Appendix B.

Alden Research Laboratory Report

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Productive Capacity Study of Shellfish Aquaculture Farm

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CHAPTER 1

Introduction

Figure 1: Totten Inlet, Puget Sound, Washington

Totten Inlet is an embayment located in Puget Sound, Washington. The water body is presently used for the culture of Mytilus galloprovincialis (Gallo) mussels along with oysters (Pacific and Olympia) and clams (Manila). One of the larger operations, in Totten Inlet, uses eight raft arrays each consisting of six square raft sections (Figure 1). While the inlet provides an ideal location for mussel raft operations in terms of water properties, food supply, and flushing of waste materials: the optimum deployment scheme for the rafts is not known.

The primary objectives of this study are to:

1. Develop a baseline understanding of conditions at the aquaculture site.
2. Construct computational hydraulic models of the floating aquaculture rafts.
3. Determine if aggregate seeding strategies for the rafts are appropriate for the range of typical flow conditions.

This summary document reports results of the Totten Inlet study. The experimental design is presented in Chapter 2, and the modeling approach used to for the hydrodynamic calculations is described in Chapter 3. Data acquisition techniques are explained in Chapter 4. Results and analysis are presented in Chapter 5. Conclusions and recommendations are made in Chapter 6. Appendices A and B contain photographs and a summary of the field data collection program.

CHAPTER 2

Experimental Design

Overview

A combination of data collection and state-of-the-art computer simulation was used to assess the design of mussel rafts used in Totten Inlet. Studies, prior to this one, have tended to focus on data collection. In this study, we sought to capitalize on the strengths of numerical modeling to develop a comprehensive understanding of the performance individual raft and multiple raft arrays.

The field program was carried out in the fall of 2003. Upon collection and review of the data, flow patterns through individual mussel rafts were computed and compared with measured results. This information, combined with other physical data collected during the field program, was used to develop recommendations for improved animal husbandry and raft deployment schemes.

Data Collection

Two types of data were collected on site:

- velocity measurements; to measure spatially varying 3-dimensional velocities in and around the aquaculture rafts at different times during the tidal cycle, and

- fluorescence measurements; to measure relative phytoplankton concentrations and to estimate food demands of individual aquaculture rafts.

The primary objectives of the data collection were to gather information describing flow patterns in the vicinity of the rafts and information used to estimate the depletion of phytoplankton concentrations caused by the feeding of the mussels. Details regarding the data acquisition techniques and equipment used to gather the information are presented in Chapter 4 and Appendix B.

Computer Modeling

Finely detailed, numerical models of individual raft strings (Figure 2) and the eight raft array were used to estimate the distribution of flow and phytoplankton (food) within the aquaculture lease site. These models were ultimately used to evaluate the performance of the current raft deployment scheme.

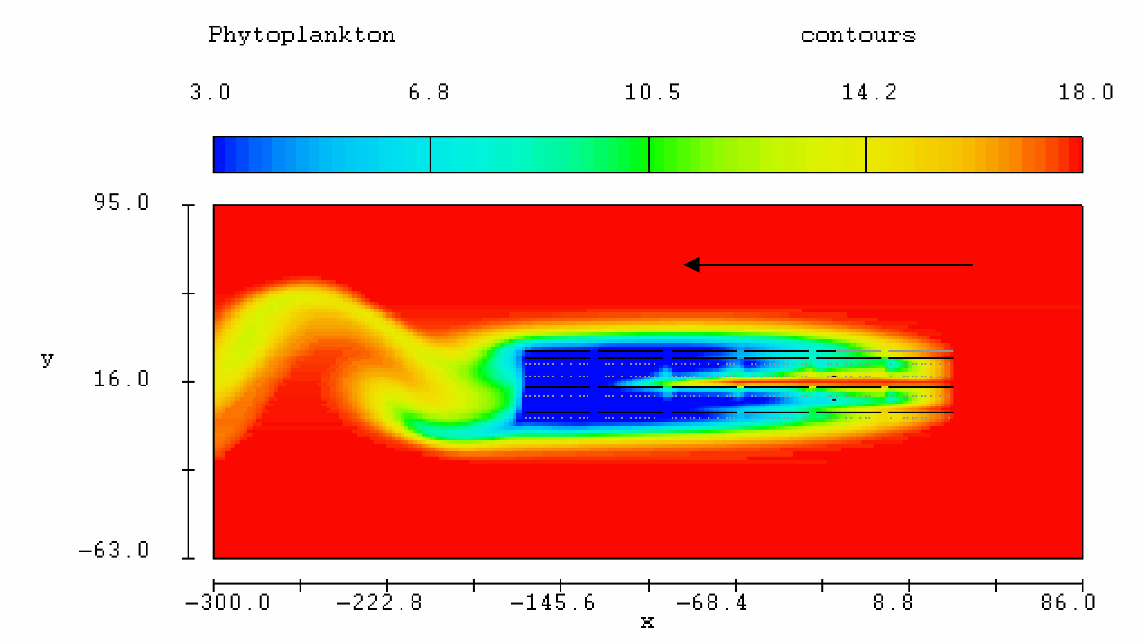


Figure 2: Distribution of Phytoplankton within Raft String
(colored by concentration - µg/l, x & y coordinates – ft, arrow shows nominal direction of flow)

Details regarding the computer modeling techniques used to simulate the flow through the rafts are presented in Chapter 3.

CHAPTER 3

Modeling Approach

Overview

Small scale, numerical flow models of individual mussel rafts were used to estimate the distribution of flow and phytoplankton (food) within the aquaculture lease site. In following sections these models are referred to as Raft-Scale Models. Computed results, from the raft-scale models describe the movement of water through individual rafts and were used to evaluate the current deployment scheme used for the eight raft array.

Raft-Scale Modeling

Three-dimensional simulations of flow through individual mussel rafts were developed within the framework of the ***FLOW-3D*** software system. ***FLOW-3D*** is a Computational Fluid Dynamics (CFD) software package designed to analyze complex flows (*e.g.,* hydraulic jumps, Figure 3).

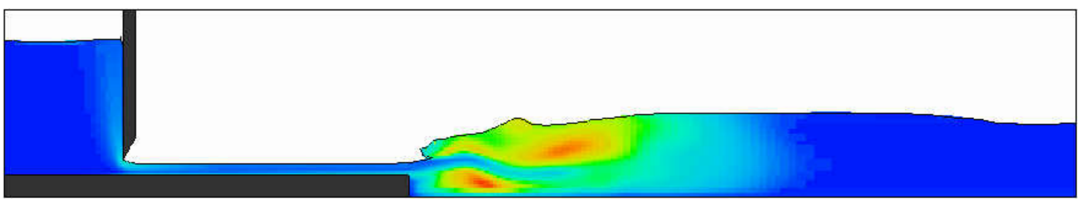


Figure 3: Hydraulic Jump Controlled by an Abrupt Drop
(colored by turbulent kinetic energy)

What is CFD?

Computational Fluid Dynamics involves the use of a computer to investigate the dynamic behavior of liquids and gases. The abbreviation, CFD, is commonly used in reference to computer programs for determining fluid motion in three-dimensions (i.e., Navier-Stokes based solvers).

CFD programs are designed to produce simulations of fluid flows influenced by a wide variety of physical processes (*e.g.,* heat conduction, solidification, cavitation, and surface tension). Because these programs are based on the fundamental laws of mass, momentum, and energy conservation, they are applicable to almost any type of flow process. For this reason CFD programs are referred to as "general purpose" solvers.

The roots of CFD, in the United States, may be traced back to original developments at the Los Alamos National Laboratory (LANL) beginning in the early 1960's. Many basic numerical techniques originated there for the solution of compressible and incompressible flow problems.

Widespread commercial use did not begin until the early 1980's when CFD analysis was adopted by the aerospace industry for solving external flow problems (aerodynamics) and for designing fuel control systems (sloshing see Figure 4). Today, CFD is used extensively by hydraulic engineers, bio-medical engineers, automotive engineers, metal casters and inkjet designers to solve difficult flow problems.

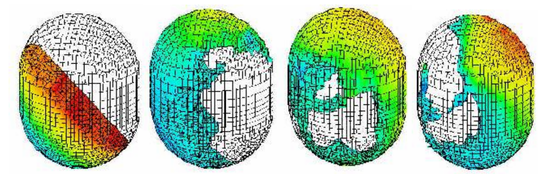
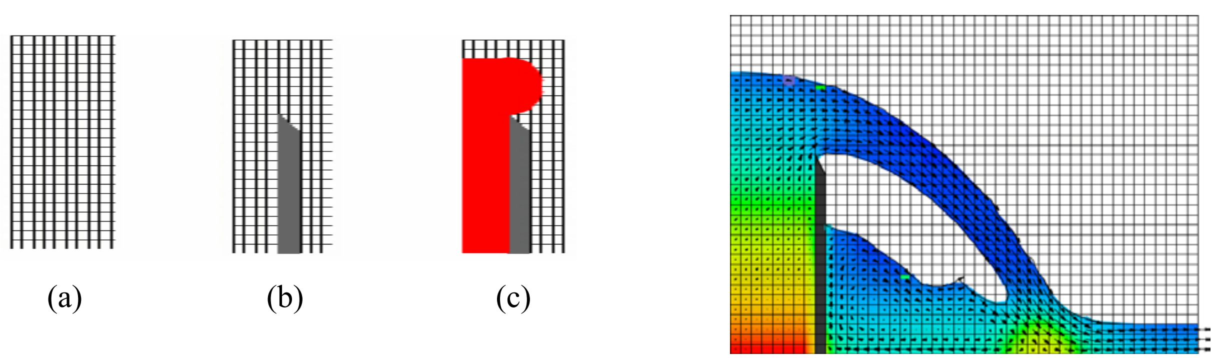


Figure 4: Fuel Slosh (colored by pressure)

How Does it Work?

CFD involves the solution of the governing equations for fluid flow (*i.e.,* Navier-Stokes) at thousands of discrete points within a computational grid. All of the computations presented in this report were done using a fixed (Eulerian) grid of rectangular control volumes because these are efficient to generate and they possess many other desirable properties (*e.g.,* increased accuracy, smaller demands on memory, and simpler numerical approximations). Next, a special technique called the **FAVOR** (**F**ractional-**A**rea-**V**olume-**O**bstacle-**R**epresentation) method was used to define general geometric regions within the rectangular grid (Figure 5 [a-b]). This method uses partial control volumes to provide the advantages of a body-fitted grid but retains the construction simplicity of ordinary rectangular grids. The method also allows for the calculation of flow through "porous" media (*e.g.,* an aquaculture raft).

