AquaModel Simulation of Water and Sediment Effects of Fish Mariculture at the Proposed Hubbs-SeaWorld Research Institute Offshore Aquaculture Demonstration Project

Prepared for

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Final Report

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1. Executive Summary

This document is a technical analysis of potential water column and benthic effects of an open ocean fish farm proposed in the Pacific Ocean offshore of San Diego, California. The proponent is Hubbs-Sea World Research Institute of San Diego, an organization long involved in fisheries research and stock enhancement in Southern California. The project has been envisioned as a demonstration farm, to assess the technical and environmental feasibility of offshore fish farming in the Southern California Bight. The plan is to closely monitor benthic or other effects and to start quite small, with 8 individual 25 meter diameter cages to rear about 1,000 metric tons of striped bass (*Morone saxatilis*). Eventually the farm will be increased to 24 cages and 3,000 metric ton annual production. Striped bass are relatively widely distributed on the U.S. west coast and Mexico, ranging from northern Baja, California, Mexico to the Columbia River. The species has been intensively studied by physiologists and has good fish cultural and market acceptability.

The proposed fish culture area may be characterized as exposed, deepwater (~91 m) coastal shelf, remote from sensitive habitats such as nearshore kelp beds, seal or sea lion haul outs or other aquatic resources areas. Bottom sediments are a mixture of shell, sand and ~24% fines which reflects the moderate strong bottom currents. A bottom mounted acoustic Doppler current meter was deployed at the site for 96 continuous days during the winter of 2007-2008. The subject area is remote from islands, seamounts and any other abrupt changes in bottom bathymetry and was also selected to avoid interference with usual navigation lanes.

Our proprietary modeling program AquaModel was used to simulate water and sediment quality effects of the proposed demonstration fish farm. It is the first comprehensive model for net-pen aquaculture that simultaneously calculates and displays real time feed ingestions, growth, respiration, excretion, and egestion by the fish. It includes the transport of dissolved waste away from the farm by currents and the response of the planktonic community to the increased concentration of inorganic nutrients within the waste plume, as well as the transport of particulate wastes to sea bottom sediments and the response of the benthic community to such organic deposition.

AquaModel is composed of interlinked submodels of fish physiology, hydrodynamics, water quality, solids dispersion and assimilation. The system provides the user a 3-dimensional simulation of growth, metabolic activity of caged fish, associated flow and transformation of nutrients, oxygen, and particulate wastes in adjacent waters and sediments. AquaModel resides within a Geographic Information System (GIS) program designed for oceanographic use but is compatible with other common 2-dimensional GIS software.

The goal of our study was to describe objectively and quantitatively the fate of waste material produced by the farm, both its distribution and its biological fate. The study consisted of 4 steps. First, we gathered and examined the design and proposed operating conditions for the farm, oceanographic information on conditions within the Southern California Bight and morphometric and metabolic information on striped bass necessary to characterize farm operations and particularly waste production. Second, we entered such information into *AquaModel* simulation software that calculates and maps the dynamics of farm operations and with particular focus on

the production, transport and ecological transformations of farm waste. Third, we tuned the model to field measurements of environmental impact for salmon farms that have been closely monitored in Washington State for several decades. Fourth, we then ran 50 day to 1-year simulations with *AquaModel* starting with all 24 pens loaded at 10 kg/m^3 or 2/3 of the maximum annual loading. The inputs and outputs from these simulations were then stored in a spreadsheet database for analysis. The results are also conveniently stored as a continuous time series of maps of the distribution of farm wastes and associated biological processes over the simulation period. We then analyzed our simulation in order to assess whether the farm would impact ecological conditions at the site. Our calculations and assessment were conservative; we purposely simulated using worst-case conditions or most conservative parameters in order to offset any limitations or inaccuracies of the model. Model runs that were relied on most were those that started at 2,160 MT loading and ran for 96 days (the length of the current meter record) and ended with biomass of 2,700 MT or 10% less than the anticipated full annual production. In separate simulations, we extended the simulation for a full year beyond the starting point and found essentially the same findings.

The results of this study indicated that in all our modeling assessments (short or long time periods mentioned above, partially and near fully loaded to 2,700 MT), that organic carbon deposition and impact will be so minimal as to be largely not detectable by chemical measurements such as assays of total organic carbon. The bottom currents are sufficiently strong to prevent consolidation of the waste material. There are short periods of quiescence, but they are followed by periods when the near bottom currents are sufficient to resuspend, transport and aerate the wastes. The sea bottom's ability to assimilate (absorb and respire) the carbon will not be exceeded or forced towards unacceptable levels. At the anticipated low levels of enrichment the benthic fauna will benefit from enrichment as described in prior studies including the classic paper by Pearson and Rosenberg (1978). Several factors account for this desirable condition including relatively great depth of the site (91m, about three times an average inshore site depth in North America), modestly strong currents (21 cm s^{-1} surface current average) and generous pen spacing that allows for a less concentrated source of wastes nutrients.

In the case of dissolved wastes, moderate surface currents, which persistently flow through the site with little slack water periods are moved in directions determined by prevailing ocean currents, winds and tides, will carry these wastes away from the farm and horizontal and vertical turbulent diffusion will rapidly mix and dilute the waste plume as it is transported away from the farm. Because of such rapid dilution the plume will not create a plume of elevated phytoplankton concentrations downstream of the farms.

In the case of particulate wastes, waste feces and uneaten feed were estimated to sink to the bottom at average rates of 3.2 cm s^{-1} and 9.5 cm s^{-1} as they are transported from the farm site. Because of the sifting in direction and velocity of currents within the underlying, deep water column, rates of deposition will be low relative to coastal farms moored in much shallower waters. The coarse-sized nature of the sea bed sediments indicate that the site is generally not "depositional" but mostly "resuspensional" with bottom currents often above the 4.5 cm s^{-1} threshold for deposition that we used from literature sources. This information is further supported by acoustic Doppler current meter records throughout the water column that bottom currents, which average about 8 cm s^{-1}, are sufficient to hold fine waste particles in suspension for considerable time before deposition and often strong enough to exceed the threshold for resuspension that is about 9.5 cm s^{-1}. Transient increases in bottom currents can suspend particles that have been deposited earlier when flow was slower, provided they had not remained on the bottom too long and become consolidated. Due to the nature of the bottom currents, we found that varying the rate of waste particle consolidation from 0.1% to 5% per day had little effect on the outcome of the simulations. Had the currents been slower near the bottom for longer periods, this would have had an effect.

While we do expect that it will be difficult to find an effect of the fully built out fish farm on sediment chemistry, there could be an effect on the food web and infauna. We expect the effect to be generally positive in terms of increased diversity (number of species) and biomass and these effects will likely be detectable by infauna sampling. Weston (1991) showed that invertebrate infauna respond more quickly and measurably than sediment chemistry measures. In the present case, because the loading to the sediments will be far below 1 gram carbon per m^2 per day (a commonly accepted threshold of loading that begins to result in adverse effects on the surficial sediment layer thus the anticipated effects should be positive, providing increased organic food supply and resulting in enhancement of the biota.

Water column effects of fish farms are much more transitory and of limited range and in the present case we do expect to see very minor decreases of dissolved oxygen and increases of dissolved inorganic nitrogen within the cages and immediately downstream. The organisms at greatest risk to compromised water quality in any net-pen fish farm operation are the farmed fish themselves, not wild fishes or invertebrates, thus the incentive is to maintain healthy conditions at all times. Large spacing of cages, strong and persistent currents and modest loading densities reduces such risks of a water column effect on pelagic wild fish or invertebrates to a very minimal level at the proposed site, as discussed in this report.

2. Introduction

Objectives, purpose and origin of model

The purpose of this report is to document the application of computer simulation software known as AquaModel to simulate the water column and benthic effects of an open ocean demonstration fish farm proposed for the California Bight offshore of San Diego, California. The fish farm would be operated by Hubbs-Sea World Research Institute (herein, HSWRI) of San Diego, California. http://www.hswri.org/ The model is a product of the work of Systems Science Applications, Inc. (Dale Kiefer and Frank O'Brien) and Jack Rensel (Rensel Associates Aquatic Sciences). Dr. Kiefer, his co-workers and Dr. Jack Rensel have been involved in modeling aquaculture effects since 1990 (Kiefer and Atkinson, 1988, 1989, Rensel 1987, 1989a, 1989b). Dr. Rensel has been involved in aquaculture effects studies since 1972.

The first application of AquaModel was for simulating the water column effects of salmon farming in the Pacific Northwest, in work performed for NOAA and the Washington Fish Growers Association (Rensel et al. 2007). Subsequently, the model was adapted for use in the Caribbean Sea for the culture of a fast-growing fish known as cobia (*Rachycentron canadum)*. AquaModel is unique among aquaculture models as it simultaneously calculates and displays real time images of physiological effects of fish aquaculture including their respiration (oxygen consumption), nitrogen excretion (mostly ammonia and minor amounts of urea that both rapidly convert to nitrate in the environment), microalgal (phytoplankton growth) resulting from the nitrogen excretion and zooplankton grazing upon the available stocks of phytoplankton in the modeling domain.

Subsequently, AquaModel has been expanded to include simulation of discharge and flux of carbon-containing solids from fish feces and waste feed that sink at known rates toward the bottom, are deposited upon surficial sediments and resuspended and re-transported laterally when near bottom current velocities exceed threshold values. The benthic submodel bears some resemblance to other aquaculture models including DEPOMOD (Cromey et al. 2002a, 2002b) which in turn was derived in part from the well-known G-model of carbon degradation (Westrich and Bernier 1984) and subsequent studies described herein. No code or specific information was borrowed from DEPOMOD, all algorithms and code were developed independently from the underlying literature and known stoichiometric mass-balance relationships, although some calibration settings are shared.

AquaModel may be classified as a multibox model with either 2 or 3 dimensional (2D or 3D) hydrodynamic flow options. It is structured to allow use of single point or ADCP current meter data inputs. It can also simulate tidal flows based on site specific tidal characteristics and can utilize advanced 3D hydrodynamic model output. AquaModel is one of several "plug in" models developed for use within Geographic Information System software known as Environmental Analysis System (EASy) which has multiple functions and purposes. At present the model is a consulting tool of Science Systems Applications (SSA) which is owned by Dr. Dale Kiefer and Mr. Frank O'brien. Dr. Jack Rensel is a third partner in the team and is an aquaculture effects specialist who works with SSA on model design, testing and application. Dr. Katsuyuki Abo of the Japanese Fisheries Research Agency has also contributed in development of the hydrodynamic submodels.

3. Detailed Model Description

Overview

To our knowledge our EASy AquaModel is the only software that provides a complete, dynamic model of farm operation and environmental impact. It is also the only software that fully integrates environmental information with model computations within a GIS. More information can be found at www.AquaModel.org and simplified demonstrations of model use can be found at http://netviewer.usc.edu/projects.htm (only use Internet Explorer and closely follow browser options). The GIS program EASy is described at http://www.runeasy.com/

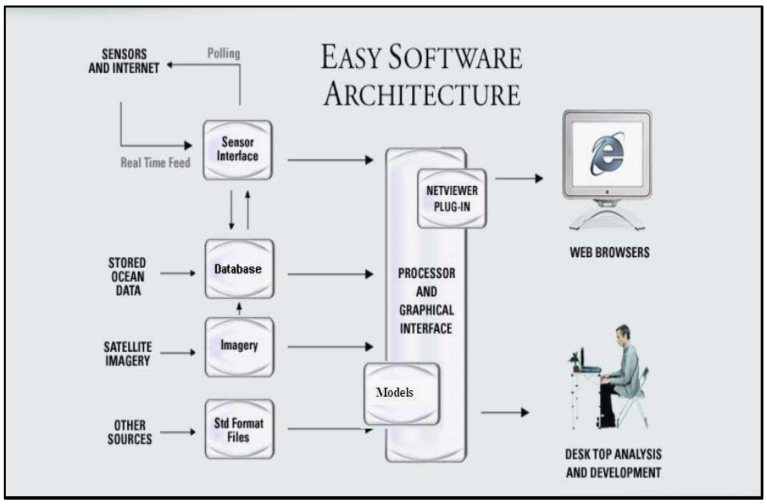


Figure 1. EASy software architecture and data integration processes.

AquaModel and the underlying EASy GIS system have the capability to contain environmental information obtained from satellite-ocean thermal and color sensors and field surveys or remote sensing and reporting of currents, nutrients, oxygen, chlorophyll and other related parameters. It also contains a simulation of virtual fish farms that can be "placed" within given water body and operated according to the conditions found at that location. Most importantly, the information system fully integrates field surveys of conditions in the water body with a dynamic model describing the growth and physiology of penned fish under any operating conditions selected by the user.

The GIS software EASy provides a 4 dimensional framework (latitude, longitude, depth, and time) to run simulation models and analyze field measurements as graphical, numerical and statistical outputs. EASy, whose components are summarized in Figure 1, is an advanced, PC-based geographical information system designed for the storage, dissemination integration, analysis and dynamic display, of spatially referenced series of diverse oceanographic data.

AquaModel graphically renders dynamically in time, within their proper geo-spatial context, both field and remotely sensed data and model outputs as diverse types of plots, including vector, contour, false color images and includes a built-in data contouring feature. Vertical structure of data, critical in oceanographic applications, is depicted as vertical contours for transects or depth profiles at selected point locations. Time series for measurements and relationships such as vertical profiles within the database at individual stations can also be visualized interactively as XY-plots. Presently there are over 50 different X-Y plots available for different parameters viewed as vertical profiles or horizontal cross sections that are dynamically updated in real time simulations. The software also provides access to data, integrated visualization products, and analytical tools over the Internet via Netviewer, a client-server, plug-in for EASy.

AquaModel consists of 4 components: a 2 or 3 dimensional description of water circulation, a description of the growth and metabolic activity of the cultured fish within the farm, a description of the planktonic community's response to nutrient loading, and a description of benthic effects (Figure 2).

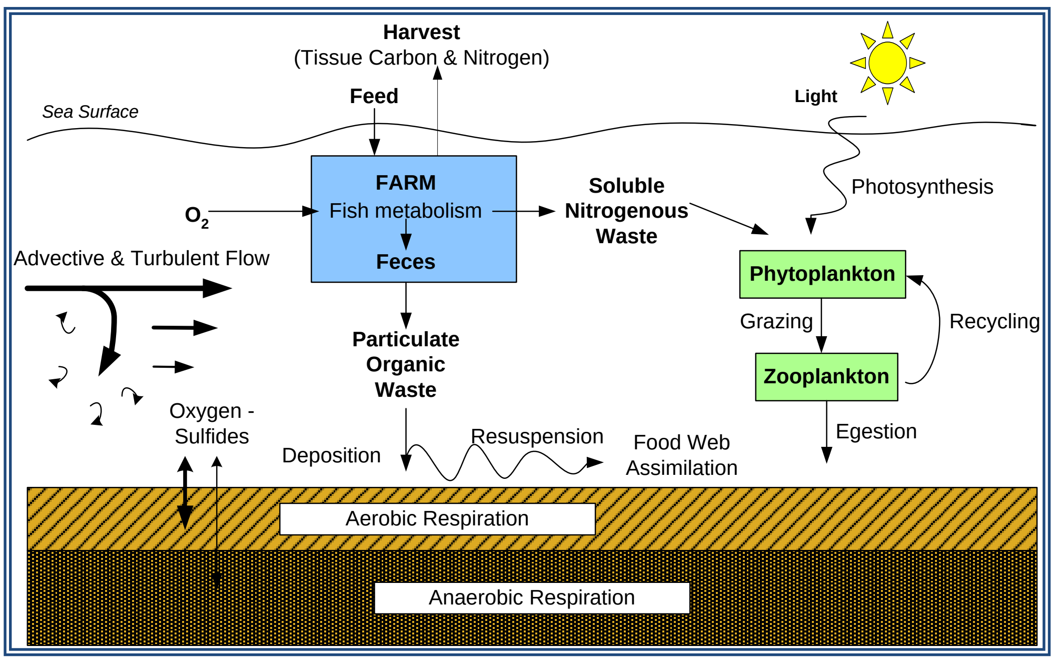


Figure 2. Diagrammatic representation of key processes simulated in AquaModel.

The primary benthic parameter of interest is the loading of total organic carbon, but the model also simulates the status of sulfides, interstitial dissolved oxygen, aerobic and anaerobic bacteria biomass, carbon dioxide and related parameters in the sediments. AquaModel uniquely tracks waste feed and fish fecal matter separately and is pre-equipped with pertinent coefficients and functions to simulate salmon, cobia, striped bass and other species soon to be completed.

Parameters of the model, including pen array center, location in the Cartesian coordinate system, cell (grid) size, farm dimensions, capture cell locations (i.e., vertical profiles from specific locations that is exported to spreadsheets), fish loading and feed rates, etc. Many are set interactively with drop down menu selection. Virtually all parameter settings and coefficients are user adjustable, either in drop down menus (See Figures 3 to 9). or using a text editor in the accessible software files.

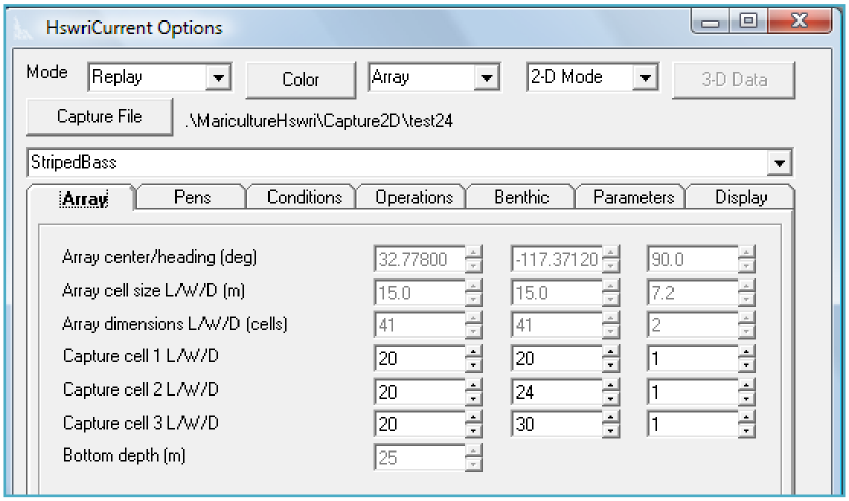


Figure 3. Array settings for AquaModel operation including location of center or farm(s), bottom depth (for 2D only, variable settings for 3D) and capture cell locations to output spreadsheet or database results.

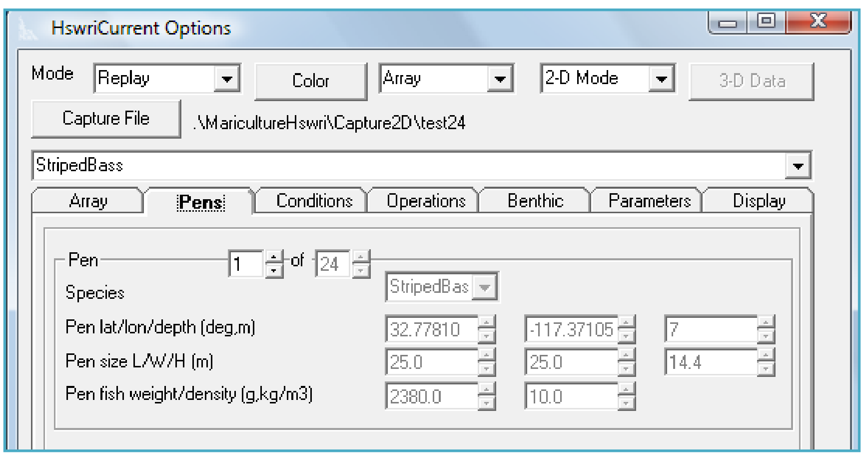


Figure 4. Pen location, size and initial loading settings.

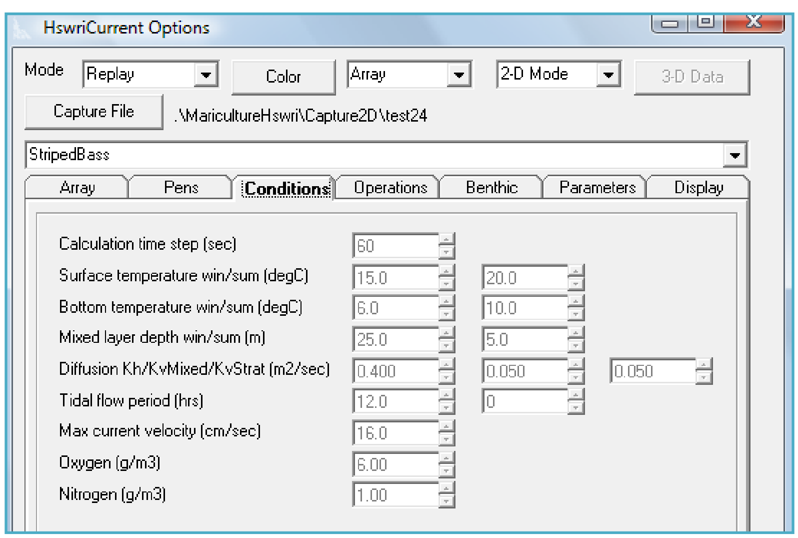


Figure 5. Water column conditions and optional synthetic tidal flow simulation settings, not used when current meter or 3D flow field data are available.

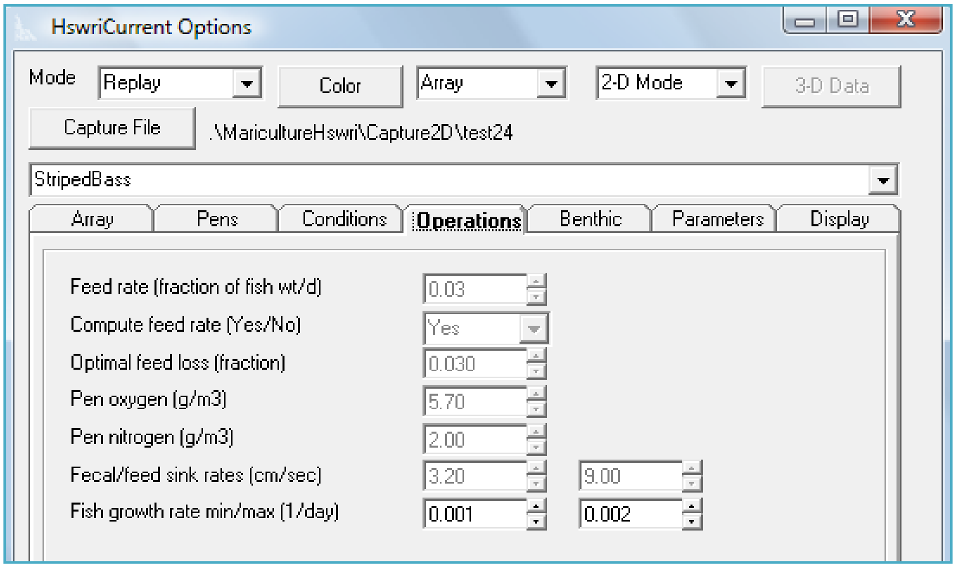


Figure 6 Feed rate override settings, compute optimum feed use settings, percent feed loss level, initial pen oxygen and nitrogen settings, fecal and waste feed sinking rate, fish growth range bounds.

