Brooks and Churchill (1991) are also shown. For the east-west components, our model output and the field data have the same magnitude and both show a higher flooding velocity than ebbing velocity. The MECCA model results of Brooks and Churchill (1991), on the other hand, show complete symmetry. For the north-south components, the field data show that ebbing is much more stronger than flooding; our model output shows this dominance, but to a smaller extent; the magnitude also is smaller. The results of Brooks and Churchill (1991) are, as before, symmetric. This is probably due to the coarser grids used in their study, which makes it difficult to properly represent the coastal topography, and due to a linear model run.

Although our 2-d model simulations of the flow in Cobscook Bay are successful, it is quite time-consuming to run such a large job (within the framework of the priorities of the University of Maine computer center). This makes it difficult to perform repeated runs to study local features at particular regions of interest. For example, Fig. 4.4 shows the presence of a gyre in Broad Cove. Such a gyre is known to exist, but previous modeling efforts have been unable to simulate it, possibly due to the use of a coarse resolution. To investigate such local features, it is more convenient to make improvements to the topography and perform simulations on a subdomain scale. This method of making model runs consists of isolating various subdomains prior to a full model run. The necessary information on the boundaries of the subdomain are saved and used to force a subsequent model run for this subdomain only. This option was also used to model the effects of flooding and drying of shallow areas. The desirability of incorporating such dynamic boundary effects had been emphasized by Brooks & Churchill (1991). However it is too time-consuming to do so for the entire Cobscook Bay model domain. To facilitate detailed

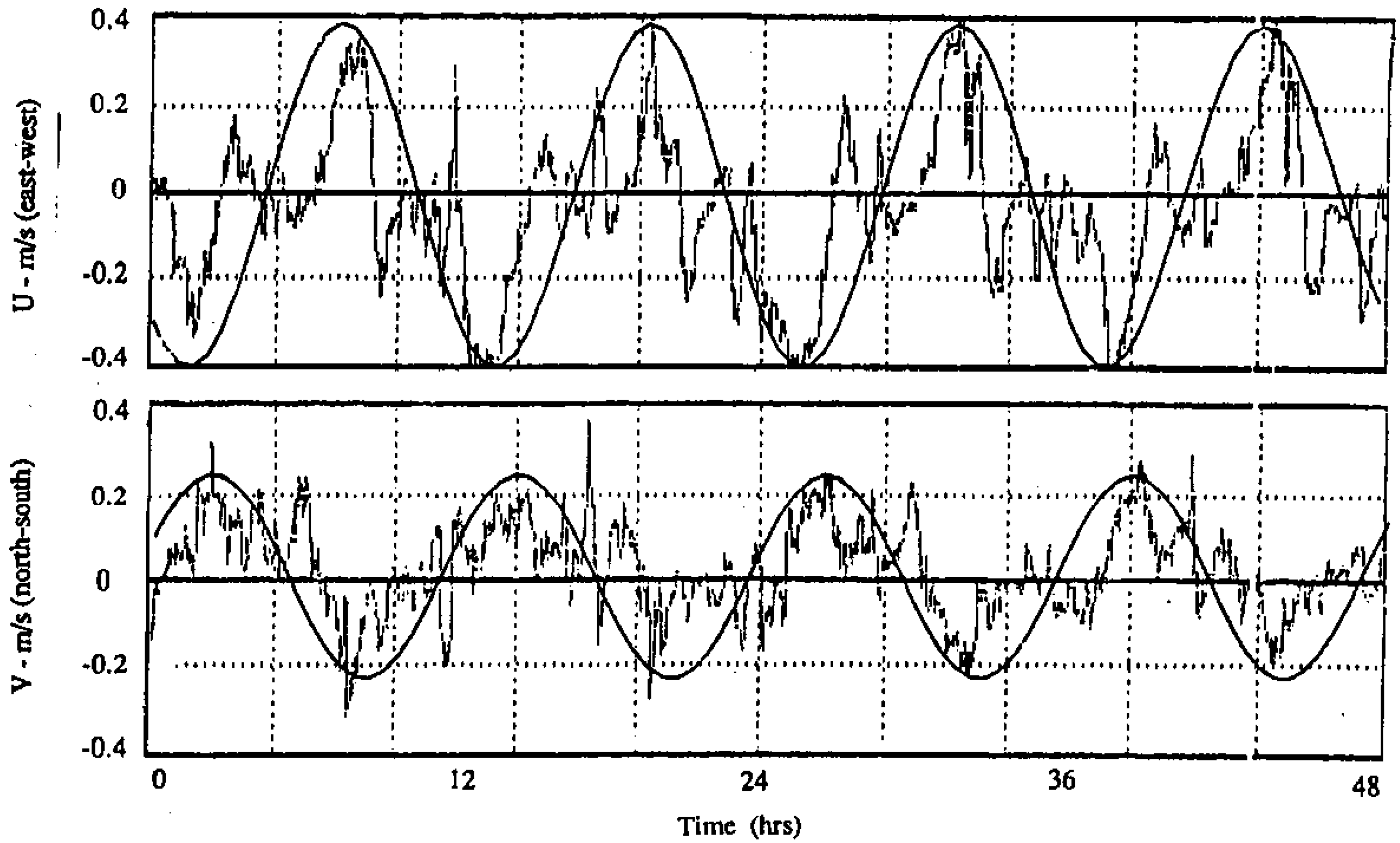
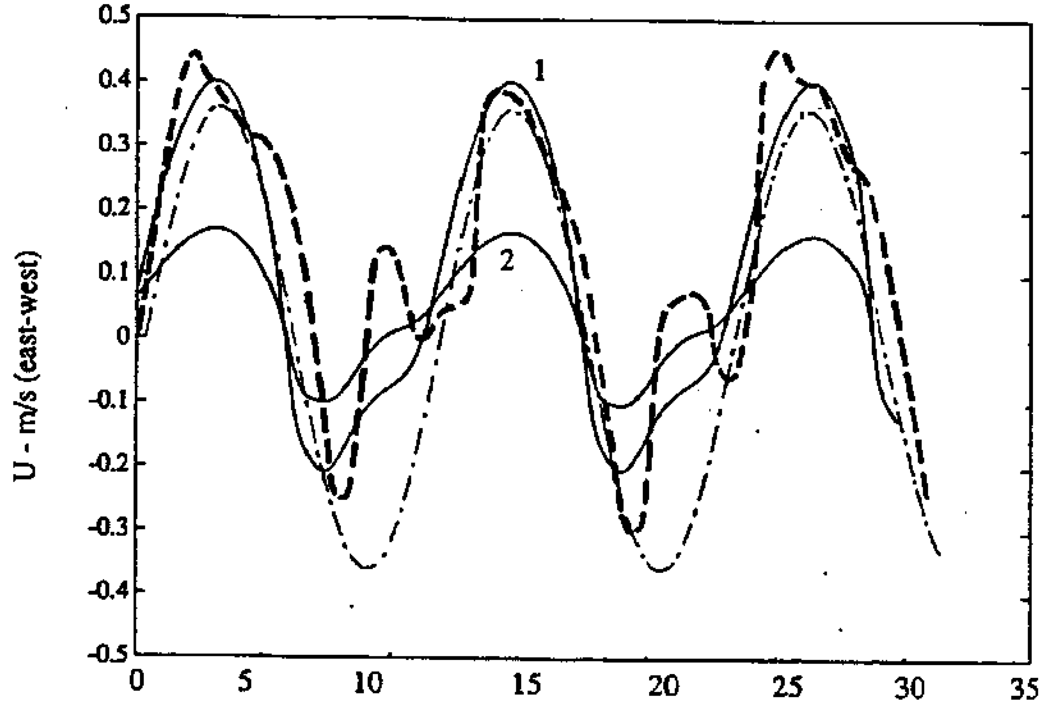


Fig. 4.5 Tidal velocity comparison in Broad Cove
observed ——— model



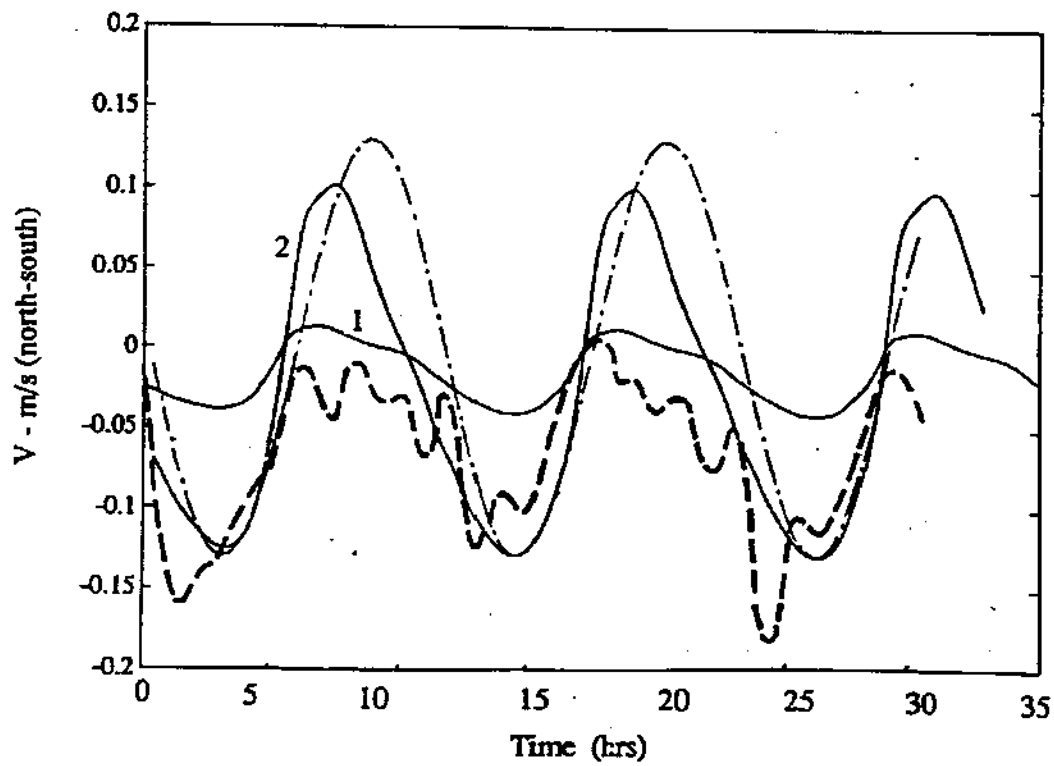


Fig. 4.6 Tidal velocity comparison in Sheep Cove

— — — observed (Brooks & Churchill, 1993)

—· — model (Brooks & Churchill, 1993)

__1__ model (Present Study), Point 1

__2__ model (Present Study), Point 2

examination of the hydrodynamic features in regions where aquaculture activities are located, three subdomains were chosen: Broad Cove, Deep Cove, and Comstock Point. For these runs, we retained the same grid size (75 m) as that for the overall model, for two reasons. First, we wished to avoid further interpolation of the topography, which would cause loss of accuracy around the land-sea interface, and difficulties in redefining the computational and non-computational grid points along the coastline. Second, a resolution finer than 75 m would require immense memory to store the current and depth information for all grids for the subsequent task of modeling the contaminant transport.

Fig. 4.7 (a-l) shows the hydrodynamic features in Broad Cove. The dashed line represents the moving shoreline. It can be seen that the dry area gradually increases to its maximum at low tide and then shrinks until the shoreline coincides with the fixed land boundary at high tide. For the model simulation, the energy of the system will be changed as a result of such flooding and drying. This manifested itself in the form of irregularities and rapid changes in some of the modeled coastal velocities (not shown).

Fig. 4.7(a-l) also shows the generation, dissipation, and reformation of a gyre in Broad Cove. (Gyres are seen elsewhere as well.) The position and the flow pattern of the gyre in Broad Cove changes in intensity: once generated in the Cove, it moves outwards before dissipating in the main channel of Cobscook Bay. As the tidal flow direction reverses, it reforms with a reverse pattern. Langoen & Kranenburg (1993) recently performed measurements and computations of the flow in a model harbor connected to a river with an oscillatory current, varying sinusoidally in time with a period of 500 seconds. Their measurements show the presence of a gyre similar to that obtained in Broad Cove. Fig. 4.8a shows the measured flow and Fig. 4.8b shows the comparison of their measurements with the results of a 2-d flow model along two transects through the center of the gyre. When the currents are at a maximum, a gyre is generated in the harbor; when the velocity in the river decreases, the gyre starts to increase in size and move towards the river until it disintegrates. Then a new gyre with a reverse flow pattern develops as the current changes direction in the river. Our results for Broad Cove show essentially all these features, which further instills faith in the performance of our simulation. Langoen & Kranenburg's (1993) assertion that the mesh size is important in order to simulate this phenomenon is supported by the modeling studies in Cobscook Bay: our study was able to simulate the gyre (with a 75 m grid), and that of Brooks & Churchill (with grid size of 225 m) was unable to do so.

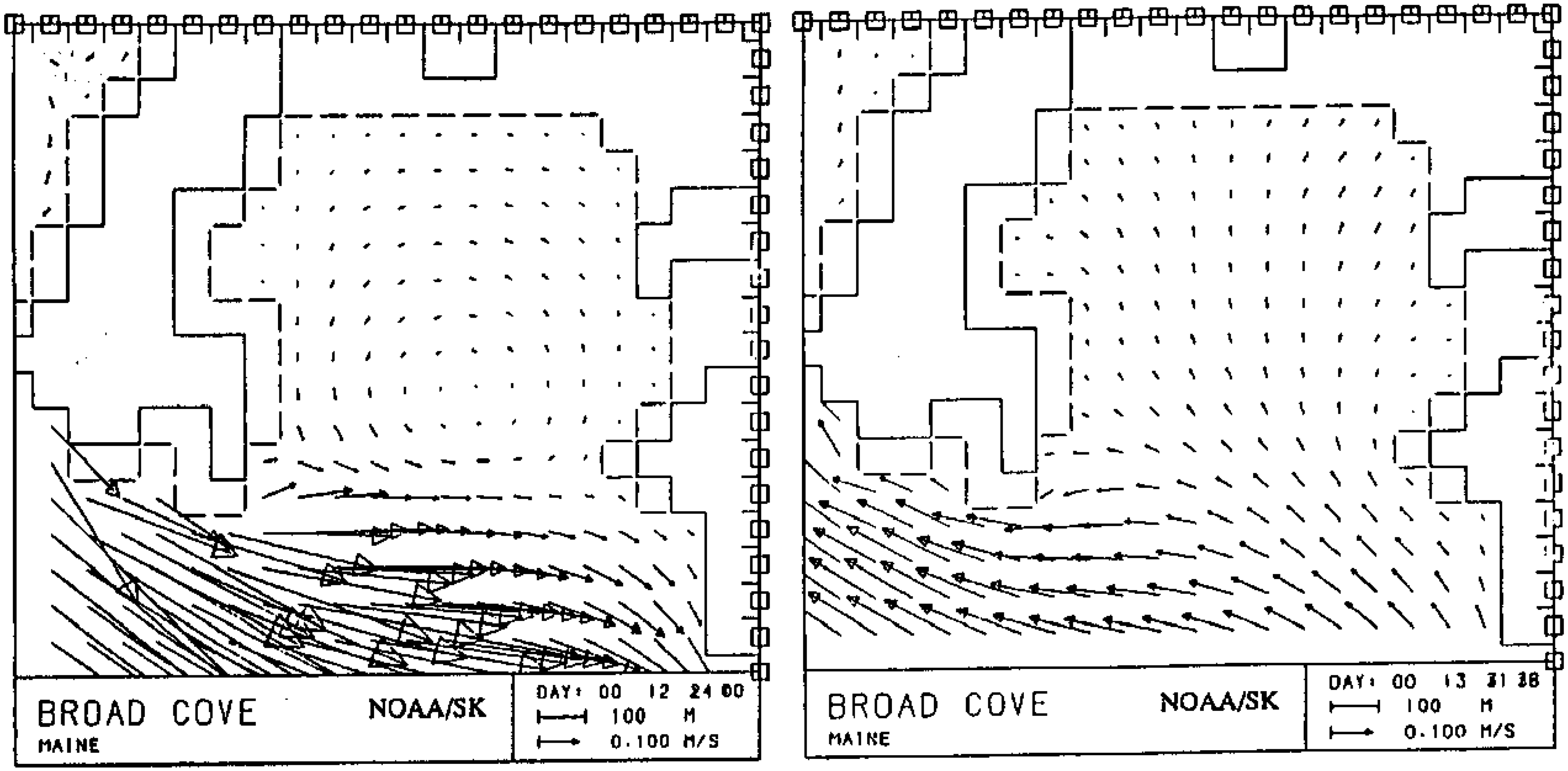


Fig. 4.7 Modeled velocities in Broad Cove
a (left): t = T, just before low tide; b (right): t = T+1hr

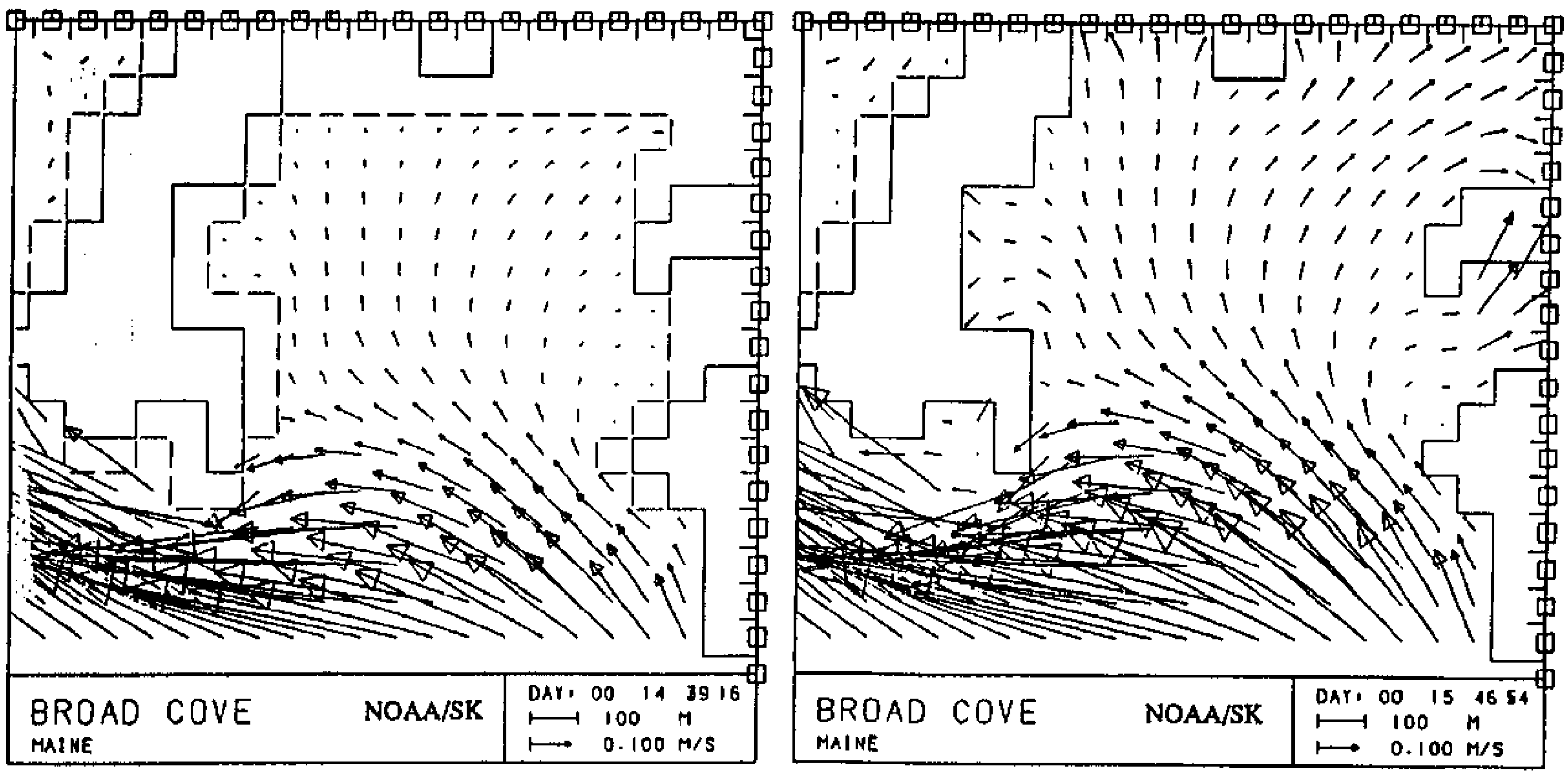


Fig. 4.7 Modeled velocities in Broad Cove
c (left): t = T+2hrs; d (right): t = T+3hrs

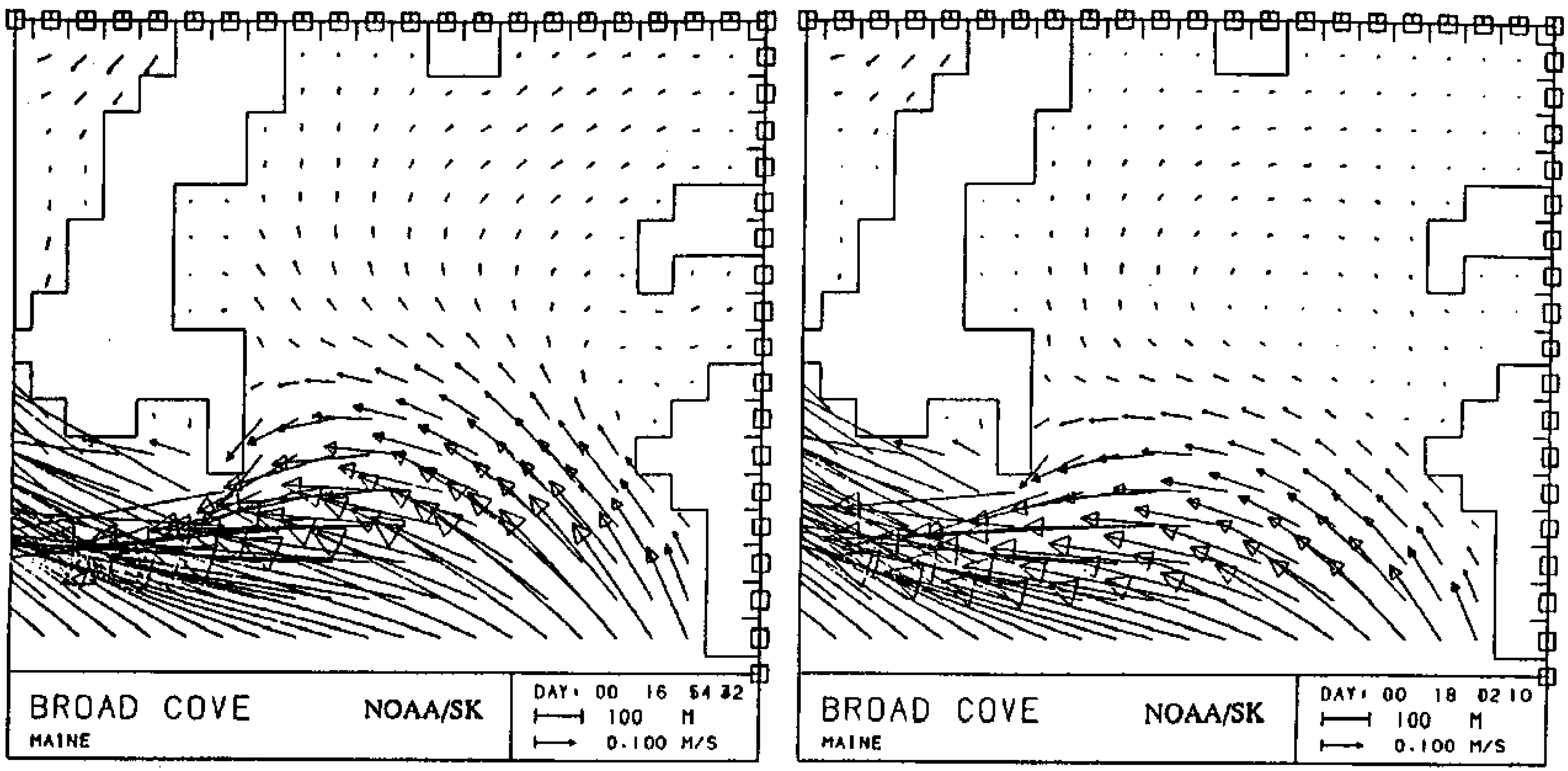


Fig. 4.7 Modeled velocities in Broad Cove
e (left): t = T+4hrs; f (right): t=T+5hrs

