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Application of a comprehensive modeling strategy for the management of net-pen aquaculture waste transport

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Abstract

An efficient mathematical modeling package called Aquaculture Waste Transport Simulator (AWATS) provides first-order estimates of the physical dispersion of finfish aquaculture wastes for regulatory purposes. The modeling strategy entails the utilization of a vertically averaged, two-dimensional flow model to produce flow-field information. This information is input to a particle-tracking waste transport model to simulate the resulting transport of wastes. Since earlier studies have shown that the transport modeling results are sensitive to the threshold shear stress at which settled fish-pen wastes are resuspended, fieldwork was conducted to improve the parameterization of erodibility in the transport model. Application of AWATS to aquaculture sites in coastal Maine (selected by the Maine Department of Environmental Protection) shows that it is a convenient tool in the regulatory process. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Regulators invest considerable effort to monitor hydrodynamic, water quality and benthic conditions, and to evaluate environmental impacts of net-pen aquaculture

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operations. However, the efficiency of this work may be significantly enhanced through the use of mathematical models that give more complete information regarding the physical conditions in the domain. For example, Panchang et al. (1997) have shown that the use of blanket guidelines for minimum current speed and water depth do not automatically ensure favorable hydrodynamic conditions for net-pen operation. The flow-fields seen in many coastal areas are complex and it is often difficult to discern prevailing current direction and overall flow-fields from discrete, site-specific, measurements over limited periods. The latter data fail to ascertain the spatial and temporal variations of the hydrodynamic environment within aquaculture sites (induced, for example, by vorticity, wind, seasonal effects, etc.) or the cumulative effects of several operations within a coastal embayment.

While elementary models describing the dispersion of net-pen wastes have been described by Gowen et al. (1989) and Gillibrand and Turrell (1997), Panchang et al. (1997) developed a comprehensive modeling strategy involving an investigation of tidal and storm-induced currents, wave effects, and net-pen waste transport mechanisms such as settling, resuspension and decay. This approach was shown to be successful in assessing the impact of aquaculture operations in Cobscook Bay and Toothacher Bay, ME, USA. First, a vertically averaged flow model was constructed to simulate the spatial and temporal variations of currents induced by tides and storm winds. This two-dimensional flow model based on the shallow water equations was shown to be adequate for this task (rather than a more intensive three-dimensional model). The resulting flow-fields were used as input to a particle-tracking waste transport model. The waste distribution results showed that, at some sites, inferences drawn using a combination of modeling methods and field data could be quite different from those drawn using isolated field measurements. The potential of the modeling methods for site selection and in deciding a priori which sites needed a greater level of monitoring was also demonstrated.

Before the modeling techniques can be adopted in regulatory practice, however, the work of Panchang et al. (1997) suggests that two problems need further attention. First, a more reliable description of the resuspension of settled wastes is needed. Since resuspension involves complex mechanisms that are not well understood, it was modeled using a parameter U_{crit} describing a threshold or critical current velocity at which settled waste material would be resuspended. Panchang et al. (1997) found that the waste dispersion and accumulation results were very sensitive to the threshold shear stress at which settled fish-pen wastes are resuspended, thus limiting the usefulness of the models for site selection. Secondly, most available models still fall within the realm of research and do not offer tools that can be readily applied by regulators. The availability of such tools may help overcome the complex and restrictive regulatory environment that is viewed as a limiting factor in the growth of the aquaculture industry in the United States (Schneider and Fridley, 1993).

We describe efforts to improve estimates for the critical resuspension velocity of net-pen wastes, and to create a modeling package that could be routinely used to aid regulators with site evaluation and decision-making. Specifically, field measurements were made to estimate in situ erodibility of net-pen waste materials. A submarine annular flume (Amos et al., 1992b) was used.

In the interest of packaging the modeling technology for regulators, flow fields from commonly available 2-D flow models are assumed to be available. For demonstration, here we have used the output from a finite-difference model called DUCHESS, which was developed at Technical University Delft, the Netherlands, and is widely used for two-dimensional tidal and storm surge computations (e.g. Booij, 1989; Jin and Kranenberg, 1993). The transport model developed by Panchang et al. (1997) was enhanced and packaged with an interface used to extract flow solutions, and to graphically display flow and transport results. This work led to a package called Aquaculture Waste Transport Simulator (AWATS), described briefly in Section 2. Application of AWATS to three aquaculture sites (Machias Bay, Blue Hill Bay, and Cutler Harbor) selected by the Maine Department of Environmental Protection is described in Section 3.

2. Materials and methods

2.1. Fieldwork to estimate erodibility

In the initial development of the waste transport model, Panchang et al. (1997) found that the transport of net-pen aquaculture waste was sensitive to the ability of the currents to resuspend material once it had settled on the bottom. With settling rates of 3–10 cm/s and typical depths beneath pens of 15–25 m, net-pen wastes will settle in the vicinity of the pens in a matter of minutes. In constant low-velocity environments such as fjords, local settling can have adverse environmental impacts; in high-velocity environments the material may be resuspended and more effectively dispersed. Lacking applicable information regarding the complex process of resuspension in aquaculture environments, Panchang et al. (1997) modeled multiple transport scenarios by varying the values of U_{crit} and found that the resulting waste dispersion was very sensitive to the range of values of U_{crit}. For example, waste removal from the domain used to examine a commercial lease site in Deep Cove, Cobscook Bay, varied between 83% and 0% when U_{crit} was varied between 10 and 40 cm/s. The area affected by the wastes also varied substantially.

Erosion of sediments is a function of bottom stress, which is often expressed as shear velocity. In this sense, U_{crit} is intended to be a measure of the threshold stress at which net-pen wastes would be eroded and resuspended. To obtain more reliable information regarding this mechanism, measurements were made at the Connors Brothers commercial lease site at Deep Cove in Cobscook Bay (Fig. 1) near Eastport, ME. This site contains three pen-systems (Fig. 2) consisting of net-covered cages arranged in rows of 10 cages, with two rows forming an independent floating pen-system, each holding about 5000 fish. Since it was possible that the erosion threshold varied with the amount of material already accumulated, the Sea Carousel was deployed at nine locations to measure seabed erosion: three near the center of the site, four locations at different points on the sedimentation gradient, and two control locations closer to land deemed to be unaffected by the net-pen operation. As a consequence of higher feeding rates in the summer, and more frequent storm-induced erosional events in the winter, there is likely to be seasonal variation in the amounts of net-pen wastes present. Data were hence collected at two different times: in April 1996 and in September 1996.

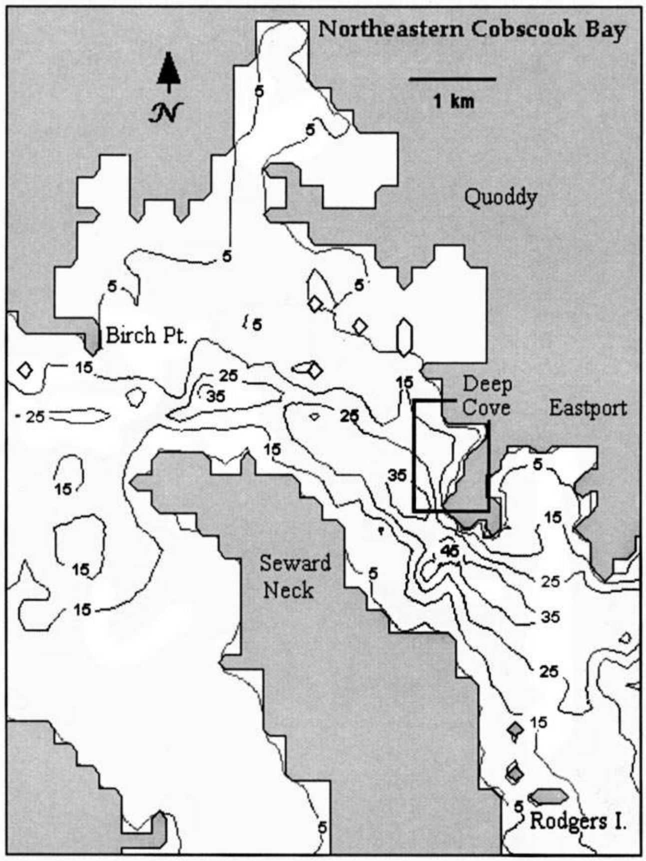

Fig. 1. Northeastern Cobscook Bay, Washington County, ME.

The Sea Carousel consists of an annular flume (Fig. 3) inside which a current is generated after lowering it to the benthos from the side of a boat. The current was slowly increased in magnitude in a stepwise fashion. Each deployment consisted of a 10-min still-water phase for determination of ambient concentrations of suspended particulate matter (SPM), followed by a 5-min erosion phase, and concluded with a 15-min still-water phase to determine the settling rates of the eroded material. At each step over the course of the erosion program, a video of the erosion process was obtained in conjunction with water samples and turbidity measurements. The resulting turbidity measurements were correlated with shear velocity to provide values of critical resuspension velocity (Amos et al., 1992a).

During the fieldwork, locations of the net-pen sites, current gauges, and Sea Carousel deployments were determined via GPS. A summary of the erodibility threshold results is given in Table 1, in terms of $U_{(100)}$, the current velocity at 100 cm above the bottom. The $U_{(100)\mathrm{crit}}$ values were determined from plots of SPM against $U_{(100)}$ where SPM was observed to be considerably higher than the preceding ambient SPM concentrations. The

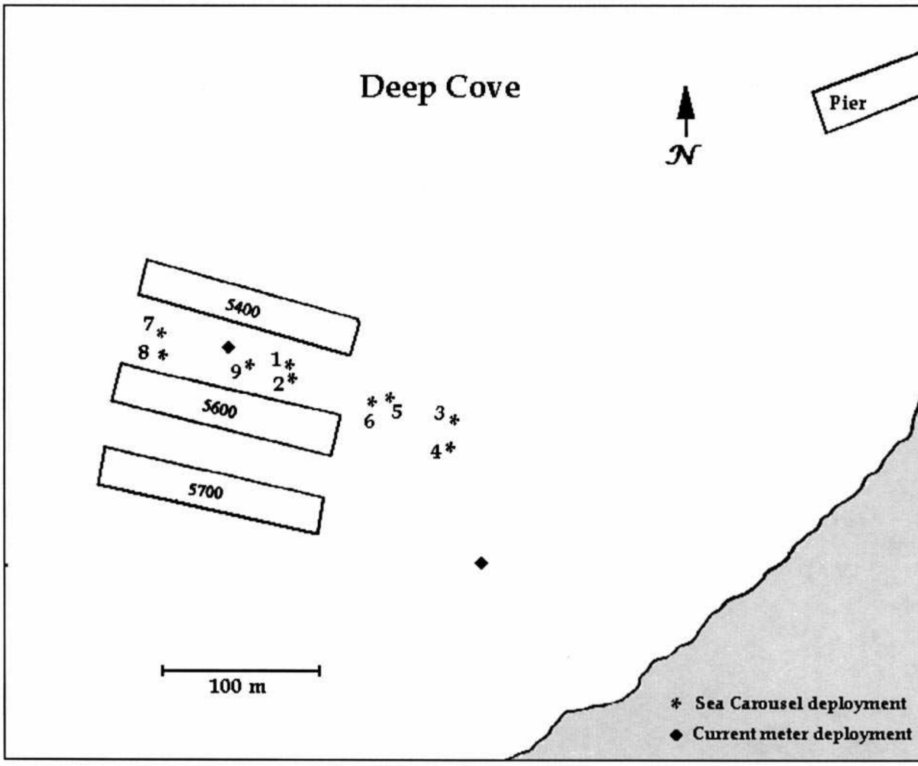

Fig. 2. Locations of Sea Carousel and current meter deployments near the Connors Bros., net-pen systems 5400, 5600 and 5700, Deep Cove. Sea Carousel deployments numbered 1–9.

