AquaModel Fish Aquaculture Simulation Model and GIS in Nova Scotia and Gulf of Maine: Validation and Adaptation for Government and Industry Management Use

Washington Sea Grant project R/LME/N-6 Summary Report.

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Overview: Marine fish farming's world food contribution is potentially large, but there is a need to predict environmental effects during the site selection process. Sea-bottom deposition from fish farms with insufficient water flows can prevent the normally rapid food-web assimilation of particulate organic wastes from fish farming. Until now, no adequate modeling tool has been available to help government and industry managers accurately anticipate these effects and evaluate prospective farm sites for environmental and operational efficiency. Fish growers have had to configure and manage their operations by trial and error of use other models that do not faithfully simulate actual effects.

We systematically tested, refined, and validated AquaModel, a user-friendly and dynamic software tool that is a true mechanistic, mass balance model (Rensel et al. 2007). It was designed to evaluate the benthic and water-column effects of fish farms, determine regional environmental carrying capacities, and help growers configure and operate their sites more efficiently. We used high quality field data and operational records from existing sites in Atlantic Canada and the Gulf of Maine to test, calibrate and validate the benthic components of AquaModel. Complementary studies have been completed in Hawaii and are ongoing in Southern Chile, both for government agencies. During this study, we additionally corrected software bugs, added or improved several utilities and simplified the user interface.

The testing and validation process resulted in optimal model settings that accurately predicted sediment organic matter loading and food web processing. The species-specific physiology submodel accurately simulated fish growth, physiology, and waste production. AquaModel has been used as the primary water column and benthic effects tool to assess the siting and feasibility of fish farms in the U.S. exclusive economic zone. Governments in Asia, South America, and Canada are also testing or using AquaModel.

Objectives: The primary objective of this project was to tune and calibrate (i.e., validate) the fish physiology and benthic submodels of AquaModel software to allow for government use in managing the net pen aquaculture industry in the United States and worldwide. The software was already being used and had been preliminarily tested, but systematically evaluation was necessary to assure model efficacy and accuracy in predicting benthic impacts and improving fish farm operational efficiency.

Rationale: Fish aquaculture in marine coastal waters is among the fastest growing forms of protein production in the world, now exceeding wild fish capture in total volume. Wild fish stocks are mostly fully exploited or over exploited, leaving little possible additional production. Prior to AquaModel software, there have been no readily available, user-friendly software tools for governments or industry to use to evaluate site-specific and cumulative effects of net pen mariculture. Without exception, prior models were non-dynamic and typically estimated only a single time point effect, usually at the end of a production cycle when calculating the effects of particulate organic waste products on the sea bottom. Other programs do not allow for accurate prediction of waste particle movement across the sea bottom or the maintenance of background organic matter conditions in reference areas. As a result, it has had to be operated in "depositional" mode only and tends to overestimate benthic deposition at the first contact point where particles land on the seabottom. This may be appropriate for some locations with very slow water motion, but not many modern net pens sites that experience relatively fast water flow. AquaModel was designed to be a dynamic model that produces results in a time series of steps from minutes to hours or longer. It shows real time streaming video output while capturing all data from all cells and processes. Also unlike other prior programs, AquaModel is fully transparent in its settings, calibration, inputs and outputs. Improved accuracy is also possible by tuning the model to specific ecoregion conditions, as was done in this study.

A goal of AquaModel use is to design net-pen sites to produce only small amounts of organic enrichment for a given area of the sea bottom. This can produce beneficial biological effects such as increased biodiversity of invertebrate infauna as first demonstrated by Pearson and Rosenberg (1987). Prior to AquaModel availability, trial and error was the principal means of net pen siting, re-siting and reconfiguring net pen aquaculture to meet government performance standards. Another model from Scotland was available and useful in sea lochs there, but it did not produce accurate particle resuspension simulation. There are major costs in re-permitting and reconfiguring pens, anchors and other facilities as well as potential lost fish production if performance standards are not met. Additionally, government needs to know where best to require monitoring, rather than assuming that effects will occur in one area or another. In this way modeling can inform required monitoring.