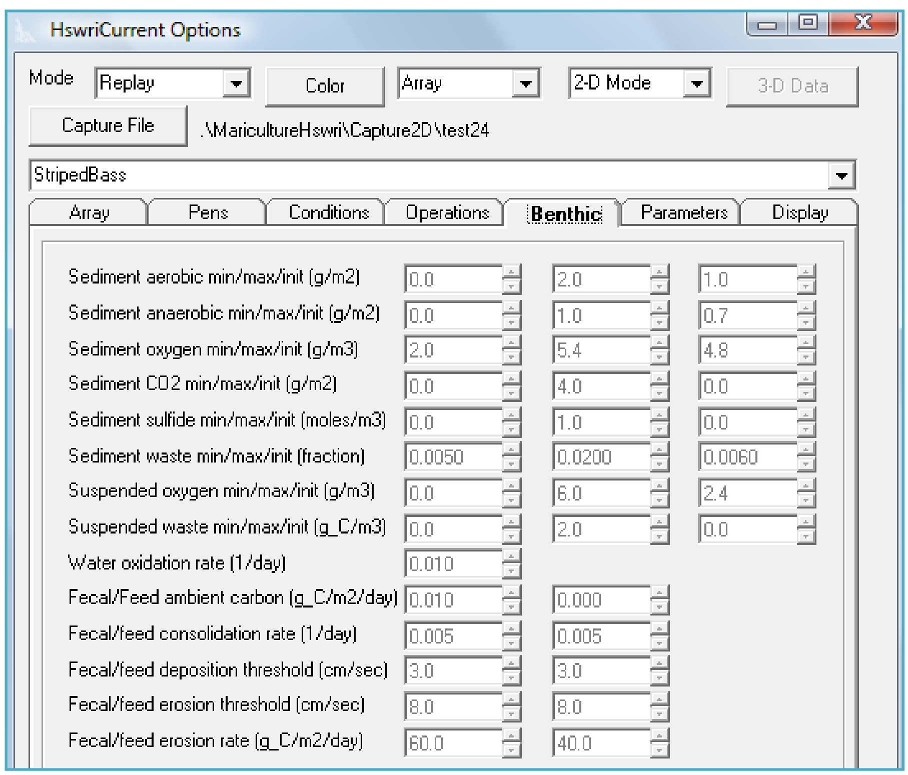


Figure 7. Sediment fecal and feed properties settings.

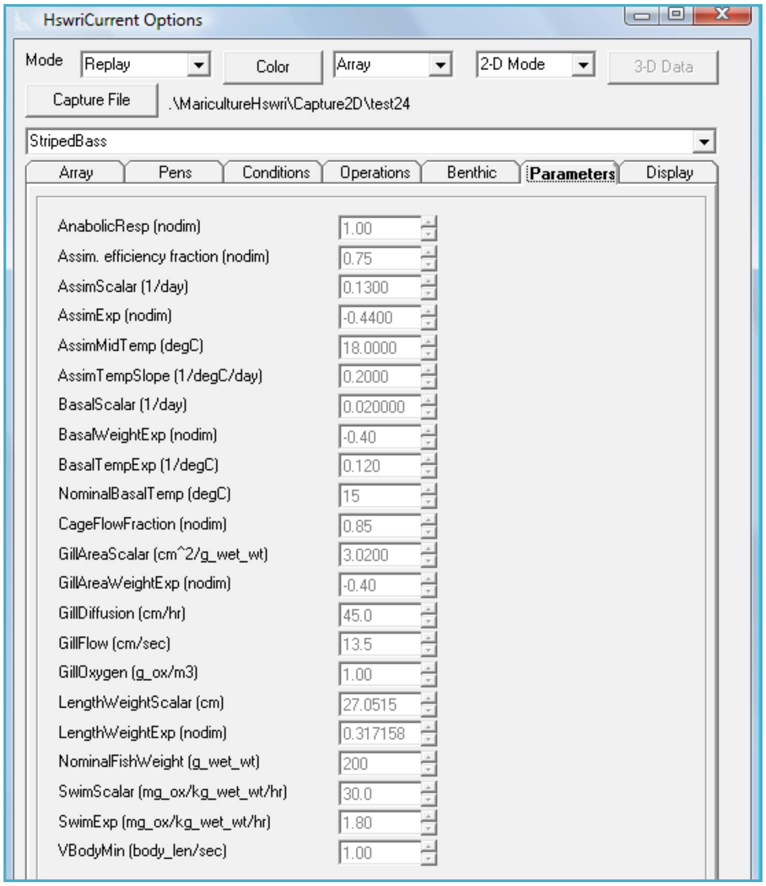


Figure 8. Several of the fish physiological parameters and coefficients obtained from best fit to striped bass literature and HSWRI growth experiments.

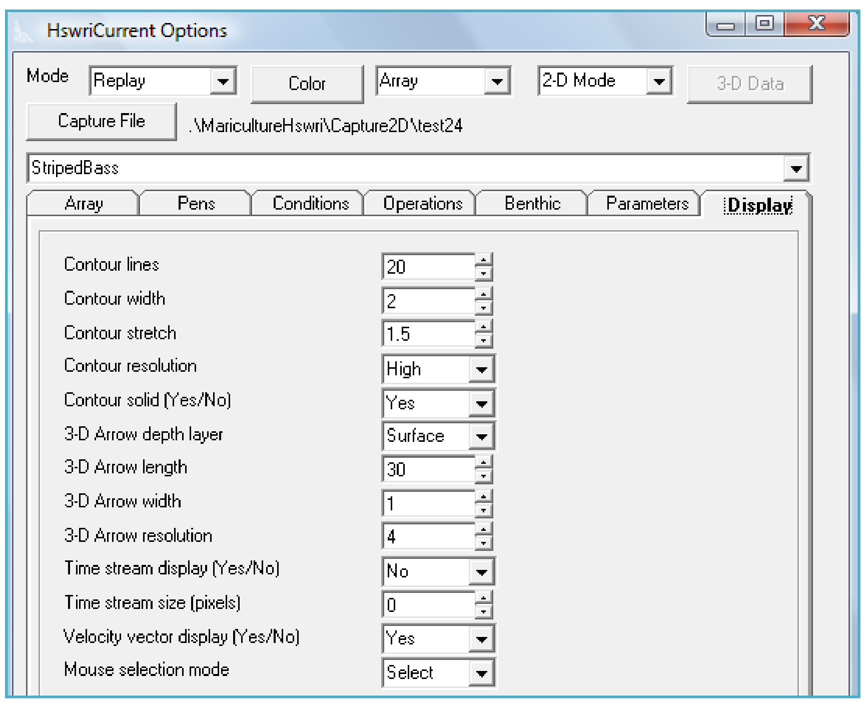


Figure 9. Contouring, current vector display, time stream and other display settings.

Next we describe the model by submodel (routine) components in more detail.

Circulation Submodule

AquaModel's circulation routine flushes cages with ambient waters and transports wastes from them. The computations during each step of the simulation occur within each element of a 3-dimensional grid of rectangular cells that populate an array of such cells. The size, orientation, and geospatial location of the array as well as the number and dimension of the cells that populate the array are entered by the users. The array of cells begins at the sea surface and extends to the sea floor. The geometry and flow at the sediment/water interface is described in more detail in the Benthic Routine Section and the farm layout is described in the site description section. The time steps for the simulation vary between 1 and 5 minutes depending upon the speed of the currents.

The system of equations describing circulation is a simple finite element description of advection and dispersion. Each element of the array is treated as a box model in which materials flow across the 6 interfaces of each element, top, bottom and the four sides. Each element is treated as instantly mixed throughout. These movements are determined by a simple, finite difference calculation that is most simulations of coastal water flow. The maintenance of conservation of mass of conservative a tracer such as water itself is a key constraint upon the calculations. Water and dissolved and suspended materials also move across the side boundaries of the array; however, here the values for the concentrations of dissolved and particulate materials at the boundaries remain constant and equal to the initial, ambient concentrations of tracers entered by the user at the start of the simulation. If the calculations of such a model are to be trusted, the array must be sufficiently large such that the exchange across the boundary does not significantly perturb the results of calculations.

The circulation at the sediment-water column interface, where uneaten feed and feces from the farm not only transported but also deposited into the sediments, resuspended from the sediments, or consumed by benthic organisms will be described in the benthic section.

The flow field in AquaModel is either of two modes. As the name suggests the calculated flow field in the "3-dimensional mode" is in 3 dimensions. Exchange of water between adjacent cells has no constraints other than the requirement of conservation of mass. Convergent and divergent motion can be represented within the array as well as local eddies. In addition the water depth can vary within the array. Unfortunately, such detailed descriptions of motion are difficult to measure at small scales and thus rarely measured in coastal waters. Thus, such types of description come from coastal circulation models which include such drivers of circulation as winds, tides, and local gradients in water density due to thermal exchange as well as evaporation and precipitation. *AquaModel* assimilates output from such coastal circulation models. For example we have assimilated data on circulation in the Southern California Bight proved by runs from the Jet Propulsion Laboratory's ROMS Model. Because we have only been provided output of short duration at this point, we have not included them our assessment.

In the "2-dimensional mode" at any time step of the simulation both horizontal and vertical motions are uniform throughout the array. Unlike the "3-dimensional mode" there is neither divergence nor convergence flow within the array. In the case of horizontal motion both advection and turbulent exchange between adjacent sides of the cells are equal throughout the array. In the case of vertical motion exchange between adjacent sides of cells are also equal throughout the grid, but restricted to turbulent exchange in which flow across the upper and lower sides of adjacent cells is equal. The “2-dimensional flow” mode also consists of two layers, an upper mixed layer and the lower stratified layer. The depth intervals of the mixed layer and the stratified layers vary with season as a sinusoidal oscillation. Finally, in this mode the depth of the water column is uniform throughout the array. Much of the data on circulation collected at mariculture sites come from acoustic Doppler current profilers that provide information that is incorporated into this more simple description of circulation. Calculations for the demonstration fish farm model were in the 2-dimensional mode and the flow field was driven by a Doppler current meter record deployed for a 96 day period at a single site off San Diego. (See site description section.) In such a mode, turbulent and advective exchange of water is the same across the 4 lateral sides of all cells and there is no divergence or convergence of water motion.

Fish Physiology and Farm Module

In AquaModel simulations, a fish farm is characterized by its two main properties, the farm’s physical settings and layout and the farm’s stocking, feeding, and harvesting regime. The physical layout requires entry of the following types of information that are specified later in this report:

- The number of cages
- The location of the cages as described by their geographic co-ordinates (latitude, longitude, depth)
- The size of the cages length, width, height and slight adjustments to approximate fitting into the square grid system
- The fractional difference between the current speed within the cages and ambient current speed

Farms operations require entry of the following information for each cage:

- Species of fish.
- Metabolic model of the fish as described below. Although the system of equations describing growth and metabolism is invariant with species, the coefficients found within the equations likely vary with species
- Mean weight of fish in grams wet weight at initial stocking or a selected time intervals
- Density of fish in number of fish per cubic meter at initial stocking or at selected time intervals
- Feed rate in grams dry weight of feed per day. This rate can be entered manually or calculated automatically by AquaModel as an optimal feed rate
- Estimate percentile of uneaten feed loss from the cages.

System Science Application has developed *AquaModel*’s routine describing the metabolism of modeled fish; it is based upon extensive review and parameterization of basic bioenergetics studies as well as some of our own unpublished laboratory experiments (See Rensel, Kiefer and O'Brien 2006 for more background). Its unique feature is its inclusion of equations for oxygen-limited metabolism, a feature necessitated by its importance in farms where fish are cultured at relatively high densities and in waters of moderate or lower dissolved oxygen concentration. Dissolved oxygen is a primary limiting factor to net pen carrying capacity and is therefore of considerable modeling interest. As indicated in figure 10, the routine includes the processes of ingestion, egestion, assimilation, respiration, excretion, and growth. Carbon, nitrogen, and oxygen fluxes are all computed, and of course the rates of these fluxes vary with operational and environmental conditions. The operational independent variables are listed above while the environmental variables that determine metabolism are:

- Water temperature
- Ambient oxygen concentration which is one of the determinants of the concentration of oxygen with a cage
- Ambient current velocity, which is another determinant of oxygen concentration within the cage as well as a determinant of the respiration rate required of the fish to swim at a speed in order maintain their position within the cage.

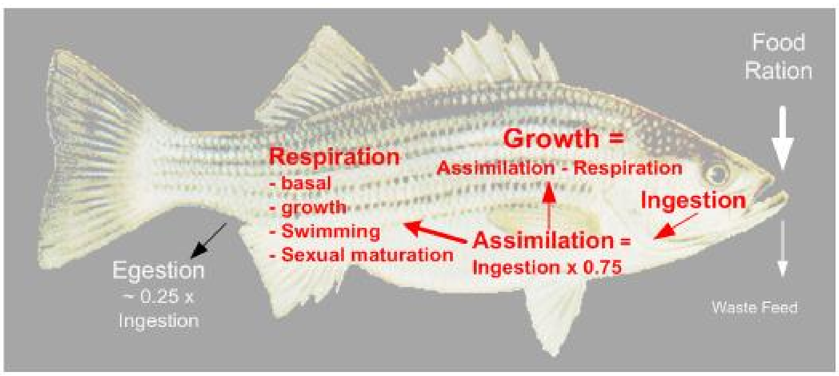


Figure 10. Generalized fish metabolic processes described by the routine for fish metabolism.
(Background drawing by Duane Raver, USFWS).

The striped bass routine consists of a series of functions describing the fluxes of carbon, nitrogen, and oxygen as determined by the basic features of metabolism, ingestion, egestion, assimilation, respiration, and growth. Specifically, each element is tracked according to these 5 basic features, which are related to each other by conservation of mass:

1. ingestion rate = egestion rate + assimilation rate
2. assimilation rate = rate of respiration + rate of growth
3. respiration rate = resting rate of respiration (i.e. basal) + respiration rate of activity (i.e. swimming) + respiration rate of anabolic activity (i.e. growth)
4. rate of feces production = egestion rate
5. rate of loss of uneaten feed = feed rate – ingestion rate

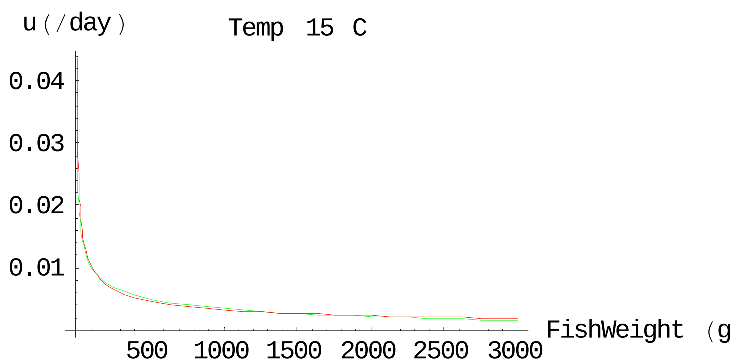
The functions for the 5 basic metabolic processes can be summarized as follows. Ingestion rate is determined by both the rate of supply of food and rate at which the fish can assimilate ingested food (Equation 1). If the rate of supply of food exceeds the sum of the rate of egestion and the rate of assimilation, then a fraction of the food will be uneaten and contribute to the particulate waste produced by the cage (Equation 5). As indicated in Figure 10, egestion is assumed to be a fixed fraction of ingestion as determined largely by the nutrient composition of the feed. The rate of egestion is in fact the rate of feces production (Equation 4). The assimilation rate of the fish will be a function of the size (age) of the fish, the temperature of the water, and the concentration of oxygen within the cage. The assimilated nutrients are then either consumed by respiration or contribute to the growth of the fish (Equation 2). (We assume that there are no reproductive demands within the cage.) The rates of respiration, which include both the consumption of oxygen and excretion of nitrogen, are determined by three processes, basal metabolism, swimming metabolism, and anabolic metabolism demanded by growth (Equation 3). Basal metabolism is a function of water temperature and the size of the fish, swimming metabolism is a function of the fish size and its swimming speed, and anabolic metabolism is proportional to growth rate. The growth rate of the fish is simply calculated by subtracting the rate of respiration from the rate of simulation.

Information on *Morone saxatilis* metabolism that we used to calculate or estimate the values for coefficients found in the equations of the subroutine came from a number of sources. For example information on morphometrics as well as rates for respiration and growth were obtained from FishBase on line www.fishbase.org. Data from FishBase was supplemented by recent measurements of growth rate by Hubbs-SeaWorld Research Institute, and more detailed information on growth and respiration rates for fish of different ages, cultured at different temperatures, and swimming at different speeds were obtained from recent unpublished measurements as well as references listed in our bibliography. Information for wild stocks was reviewed (e.g., Hung et al. 1993, Chesney et al. 1993, Duston et al. 2004) but typically wild stocks often do not grow (or survive) as well as cultured stocks so the HSWRI information for Southern California is the best available. More information from pens in the region will be available soon from a project occurring near Ensenada, Mexico although the water temperatures are relatively cool there.

Some examples of the predictions of the striped bass bioenergetic routine are presented below.

Figure 11 shows the calculated specific growth rate of *M. saxatilis* plotted against the weight of the fish over time. Two curves are plotted; one is results of calculations with our *AquaModel* routine and the other is derived from the von Bertalanffy growth curve. The two curves fall on top of each other. The *AquaModel* routine was calculated for fish that are well fed, at rest, and cultured in waters that are aerated and at a temperature of 15 °C. Figure 12 is a plot of the calculated specific growth of a 2380 gram *M. saxatilis* growing under optimal conditions at temperatures between 15 - 25°C as determined by variations in specific feeding rate. We expect that the HSWRI demonstration farm will harvest fish at a size of 1 to 1.5 kg. We have chosen to run all of our simulations of operations and environmental impact for these large adults since at this time the cages will contain the highest biomass of fish and produce maximal rates of waste production. Under the environmental conditions found at the site we calculate that on a daily basis these adults will ingest 1.6% of their body carbon, of which they will respire 60%, egest 26%, and acquire 14%. This is a very efficient conversion of feed to animal protein. We have made a variety of such calculations that describe changes in rates of metabolism with changes in temperature, oxygen concentration, swimming speed, and daily food ratio. Although the database on *M. saxatilis* metabolism is limited, those measurements that we have gathered from literature agree well with our calculations.

Figure 11. Calculated specific growth of 2380 gram *M. saxitalis* growing under optimal conditions at temperatures between 5 °C and 25°C.



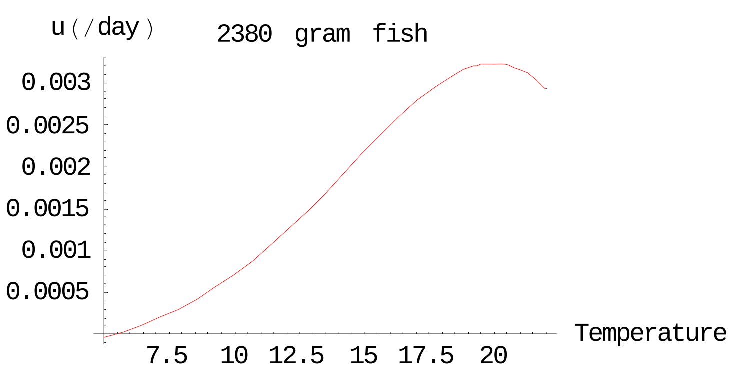


Figure 12. Calculated specific growth rate (u/day) of *M. saxitalis* at 15 °C plotted against fish weight.

The component describing the growth and metabolism of the fish within the farm includes the processes of ingestion, egestion, assimilation, respiration, excretion, and growth (figure 4). Carbon, nitrogen and oxygen fluxes are traced and interrelated, and rate functions vary with operational and environmental conditions. Operational conditions are the size and position of the pens, the quantity and composition or rations, and the density and size of the fish. Environmental factors that determine metabolic rates are current speed, the temperature of the water and the concentration of oxygen in the water. As water passes through the farm, a “waste water plume” and a “waste particle plume” are created downstream. The characteristics of this plume will depend upon the metabolic activities within the farm as well as the advective and turbulent flows that shape the plume.

Several variables including the water temperature, the dissolved oxygen concentration, current speed, average wet weight of the fish, their density within each pen and the daily food ration define the initial state of conditions in the fish farm. Each pen is tracked separately and different species can be stocked in separate pens and each pen allows for different initial size of fish. Outputs from the simulation include three dimensional maps of the two types of waste plumes (dissolved and particulate) created by egestion, excretion, and respiration by the farmed fish. Outputs also include the growth rate and standing stock of the fish, and the concentrations of nitrogenous nutrients, oxygen, and particulate waste (feces) within the farm. Many other parameters and plots of vertical profiles or transects can be viewed simultaneously, and all data can be written to spreadsheet or database to allow statistical and other types of post-model processing.

Plankton Module

The plankton module describes the cycling by plankton of nitrogen and oxygen within each element of the array, both within the farm and the surrounding waters. This model is similar to the PZN models that have been published by Kiefer and Atkinson (1984) and Wroblewski, Sarmiento, and Flierl (1988). The “master” cycle describes the transforms of nitrogen between three compartments, inorganic nitrogen, organic nitrogen in phytoplankton, and organic nitrogen in zooplankton. The three biological transforms are:

- Photosynthetic assimilation of inorganic nitrogen by phytoplankton which is a function of temperature, light level, DIN (dissolved inorganic nitrogen consisting of ammonia, nitrite and nitrate) concentration
- Grazing by zooplankton on phytoplankton which is a function of temperature and concentrations of zooplankton, and phytoplankton
- Excretion of DIN by zooplankton, which is a function of temperature and the concentration of zooplankton.

All three components are transported by advective and turbulent flow as described above. The model displays predator-prey oscillations, which dampen over time and reach a steady state. The default simulations for DIN, phytoplankton, and zooplankton stabilize at roughly 1 mg-at N m^{-3}, for all 3 components respectively. In order to calculate the concentrations and rates of loss by respiration and production by photosynthesis, we have assumed a constant flux ratio of oxygen to nitrogen of 6 moles O_2 gm-at N, consistent with the Redfield ratio. The inputs to this model consist of the time series of exchange coefficients produced by the hydrodynamic model, surface irradiance, and water temperature as well as concentrations of dissolved oxygen, dissolved inorganic nitrogen, cellular nitrogen in phytoplankton and zooplankton. Outputs of this model consist of a time series of the concentrations of dissolved inorganic nitrogen and oxygen, phytoplankton (traced as chlorophyll), and zooplankton. Since plankton dynamics proved to play a very small role in the present simulation, we have chosen not to describe the system of equations in any detail.

Benthic Module

Physical Dynamics

The benthic loading component of our model is based upon several literature citations and functions found in the existing, previously-verified DEPOMOD model (Cromey et al. 2002a, 2002b) that in turn was based on the G-model of carbon degradation (Westrich and Bernier 1984 and subsequent papers). Despite some limitations involving lack of user control and flexibility, DEPOMOD is presently the international standard for assessing the impact of loading of organic carbon in sediments underlying fish farms and in some countries calculations with the code are a requirement for obtaining fish farm permits. Since the DEPOMOD model is proprietary and only addresses benthic processes, we have written our own code to describe the fate of farm wastes that are deposited in sediments. Two processes, the physical dynamics of waste transport through the water column and deposition into the sediments and the biological dynamics of waste assimilation and remineralization by the benthic community, most conveniently describe our benthic routine.