$U_{(100)\mathrm{crit}}$ value was taken as the mean of the $U_{(100)}$ speed settings at that transition point. An example is illustrated in Fig. 4, which shows results for the April 1996 Sea Carousel deployment at station 4 in Deep Cove, ME. Based on the significant change in SPM illustrated in Fig. 4, $U_{(100)\mathrm{crit}}$ for this particular experiment is estimated to be 0.33 m/s.

The results for all erosion experiment locations (Table 1) show that, in general, the erosional velocity increases along a transect in the direction of the net-pen. Similarly, the values are higher in the summer than in the winter. This suggests that U_{crit} is indeed affected by the amount of material present. The modeling strategy described later only allows for the specification of a constant U_{crit}. Average values of 0.40 m/s for the winter/spring and 0.50 m/s for the summer/fall are used. These numbers are close to anecdotal evidence provided by divers (R. Findlay, Dept. of Microbiology, Miami University, pers. comm.) that material seems to be resuspended when the flow speeds are greater than about 0.30 m/s. It is important to note that the U_{crit} values in Table 1 include values for all sediment types encountered in the field sessions, from fine gel mud to coarse material, and it includes erosion of native material as well as net-pen wastes.

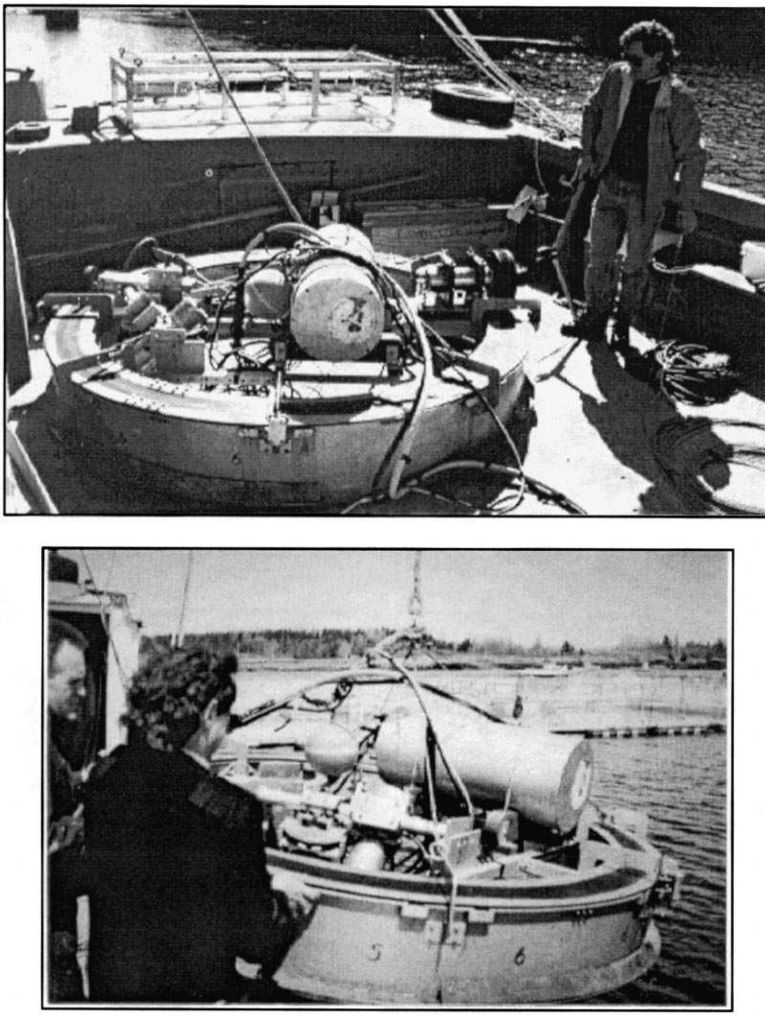

Fig. 3. The Sea Carousel on deck in preparation for deployment (top). The Sea Carousel about to be lowered to the benthos at the Connors Bros. aquaculture site in Deep Cove (bottom).

2.2. Hydrodynamic models

In the interest of assembling a user-friendly modeling software package to be used by regulators, we evaluated the ease of operation and accuracy of both finite-element and finite-difference two-dimensional flow models. Although finite elements usually afford greater flexibility in describing complex coastal boundaries and domains, their implementation was extremely time-consuming and problematic for some of our applications. The model also presented added complexity for regulators due to its sensitivity to grid sizes, requiring greater efforts in the construction and refinement of finite-element

Table 1
Mean $U_{(100)crit}$ values from Sea Carousel data near Connors Brothers, aquaculture farm, Deep Cove, ME

Station	$U_{(100)crit}$ (m/s)			
	April, 1996		September, 1996	
	Value	Mean	Value	Mean
1	0.47	0.47	0.62	0.66
2	0.47		0.69	
3	0.47	0.40	0.47	0.51
4	0.33		0.55	
5	0.33	0.33	0.47	0.44
6	0.33		0.40	
7	0.33	0.44	0.47	0.44
8	0.55		0.40	
	all stations	0.42	all stations	0.51

meshes. Mesh construction and refinement is a complex problem requiring evaluation of domain geometry and bathymetry. While all modeling involves a certain level of trial-and-error before successful simulations are obtained, it was found that working with finite-element models would be too cumbersome from the point of view of routine management.

Most finite-difference models, in comparison, require only a single resolution throughout, and entail a straightforward relationship between the time step and the grid size. Although the flexibility of enhancing the resolution in specific parts of the domain is compromised, some finite-difference models allow options for subsequent simulations in ‘‘nested domains. In our work, we have used the output from the model DUCHESS, which has been previously used for investigating aquaculture waste transport in Cobscook Bay and Toothacher Bay (Panchang et al., 1997). The model has also been successfully applied to other fisheries-related problems (Newell, 1991) and has been found to be generally robust.

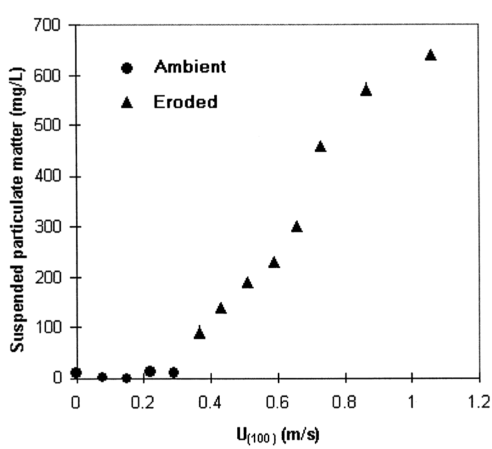

Fig. 4. Turbidity data for Station 4, Deep Cove.

One limitation of DUCHESS and many other finite-difference models is that they lack a convenient graphical user interface to expedite the modeling process by aiding the user in model construction, and viewing and interpreting model output. For this reason, we made efforts to interface DUCHESS with a software package called Surface-water Modeling System (SMS) developed at the Brigham Young University Engineering Computer Graphics Laboratory (ECGL) in cooperation with the Army Corps of Engineers (Jones and Richards, 1992; ECGL, 1995). The SMS software provides the user with various tools and pull-down menus to facilitate digitizing scanned topography maps, constructing computational meshes, and displaying and animating solution data sets with color contouring and vectors. Although originally intended for finite-element grid generation, we developed a utility program called DUCHSMS which indirectly links any finite-difference model to the graphical features of SMS. DUCHSMS facilitates construction of the model domain using SMS, and graphical viewing of the flow model output. It enables bathymetry digitized with SMS to be exported in a form required by DUCHESS as input and also transforms DUCHESS output into a form readable by SMS. This allows easy graphical display and animation of flow solutions obtained from DUCHESS in SMS.

In addition to two-dimensional flow modeling, wave modeling was performed for the determination of wave induced velocities. The Automated Coastal Engineering System (ACES) (United States Army Corps of Engineers, 1992) was incorporated into the AWATS modeling strategy to estimate wave conditions for coastal areas subject to significant wind fetch. The model requires, as input, a description of the coastal geometry in the form of fetch lengths in various compass directions converging on the point of interest and the water depth. The model also requires the input of wind speed and direction. Using representative wind speeds and durations to simulate storm events, the resulting wave height (H) and period (T) output by ACES can be used with Airy theory to compute the wave velocity (U_{wave}) using the following equation (Dean and Dalrymple, 1984):

$$U_{\mathrm{wave}} = \frac{\pi H \cosh(k(z+d))}{\sinh(kd)} \cos(kx - \omega t) \tag{1}$$

where d is the total water depth, x and z represent the horizontal and vertical coordinates of interest ($z = 0$ at the surface and $z = -d$ at the bottom), ω is the wave frequency ($= 2\pi/T$), and k is the wave number determined by the wave dispersion relationship ($\omega^2 = gk \tanh(kd)$).

2.3. Transport model

A transport model called TRANS was developed at the University of Maine to simulate the advection and dispersion of finfish aquaculture wastes. It is included in the AWATS package, and models the mechanisms of settling, advection and resuspension to describe the physical transport of fish-pen waste materials. To accomplish this, TRANS requires spatial and temporal flow-field information, bottom topography data, and properties describing the net-pen wastes such as resuspension threshold (U_{crit}), settling rates, and the location and the frequency of the introduction of wastes into the water. Parameters describing the aquaculture farm are input by the user providing coordinates of each net-pen in the domain coordinate system, as well as the size of each pen, its stocking density and daily feed quantity. Other user-specified parameters in the model include: the simulation duration, begin and end times for food and fecal matter introduction each day, the uneaten food ratio as a percent of the daily food mass introduced, the daily fecal pellet production in g/kg of fish, percentage of organic carbon contained in the waste depending on the feed used, and first-order decay coefficient estimates for food and fecal matter.