In this study, the **V**olume-**o**f-**F**luid (VOF) technique was used to track the motion of fluid through the grid (Figure 5 [c-d]). The VOF method consists of three elements: a volume-of-fluid function for defining fluid regions, a special advection method that maintains a sharp definition of fluid surfaces as they move and deform within the computational grid and the application of normal and tangential stress boundary conditions at the fluid surfaces. The VOF method is capable of modeling extremely complex fluid behaviors involving any number of independent free fluid surfaces. The VOF method also allows for the breakup and coalescence of fluid surfaces.



(a) (b) (c)

Figure 5: Modeling Methods

(a) rectangular grid, (b) sharp-crested weir using FAVOR, (c) fluid regions –w- VOF

Mussel Raft Modeling

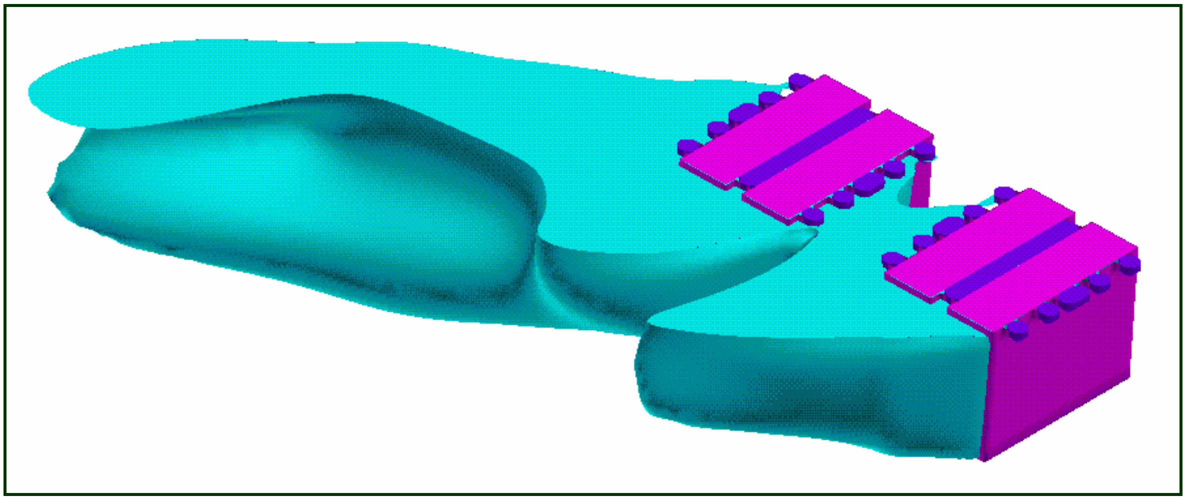


Figure 6: Wake Formation Downstream of Two Mussel Rafts

The ***FAVOR*** method was used to construct numerical models of the raft used for aquaculture in Totten Inlet. Regions where mussels are located (*i.e.,* on individual lines) were assigned porosities according to the density of mussels found in those areas (purple areas in Figure 6). Coefficients controlling the loss of energy experienced by the flow as it passes through the porous regions were also calculated. The values of these coefficients depend on a characteristic length (*e.g.,* a length proportional to the diameter of the lines with mussels attached) and a roughness parameter.

In this study, as in past applications, we found that the calculated distribution of flow within the rafts compares closely with the measured distribution of flows. The results of the raft-scale model simulations were used to evaluate the current deployment scheme used for the eight raft array.

CHAPTER 4

Data Acquisition

Overview

An understanding of phytoplankton concentrations and flow speed is critical to estimating the performance of aquaculture rafts. Preliminary data gathered by the Pacific Shellfish Institute provided velocity and fluorescence measurements made at different locations near the aquaculture rafts. To expand on this work, the 2003 field study was organized. Follow-up experiments designed to measure the depletion of phytoplankton within individual rafts were planned. These experiments involved:

1. the measurement of velocities in and around the aquaculture rafts, and
2. the measurement of phytoplankton concentrations in and around the rafts,

The field work was performed between 3 September 2003 and 5 September 2003. The basic outline of the study program follows:

I. Orientation & Mobilization

Travel and transfer of equipment to Totten Inlet, Washington took place on 2 September 2003. Upon arrival at Totten Inlet, a staging area for the field program was setup in a cabin located near the mouth of the inlet.

The mobilization concluded with the testing of equipment on the first day of field work and the deployment of instruments for continuous sampling of currents speeds and phytoplankton concentrations.

II. Data Acquisition

Data was acquired in around the aquaculture rafts from 3 September 2003 to 5 September 2003.

The following apparatus were used for the data acquisition: 2 YSI Sonde CTD's, a Seabird Profiling CTD, and an Interocean S4 current meter.

III. De-Mobilization

A presentation of preliminary results was made to the Pacific Shellfish Institute on 5 September 2003. The staging area was broken down on 6 September 2003, and all equipment was transferred back to Tenants Harbor, Maine.

Data Collection

Two fundamental types of data were collected during of the field experiment. These data included measurements of velocities, and fluorescence. A summary the techniques used to collect these data follows:

Velocity Data

Figure 7: Interocean S4 Current Meter

Continuous velocity measurements were made off a wood boom (5m outside the rafts, north side), inside the mussel rafts, and downstream of the mussel rafts (south side). These measurements were made with an Interocean S4 current meter set to sample average speeds every minute during the deployments (Figure 7).

Vertical velocity variations (*i.e.,* profiles) were also measured with the S4 current meter. To acquire these data, samples were acquired instantaneously.

Fluorescence

(a) (b)

Figure 8: (a) Profiling CTD, (b) Multi-Parameter Sonde
(courtesy of Seabird Electronics, Inc. and SonTek/YSI, Inc.)

To estimate phytoplankton concentrations, chlorophyll a (chl a) *in-vivo* fluorescence was measured upstream of the mussel rafts, inside the mussel rafts, and downstream of the mussel rafts using a Sea-Bird CTD (Figure 8[a]) equipped with a fluorescence probe and two YSI sondes (Figure 8 [b]). Each deployment began with the measurement of chl a with all three instruments positioned at the same location outside of the rafts (2.5 m water depth off the end of the north boom). At the same time water samples were taken for extracted chl a, so that the fluorescence results could be correlated with the phytoplankton concentrations found in the water samples. Previous deployments of the Sea-Bird in Maine have provided data that yields a 1:1 relationship between extracted chl a and the *in-vivo* fluorescence measurements (personal communication with Carter Newell, Great Eastern Mussel Farms). Note: the data recorded on the YSI Sondes appeared to be quite noisy compared to the information recorded on the Sea-Bird. The data provided by the Sea-Bird was considered to be superior to that recorded by the YSI instruments and only the Sea-Bird data was used in the final analysis.

CHAPTER 5

Results and Analysis

Overview

A primary source of food for mussels in Totten Inlet is phytoplankton carried into the inlet from the adjacent waters of Puget Sound.[1]

To determine the average rate of phytoplankton consumption by the mussels; measurements of phytoplankton concentrations and flow velocities within the rafts were compared to similar measurements taken in Totten Inlet (*i.e.,* away for the rafts). These data were used to calibrate numerical models of the rafts deployed in the configuration shown in Figure 1. Additional calculations, to determine the optimum orientation of the raft array, were also performed.

Results of the field study and analysis (described above) are presented in the following sections titled: data collection, modeling, and analysis. Significant findings under each heading are stated summarily.

1. Data Collection

Two different types of data were collected during the September 2003 field program. These data took the form of: velocity measurements, phytoplankton concentrations measured within the aquaculture rafts, and phytoplankton concentrations measured in the adjacent waters of Totten Inlet. Together, these data were used to determine the optimum orientation of the raft array.

Velocity Measurements

Velocity measurements made in the vicinity of the mussel rafts were used to estimate the average amount of water passing through a raft over a 24 hour period. Velocity measurements made at all raft locations display distributions similar to those shown in Figure 14. That is to say, flow approaching the rafts slows rapidly as it passes through the rafts and accelerates to either side of the rafts.

The ratio of average current speeds measured inside and outside of the mussel rafts was calculated. As shown in Figure 11, measured current speeds were about 3.5 times lower inside the first raft and were about 13 times lower inside the second raft (raft one is the first raft in the string – *i.e.,* the "upstream" most raft, and raft two is the second raft in the string). This reduction in flow speed was reproduced by the numerical (see Appendix B for additional findings).

[1] Another food source not measured as part of this study is derived from non-phytoplankton seston (*e.g.,* dissolved and particulate material) as noted by Joth Davis (Taylor United, Inc.).

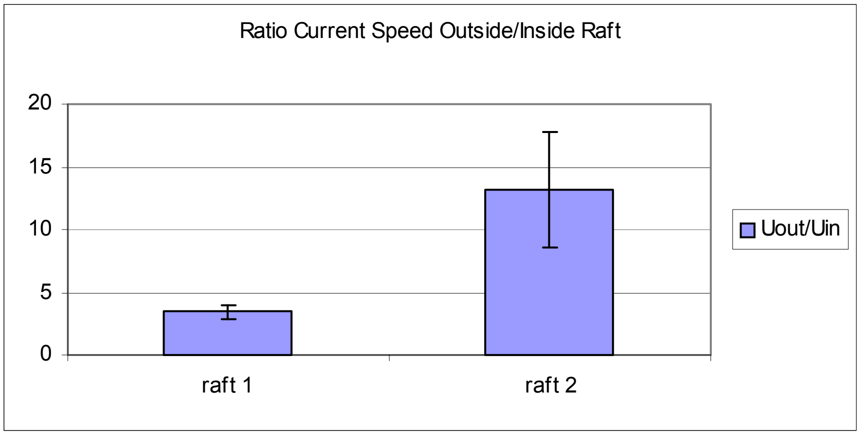


Figure 9: Ratio of Flow Speeds Inside and Outside of Rafts
(angle of incidence ~ 0 degrees)

Chl a Fluorescence

Relative fluorescence at depths between 0.0 and 10.0 meters was measured outside the perimeter of the aquaculture rafts and between 0.0 and 6.0 meters inside the aquaculture rafts. Figure 12 shows representative fluorescence data measured outside and inside one of the raft strings. The results show a rapid depletion in fluorescence as water moves through the raft system (*e.g.,* phytoplankton concentrations are reduced from values of 14-18 µg/l outside of the raft strings to less than 4 µg/l inside the raft strings) for this single incoming tide (*i.e.,* the reported chl a concentrations are not averages, but instantaneous measurements made during a particular incoming tide).