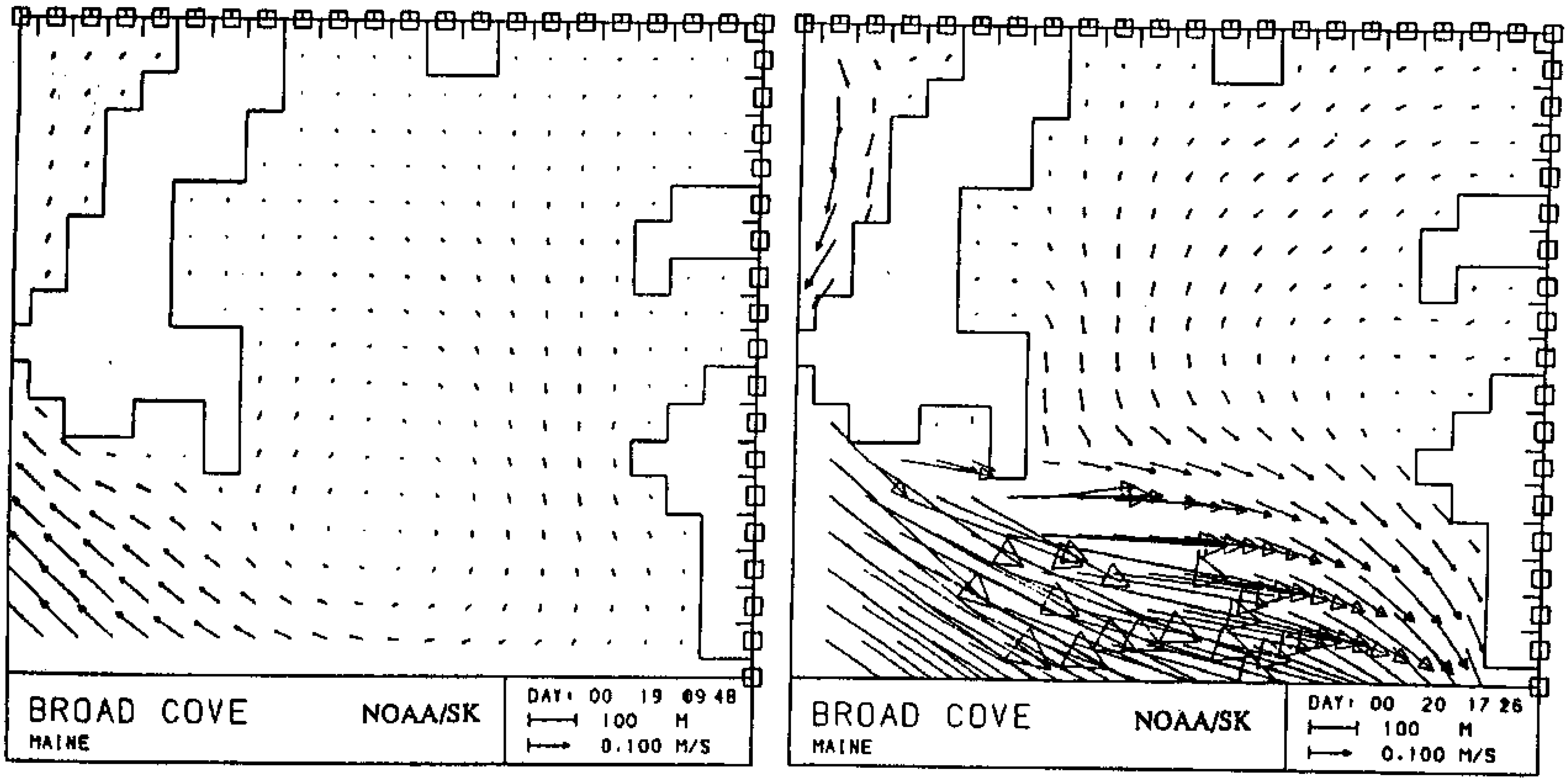


Fig. 4.7 Modeled velocities in Broad Cove
g (left): t = T+6hrs, just before high tide; h (right): t = T+7hrs

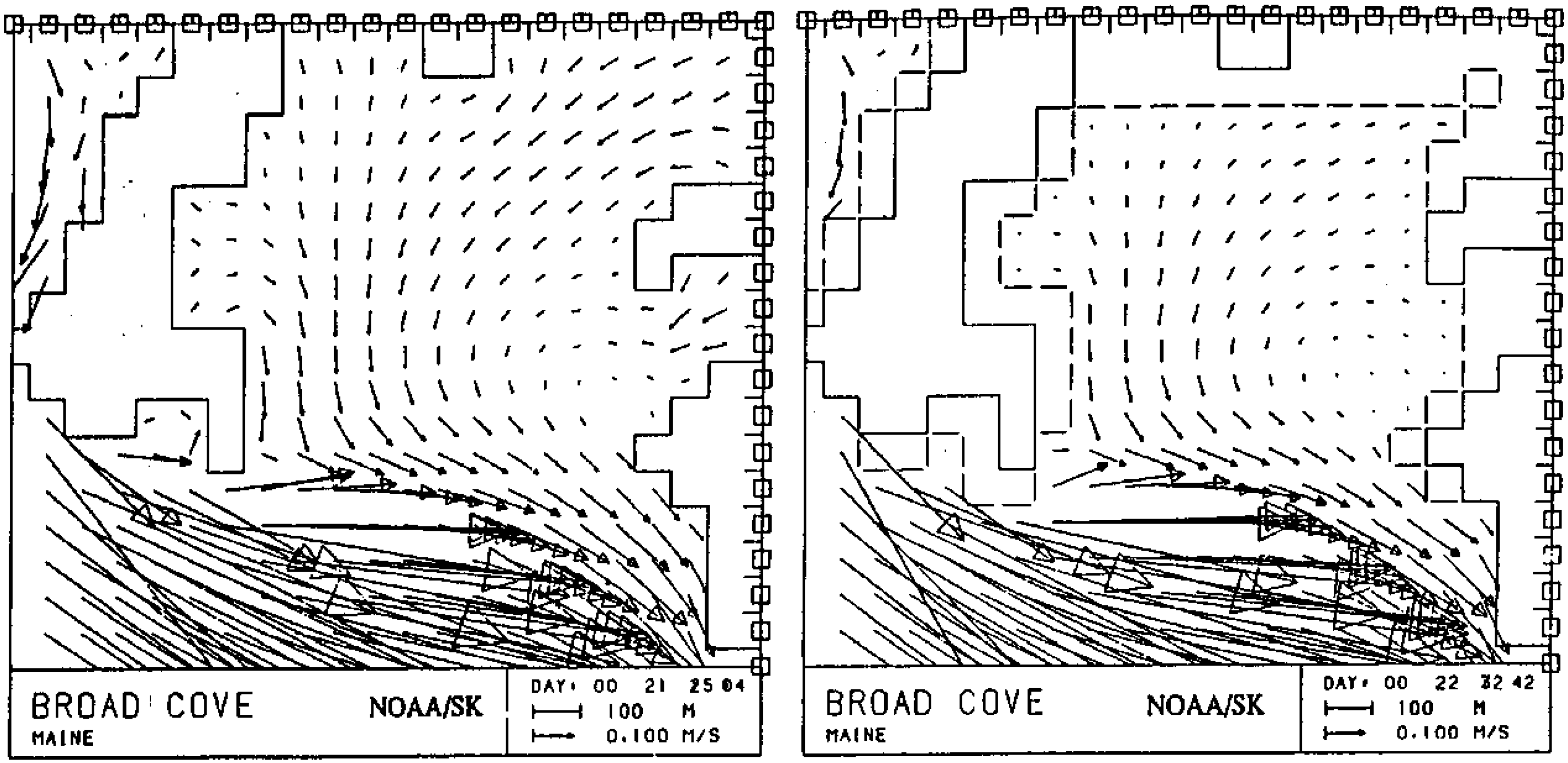


Fig. 4.7 Modeled velocities in Broad Cove
i (left): t = T+8hrs; j (right): t = T+9hrs

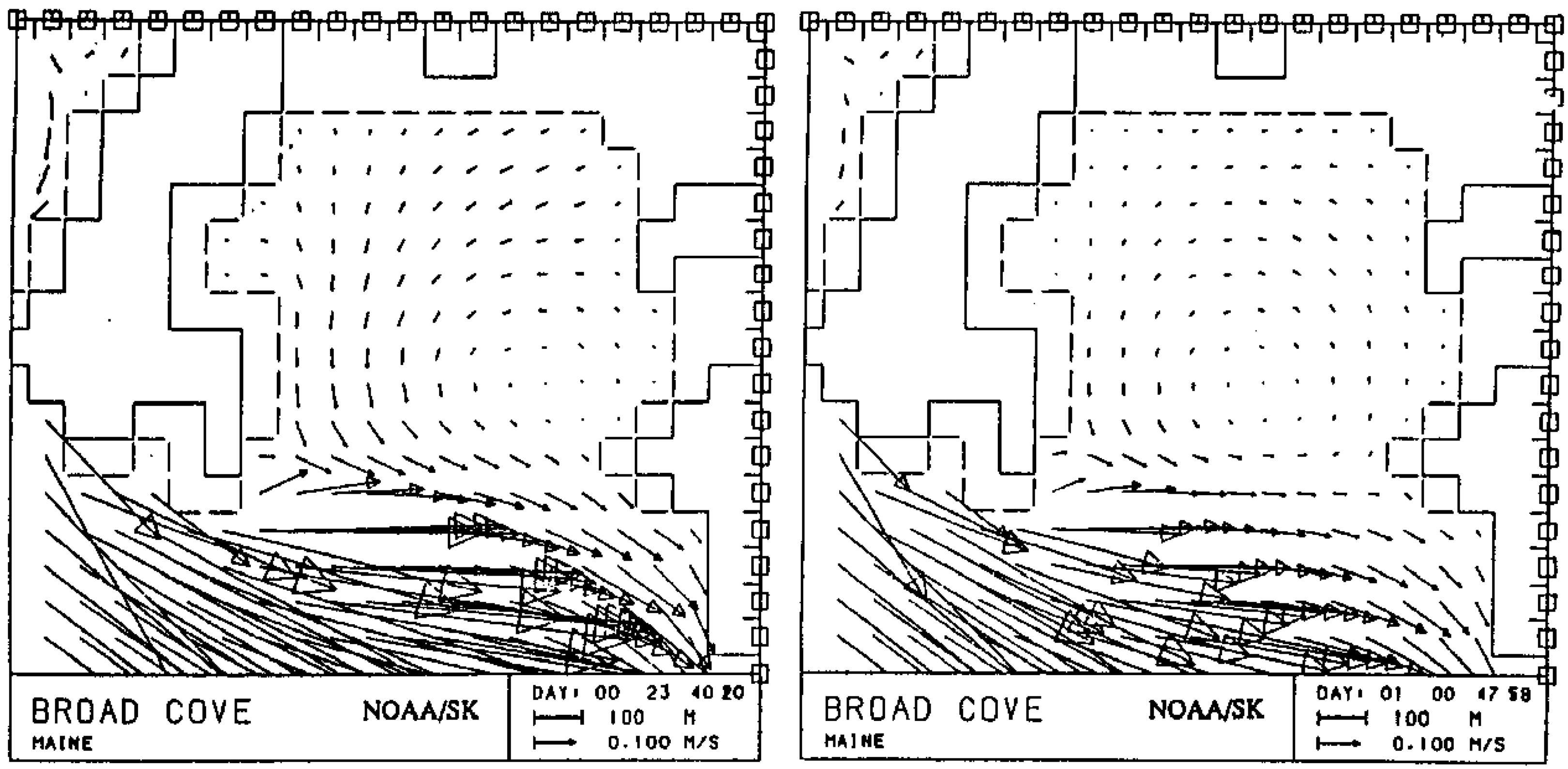
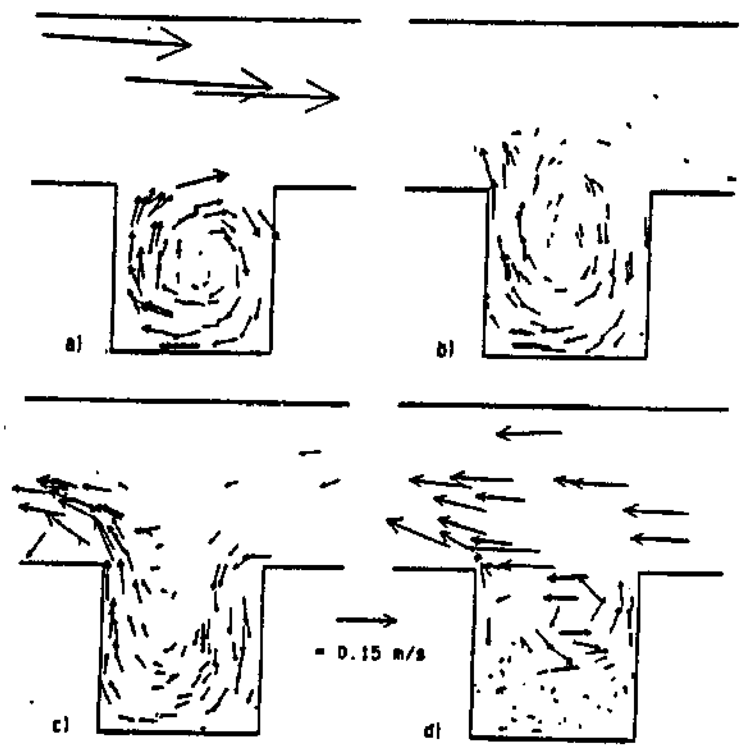
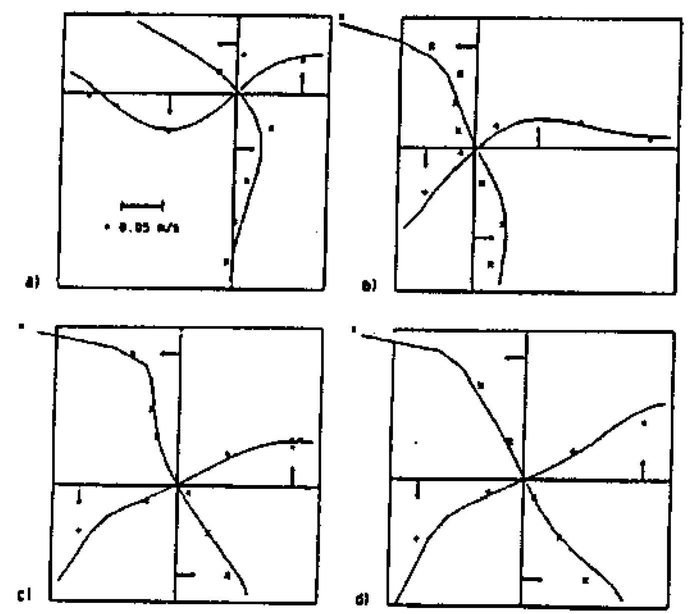


Fig. 4.7 Modeled velocities in Broad Cove
k (left): t = T+10hrs; l (right): t = T+11hrs



a. Measured Depth-Averaged Flow
a) t=150s b) t=250s c) t=260s d) t=280s



b. Velocity profile along two transects through the center of the computed gyre
a) t = 280s b) t = 310s c) t = 340s d) t = 375s
+ measured — computed

Fig. 4.8 Physical and numerical model simulations of unsteady flow in harbors (from Langoen & Kranenburg, 1993)

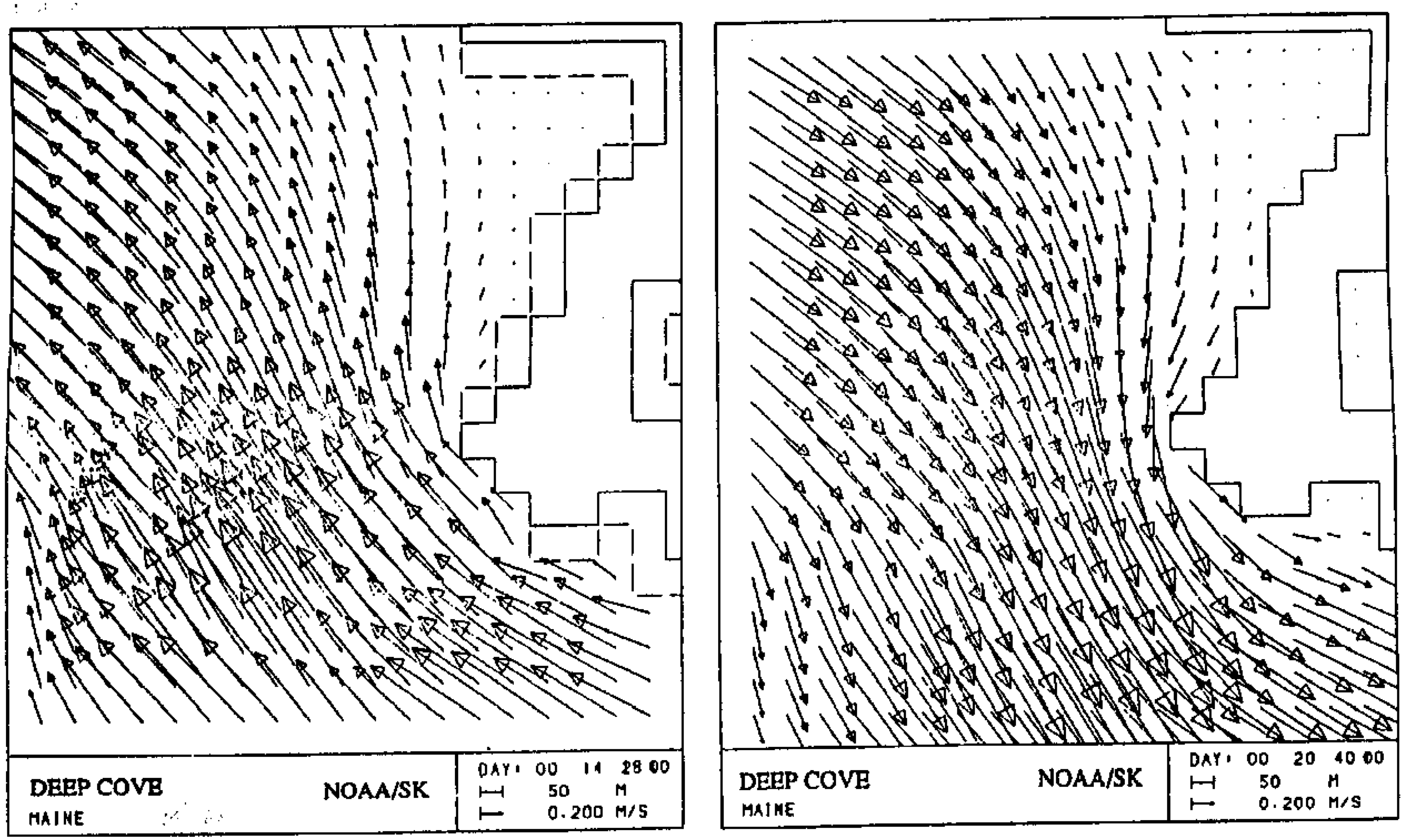


Fig. 4.9 Modeled velocities in Deep Cove

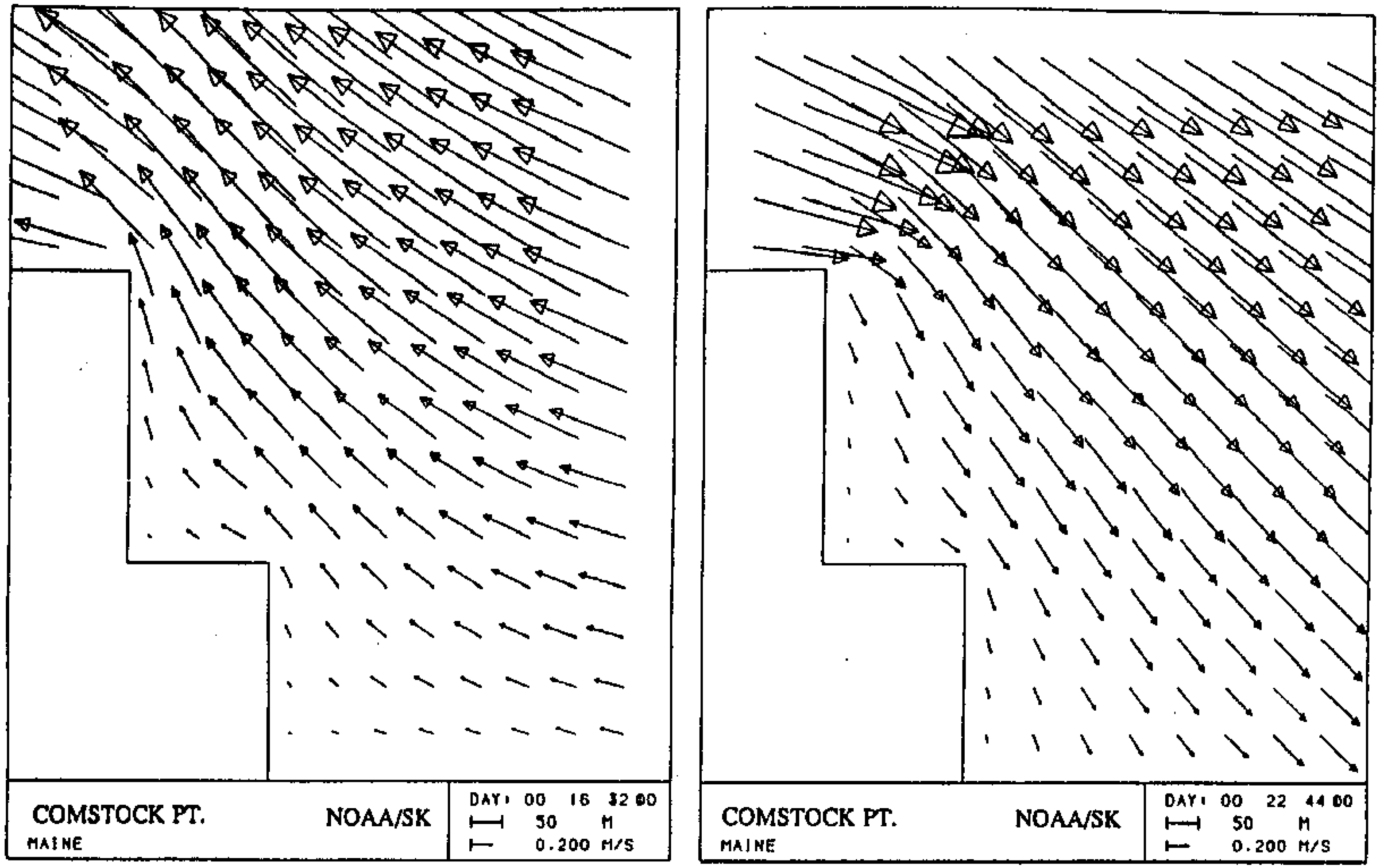


Fig. 4.10 Modeled velocities in Comstock Point

Subdomain model runs for Deep Cove and Comstock Point are shown in Fig. 4.9 and Fig. 4.10, respectively.