The transport model computations involve breaking the daily feed and fecal introductions down into particles and tracking their dispersion throughout the model domain as they are advected by the currents computed by the hydrodynamic model. Each particle represents a user-specified amount of mass representing a part of the total mass introduced over the course of the simulation. The particles are tracked until they leave the transport domain at which point they are considered to have been flushed away, and are not allowed to return. As the particles sink, they are advected by the flow-field until they reach the bottom. For modeling purposes, we chose sinking rates of 3 cm/s for fecal particles and 10 cm/s for feed particles (Panchang et al., 1993). Once on the bottom, a check is made at each time step against the specified U_{crit} to determine whether or not the particle is eroded from the bottom and resuspended in the water column to be further transported.

Particles can decrease in mass over the course of a model run due to first-order exponential decay. Values used for the decay coefficient depend upon the environment and oxygen availability. Values in fjords have been found to vary between 0.1 and 0.5 year^{-1} (Aure and Stigebrandt, 1990; Hansen et al., 1991). When examining the decay of wastes in low velocity environments, the application of a singular first-order decay coefficient may not be appropriate since the availability of oxygen required for decay is dependent upon current speed and water exchange. Findlay and Watling (1994) have performed calculations to estimate the current speed dependent oxygen delivery rate for sea water at 20°C for currents less than 8 cm/s. This oxygen delivery information provides a useful tool for determining whether organic carbon loading rates in a low velocity environment have the potential for outstripping the rate of aerobic decomposition of the wastes.

At the end of the simulation, TRANS outputs waste distribution snapshots at a user-specified time interval and a simulation summary. All particles remaining inside the model domain at the end of the simulation are assumed to contribute to organic carbon loading to the benthos. The loading concentration, in g/m^2, is computed by dividing the total mass in each transport model grid cell by the area of the cell. TRANS will interpolate for transport model grid and time step sizes that are smaller than those of the flow model. A typical transport scenario is run for 15 days to approach a steady-state loading pattern. The output snapshots represent the estimated concentration of net-pen wastes as a measure of organic carbon as it is distributed over time throughout the domain. These snapshots are output in a form readable by SMS for easy graphical display and animation (described later). TRANS reports all model parameters as well as the amount of material flushed out of the domain, the residence time for material introduced on the first day of the simulation, and the maximum load rate and its location in the model domain in the summary file.

2.4. The AWATS modeling package

We have constructed a package called AWATS that may be suitable for regulatory use. This package conveniently links the hydrodynamic and transport models with information regarding the net-pen operations and graphically displays results. AWATS includes the waste transport program TRANS, the graphical interface SMS, and the flow model DUCHESS. (In the event that the user does not have DUCHESS, output from another flow model may be used.) It also includes a utility program, DUCHSMS, which was developed to extract flow and bathymetry data for the subdomain of interest (i.e. the general vicinity of the net-pen, specified by the user in the form of a rectangle) from the output files of the flow model (DUCHESS or alternative) and use this information to run TRANS. Details regarding practical use of the various components of AWATS are described in Dudley et al. (1998).

Executing AWATS produces two forms of output. First, the simulation summary describes all user-defined parameters and calculated quantities like flushing efficiency for particles introduced into the domain, residence time, and the sedimentation rate and location of the point with greatest accumulation in the subdomain. The other is a data file that contains snapshots of the dispersion of net-pen wastes over the simulation, suitable for plotting in SMS for viewing/animation. TRANS uses the model flow solution to compute the mean and maximum velocity at the location of greatest organic carbon loading, and also the tidal prism ratio (TPR) of the transport domain. The TPR can provide a first-order estimate of water exchange in the domain due to tidal flushing, which provides more oxygen to aerobic organisms for decomposing organic wastes. The ratio is defined:

$$\mathrm{TPR} = (\mathrm{BVHT} - \mathrm{BVLT}) / \mathrm{BVHT} \qquad (2)$$

where BVHT and BVLT are the basin volumes at high and low tide, respectively, and the numerator is known as the tidal prism. Use of the TPR is considered to be a reasonable method for comparison of flushing of small harbors that are directly connected to ambient waters and do not have freshwater inflows (Nece and Falconer, 1989). Gillibrand and Turrell (1997) use similar flushing parameters as a method to help evaluate the hydrography of fjordic sea lochs and model the potential impact of fish farms. Computation of flushing of bays can provide regulators with another factor for identifying aquaculture sites where organic enrichment is likely to become a problem.

3. Results and discussion

3.1. Simulation of net-pen waste distribution in Machias Bay, ME

An aquaculture operation run by Atlantic Salmon of Maine (ASMI) is located in Northwest Harbor off Cross Island. The island is situated near the mouth of Machias

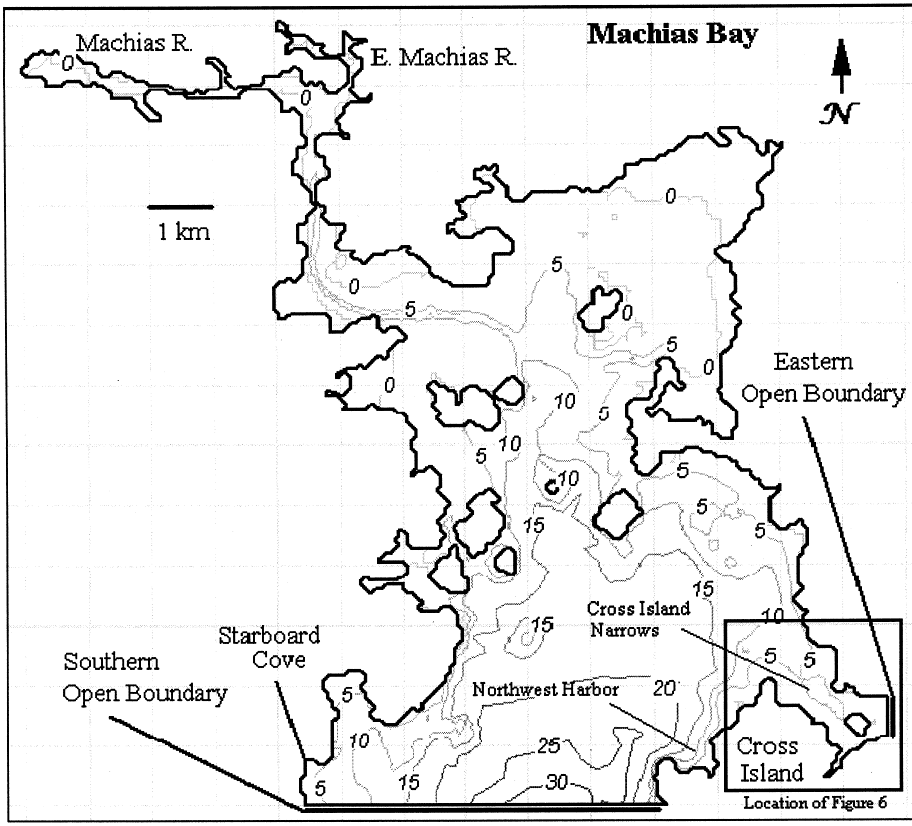

Fig. 5. Machias Bay domain illustrating bathymetry and open boundaries.

Bay (ME) close to the mainland where it forms the Cross Island Narrows to its northeast (Fig. 5). The tidal range near the aquaculture site is about 4 m, with mean currents of around 3 cm/s, and a depth beneath the pens of about 12 m at mean low water.

Bathymetric data for Machias Bay (Fig. 5) were obtained by digitizing NOAA chart 13326 on a 75-m finite-difference grid using SMS and the utility program DUCHSMS. The hydrodynamic model was forced with the lunar component of the tide along the two open boundaries shown in Fig. 5. For initial simulations, the forcing functions (tidal amplitude and phase data) were obtained from a larger mathematical model encompassing the entire Gulf of Maine (Sucsy et al., 1993) after performing appropriate interpolations (Dudley et al., 1998). The southern and eastern boundaries were forced with tidal amplitudes of 1.9 and 1.94 m, respectively, with negligible phase difference between the two boundaries.

Current data obtained by the Norwegian company *Akvasafe* on behalf of the Maine Department of Marine Resources were used to tune the model. These measurements, covering the period from December 26, 1989 to February 8, 1990, pertained to a depth of 2 m beneath the surface in the vicinity of the net-pens; however, owing to various

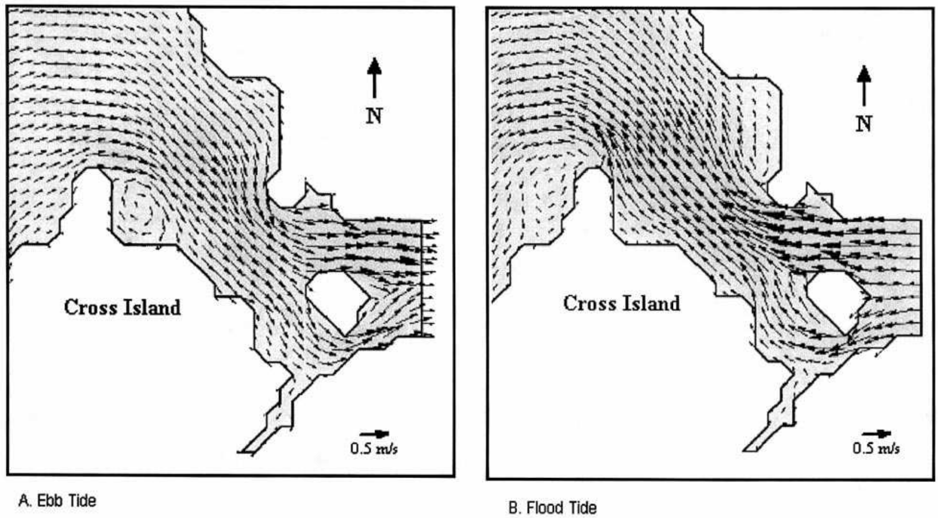

Fig. 6. Cross Island Narrows vector plots for ebb and flood tides.

difficulties (such as insufficient detail in the data report and occasional movement of the pen systems), we were able to determine their location only approximately.