Study Sites and Methodology: Although fish aquaculture is practiced in Puget Sound and some of the suitable data is available, some important components such as reliable or extensive current meter data were not available. Moreover, several of the sites in Puget Sound have complex current flow conditions where a current meter would not provide an accurate description of the physical transport. Three dimensional, far field circulation models are available for Puget Sound waters but these are general circulation models, not high-resolution models necessary to predict particle transport with the needed degree of accuracy. Accordingly, we looked to other ecoregions and found cooperators in Atlantic Canada and the Northeast United States in the Gulf of Maine.

The first site is a large salmon farm operated in Southern Nova Scotia by a major fish farming company. The site location and name are anonymous and herein are referred to as the Nova Scotia site. Benthic data was collected by an experienced third-party consulting company, Sweeney International Management Corp., as part of a routine government-required monitoring program. A new regional-specific physiological submodel of Atlantic salmon (*Salmo salar*) was created and tested. It was designed with close compliance to actual measured growth and food conversion rates at the site and is applicable for conditions in the Northeast U.S. and southern Atlantic Canada. The submodel is significantly different compared to the existing west coast North American and Chilean Atlantic salmon submodel. Although AquaModel's fish submodel responds to key physical and operational inputs, winter water temperatures are much colder in the Atlantic Canada and that necessitated a special submodel adapted to that region. Maximum peak biomass at the second of two sampling dates was 1,508 MT when average fish size was about 3.9 kg, somewhat less than normal market size fish at 5.2 kg. No monitoring data were available from the growout completion and harvest timing of the pens.

The second site was operated by the University of New Hampshire (UNH), Open Ocean Aquaculture (OOA) project as a several years, multi-disciplinary research effort to investigate the feasibility of growing fish in exposed, open ocean waters of that region. The project included personnel with expertise in biology, engineering, operations and environmental science and Dr. David Fredriksson collaborated with us in the modeling effort. High quality current meter and other physical, chemical and biological data were available from the time of fish culture through our collaboration with Dr. Fredriksson. Long-term seafloor monitoring results and a potential adaptive protocol were published by Grizzle et al. (2014) as one of the results of the environmental monitoring efforts of the OOA project. The work included determination of sediment organic matter represented by Loss on Ignition (LOI) analyses (similar to total volatile solids), sediment grain size and benthic infauna community information from box-core samples. AquaModel was configured to simulate a grow-out period between February and November of 2005 when a stock of Atlantic cod were contained in a submersible fish cage at the site. A new AquaModel physiological submodel of Atlantic cod (*Gadus morhua*) growth and metabolism was prepared, tested and utilized to calculate the growth of Atlantic Cod.

For both study sites, operational data such as fish stocking rates, survival, feed use, mortality and harvest timing were obtained and entered into AquaModel via a spreadsheets utility system to allow validation of the model in simulating the actual operations. This utility is not required for routine use of AquaModel to evaluate sites as optimal feed rates are determined by the model and users can assign custom feed loss rates, usually about 3% of total feed fed. But the spreadsheet utility is indispensable for model tuning, calibration, and validation.

Conversion was made from measured total volatile solids to total organic carbon based on splitting of sample for both measurements (Nova Scotia site) or literature estimates (New Hampshire site). The Nova Scotia site had three replicate samples per sampling site for both a summer and fall sampling period later in the fish culture cycle.

Current meter data from bottom mounted ADCP units were processed by removing near surface bins subject to backscatter interference and examined statistically for high range outliers. AquaModel has a utility that provides missing current meter data points by linear interpolation that was used to fill in short periods of missing data (< 1 hours periods in most cases). Only a few percent of the entire current meter deployment were missing and only from a few depth bins. The data were converted by the AquaModel utility that alters spreadsheet data to binary data so that model start up times could be reasonably short. Current vector roses were prepared for different depths and compared to the pattern of organic carbon distribution in false color images and contours prepared automatically by AquaModel. An example of a vector rose is below, for the UNH Open Ocean Site in Figure 1.