4.2 Velocity Profile

A model based on eq. 2-5 and eq. 2-6 to calculate the vertical variations in horizontal velocities was developed. It uses, as input, the surface slopes (calculated by differencing surface elevation data at adjacent grid points of the 2-d flow model) and the vertically-averaged velocities. One location near the net-pens in Broad Cove is chosen for this calculation. The model is started from rest and run until time-harmonic steady-state is reached. Eleven grid points (with a dz of about 1.2 m) and a time-step of 40 seconds were chosen.

As noted in Section 2.1.2, the vertical eddy viscosity is a parameter in this model; a range of values between 0.00875 m^2/s to 0.065 m^2/s, suggested by Lardner & Cekirge (1988) and by Tee (1982), was considered. A constant eddy viscosity was initially chosen. The results are shown in Fig. 4.11(a-c). It is observed that the lower eddy viscosities result in bottom velocities that are much too high (about 2.0 ms^{-1} when the vertically-averaged velocity is only about 0.3 m/s). The measured data in Broad Cove, however, do not support such results; it would thus appear that the higher eddy viscosities are inappropriate.

The effect of varying the vertical eddy viscosity was next examined. The 4 profiles shown in Fig. 2.1 were used. The results shown in Fig. 4.12 appear to be essentially the same as that when a constant eddy viscosity of 0.065 m^2/s is used, except for some differences near the bottom. The varying eddy viscosity profiles also appear to produce excessively large bottom velocities. A comparison of all these results with the data shown in Fig. 4-13a implies that it is sufficient (and simpler) to use a constant vertical eddy viscosity of 0.065 m^2/s for further calculations.

An important feature of all these profiles is that the velocity is largely uniform in the vertical, except for some variation within the bottom one or two meters. The measured data also confirmed this. However if a location directly under the net-pen was chosen, the measured data show non-uniform profiles (Fig. 4.13b). These variations are due to the influence of the net-pen itself. The water depth near the fish-farm in Broad Cove is about 14 m, and the net-pen is about 7 m deep. Thus almost half the depth is occupied by net-

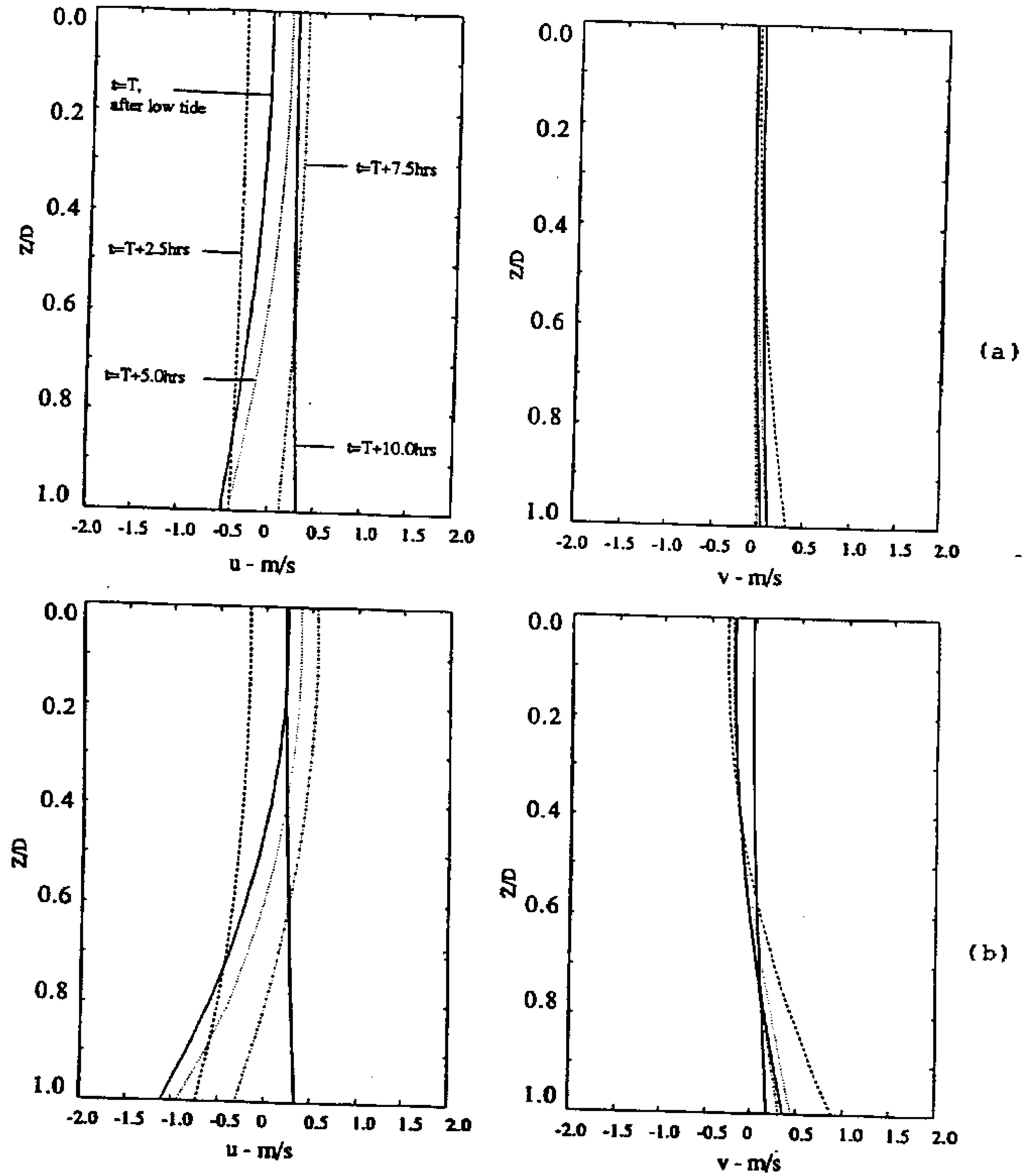


Fig. 4.11 Velocity profiles with constant vertical eddy viscosities
a: $N(z) = 0.065\ m^2/s$ b: $N(z) = 0.020\ m^2/s$
c: $N(z) = 0.00875\ m^2/s$ (on following page)

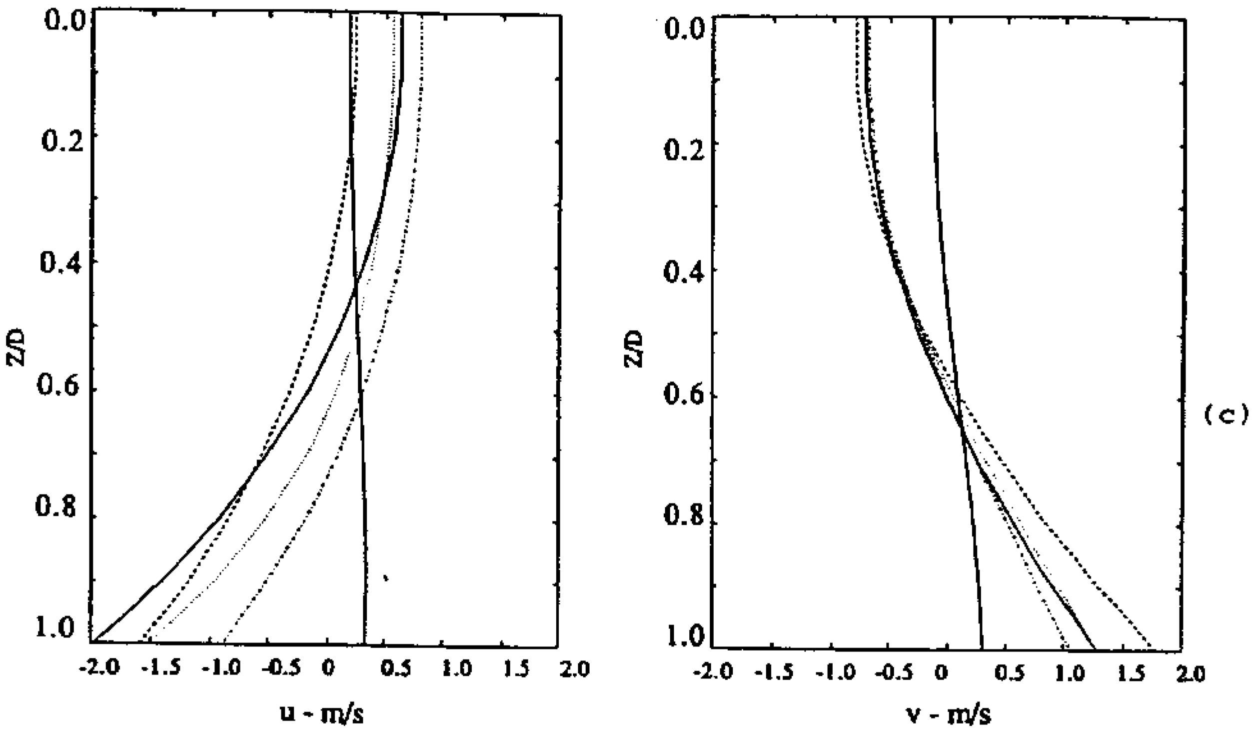


Fig. 4.11 (Continued)

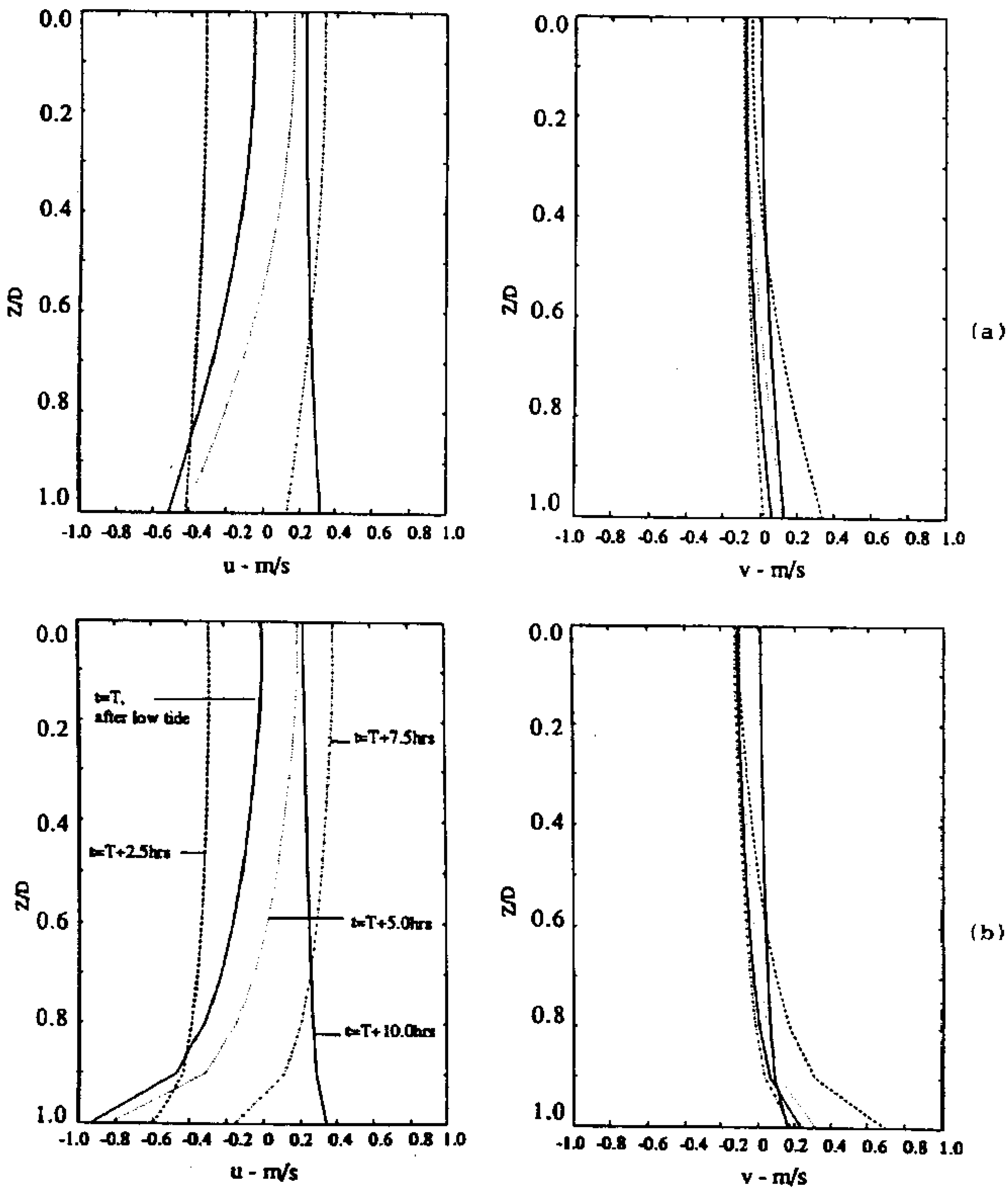
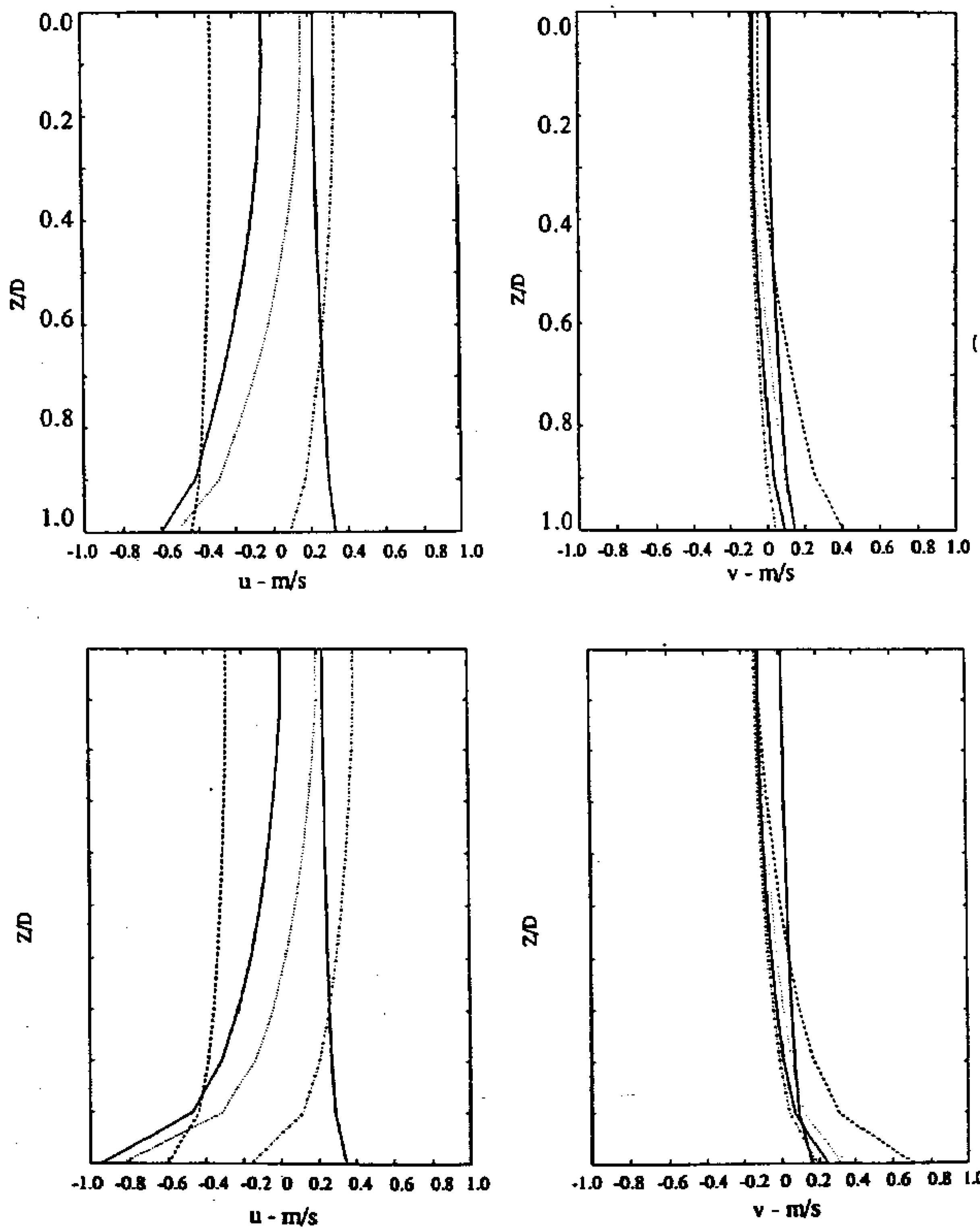


Fig. 4.12 Velocity profiles with varying vertical eddy viscosities
a: Constant, $N_{(z)} = 0.065\ m^2/s$ b: Parabolic, $N_{max}=0.065\ m^2/s$
c: Sublayer, $N_{max}=0.065\ m^2/s$ (on following page)
d: Combined, $N_{max}=0.065\ m^2/s$ (on following page)



(c)

(d)

Fig. 4.12 (Continued)

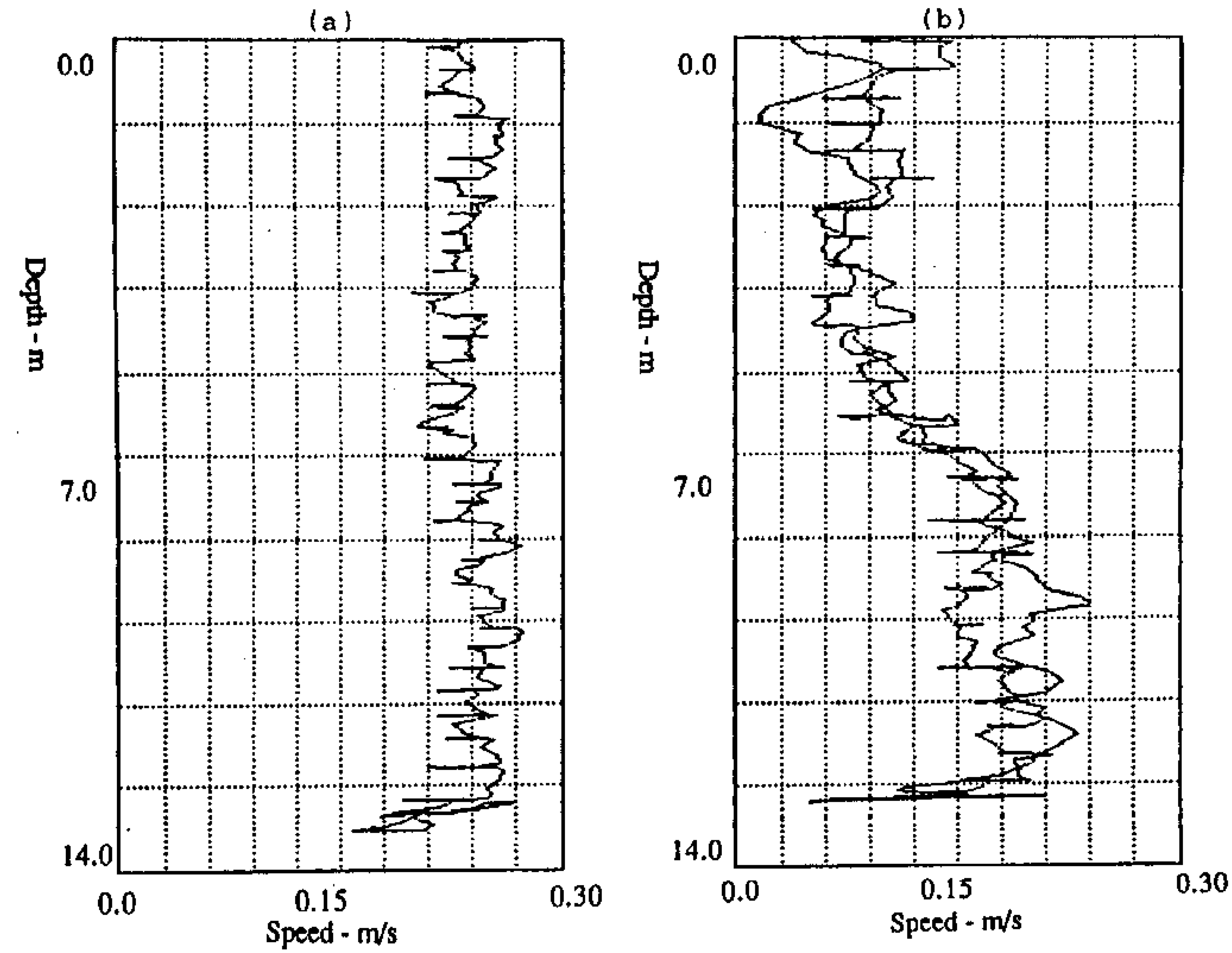


Fig. 4.13 Velocity profile data in Broad Cove
a: away from net pen site b: in the middle of pen area

pen, influencing the velocity profile considerably. A comparison of Fig. 4.13a and Fig. 4.13b shows that the effect of the net-pen is to increase the velocity in the lower part of the water column. No attempt was made to model this feature.

Since the modeled velocity profile is largely uniform (except immediately under the pen), it would appear that the effort required to store the exact velocity profile data (for each point in the vertical and for every time-step) for modeling the waste dispersion is not warranted. The exact velocities near the bottom are required only for calculations involving resuspension of settled wastes. (Without resuspension, the displacement of a particle calculated with a varying velocity profile would of course be the same as that calculated with the average). However, there are so many uncertainties regarding resuspension (as noted in Chapter 2) that the minor deviations from the average seen in the bottom region are unlikely to be a significant source of error in model calculations. The uniform 2-d velocity obtained from DUCHESS is therefore used to model the transport of net-pen wastes.

4.3 Contaminant Transport Model

Three aquaculture sites in Cobscook Bay were selected for studying the dispersion of net pen wastes: Broad Cove, Deep Cove, and Cornstock. At these sites, the net-pens are square (15 m x 15 m), containing groups of 20 cages bound together (2 rows with 10 cages in each row). Each group is shown by a small rectangle in Fig. 4.14 (provided by Connors Bros., Limited). The distance between each group is about 15 m.