As uneaten feed and feces produced by fish in each cage sink through the water column, they are transported downstream of the cage. Since uneaten feed is larger and denser than feces it must be treated separately. Not only will these different classes of particles sink at different rates and be transported at different distances from the farm, but when they reach the bottom boundary layer their shear thresholds for deposition and resuspension will also differ, leading to further separation. Eventually, both uneaten feed and feces will either be consumed by the benthos or consolidated into the sediments and no longer subject to resuspension. Thus, AquaModel has three categories of particulate waste: uneaten feed, feces, and consolidated waste contributed by both the uneaten feed and feces that have been deposited for a sufficient length of time on the bottom that are no longer erodible.

As illustrated in the figure 13, we have simplified the formulation of physical processes. This was required because simulations running on a PC became too time-consuming or mathematically unstable with a more detailed formulation. Waste particles produced in the farm are “collected” over a specified time interval as “capsules” that sink through the water column at a rate determined from measurements in the laboratory. These capsules are shown as brown dots in the figure. As these capsules sink, the ambient currents transport them through the 3-dimensional array of cells. This is somewhat analogous to water moving through an unsecured garden hose that is in continual motion but in this case is driven by variations in current velocity and direction. The waste particles are however not subject to turbulent dispersion as is the case for the dissolved wastes. As the capsules near the bottom the waste particles are “released” and evenly distributed into an underlying cell that is part of the grid of the suspension layer of the water column. The length and width of these cells are the same dimensions as the cells within the overlying water column, but their depth is user selectable. In the case of the demonstration farm, we have chosen a depth of 1 meter. Once released into the suspension layer the particles are now treated as suspended particles and subject to both advection and turbulent dispersion.

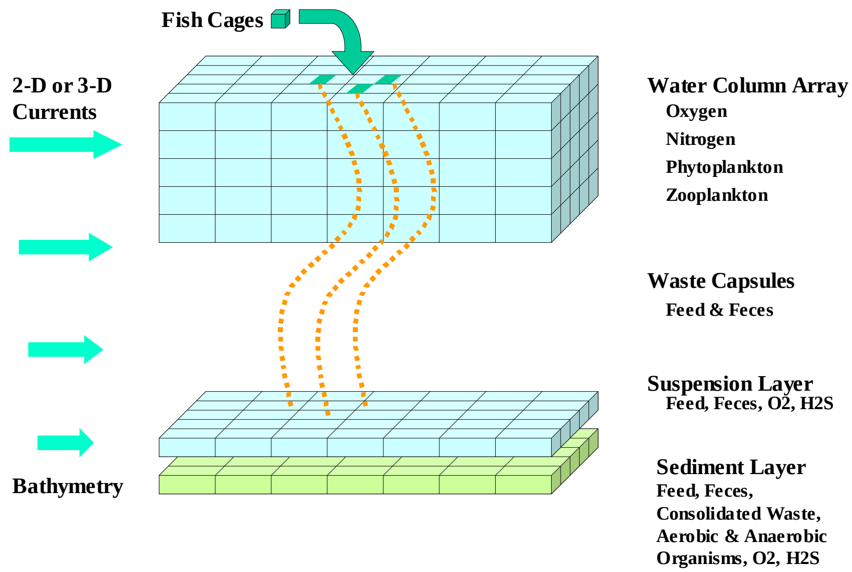


Figure 13. Conceptual diagram of waste transporting model components.

Following the logic and formulations of DEPOMOD (Cromey et al. 2002a, 2002b), when shear between the sediment and the bottom water falls below a threshold value, waste particles in the suspension layer are deposited into the sediment layer. Furthermore, the rate of deposition not only increases with the concentration of particles in the layer but will also increase with decreases in shear. When shear at the interface exceeds a threshold value, waste particles in the sediment layer will be resuspended into the suspension layer and thus subject to additional transport (and dispersion) from the site. The thresholds for deposition and resuspension differ with the size, density, and stickiness of the particles and thus will differ between feed and feces. When shear at the bottom falls between the threshold for deposition and the threshold for resuspension, the particles in the suspension layer will be remain in suspension and thus dispersed.

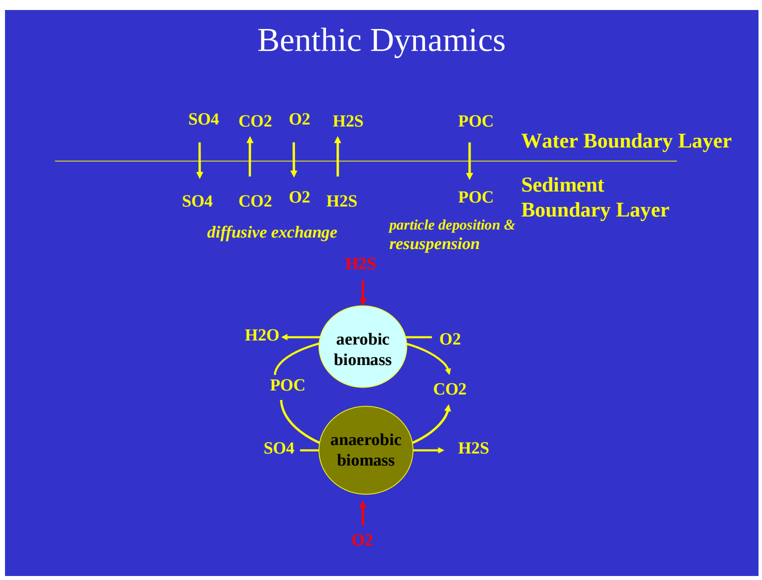
The wastes deposited in the sediment undergo aggregation and compaction, and will consolidate into organic particles that are no longer subject to resuspension. Cromey and his co-workers have derived a function for this process in which compaction begins at a given rate after a 4 day delay. We have on the other hand chosen a simple first order rate function in which a fixed fraction of the mass of feed and feces in the sediments consolidates each day. We have selected for our simulations the same values found in reference above for shear thresholds and the rate constant for resuspension of wastes. Finally, we have selected a consolidation rate for sediment wastes of 2% per day, as discussed later in this report, after some sensitivity testing.

Dynamics of the Benthos

The 3 types of waste found in the sediments, uneaten feed, feces, and consolidated waste (from feed and feces) are energy and nutrient sources for the benthic community, which consist of both macroscopic and microscopic organisms. Thus, at any given time, the concentration of waste in the vicinity of a farm will depend upon the previous history of deposition and resuspension, but also upon the previous history of growth and remineralization by the benthos. As shown in Figure 13 above, we treat the sediment layer as a single layer; this is despite the fact vertical profiles within sediments indicate sharp, predictable biological and chemical gradients within. In our simulations we have chosen a depth interval of 2 cm for each cell of our sediment array. This depth was chosen because it is the standard depth for sediment monitoring (core collection) in and around fish cages in many North American jurisdictions. The length and width of these cells are the same as those within the water column and suspension layers. Our functions are based upon the assumption that they provide a prediction of average biological and chemical conditions within the layer. Describing the complexity and biochemical processes within the sediment layer has challenged marine scientists, and the models that have been developed (including ours) are relatively crude and lacking in comprehensive testing. Despite these limitations, field data describing benthic responses to variations in organic loading of the sediments show clear understandable patterns, and that when tuned to local conditions models such as the pioneering G-Model of Westrich and Bernier (1984), can provide good quantitative estimates of the response. Testing of our submodule components is completed in Mathmatica software before assembly into AquaModel code, when additional testing occurs.

Figure 14 below shows the components and process that are described by our benthic routine. The processes described here are all formulated in the series of equations found in the routine. As shown the components of the routine consist of 4 dissolved compounds species, oxygen, sulfate, hydrogen sulfide, carbon dioxide, which flow between the suspension and sediment layer by diffusion. It also consists of particulate organic carbon (POC) produced in overlying waters from farm waste or the planktonic community, and the benthos, which consists of two groups of macro and microscopic organisms that mediate the chemical transformations.

Figure 14. Conceptual model of benthic dynamics processes.



The aerobes respire particulate organic material (POC in the diagram) and oxygen in order to grow and meet other metabolic needs. The main by-products of their metabolism are carbon dioxide and water. If either the concentration of oxygen or POC decreases below saturating concentrations, rates of growth and respiration will decrease. Furthermore, at the lower extremes of oxygen or POC availability, aerobe growth will stop and respiration will be reduced to a basal level. The anaerobes, which here consist only of the sulfate reducing micro-organisms, respire POC and sulfate in order to grow and meet other metabolic needs. The main by-products of their metabolism are carbon dioxide and hydrogen sulfide (or other reduced sulfur compounds). If either the concentration of sulfate or POC decreases below saturating concentrations, rates of growth and respiration will decrease. Additionally, at the lower extremes of oxygen or POC growth will stop and respiration will be reduced to a basal level. If produced at a sufficient rate the hydrogen sulfide produced by anaerobes will inhibit the growth of the aerobes. On the other hand, oxygen inhibits the growth of the anaerobes.

It is clear from Figure 14 that the size and growth rate of the aerobes can be limited by the supply of oxygen from the overlying water column. In our routine the rate of supply of oxygen to the sediments is determined by the diffusion of oxygen from the suspension layer into the sediment layer, and the rate of diffusion will be determined by the difference in the concentration of oxygen in the suspension layer and the sediment layer, the thickness of the diffusion boundary layer at the interface:

$$\mathbf{JO2} = \frac{\mathbf{O2DiffCoef}[\mathbf{temperature}] * (\mathbf{O2\ suspended} - \mathbf{O2sediment})}{\mathbf{Z}[\mathbf{velocity}]}$$

Where JO_2 is the flux of oxygen into the sediment layer, O_2DiffCoef is the diffusion coefficient of oxygen, which varies with temperature, O_2suspended is the concentration of oxygen in the suspended layer, O_2sediment is the concentration of oxygen in the sediment layer a, and Z is the thickness of the diffusion boundary layer, which is less than a millimeter in most open waters, and as indicated varies with the velocity of flow in the suspended layer. If the current speed in the suspension layer increases the thickness of the boundary layer will decrease and the rate of diffusion will increase. The concentration of oxygen in the sediments is assumed to be in quasi-steady state such that the rate of oxygen consumption by the aerobes, which varies with the concentration of oxygen and the concentration of particulate organic carbon within the layer, is equal to the rate of oxygen supplied by diffusion.

Figure 15 below, which is an example of a calculation by the routine, illustrates relationship between organic loading of the sediments and the oxygen concentration within the sediments. In the figure we see straight line, which is calculated from the equation above, describes the flux of oxygen into the sediment layer as determined by the concentration of oxygen in the sediment layer. In this example the concentration of oxygen in the suspension layer is 10 g m^{-3} (= mg/L). The curved lines show the rate of respiration by the aerobic members of the benthic community as determined by the concentration of oxygen in the sediment layer. The lower curve shows the respiration rate of the aerobes when the deposition rate of POC is 1g carbon m^2 d^{-1}, and the upper curve shows the respiration rate of the aerobes when the deposition rate of POC is 5 g carbon m^{-2} d^{-1}. Both curves represent steady state conditions for the aerobes at which growth rate of the community is zero and the respiration rate is basal. This condition occurs when the concentration of POC has been reduced to a concentration at which it cannot support growth. Thus, the upper curve is the consequence of catabolic metabolism by a high concentration of aerobes in the sediment layer, and the lower curves the upper curve is a consequence of catabolic metabolism by a low concentration of aerobes.

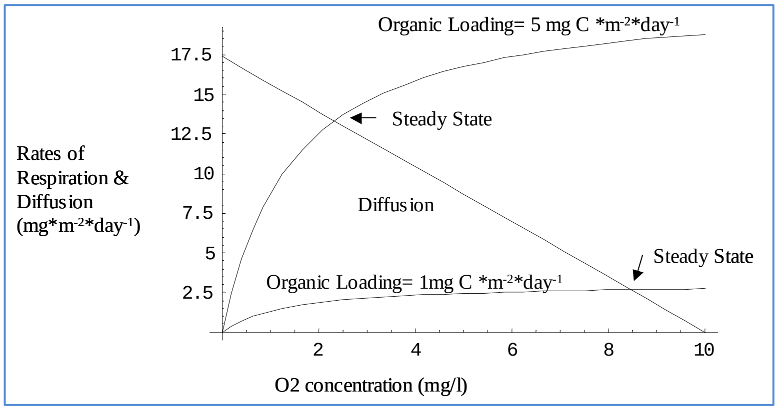


Figure 15. Organic loading to sediments and interstitial oxygen concentration relationship.

A similar diagram and similar arguments can be presented for regulation by POC deposition and sulfate diffusion for the anaerobes. However, because of the high concentrations of sulfate in seawater, the rates of diffusion of sulfate into the sediments layer are sufficiently high to rarely constraint the growth rate and biomass of the anaerobic community in the upper sediments.

It is clear from this diagram that increases in organic loading decreases the concentration of oxygen in the sediments, thereby releasing anaerobic organisms from their oxygen limitation of growth. As a consequence, the biomass of anaerobes will increase and possibly competing for POC with the aerobes and producing hydrogen sulfide. The latter may inhibit the metabolism and growth of the aerobes. Consequentially, if the gross metabolism of the aerobic community declines, oxygen concentrations will increase inhibiting the gross metabolism of the anaerobes. Such interactions will tend to drive the system toward a well defined steady state determined by the rate of organic loading, as well as the temperature, concentration of oxygen, and current velocity in the suspended layer above the bottom.

The importance of these dynamics to the management of fish farms is that provided the organic loading rate of the sediments is not too large, the respiratory activity of the benthic community will remineralize much if not all of the particulate organic material thereby releasing carbon dioxide into the sediments and water column. These predictions from our benthic routine have been confirmed by field studies such as those of Findlay and Watling (1997) and modeling work of Chamberlin and Stucchi (2007). In fact we have conducted a general tuning of the benthic routine to match the data of Findley and Watling's measurements of benthic dynamics under a salmon farm at Toothacre Cove in Maine and Stucchi and Chamberlin's modeling of salmon farms in British Columbia.

After this initial work we then conducted a more detailed tuning of our routine to observations of waste loading by salmon farms in Puget Sound, described in the next section. We will see in our concluding section on impact assessment that the rate of waste deposition under the HSWRI demonstration farm is so low because of large dispersion over a broad area that the perturbation to sediment chemistry or the benthic community will be exceedingly small and likely undetectable. Our benthic routine indicates that the major response of the sediment under the farm will be a slight increase in the density of aerobic organisms and a corresponding increase in benthic respiration that will prevent the accumulation of farm waste and actually embellish food supply for the benthic food web.

4. Prior Validation

The intent of the model calibration process is to refine the model "to achieve a desired degree of correspondence between the model output and actual observations of the environmental system that the model is intended to represent" (EPA 2002). As in any simulation model, testing and validation is necessary (Cromey and Black 2005, Rensel et al. 2006). Testing and validation of AquaModel has been done in several stages. First, it is conducted upon initial equation development when we create mathematical formulas to characterize known physical and biological processes. Then it is tested when linked to other interdependent functions and processes. Curves are fitted to natural processes such as growth rates and the best possible equations are derived to describe them.

Our first work was with salmon as so much is known about their physiology that we did not need to conduct any additional laboratory work. The comparison of predictions of growth and metabolic activity for fish (salmonids) growing over a broad range of environmental conditions with published data displayed good agreement (Rensel, Kiefer and O'Brien 2007). Figures 16 and 17 show two comparisons of model predictions with laboratory measurements. Figure 16 shows predicted (dashed lines) and measured (solid lines) growth rates for young sockeye salmon grown at different temperatures (abscissa) and different feed rates (legend). The growth rates are in units of the fractional change in body weight per day, and the feed rates of 0.06, 0.03 and 0.015 are in units of fractional body weights of food per day. Note that the model accurately predicts the decreases in the temperature of optimal growth with decreases in feed temperature.

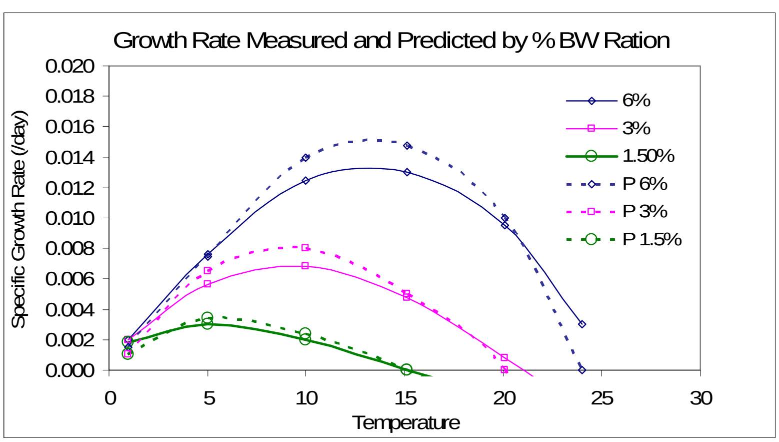


Figure 16. Growth rate measured in culture versus predicted (P) by model for initial calibration runs.

Figure 17 shows predicted (dashed lines) and measured (solid lines) respiration rates for young sockeye salmon swimming at different speeds (see legend) and at different temperatures (abscissa). The swimming speeds found in the legend are in units of body lengths per second. The upper graph shows respiration rates for maximum swimming speed record for a given temperature. Although our model describes steady state conditions as opposed to the short time interval during which the measurements was made, the fit is still good except at maximal swimming speeds.

These types of analyses were made for striped bass from literature and laboratory data, as described elsewhere in this report.

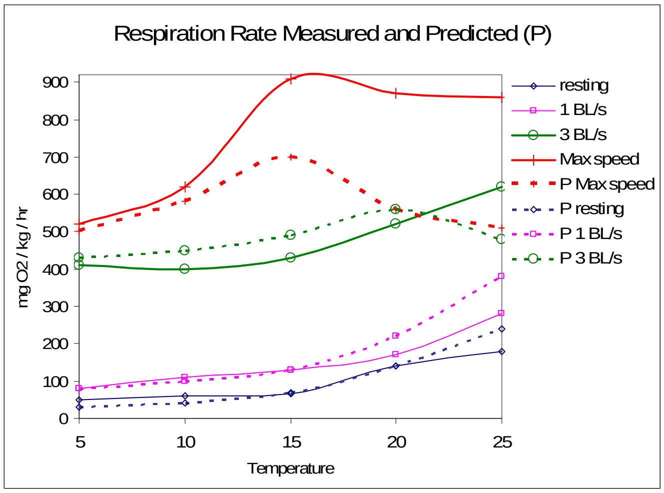


Figure 17. Laboratory measured vs. model predicted (P) respiration rate for initial calibration runs.

With respect to water column effects, Rensel (in WDF 1991 appendices and subsequently collected unpublished but reported NPDES monitoring data) has examined nutrient and dissolved oxygen deficit plumes around commercial net pen farms. In both cases the extent to which the plume can be detected is typically less than 30m for these large farms with 1,000 MT (2.2 million pounds) or more of fish biomass as shown in Figures 18 and 19, respectively. For dissolved oxygen, thousands of measurements have been collected in Maine by C. Heinig, yielding similar results (Normandeau Associates and Battelle 2003).

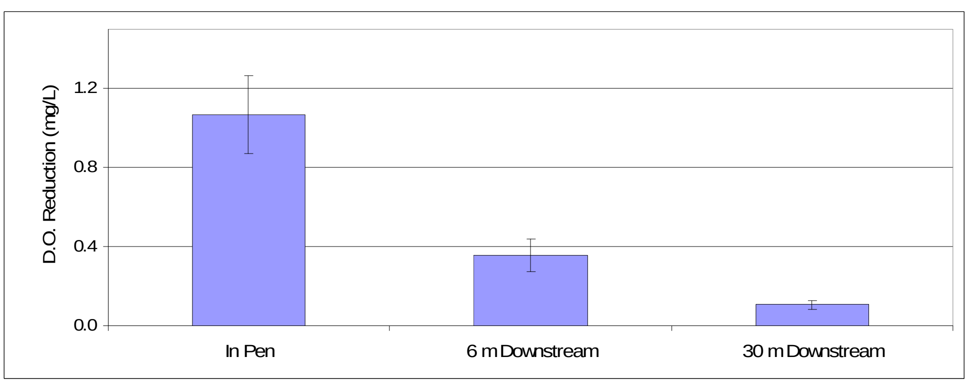


Figure 18 Summary of dissolved oxygen deficit compared to background (upstream) conditions for commercial net pens in prior studies. N = 12.

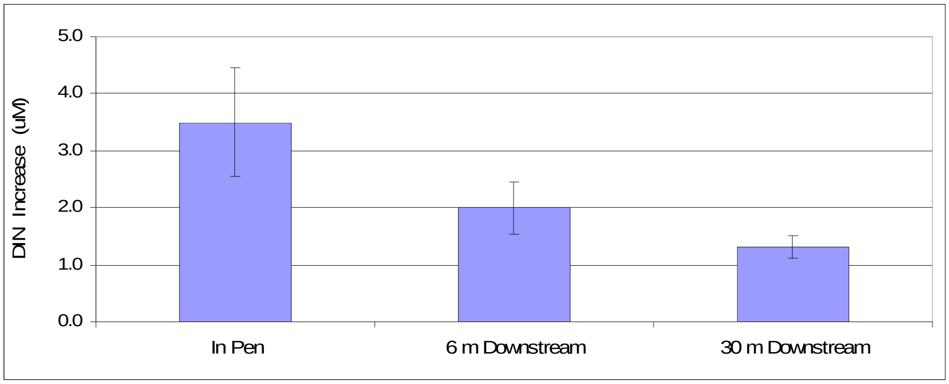


Figure 19. Summary of dissolved inorganic nitrogen increases inside commercial net pens and immediately downstream relative to ambient conditions as described in text. N = 12.

Previously we have conducted sensitivity analyses of key factors used in AquaModel simulations (Rensel, Keifer and O'Brien 2006). The sensitivity analysis we performed demonstrated the importance of resuspension as a factor that limits carbon deposition and allows for broad transport of waste particulates. This effect has previously been demonstrated with a benthic model (DEPOMOD) using a fluorescent tracer in a situation where current velocity was significantly less than the OHA site (Cromey et al. 2002b, mean velocity 4.9 cm s^{-1}, maximum velocity 23 cm s^{-1}). In our prior studies, the largest factor controlling water column and benthic effects was fish biomass (a function of fish density and size) and at the highest levels tested would produce significant and undoubtedly adverse effects if current velocity (primarily) and depth (secondarily) were minimal.

5. Description of Farm Site and Operation

Location and Site Layout HSWRI Demonstration Farm

Here we describe the proposed farm site, its center location, dimensions, configuration and other attributes and factors used in our simulation modeling. Figures 20 and 21 are vicinity maps and Table 1 includes location of the center of pens used in modeling the proposed demonstration fish farm.