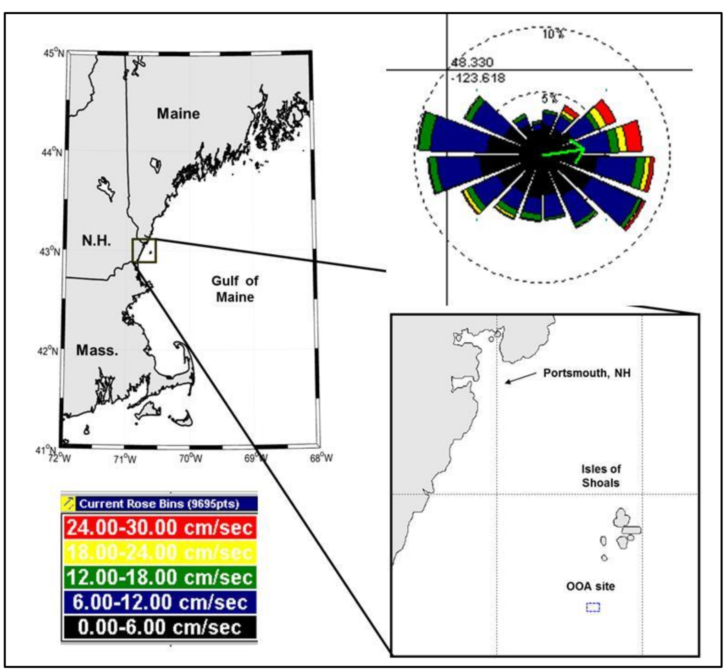

Figure 1: University of New Hampshire Open Ocean Aquaculture (OOA) net pen site approximately 10 km offshore of Portsmouth, New Hampshire (USA) with 33 m deep current vector rose (upper right) and scale (lower left).

Some of the key factors considered for this benthic submodel validation are presented in Table 1. This table ranks the relatively uncertainty of optimum settings for each parameter, based on our experience, knowledge and literature citations.

Our testing strategy was to perform a hierarchical approach starting with what we knew without doubt to be the most influential parameter in AquaModel's benthic submodel (see Figure 2).

Table 1. Some primary of the AquaModel parameters subject to benthic calibration and tuning in this assessment with relative index of uncertainty regarding calibration.

Parameter	Units	Why it Counts	Uncertainty 1 low 3 high
Sediment carbon assimilation factors	grams C m^{-2}	Aerobic populations dominate in reference areas so easy to set. Anaerobic populations begin to take when the TOC rate exceeds about 1 gram C m^{2} d^{-1}	**1**
Sediment carbon assimilation maximum rate coefficients	per day (d^{-1})	Steady state rates in reference areas also easy to set. Critical factor is anaerobic maximum rate at pen sites.	**1 - 2**
Erosion rate constants*	g carbon m^{2} d^{-1}	The other part of the resuspension process. Responds to several cues, not a static process	**3**
Consolidation rate	fraction d^{-1}	At steady state, how much TOC is "cemented" in the surficial benthic layer	**2**
Particle settling rates	cm s^{-1}	How fast particles settle, easy to measure (and not necessarily bimodal flux distribution)	**1**
Waste Feed Loss Rates	Percent d^{-1}	Percent of fish feed used but not consumed, very difficult to measure. Validation shows the 3% industry estimates seem to be optimum for model fit to measured sediment TOC diagenesis model.	**2**
Waste feed & fecal deposition & resuspension thresholds	cm s^{-1}	Controls particle distribution until they touch the bottom & part of resuspension processes	**2**

* These are not fixed rates but rather part of a computational system that includes varying near bottom flow rates and other factors.