According to Connors Bros., Limited, fish feeding is done from 7:00 am to 3:00 pm, pen by pen, twice daily. The amount of food provided is a percentage of the body weight and also depends on the water temperatures, as discussed in Fig. 3.2. Estimates of the amount of uneaten waste food entering the water as waste varies between roughly 1% and 30%, depending on the method of feeding. Fecal pellet production is reported to be 1.7 g to 2.1 g per kg of fish per day, and the pellets enter the water about 4 hours after feeding.

Based on this information, we assumed a typical summer situation and used the following loading conditions for model input:

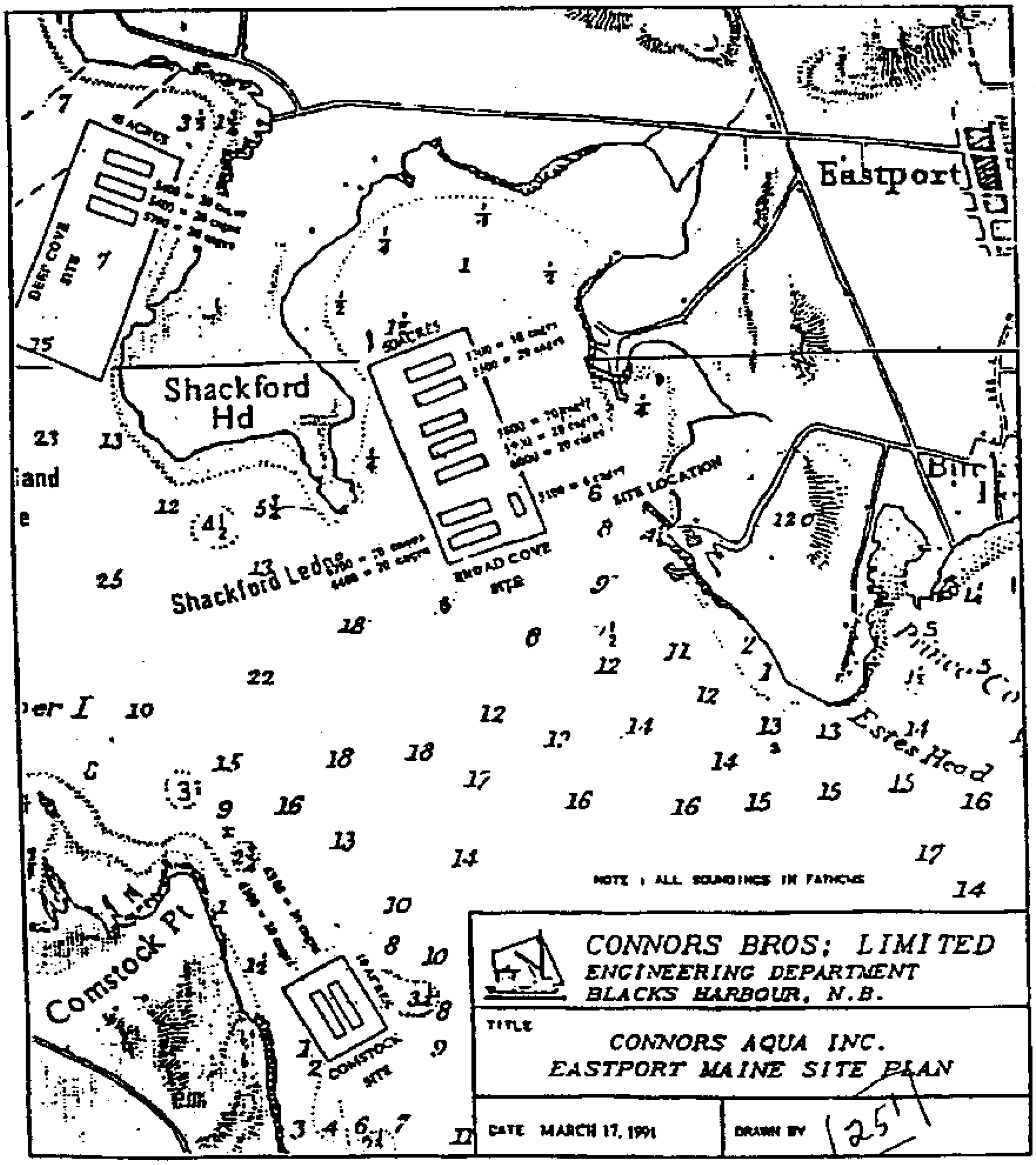


Fig. 4.14 Aquaculture sites in Broad Cove, Deep Cove and Comstock Point (from Connors Bros., Ltd.)

Fish weight: 675 g
Number of Fish: 5000 per cage
Temperature: 10° C
Fish feeding rate: 2.35% of body weight per day
Uneaten food ratio: 5%
Food moisture: 36%
Fecal pellet production: 1.9 g per kg fish per day

Thus the net-pen wastes would consist of 2.6 kg/day/cage of (dry) uneaten food and 6.4 kg/day/cage of fecal matter. For modeling purposes, we assumed that the loading rate for both kinds of waste particles is uniform throughout a period of 8 hours everyday. This loading was input to the model at half-hour intervals. Other model parameters are:

Settling velocity : 10 cm/s for fish food and 4 cm/s for fecal pellets
Tracking time-step : 10 seconds for the problem without particle resuspension and 10 minutes for the problem with resuspension.

Current velocities and water depths are obtained from the DUCHESS output on a 75 m grid. Application of this model and the results at the three aquaculture sites are discussed as below.

Broad Cove

There are 142 fish cages in Broad Cove, arranged as shown in Fig. 4.15. The waste transport model was run in 2 modes, with and without resuspension of settled wastes.

Model simulations without resuspension

Every 15 x 15 m^2 cage was treated as one point source. The particles from all 142 cages were tracked until they settled. The results are shown in Fig. 4.16 in the form of contour plots of net-pen waste concentration accumulated in eight days.

It takes about 1 - 2 minutes for the fish food and about 3 - 4 minutes for the fecal pellets to reach the bottom. In such a short time, the particles travel only a short distance, as shown in Fig. 4.16. Most of them settled down right underneath the pen, and some (those that enter the water when the currents are high) travel to a distance of about 20 m to 30 m away from the pen. Very low concentrations were found at distances greater than 30 m; these were mostly due to fecal pellets which take longer to settle.

Comparison of model output (without resuspension) with field data

Findlay et al. (1993) collected aquaculture wastes using 4 sediment traps near Pen 6200 (see Fig. 4.15) during the summer of 1991. The traps, of diameter 10 cm, were located as shown in Fig. 4.15. Particles that settled in these traps could not be resuspended. Dr. R. Findlay kindly provided these data for comparing with our model output.

Based on the previous model results (Fig. 4.16), it is clear that only particles from cages in Pen 5100, 6200, and 6000 could contribute to the trap sites; therefore only these pens are selected as the loading source for this run. To obtain a meaningful comparison, the waste loading is assumed to uniformly distributed over 9 point sources (each representing a 5m x 5m area), instead of only one point source for each cage.

The sediment trap data obtained by Dr. R. Findlay during 3 different periods are shown in Table 4.2. The sediment traps were placed at locations N1 and E1 (which are 1 m north and east of the net pen, respectively) and locations N25 and E25 (which are 25 m north and east of the net pen) and the data are shown in Table 4.2. In some cases, two measurements were made very near each other (e.g. E1A and E1B, etc.). The measured data give the weight of the total sediment in the trap and its carbon content (Findlay et al. 1993). To calculate the carbon loading from the model, the fish food and fecal matter were separated, and assumed to contain 45% and 28% carbon. Since precise information on loading rates, etc. were unavailable, model calculations for the three periods were obtained simply by proportionately modifying the 8-day results of Fig. 4.16 for the appropriate data duration.

An examination of the sediment trap data shows that it is very difficult to compare them with model results. Sediment trap data are influenced by the presence of material that cannot be directly attributed to the net-pen (Findlay et al. 1993). Dealing with this ambient effect is not straightforward, as can be seen by some negative data values in Table 4.2. Differences in concentrations derived from modeling and from sediment traps also relate to the method of calculating the concentrations. For modeling purposes, the particles settling in a 5m x 5m area were counted, and the 25 m^2 area was used to calculate the concentration. This assumes a uniform distribution in this area, and leads to the smooth contour plots shown in Fig. 4.16. The field measurements, on the other hand, are obtained by collecting the particles falling in an extremely small area (the trap is essentially like a coffee mug). The effect of such a small target area is that several sediment traps collect no pellets at all (as noted by Findlay and Watling (1993) in the context of Toothacher Bay). The measurements in Table 4.2 also show similar effects: for each of the 2 traps at locations E1, the concentration levels differ significantly, and extrapolating the trap data over large areas may lead to inconsistencies (as confirmed by Dr. Findlay). Mathematical model results also experience the same problem; the concentrations depends somewhat on the size of the area used to count the number of pellets. Since the actual distribution is not truly uniform, comparing the model concentration based on 25 m^2 area to that based on a small target area (the trap diameter is 10 cm) is difficult. Finally, the sediment traps near the net-pen appear to show a lower mass accumulation than the trap farther away (e.g. N1 and N25). In addition to the small target size and the ambient loading problem, such effects are likely to be caused by the fact that the traps are not closed to resuspended wastes; resuspension is not part of this model run.

In spite of these difficulties in comparing the smooth contour plots to the somewhat sporadic measurements, the overall results appear to show that the model simulation of the concentration levels are at least as representative and reasonable as those obtained from the measurements.

With resuspension

Resuspension of settled wastes by currents causes them to be redistributed. However, as noted in Chapter 2, it is difficult to correctly model all of the associated mechanisms; it was decided to rely on a threshold velocity and to treat it as a parameter. Dr. R. Findlay, who has considerable diving and fieldwork experience in the vicinity of net-pens, indicated that at about 0.20 m/s the particle are almost always eroded. Four different values, ranging from 0 to 0.3 m/s were selected as the threshold velocities (Ve) for the particle resuspension problem. (If Ve is higher than the actual current velocity at that location (e.g. Ve = 0.3 m/s), particles on the bottom are never resuspended.) The results are shown in Fig. 4.17 and Table 4.3. The amount of wastes accumulating within the bay decreased as Ve decreased. However, unlike the other sites, not all wastes are flushed out of the computational domain even for a Ve = 0 m/s; apparently 22 % of the waste load is remain in the bay, trapped by the gyre. (This is verified by Fig. 4.18, which shows the computed tracks of some of the particles in the central part of the overall computational domain for Broad Cove). It is important to note from Table 4.3 that the percentage of the sediments that gets washed away and the percentage that remains in the embayment depends directly on the threshold velocity at a certain location. This is thus a key factor in the success of the modeling exercise.

Deep Cove

The size of the fish-farm in Deep Cove is smaller than in Broad Cove, with a total of 60 cages; Fig. 4.19 shows the pen locations. The same assumptions for waste loading and for model parameter values were used as that in Broad Cove. Sediment concentration values without resuspension are shown in Fig. 4.20, and with resuspension in Fig. 4.21 (for 3 threshold erosion velocities).

Table 4.3 shows the percentage of sediments that get advected out of Deep Cove for different threshold velocities. Compared with Broad Cove, it is found that a higher percentage of particles was washed out of Deep Cove, for a given threshold velocity. This is due to the considerably different topography in these two regions. Deep Cove is a more open region and closer to the main channel than Broad Cove and has higher current velocities; Broad Cove is more enclosed and has a gyre which makes it more difficult for the particles to get advected out.

The model was also used to study how the location of the net-pens affects the distribution of wastes. The location of the fish farm was moved 100 m to the south and 100 m to the west, toward the open side of Deep Cove (see Fig. 4.19). The sediment concentration values with the same input loadings are shown in Fig. 4.22. The percentage of sediments leaving Deep Cove is shown in Table 4.3. In general a far greater percentage of the sediments were carried out of the computational domain than when the net pens are at the original (actual) location, e.g. at Ve = 0.2m/s, the percentage of removal increased from 43% to 80%, and at Ve = 0.3m/s, from 21% to 75%. Thus the location of the fish farm can make a large difference in the environmental regulation of aquaculture. Careful selection of the location of the fish farm will greatly reduce the pollution level.

Comstock Point

There are 40 cages in the fish farm at Comstock Point (Fig. 4.23). The same assumptions for waste loading and model parameter values as before were used. Sediment concentration values are shown in Fig. 4.24 and Fig. 4.25 for the runs with and without resuspension, respectively.

One difference between Comstock Point and other two sites is that net-pen is much closer to the main channel of Cobscook Bay than the other 2 sites, and thus has much higher current velocities. However, there are some differences between the observed and modeled velocities. The observed velocity is as high as 1m/s (L. Churchill, Maine Department of Marine Resources), whereas the modeled current velocity is about 0.5 m/s. The reason for this difference is the complex nature of the bathymetry, e.g. the depth near the coastline increases quickly to 15 m within a distance of only 100 m. Such changes require a better representation of the coastline and the bathymetry than that obtained by interpolating from a coarse 225 m grid. The results shown for Comstock Point may thus not be completely satisfactory.

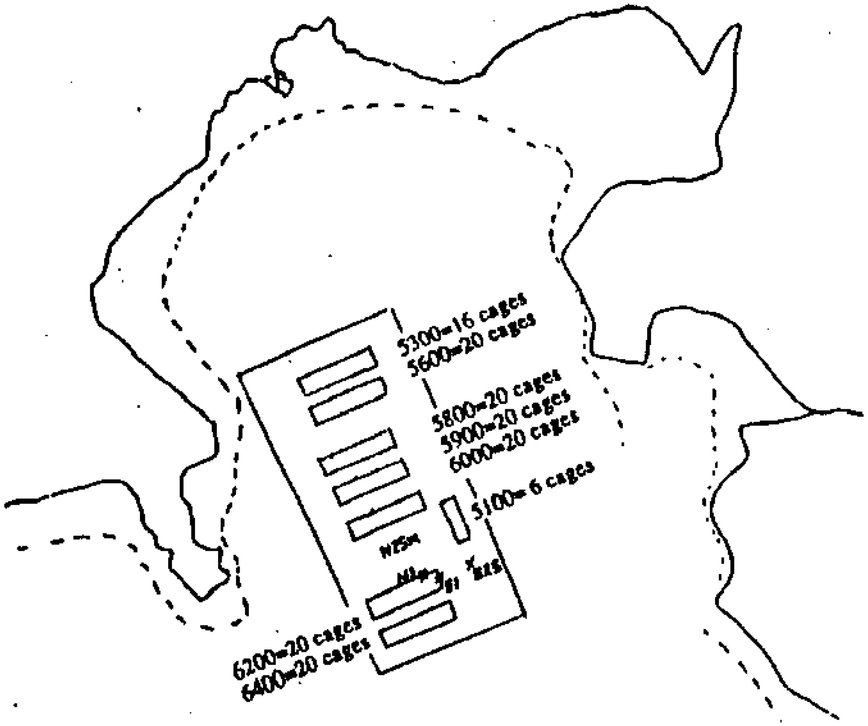


Fig. 4.15 Net pen and sediment trap locations (crosses) in Broad Cove

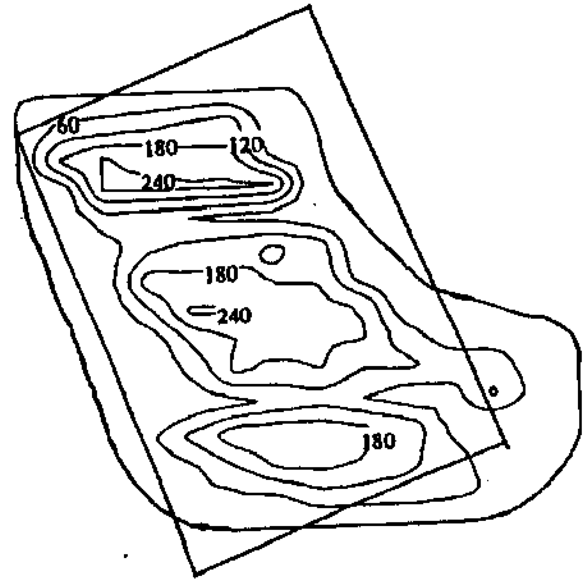


Fig. 4.16 8 Day loading to benthos at net pen site in Broad Cove, g/m^2 (no particle resuspension)

Table 4.2 Comparison of model output with sediment trap data in Broad Cove

Date	Trap Site	Trap Data Sediment weight kg/m^2	Trap Data Carbon g/m^2	Model Output Sediment weight kg/m^2	Model Output Carbon g/m^2
6/20/ - 7/18, 1991	N1	0.044	28.3	0.200	72.2
(28 days)	N25	1.219	76.4	0.236	66.2
	E1A	0.007	63.8	0.404	144.8
	E1B	0.199	77.7		
	E25A	—	—		
	E25B	—	—		
7/18 - 9/15, 1991	N1	(-)	(-)		
(47 days)	N25	—	—		
	E1A	1.266	114	0.679	243.1
	E1B	(-)	(-)		
	E25A	—	—		
	E25B	—	—		
9/5 - 10/18,	N1	1.684	72.1	0.321	116.0
1991 (45 days)	N25	—	—		
	E1A	—	—		
	E1B	0.771	30.0	0.650	232.7
	E25A	0.844	43.2	0.063	18.0
	E25B	0.632	26.9		

— no measurement (-) negative, lower than ambient

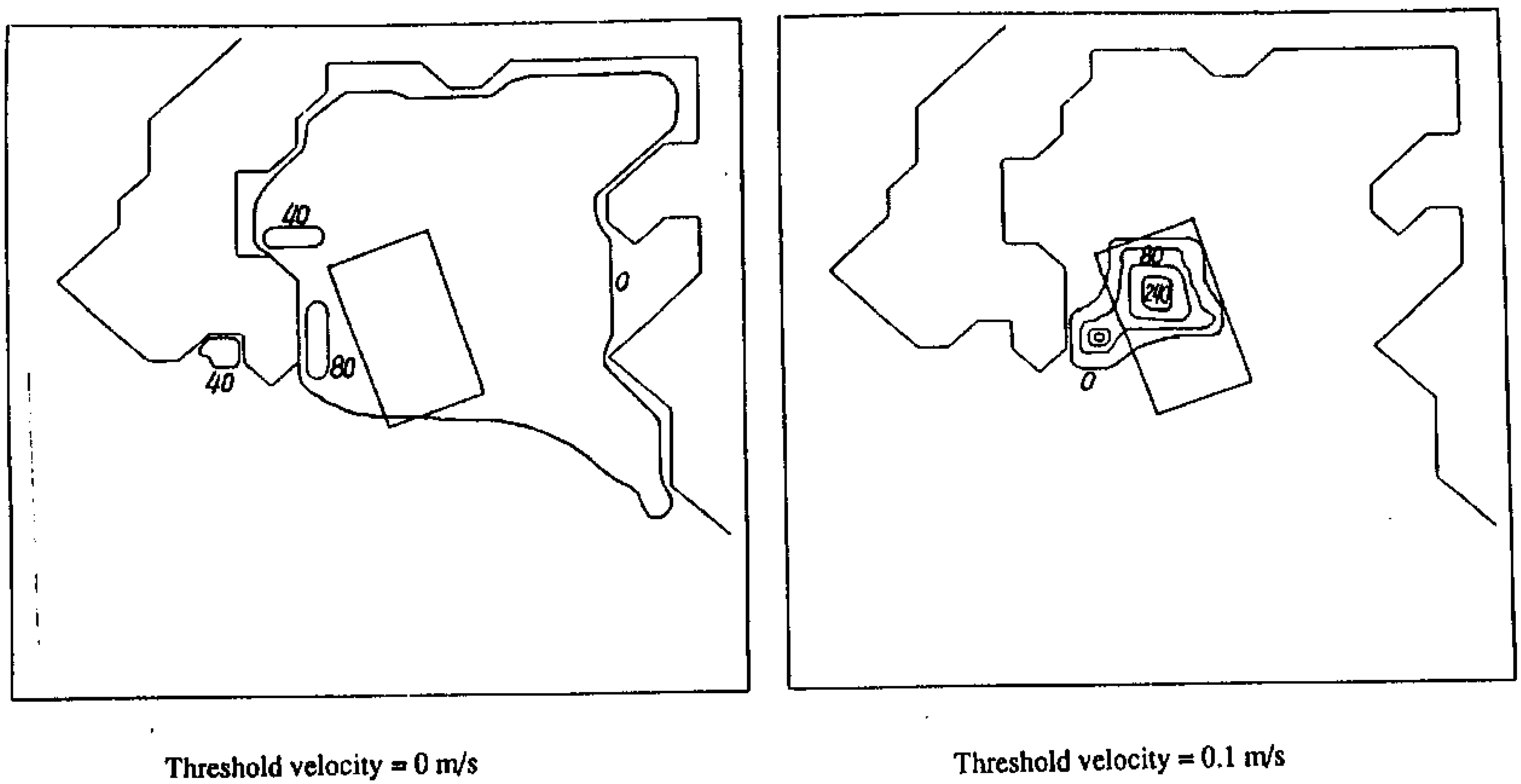
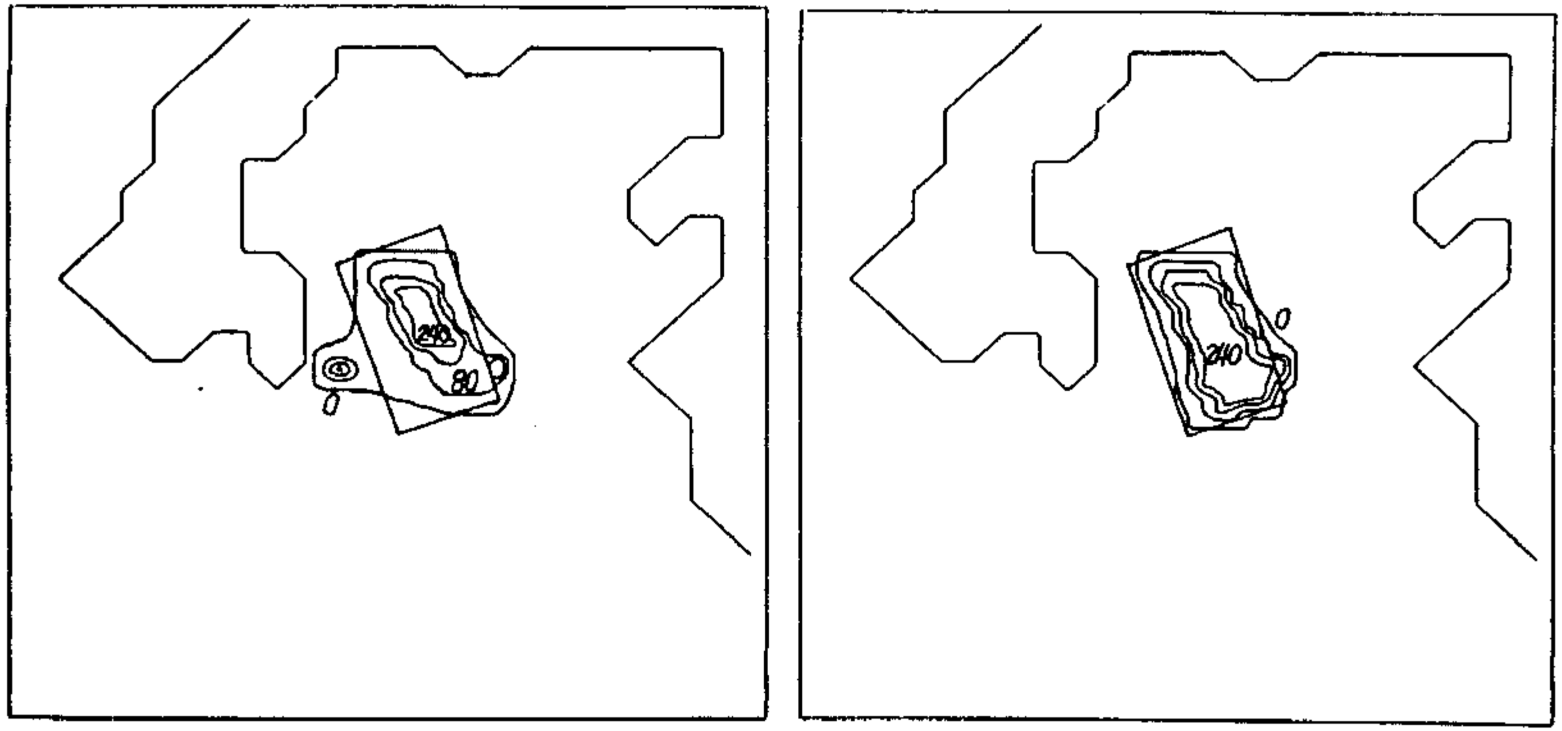