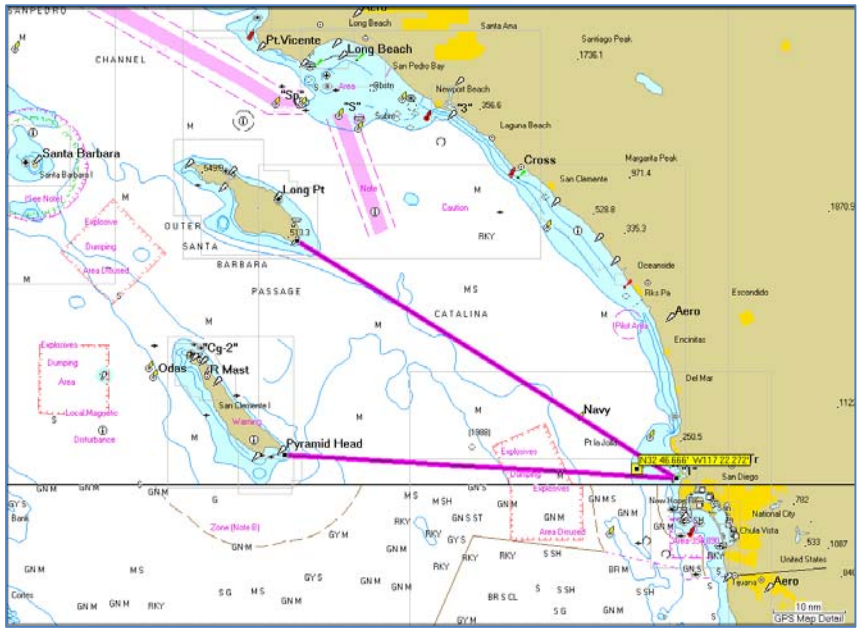


Figure 20. Vicinity map showing site location (yellow square with black center) and principal navigation paths to San Clemente (south) and Santa Catalina Islands (north) shown as purple lines.

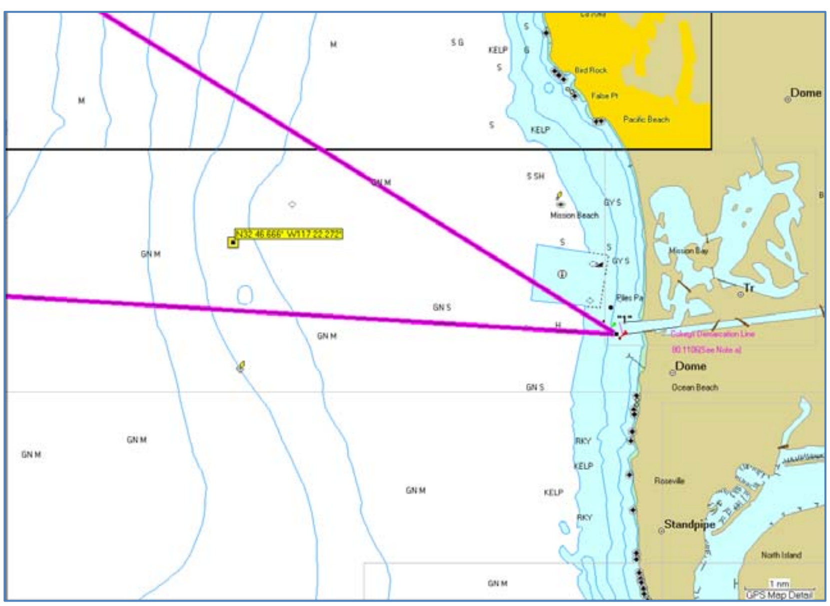


Figure 21. Close up of vicinity map

Table 1. Proposed fish production pen locations, indicated as centers. Locations are approximate for modeling, slight variation may occur in actual location but it doesn't affect modeling results.

Pen Number	Latitude	Longitude
1	32.7781	-117.3708
2	32.7773	-117.3708
3	32.7781	-117.3716
4	32.7773	-117.3716
5	32.7781	-117.3699
6	32.7773	-117.3699
7	32.7781	-117.3725
8	32.7773	-117.3725
9	32.7781	-117.3691
10	32.7773	-117.3691
11	32.7781	-117.3733
12	32.7773	-117.3733
13	32.7781	-117.3682
14	32.7773	-117.3682
15	32.7781	-117.3742
16	32.7773	-117.3742
17	32.7781	-117.3674
18	32.7773	-117.3674
19	32.7781	-117.3750
20	32.7773	-117.3750
21	32.7781	-117.3665
22	32.7773	-117.3665
23	32.7781	-117.3759
24	32.7773	-117.3759

6. Comparison Fish Farm and HSWRI Site Scenarios

Modeling was conducted for the HSWRI proposed demonstration farm site and another "comparison" site that was designed to be similar except for four key differences. The comparison site was structured to be similar to an inshore site used in commercial aquaculture such as the sites that have been operated in Puget Sound, Washington for the past 20 to 30+ years. While there is limited information on the environmental impact of an offshore commercial fish farm, the operations and impact of salmon farms in Puget Sound (and Maine) have been intensively studied for many years (Rensel 2001). Critics will point out that conditions are not the same, but we are well aware of the differences and have accounted for the physicochemical differences in our model simulations.

The inshore Puget Sound sites have achieved "steady state" operation in which there is temporal change in bottom conditions but there has been adequate sampling over the decades to know that the range is small and all operations typically rear a similar amount of fish annually. Background surficial sediment TOC in many deep temperate water environments does not vary much seasonally (Nichols 1975) so we modeled average seasonal condition with temperature varying among summer and winter periods in a sigmoidal distribution. The metabolism and rate of waste production of striped bass and Atlantic salmon are similar at the temperatures that we used in the simulation (~15°C).

The purpose of this comparison was to illustrate the merits of the proposed HSWRI site compared to state-of-the-art inshore sites, not to denigrate nearshore sites. A comparison could also be made with salmon farming sites of 35 years ago, but such a comparison would be outdated and irrelevant as siting, operation and regulatory practices have advanced exponentially since then.

Differences between the comparison and HSWRI fish farm simulations are described below and in Table 2 that include:

1) Shallower (25 m depth vs. 91 m for the HSWRI site)

2) Pens configured closer together (centers ~25 m apart vs. about 78 m)

3) Less current velocity: Near-surface average current velocities of about 16 cm s^{-1} **v**ersus the 22 cm s^{-1} surface velocities at the HSWRI site. The same current meter record was used, but near surface currents were reduced by 25% in magnitude for the comparison site to more closely approximate a Puget Sound inshore site in terms of average, but likely not maximum rates.

Similarities of the two scenarios include:

1) Pen size the same (9,000 m3) and depth (14.4 m)

2) Fecal and waste feed settling rates the same

3) Current direction over time the same

4) Other model calibration the same,

5) Striped bass was the species virtually reared in both settings

Salmon farms in Puget Sound have operated continuously since the 1970s in many cases and the conditions and effects have been closely scrutinized by both academics and regulators. Water currents for production sites (i.e., grow out sites) are without exception considered strong, which allows more than adequate dispersion of wastes over large areas where these organic wastes are rapidly assimilated under aerobic, surficial sediment conditions. Sites are relatively shallow compared to the HSWRI proposed site, varying from about 20 m to 65 m and current velocity at several of these sites has been measured in the past (Weston and Gowen 1991, Rensel unpublished data). In general, all grow out sites have average velocities averaging 15 cm sec^{-1} although a few sites far exceed that rate. All sites are composed of steel cages with each square or rectangular cage in a 2 by array of 10 or more cages. And most farms have met performance standards for total organic carbon not exceeding background levels at a distance of 30 meters. Those that did not were voluntarily reconfigured or loaded differently so as to avoid regulatory action and eventually meet performance standards. These fish farms all experience recurring tidal flows that repeat on a lunar month basis, with direction of flow alternating on ebb and flood by ~180° (+/- ca. 30°). In contrast, the HSWRI site experiences more temporal variation in direction of flow, but a strong tendency toward a net southern flow direction commensurate with the dominant California current. This large-scale oceanic current pattern is part of the North Pacific Ocean gyre and is affected by the Davidson (counter) Current that flows in a reverse direction at times in the winter.

Puget Sound net pens meet strict environmental performance standards that allow no measurable TOC or infauna effects more than 30 m distant from pen perimeters (with allowance for footprint shift in the case of unequal current forces), a standard that has been in place for over 10 years. Within a sediment impact zone, some of the sites have increased total organic carbon deposition and resulting alteration of benthic infauna, but the total affected area is only about 50 acres within an area of three million acres of sea bed. In order to meet the strict 30m distant impact zone requirements, however, conditions immediately under the pens must be relatively pristine. By that we mean <u>not</u> azoic (without infauna) and with typically no or small amounts of sulfur reducing bacteria mats (*Beggiatoa* spp.) on the sea bed.

Given the great deal of information about salmon farms effects on water column and benthic conditions, we used this knowledge to sensitivity test the model for optimum performance of the few parameters that are less well known than others. We constructed a virtual salmon farm with the following characteristics and in the same table compare the proposed HSWRI site:

Table 2. HSWRI demonstration farm and comparison farm characteristics.

Characteristic or Parameter	Actual or Modeled Value
Diameter & vertical footprint area of single cage	25 m Diameter; 491 m^2 plan view area
Cage type, Number of cages	Polyethylene circular surface cages, 8 initial, 24 later
Effective cage volume, each cage	9,000 m^3 (approximate)
Cage volume for all 24 cages	216,000 m^3 (approximate)
Modeled cage depth	14.4 m
Distance between cage centers HSWRI	78 m
Distance between cage centers comparison “shallow” site	25 m
Site depth, HSWRI	91 m, flat bottom (for 2D, 3D bathymetry variable)
Site depth, comparison “shallow” site	25m, flat bottom
Proposed cage array configuration	2 rows of 12 each, rectangular array, aligned perpendicular to prevailing current direction
Dimensions of 2 x 12 array	125 m x 930 m (estimated from AquaModel scaling)
Single cage footprint area	Radius =13.25 m; Area = 3.14 x r^2 = 551.5 m^2
Area of all 24 cages	5,515 m^2 = < 2.2% of production zone
Entire Modeling domain HSWRI site	51 x 51 cells L x W, each cell 25 m square = 1.275 km L x W = 1.63 km^2
Entire Modeling domain comparison “shallow” site	41 x 41 cells L x W, each cell 25 m square = 1.025 km L x W = 1.05 km^2

Table 3 summarizes the expected range of pertinent, ambient hydrographic parameters used in modeling both the HSWRI and hypothetical, comparison farm sites.

Table 3. Background, ambient hydrographic, physical and sediment characteristics of proposed site and vicinity.

Parameter	Values	Source or Comment
Surface water temperature range	Winter 15°C Summer 20°C	D. Kiefer, personal experience, CALCOFI database
Bottom water temperature range	Winter 6°C Summer 10°C	D. Kiefer, personal experience, CALCOFI database
Mixed layer depth, seasonal thermocline	Winter 40m Summer 15m	D. Kiefer, personal experience, CALCOFI database
Dissolved inorganic nitrogen concentration	1 µM mean	D. Kiefer, personal experience, CALCOFI database
Dissolved Oxygen concentrations	4 – 7 mg L^{-1}	D. Kiefer, personal experience, CALCOFI database
Modeled initial DO conc.	5.6 mg L^{-1}	Average DO concentration estimate
Background sediment total organic carbon in general	0.6 % dry wt.	M. Shane, unpublished site data
Sediment characteristics at proposed site	Sand, shell with balance of ~24% silt/clay	M. Shane, unpublished site data
Current velocity data	Same source for HSWRI and comparison sites, but latter attenuated by 25% and filtered with 100 cm s^{-1} maximum cap to produce velocity distribution somewhat similar to inshore fish farming sites in the Pacific Northwest.	
Mean current velocity, near surface and near bottom cells	HSWRI surface: 21.6 cm sec^{-1} HSWRI bottom: 8.3 cm sec^{-1} Comparison site S: 15.97 cm sec^{-1} Comparison site B: 6.2 cm sec^{-1}	98 d time series with observations every 15 minutes 12/14/07 to 03/20/08, surface currents capped at 100 cm s^{-1}
Current velocity 10th percentile value	HSWRI surface: 7.3 cm sec^{-1} HSWRI bottom: 3.1 cm sec^{-1} Comparison site S: 5.5 cm sec^{-1} Comparison site B: 2.3 cm sec^{-1}	ADCP current meter record Dec 14, 2007 to March 24, 2008.
Current velocity 90th percentile value	HSWRI surface: 36.9 cm sec^{-1} HSWRI bottom: 14.0 cm sec^{-1} Comparison site S: 27.7 cm sec^{-1} Comparison site B: 10.5 cm sec^{-1}	ADCP current meter record Dec 14, 2007 to March 24, 2008.
Mean flow direction	HSWRI surface: 175.2° M HSWRI bottom: 199.9 M Comparison site surface: 175.2 M. Comparison site bottom: 199.9 M.	Net flow to the south, when corrected from magnetic (M) to True (T) almost due south.

Parameter	Values	Source or Comment
Maximum current velocity recorded, by depth& location	HSWRI surface: 100 cm sec^{-1} HSWRI bottom: 28.8 cm sec^{-1} Comparison site surface: 30cm sec^{-1} Comparison site bottom: 21.6 cm sec^{-1}	HSWRI surface current data filtered at 100 cm s^{-1} No filter for comparison site
Degree of current direction variability	Moderate, indicated standard deviation of 79.2° and 92.0° for both HSWRI and comparison site	No difference among virtual site direction of flow as the same data were used.

Current velocity and depth are two of the most critical factors influencing waste distribution and assimilation into the food web. The ideal fish farm site is relatively deep and has moderately strong current velocity. Literature ranges are quite broad (e.g., 10 to 60 cm s^{-1} range considered ideal by Beveridge, 1987) but in the upper limits are less limiting to cage structures than they are to the size of fish to be stocked. Smaller fish may be unable to deal with sustained velocities beyond 2 to 3 body lengths s^{-1} and fish farm net and anchor system maintenance is more difficult in strong current situations.

Stronger currents not only disperse waste feces or feed further to initial point of bottom contact, but will allow for resuspension and further transport. Cumulatively, these properties of a suitable net pen aquaculture site allow the waste materials to be aerobically assimilated by the surficial bottom sediments. Without such currents, the wastes would fall and be maintained in a smaller area and may exceed the carrying capacity of the sea floor organism to process them. This may result in a rise of the redox potential discontinuity layer (i.e., the RPD or "black layer") towards the surface of the bottom, and concomitant shift to anaerobic bacteria decomposition of the wastes. This process involves the use of sulfate rather than oxygen as a primary substrate for reduction and may result in hydrogen sulfide production which may be undesirable for marine life or the cultured fish above.

Optimum water currents are also desirable for maintenance of healthy levels of dissolved oxygen within the fish cages and removal of ammonia and urea. In tidal channels, currents often drop to nil during slack tide and it is at this point that fish may become stressed due to these factors. This may happen repeatedly and during naturally occurring low dissolved oxygen periods; such stress may contribute to less than optimum growth and survival. By contrast, open ocean areas that are subject to prevailing oceanic currents typically have much more sustained and continuous periods of current motion. In the present case, for example, near-surface current velocity dropped below 0.5 cm s^{-1} only 1.4% of the time during the 98 day current meter record. In areas with tidal energy as the principal component of water motion, this rate may be 10% or more of the time in distal areas of some marine water areas in North America where fish are reared in net pens[1].

[1] Notable exceptions include the entire Strait of Juan de Fuca between Washington State and British Columbia as well as parts or coastal northern Maine.

Figure 22 illustrates current direction frequency and Figure 23 shows current speed frequency for three depth ranges for the for the current meter record.

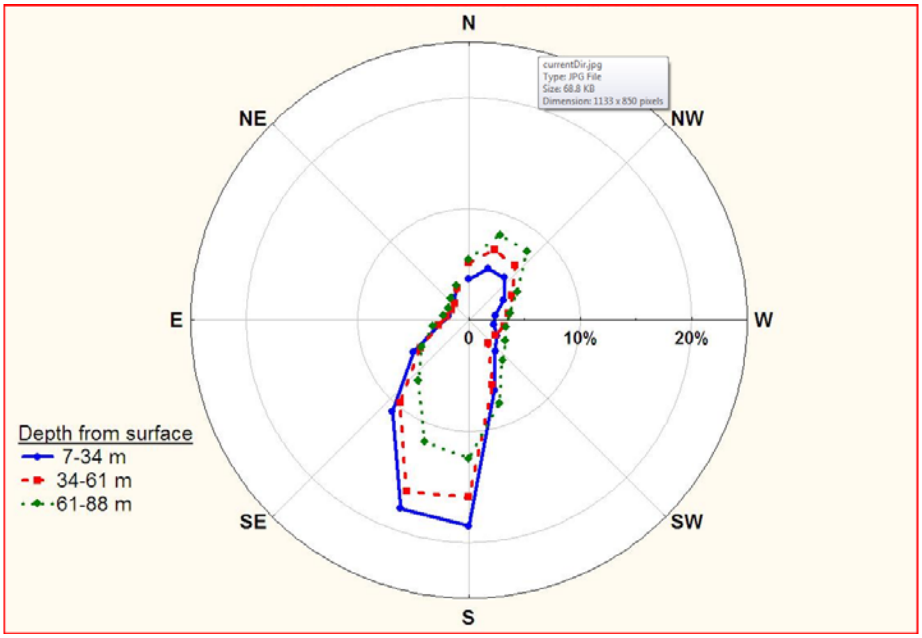


Figure 22. Current direction rose (in magnetic units) from M. Shane, December 14, 2007 to March 20, 2008 data grouped by three depth ranges

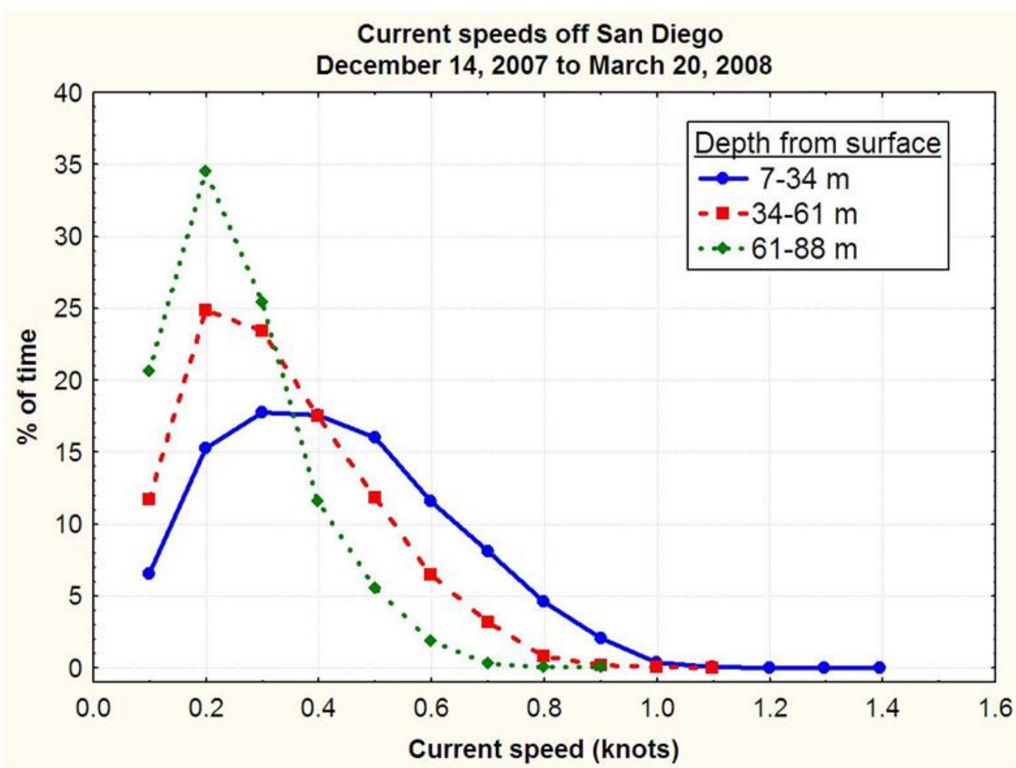


Figure 23. Current speed frequency diagram from M. Shane, December 14, 2007 to March 20, 2008 by three depth ranges.

Current direction was predominantly southward during the current meter record, with progressively less extent by depth. Current velocity frequency was strongest at the surface, as expected but remained surprisingly strong with only 10% of the observations less than 0.2 knots (10 cm s^{-1}). These conditions are desirable for sustainable, long term maintenance of sea bottom infauna, for example, maintenance of aerobic conditions of surficial sediments, resuspension and saltation of particulates to expedite transport, respiration and assimilation of waste carbon and solids.

Long-term current meter record

Bottom-mounted, Acoustic Doppler current profile (ADCP) data of about 4 months duration were collected for this analysis as described above. This duration is more than adequate for simulation of near shore or inshore net pen aquaculture where tidal currents repeat on a 28 day lunar cycle. However, offshore current in Southern California are more influenced by broad scale ocean currents, countercurrents, wind stress, internal waves and other forcing factors so a longer record is desirable to insure that the strength of currents are adequate for net pen aquaculture operation and organic waste assimilation. ADCP summary data that spanned a 22 month period[2] were obtained from Dr. Ed Parnell of the Scripps Institute of Oceanography (UC San Diego) that were collected near the site of the Point Loma Ocean Outfall (PLOO) from the City of San Diego's sewage treatment plant outfall. The outfall location is slightly deeper and 13 km south of the proposed HSWRI offshore aquaculture demonstration site and is the subject of high quality and extensive water and sediment quality monitoring throughout the immediate region including locations just south of the proposed HSWRI site (City of San Diego 2008).

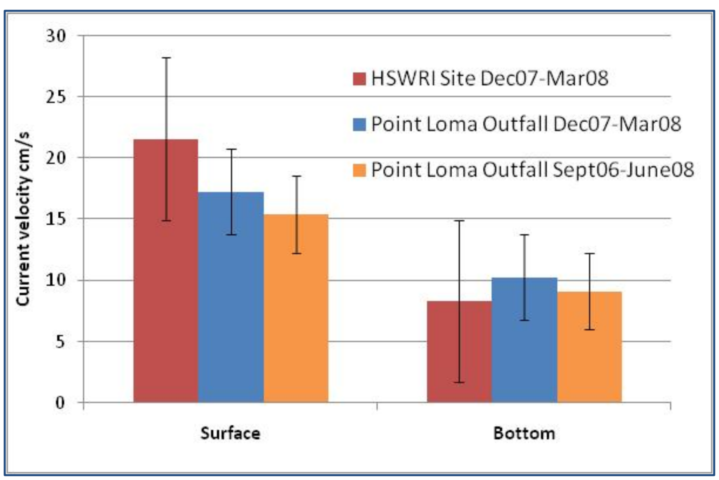


Figure 24. Mean and standard error of near-surface or near-bottom current velocity for the HSWRI and PLOO sites during the time periods indicated.