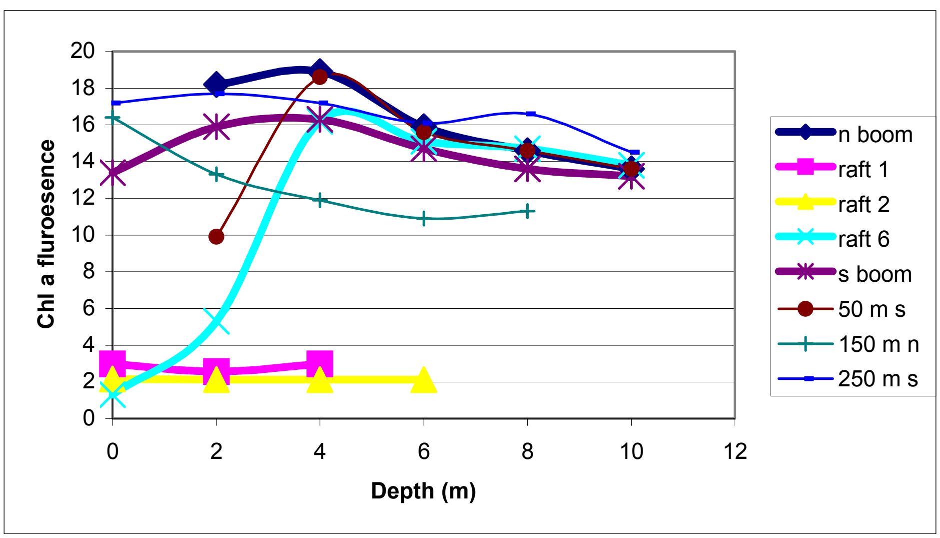


Figure 10: Representative Fluorescence Data
(angle of incidence – 0 degrees)

Lateral Variation of Phytoplankton Concentrations

A reduction of phytoplankton concentrations within the mussel rafts (at similar depths) was measured throughout the study. The reduction of phytoplankton concentrations within the rafts is caused by the grazing of the mussels. The average reduction in phytoplankton concentration was used to estimate the demand of the mussel rafts.

Concentrations of phytoplankton in the wake of the rafts varied widely due to an upwelling effect caused by the acceleration of flows beneath the rafts and lateral mixing induced by the wake of the raft.

Vertical Variation of Phytoplankton Concentrations

Phytoplankton concentrations generally decreased with depth. However, the variation of phytoplankton concentrations is not considered to be significant (Note: existing aquaculture rafts only extend to depths of about 5 meters).

Consumption

The amount of phytoplankton depletion caused by the raft array in Totten Inlet was estimated from fluorescence measurements made inside and outside the bounds the mussel-culture rafts. Reduced fluorescence levels inside the rafts is caused by the consumption of phytoplankton by the mussels. The average reduction in chlorophyll concentration across an aquaculture raft was measured to be 2.05 micrograms/liter.

2. Modeling

Numerical modeling relied on the ***FLOW-3D*** CFD software package used to simulate the flow through the mussel raft arrays. Boundary conditions for these simulations were derived from measurements taken during the September 2003 field trip. The results of the ***FLOW-3D*** simulations provide:

1. a means by which the design of the mussel rafts can be critiqued, and
2. a platform from which the performance of other innovative designs can be evaluated.

Raft-Scale Modeling

The ***FLOW-3D*** computer software package was used to construct detailed numerical models of the mussel rafts currently in use in Totten Inlet (note: details concerning the approach used in the numerical analysis are given in Chapter 3 of this report). The detailed raft-scale models accurately predict the attenuation of flow induced by the floating rafts and the results of the simulations enable the determination of the optimum orientation of the raft arrays.

The most common raft design used in Totten Inlet is one where mussels are suspended by ropes. This raft design requires that mussels be attached to ropes that are hung vertically downward into the water from a floating support structure. Once in place, tidally driven currents flow between the ropes carrying phytoplankton and other nutrients to the mussels on the ropes.

The most significant parameter, relative to the design of these rafts, is the spacing used to separate the individual ropes onto which the mussels are attached. In Totten Inlet we measured phytoplankton concentrations sufficient for good mussel growth (phytoplankton concentrations > 3 μg/l) in half of the raft string during peak flow conditions. Figure 11 shows the results of a computation where the approach flow is moving at a speed of 0.5 ft/s from the right of the figure towards the left. Phytoplankton concentrations in the approach flow are 18μg/l. The raft string is made of six different rafts. For this flow condition, phytoplankton concentrations in three of the rafts are calculated to be less than 3 μg/l (a minimum food concentration required for adequate mussel growth). Since the direction of flow through the rafts changes direction; the part of the raft that <u>does</u> <u>not</u> receive adequate food during the first half of the tidal cycle <u>does</u> receive adequate food during the second half of the tidal cycle. If an additional raft was added to the raft string, then the center raft might never receive food in adequate quantities. Thus, we would not recommend increasing the length of the individual raft strings (*i.e.,* six is maximum according to this analysis).

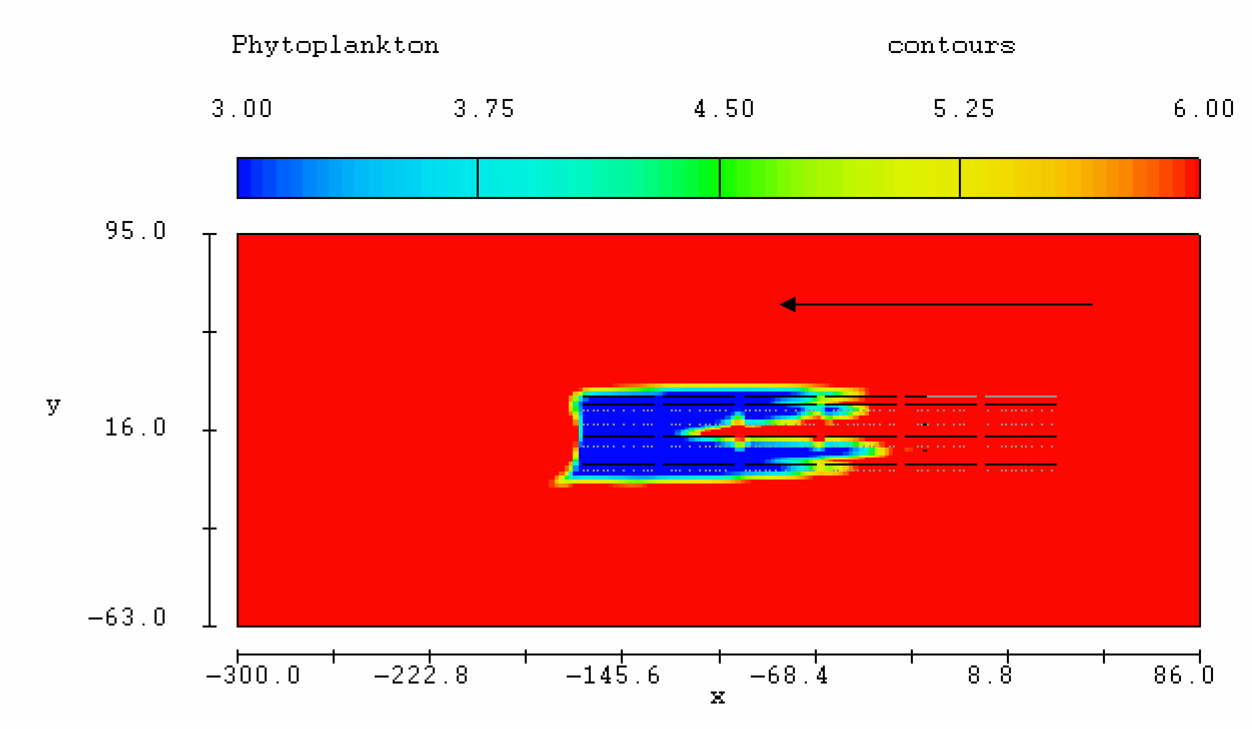


Figure 11: Calculated Phytoplankton Concentrations within Aquaculture Raft (dimensions are in ft, concentrations are in μg/l, arrow shows nominal direction of flow)

Figure 12 was produced from the results of the same simulation; however, in this figure the field is colored by speed. In these results, the flow rapidly slows by a factor of five or more. The fact that the flow moves slowly through the raft string contributes substantially to the low phytoplankton concentrations calculated (and measured). Because flow speeds within the rafts are so low and because predator nets are used at this site we would not recommend that the spacing between ropes be decreased (*i.e.,* we would not recommend that more ropes be added to the rafts). In fact, some experimentation involving a decrease in the number of ropes per raft could be considered to increase mussel growth rates.

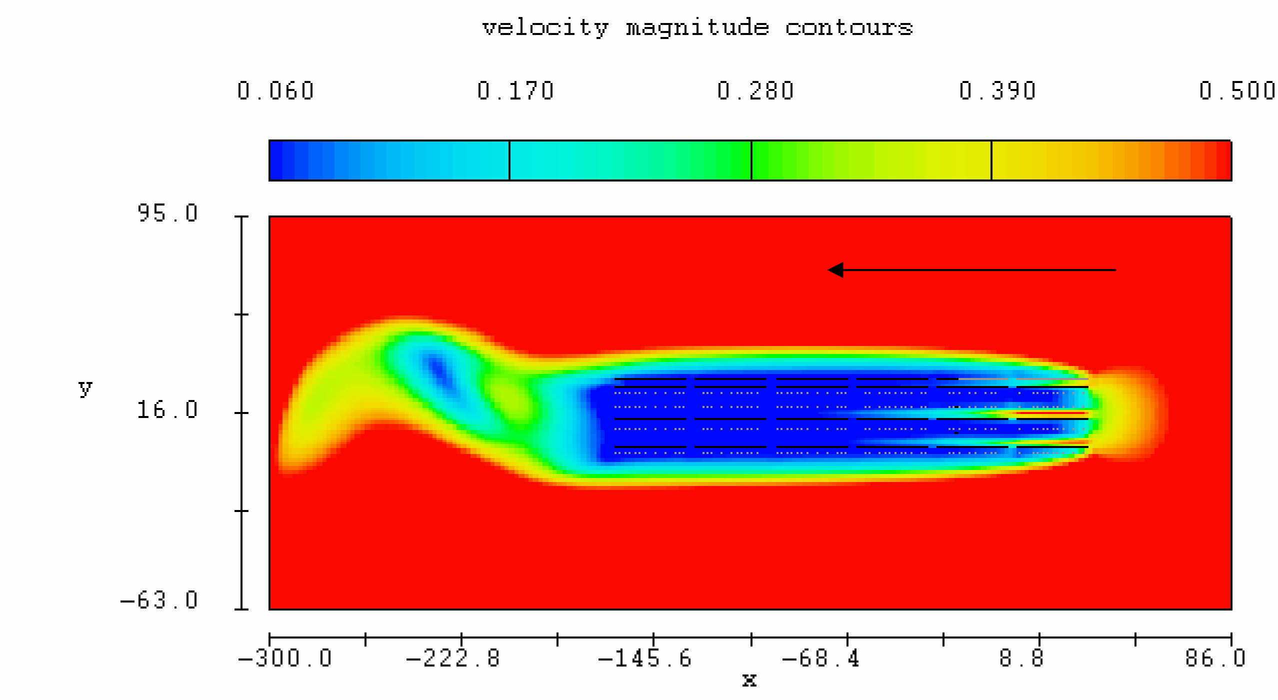


Figure 12: Calculated Flow Speeds within Aquaculture Raft
(dimensions are in ft, speed is ft/s, arrow shows nominal direction of flow)

Note: Results of the computations shown in Figures 11 and 12 represent nominal conditions existing in each of the eight raft strings that make up the Totten Inlet array shown in Figure 1. When the angle of incidence of the approach flow is about zero, as is the case in these calculations, the effects of adjacent rafts are minimal.