Initial efforts in tuning the model yielded reasonable simulations which matched current data in the vicinity of the net-pens; however, the flow patterns in other areas of the model did not appear to be entirely realistic. In particular, while the model produced currents with appropriately high magnitude in Cross Island Narrows (which is validated

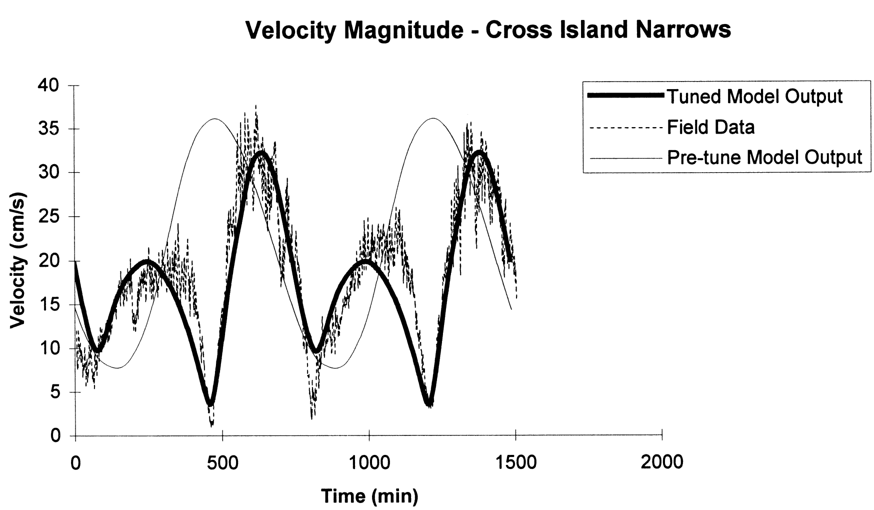

Fig. 7. Tuned and pre-tuned model current velocity magnitude output compared to field data for Cross Island Narrows in the Machias Bay hydrodynamic model.

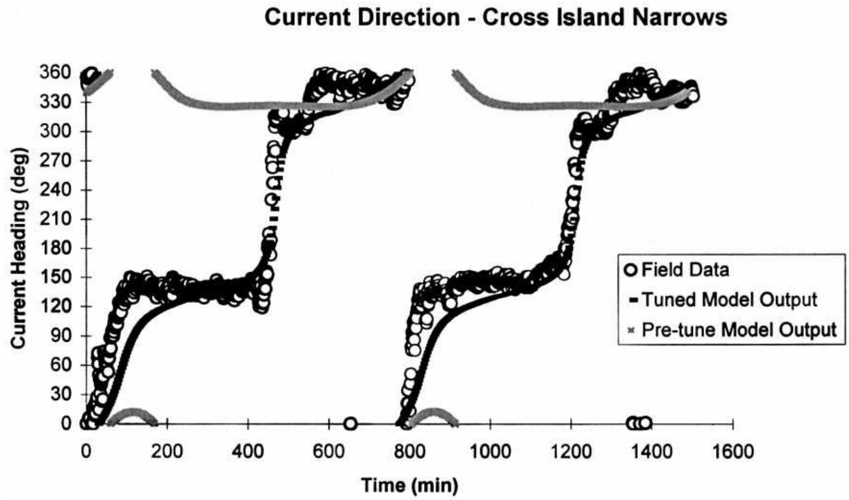

Fig. 8. Tuned and pre-tuned model current direction output compared to field data for Cross Island Narrows in the Machias Bay hydrodynamic model.

by anecdotal evidence), the direction of the current never reversed over the course of an entire tidal cycle. Additional current data were therefore collected in Cross Island Narrows on August 15, 1997. These data allowed the adjustment of friction coefficients

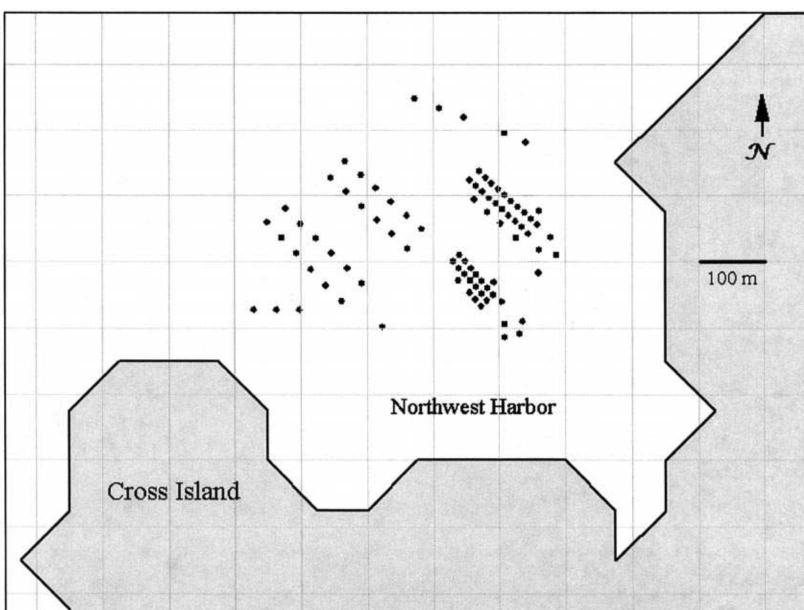

Fig. 9. Point source configuration for aquaculture waste input simulation in Northwest Harbor, Cross Island in Machias Bay.

over various zones, varying from 0.008 to 0.03, as well as improved specification of tidal amplitudes and phases at each open boundary. Model results shown in Fig. 6 indicate that the currents in Cross Island Narrows reverse directions over a tidal cycle. Further, Figs. 7 and 8 show modeled velocity magnitudes and directions for a point in Cross Island Narrows before and after tuning with the August 15, 1997 data. This illustrates the importance of using some field data for producing reliable model simulations in the overall domain. At several grid points in the vicinity of the aquaculture net-pens at Cross Island, the model produces currents of 3–5 cm/s predominantly in the east–west direction, which is consistent with the *Akvasafe* data. Flow model outputs illustrated in Figs. 6–8 were used as input to the transport model.

Aerial photographs provided by the Maine Department of Marine Resources showed the locations of 86 different pens for the ASMI operation in the Northwest Harbor of Cross Island. For the simulations, approximate locations of the pens were determined on the basis of their position relative to coastal features, using the size of the pens as a scale. Fig. 9 shows their point-source configuration for input to the transport model. The depth of all pens was estimated to be 2.0 m to compute pen volumes.

Exact stocking and husbandry information for this and all modeled sites is confidential. For modeling purposes, therefore, general husbandry data pertaining to a comparable aquaculture operation in Cobscook Bay (courtesy of Connors Brothers) were used in

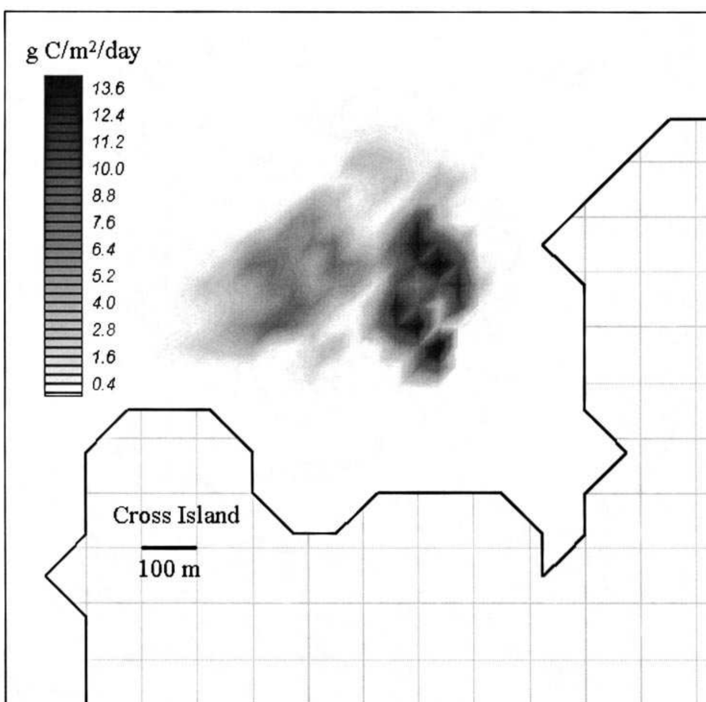

Fig. 10. Modeled organic carbon loading (g/m^2/day) in Northwest Harbor, Cross Island, in Machias Bay after a 15-day loading simulation.

conjunction with data from Laird and Needham (1988). These data were used to estimate pen stocking density, daily feed quantities per pen and fecal production per unit mass of fish for the each site. Stocking densities can range from 10–50 kg/m^3 and daily feed quantities can range from 0.1–8.0 kg/100 kg fish biomass (Laird and Needham, 1988; Beveridge, 1996; Panchang et al., 1997). For transport modeling purposes for this study, a stocking density of 20 kg/m^3 and daily feed quantity of 1.5 kg/100 kg fish were used. It is important to note that this nominal aquaculture husbandry information was used only for illustrating the application of AWATS. Naturally, regulatory agencies would have to use specific husbandry information for each site to perform more realistic, site-specific simulations.

Since the model tracks organic carbon as an indicator of waste, the fraction of feed and fecal matter that is organic carbon must be defined. While these fractions can vary, values of 45% and 28% for feed and fecal matter, respectively, were used for modeling purposes (Findlay and Watling, 1994). The percentage of feed that goes uneaten and sinks as waste also varies between 1% and 40%. Findlay and Watling (1994) recommend using a value of 5% or lower for modern Maine aquaculture farms, in particular those that hand-feed. According to Connors Bros., fecal production is estimated to be 1.7–2.1 g/kg fish. An intermediate value of 1.9 g/kg fish was used for modeling. Sinking rates of fish feed and fecal matter were experimentally determined by Panchang et al. (1997). Settling rates of 50 observations of fecal pellets resulted in a mean settling rate of 3.2 cm/s with 70% of the observations between 2 and 4 cm/s. Settling rates for feed and fecal pellets of 10 and 3 cm/s are used in the transport modeling (Warren-

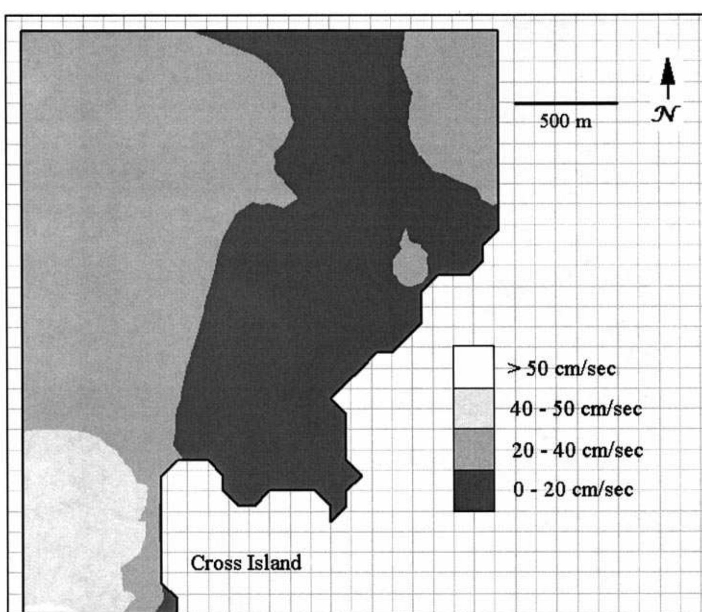

Fig. 11. Modeled maximum current velocities for Northwest Harbor, Cross Island.