Figure 24 indicates the mean velocity for the December 2007 to March 2008 period for data collected at both sites simultaneously by PLOO and HWSRI researchers respectively. The proposed HSWRI site had slightly stronger mean near-surface current velocity but slightly lower

[2] Data period September 2006 to June 2008, with missing months of April 2007 (surface and bottom) and May 2007 (surface only).

near bottom current velocity (21.6 vs. 17.2 and 8.3 vs. 9.5 cm s^{-1} respectively). The same figure also includes the mean current velocity for the 22 month time span for the two depths at the PLOO site.

Figure 25 compares mean monthly current velocity at the two above mentioned locations during the concurrent data-collection period. Mean near-surface current velocity increased significantly for the PLOO site in this time span and was similar to the HSWRI site only in February. The HSWRI maintained stronger currents with no apparent trend for near surface waters but overall the near surface current velocity was slightly less in strength than at the PLOO site.

Near surface mean monthly currents were poorly correlated (r = 0.28) while near bottom current velocity were even less well correlated (r = 0.05). Near-surface and near-bottom current velocities were not positively correlated at the PLOO site at all (r = -0.01).

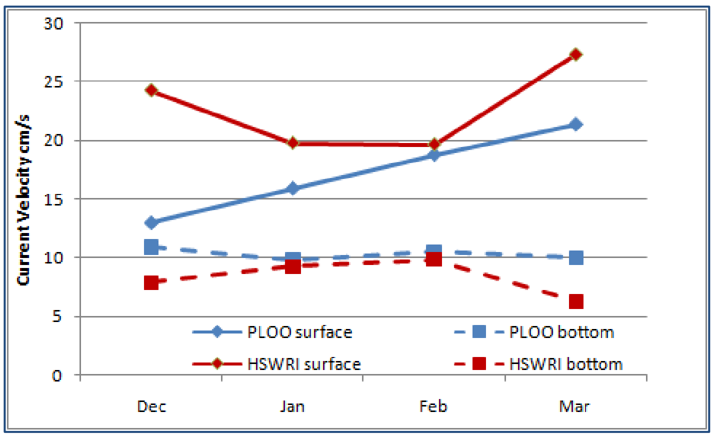


Figure 25. Mean monthly near surface or near-bottom current velocity for the HSWRI and PLOO sites during December 2007 through March 2008.

Collectively, these data indicate considerable variability both within sites (surface to bottom) and among sites (during the 4 month comparison period) that is to be expected with the preponderance of eddies and shifting forcing factors that occur in the Southern California Bight (Hickey 1992). The data, if representative of longer term patterns, suggest that the HSWRI site and nearby region is subjected to surface currents that are near ideal for marine fish net-pen aquaculture. Opinions vary on what the optimum mean velocity and range should be, but one authoritative source (Beveridge 1996) cites a suitable <u>extreme</u> range of 10 to 50 cm s^{-1}.

In our experience, successful near shore commercial net pens typically have mean velocity in the range of 15 to 25 cm s^{-1}, matching what was seen at both sites in this analysis. Sites with mean velocity greater than 25 cm s^{-1} may be useful, but the smallest fish may be unable to maintain swimming position in the strongest current velocity. A general rule of thumb for many species is that fish grow and convert feed best around 1.5 body-lengths per second. They can sustain position for shorter periods above 2.0 body-lengths per second, but growth may suffer and some species may fatigue. For the HSWRI site, the small striped bass are to be held in smaller mesh nursery nets within the larger nets for a few weeks after stocking while they rapidly grow. Smaller mesh size of such nets will shield them from the brunt of the ambient currents by a factor of up to 50% (about 15% reduction by the surrounding large pens and the remainder by the nursery net current deflection).

For near-bottom velocities (specifically 2 m above the bottom, the depth at which sediment-water interface resuspension calculations are typically estimated) it would be ideal to have frequent and persistent velocities above the resuspension threshold of approximately 6 cm s^{-1}, the coefficient used in this report for fish feces. Frequent and regular rates above the threshold will act to prevent consolidation of organic carbon from fish feces into the seabottom while aerating and dispersing them over a broader area for aerobic assimilation by benthic bacteria and food-web organisms. At the HSWRI site, velocities less than this rate occur less than 8% of the time which greatly reduces the chance of excessive deposition of organic waste matter. Additional current meter data collection is planned for the HWSRI site to further characterize the area.

Fish Culture Characteristics

Table 4 summarizes characteristic of the fish culture plan.

Table 4. Proposed site: Fish culture characteristics.

Characteristic or Parameter	**Actual or Modeled Value**
Fish stocking size	5 gram
Size at harvest	1.5 kg average
Maximum density of fish at harvest to maintain health, initial modeling density	15 kg m^{-3}, 10 kg m^{-3}
Feeding rate during modeling period	Varies with fish size from 7% to <2% d^{-1}, see text.
Initial fish loading of all simulations	10 kg m^{-3} x 24 cages x 9,000 m^3 each = 2,160 MT
Types of simulations for HSWRI site	1) Full current meter record of 98 days with ending biomass of 2,700 MT (10% less than full build out) 2) One year simulation with 10 kg m^{-3} fish loading, but benthic only effects
Types of simulations for comparison (shallow, salmon pen array) theoretical site	1) 50 day runs with differing consolidation rates from 0.1% to 5% d^{-1} and biomass varying from 2,160 MT to 2,410 MT
Feed moisture content	~ 8%
Feed C & N composition	Carbon 0.44, Nitrogen 0.07
Fecal settling rate	3.2 cm s^{-1} see text, highly conservative choice

7. Other Model Coefficients

The following coefficients were evaluated for this specific application and used in the model. Several have been previously evaluated for proper range through a sensitivity analysis (Rensel, Kiefer and O'Brien 2007).

Fish fecal Settling Rates

Fecal settling rates for salmonids dominate the literature but these are necessarily representative of other fishes including striped bass. Findlay and Watling (1994), Elberizon and Kelly (1998), Panchang et al. (1997), Chen et al. (1999) all examined settling rates of salmon feces, from small (25g) to relatively large (1kg) fish. Reid et al. (in press) recently reviewed the literature and found considerable variability because of differences in diet, water viscosity, fish size and methodologies. Rates cannot be estimated from physical science calculations but despite all this salmonid settling rates are fairly well characterized over a range of fish size. The mean settling rates varied from 2 to 6 cm s^{-1} and rate was related to fish size as expected. Cromey et al. (2002a) examined fecal pellets from even larger fish (*Salmo salar)* of 3.4 kg mean weight, and found settling rates averaging 3.2 cm s^{-1}. Determination of fecal setting rates is not easy, one of us has considerable experimental experience in this work and note that it is known that that fecal pellet sinking rates for marine species are often multi-modally distributed (i.e., there are differing size and density fractions that settle at different rates but the mean rates can still be determined).

Marine fish fecal settling rates are scarcer, but perhaps of higher quality. With the exception of Japanese *Seriola quinqueradiata* (Japanese yellowtail, Iikura 1974, 5 cm s^{-1} but likely large fish) marine species studied had diffuse, slowly sinking fecal matter. Magill et al. (2006) in Scotland and in the Mediterranean Sea area have done most of this marine fish fecal settling work, focusing on gilthead sea bream, *Sparus aurata*, and sea bass *Dicentrarchus labrax*, that are raised in pens in the Mediterranean Sea. They collected fecal matter from sediment traps suspended below net pens for 2.5 to 6.75 hours and transferred the contents to the laboratory for resuspension in 2 m high Plexiglas cylinders. Using advanced but laborious video tracking methods applied to over 1000 particles for each species, they found mean settling rates of 0.70 and 0.48 cm s^{-1} for sea bass and sea bream fecal matter respectively. These authors carefully documented that the settling rates were not unimodal, as discussed above.

Settling rates for striped bass are not known or estimated. But anecdotal evidence from HSWRI hatchery staff indicates fecal matter is more similar to other marine fish, rather than salmonids. For model calibration we maintained use of the salmonid rates AND as a highly conservative measure we also used that rate (3.2 cm s^{-1}) for modeling of the proposed project site. Using a slower rate would decrease deposition nearer the proposed pens and increase assimilation of the carbon over a much broader area, resulting even less effect than was observed.

Waste fish feed settling rates

In comparison to fish feces, waste feed particles are easily studied and quantified within columns or containers. A range of values have been obtained but we chose to use 9.5 cm s^{-1} for our evaluation with larger fish that will require a larger and therefore slightly faster sinking pellet.

Waste fish feed loss rates

It should be noted that waste fish feed loss rates that were once relatively high (5 to 20%) are now thought by most authorities as averaging about 3%. Other modelers have recently used this rate and we believe it is appropriate for the relatively clear waters of offshore Southern California where the fish can see the feed easily. EPA requires some kind of feed loss prevention feedback mechanism for all U.S. marine fish farms, so 3% loss can easily be achieved.

Waste feed loss rates have fallen dramatically in the past decade for several reasons. First, feed is the single largest cost of marine fish farming and no fish farmer could stay in business long if loss rates were consistently high. Waste feed is much richer in carbon and nitrogen than waste feces and it sinks much faster, therefore the adverse effects of oxygen demand on and in the seabottom will be most pronounced from waste feed compared to fish feces (dry wt. basis). Waste feed can be eaten by wild fish and invertebrates and this has been demonstrated as a significant mitigating factor in semitropical and tropical environments in particular. Use of chemical therapeutants or antibiotics in the feed is rare with modern fish mariculture due to use of effective vaccines and maintenance of proper BMPs.

Resuspension threshold

In recent years several studies have indicated that resuspension and transport of fish farm wastes are among the key factors to understand in modeling the effects of fish farms on sediments (Panchang et al. 1997, Cromey et al. 2002a, 2002b, Riedel and Bridger 2003).

At less than a given, species-specific current velocity, fish fecal and food wastes will settle to the bottom and remain in the same location, which is termed a "depositional " condition.

At higher rates of flow, wastes are resuspended and hop, skip and move across the bottom in a process termed "saltation" until current velocity decreases again. This often occurs in "erosional" conditions and of course there is a continuum between the two extremes that we term "transitional" conditions. Most modern fish farms are located in these transitional conditions and as long as the sediments do not remain on the bottom for extended periods (i.e., days), the recently deposited sediments are subject to being resuspended and transported in the process of saltation. In this process, particles are eroded into smaller sized particles and more easily moved and are of course available to the food web for assimilation. Some fraction of the deposited materials will remain behind under all but the most erosive conditions, a process known as "consolidation" that is discussed below.

AquaModel allows for separate particle tracking of feces and feed fate, unlike any other available models that only track all solids together. The best estimate of threshold for resuspension rates for salmonid wastes (feed and feces combined) is 9.5 cm s^{-1} as measured or modeled 2 m above the bottom (Cromey et al. 2002a, 2002b, Cromey and Black 2005). Yet we know that striped bass fecal matter is much less dense than salmonid feces, so that rate is not appropriate for striped bass. We selected a threshold of erosion rates of 6.0 cm s^{-1} for striped bass feces and 9.5 cm s^{-1} for waste feed, although the latter will be resuspended quicker after soaking and being abraded by bottom currents. Previously we used the same calibration for fish to be grown in Puerto Rico (cobia, see Rensel, Kiefer and O'Brien 2007). In that prior study sensitivity analysis showed that varying this factor had a major effect on the deposition of carbon near the cages. But as discussed later, even at the combined salmonid fecal and lost feed rate of 9.5 cm s^{-1} there would not be detectable amounts of carbon deposited on the bottom anywhere. Once the threshold is exceeded, we quantify the rate of erosion for feces of 60.4 g C m^2 d^{-1} and 40.0 g C m^2 d^{-1} but this rate is indexed to flow above the threshold rate similar to what other modelers have done.

Deposition threshold

A contrasting calibration parameter to the erosion threshold is the deposition threshold, the near bottom water velocity at which fish fecal and waste food particles settle out. We selected 3.0 cm s^{-1} for fish feces and 4.5 cm s^{-1} for waste feed. The literature combined values for salmonids are not well defined, but Cromey et al. (2002a, 2002b) used 4.5 cm s^{-1} for the combined value and since the fecal matter of striped bass is likely less dense than salmon fecal matter, we scaled its threshold rate down commensurately. Both erosion and deposition thresholds are indexed to 2 m above the bottom, which allows the use of bottom mount ADCP current meter data.

Consolidation rate

For long-term modeling of the effects of fish farming on the sea bottom chemistry and infauna, an important consideration is the degree of consolidation of waste particle. As described by Cromey et al. (2002a, 2002b) this is the stickiness of materials that may remain consolidated upon the bottom despite elevated rates of flow over the bottom. There is evidence that the rate increases with elapsed time of slow velocities, but it has not specifically been studied for fish wastes. Since this factor is poorly known or described we opted to consider this the primary variable to vary in our calibration runs. The values selected ranged two orders of magnitude from 0.1% d^{-1} to 10% d^{-1} and we found that values near the lowest end of the range produces results that were most realistic. We are comfortable with this approach as we essentially have only one unknown in this analysis and the factor has both time of flow below the deposition threshold and near bottom current velocity as primary components so we need not change the calibration for differing conditions. We found that consolidation rates are important for fish farms in more quiescent waters, but for the HSWRI offshore aquaculture demonstration site the effects of varying consolidation are muted. This is because there simply are not prolonged periods of minimal flows. Any drop in near bottom current velocity is short-lived and does not allow an extensive accumulation of organic carbon containing wastes.

Carbon oxidation rates

Another important factor in modeling fish farm effects is the rate at which carbon deposited on, or moving along the bottom is oxidized by bacteria or assimilated by the food web. The rate of organic matter degradation by microorganisms is often estimated using a first order kinetics or a Michaelis-Menton kinetics approach with similar result in cases where substrate, instead of microbial biomass, is limiting. When a fish farm begins operating at a new site, the biomass of microorganisms on and in the sediments beneath and immediately adjacent to it will increase in abundance commensurate with the increase in organic matter provided by the farm. Within reasonable bounds, after the farm operates for some period of time the microbial biomass (and macrofauna too) approximate a steady state to process the wastes. Beyond reasonable bounds, if too much carbon is deposited, sediment bacterial communities shift to anaerobic (sulfide reducing) which tends to extirpate many sensitive invertebrate macroinvertebrates, infauna or epifauna. Generally, up to 1 to 1.5 percent total organic carbon added to the top 2 cm will not result in the shift to anaerobic conditions, depending on sediment grain size and water temperature. Here we deal with the carbon to be added by the fish culture operation, keeping in mind background levels of TOC that are relatively low, approximately 0.6 percent. Total carbon levels are much higher but most of this carbon is locked up as biogenic, refractive carbonates from shell.

Tlusty et al. (2000) demonstrated that fish fecal matter had a very high solubility potential, loosing approximately 50% of its organic matter in 12 day exposures to water flow. Fish feces are thus “non-refractile” forms of carbon, unlike carbon more tightly locked up in refractile forms such as tree trunks or bark or carbonate carbon such as shell.

Prior modelers of fish farm carbon oxidation rates (Fox 1991, Pachang et al. 1993) in Washington State and Maine have often used the value of 1 percent per day, which stems from an EPA (1982) document dealing with sewage sludge oxidation. The reaction is temperature dependent and likely somewhat similar in the deep, relatively cool bottom waters at the proposed site in Southern California.

Hendrichs and Doyle (1986) found carbon in phytoplankton cells (*Cyclotella sp.* diatom) decomposed at rates > 0.14 d^{-1} (1.4% per day), but that was for a mean temperature of 7°C. This low compared to summer bottom water temperatures but just about similar to winter bottom water temperatures at the subject site.

Fujii et al. 2003 found carbon decomposition rates for *Skeletonema* of 1.4% day^{-1} and semi-refractory carbon in the form of POC at 0.08% d^{-1}, both at 20°C. From the literature it is clear that most fish farm waste carbon is highly labile (i.e., not refractory) so the former rate would apply for the present analysis.

Given the above, we conservatively choose to use 1.0% d^{-1} carbon oxidation rate in sediments and during the interval that particles are in the water column. A higher rate may have been justified, but without more experimental and observational data regarding fish farm wastes, we selected a lower rate. Water temperatures of bottom waters at the proposed site are approximately equal to or less than in most of the studies above which is one factor in our choice.

8. Simulation of the Comparison Fish Farm

The objective of our validation study was to provide us with a frame of reference to compare the environmental impact of the HSWRI offshore demonstration fish farm with a similar operation placed nearshore. As described previously in this report, the two scenarios differed only in depth, distance among pens and current velocity. The small differences in conditions between the two virtual fish farm sites allowed us to compare model predictions with the large database on waste concentration and distribution that has been acquired in Puget Sound and similar operations in Maine. Our comparison farm simulations, which run from 51 days to 12 months, provided robust and reliable predictions of the patterns that have been observed in the region.

The figures below are examples of single time steps during a 12-month simulation. They illustrate the dynamic conditions that prevail in and around the comparison farm. The types of information available at any time during a simulation are shown in Figure 26, which is a screen print of the results of a time step after a period of deposition of waste early in a simulation. The figure shows a base map of the organic carbon in the sediments in units of gram of carbon waste per gram dry weight of sediment. As indexed by the color legend in the upper right corner, background fraction of total organic carbon (TOC) in ambient sediments at the HSWRI site were used and are 0.006 (0.6% by dry weight) as designated as white in color. This is typical of conditions at Puget Sound net pens that typically have 15 to 20% silt and clay, although some have up to 70% fines. The TOC footprint of waste carbon from the 24 cages of the farm (shown as dark green circular dots) is shown in varying shades of color indicating degree of TOC effect as follows:

- Light blue is an increase to a fraction of about 0.001 (0.1%) which covers a relatively large area (~280 x 400m), but would not be measurable given sampling and analysis error and natural variation. This area would be considered the “halo” area where enrichment of the infauna will undoubtedly occur and likely will be measurable in terms of increased diversity and biomass as described in the classic paper of Pearson and Rosenberg (1978).
- Light green color indicates a region where TOC fraction is about 0.02 (2%) and is a region where measurable chemical and biological changes would occur. In regulatory language, this is the “sediment impact zone” or SIZ. It is shifted slightly south in accordance with the persistent north to south current direction in the current meter record
- The narrow yellow regions are peak TOC values of about 0.03 (3%) where we would expect reduced diversity of infauna and occurrence of opportunistic species such as *Capitella capitata* that are able to tolerate the level of organic enrichment occurring here.

- The light red areas indicate a TOC fraction approaching about 0.04 (4%) which would have conditions similar to the yellow region but slightly more intense.

In the lower right corner is the simulation control panel which provides the means, sets the start and end times of the simulation as well as the time step at which the results of calculations are rendered on the computer screen.

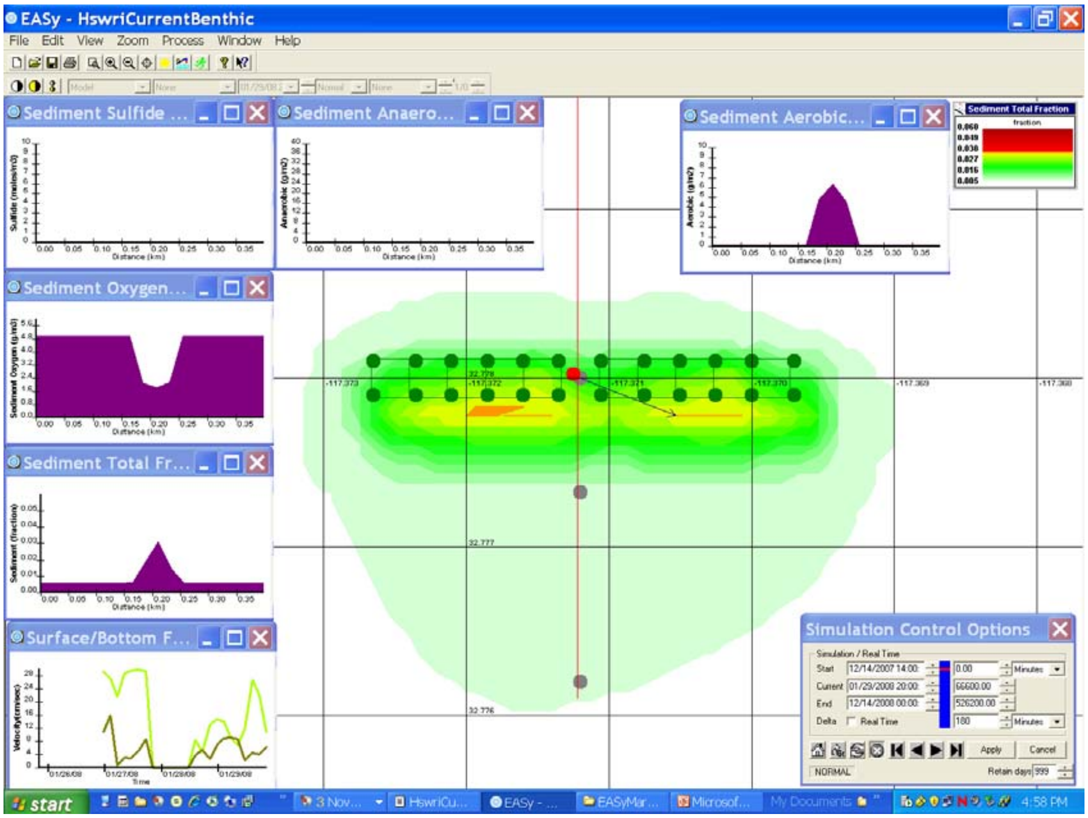


Figure 26. Example of graphical output from the simulation model at 46 days run time showing selected benthic effects components of the output only.

Next we describe the X-Y plots clustered around main image of Figure 26. The lower left corner has a graph showing the speed of currents at the surface and in the suspended layer above the bottom for the previous 3.5 days. The remaining graphs provide values on several key variables along the red transect line that runs through the center of the base map as follows. (These are just a few of the ~50 such graphs available to examine vertical profiles or cross sectional transects). Moving from bottom to top and then from left to right, these are the:

- Total organic carbon fraction in sediments along the transect reached a maximum value of 0.03 (3%) immediately south of the cages at this point in the simulation,
- Sediment oxygen concentration, which reaches a minimum value of 1.8 g O_2 m^{-3} (same units as mg/L) and is a mirror image of the distribution of organic carbon,

- Hydrogen sulfide concentration in the sediment layer, which is in moles H_2S m^{-3} and negligible,
- Biomass of anaerobic organisms in the sediment layer, which is in g C m^{-2} and negligible ,
- Biomass of aerobic organisms in the sediment layer, which peaks at 6 g C m^{-2} and is a mirror image of the distribution of organic carbon.

Finally, the base map (main image) shows a vector that indicates the velocity of the current in the suspended layer, three gray dots that are sites we have selected to store the results of computations at each time step for the entire simulation. The red dot is a site we have selected to obtain a vertical profile of parameter values in the water column. One can also double click on any cage to obtain information of stock density, fish size, feed rates, growth rates, and rates of waste production.

Surface and bottom velocities over the past few days of the run and at the current time are shown in the lower left corner of Figure 26.