CHAPTER 6

Conclusions and Recommendations

Conclusions reached as a result of this study are as follows:

<u>Design of Rafts</u>

- Rope spacing used in the existing raft design is adequate for aquaculture within Totten Inlet. Phytoplankton concentrations in all parts of the raft string are substantially less than those measured in the surrounding waters. Therefore, an increase in the number of ropes carried by a single raft is not recommended.

- For the existing raft design: the number of rafts that make up a string (six) is maximum for flow conditions in Totten Inlet. If the number of rafts in a string were increased, then the number of ropes on each raft should be decreased.

<u>Orientation of Rafts</u>

- The existing raft array should be rotated 30 to 50 degrees to increase mean flow speeds within the raft array. Figure 15 shows results of a series of calculations where the direction of flow approaching the raft array was changed 90 degrees. Maximum velocities inside the rafts on average occur when the raft array is rotated between 30 and 50 degrees.

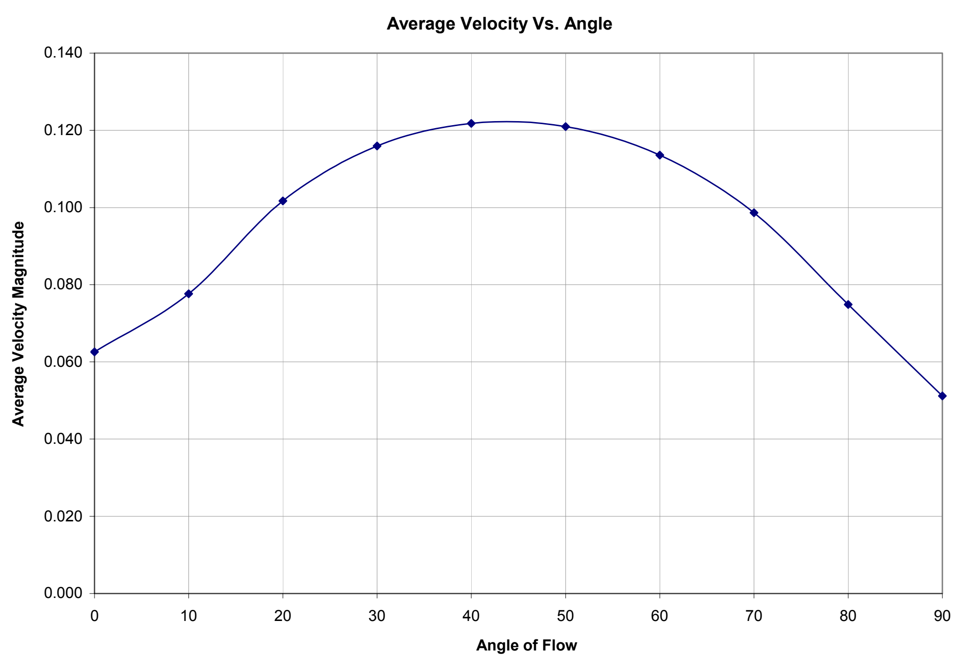


Figure 13: Average Flow Speeds Versus Approach Flow Angle
(angle of flow in degrees, speed is ft/s)

Based on the findings of this analysis, we recommend the following:

- Rotate the raft array 30 to 50 degrees to increase flow speeds through the rafts. By changing the positioning of the rafts more food would be provided to the mussels, thus, faster growth rates might be observed. Alternatively, if the rafts were rotated, then it would be possible to increase the seeding density of mussels per rope without reducing growth rates.

- Use ropes with pegs and biodegradable cotton sockings to more evenly distribute mussels, promote faster growth, and decrease drop-off.[2]

- Replace the small predator nets, with bottoms, with larger mesh nets, without bottoms, when the mussels reach a predator resistance size to fish. If this is not possible, then the nets should be changed more frequently to increase food supplied to the mussels (note: we observed significant reduction in flow and food concentrations inside the mussel rafts due to the predator nets).

[2] Mussel distribution along the mesh socks was uneven; with large bunches at the location of the inserted discs (see Figure A-3).

APPENDIX A: Photographs

Figure A-1: Totten Inlet

Figure A-2: Feeding Chamber

Figure A-3: Measuring Line Diameters

Figure A-4: Barge with Crane

Figure A-5: Mussel Line

APPENDIX B: Site Visit Summary

a. Introduction.

We performed a site visit from September 2-6, 2003 at the Taylor Mytilus galloprovincialis (Gallo) mussel raft lease area in the Totten Inlet, Puget Sound, Washington. The Gallo mussel rafts were composed of plastic floats, wood and aluminum pontoons, and 2x4 inch wood crossbeams from which the mussel droppers were attached. The mussel droppers, which were tied to the crossbeams, were composed of tubular mesh with coconut rope inside, and had discs attached along the line and cement dropper weights attached to the bottom. These 5m long lines were attached to 6 total rafts moored together in a line of 6 rafts per moored array. There were a total of 6 active arrays in the lease site. The rafts were surrounded (sides and bottom) by a predator net which was heavily colonized by fouling organisms.

Seed obtained from a hatchery (both diploid and triploid) were cultured on window screen PVC frames and seeded into tubular mesh socks for grow-out.

b. Tides

The semi-diurnal tides with a period of 24.8 hours were characterized by a low tide (-.3 ft.) at 5:00 A.M. on Sept. 3 followed by a high of 9.6 feet at 12:17, a low of 6.5 feet at 17:01, and a high of 10.8 feet at 22:37 A maximum flood tide occurred during the mid-morning during our site visit when we did profiles of current speed and chl a. A 25 hour period was chosen to encompass all tidal cycles for estimates of mussel raft consumption.

c. Data collection techniques.

We used an Interocean S4 current meter, a Sea-Bird 19 plus CTD with fluorescence probe, and YSI Sondes (2 from Maine, 9-3 to 9-5-2003, and 2 from PSI (9-11 to 9-14-2004) to collect data on the ambient currents and the distribution of chl a outside and around the mussel raft system. Current data was also collected during 2002 from the PSI group, as well as chl a concentration and data from these deployments is also included in this report.

i. The S-4 current meter was set to sample average speeds every minute during deployments, both off the wood boom 5m outside the rafts and inside the mussel rafts. Current data obtained from PSI in 2002 from locations inside and outside the mussel rafts was also used in the analysis.

ii. We measured chl a *in-vivo* fluorescence using a Sea-Bird CTD with a fluorescence probe in profile mode and for moored mode, we used two YSI Sondes. We measured chl a with all 3 instruments (1 Sea-Bird, 2 Sondes) at a location outside the rafts (2.5 m depth off the N boom) prior to each deployment, at which time water samples were taken for extracted chl a (PSI data). Previous deployments of the Sea-Bird in Maine have resulted in a 1/1 relationship between extracted chl a and in-vivo fluorescence. We noticed that the YSI Sondes had a lot of noise in the data, whereas the Sea-Bird was quite stable in its readings. This is probably because the Sea-Bird pumps a large volume past the probe while the Sondes depend on water passing by the probe. We also used Sonde data from previous PSI deployments to estimated chl a inside and outside the mussel rafts, based on samples taken every minute.

iii. We did a series of profiles upstream and downstream of the raft systems in the vicinity of the farm to determine if there were far-field effects of the raft system on chl a concentration.

iv. Consumption by the mussel rafts was estimated by determining the mean flow through the mussel rafts and the difference between chl a concentration inside and outside the rafts. The equation for consumption is: flow rate ($m^3\ h^{-1}$) x ln (c_o/c_t) where c_o is concentration of chl a outside the raft, and c_t is concentration of chl a by the time the water passes through the raft.

v. Mussel raft dimensions were measured with a tape measure and obtained from Taylor staff. The distance between each 6-raft array was estimated using a hand-held GPS. Mussel raft sock diameter was measured with a ruler over several representative locations along the mussel socks at the different rafts investigated. We used a crane scale to measure the weight of mussel socks in the water, and out of the water to determine the relationship between mussel weight in and out of the water. The biomass can be determined the following formula: mussel live wt/sock = ($weight_{water}$)*($weight_{air}$ / $weight_{water}$)* F where F = % of weight of sock out of water as live mussel biomass

d. Results

i. Current data taken with the S4 on the flood tide of the two raft systems are summarized in Figure B-1. Current speeds were measured at upstream boom locations (outside data locations in Figure B-1) and at two locations inside the raft strings (*i.e..,* the second raft in – inside 1, and in the center of the "downstream" most raft – inside 2)at a depth of 2.5 meters.