Hansen, 1982; Findlay and Watling, 1994; Panchang et al., 1997). For modeling purposes, the introduction of waste feed and fecal pellets is assumed to be uniform and to occur 24 h a day. Feed and fecal particles are introduced in the model simultaneously every 2 h from every point-source pen. Though TRANS can accommodate any desired particle introduction schedule (including a time lag between feed and fecal material), a uniform introduction scenario would more closely model a steady-state loading result. A simulation duration of 15 days was chosen to estimate a steady-state loading pattern, since the daily 0.8 h shift in the lunar tide causes the tides to exactly repeat after this duration.

Fig. 10 shows the modeled loading pattern of organic carbon (g $C/m^2/day$) at the ASMI aquaculture site as obtained from AWATS. The results are averaged over a 15-day loading simulation. For this simulation, the U_{crit} value was set at 40 cm/s. The eastern and southeastern portions of the aquaculture site receive the highest loading receiving a maximum organic carbon loading rate (averaged over 15 days) of 14.1 $g/m^2/day$.

A maximum velocity map obtained from AWATS (Fig. 11) shows that modeled tidal currents in Northwest Harbor never exceed 20 cm/s, suggesting that the ASMI

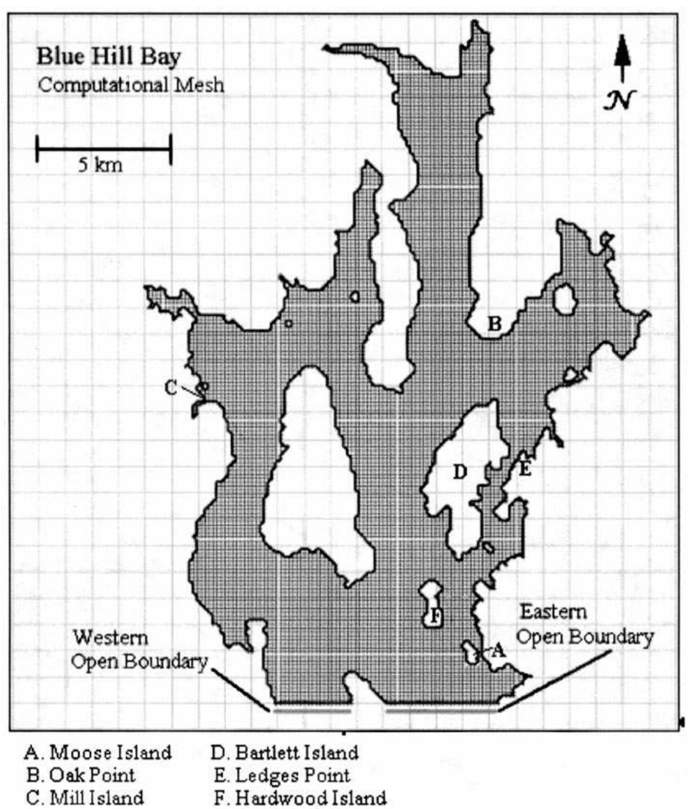

Fig. 12. Blue Hill Bay tidal model computational domain.

aquaculture operation may be located in a depositional area. The mean and maximum velocities computed by the model for this particular area are 3.9 and 6.8 cm/s, respectively. Though not high enough to exceed the U_{crit} criterion for resuspension, the currents in this area could supply sufficient oxygen to the benthos for adequate rates of decay of the effluent as well as high rates of water exchange in the embayment to prevent adverse impacts on the macrobenthos (Drake and Arias, 1997). The estimated theoretical maximum aerobic oxidation for an environment with a minimum 2-h average current velocity of 4 cm/s is nearly 17 g/m^2/day of organic carbon (Findlay and Watling, 1994), which exceeds the highest loading calculated for Machias Bay in the previous paragraph.

3.2. Simulation of net-pen waste distribution in Blue Hill Bay, ME

The aquaculture site of interest in Blue Hill Bay is located east of Hardwood Island, ME, and is operated by Trumpet Island Salmon Farm (TISF). Bathymetric data for this region was digitized from NOAA chart 13316 using SMS. The domain for this site is much larger than the Machias Bay domain, and to avoid inordinately long run times, a coarser (150 m) grid resolution was used for the for the flow model. Fig. 12 illustrates

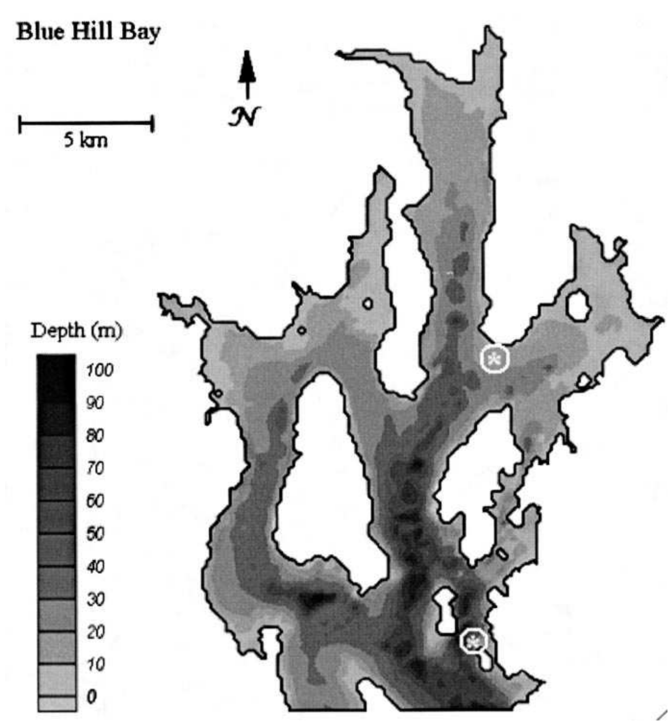

Fig. 13. Blue Hill Bay domain bathymetry. Asterisks illustrate locations of tide gauges.

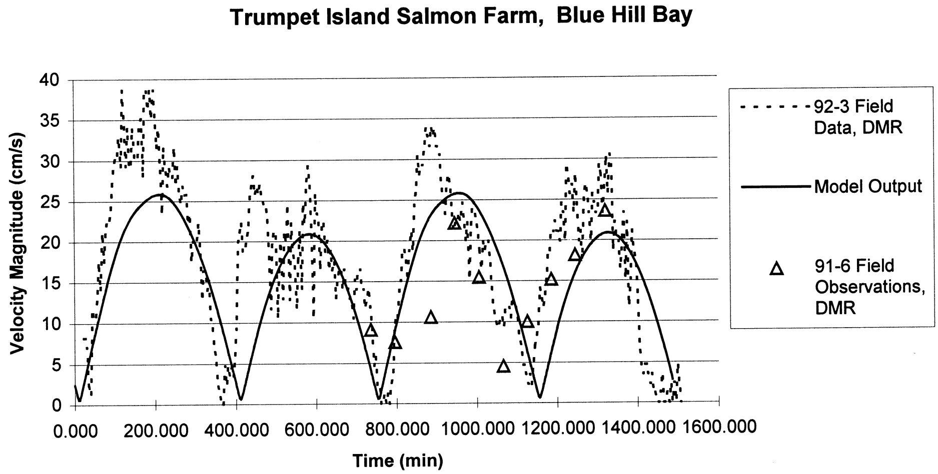

Fig. 14. Comparison of current velocity magnitude field data and hydrodynamic model output near Hardwood Island, Blue Hill Bay.

the Blue Hill Bay domain that was constructed. Tidal amplitude and phase data were obtained from the larger Gulf of Maine model data set (Sucsy et al., 1993) and the model was forced by an amplitude of 2.2 m along the southern edge of the domain on each side of Tinker Island (Fig. 12), with a phase difference of 0.02 radians between the eastern and western edges of the open boundary.

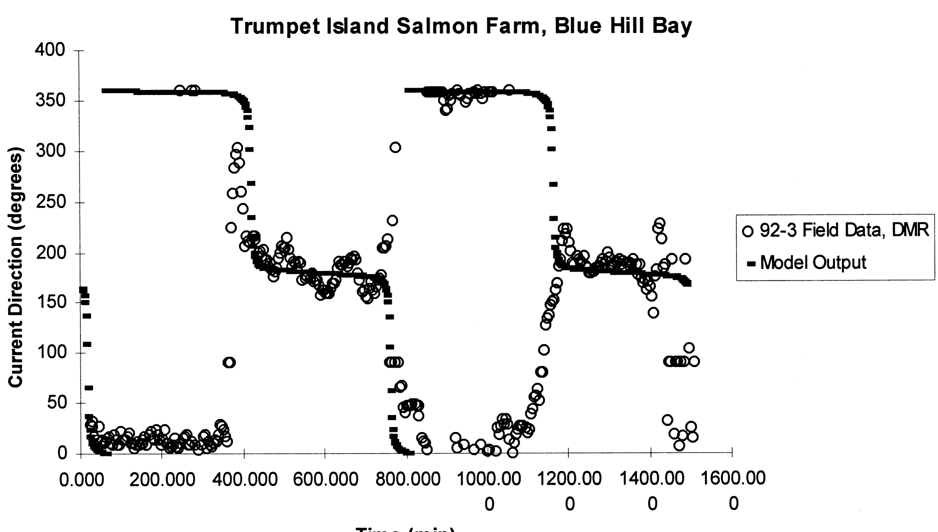

Fig. 15. Comparison of current direction field data and hydrodynamic model output near Hardwood Island, Blue Hill Bay.