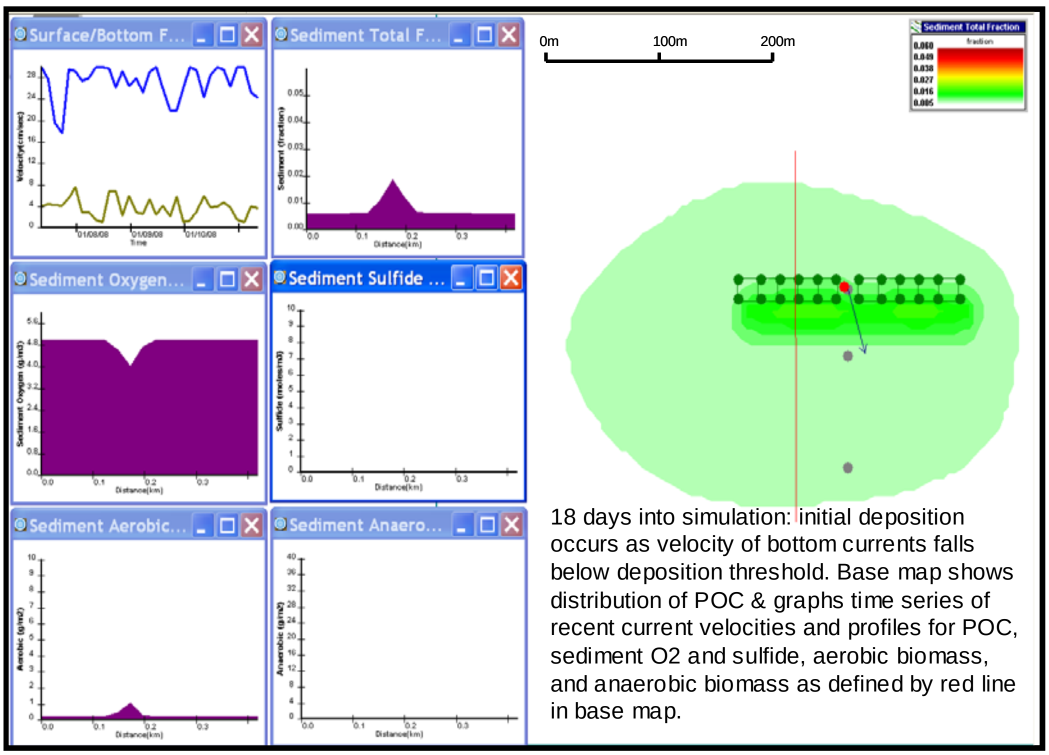


Figure 27. Early in a simulation of the comparison farm (18 days) with plots (left) and main image of fractional TOC (right).

Figure 27 is a snapshot of conditions 18 days into the simulation of the comparison fish farm. This is an early deposition event during which the current velocity within the suspension layer has fallen below the threshold of deposition (3 cms^{-1}) for sufficient time that significant amounts of particulate waste have been deposited(see bottom velocity record of plot in upper left corner.) Immediately to the south of the farm TOC has increase from an ambient level of 0.006

to 0.02 g carbon per g dry wt. (0.6% to 2%) of sediment. This is a rapid increase expected from a fully stocked, large fish farm. There is also a “light dusting” of 0.008 carbon fraction (0.8%) over a much broader area. The red transect line indicates that this deposition event was of sufficient duration and intensity that the aerobic community within the deposition footprint increased from an ambient value of 0.2 to 1.0 g carbon m^{-2} (small rise in the bottom left graph), and the oxygen concentration in the sediment decreased from an ambient value of 4.9 g $O_2 m^{-3}$ to 4.0 g O_2 m^{-3} (middle left plot). Since the aerobic biomass did not increase enough to draw the concentration of oxygen in the sediment below 3.0, the anaerobes remained dormant in the modeled surficial sediment layer (lower right plot) and consequentially no hydrogen sulfide was produced (middle right plot). Shortly after this event currents in the suspension layer increased above threshold levels and the TOC footprint was swept away. Had the event been more long-lived, consolidation of the particulate wastes would have occurred, cementing a small fraction to the bottom where it would be subject only to bacterial respiration, not resuspension.

Figure 28 is a snapshot of conditions at one point on day 132 of the simulation after fairly prolonged period of deposition. The biomass of aerobes has grown sufficiently to draw down oxygen to a level that allowed anaerobic growth and for the anaerobes to produce significant concentrations of sulfides in the sediment layer.

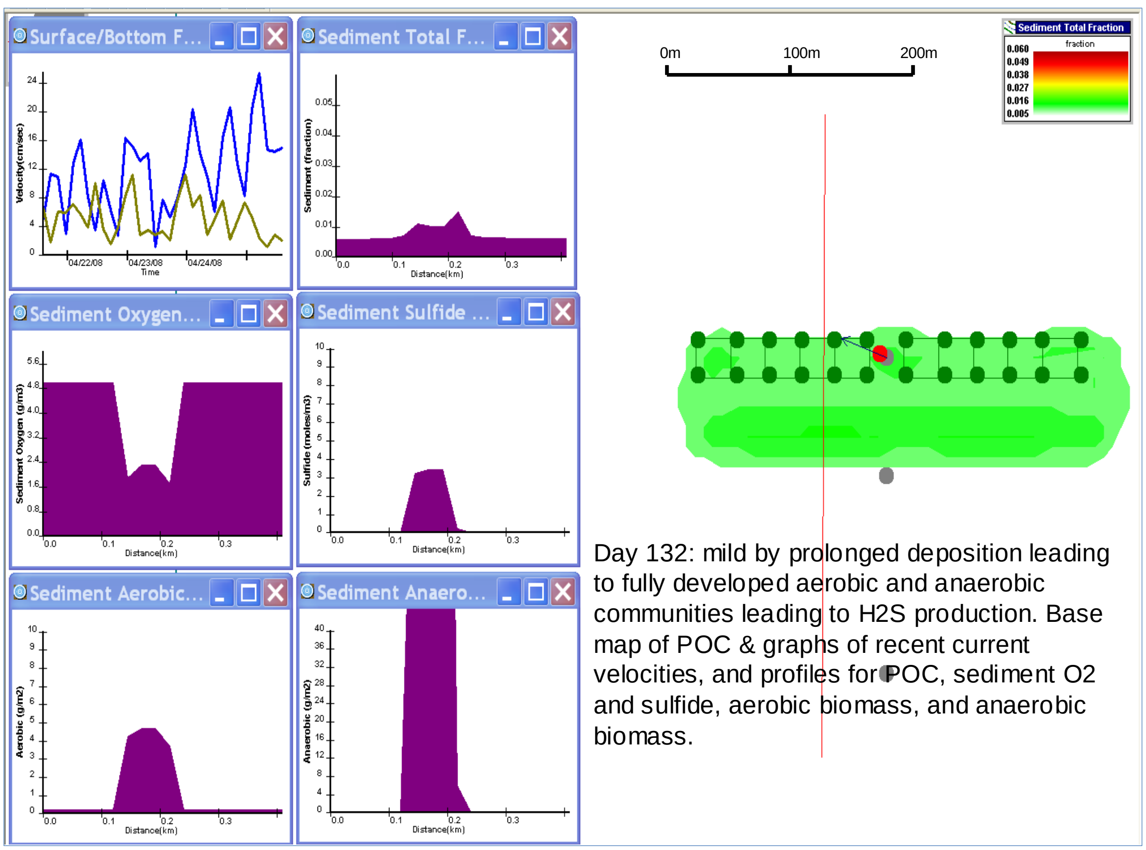


Figure 28. Day 132 in a simulation of the comparison farm with plots (left) and main image of fractional TOC (right).

Compared to the snapshot on day 18, the footprint of higher concentrations of TOC has increased in size, although the peak concentration is a lower value of 0.017 (1.7%). The major axis of this footprint, which is displaced to the south of the cages because of the prevailing southerly direction of the currents, is about 120 meters in width and 220 meters in length . Within the footprint the aerobes now have reached a biomass of 5 g carbon m^{-2} (lower left plot) and they have drawn down the concentration of interstitial dissolved oxygen to a minimum of just below 2 g O_2 m^{-3} (middle left plot). Such oxygen depletion and the availability of relatively high concentrations of TOC, has provided the anaerobes with an opportunity to grow, and they have responded by reaching a peak biomass of over 50 g carbon m^{-2} (lower right plot). The respiration of these anaerobes has enriched the sediments with sulfide, which reached a peak concentration of 4 moles H_2S m^{-3}. Such a value of sulfide concentration is frequently found under salmon farms located in relatively quiescent current flow regimes (mostly depositional environment) during summer periods of peak production (Brooks, 2001; Chamberlin and Stucchi, 2007).

Figure 29, which is a snap shot for day 137, shows that the footprints of farm waste as expressed by TOC, hydrogen sulfide, aerobic biomass, and anaerobic organisms that are very similar. However, there are small differences including peak biomass of the aerobes being closer to the net pens than the anaerobes and that peak concentration of hydrogen sulfide is displaced from the peak concentration of TOC. The comparison illustrates lack of symmetry that results from differences of time scale of responses for each component over days to several weeks.

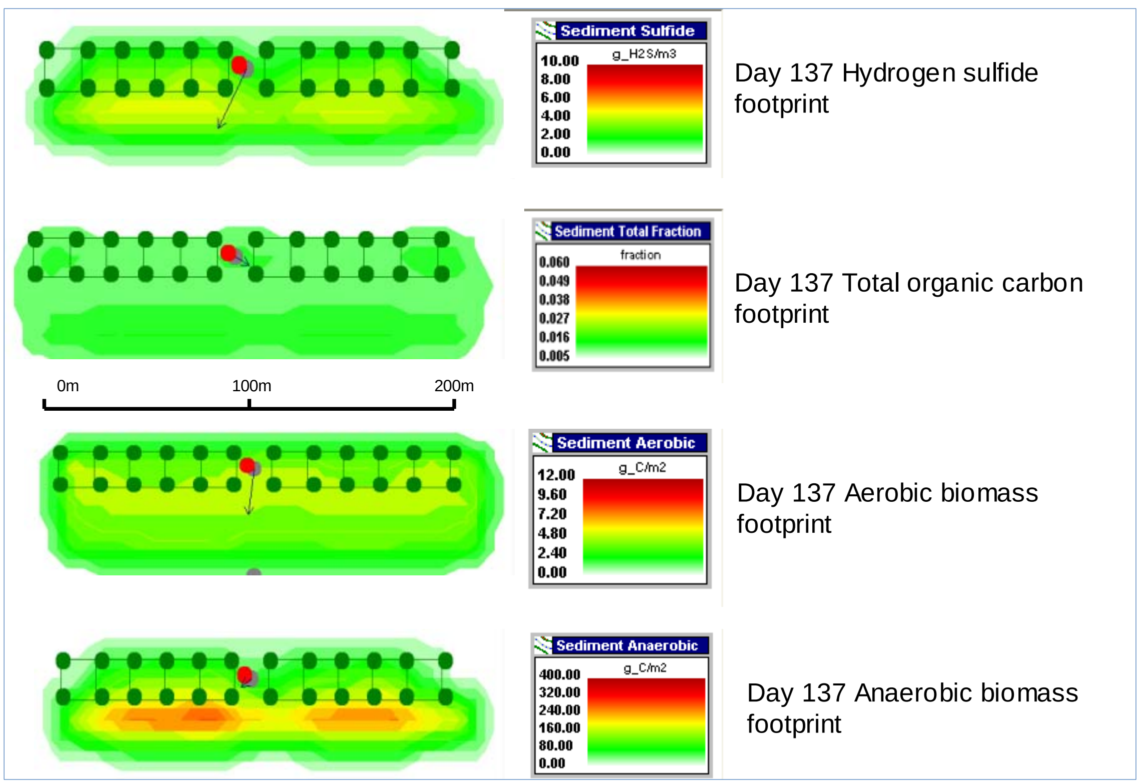


Figure 29. Day 137 in a simulation of the comparison farm several main image of different parameters (left) and accompanying scaled legends (right).

Finally, Figure 30, which is a snapshot of day 161 in simulation, shows the decay of a deposition event and illustrates the harmonics of the benthic system. After a sustained period of deposition and growth of both aerobic and anaerobic organisms, increased bottom currents have reduced rates of deposition and the benthic community that has built up is starving for additional sustenance. The mass of TOC within the footprint is now slightly below ambient levels (upper right graph); the aerobic biomass, which is still at levels much higher than ambient (lower left graph), are dying for lack of substrate and consequentially the concentration of oxygen in the sediment is at ambient levels (middle left graph). The biomass of anaerobes, which respond more slowly to conditions than the aerobes, is high (lower right graph) but they are also dying because of the increased oxygen concentrations and lack of organic substrates. Consequentially, sulfide concentrations are negligible (middle right graph).

The sequence of figures in this section illustrates the dynamic and erratic nature of waste deposition in waters of varying current velocities. If the mean current velocities are close to threshold levels of deposition and erosion, small changes in current cause rapid, frequent, and dramatic changes in local rates of waste deposition. Deposition and erosion of wastes near a fish farm change rapidly with relatively small changes in velocity.

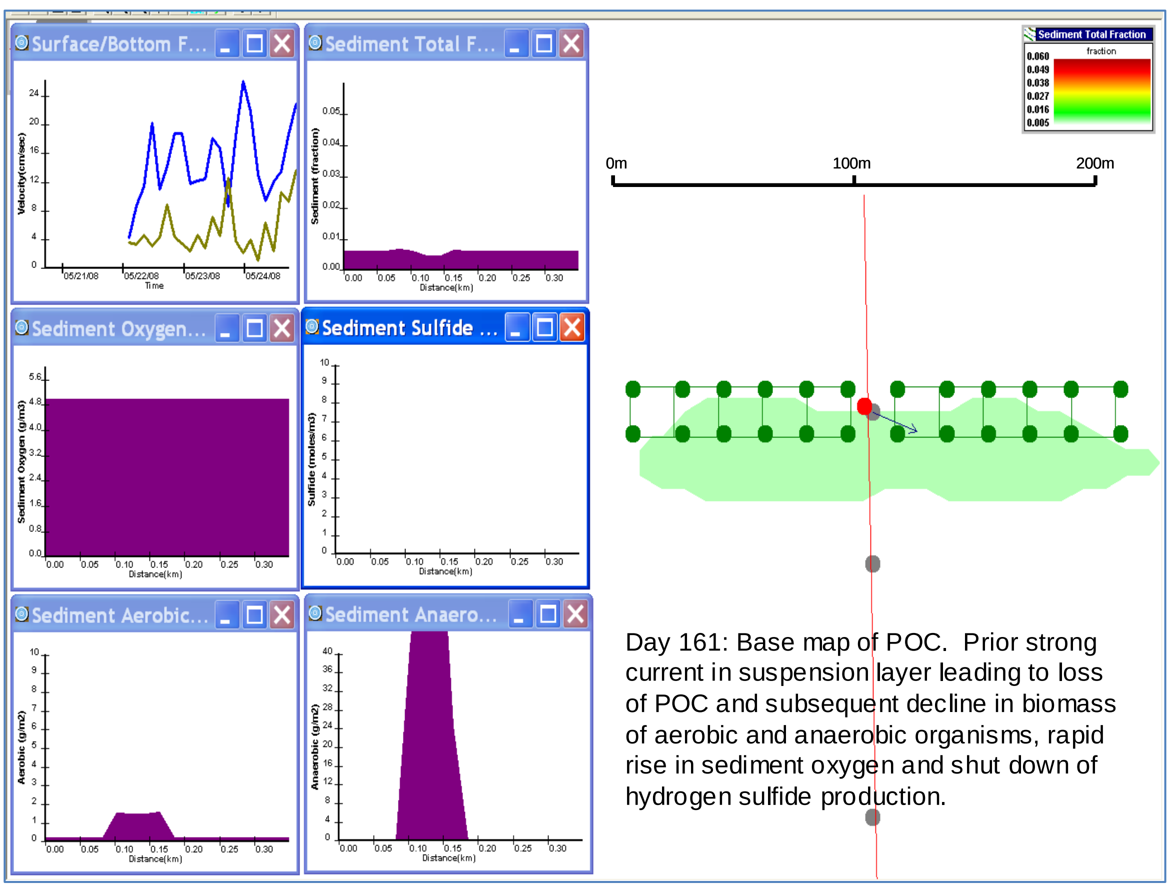


Figure 30. Day 161 in a simulation of the comparison farm with plots (left) and main image of fractional TOC (right).

We conclude this sequence by saying that the simulations from the comparison fish farm indicate that if the HSWRI demonstration farm where operated under conditions similar to those of the salmon farms in Puget Sound, that the environmental impact would be similar and acceptable by the standards of Washington State. The rules include the allowance of footprint shift but as discussed above, allow for perturbations within a sediment impact zone. Outside the impact zone, statistical analysis of replicate TOC samples must show no significant difference compared to reference (control) or pre-farm conditions.

During deposition episodes when bottom currents are slow and surface currents are slow to moderate, farm waste will accumulate after several days to weeks stimulating the growth of benthic organisms and there-by reduce the concentration of oxygen. If deposition continued for a long period, the benthic community, consisting of both aerobes and anaerobes, would grow in biomass to quasi-steady state level in which the rate of remineralization of waste is on the average equal the rate of waste deposition. Our records of current velocity indicate that such a steady state is unlikely because of the continuous large variability in bottom currents. Relatively short deposition events that occur at velocities of less than 3 cm s^{-1} (for fish feces) or 4.5 cm s^{-1} (for waste feed) are followed by either of two events. Erosion events occur when bottom currents exceed the threshold of 6.0 cm s^{-1} (for waste feed) or 9.5 cm s^{-1} (for waste feed) and deposited waste is resuspended and transported, often further from the fish farm site. We emphasize that bacterial as well as vertebrate and invertebrate consumption and respiration of organic carbon containing waste matter is occurring continuously and resuspension events serve also to provide oxygen to maintain the process as aerobically based.

Dispersion events occur when the velocity of bottom currents are between the thresholds of deposition and erosion. Under such conditions, deposition near the farm either stops or is greatly reduced and wastes from the fish farm are transported and dispersed over a much wider area and deposited at reduced rates. Thus, in the case of the comparison fish farm the accumulation of excessive waste products are prevented by two mechanisms that tend to work in concert despite quite different harmonics. The first mechanism is simply the “periodic sweeping of the floor” by variability in the velocity of the bottom currents, which is characteristic of the site. The second mechanism is the relatively rapid growth and subsequent increase in remineralization by aerobic species in response to substrate enrichment. This latter mechanism requires sufficient concentration of oxygen in the suspension layer at the sediment interface. As we will see in the next section, simulation of the HSWRI demonstration fish farm indicates that these two mechanisms play a secondary role in determining the fate of farm waste. In that case, dispersion by strong currents over a deep water column plays the dominant role.

9. Benthic Simulation of the HSWRI Demonstration Fish Farm

As previously explained, simulation of the HSWRI demonstration fish farm is identical to that of the comparison farm with three exceptions. The current velocities throughout the water column are 25% higher thus matching the Doppler current meter record that was recorded in the winter of 2007-2008 at the proposed site. The depth of the water column was increased from 25 to 91 meters in order to match the proposed offshore site. And the spacing of the cages was increased by greater than three times. These changes profoundly change the fate of particulate organic wastes produced by the farm as well as the effects on water column parameters such as dissolved oxygen and nitrogen concentrations, discussed later in this report.

Figures 31-34 are a sequence of snapshots taken at different times on day 17 of the simulation. <u>It is important to note in comparing these figures to the comparison farm figures that the scale of effects, as shown in the range of the legends (upper right color scale) was greatly reduced in order to show any type of visual effect. Had we used the same scales as previously used for the comparison fish farm, no effects would have been seen.</u>

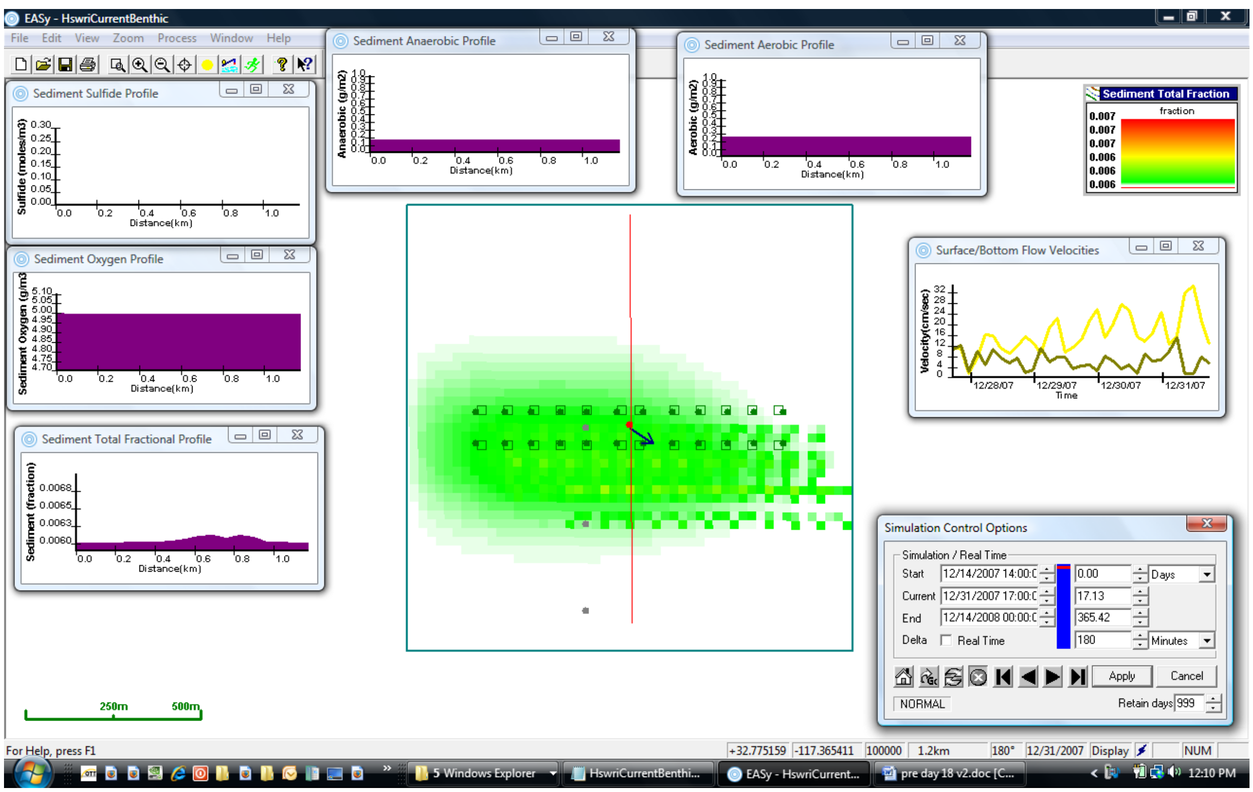


Figure 31. HSWRI Demonstration Fish Farm simulation at day 17.13.

In Figure 31, the base map shows the spatial distribution of TOC in the vicinity of the farms. This deposition event was initiated by a drop in bottom current velocity within the suspension layer to a rate below the threshold of deposition for waste feed for certain and at times for waste feces. As indicated in the plot of current velocity (mid right plot) the bottom current decreased to a relatively slow range periodically for several days prior to the snapshot. This event is best considered a dusting of the sediments around the farm since the amount of organic material deposited is extremely small; so small in fact that we were forced to increase the sensitivity of the legend color palette 30-fold in order to obtain sufficient contrast to visualize this weak footprint. As indicated by the color legend (upper right), the ambient concentration of TOC was set at 0.006 g carbon per g sediment (0.6% by dry weight), which is the same as that of the comparison farm simulation. Yet the peak concentration of TOC within the footprint is only about 0.0063 g carbon per g sediment dry wt. (= 0.63%, lower left plot). This difference is probably undetectable by the most accurate sampling and analytical techniques.