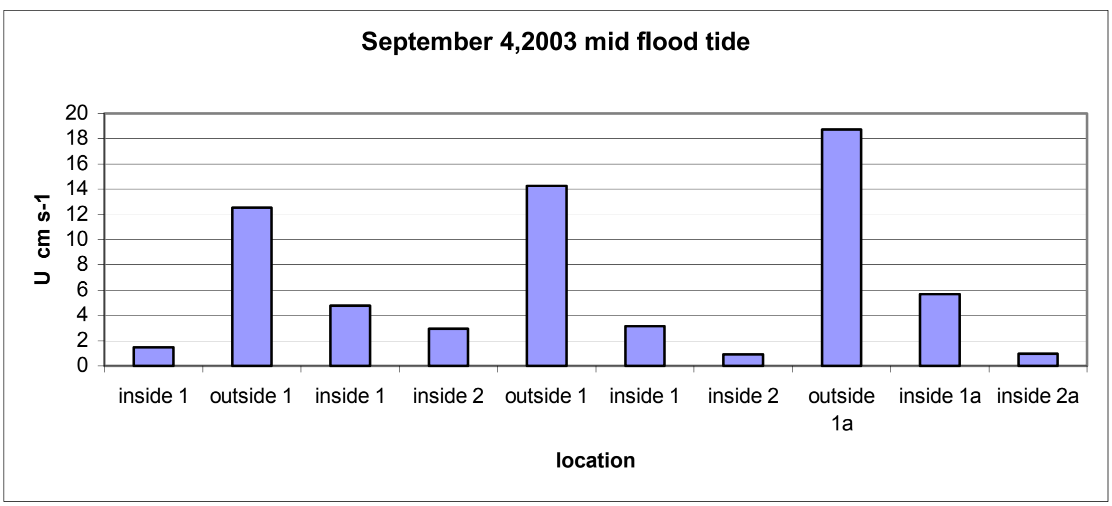


Figure B-1: Current speed on the flood tide relative to outside and raft location.

The ratio of current speed outside the raft for two series of measurements on raft arrays 1 and 1a relative to the inside of rafts 1 and 2 from the end at a depth of 2.5 m are presented in Figure B-2 (mean +/- standard error). Current speed is about 3.5 times lower inside raft 1, and about 13 times lower inside raft 2 than upstream of the raft system.

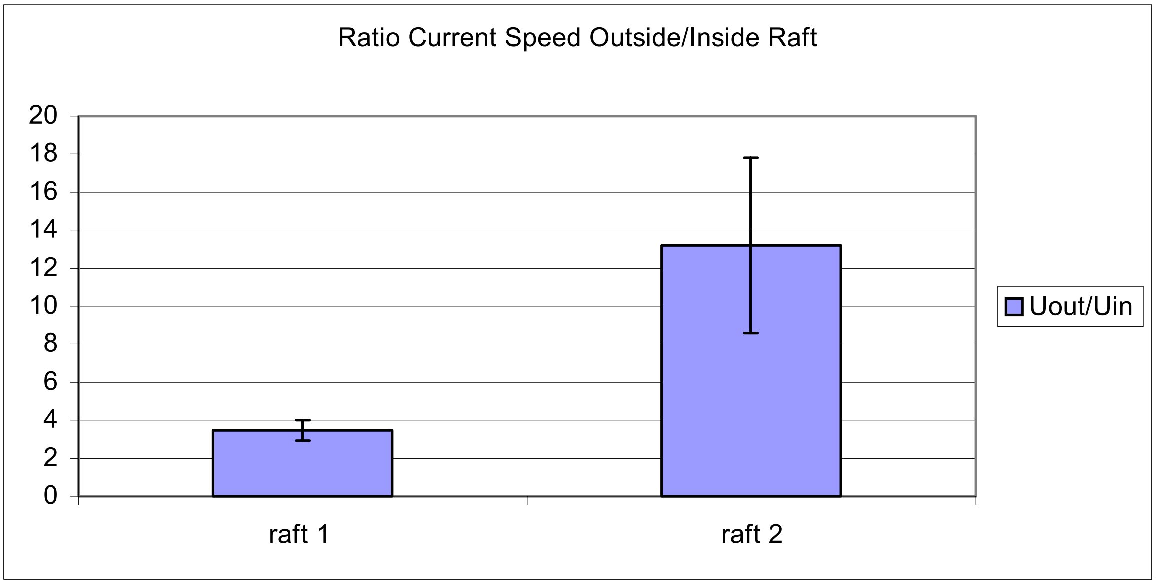


Figure B-2: The ratio of current speed outside/inside rafts for both systems combined.

ii. Sea-Bird profiles upstream and inside the raft systems are presented in Figure B-3.

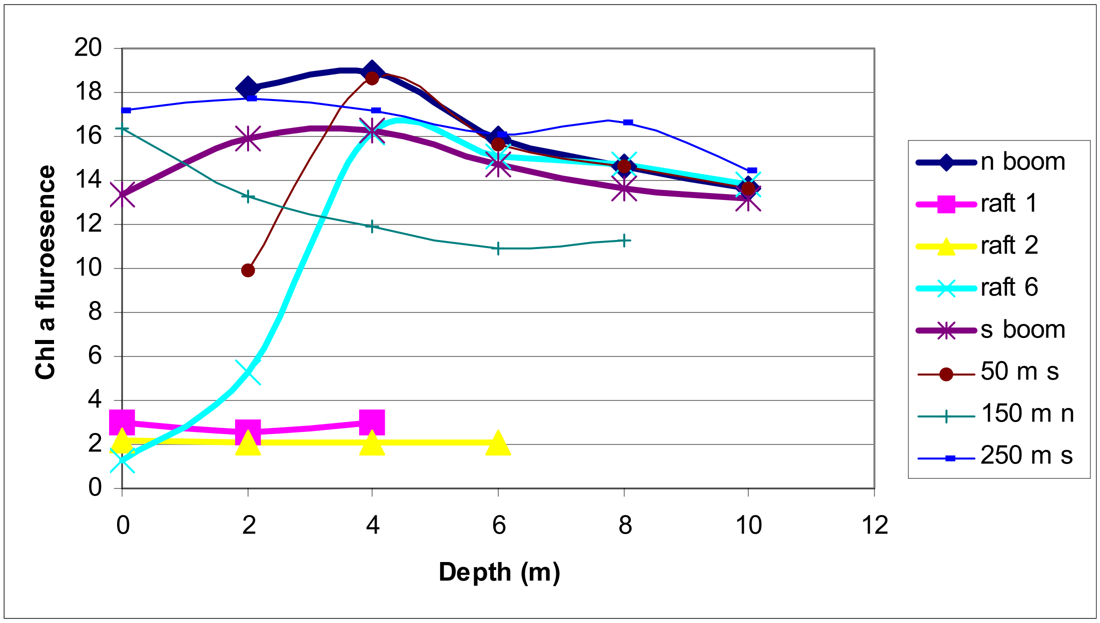


Figure B-3: Chl a on the flood tide upstream, in three rafts, and downstream of a six raft array

The ratio of chl a upstream to downstream is presented in Figure B-4. There was about 6.5 times as much chl a outside the raft then inside raft 1, and about 8.5 times as much chl a outside the raft than inside raft 2. Ln (co/ct) values of about 1.9 could be combined with flow rates through the rafts estimated by raft cross-sectional area times a mean flow speed of 3 cm s-1 to estimate mussel raft consumption.

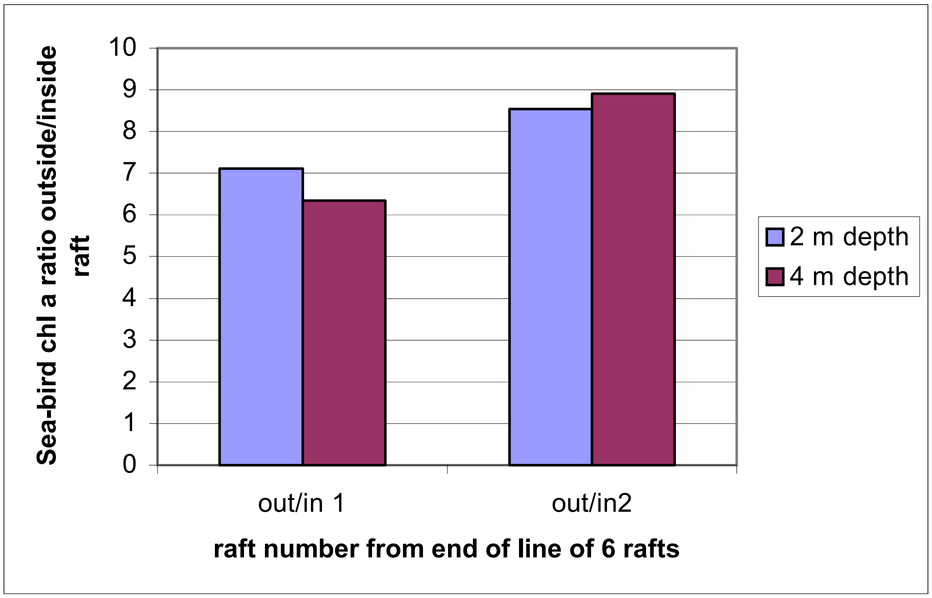


Figure B-4: Ratio of chl a outside/inside rafts 1 and 2m and 4m depth.

iii. Pacific Shellfish Institute current data was also provided for 2002 rafts of a slightly different design (2 instead of 3 pontoons). The data is presented in Figure B-5. The average velocity in 2002 was 3.8 times higher outside than in the center of the mussel raft array.

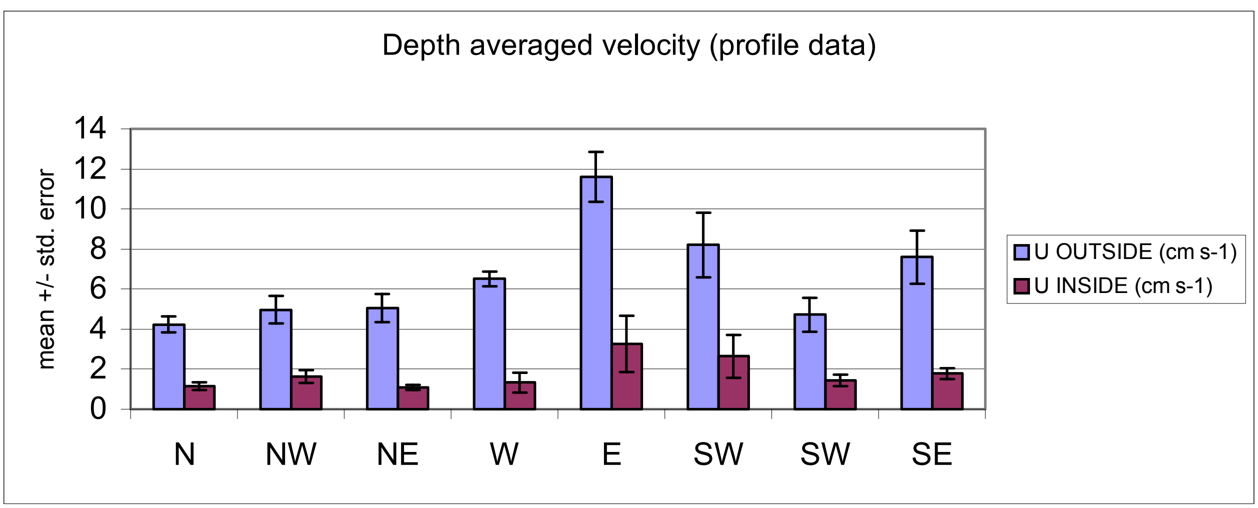


Figure B-5: Depth averaged velocity outside and inside mussel rafts in 2002
(values are mean +/- std. error for all depths at each location)

Current measurements at 3 different depths in the center of the middle mussel raft in November, 2002 are presented in Figure B-6. The mean velocity was about 3 cm s^{-1} for all depths.