Fig. 4.17 8 Day loading to benthos at net pen site in Broad Cove, g/m^2
(with particle resuspension, continued on following page)



Threshold velocity = 0.2 m/s

Threshold velocity = 0.3 m/s

Fig. 4.17 8 Day loading to benthos at net-pen site in Broad Cove, g/m^2
(with particle resuspension, continued from previous page)

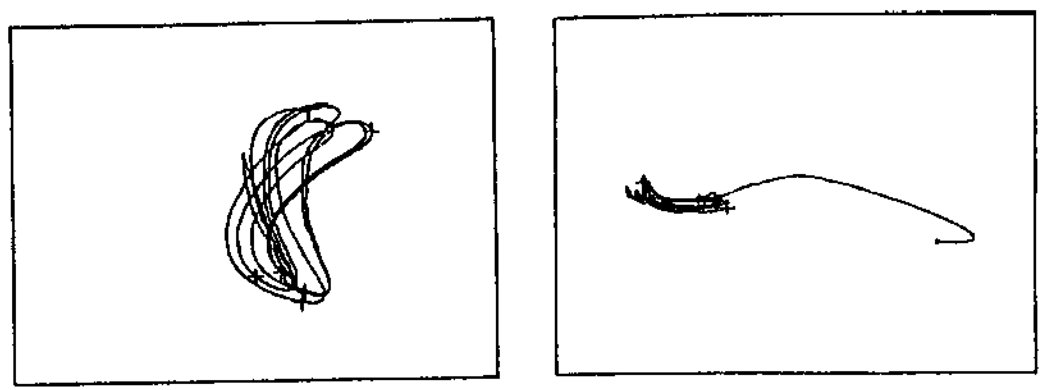


Fig. 4.18 Tracks of some waste particles in Broad Cove. The rectangle represents a region smaller than the Broad Cove domain

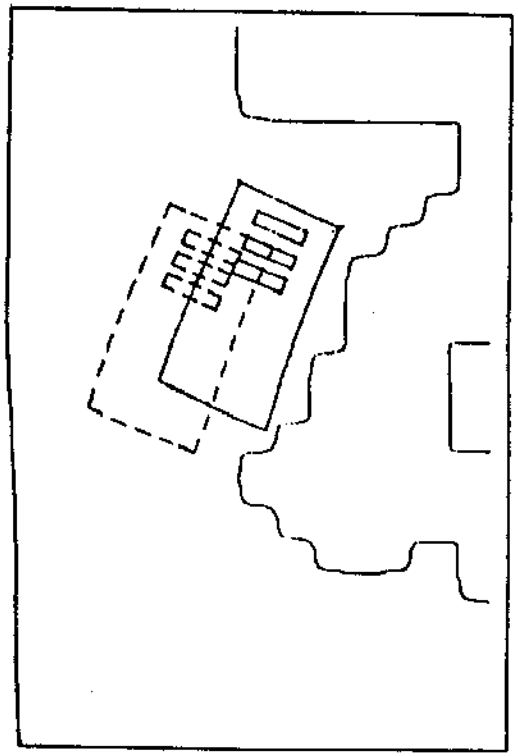


Fig. 4.19 Net pen locations in Deep Cove
—— present location
- - - - test location

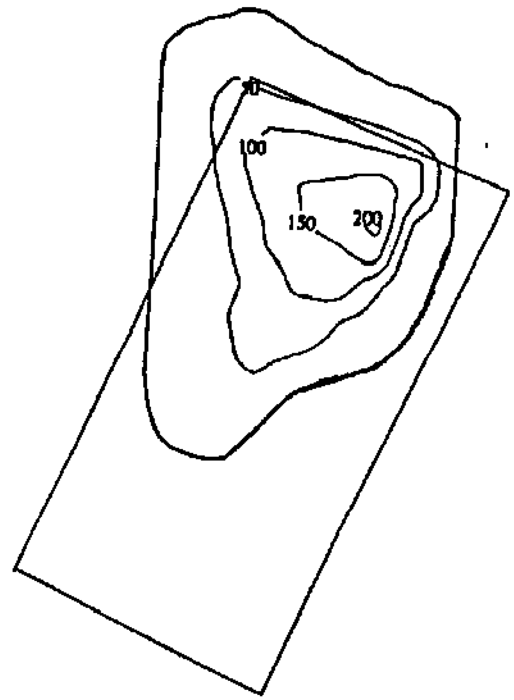
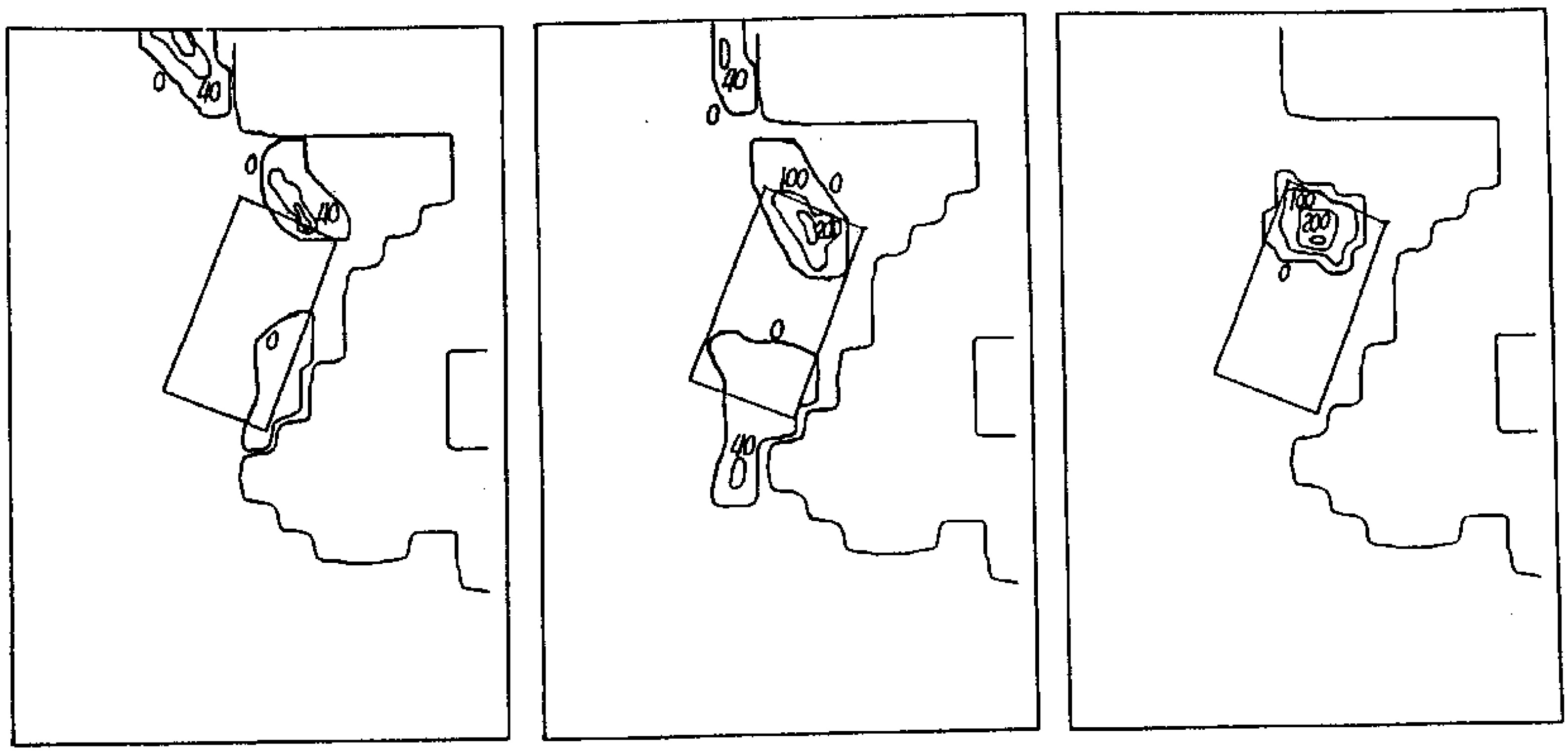
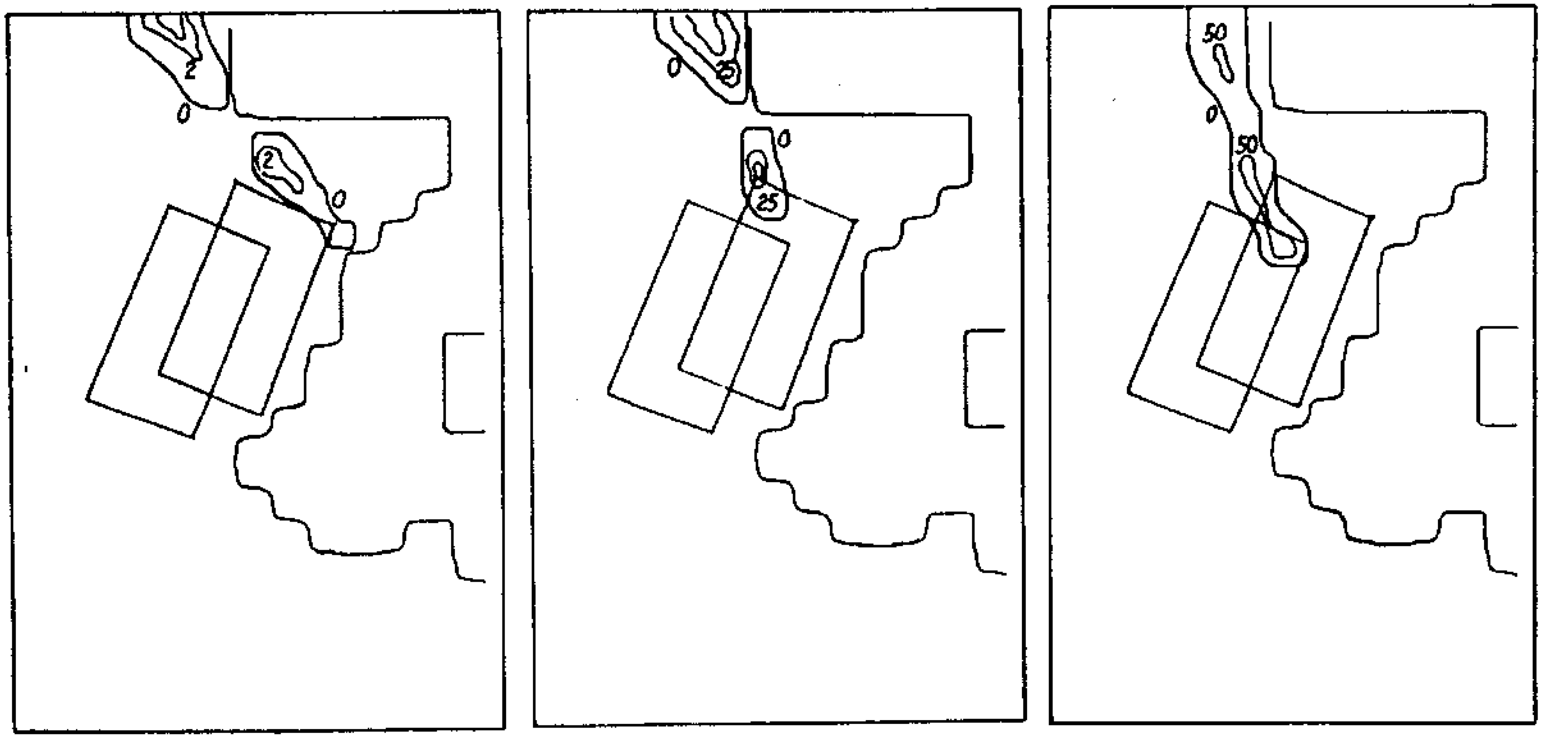


Fig. 4.20 8 day loading to benthos
at net pen site in Deep Cove
(no particle resuspension)



Threshold Velocity = 0.1 m/s | Threshold Velocity = 0.2 m/s | Threshold Velocity = 0.3 m/s

Fig. 4.21 8 day loading to benthos at net pen site in Deep Cove, g/m^2
(with particle resuspension, continued on following page)

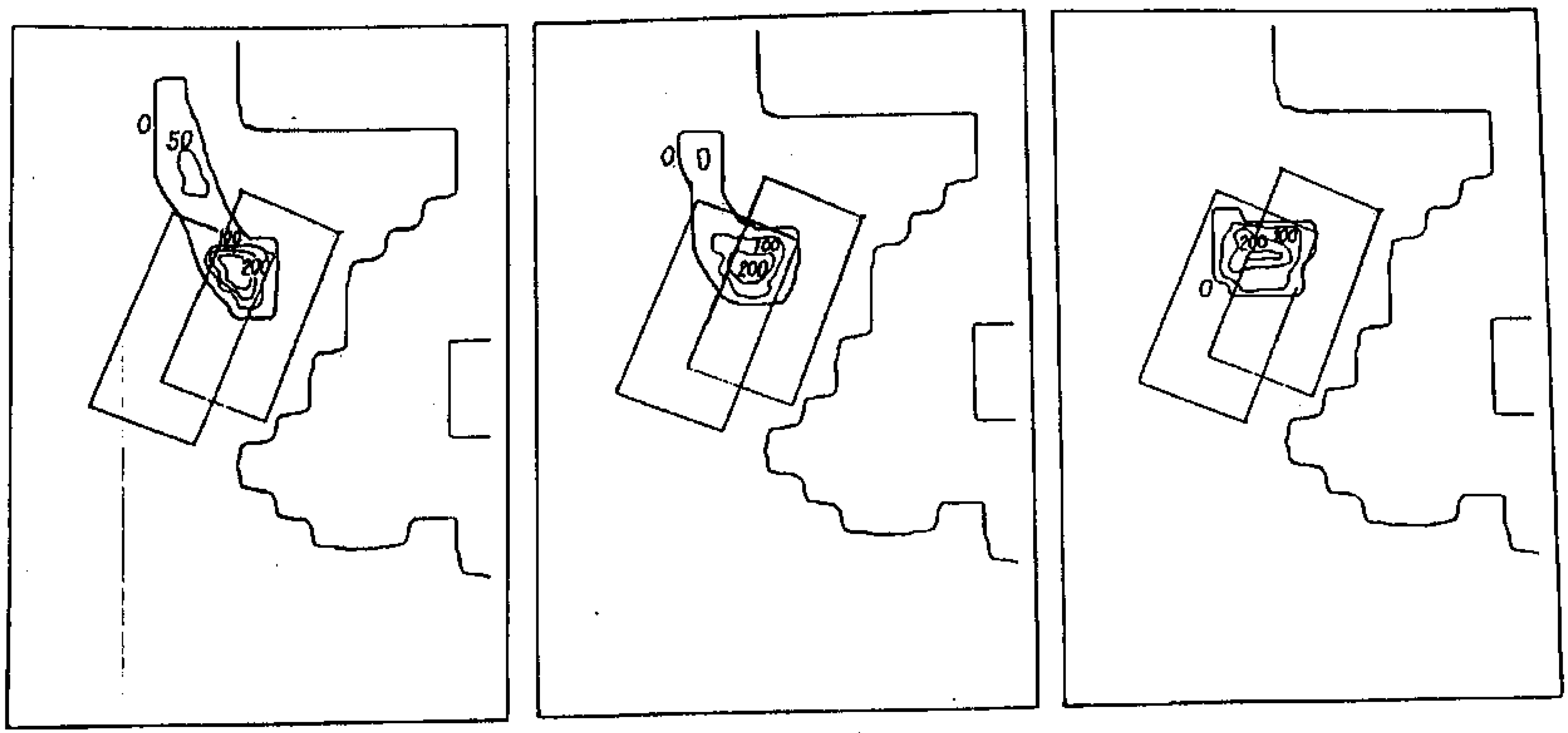


Threshold Velocity = 0.1 m/s

Threshold Velocity = 0.2 m/s

Threshold Velocity = 0.3 m/s

Fig. 4.22 8 day loading from test location to benthos in Deep Cove, g/m^2
(with particle resuspension, continued on following page)



Threshold Velocity = 0.4 m/s   Threshold Velocity = 0.5 m/s   Threshold Velocity = 0.6 m/s

Fig. 4.22 8 day loading from test location to benthos in Deep Cove, g/m^2
(with particle resuspension, continued from previous page)

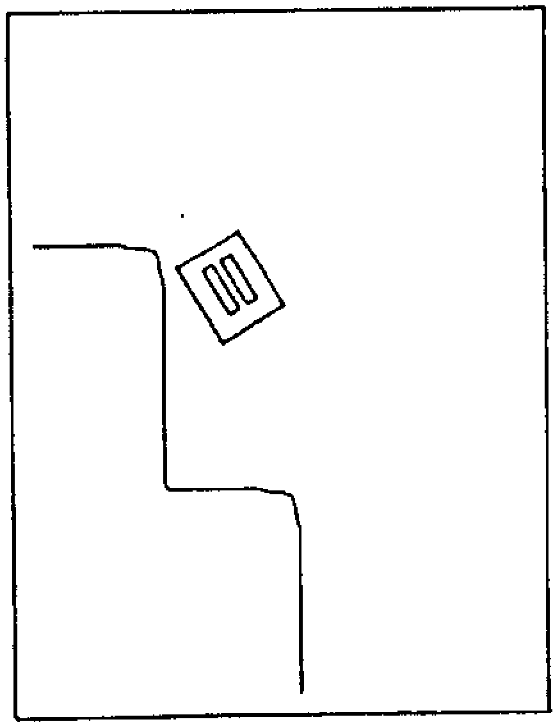


Fig. 4.23 Net pen locations at Comstock Point

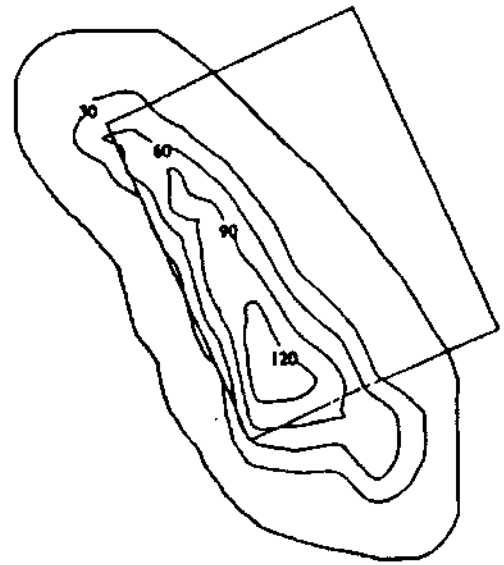
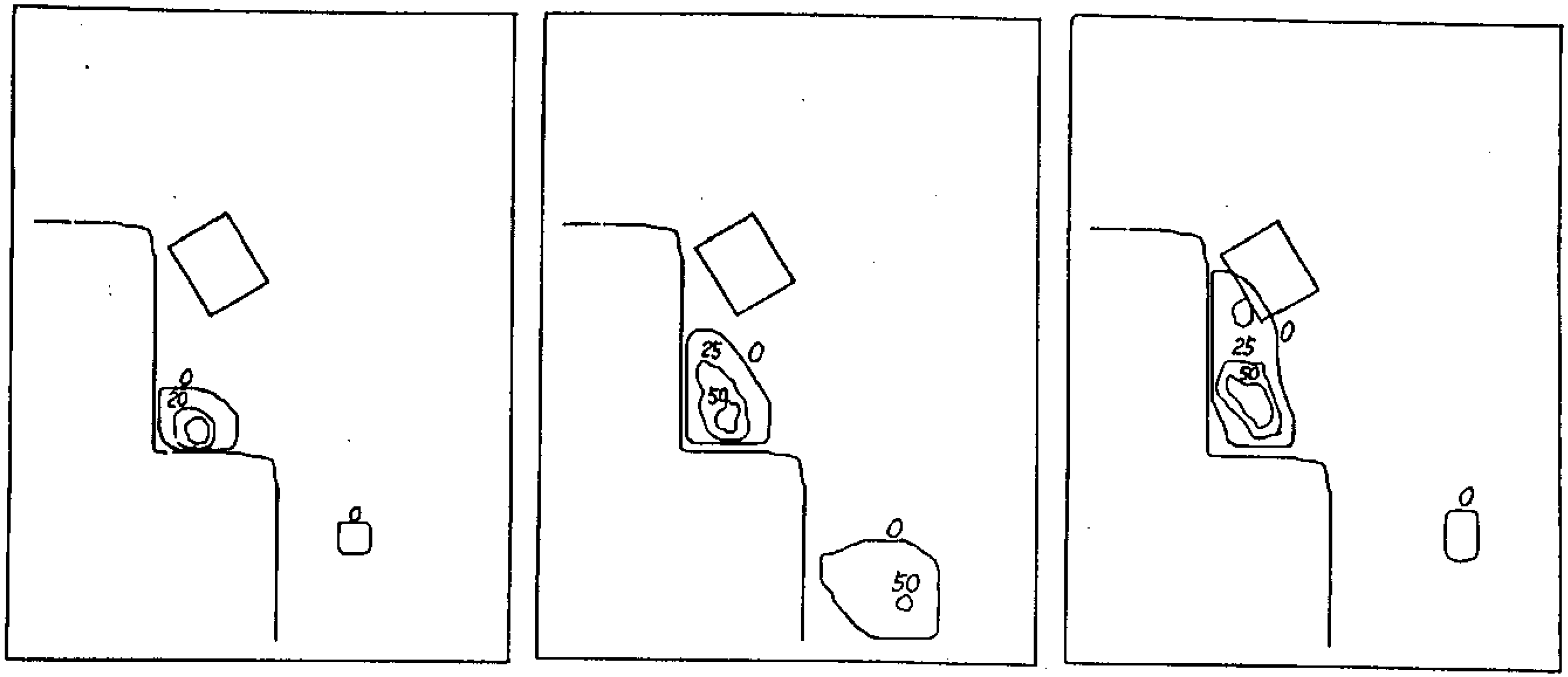


Fig. 4.24 8 day loading to benthos
at net pen site at Comstock Point
(no particle resuspension)