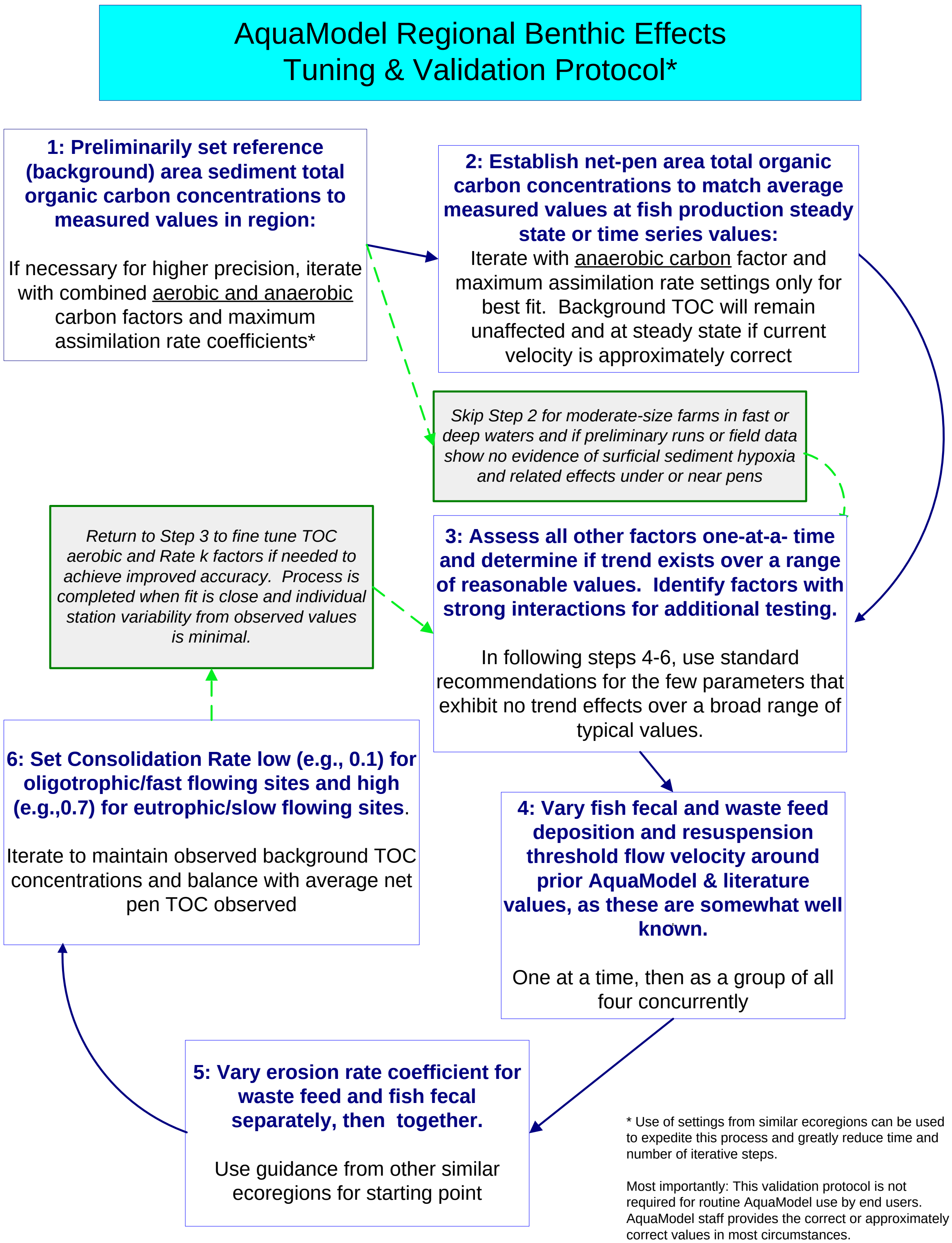

Figure 2. Flow chart for calibrating and tuning AquaModel to individual ecoregions. Process is performed by AquaModel (SSA) staff, not coastal managers or industry users. Blue arrows main = main path, green arrows = alterative paths.