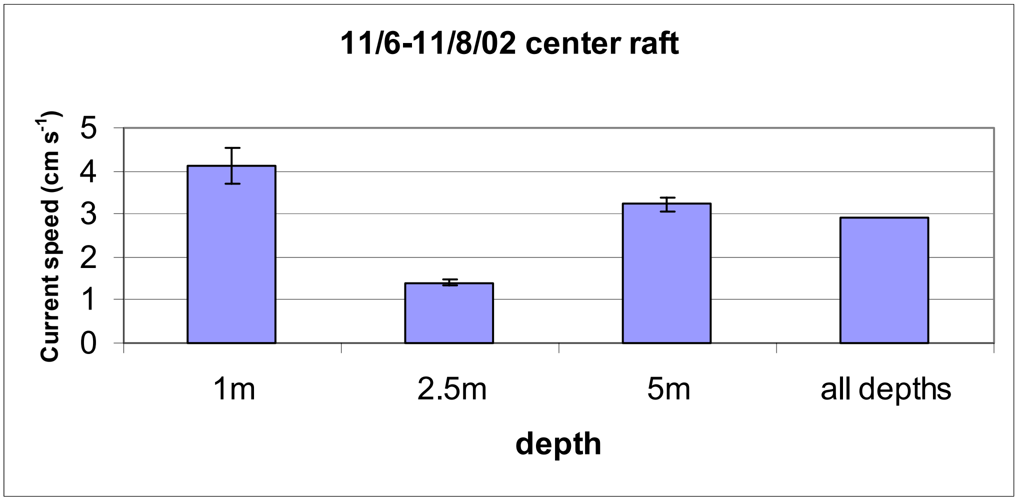


Figure B-6: Current speed at different depths in the middle raft of a 6 mussel raft array (values for 1, 2.5 and 5 m depths are mean +/- standard error)

iv. The current speed outside and inside a mussel raft with predator nets and without (nets actually dropped to the bottom, not removed) is presented in Figure B-7.

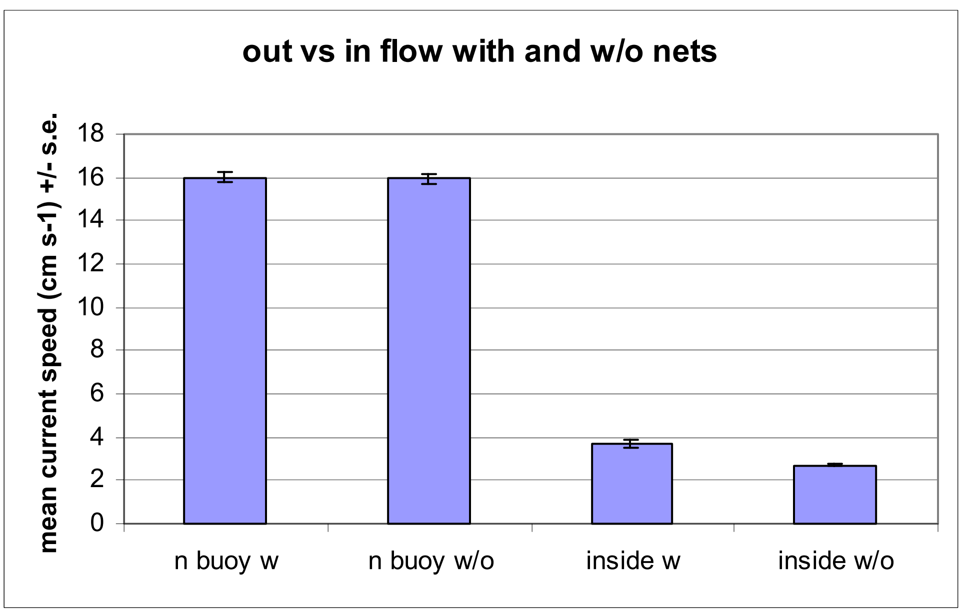


Figure B-7: Current speed outside mussel rafts and inside with and without predator nets (mean +/- std. error)

Graphs of current speed along the north buoy and inside with and without nets are presented in Figures B-8 through B-11.

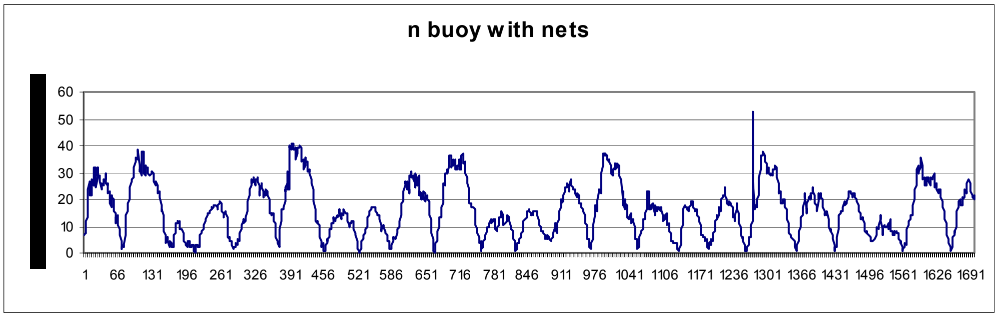


Figure B-8: Current speed at 2.5 m depth outside the mussel rafts in 2002 over 5.7 days

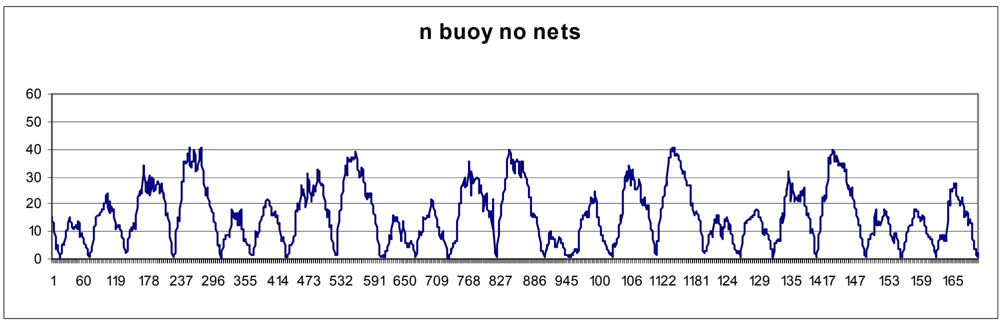


Figure B-9: Current speed at 2.5 m depth outside the mussel rafts with no nets over 5.7 days

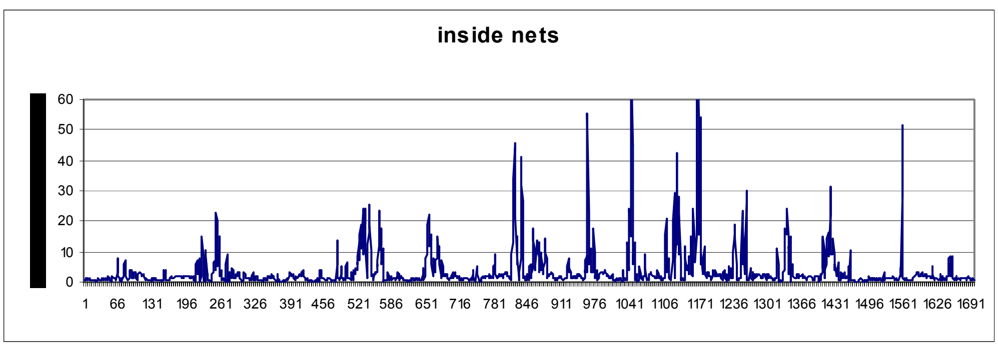


Figure B-10: Current speed inside mussel rafts with nets over 5.7 days at 2.5 m depth

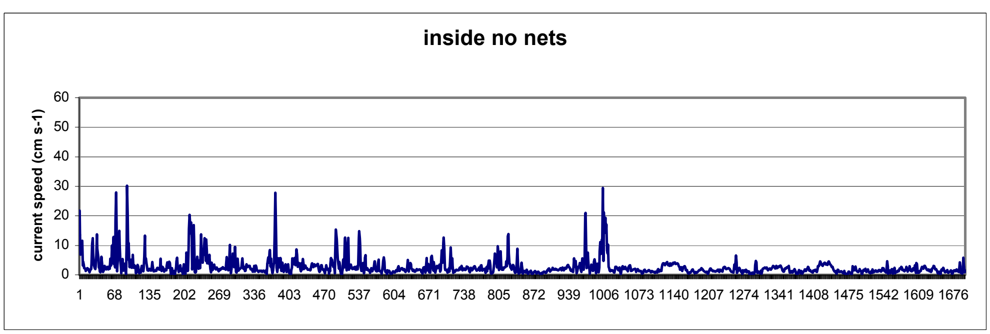


Figure B-11: Current speed inside mussel raft with no nets over 5.7 days at 2.5m depth

YSI Sonde data had problems with large spikes in the data, and long-term averages based on samples every minute were not used in the analysis. During our moored deployments with the site visit, two of the Sondes did not collect data so additional data was collected by PSI staff from Sept. 11-14, 2003. The data also has considerable noise (Figure B-12) and was not used in the analysis.