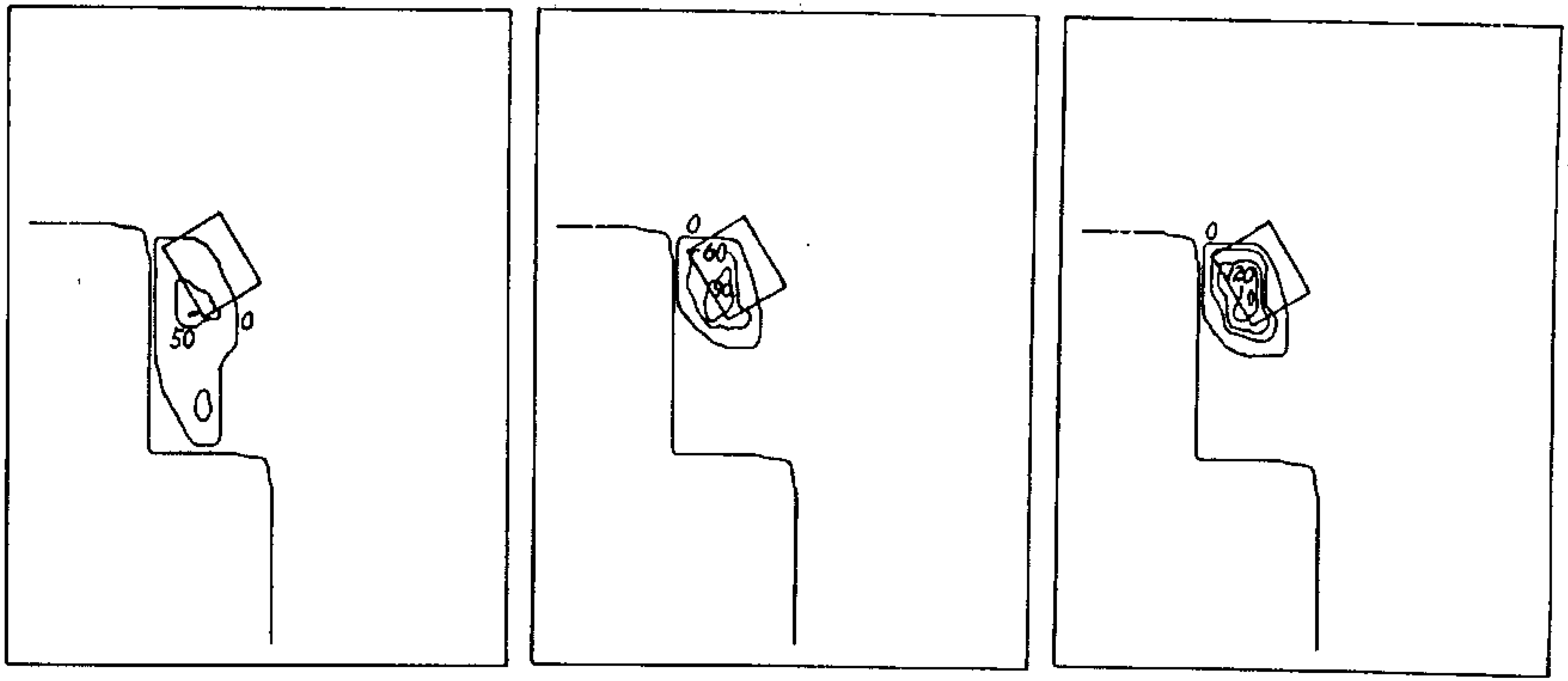


Threshold Velocity = 0.1 m/s

Threshold Velocity = 0.2 m/s

Threshold Velocity = 0.3 m/s

Fig. 4.25 8 day loading to benthos at net pen site at Comstock Point
(with particle resuspension, continued on following page)



Threshold Velocity = 0.4 m/s

Threshold Velocity = 0.5 m/s

Threshold Velocity = 0.6 m/s

Fig. 4.25 8 day loading to benthos at net pen site at Comstock Point (with particle resuspension, continued from previous page)

Table 4.3 Comparison of the sediment removal percentage under different thresholds for Broad Cove, Deep Cove and Comstock (expressed as percentage of the total waste loading)

Threshold velocity m/s	0.0	0.1	0.2	0.3	0.4	0.5	0.6
Broad Cove	78	36	12	0	0	0	0
Deep Cove (present location)	100	83	43	21	0	0	0
Deep Cove (test location, move 100m west, 100m south)	100	81	80	75	52	23	5
Comstock Point	100	92	51	43	36	18	4

4.4 Decomposition of Accumulated Wastes

The concentration levels shown in the contour plots in Fig. 4.16 to Fig. 4.25 all result from a waste loading duration of 8 days. Due to linearity of the mechanisms modeled, the concentration level after 16 days will be twice those shown in these figures, etc. Theoretically the concentration levels can increase indefinitely. This is prevented by three mechanisms: resuspension (as modeled earlier and that resulting from occasioned storm events, see Chapter 5), grazing by other fauna (which was not modeled), and decomposition of the wastes. Although the exact exponential decay coefficients are not known, 5 values were considered. Studies of net-pen waste accumulation in fjords (e.g. Aure and Stigebrandt, 1990; Hansen et al. 1991) suggest that the decay coefficient varies between 0.10/year and 0.51/year. Four values in this range, 0.5/year, 0.4/year, 0.3/year, 0.15/year, were therefore selected. In addition, a decay coefficient of 0.01/day used in EPA (1982) for sewage was considered. Assuming the initial waste concentration to be zero, and the average loading rate (based on the mass accumulation shown in Fig. 4.16 to Fig. 4.25) to be 6.8 kg/m^2/yr (18.6 g/m^2/day), the waste concentration levels at different times are calculated via eq. 2-22. The results are shown in Table 4.4 and Fig. 4.26.

It is thus anticipated from these results that it will take several years to reach a steady state. With the highest decay rate suggested (0.5/yr), 4.6 years are needed to reach 90% of steady state value (which is considered as steady state for practical purposes); for a decay rate of 0.3/yr, it takes about 7.7 years. For reference, using the decomposition value for sewer wastes (0.01/day), about 8 months are required to reach steady state. These results (or eq. 2-24) can be easily applied to modify the plots in Fig. 4.16 to Fig. 4.25, e.g. in Fig. 4.16 the contour marked 180 g/m^2 per 8 days corresponds to a steady state contour of 16.4 kg/m^2/yr at the decay rate of 0.5/year, etc.

Table 4.4 Accumulation of wastes as a function of decay coefficient (based on the loading rate of 6.4 kg/m^2/year)

Percentage of steady state concentration level (Cs)	10%Cs	20%Cs	50%Cs	90%Cs	Cs
Decay Rate = 0.5/yr					
Time - yr	0.2	0.4	1.4	4.6	
Concentration - kg/m2	1.4	2.7	6.8	12.2	13.6
Decay Rate = 0.4/yr					
Time - yr	0.3	0.6	1.7	5.8	
Concentration - kg/m2	1.7	3.4	8.5	15.3	17.0
Decay Rate = 0.3/yr					
Time - yr	0.4	0.7	2.3	7.7	
Concentration - kg/m2	2.3	4.6	11.5	20.7	23.0
Decay Rate = 0.15/yr					
Time - yr	0.7	1.5	4.6	15.4	
Concentration - kg/m2	4.5	9.1	22.7	40.8	45.3
Decay Rate = 0.01/day					
Time - yr	0.02	0.06	0.2	0.6	
Concentration - kg/m2	0.2	0.4	0.9	1.7	1.9

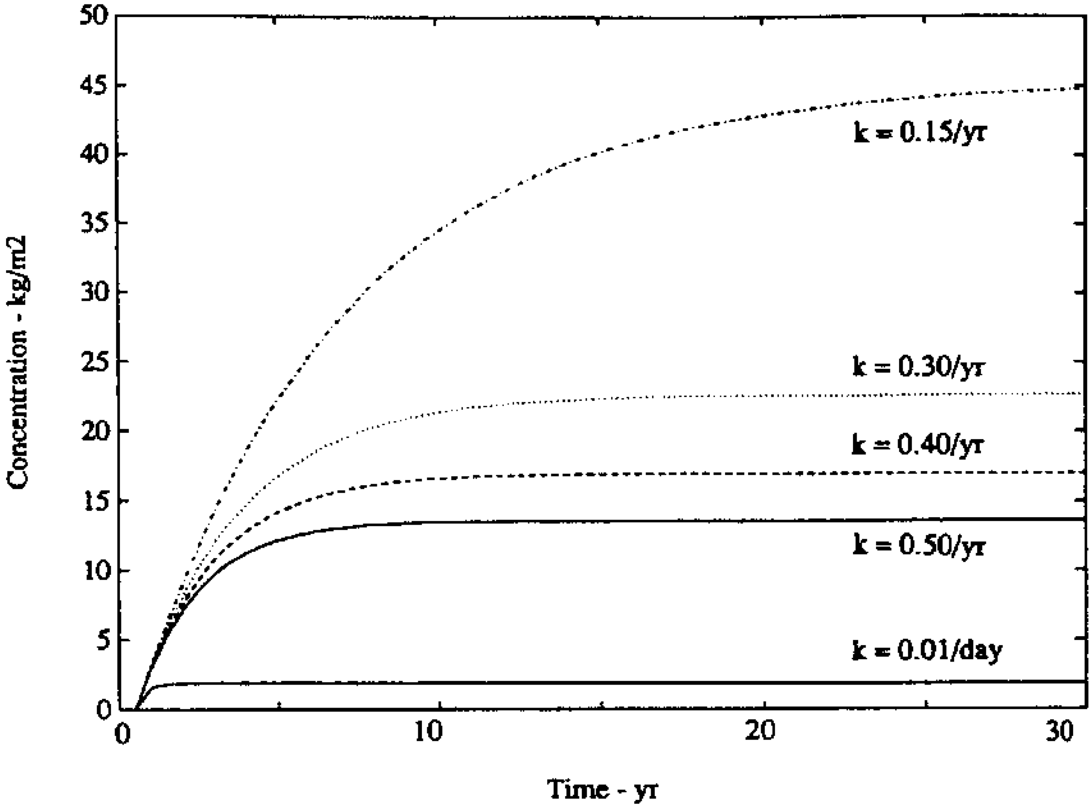


Fig. 4.26 Accumulation of wastes as a function of decay coefficient

5. AQUACULTURE WASTE-DISTRIBUTION IN TOOTHACHER BAY

Toothacher Bay is located to the south of Swans Island in the Gulf of Maine. To its south and south-east, it is open to the Gulf of Maine; Swans Island is to its north. To its west and south-west are several islands within a distance of a few miles. In comparison with Cobscook Bay, Toothacher Bay is a much smaller region with an area of about 2.5 x 2.5 km^2, but is far more open to the Gulf of Maine (Fig. 5.1). There is only one net-pen operation in Toothacher Bay.

5.1 2-d Flow Model Application

Since Toothacher Bay is more exposed to the ocean than Cobscook Bay, the 2-d flow model DUCHESS was forced by both tides and winds in our study. To our knowledge, no modeling studies have been performed in this area prior to this.

Tidal Flow Simulation

Bathymetric information obtained from NOAA Chart 13313 was manually digitized to construct the required input file. The domain was discretized into 26 x 23 grids with a grid size of 100 m. There is one open boundary to the south of the model domain (Fig. 5.2).

As noted in Chapter 3, three tide gages and one current-meter were installed in Toothacher Bay (Fig. 5.2). One of the tide gages provided the necessary tidal elevations along the open boundary to force the model. An average tidal amplitude of 1.7 m was applied uniformly along the open boundary.

Since the domain is fairly small with relatively simple bottom topography, a constant friction coefficient ($f = 0.01$) was used in the model. The time step was 80 seconds. Model simulation required 5 minutes of CPU time per tidal cycle, and about two cycles were required for spin-up.

The somewhat simple nature of the model domain results in the modeled tidal elevations being spatially uniform; the phase difference between any two points is also

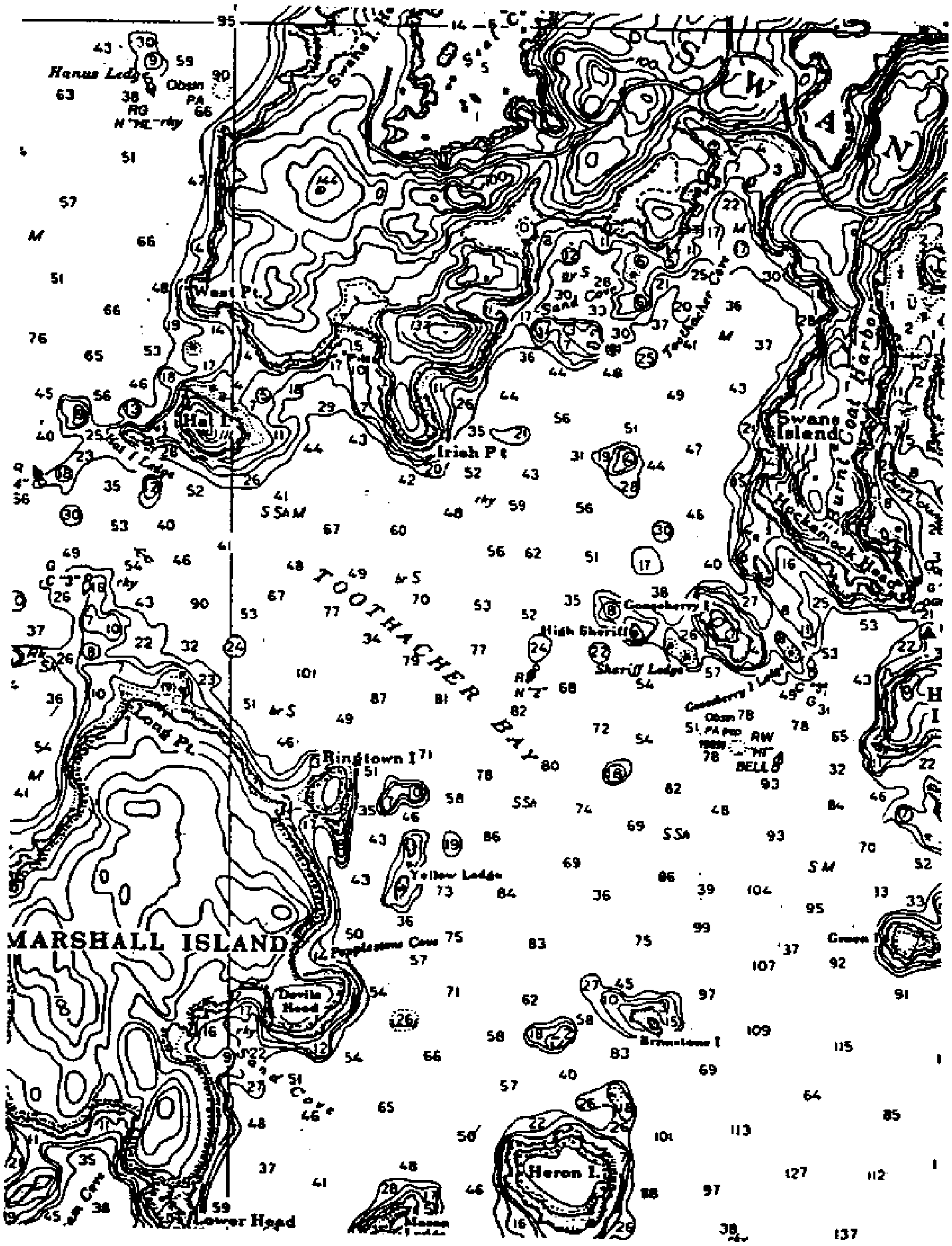


Fig. 5.1 Toothacher Bay (from NOAA Chart 13313)

negligible. This is completely consistent with the measured data at three locations. The modeled tidal velocities are shown in Fig. 5.3. The velocities are very small; the maximum velocity is about 4 cm/s. Compared with the 15 - 50 cm/s currents near the fish farms in Cobscook Bay, the tidal velocities in Toothacher Bay cannot be expected to contribute much to the transport of waste particles out of the Bay.

Although the modeled tidal velocities are small, our measurements during 18 to 23 December 1992 show that the velocities were much higher. These were clearly a consequence of strong winds that accompanied our measurement program (i.e. storm conditions). Thus model output resulting from the combined influences of winds and tides was necessary to make comparisons with our data.

Wind-driven and tidally-driven flow simulation

Wind data for 16 - 23 December 1992 obtained from Mount Desert Rock are shown in Fig. 5.4. These winds and the surface elevations measured at gage 2 were used simultaneously to force the model. (The elevations at gage 2 were essentially sinusoidal with an amplitude of 1.7 m; compared with the velocities, the tidal elevations showed the effect of the wind to an extremely small extent). Constant winds of 20 mph were applied for a period of one day for model spin-up. The wind data shown in Fig. 5.4 were then applied at intervals of 6 hours. Model results are influenced by the wind drag coefficient (C_d). Three sets of results for point 1 (Fig. 5.2) with different values of C_d are shown in Fig. 5.5. In general, all the modeled velocities show good correlation with the wind; all peaks in the wind produce peaks in water velocity. The magnitude of the velocities depends on the value of the drag coefficient. For $C_d = 0.00325$, on calm days (e.g. December 17, 19, and 23), the model response is essentially tidal (four peaks everyday, of a magnitude comparable to the results from tidal simulation described earlier). When the winds are higher (e.g. December 20 and 21), the modeled currents increased to about 10 cm/s. For higher values of C_d, the influence of the wind dominates the tidal forcing; the small oscillations due to the tide decrease and the magnitude of the larger peaks due to wind increase. For $C_d = 0.0145$, the oscillations due to the tide mostly vanish, and the variations of the modeled currents show a good correlation to that of winds (Fig. 5.5). A further test run was made with no tidal forcing. Model results then showed no oscillations due to the tide. Variations in the currents are seen to be quite similar to those of the wind (Fig. 5.5b).

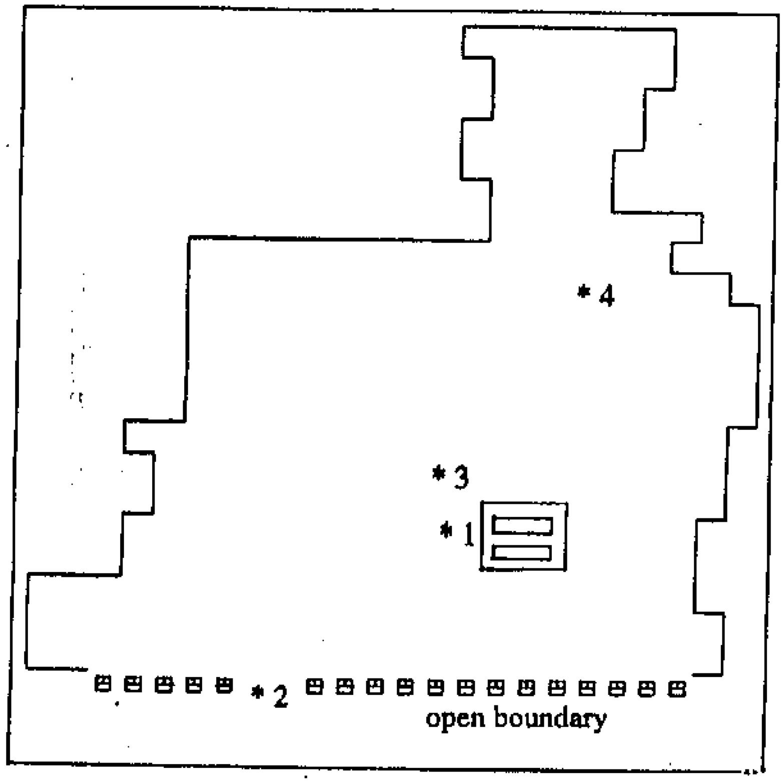


Fig. 5.2 Model domain in Toothacher Bay
point 1: net pen site, current meter;
points 2, 3, 4 : tide gages

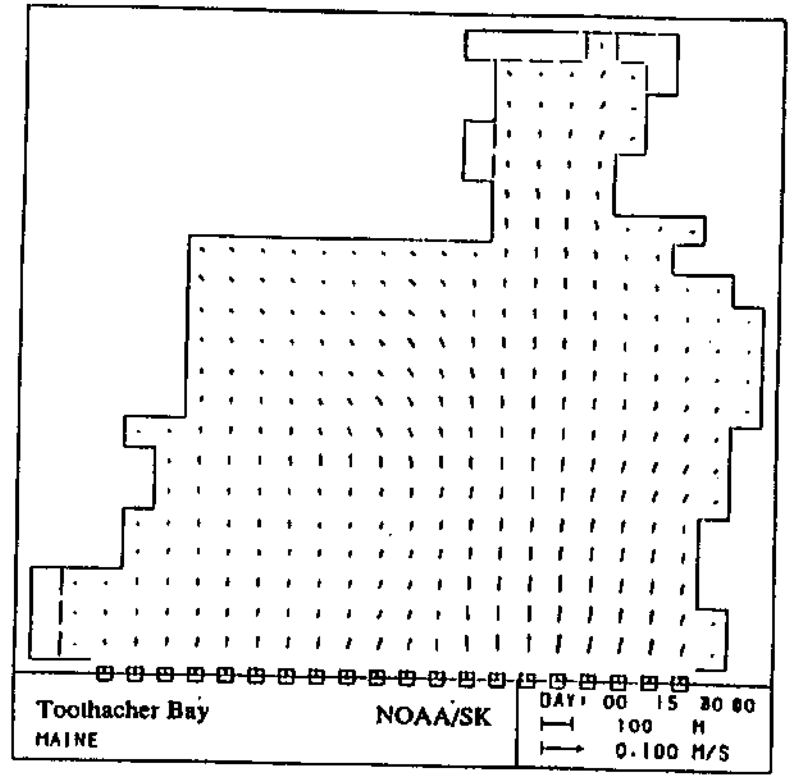


Fig. 5.3 Modeled tidal velocities in Toothacher Bay (mid-tide)

There are some periods when the correlation between the winds and the currents is not good. Some peaks in the windspeed (e.g. December 16 and 17) produced no peaks or peaks smaller than expected in the water velocities. These discrepancies were found to result from the North-South wind events and can be attributed to the bay geometry. This can be verified by examining the output shown in Fig. 5.6 for periods when winds of comparable magnitude differed only in direction: they were strictly North-South or strictly East-West. It can be seen that the shape of bay results in producing a stronger model response under East-West winds than under North-South winds.

A coefficient of $C_d = 0.00585$ generated a good match of the current velocities with measured data at near the net-pen during this period. A comparison is shown in Fig. 5.7. While most important aspects of the velocity variations are well-reproduced, the match is not perfect at some instants of time. Also, the data show a strong response even to North-South wind events. The mismatch can be ascribed to differences in the winds between the net-pen site and Mount Desert Rock, wave activity not accounted for in this run, the fact that the measurements represent velocities 3 m above the bottom while the model results represent vertically-averaged velocities, and the use of a constant wind-drag coefficient.