The validation process involves the following components:

1) Determining the modeling outcomes for variation of most important single or multiple combined parameter settings to find an interim best-fit value.

2) Combining the best initial fits for all other parameters with those of number 1 above and varying all of them concurrently within a reasonable range of settings to estimate best fit for at least one time in the simulation (e.g., a two-week period prior to fish harvest).

3) Determining if any of the factors had strong interaction effects with other factors and conducting additional testing if so.

4) Combining and contrasting the best-fit observations for separate endpoint times to estimate the cumulative time-period best-fit settings while focusing on principal factors and those with known interactions.

Once we were certain about the best fit of the model output compared to the measured data, we conducted additional one-at-a-time assessments of each of the other independent and lesser important factors. Then we looped back through the process until it was clear what combination of settings for all the factors produced the least difference of sediment TOC between measured and modeled data as shown in Figure 2.

Results

Examples of plotting conducted for one-at-a-time and two-at-a-time validation comparisons are shown in Figures 3 and 4. These figures show the results of several model runs where specific factors were varied in an iterative process to determine optimum aerobic/anaerobic carbon factors (Figure 3) and the associated maximum rate coefficient factors (Figure 4). Anaerobic factors were not considered for reference areas, as initial testing indicated no effect on modeling outcome. This is reasonable as the surficial sediments in such sandy areas are usually well aerated and without indications of a reducing environment.

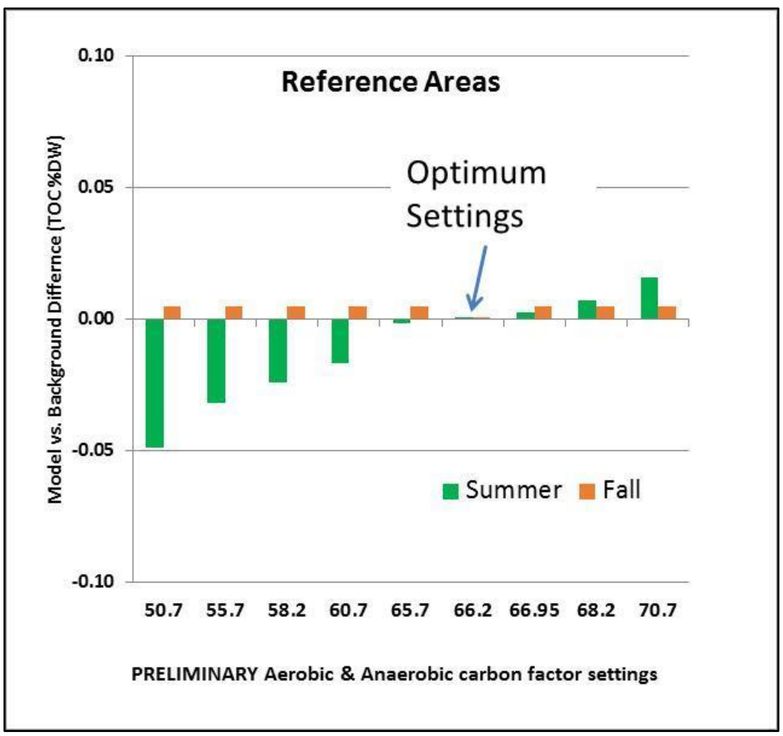

Figure 3. Nova Scotia project reference area settings for reference area carbon factors before fish are added to the simulation. Optimum setting of 66.2 to achieve the minimal difference between measured and modeled of only < 0.01% total organic carbon.