Some trial simulations with various friction specifications led to model failure at about 11 h into the simulation; investigation revealed that excessively high velocities were being produced in the vicinity of Tinker Island. However, each failed simulation provided a guide to an improved specification of the frictional coefficients, leading to satisfactory results in about six trials. (See Dudley et al. 1998 for further details regarding calibration.) Field data from three locations were used to judge model performance: field data collected by the DMR in the general vicinity of the net-pens (exact location unknown) in June 1991 and March 1992, and two tide gauges that we deployed near Moose Island and Oak Point (Fig. 13) in 1997. Modeled current speeds,

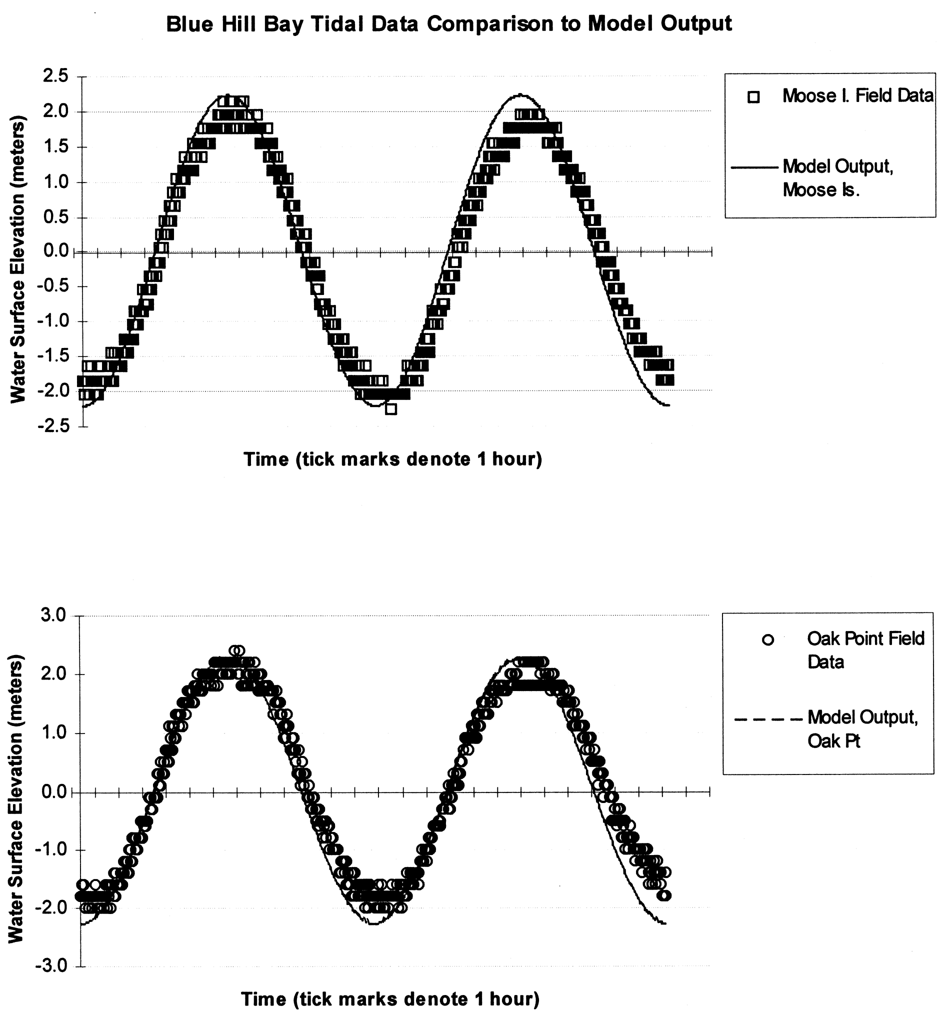

Fig. 16. Comparison of tide gauge field data and hydrodynamic model output at Oak Point and Moose Island, Blue Hill Bay.

directions, and water surface elevations correspond fairly well to field data at all three locations (Figs. 14–16). An overall solution is shown in Fig. 17. Although high velocities (approximately 60 cm/s) are obtained near Mill Island in the narrows south of Blue Hill Harbor and also east of Bartlett Island near Ledges Point, anecdotal evidence suggests these ‘‘choked narrows do indeed have high velocities and are popular ‘‘reversing falls locations for canoers and kayakers. Elsewhere, modeled velocities have a maximum of around 30 cm/s.

Aerial photographs showing the location of 9 different circular pens for the TISF in Blue Hill Bay were used to approximate the locations of waste introduction (Fig. 18) for modeling purposes. Although the modeled mean tidal currents in the vicinity of the TISF operation are less than 20 cm/s (suggesting that this may be a waste depositional area), maximum tidal velocities shown in Fig. 18 do reach approximately 40 cm/s in the vicinity of the easternmost pens, allowing resuspension and considerable spatial transport. These high velocities will also provide greater amounts of oxygen for decomposition of the organic wastes.

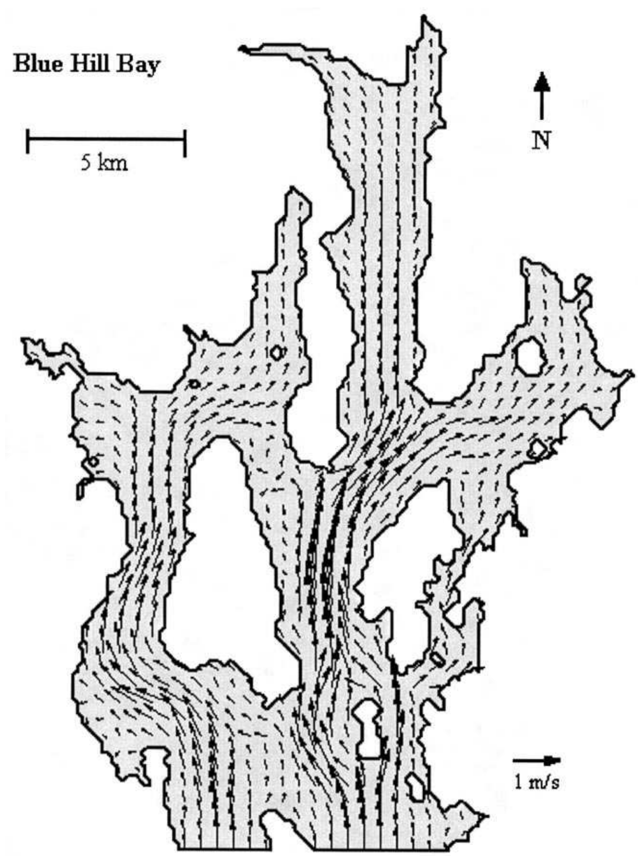

Fig. 17. Vector plot illustrating the flooding tide in Blue Hill Bay. Vector lengths are scaled to current magnitude.

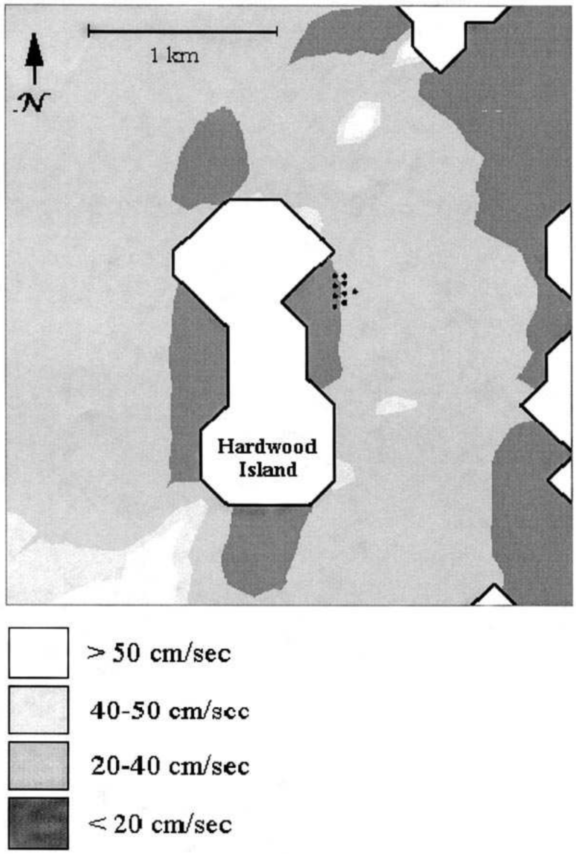

Fig. 18. Modeled maximum current velocities around Harwood Island, Blue Hill Bay. Black dots represent nine net pens.

The modeled loading pattern of organic carbon at the TISF aquaculture site (Fig. 19), averaged over a 15-day loading simulation, shows that there is a significant amount of waste dilution, particularly for the waste introduced by the easternmost net-pens. The ebb and flood of the tide disperses the waste offshore to the north and south of the net-pen configuration. The area of greatest loading occurs beneath the western pens (2.2 g $C/m^2/day$). In addition, the mean and maximum currents in this region are 14.4 and 24.2 cm/s, respectively, which provide high rates of water exchange and dissolved oxygen at the pen system and further diminish any adverse impact.

3.3. Simulation of net-pen waste distribution in Cutler Harbor, ME

Cutler Harbor (Fig. 20) is located in Washington County, ME. The mean tidal range for Cutler Harbor is about 4 m. The aquaculture site of interest for this domain is

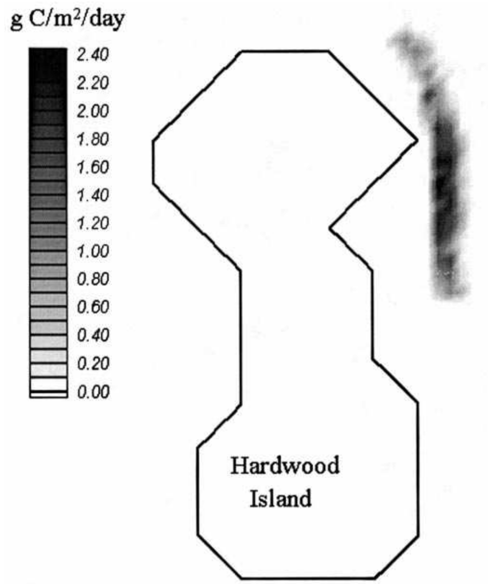

Fig. 19. Modeled organic carbon loading ($g/m^2/day$) at the aquaculture site off Hardwood Island, Blue Hill Bay after a 15-day loading simulation.

operated by Maine Coast Nordic (MCNC). Approximate locations of 12 pens for the MCNC aquaculture operation off the northern and southern shores of Cutler Harbor in March 1996 are shown in Fig. 21. Current meter data collected by DMR in 1992 in the vicinity of the northern pen-system were used for tuning the hydrodynamic model.

The domain coastline and bathymetry were digitized to 30 m resolution in SMS using a computer-scanned image of NOAA nautical chart 13327. This bathymetry was input to the finite-difference flow model to simulate the tidal currents. The tidal forcing functions (2.1 m amplitude) at the Gulf of Maine/Cutler Harbor open boundary (Fig. 21) were obtained from results of Sucsy et al. (1993). The orientation of Cutler Harbor was rotated with respect to geographic north to create a vertical open boundary orientation on the eastern edge of the domain required for the finite-difference grid construction. All flow results were re-adjusted to correspond to true north for comparison to field data.

For tuning purposes, a point in the vicinity of the northern pen site was chosen for comparison to the DMR field data. Initially, model output in the vicinity of the northern pen site did not compare favorably to the field data for the period of September 26–30, 1992. Modeled velocity magnitudes were too small and modeled current directions did not coincide with measured directions. The tidal phases along the open boundary and bottom friction values in various zones throughout the domain were altered to bring the model results into reasonable agreement. Figs. 22 and 23 show current velocity components plotted against field data in the vicinity of the northern pen system.