This minor sedimentation event did not perturb the virtual benthic community in this case. The concentration of oxygen in the sediments remained high, 5.0 g O_2 m^{-3}, similar to O_2 concentration in the suspension layer (water column above immediately above the bottom) and the hydrogen sulfide concentration of hydrogen is negligible (upper left plot). The biomass of aerobic organisms (mid right plot) is low, 0.25 g carbon m^{-2}, and anaerobic (mid left plot) is low and decreasing with time because of oxygen inhibition.

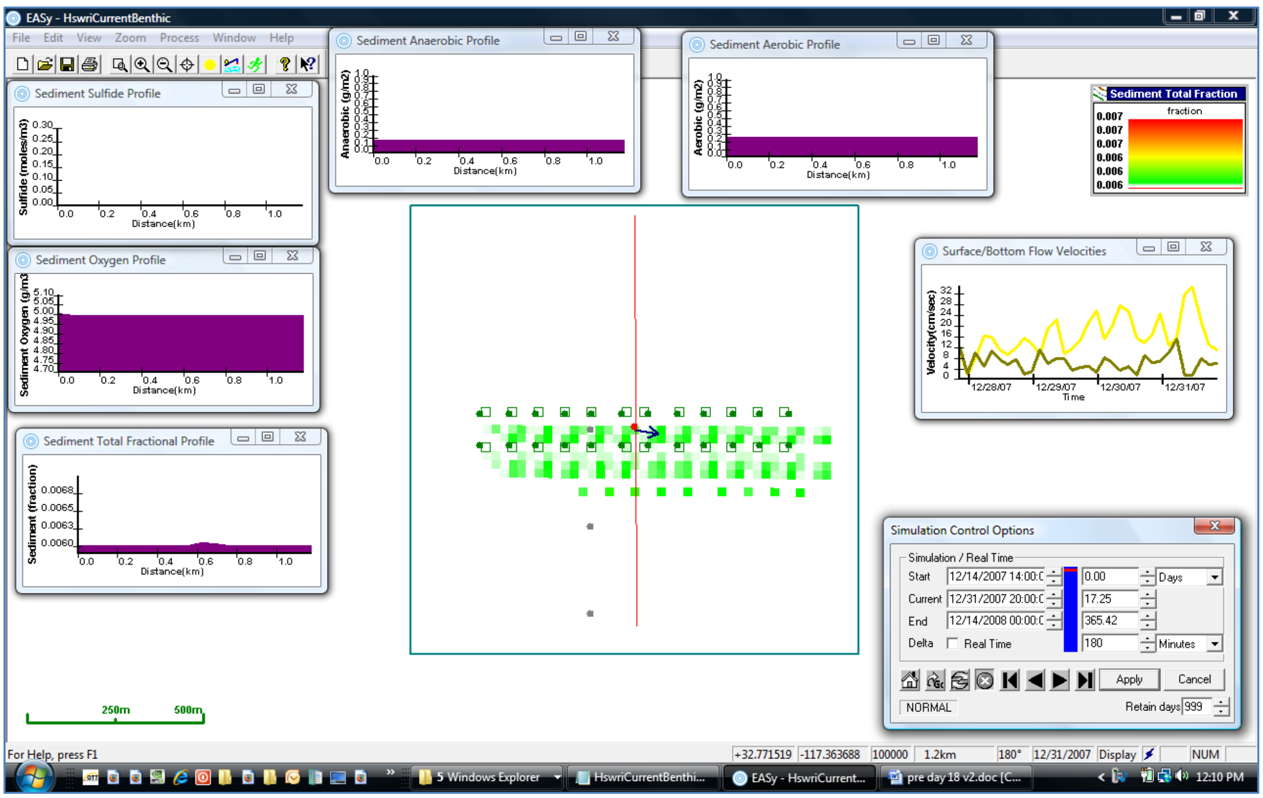


Figure 32. HSWRI Demonstration Fish Farm simulation at day 17.25 (3 hours after previous figure).

Figures 32 and 33, which are snapshots of conditions taken 3 and 9 hours, respectively, after those shown in figure 29, illustrate the transient nature of the “dusting” of the bottom with TOC. We see in Figure 32 that 3 hours after current velocity has exceeded the threshold value of erosion and most of the recently-deposited fish farm TOC has been resuspended, and the footprint is now small and patchy. In Figure 33 after 9 hours, no remnant of the deposition event remains. This sequence of a “light dusting” of the sediments by waste followed shortly thereafter by “sweeping” characterizes the processes of waste dispersion as describe by our simulation of the HSWRI demonstration farm. Under such circumstances perturbations to the benthos are minor and short-lived. One might expect at most that the only change in the sediments caused by the farm would be a small increase in the biomass of the aerobic organisms and possibly some minor increases of infauna diversity and biomass associated with the “halo effect” first described by Pearson and Rosenberg (1978).

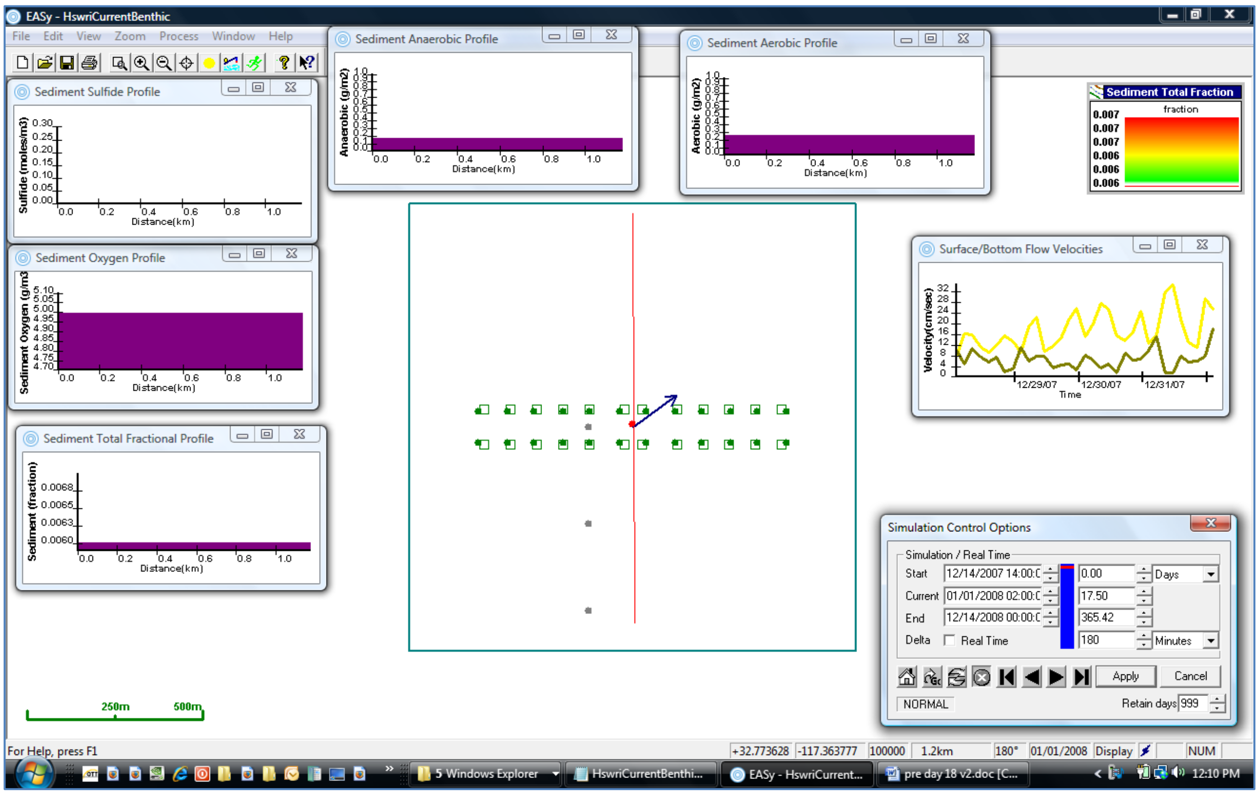


Figure 33. HSWRI Demonstration Fish Farm simulation at day 17.5 (9 hours after previous figure).

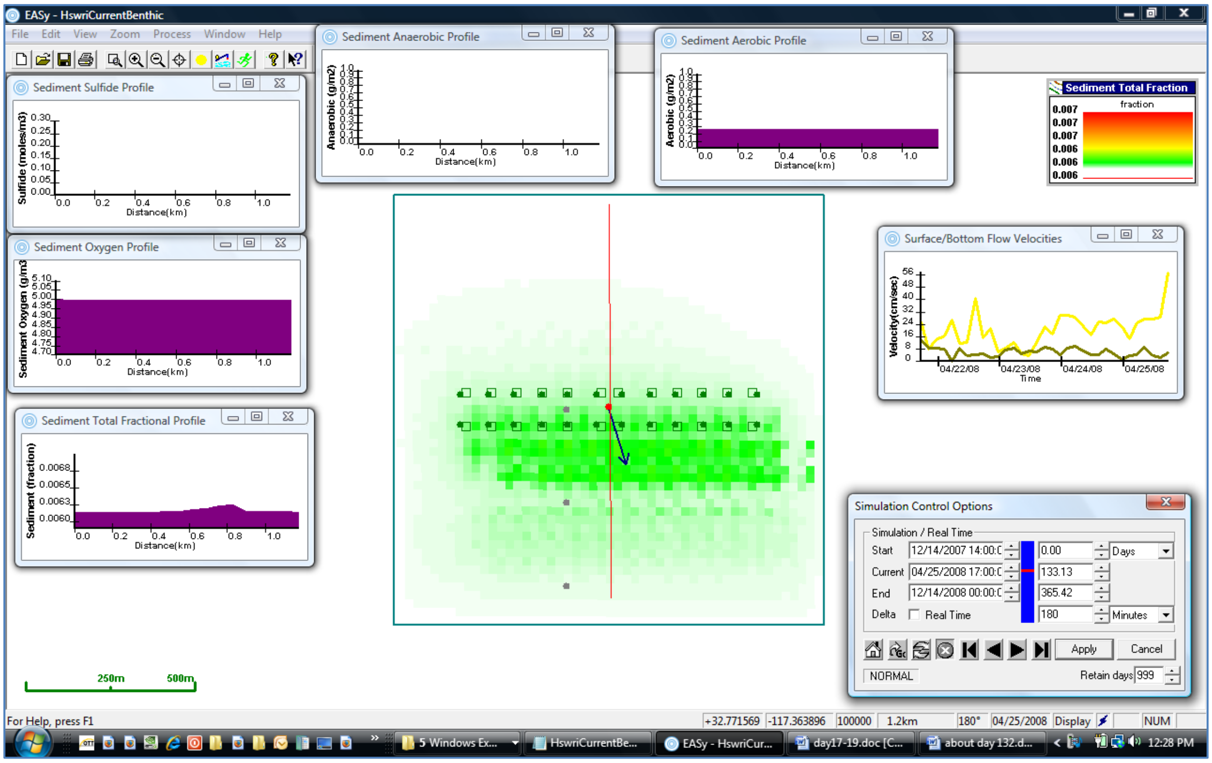


Figure 34. HSWRI Demonstration Fish Farm simulation at day 137.

Figure 34 is a snapshot of a deposition event on day 137 of the simulation. As indicated by the plot of current velocity, the bottom current (green line), oscillated between deposition, resuspension, and dispersion for at least 3 days prior to the snapshot. The footprint of such motion is complex in spatial structure and relatively large. It is however, probably undetectable by even the most careful sampling methods. The peak TOC within the footprint, about 0.0062 g carbon/g , is slightly more than 1% higher than ambient. One should note that the oxygen concentration and the biomass of aerobes are the same as they were on day 18. The anaerobes were not a component of the surficial benthic community in this snapshot because of the high concentration of oxygen.

Figure 35 is a snapshot of a deposition event on day 161 of the simulation. In this case, slow prior currents deposited fish farm waste north of the cages.

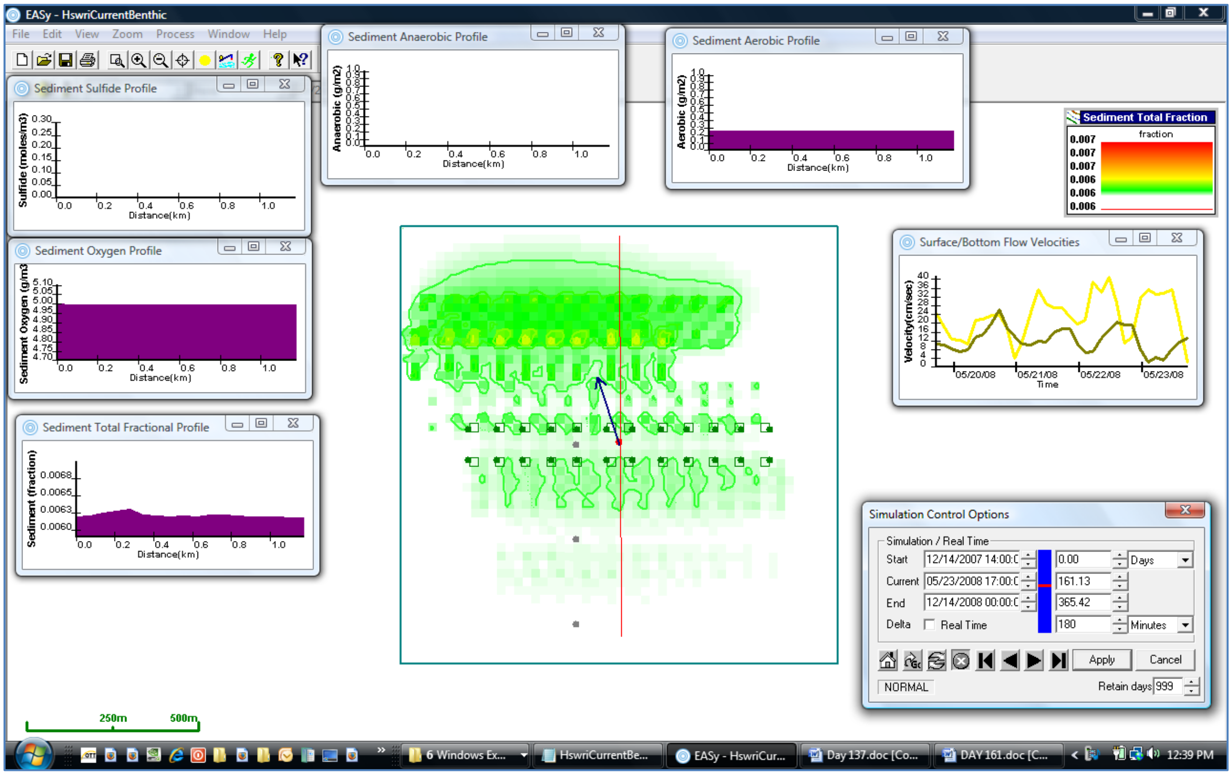


Figure 35. HSWRI Demonstration Fish Farm simulation at day 161.

The footprint of the farm at the time of Figure 35 is spatially large and complex, but nevertheless, organic carbon enrichment is barely above ambient values. The values for benthic parameters shown in the plots have not changed significantly.

We suggest that the low rates of waste deposition at the HSWRI demonstration fish farm site result from these factors:

- The additional time required for the waste particles to reach the sediment insures that they will be carried a greater distance from the farm. This additional time to fall through the water column insures greater dispersion (dilution of the waste) at the time of deposition. The dispersion has three components, turbulent dispersion during transport to the bottom, frequent changes in the direction of advective flow largely due to changes in wind or ocean current-driven forcing, and frequent changes in the speed of advection largely due to the same causes. A simple argument may clarify this point. The time required to reach the near-bottom suspended layer for the HSWRI is roughly 4 times greater than the time required at the comparison farm. If the direction of the current were constant but the speed of the current varied at a constant rate between zero and a specified maximum value the waste would be deposited uniformly along a line whose length would be 4 times greater for the HSWRI demonstration farm than the comparison farm and the rate of deposition of waste by the demonstration would be ¼ that of the comparison fish farm. If in addition to such variation in speed, the direction of the current were rotated through a full circle at a uniform rate then the area of deposition by the demonstration farm would be 16 times that of the comparison farm, and the rate of deposition would be 1/16 that of the comparison farm.

In fact our simulations indicate that the rates of deposition at the comparison farm are over 20 times greater than the rates at the demonstration farm. A value not too far from the value predicted from this crude analogy, and perhaps explained by the fact that the currents used in the demonstration farm simulation were 25% faster than those of the comparison farm.

- The differences were also due to frequent occurrences of erosion and dispersion events within near-bottom suspension layer that would be more frequent at the HSWRI demonstration site due to a 25% increase in current velocity results in shifting most of the weaker currents above the thresholds for deposit or resuspension.

- A third factor is the effect of the strong currents on the consolidation factor. There is rarely a time period in the current meter record where currents are nil for any extended period. We spent considerable time studying the effect of varying consolidation rates for both the comparison and HSWRI demonstration fish farm sites and conclude that neither was subject to significant consolidation effects. We ran the model for a full year and did not see any trends in this regard.

Finally, we emphasize that the model images shown above in this section overstate the average conditions likely to occur under and near the proposed project. Figure 36, below, more appropriately indicates those conditions and is quantitatively proven by AquaModel's capture cell output database information. Those data are voluminous (up to ½ million lines of data per run) and not included here for brevity, but they were closely inspected and analyzed for basic statistical properties.

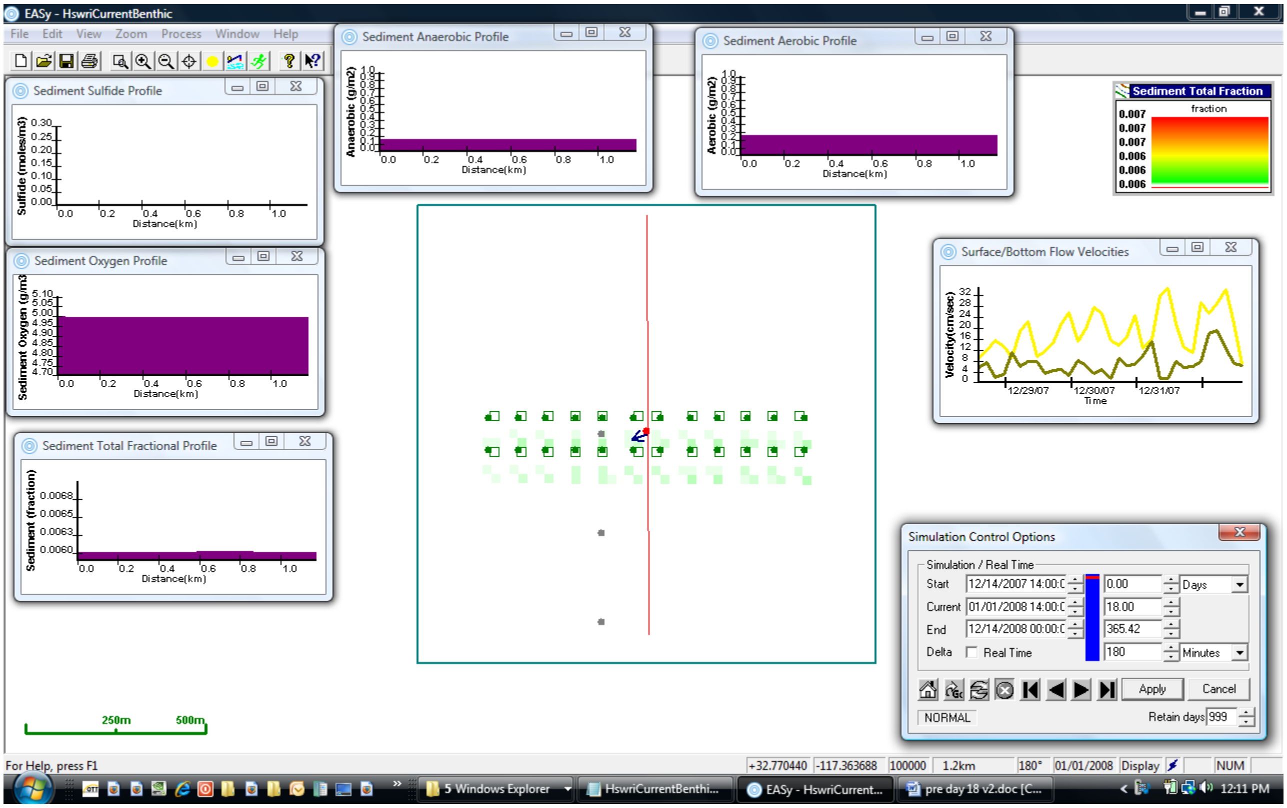


Figure 36. Typical benthic conditions at the proposed fish farm site during the vast majority of the time periods assessed.

10. Water Column Simulation of HSWRI Demonstration Fish Farm

One of the major concerns regarding fish farm operations is the nutrient enrichment of surface waters and the subsequent algal blooms that may be harmful. This is particularly a concern of some in areas where background dissolved inorganic nitrogen (DIN) concentrations and flux are low, as any added DIN could be used for phytoplankton growth. Most phytoplankton are beneficial, but too much nutrient, principally in estuarine waters, has been positively linked with adverse habitat and food web effects and even in some cases harmful algal blooms. Most inshore marine fish farms in the U.S. are located in nutrient insensitive waters (Rensel and Foster 2007) and in the Pacific Northwest it has been shown that harmful blooms originate in remote locations and are advected past fish farms (Rensel 2007). But waters of Southern California are subject to relatively low DIN concentrations, so we examined the possibility that the proposed fish farm could cause an algal bloom or series of blooms.

Recall from Figure 2 that *AquaModel* includes a routine describing the cycling of dissolved inorganic nitrogen (DIN) by the planktonic community. The three components of this routine are dissolved inorganic nitrogen, phytoplankton, and zooplankton. This routine is based upon the model of Kiefer and Atkinson (1984).

In order to assess the environmental impact of the dissolved waste produced by the demonstration farm, we examined the concentration and spatial distribution of (DIN) within the plume is determined by the rates of production within the cages, ambient concentrations, and the rates of advective and turbulent flow. DIN is the sum of all species of nitrogen including ammonia, nitrite and nitrate. The main excretory product of most teleost fishes is ammonia, but some fish produce small amounts of organic N waste too (urea). We also examined predictions from the simulation of the concentration and spatial distribution of phytoplankton.

Figures 37 and 38 are representative snapshots of time steps in the simulation with selected water column plots on the left and dissolved inorganic nitrogen in the main image on the right. Since the time scale of response of the planktonic community to eutrophication are much shorter (1 to 2 days) than the response of the benthic community (days to many weeks) to organic loading, we have drawn on snapshots from early in the simulation.