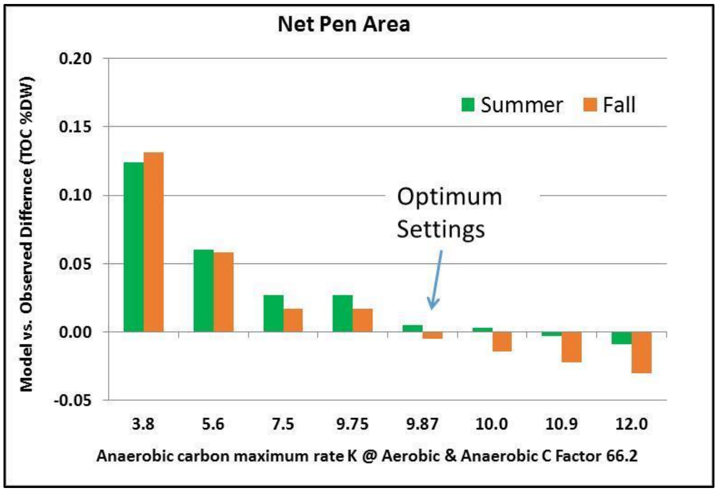

Figure 4. Nova Scotia project net pen area sediment anaerobic carbon maximum rate coefficient setting results showing optimum setting of 9.87 for a difference between measured and modeled of ~ 0.01% (summer) and ~0.005% (fall) total organic carbon (when combined with the optimum settings for sediment carbon factor (Figure 3).

Figure 5 illustrates the main screen print and several XY plots for the Nova Scotia study site with fraction of sediment TOC (dry weight) shown after using the contour utility. Pens are shown as green dots while the location of routine sampling by the environmental contractor (SimCorp Co.) are shown with associated capital letter.