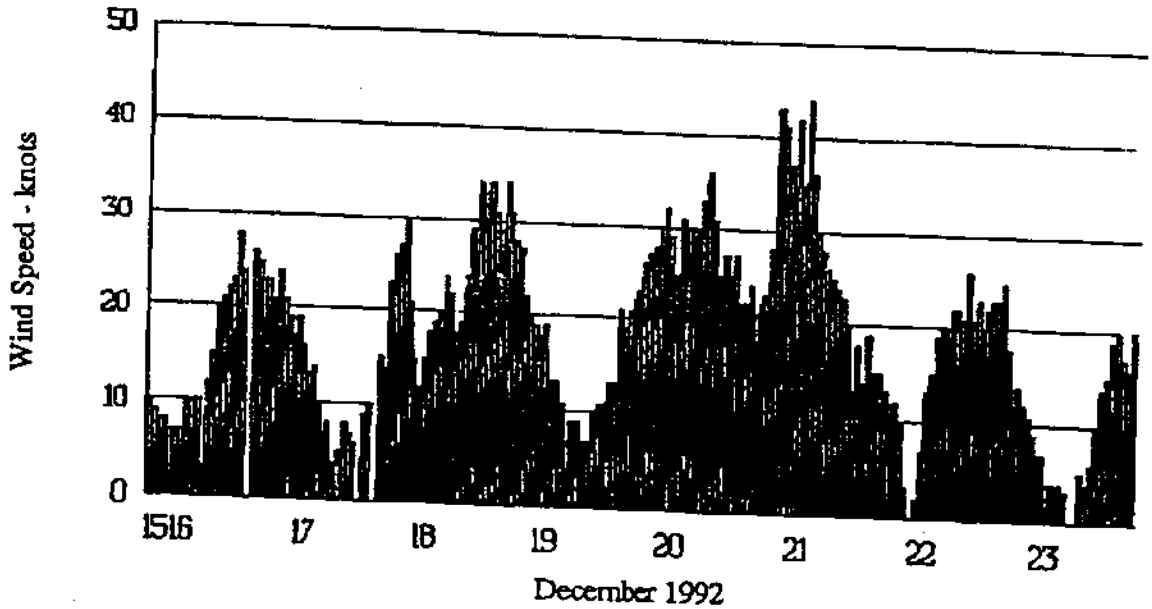
5.2 Contaminant Transport Model

There is only one aquaculture operation in Toothacher Bay. There are a total of 18 round cages (2 rows with 9 cages in each), as shown in Fig. 5.8. The cages are 15.25 m in diameter and 7.3 m deep.

The transport model was applied under both conditions, i.e. with tidal currents only and with both tidal and wind driven currents. All assumptions for the model input were the same as that for Cobscook Bay. Since the maximum (modeled and measured) current velocity is less than the critical erosion velocity (approximately 20 cm/s), no particle resuspension can be considered in these runs. The results are discussed respectively as below.

Tidal Currents

Net-pen waste concentrations were specifically examined for Pen 2. The results are shown in Fig. 5.9. Since the tidal currents are so small (less than 4 cm/s), distribution of



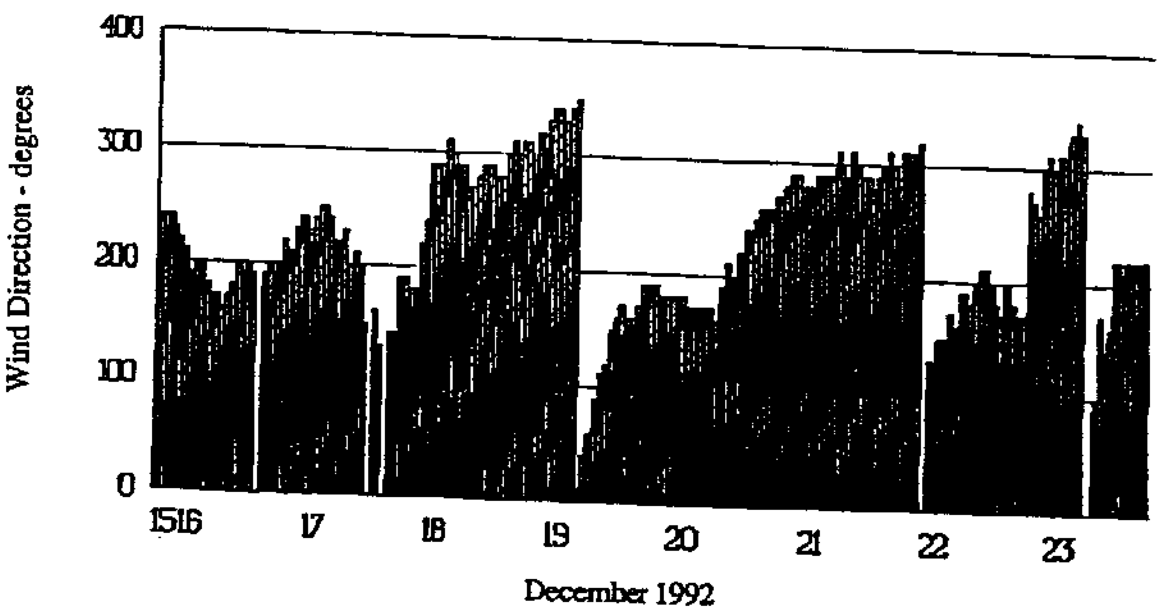


Fig. 5.4 Wind data from Mount Desert Rock

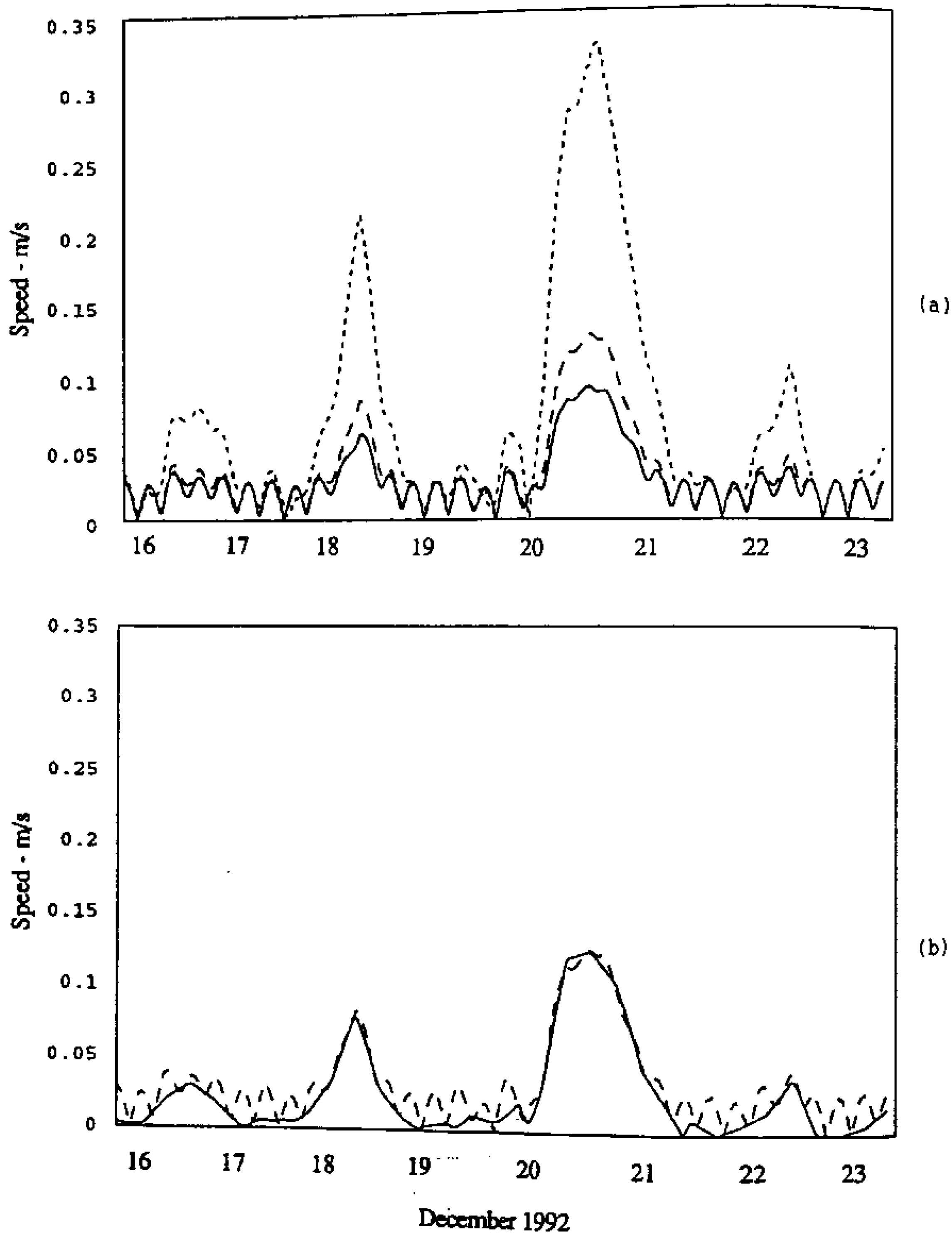


Fig. 5.5 Modeled velocities at aquaculture site with different wind drag coefficient
a : tidal and wind driven currents
——— Cd1=0.00325 – – – Cd2=0.00585 ······· Cd3=0.0145
b : – – – Cd2=0.00585, tidal and wind driven currents
——— Cd2=0.00585, wind driven currents

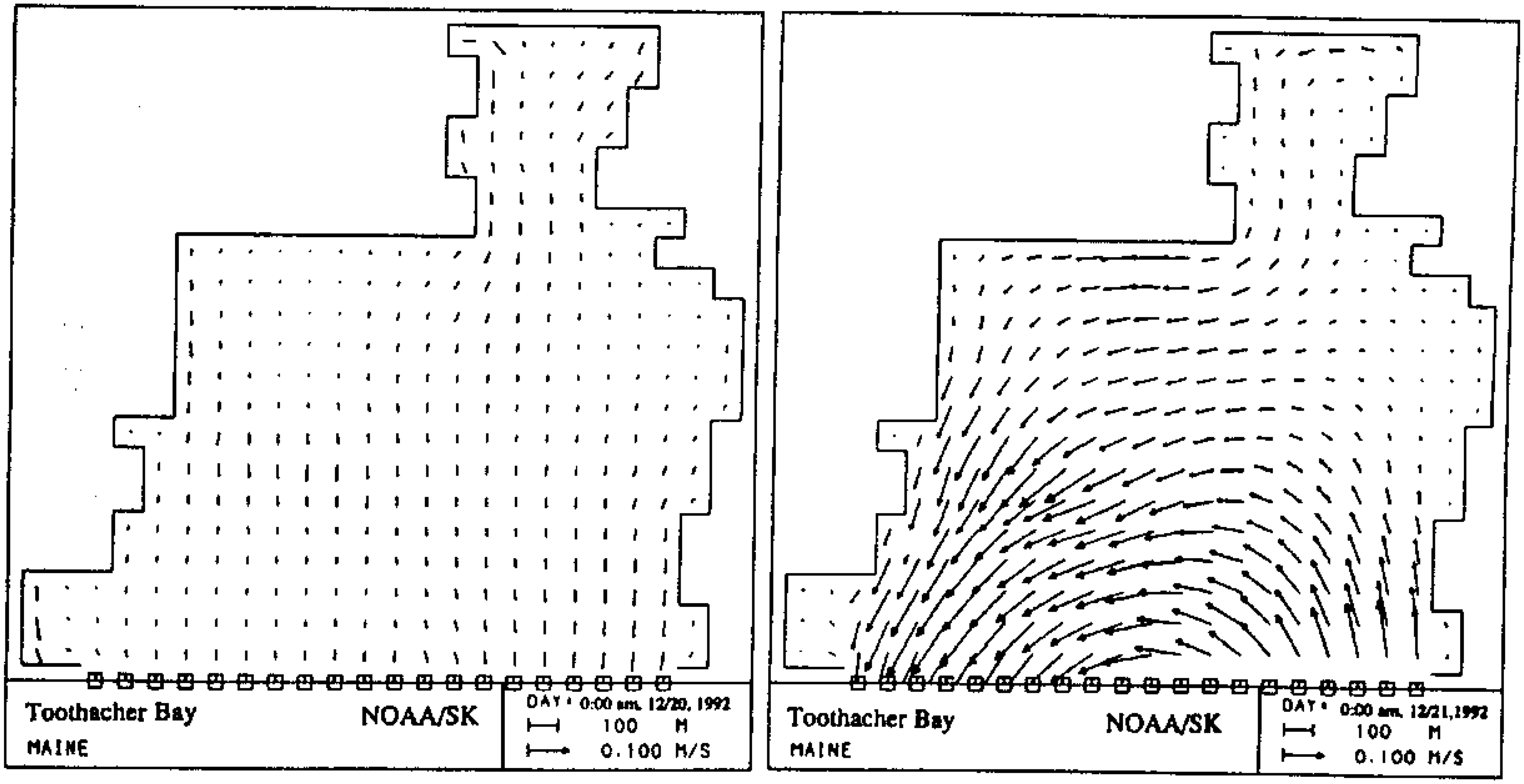


Fig. 5.6 Modeled velocities under two different wind events
left : 0000 hours, 12/20/1992, north-south wind
right : 0000 am, 12/21/1992, east-west wind

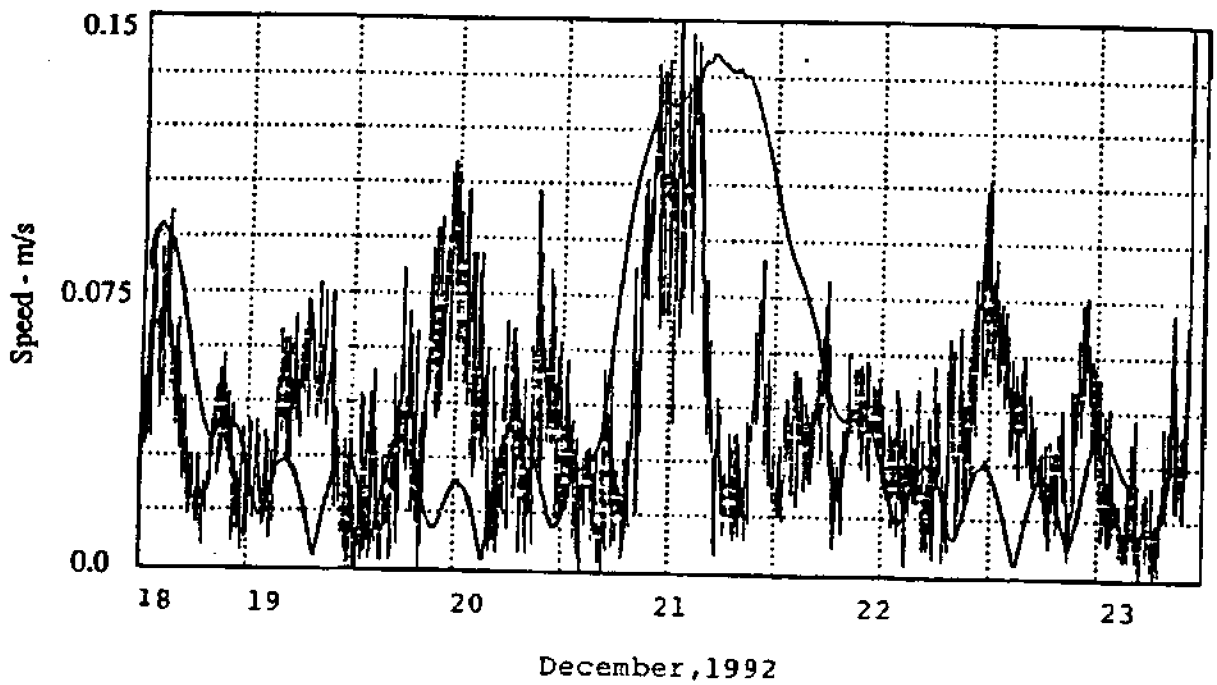


Fig. 5.7 Velocity comparison
observed —— model

settled wastes was contained in a region within 10 m of the edge of the pen. The waste concentration was quite high directly under the pen.

Tidal and Wind Driven Currents

The distribution of net pen wastes under the influence of tidal and wind driven currents for Pen 2 was studied. Wind data from Mount Desert Rock for 18 to 23 December 1992 were used (as described earlier). The results are shown Fig. 5.10. Although the current velocity now is larger than the tidal currents, the area where the net-pen wastes settle is larger than in Fig. 5.9. Since it takes only a few minutes for the particles to reach the bottom, most of them still settle down right under the pen. The farthest distance traveled by the particles is about 20 m. Under the influence of other events, the velocity field could be different from that used in this simulation, but the overall waste distribution is not likely to be very different from that shown in Fig. 5.10, since the particles are in the water column for such a short time. Thus, the inaccuracies in the modeled wind-driven currents are not particularly significant.

Comparison with Measurements

Findlay et al (1993) describe their efforts to obtain field data pertaining to net pen wastes in Toothacher Bay. They report sediment trap data measured during 5 deployment period in 1991. There is general agreement between our results and their data in that, like the model results, they found high concentration of wastes directly underneath the net pens and little or no impact at distance greater than about 10 m. However, the field data at the sediment traps show much variability. In fact, the average daily waste accumulation in some traps is actually higher during storm periods. This can only be explained by the fact that the trap does not allow material settled in it to be transported out of it, leading to elevated amounts of waste levels. These and other difficulties noted in Chapter 4 preclude a more systematic comparison of our model results to their data.

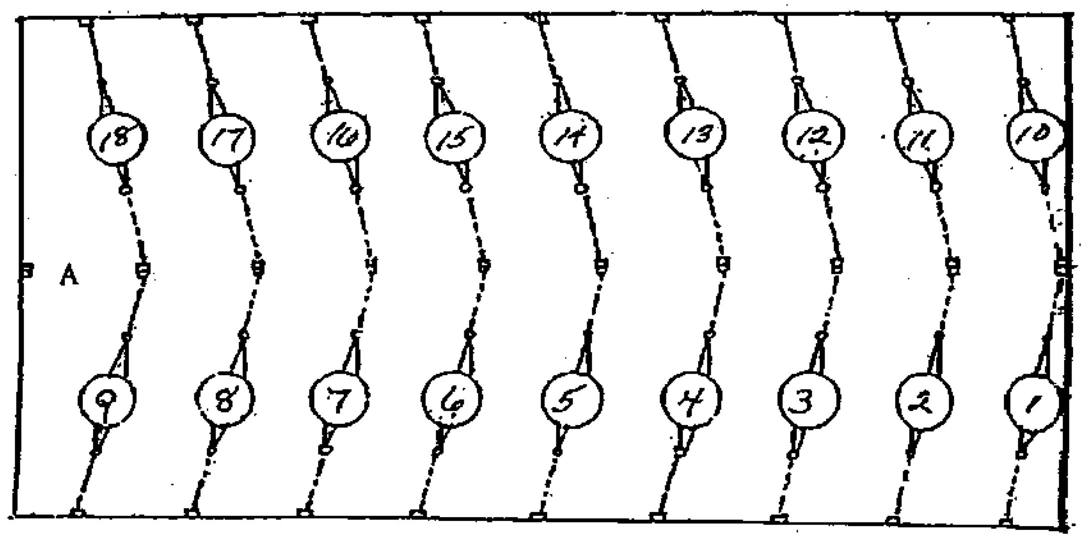


Fig. 5.8 Fish cages in Toothacher Bay
point A: current meter

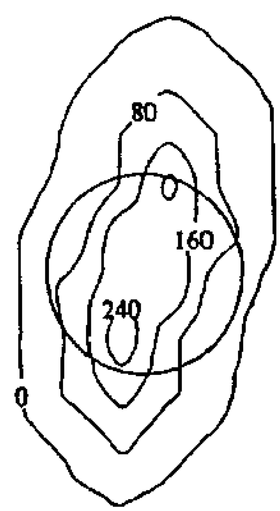


Fig. 5.9 8 days loading from Pen 2 under tidal currents in Toothacher Bay - g/m^2

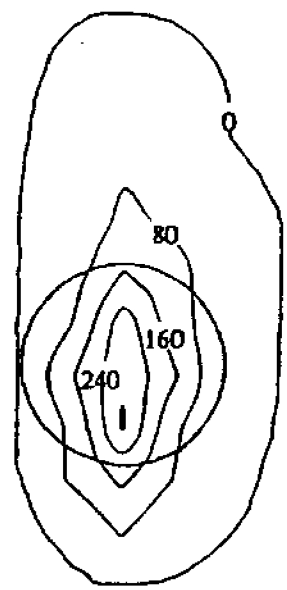


Fig. 5.10 8 days loading from Pen 2 under tidal and wind driven currents in Toothacher Bay - g/m^2

5.3 Wave Effects in Toothacher Bay

When orbital velocities resulting from storms-generated waves are large enough, settled waste particles can be picked up into the water column and moved back and forth with the wave oscillations. Large storms and swell can result in waves of large height or large period. Currents can further enhance the shear velocities experienced by bottom sediments (Kachel & Smith, 1989).

Possible Wave Growth in an Open Water Area

The SPM model (1984) was first used to estimate wave conditions resulting from hypothetical 10 to 50 miles /hr winds in an open area. The wave velocities were calculated via eq. 2-24. The results are shown in Table 5.1. Clearly the magnitude of the bottom velocities is much larger than the tidal and wind-driven velocities described earlier, and much larger than the critical erosion velocities (about 20 cm/s) used in Cobscook Bay. Since Toothacher Bay is exposed to a large fetch to its south, expectation of wave velocities of a magnitude comparable to those shown in Table 5.1 is reasonable. The SPM model was therefore applied to the actual geometry of Toothacher Bay in conjunction with wind data obtained from National Climatic Data Center.

Wave Conditions in Toothacher Bay

The wave model requires (as input) fetch lengths in various directions from the area of interest, the water depths, and the wind speed and direction. Our representation of Toothacher Bay for wave modeling is shown in Fig. 5.11.

Since our interest is in determining the frequency with which wave turbulence can cause resuspension of net-pen wastes, we first determined minimum wind conditions required for such resuspension. Several runs were made with different wind speeds. The results, shown in Table 5.2, indicated that for wind speeds exceeding 20 miles/hr (in any direction), resuspension is likely to result; the minimum bottom velocity in Table 5.2 is 0.37 m/s for this wind speed.

To determine the frequency with which such events occur, climatic summaries from the National Climatic Data Center were analyzed. The results for three years of wind data are summarized in Table 5.3. For this analysis, it is sufficient to examine the data on the basis of daily wind values (i.e. one value per day). It is clear from Table 5.3 that winds exceeding 20 mile/hr occurred about 25% of the time.

Although wave velocities could be altered by processes like refraction, diffraction, etc., an examination of Tables 5.2 and 5.3 show it is still reasonable to expect that the wave velocities at the bottom near the net pen are well above the threshold velocity (about 20 cm/s) during some time each year, resulting in periodic resuspension of settled wastes. The higher wave velocities occur often during the winter and spring months than in the summer months (Table 5.3).

Comparison of Wave Velocity With Field Data

Field data for 16 and 17 December 1992 are shown in Fig. 5.12a. The presence of waves about 0.2 - 0.3 m high is evident; also, the 8-second wave seems to be the dominant component of the record. This is clearly a swell component, since the wind data show this period to be relatively calm. Such wave conditions (e.g. wave height 0.2-0.3 m and period of 8 seconds) result in a bottom velocity of about 0.15-0.20 m/s from the eq. 2-24. Such velocities are confirmed by the data shown in Fig. 5.12 (b and c).