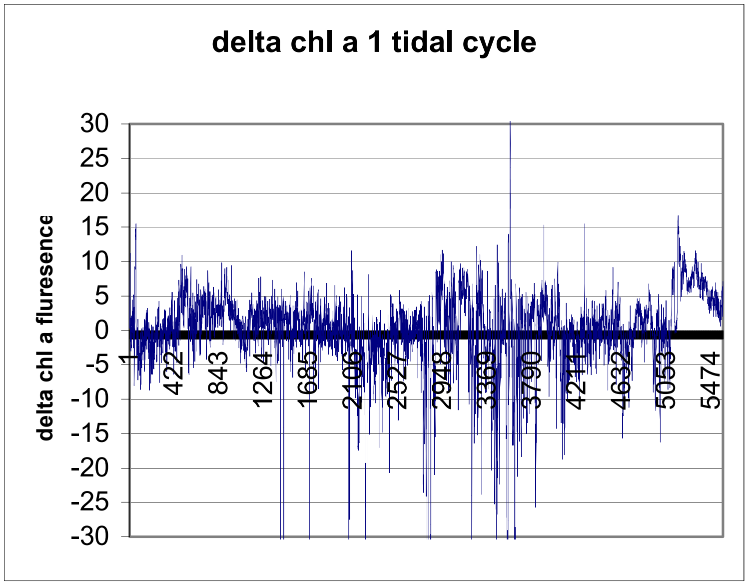


Figure B-12: Outside - inside chl a based on Sonde data from Sept. 11-14, 2003

e. Husbandry Recommendations

i. During our field trip, we observed significant reduction in flow and food concentration inside the mussel rafts due to predator nets. If the small nets with bottoms could be replaced with larger mesh nets without bottoms, as the mussels reach a predator resistance size to fish, much greater flow would provide more food to the mussel, faster growth rates, and less fall-off. If this is not possible, nets should be change frequently to increase food supplies to the mussels.

ii. Mussel distribution along the mesh socks was uneven, with large bunches along the inserted discs. Use of ropes with pegs and biodegradable cotton socking could provide for much more even distribution, faster growth and less drop-off.

APPENDIX C: Additional Graphics (arrows show nominal direction of flow)