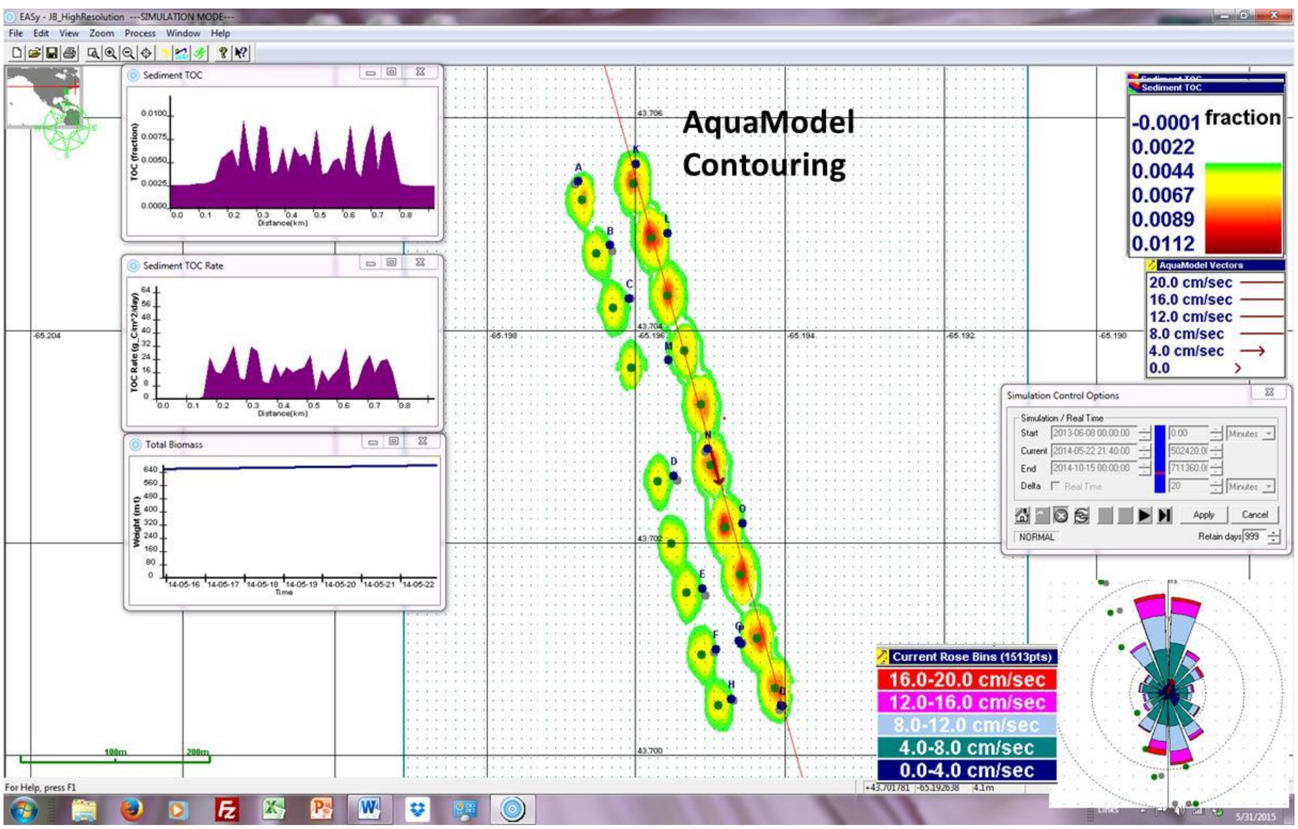

Figure 5. Nova Scotia project site model screen-print showing sediment total organic carbon distribution after applying contouring utility. Fractional units of dry TOC x 100 = percent TOC in this case do not exceed one percent at maximum fish biomass. Note strong north to south flow in the current vector rose in lower right corner with the associated color scale numerical legend.

In Figure 5 the right bank of pens has higher biomass at this point in time that resulted in greater effect on the seabottom, but the maximum total organic carbon concentrations are still relatively low at about 1% dry weight (0.01 fraction). Optimum settings determined from over 250 simulations are shown in Table 2.

Variable	Category	Setting
Sediment carbon assimilation factors	Both aerobic & anaerobic	66.2
Sediment carbon assimilation maximum rate coefficients	Aerobic	1.6
	Anaerobic	9.8
Deposition thresholds	Waste Feed	6.0
	Fish Fecal	8.0
Resuspension thresholds	Waste Feed	8.0
	Fish Fecal	10-12
Erosion Rate Coefficients	Waste feed & fish fecal	0.1
Consolidation rate	Waste feed and fish fecal	1%
Waste feed loss rate	Waste feed	3%

Table 2. Optimum settings for Nova Scotia project to achieve best model fit to observations. See Table 1 for parameter units.

Figure 6 shows the estimated effect of the submerged codfish pen operation on the seabottom with sediment total organic carbon as the main image outcome.