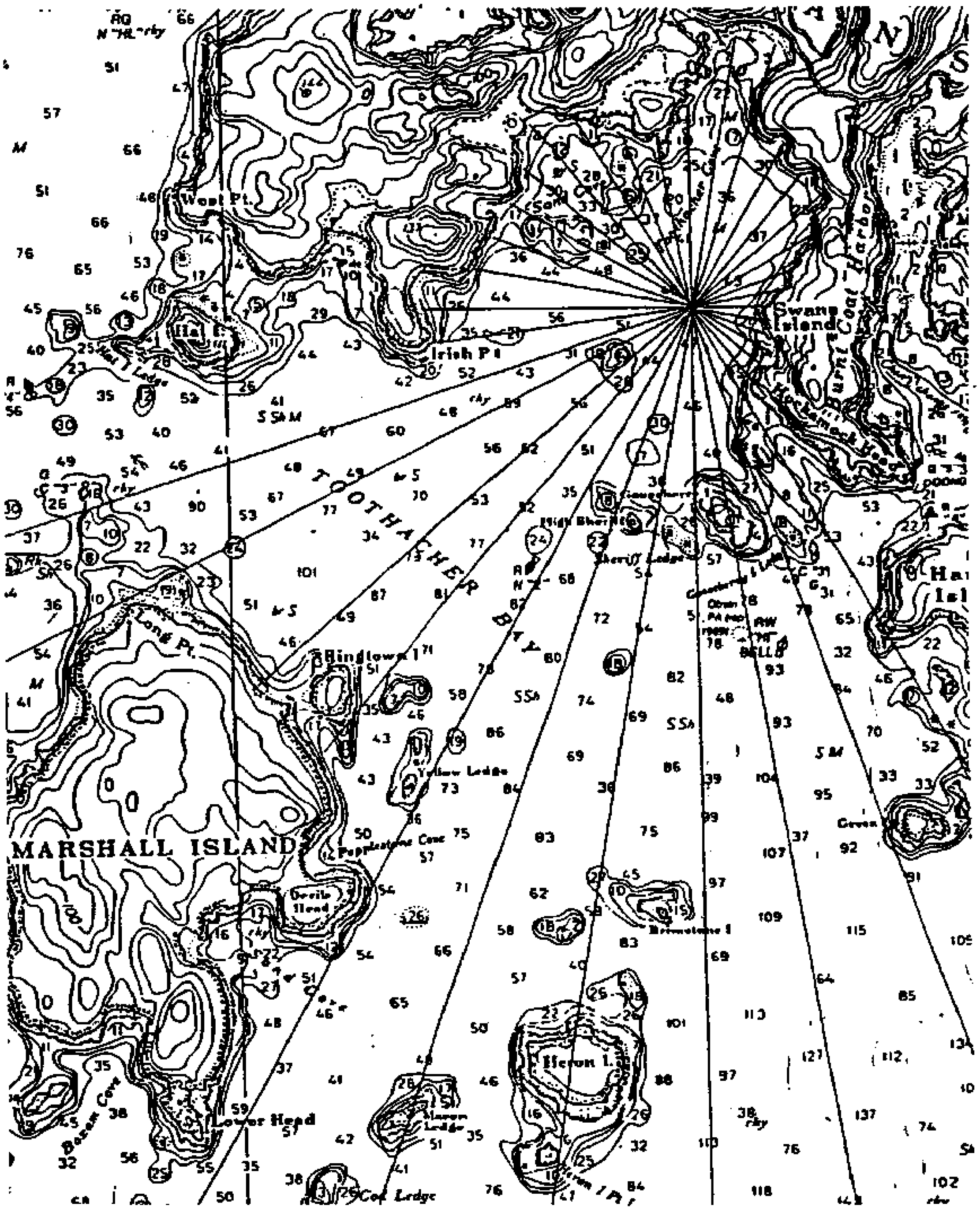


Fig. 5.11 Wind fetch lengths in Toothacher Bay

Table 5.1 Wave growth in an open water area

Fetch Length mile	Water Depth m	Wind Speeed mile/hr	Height m	Period s	Bottom Velocity m/s
20	15	10	0.36	2.52	0.45
	15	20	0.88	3.69	0.75
	15	30	1.42	4.46	1.01
	15	40	1.98	5.08	1.25
	30	10	0.37	2.56	0.45
	30	20	0.92	3.82	0.76
	30	30	1.52	4.65	1.03
	30	40	2.18	5.31	1.29
	50	10	0.37	2.58	0.45
	50	20	0.93	3.08	0.95
	50	30	1.55	4.74	1.03
	50	40	2.24	5.42	1.30
100	15	10	0.55	3.10	0.56
	15	20	1.51	5.01	0.96
	15	30	2.29	6.19	1.25
	15	40	2.97	7.08	1.50
	30	10	0.55	3.20	0.55
	30	20	1.75	5.39	1.02
	30	30	2.89	6.78	1.35
	30	40	3.98	7.83	1.65
	50	10	0.55	3.23	0.54
	50	20	1.83	5.58	1.03
	50	30	3.15	7.10	1.40
	50	40	4.49	8.25	1.72
Deep Water		10	0.24	2.04	0.37
		20	0.69	3.32	0.65
		30	1.33	4.47	0.93
		40	2.14	5.57	1.21

Table 5.2 Wave growth in Toothacher Bay (examined at net pen site)

Wind Speed mile/hr	Wind direction degree	Wave Height m	Period s	Bottom Velocity m/s
10	0	0.08	1.01	0.25
	45	0.07	0.97	0.22
	90	0.14	1.70	0.27
	135	0.52	3.12	0.53
	180	0.59	3.31	0.56
	225	0.52	3.12	0.53
	270	0.14	1.70	0.27
	315	0.07	0.98	0.21
20	0	0.18	1.48	0.37
	45	0.16	1.41	0.36
	90	0.71	3.59	0.63
	135	1.72	5.63	1.00
	180	1.83	5.86	1.03
	225	1.72	5.63	1.00
	270	0.71	3.59	0.63
	315	0.19	1.59	0.37
30	0	0.29	1.85	0.50
	45	0.27	1.77	0.48
	90	1.48	5.15	0.92
	135	2.51	7.26	1.25
	180	2.61	7.48	1.29
	225	2.51	7.26	1.25
	270	1.48	5.15	0.92
	315	0.32	2.04	0.49
40	0	0.42	2.17	0.61
	45	0.39	2.08	0.59
	90	2.08	6.35	1.11
	135	3.10	8.42	1.46
	180	3.21	8.64	1.50
	225	3.10	8.42	1.46
	270	2.08	6.35	1.11
	315	0.46	2.43	0.60
50	0	0.57	2.47	0.72
	45	0.52	2.37	0.69
	90	2.53	7.30	1.26
	135	3.62	9.34	1.66
	180	3.75	9.55	1.70
	225	3.62	9.34	1.66
	270	2.53	7.30	1.26
	315	0.62	2.78	0.70

Table 5.3 Frequency of winds exceeding 20 mph during 1989-1991 in Portland, Maine

Month	Wind Direction - Degree				Total
	0 - 90	90 - 180	180 - 270	270 - 360	
Jan	6	0	9	11	26
Feb	3	1	4	8	15
Mar	6	2	13	10	31
Apr	3	9	7	9	28
May	5	8	10	8	31
June	4	1	5	5	14
July *	0	0	2	3	5
Aug	2	1	2	4	9
Sep	2	4	7	9	24
Oct *	5	5	6	3	19
Nov	5	5	4	15	29
Dec	2	2	4	10	18
Total	43	38	73	95	249

* Two years

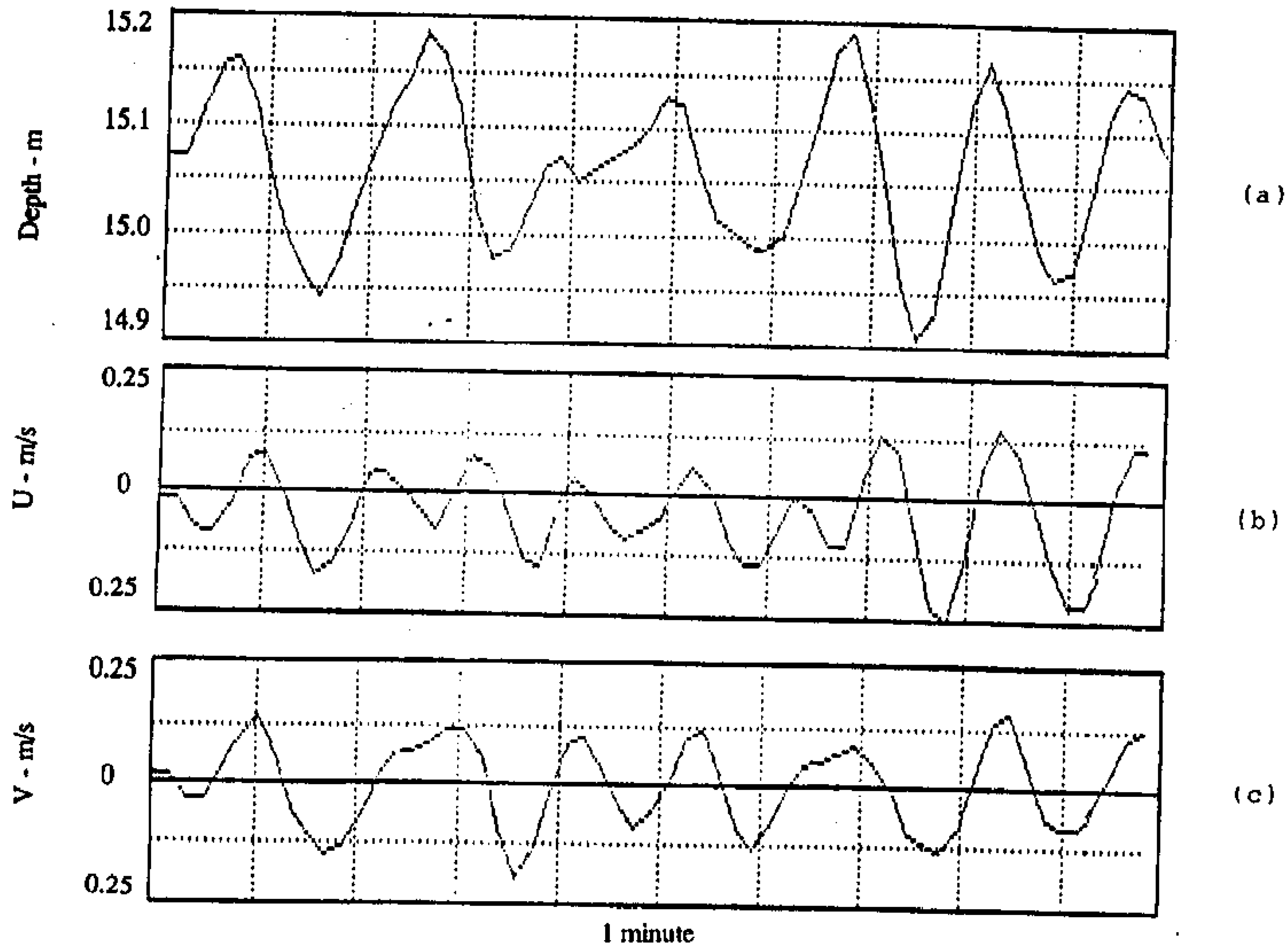


Fig. 5.12 Measured wave conditions in Toothacher Bay

5.4 Particle movement due to the joint forces of wind/tidal currents and waves

Although wave action results in the periodic resuspension of settled wastes, it is beyond the scope of this study to model net-pen waste transport due to the action of waves only. Waves essentially causes a back-and-forth motion on a time scale of the order of seconds and nonlinear drift. For this study it is sufficient is to use the tidal and wind-driven currents to advect the particles, assuming they are continuously resuspended during the period when intense storm activity occurs. To determine the effect of brief periods of wind activity, the contaminant transport model was run for 8 days without the effect of winds and waves (i.e. accumulation for 8 days). This was followed by a simulation of 3 separate wind events that occurred during the storm in December 1992 shown in Fig. 5.4. These events were: period 1, 24 hours starting at 1200 hours on 16 December; period 2, 24 hours starting at 0000 hours on 18 December; and period 3, 48 hours starting at 0000 hours on 20 December. The wind/tidal currents were obtained from the flow model runs as described previously. The particles were not allowed to settle during the period of wind events.

It was found that during period 1, 63% of the wastes were carried out, while during periods 2 and 3, all of the wastes were carried out. The actual storm of December 1992 consisted of these wind events occurring in fairly rapid succession; the above simulations obviously indicate a nearly total outward flux of the wastes from the bay. It is fairly certain that forcing by other storms events would lead to similar results, as a consequence of the combination of wave-induced resuspension with advection by tidal and wind-driven currents. Compared with the results in Section 5.1 and 5.2, it is clear that waves play a very important role in reducing the pollution levels at these sites.

6. CONCLUDING REMARKS

From the preceding chapters, the following observations can be made:

1) The 2-d flow model, DUCHESS, gave extremely reasonable simulations of many of the features of the coastal circulation. The modeled tidal amplitudes and phases are consistent with observations at many locations in Cobscook Bay and Toothacher Bay. Compared with a previous modeling study in Cobscook Bay (with a resolution of 225m), this study (with a finer resolution of 75 m) was able to simulate the flow characteristics in more detail, such as the eddy circulation in Broad Cove, the unique flow pattern in the Reversing Falls area, and the flooding/drying of shallow regions. These properties are significant for determining the net-pen waste distribution.

2) Although 3-d velocities were examined, it is adequate to use 2-d (vertically-averaged) velocities for studying aquaculture waste transport in coastal Maine. The modeled velocity profile is largely uniform except for some variations within the bottom one or two meters, which appear to be unrealistic. The minor differences between the average and the actual bottom velocities do not result in significant differences regarding the waste distribution. In addition, the effect of these differences is minor compared to the uncertainties regarding the critical shear velocity for resuspension of settled wastes.

3) Without the effect of particle resuspension, most of the particles settle down very close to the pen (within 10 to 30 m from the edge) at all the sites examined. With the effect of resuspension, the waste particles are more widely distributed and some get washed out of the bay. The actual distribution depends on the current velocity and the critical erosion velocity. There is very little data concerning the erosion velocity in the literature. We used a range of values from 0 to 0.6 m/s (Dr. Findlay suggested 0.15-0.20 m/s on the basis of his experience). The percentage of the sediments that get washed away and percentage that remains in the embayment depends totally on the threshold velocity at a certain location. This is a key factor in the modeling and should be a focus of future study.

4) In Cobscook Bay, the tidal current velocities can reach a maximum of about 2.0 m/s in the middle of the channel, 0.25 m/s near the lease site in Broad Cove, 0.25 m/s in Deep Cove, and 0.5 m/s in Comstock. Under the suggested threshold velocity (0.15-0.20 m/s), about 20% of the waste loading in Broad Cove and about 50-60% in Deep

Cove and Comstock will be washed out of bay. The gyre in Broad Cove inhibits the exit of the wastes from the cove. Based on the assumptions regarding the input given in Chapter 4, the loading to the benthos would be 6.5 - 10.2 $kg/m^2/yr$ close to the pen in Broad Cove, and 3.3 - 5.4 $kg/m^2/yr$ close to the pen in Deep Cove and Comstock in the absence of decay. The evolution to steady state requires a period of several years, depending on the decay rate. (See also item 8 below.)

5) In Toothacher Bay, the tidal velocities are very small (with a maximum of 0.04 m/s). Wind-driven velocities for a storm in December 1992 were much higher, of the order of 0.15 m/s. However, even these higher velocities cannot be expected to cleanse the bay of net-pen wastes, since the suggested threshold velocity for particle resuspension is about 0.2 m/s. On the other hand, wave-induced turbulence plays a significant role in cleansing the bay of the wastes. Results of our application of the ACES (1992) wave model show that waves could generate much higher bottom velocities (with a range of 0.37 - 1.03 m/s when the wind speed is 20 mile/hr). Under the influence of such high bottom velocities, waste particles on the bottom are resuspended, and our model calculation for December 1992 shows that under the joint forces of winds, tides, and waves, most or all of the wastes settled on the bottom are washed out of the Bay. Further, a statistical analysis of the wind data from Portland shows that winds exceeding 20 mile/hr occur about one fourth of the time. There is a much higher frequency of such events in the winter than in the summer. The site is thus cleansed of much of its wastes in late winter, an observation supported by Dr. Findlay.

6) Compared with contaminant transport models used to date for determining aquaculture waste distribution, the model developed here incorporated many additional realistic mechanisms. A detailed velocity field that varied in time and space, overall bottom topography, and particle resuspension have been taken into account. The model generated reasonable and representative results. In addition to the critical erosion velocity, information regarding model input (i.e. waste loading to benthos from fish pen) is a key factor in making reliable predictions of pollution on the bottom. The reported input data have a large range (for instance, the waste food percentage ranges from 1-30%). Therefore, it is probably futile to spend much effort in making detailed comparisons of model output with field trap data. Until accurate input data are available, further improvements on this model may be ineffective and unnecessary.

7) The waste concentration level on the bottom is sometimes very sensitive to the location of the net-pen. According to model results shown here for Deep Cove, the amount of waste could be reduced by half (or more) if the net-pens were moved about 100 m away from its present location. This is because of increased flushing ability (due to a different flow pattern) at the new location. This run was made for illustrative purposes only, and in no way suggests modification of existing aquaculture activity. The utility of models for site-selection is obvious, however. Compared with location, orientation of the pens will in all likelihood make little difference to the pollution level, especially when the particle resuspension is considered.

8) Attainment of steady state under the influence of regular waste loading and decay can be expected on a time-scale that is considerably different from the time-scale of erosional and flushing events. Thus the present uncertainty in the actual values of the decay coefficient is not a significant impediment at sites where the overall hydrodynamic environment prevents localized accumulation of wastes. However, at coastal sites with extremely low hydrodynamic activity, the decay coefficient would be extremely important: indeed, most available estimates of the decay coefficient have been derived from research carried out in fjords (e.g. Aure and Stigebrandt, 1990; Hansen et al. 1991). Although we have used these coefficients for our investigation in Broad Cove, we have no knowledge about the effect of the hydrodynamic activity on the decay coefficient.

This study has clearly shown the usefulness of a comprehensive modeling approach to the management of net-pen aquaculture waste. We recommend the systematic use of a suite of models that can simulate the overall hydrodynamic environment, i.e. tidal currents, wind-driven currents, and wave-induced velocities, along with a waste-transport model that includes resuspension of settled wastes. Our modeling studies in Broad Cove and Toothacher Bay justify this recommendation. From the viewpoint of existing guidelines for regulation, Broad Cove is, in all likelihood, a reasonably attractive site, since the tidal velocities obtained from isolated measurements would be high. Yet our model simulations (Table 4.3) show that a high percentage of the wastes would remain in the bay. (This is true in spite of the uncertainties in the resuspension threshold velocity: even with Vc = 0 m/s, 22% of the wastes cannot leave.) In spite of the high velocity, the high level of waste retention is due to the presence of a gyre in Board Cove: as demonstrated in Fig. 4.18, some net-pen wastes are trapped in the cove. This clearly demonstrates the importance of obtaining the overall flow pattern through the use of an appropriate model.

Toothacher Bay, on the other hand, is likely to be rejected as an aquaculture site under the guidelines presently used or even by previous modeling methods. Like our model simulations, isolated measurements would yield low tidal velocities. Indeed under the influence of tidal currents alone, Toothacher Bay *should* be rejected. However, the systematic approach that we recommend calls for the modeling of episodic events such as wind-driven currents in such cases.[1] If the modeled currents are strong enough to initiate resuspension, the percentage of wastes leaving the bay should be calculated. Our model results for Toothacher Bay showed that wind-driven currents were probably inadequate. Wave modeling must then be resorted to; in Toothacher Bay, modeled wave velocities were found to be high enough to initiate resuspension, and the tidal and wind-driven velocities are found to flush the bay fairly regularly. Our modeling work predicts minimal pollution by late winter each year, which is confirmed by the observations of Dr. R. Findlay.

A step-by-step modeling strategy as described above is well within the reach of regulators. Models similar to those used in our study are available either commercially or from US Government agencies and modern workstations facilitate their convenient implementation. Alternatively, some of the more relevant hydrodynamic parameters in several candidate areas can be obtained a priori by modeling and stored within a GIS; e.g. Ross et al (1993) demonstrate the application of geographic information systems (GIS) to site selection for salmonid cage culture. Using depth, currents, and water quality parameters (temperature, salinity, dissolved oxygen) they determined the best 1.3 hectares in a Scottish sea loch based on both husbandry and environmental impact criteria. Data bases may be sorted for ranges and optimal environmental parameters, resulting is non-subjective rating useful to both the manager and farmer. Site evaluation in this manner should reduce the monitoring required of the individual farmer, and provide the manager with a powerful tool to evaluate different scenarios of husbandry activities by the farmer.

One question that has not been addressed is what constitutes an acceptable impact. As a participant in the workshop on "Aquaculture and the Marine Environment: the Shaping of Public Policy" in Woods Hole in November 1993, one P.I. (C. Newell) participated in the waste management working group chaired by John Pitts and Robert Bowen. The first

[1] Ideally we should have followed this approach for Cobscook Bay as well. However, Broad Cove is far less exposed than Toothacher Bay, and Dr. R. Findlay's experience suggested little wind-induced hydrodynamic activity. Also, our modeling of such events would have to account for the activities of bottom draggers on a regular basis in this area. Further, time constraints did not allow additional investigations of a large domain like Cobscook Bay.

recommendation was: "Federal and state regulators need to better coordinate efforts, using the best available scientific information, to determine criteria for acceptable or unacceptable mariculture sites." Indeed, participant Chris Heinig noted that when scientists and managers observed the same videos under fish pens, the two groups had different subjective criteria of what was "acceptable".

There are other issues that must be addressed in order to make the modeling more reliable. Model estimates of the hydrodynamics are adversely affected by the paucity of wind data (e.g. for a state with over 3000 miles of coastline, there are very few buoys in coastal Maine). A correct representation of the coastal bathymetry, with finer resolution would also be of benefit. Research to estimate critical shear velocity that causes erosion of organic deposits beneath the pens is needed. Finally, better estimates describing husbandry practices (feed rates, fish stocking rates, percentage of waste food) are required to enhance the reliability of models (although the results given in Chapters 4 & 5 can easily be adjusted for other input loading rates).

As the U.S. representative on the ICES Working Group on Environmental Impacts of Mariculture (see working group reports ICES C.M. 1988 F 32, ICES C.M. 1990 F 12, ICES C.M. 1992 F 12), one P.I. (C. Newell) noted the considerable research performed in Europe and Canada, during which few, if any, environmental disasters associated with net-pen culture were observed even in enclosed fjords; their work illustrates the importance of good site selection and husbandry to reducing impacts. The new focus of the Working Group is on integration of mariculture with coastal management plans of the EEC, with a future focus on modeling the effects of fish farm effluents on the environment (ICES C.M. 1993 F:6). In this context, we have illustrated the usefulness of a site-specific modeling strategy which incorporates the local bathymetry, currents, winds and waves, in combination with a contaminant transport model, to represent the sedimentation and net accumulation of organic waste in two contrasting Maine estuaries. Modeling results, using typical values for waste loading from Maine cage culture sites, demonstrate *a priori* whether commercial-scale operations will cause high rates of net waste accumulation at a particular site. As policy leaders in the U.S. deal with aquaculture waste management issues, it is expected, on the basis of this study, that modeling will become an increasingly powerful tool to minimize the impact of salmonid net-pen effluents in coastal waters.

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