Upon examining Figs. 22 and 23, it is clear that, although modeled east–west currents match data reasonably well, the modeled north–south currents for Cutler Harbor

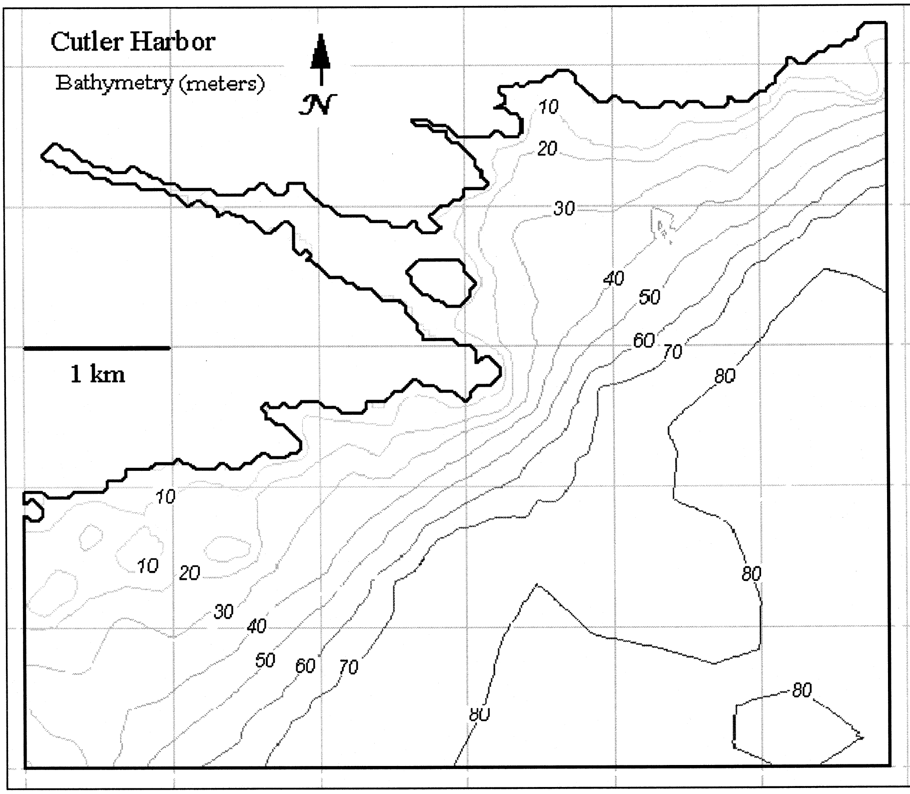

Fig. 20. Cutler Harbor and offshore bathymetry, Washington County, ME.

are clearly lower than those measured in the field. Since Cutler Harbor is open to a relatively large fetch to its east, it is likely that wind and waves exert some influence on the currents in the harbor. An examination of wind data (Fig. 24) collected at Mt. Desert Rock indicates that may be the case. Current data in Cutler Harbor, also shown in Fig. 24, appears to show a greater correlation with the wind than with a 12-h tidal forcing. A combination of wind and waves, not present in a tidal simulation, could hence raise the magnitudes of the velocities in the harbor to a higher level than shown in Fig. 23.

An effort was made to model the wind event using the Mt. Desert Rock wind data from September 26–30, 1992. First, the model was allowed to reach time-harmonic steady state under tidal forcing alone until 1100 min into the simulation, at which point wind stress representing actual wind conditions was uniformly applied to the water surface. Model results obtained with a wind drag coefficient of 0.080 provided are compared to field data shown in Figs. 25 and 26. The field data illustrated in Figs. 25 and 26 are an extension of the same data shown in Figs. 22 and 23. The simulations, too, in Figs. 25 and 26 show one tidal cycle (continuing the repeating pattern of Figs. 22 and 23) before being influenced by the wind. Model results in Figs. 25 and 26 do not match the field data uniformly well. Because Mt. Desert Rock is about 115 km to the

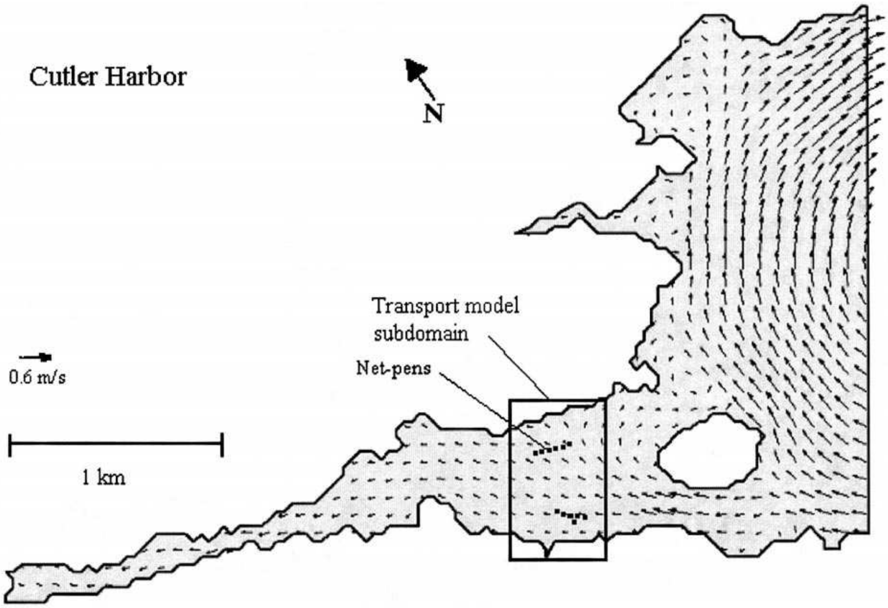

Fig. 21. Vector plot illustrating currents in Cutler Harbor. Vector lengths are scaled to current magnitude. Point source configuration and transport model subdomain for aquaculture waste transport simulation are also shown.

southwest of Cutler Harbor, whose geometry also can influence the wind conditions, the wind magnitudes and, in particular, the directions used in the simulation do not represent the actual wind conditions in Cutler Harbor during this time. As a result, it is futile to

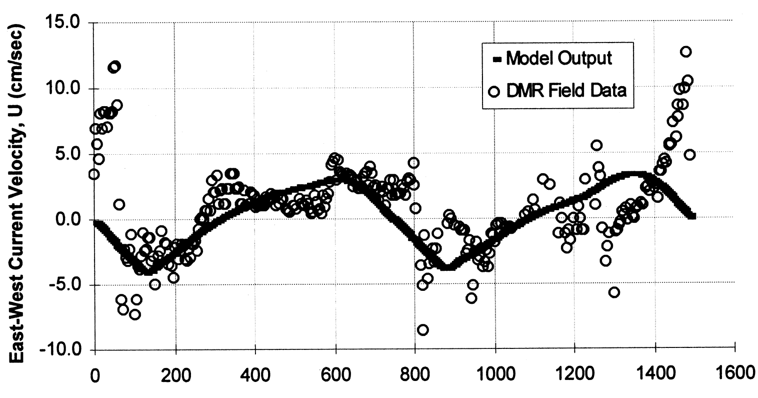

Fig. 22. Modeled and observed East–West components of current velocity in Cutler Harbor.

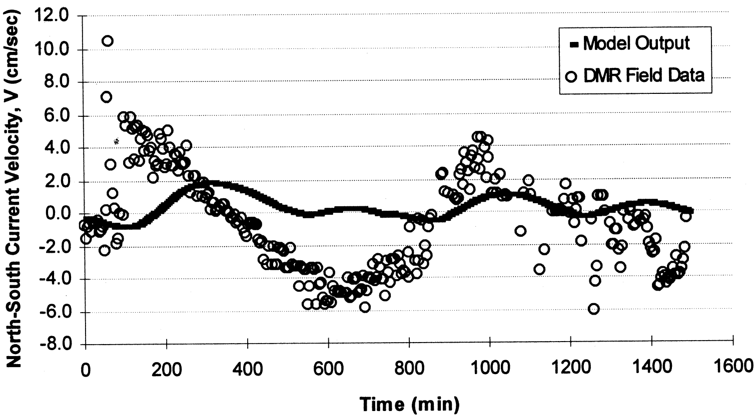

Fig. 23. Modeled and observed North–South components of current velocity in Cutler Harbor.

attempt a better simulation without more field data for currents as well as winds. While the model results shown in Figs. 25 and 26 do not accurately model this particular wind event, the results could be reasonably assumed to represent a comparable wind event for modeling transport and resuspension.

For modeling net-pen waste transport at the MCNC aquaculture site, the subdomain outlined by the box in Fig. 21 was chosen. Various utility programs in the AWATS package were used to extract the hydrodynamic solution and depths for this area of interest from the overall domain information.

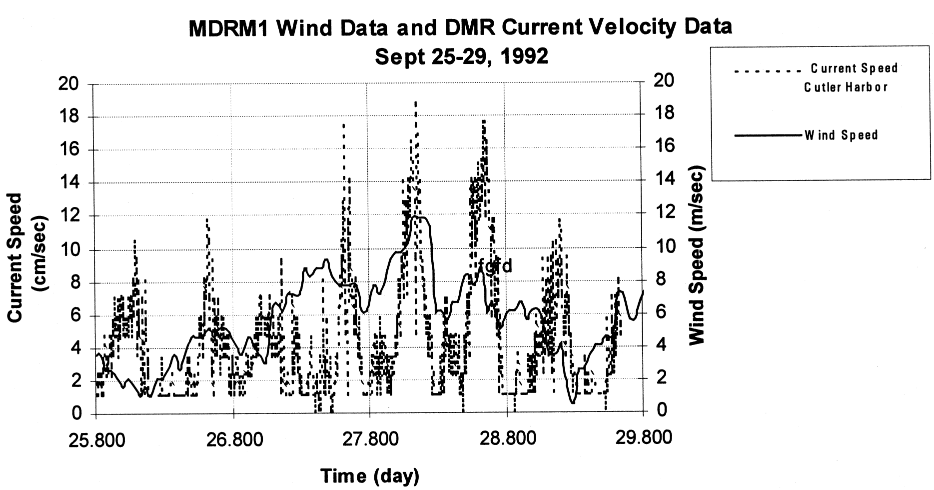

Fig. 24. DMR current data in Cutler Harbor with wind data from Mt. Desert Rock illustrating the relationship between current velocity and wind speed.

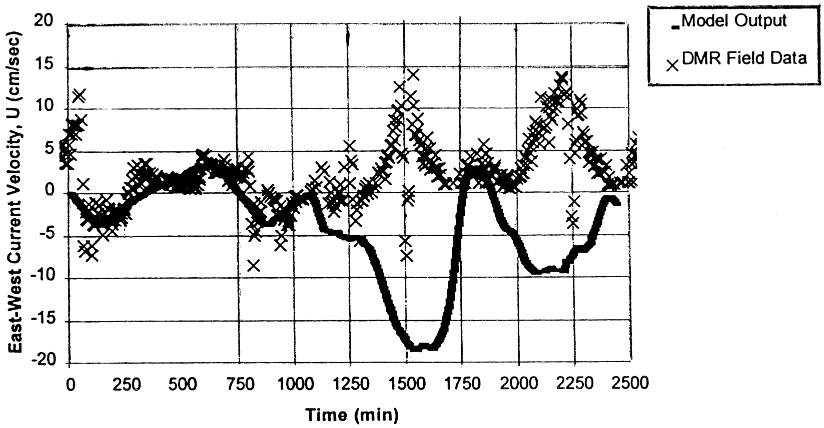

Fig. 25. Modeled and observed East–West components of current velocity in Cutler Harbor for model scenario with wind stress.