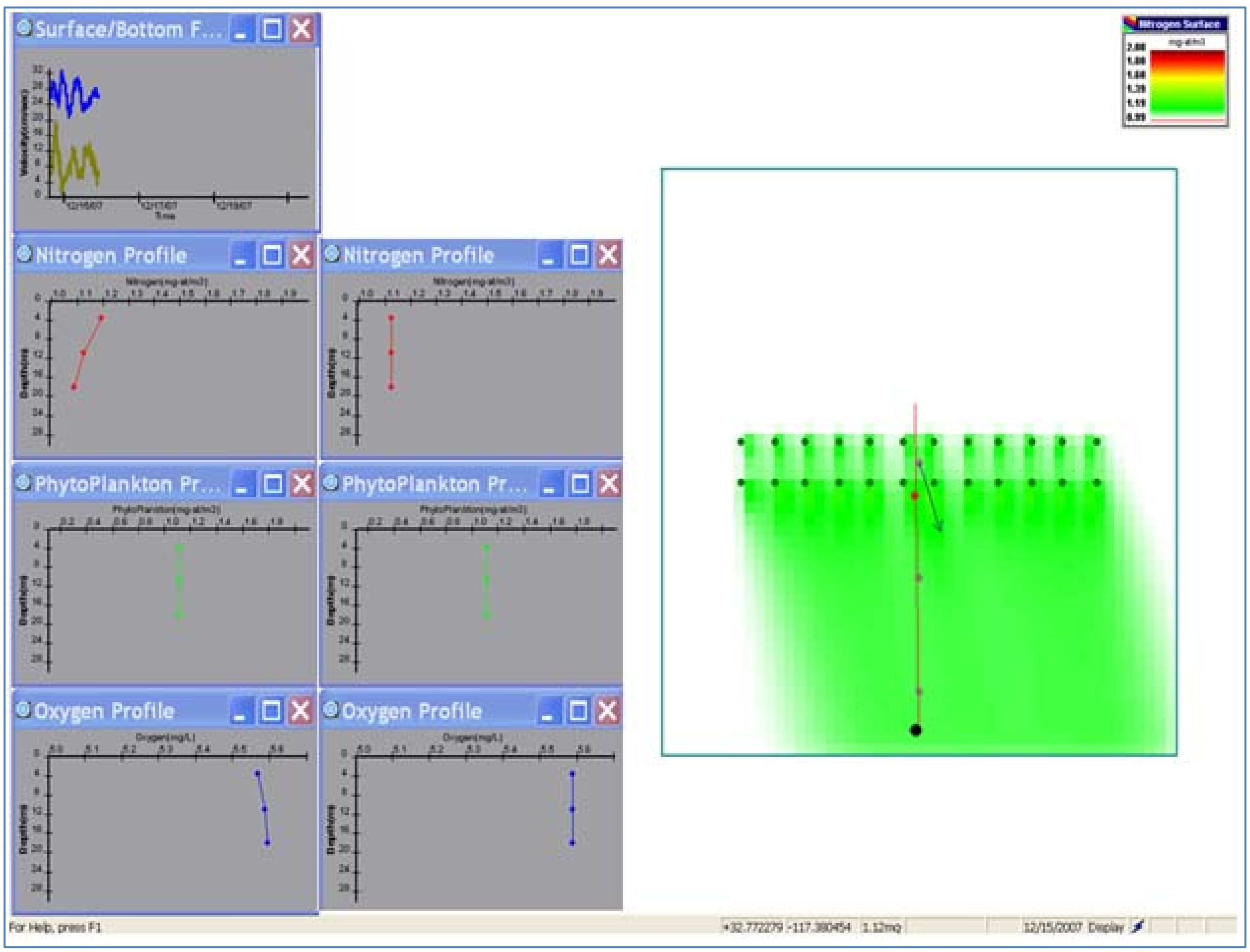


Figure 37. Snapshot of water column conditions during a relatively high current speed period. Plots on left relate to red or black dot location of vertical profiles.

Figure 37 portrays the 2nd day of the simulation during which time the surface currents were flowing at a moderately high rate of ~28 cm s^{-1}, indicated as the blue line of upper left plot. The base map and accompanying legend indicate that the concentration of DIN in the cages is about 1.2 g-at nitrogen m^{-3} and that the ambient concentration is 1.0 g-at nitrogen m^{-3}. Along the North American West coast, ambient concentrations of DIN range from undetectable to ~30 g-at nitrogen m^{-3} DIN concentrations along the California coast are generally different north and south of Point Conception, but both areas may have natural increases related to wind driven upwelling of deep, nutrient rich waters.

The red dot and the black dot found in the base map mark two locations where we "profiled" the upper water column. The red dot sampled the water column adjacent to the cages and the black dot sampled waters 525 meter downstream of the cages. The results of the profile adjacent to the farm are displayed in the lower 3 graphs on the left while those of the downstream-profile are shown in the right. We see near the cages that DIN is slightly over 1.2 g-at nitrogen m^{-3} at 2 meters and drops to 1.08 by 18 meters. Looking at the right graph we see that downstream of the cages the DIN has dropped to 1.1 g-at nitrogen m^{-3} and is uniform with depth. Since the time required for water from the cages to reach the downstream profile is only 30 minutes, this decline in concentration is best explained by mixing rather than assimilation by the phytoplankton. The profiles for phytoplankton neither change with depth nor distance from the farm. The value of 1.05 g-at cellular nitrogen m^{-3} is the same as ambient. As mentioned this is expected given the short distances and associated time interval. As expected, since excretion is coupled to respiration, the profile of oxygen is a mirror image of that of DIN. Near the cages (lower-left graph) its concentration is at 2 meters 5.35 g O_2 m^{-3} and at 18 meters its concentration is 5.4. Both values are below the ambient of value of 5.6. Downstream (lower-right graph) the concentration of oxygen is now uniform with depth but at 5.56, it remains a tiny fraction less than ambient.

Figure 38 is a screen print on the 4th day of the simulation, during which time the surface currents have been declining for several hours and are at this time at rate of 4 cm s^{-1} (blue line of upper left graph). Because of the reduced flushing of the cages, the concentration of DIN in the cages is now about 2.0 g-at nitrogen m^{-3}, twice that of ambient, but low compared to that encountered in on-shore hatcheries and and some poorly flushed marine fish farms (i.e, up to 8 g-at nitrogen m^{-3}, Sanderson et al. 2008.

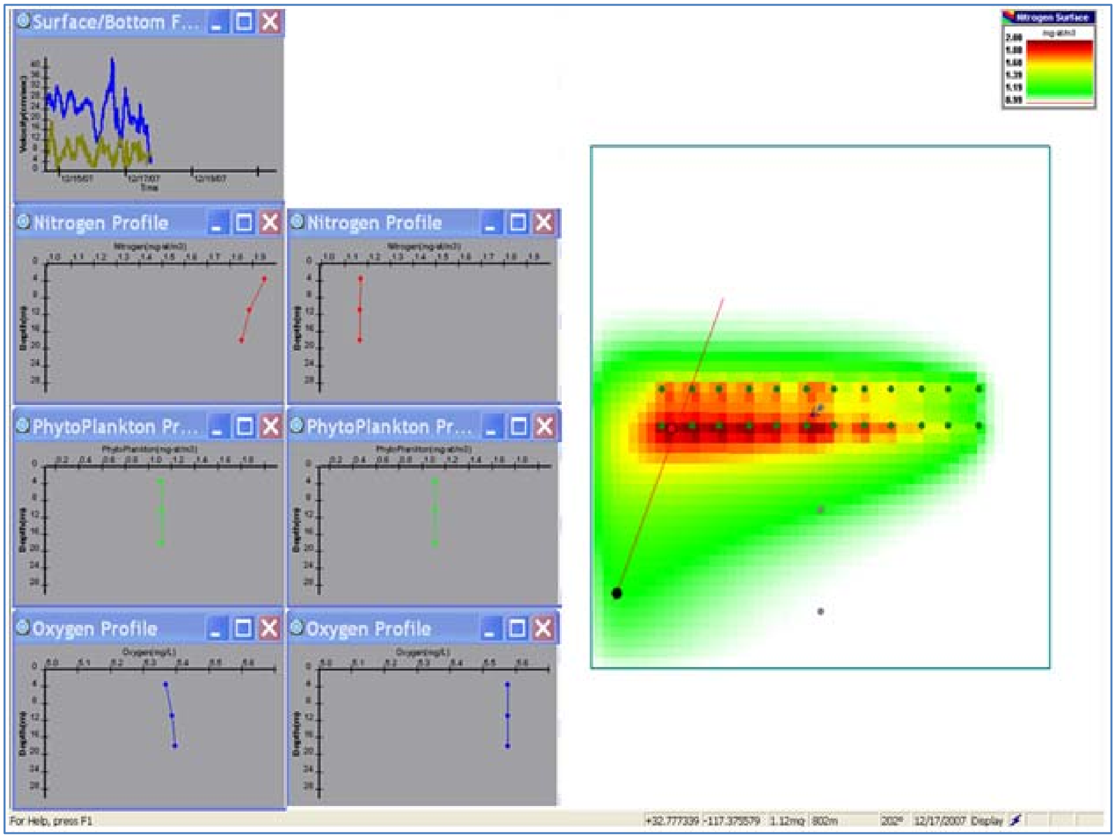


Figure 38. Snapshot of water column conditions during a relatively slow current speed period. Plots on left relate to red or black dot location of vertical profiles.

Referring to the upper left plot in Figure 38, we see that near the cages DIN is 1.95 g-at nitrogen m^{-3} at 2 meters and drops to 1.85 by 18 meters. Looking to the right we see that downstream of the cages the DIN has dropped to 1.15 g-at nitrogen m^{-3} and is uniform with depth. Since the time required for water from the cages to reach the downstream profile is only 4-5 hours, this decline in concentration is still best explained by our model as caused by mixing rather than assimilation by the phytoplankton. The profiles for phytoplankton neither change with depth nor distance from the farm and remain at the same level as ambient, 1.05 g-at cellular nitrogen m^{-3}.

Again the profile of oxygen is a mirror image of that of DIN; its concentration increases with depth: at 2 meters its concentration is 5.50 g O_2 m^{-3} and at 18 meters its concentration is 5.59, which is very close to the ambient concentration of 5.6. Downstream the concentration of oxygen is now uniform with depth and at 5.57 is also very close to ambient, and not measurably different with the most sensitive dissolved oxygen meter probes or methods.

Although the results of HSWRI demonstration fish farm simulation could be better illustrated by increasing the size of the spatial array, it is clear from the data presented above that the eutrophication by the farm will not stimulate an algal bloom. This conclusion is based upon the following considerations:

- The concentration of dissolved inorganic nitrogen within the farm itself never exceeded 2 mg-at nitrogen m^{-3}. If all of this nitrogen were assimilated by phytoplankton the concentration of phytoplankton would only increase to a concentration of 2 mg-at cellular nitrogen m^{-3}. Such levels are well below levels that are considered to be blooms which would be 5 to 10 times greater, assuming no advection and dispersion of nitrogen.
- The concentrations encountered do not exceed the half saturation constants for uptake or growth by many phytoplankton species. In other words, the amount of nitrogen added immediately downstream is not high, relative to the needs of phytoplankton.
- Dilution or mixing of the downstream plume with ambient waters is rapid. This rapid mixing is the result of the horizontal and vertical turbulence as well as the small size of the plume created by the cages, which is in the range of about 1 kilometer. We crudely estimate that the concentration of dissolved waste from the farm is diluted by at least 1/3 of its previous value every hour as it is transported downstream of the farm. Such dilution will not only rapidly reduce the concentration of DIN in the plume, but also reduce any increase in the concentration of phytoplankton, whose growth may be stimulated by the increased availability of nutrients.
- Any increase in phytoplankton concentration may also be countered by the grazing of herbivorous zooplankton, potentially aiding in sustenance for the marine food web.
- Extensive sampling downstream of open ocean cages south of the island of O'ahu Hawaii failed on most occasions to detect any significant differences compared to upstream, ambient conditions (Ostrowski et al. 2001).
- Even inshore farms have very limited spatial water column effects as previously discussed in this report. Sampling in such farms was conducted years ago when fish farms were smaller than today, but relative to their size and effects the calculated effects of the HSWRI farm are probably correct or overstated somewhat.

11. Conclusions

This report presented the results of a new version of AquaModel that has been developed over the past 9 months. Improvements in all submodels were made, but this was particularly true for benthic effects, circulation and fish physiology components.

As with any model, it is necessary to fit the simulation to local data and conditions as well as test the model against relatively well known outputs. After determining and assigning most probable calibration factors, AquaModel simulated reasonably large effects for a comparison fish farm that was representative of a nearshore fish farm.

After insuring that we could simulate an existing fish farm scenario, we changed the depth from 25 m to 91 m, the pen spacing by a factor of nearly 4 and increased the current velocity by 25%. These changes match conditions as measured at the proposed demonstration farm site.

The benthic effects were shown to be over an order of magnitude less than the nearshore comparison fish farm site. Although the nearshore sites would have met standards of the State of Washington (a leader in regulation progress and rigorousness) the HSWRI demonstration site far exceeds any standards utilized in any jurisdiction worldwide for fish farm regulation.

These results are not unexpected given the strong currents and relatively great depth at the proposed project site. Just as importantly, the currents are not excessively strong, which means that the fish farm can be operated and maintained correctly and the risk of structural failure should be less than in other environments where mean current velocity exceeds 30 cm s^{-1} for prolonged periods (Rensel et al. 2007).

As expected and seen with most modern commercial net pen farms, sediment carbon is deposited beneath the cages with flux rates controlled mostly by current velocity and depth but significant deposition will not occur in any location at the HWSRI site if best management practices are applied. The literature is filled with prior studies where adverse effects were detected but in most cases the sites were either far too large for the site carrying capacity (e.g., the Clam Bay net pen site of the 1980s, see Gowen and Weston 1991) or current velocity and depth were too minimal. More recently Brooks (2003) found subtle biological effects measured to about 150-200 m around several inshore fish farms in British Columbia, but the mean current velocities or current frequency distribution were relatively slow (> 7 cm s^{-1} in most cases) and current direction likely to be mostly bi-directional. Slow velocity and limited variation of direction act together to create a depositional environment that is less desirable for large-scale net-pen aquaculture.

While we do expect that it will be difficult to find an effect of the fully built out fish farm on sediment chemistry, we do expect that there could be an effect on the food web and infauna. We expect the effect to be generally positive and it may be detectable too. Weston (1991) showed that invertebrate infauna respond more quickly and measurably than sediment chemistry measures. In the present case, because the loading to the sediments will be far below 1 gram carbon per m^2 per day (a commonly accepted threshold of loading that begins to result in adverse effects), the anticipated effects should be positive, providing increased organic food supply and resulting in enhancement of the biota both in species diversity and biomass as explained previously.

Water column effects of fish farms are much more transitory and in the present case we do expect to see very minor decreases of dissolved oxygen and increases of dissolved inorganic nitrogen within the cages and immediately downstream. The organisms at greatest risk to compromised water quality in any net-pen fish farm operation are the farmed fish themselves, not wild fishes or invertebrates. Large spacing of cages, strong and persistent currents greatly reduces such risks to minimal at the proposed site, as discussed in this report.

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Appendix A. Modeling Team Background

1) Dr. Rensel has over 30 years experience in benthic ecology and fish farm impacts since the first study of fish mariculture impacts in Puget Sound. He conducts routine monitoring for NPDES compliance and research at several net pen facilities in Puget Sound and helped design State of Washington performance standards by working with State government and industry. He has been a contributor to phytoplankton studies worldwide including harmful algae, effects on fish and shellfish and mitigation means.
2) Mr. O'Brien is a highly experienced modeler and software engineer. He wrote much of the underlying code for EASy and developed the Mariculture module with assistance from other team members.
3) Dr. Kiefer is a professor at the University of Southern California and an experienced modeler with extensive experience in phytoplankton dynamics and physiology. He has been active for many years in fish farm effects modeling and studies.

Short version of resumes follow:

Frank O'Brien, Systems Engineer, System Science Application

Professional Preparation

University of Vermont, Burlington, VT	Mathematics	B.A.	1965
University of Vermont, Burlington, VT	Mathematics	M.A.	1967
Cal State University, Fullerton, CA	MBA (33 credits towards)		

Advanced Technical Training in DCOM, MTS, MSMQ, OLEDB, C#, and DotNet

Appointments

Director of Software Engineering, System Science Applications, CA. 2001-2006
Systems Engineering Lead, Logicon, Inc., San Pedro, CA. 1988-2001
Division Manager, Comarco Inc., Anaheim CA. 1981-1988
Program Development Manager, Logicon, Inc., San Pedro, CA. 1972-1980
Programmer, North American Rockwell, Anaheim, CA. 1969-1972.

Computer Experience

Machines: PC (26 years), Sun (years1), DEC (2years), IBM mainframes (15 years)
Operating Systems: Windows XP, 2000, NT, 98, 95, 3.1 (11 years), UNIX (1 year), DOS (22 y.)
Languages: VC++ (14 years), VB (9 years), Java (7 year), Assembler (22 years), Fortran (30 years)
Technologies: COM (8 years); ODBC, DAO (8 years); MTS, MSMQ, ADO, OLE-DB (7 years)
Extensive experience in every Phase of software development including management and business development, requirements analysis, algorithm development, and prototyping.

Synergistic Activities

- Architect and lead developer of EASy GIS software, a dynamic 3D oceanographic GIS system, and its NetViewer GIS web-server component.
- Programming for the development of a series of information systems in support of mariculture environmental analysis, fisheries management, fish tracking, marine biogeographical, hydro-optical water analysis, water quality studies, and coastal area management projects including the Gulf of Maine

Biogeographic Information System (Sloan/NOPP), NOAA-NESDIS Sea Nettles, Santa Monica Bay Virtual Ocean (SMBRP).

List of Collaborators last 48 Months

M. Domeier, PIER Institute	P. Cornillon, University of Rhode Island
R. Branton, Bedford Institute of Oceanography	B. White, LA Department of Water & Power
M. Yamaguchi, Santa Monica Bay Restoration Project	C. Brown, NOAA/NESDIS
J. Latham, SDRN, FAO-United Nations	D. Foley, NOAA/NMFS NWFSC

Dale A. Kiefer, President & Chief Scientist, System Science Applications

.1 Professional Preparation

Yale University	Biology	B.Sc.	1966
University of Oregon	Marine Biology	M.S.	1967
UC San Diego (Scripps)	Biological Oceanography	Ph.D.	1973

.1 Appointments

Professor, Department of Biological Sciences, University of Southern California, 1990-
SeaWiFS Science Team, NASA, 1993-
Visiting Scientist, Food and Agricultural Organization, United Nations, Rome, Italy 1994-98
Visiting Scientist, Laboratoire de Pierre et Marie Curie, University of Paris, France, 1987
Associate Professor, Department of Biological Sciences, Univ. of Southern California, 1981-90
Assistant Professor, Department of Biological Sciences, Univ. of Southern California, 1976-81
Assistant Research Biologist, U.C. San Diego Visibility Laboratory, 1975-76.

Short Resume: Dr. Kiefer, after working as a researcher for the Scripps' Marine Life Research Group and Visibility Laboratory, joined the faculty at the University of Southern California and is now a full professor in the Department of Biological Sciences. His research, which has been funded by numerous government agencies including NSF, the NASA, NOAA, and ONR, has received international recognition. As a member of NASA's SeaWiFS Science Team he has worked to develop algorithms for the mapping of photosynthesis and bio-optical properties from satellite ocean color imagery. In 1995 he served for 2 years as consultant to the UN-FAO in Rome, Italy, where he applied his expertise in remote sensing to fishery management. He is a member of the Heinz Foundation's State of the Ecosystem Panel for coastal waters. Kiefer has published 75 papers and 16 published reports, 47 in the field of bio-optical oceanography, 21 relating to phytoplankton dynamics and modeling, 8 on pollution/water quality issues including aquaculture, and 8 on fisheries/information systems. He has obtained 3 United States patents for inventions in optical instrumentation and wave damping floats.

He is also Chief Scientist and co-founder of System Science Applications, and has supervised the development of several federally funded environmental analysis systems. Examples include the Gulf of Maine Biogeographic Information System and The Gulf of Maine Dynamic Atlas (NOPP),, the Application of Remote Sensing Data to the Analysis of Environmentally-mediated Recruitment Variability in Harvested Fish Populations: Case study of Cod and Haddock Stocks within the Gulf of Maine (NOAA). One program, called the Hydro-Optical Analysis System (HOPAS), is currently being developed on a NSF-sponsored SBIR project for which he served as the Phases I and II Principal Investigator while at System Science Applications. He has modeled and analyzed ocean pollution problems involving fish farm operations, pulp mill and power plant waste water discharges, and offshore waste incineration. He has developed simulation models of fish populations and plankton ecosystem dynamics, and performed studies involving ocean optics, bioluminescence, and air-sea gas exchange.

Selected Publications and Reports:

1995. Ondercin, D., C. A. Atkinson, and D. A. Kiefer. The distribution of bioluminescence and chlorophyll during the late summer in the North Atlantic: maps and a predictive model. Journal of Geophysical Research, 100:6575-6590.

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J.E. Jack Rensel, Principal Investigator, Senior Scientist, Rensel Associates Aquatic Sciences

Ph.D. Fisheries and Oceanography, University of Washington, Seattle, WA
M.S. University of Washington, Seattle & Stanford University Hopkins Marine Station, Pacific Grove CA
B.S. Western Washington University, Bellingham, WA

Dr. Jack Rensel is a senior scientist with SSA and has conducted over a dozen siting and impact assessments for fish mariculture in the U.S. during the period 1980-90. Many site-specific studies were conducted after site establishment to measure performance relative to standards. After helping the State of Washington design fish farming performance standards and monitoring protocols, he served as national co-chair of the Joint Subcommittee on Aquaculture (USDA) technical net pen committee to work with U.S. EPA on their performance standard development. He previously served as primary participant in the 12-year research and rule making process for cage mariculture in Puget Sound with the Washington Department of Ecology. He recently led NOAA's efforts to organize and conduct part of an international workshop on coastal mariculture with his session focusing on modeling. Rensel is presently examining the beneficial effects of marine finfish mariculture in Puget Sound with regard to biofouling.

He has been involved in fish culture since conducting the first impact studies of fish rearing on the benthic environment in Puget Sound in 1972. Subsequently he was responsible for managing and expanding one of the world's largest public-owned net pen enhancement facilities (Squaxin Island), which included a five-year tagging and fisheries contribution published study (Rensel et al. 1988). Since 1983 he has consulted for leading fish farming companies and government agencies, here and abroad for site studies, benthic and water column impact assessment and harmful algal bloom management and monitoring studies. His experience includes dozens of circulation studies, hatchery impact studies, pesticide and nutrient monitoring efforts and related work. Presently Dr. Rensel is completing extensive studies of the dynamics of invertebrate and plant colonization of fish farm substrates.

Selected Publications

Anderson, D.M., J.M. Burkholder, W.P. Cochlan, P.M. Glibert, C.J. Gobler, C.A. Heil, R. Kudela, M.L. Parsons, J.E. Jack Rensel, D. W. Townsend, V.L. Trainer and G. A. Vargo. In press. Harmful algal blooms and eutrophication: Examples of linkages from selected coastal regions of the United States. Harmful Algae, special edition.

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