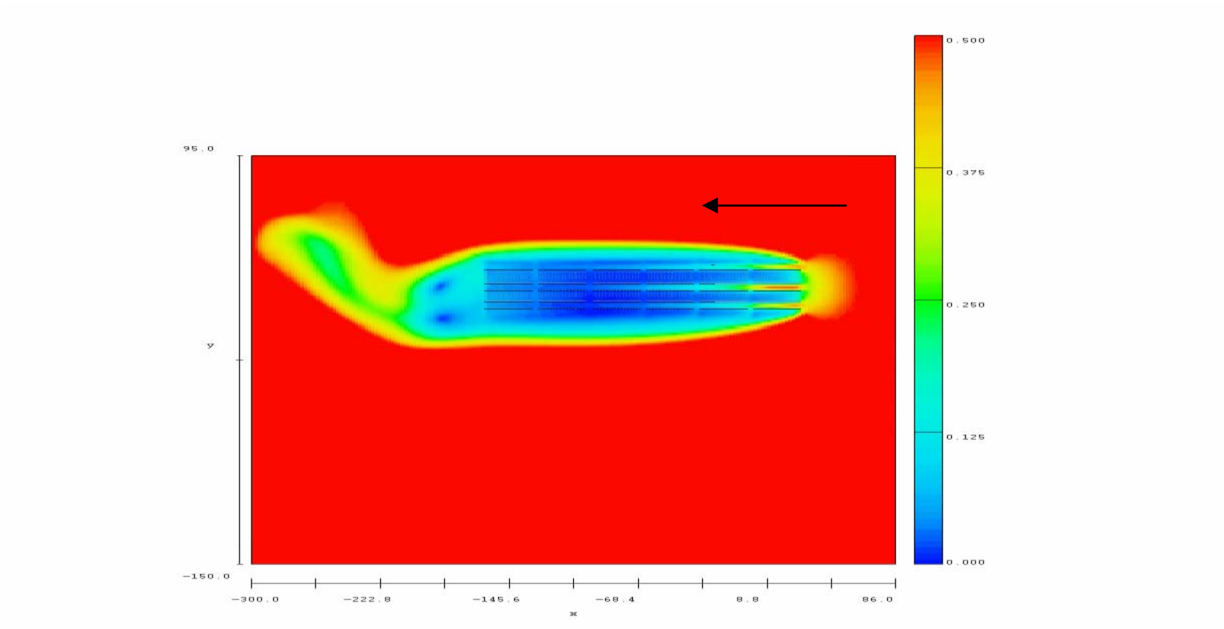


Figure C-1: Velocity Distribution, 0 Degree Angle of Incidence

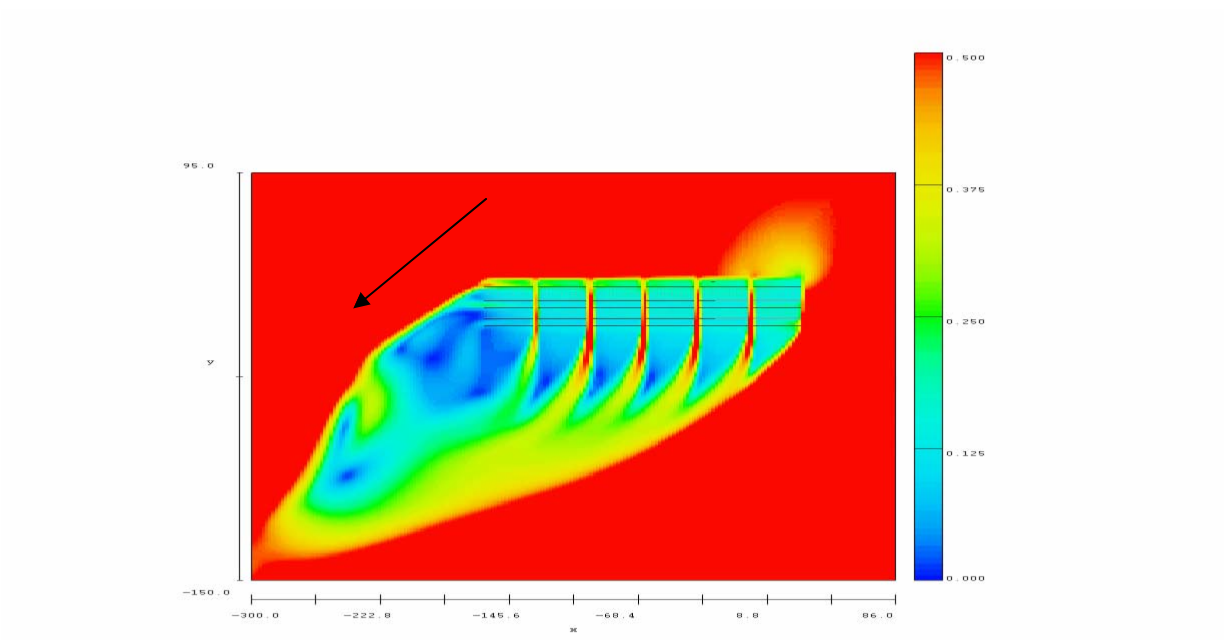


Figure C-2: Velocity Distribution, 45 Degree Angle of Incidence

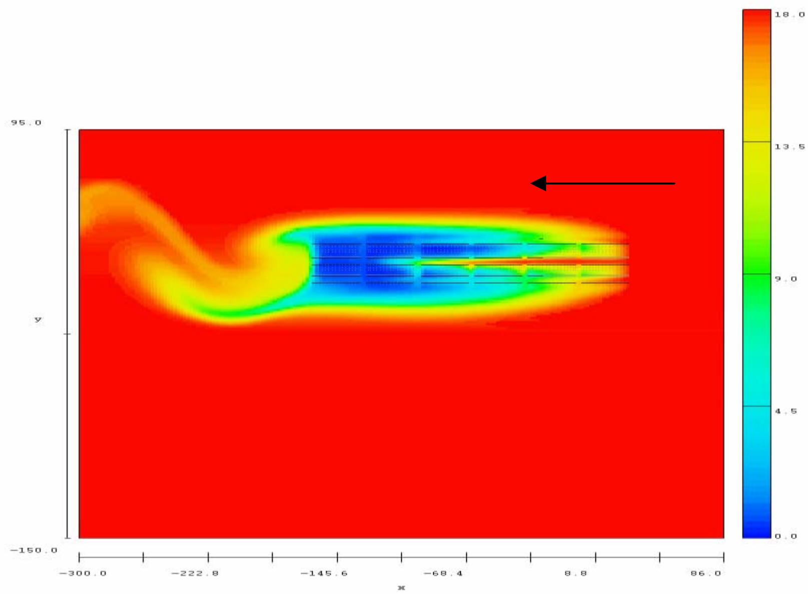


Figure C-3: Phytoplankton Distribution, 0 Degree Angle of Incidence

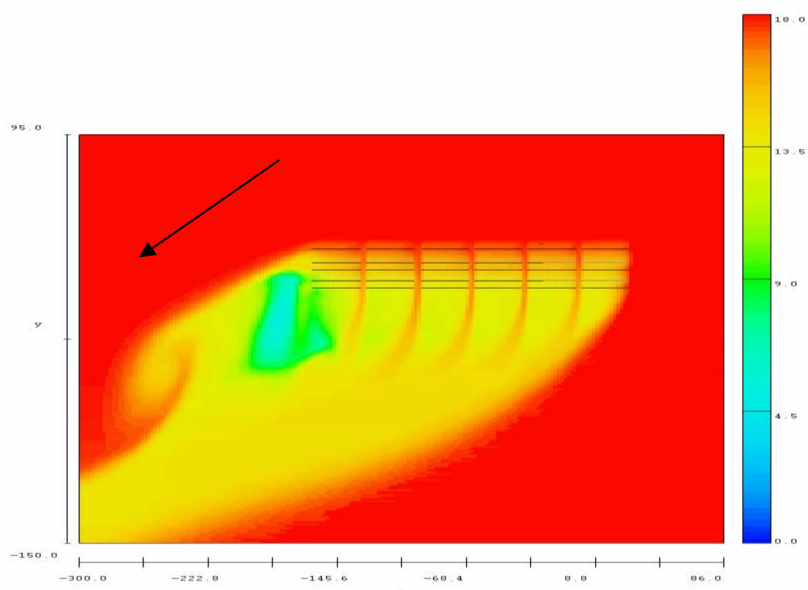


Figure C-4: Phytoplankton Distribution, 45 Degree Angle of Incidence

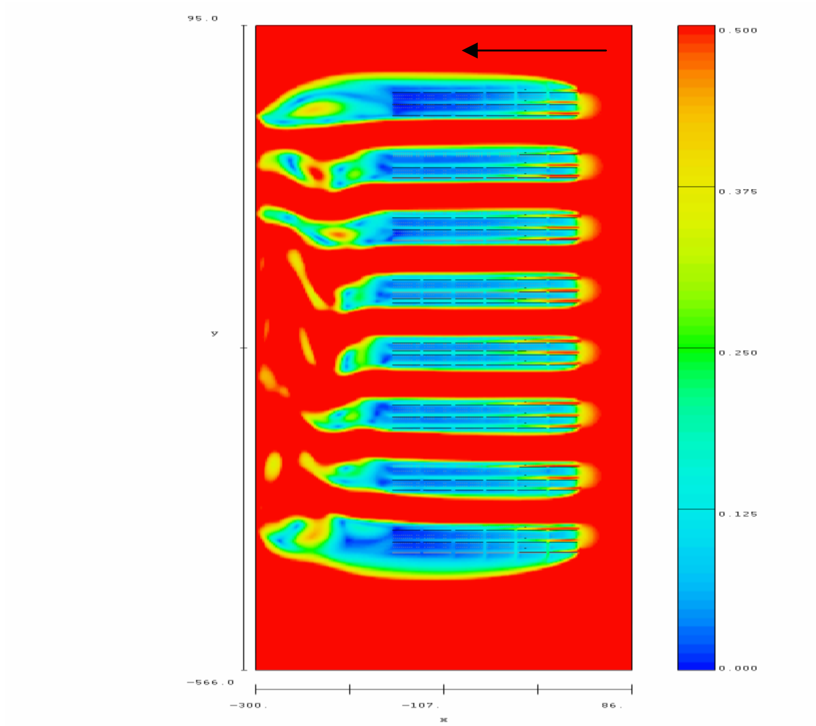


Figure C-5: Velocity Distribution, 0 Degree Angle of Incidence

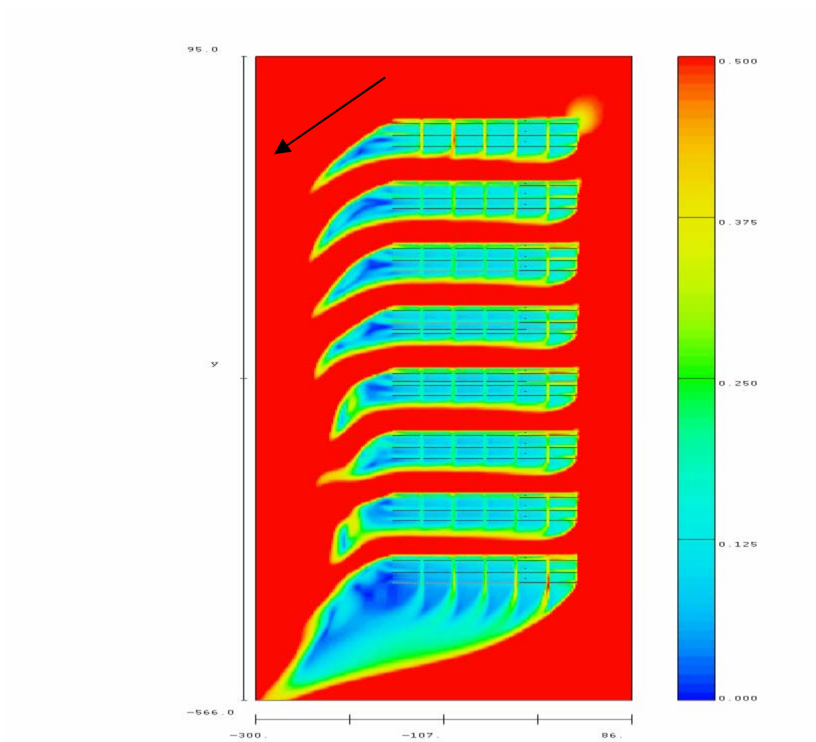


Figure C-6: Velocity Distribution 45 Degree Angle of Incidence

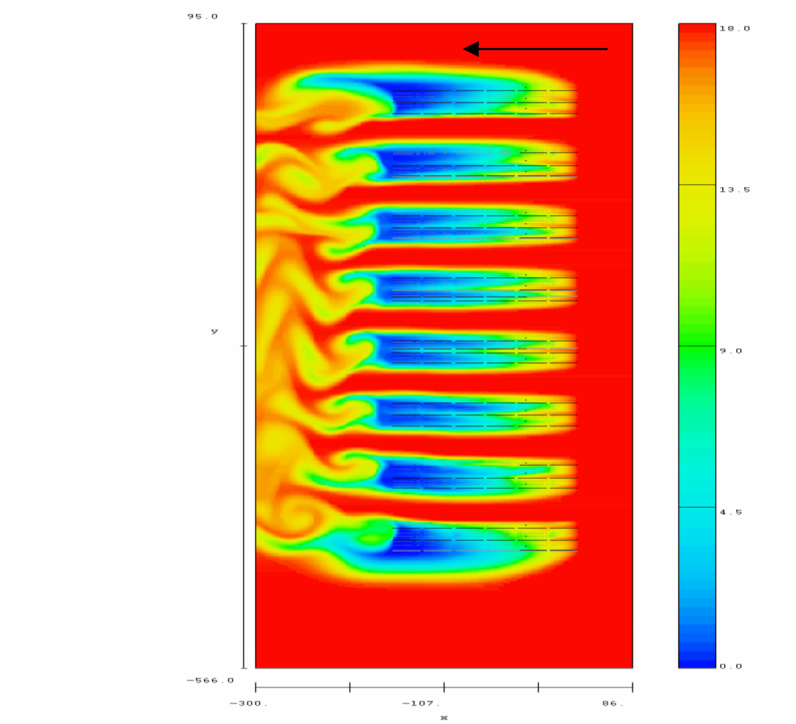


Figure C-7: Phytoplankton Distribution, 0 Degree Angle of Incidence

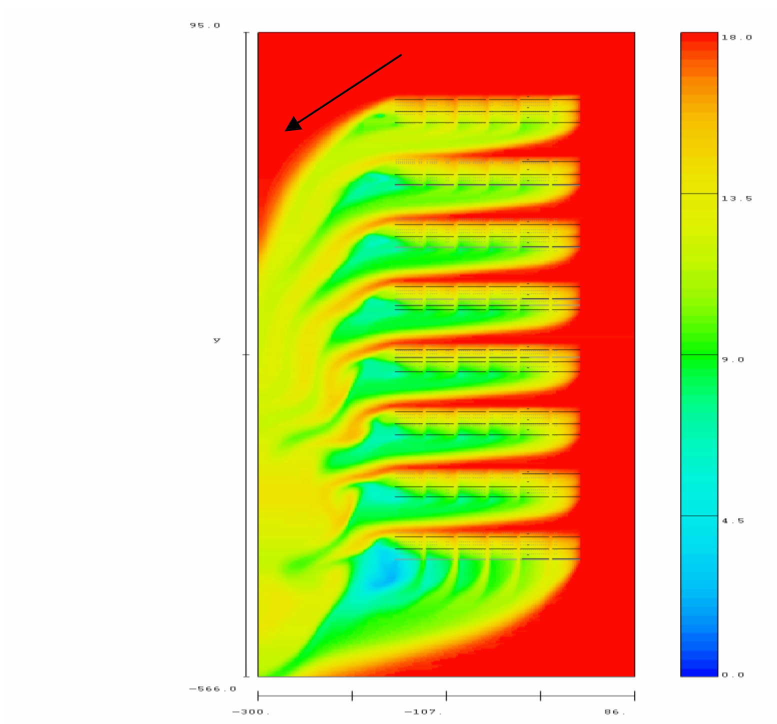


Figure C-8: Phytoplankton Distribution, 45 Degree Angle of Incidence

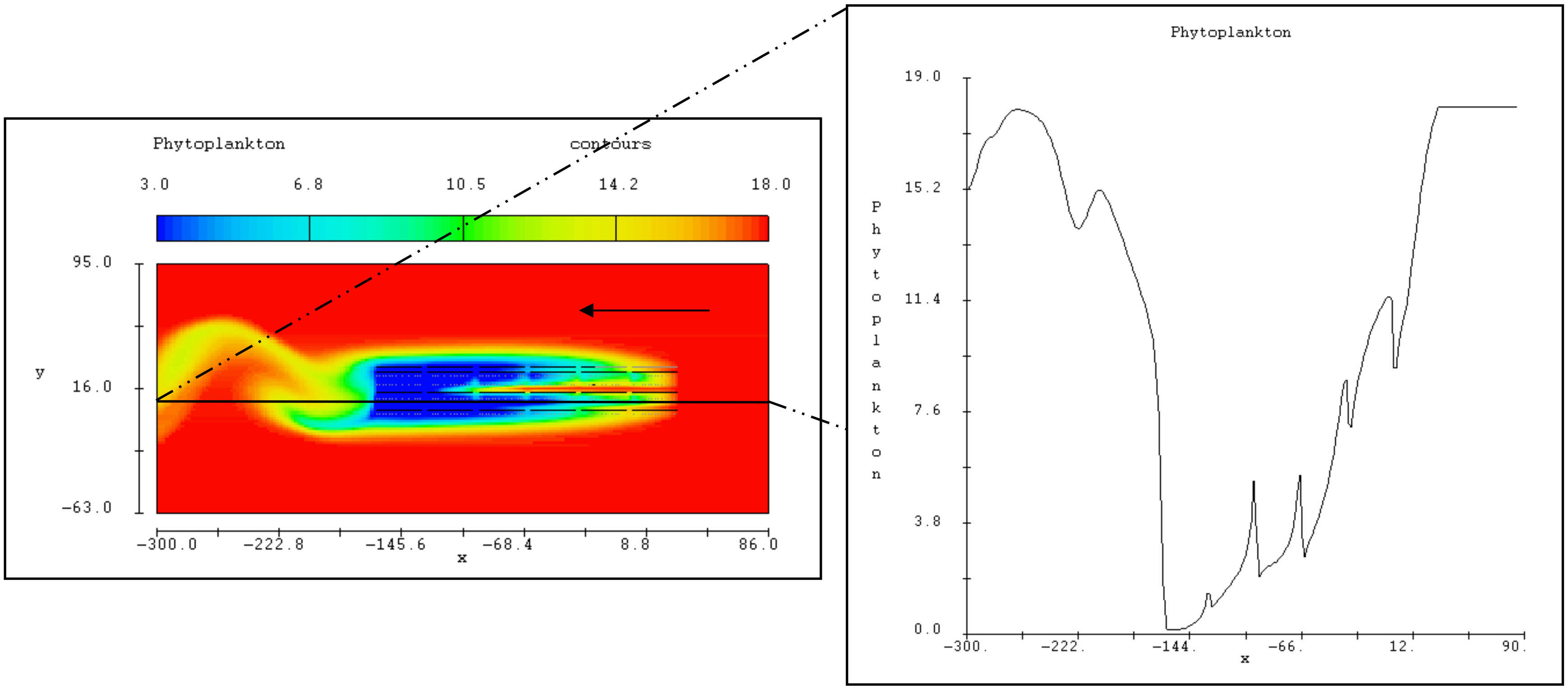


Figure C-9: Phytoplankton Distribution, 0 Degree Angle of Incidence

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