Fig. 27 shows a screen snapshot illustrating the loading pattern of finfish aquaculture waste deposition organic carbon at the Cutler Harbor aquaculture lease sites at the end of the 15-day model run. For this simulation, the currents are tidally driven and the U_{crit} value was set at 40 cm/s. The northern pen system receives a higher loading concentration than the southern system with one point receiving a maximum organic carbon loading rate (averaged over 15 days) of 17.7 $g/m^2/day$. The mean and maximum velocities computed by the model for this particular area are 2.3 and 3.9 cm/s, respectively, indicating a particularly low-velocity environment. Findlay and

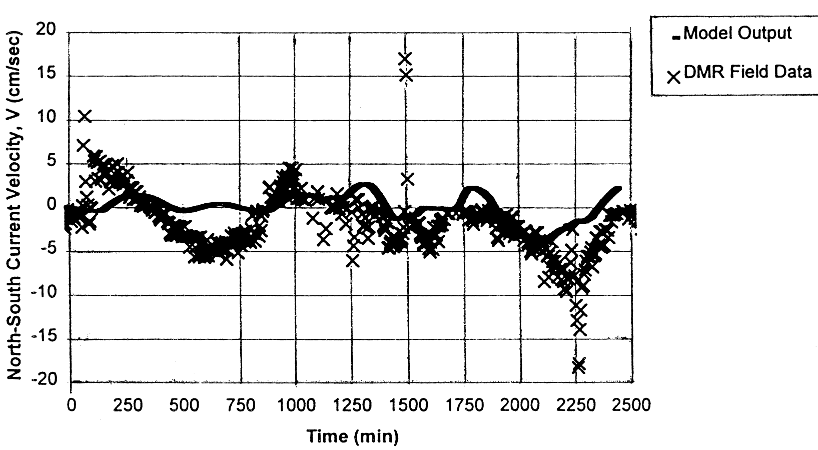

Fig. 26. Modeled and observed North–South components of current velocity in Cutler Harbor for model scenario with wind stress.

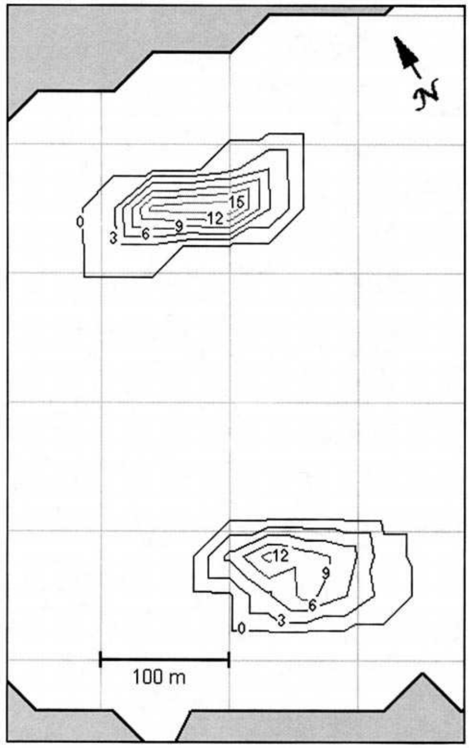

Fig. 27. Organic carbon accumulation ($g/m^2/day$) in Cutler Harbor, using modeled tidal currents.

Watling (1994) estimated that an environment with a minimum 2-h average current velocity of 2 cm/s current can deliver enough dissolved oxygen to sediments to support the theoretical maximum aerobic oxidation of nearly 16 $g/m^2/day$ of organic carbon. Without resuspension and flushing by mechanisms other than tidal currents, the transport modeling suggests that the northern pen configuration could possibly adversely impact the benthic environment over time.

Next, a hydrodynamic solution simulating part of the 1992 wind event was used to model another 15 days of transport. This scenario was modeled to approximate the effect of tidal combined with wind induced currents. Fig. 28 shows a plot of the loading pattern of organic carbon deposition as $g/m^2/day$ at the end of the 15-day model run. Note that there is greater dispersion for this scenario, although the organic loading still forms very clear footprints beneath the pen systems. The point receiving the maximum organic carbon loading rate (averaged over 15 days) occurs at the northern pen system with 16.6 $g/m^2/day$. The mean and maximum velocities computed by the model at this point are 9.9 and 18.6 cm/s, respectively. The estimated theoretical maximum aerobic oxidation for a minimum 2-h average current velocity of 9 cm/s exceeds 20 $g/m^2/day$ of organic carbon (Findlay and Watling, 1994). These results indicate that, while the

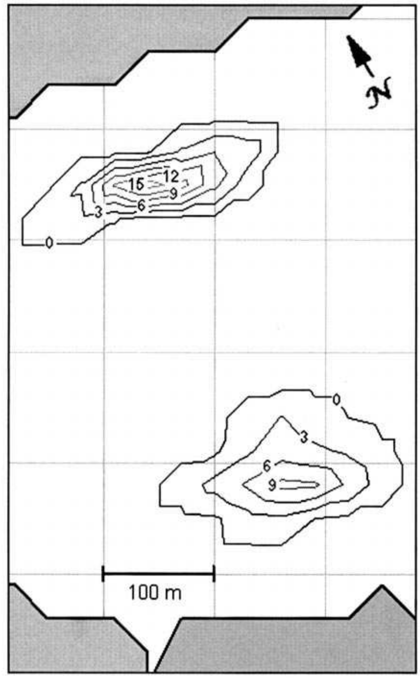

Fig. 28. Organic carbon accumulation ($g/m^2/day$) in Cutler Harbor, using modeled tidal and wind-induced currents.

wind-driven currents are not strong enough to exceed the threshold velocity for resuspension (40 cm/s), periodic wind events could facilitate the supply of oxygen to the benthos for increasing rates of decay of the effluent to prevent adverse impacts on the macrobenthos.

Wave modeling was also performed for Cutler Harbor. Fetches were delineated for Cutler Harbor and input to the wave model ACES to predict wave heights and periods for multiple wind directions and magnitudes. Bottom velocities due to wave action were computed at the mean 7.5 m depth in the vicinity of the net-pens using linear wave theory as per Eq. (1). Table 2 summarizes the wave height, period, and bottom velocities for the various wind scenarios. Wind heading and velocity data from Mount Desert Rock for the year of 1997 are also summarized in the table with frequency distributions of direction and speed. Although the data record for 1997 indicates that winds from the west and northwest predominate, it is still reasonable to expect that wave velocities at the bottom in the vicinity of the net-pens will occasionally exceed the threshold velocity (40–50 cm/s), particularly in the winter months when there is a greater frequency of higher wind events. To simulate waste dispersion by a storm event, a 3-day transport scenario assuming continuous resuspension by waves and advection by tidal and wind-driven currents was run. Modeled waste particles were efficiently flushed out of the harbor with a residence time of 0.8 days. The maximum loading rate of organic carbon found at any single point within the domain was 0.7 $g/m^2/day$. Compared with

Table 2
Wind direction and frequency, wind speed and frequency, wave growth and bottom velocities at 7.5 m depth at the mouth of Cutler Harbor, Washington County, ME (wind data from 1997 wind record at Mount Desert Rock, ME)

Wind speed (mph)	Wind direction (°)	Percent [a] occurrence	Wave height (m)	Period (s)	Bottom velocity (m/s)
20	0	9.3	0.63	3.19	0.06
Frequency of winds	45	6.7	1.20	4.28	0.31
0–20 mph is 62.1%	90	6.8	1.12	5.58	0.43
	135	9.1	2.03	5.89	0.81
	180	15.5	1.98	5.82	0.78
	225	17.2	0.75	4.55	0.22
	270	21.0	0.21	1.62	0.00
	315	14.2	0.20	1.61	0.00
30	0	9.3	1.06	4.04	0.24
Frequency of winds	45	6.7	2.04	5.40	0.75
20–30 mph is 26.2%	90	6.8	2.46	6.45	1.05
	135	9.1	4.07	8.15	1.95
	180	15.5	3.96	8.05	1.89
	225	17.2	1.73	6.92	0.77
	270	21.0	0.35	2.05	0.00
	315	14.2	0.34	2.03	0.00
40	0	9.3	1.58	4.80	0.50
Frequency of winds	45	6.7	3.03	6.42	1.29
30–40 mph is 9.3%	90	6.8	3.89	7.72	1.83
	135	9.1	6.11	9.49	3.07
	180	15.5	5.98	9.39	3.00
	225	17.2	3.15	7.23	1.44
	270	21.0	0.52	2.43	0.01
	315	14.2	0.51	2.41	0.01
50	0	9.3	2.16	5.51	0.81
Frequency of winds	45	6.7	4.15	7.38	1.91
40–50 mph is 2.1%	90	6.8	5.34	8.87	2.64
	135	9.1	8.39	10.91	4.35
For winds > 50 mph,	180	15.5	8.20	10.79	4.25
the frequency is 0.3%	225	17.2	4.42	8.18	2.12
	270	21.0	0.71	2.79	0.03
	315	14.2	0.69	2.77	0.03

[a] Percent occurrence for wind direction only. Percent value corresponds to wind direction range of all wind directions up to next wind direction entry. Examples: wind direction 0–45° occurs 9.3% of time; wind directions 45–90° occur 6.7% of time.

results with just wind and tide induced currents, it is clear that waves could play a very important role at cleansing this site.

4. Conclusions

In situ measurements near the Deep Cove aquaculture site suggest that bottom sediments near net-pen aquaculture sites are eroded at U_{100} velocities greater than about

40 cm/s in the winter and about 50 cm/s in the summer. These values are used in the development of the modeling package, AWATS, which can be used for estimating the dispersal of net-pen wastes in a coastal environment with varying currents including tidal, storm, and wave induced velocities. Application to several aquaculture sites in Maine suggests that AWATS is a convenient tool that can be used to aid with site evaluation and direction of field monitoring programs. However, the model does not completely eliminate the need for field data, which are needed to calibrate the flow model and ensure reliability. Rather, it supplements the isolated field measurements and provides a more complete picture of the flow-field, which is required if resuspension and subsequent transport is important. Of the three aquaculture sites modeled, the TISF operation in Blue Hill Bay appears to be in the best location with low accumulation rates, high currents and deep bathymetry for greater dispersion, and high water volume exchange for waste decay.

The modeling results demonstrate how AWATS can provide not only a picture of waste distribution, but information regarding spatial and temporal variations in current velocity. Such information could possibly be used in conjunction with benthic oxygen demand data to determine if organic enrichment in high-load regions has the potential to exceed the assimilative capacity of the environment. Adding mechanisms for incorporating oxygen demand of the sediment carbonaceous material to the existing modeling framework will be pursued in future research involving this modeling strategy.

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