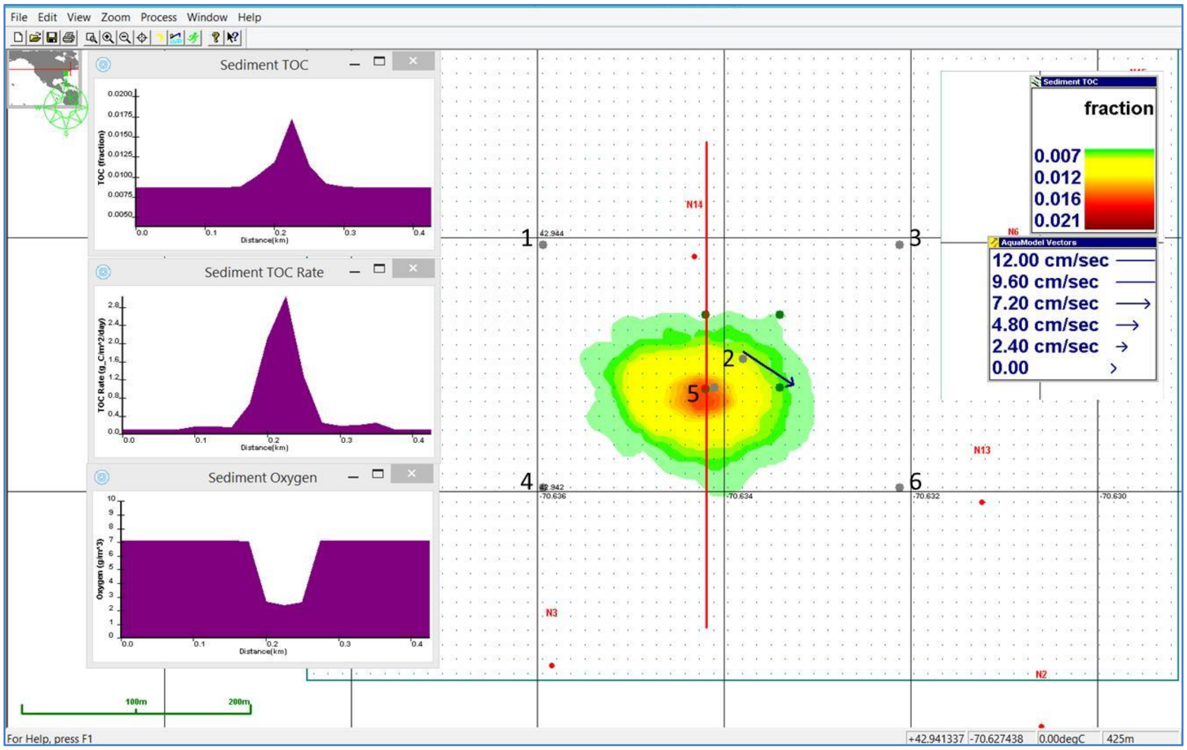

Figure 6. Open Ocean Aquaculture model run showing worst-case TOC contour characteristics below a single cage with Atlantic cod near maximum biomass. Plots on left illustrate sediment conditions along the north to south, red transect line through the site for sediment TOC, TOC delivery rate, and sediment dissolved oxygen. Upper right shows TOC fractional measure legend ranging from zero to 0.021 fraction = 2.1% dry weight total organic carbon. Red dots indicate sediment sampling locations.

In comparison to the Nova Scotia site, the estimated benthic effect was about twice as much (Figure 6), despite having a much smaller biomass. This is due to the relatively low assimilation rate of feed nutrients compared to salmon, the much slower current velocities and the location of the pen below the surface and therefore relatively near to the sea bottom.

A significant impediment to testing AquaModel at this site was that the monitoring program sampling locations were not sufficiently close to the cages to determine gradients of sediment effects. AquaModel predicted a significant increase under and near the cod cage, but no measurements were collected in these locations. While open ocean locations may have strong currents, near bottom currents at the Isle of Shoals site had moderately low currents in the summer that would not have caused regular resuspension of waste particles. The excellent and extensive current meter record indicates, however, that current speeds increased markedly in the fall to > 20 cm s^{-1}, possibly due to extreme, long-period wave events that have orbital velocities that can penetrate the depth of the entire water column to cause major sediment resuspension and transport (e.g., Fredriksson et al. 2005).

Significance

This study involved extensive AquaModel testing, error correction, recoding, retesting and new utility construction as well as development of a greatly improved user interface.

In the final testing, the Nova Scotia project produced average results under and near the cages that were within 2% (fall 2014) to 4% (summer and fall 2014 combined) of measured average values of sediment organic carbon at 10 different locations near the pens.

The model consistently simulated conditions at the two reference areas exactly with no attenuation or buildup of sediment TOC. The model should produce similar results for similar habitats throughout that ecoregion that includes coastal regions of the state of Maine. This summary report is brief as a requirement of the Sea Grant contract requirement.

See the AquaModel website www.AquaModel.org for other validation studies in different regions and for both water column and benthic effects.

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The Nova Scotia host company remains anonymous but provided funding for the regional consulting group, Sweeney International Management Corporation to interface with AquaModel staff. We are especially appreciative of both companies' assistance.

Jack Rensel was principal investigators for this project, Frank O'Brien provided extensive software code writing for new model utilities and bug fixes. Zach Siegrist assisted in model runs and results extraction. Dale Kiefer provided Mathematica analysis to assist in model bug correction and constructed the new Atlantic salmon (east coast version) and cod fish submodels. For more information about AquaModel, please visit www.AquaModel.org and the underlying GIS system visit www.runEASy.com