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Offshore finfish mariculture in the Strait of Juan de Fuca

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Abstract Finfish mariculture has existed in the U.S. Pacific Northwest for over thirty years, but for the past 15 years most effort has focused on culture of Atlantic salmon in protected, inshore cage sites. The Strait of Juan de Fuca（the "Strait"）is a large area with relatively sparse shoreline development and several apparent advantages for mariculture using offshore technology.

This study provides an overview of pertinent hydrographic conditions and possible water quality effects of marine or salmonid finfish culture in the Strait for commercial harvest or stock rehabilitation. Circulation studies, current and wave meter deployments, acoustic Doppler current profiles and phytoplankton assessments were conducted in three different regions distributed throughout the Strait near the southern, U.S. shore. Results were compared to existing inshore fish farms and analyzed with a simulation model（AquaModel）that accounts for growth and metabolic oxygen demands of caged fish and the response of phytoplankton to nutrients and grazing. An available benthic submodel was not used as current velocities throughout the water column and near the sea bottom far exceed known threshold rates for salmon farm waste resuspension. Such strong currents allow for dispersal of the organic wastes and their aerobic assimilation into the food web.

The field study results and modeling indicate no probable adverse effect of large scale fish mariculture in the Strait with regard to sedimentation or water column effects. Phytoplankton growth stimulation as a result of fish culture will not occur because nutrients do not limit microalgal growth. The area is naturally replete with dissolved inorganic nitrogen and sunlight is the primary factor limiting phytoplankton growth. Similarly, background nitrogen levels exceed half-saturation rates of seaweeds and farm plume dispersal is mostly parallel to shore in deep water so no effect on seaweeds is anticipated. Fish-killing harmful algae were rarely observed and then only in sparse numbers, although harmful Heterosigma akashiwo are known to occur throughout the waters of the Strait, Puget Sound and adjacent waters of the Pacific Ocean. Growing season phytoplankton abundance is much lower in the Strait than in nearby bays or Puget Sound.

Previously undetected and persistently lower sea surface temperatures were observed in satellite imagery for the central Strait region, especially during the summer and early fall. Surface-layer water temperature was positively correlated with dissolved oxygen concentration during the same seasons. Accordingly, there could be significantly reduced dissolved oxygen content of surface waters of the central Strait during this period, but this finding requires field verification. Eastern and western areas of the Strait may be marginally better for fish culture on this account, depending on fish species cultured.

We conclude that effects of marine fish mariculture on water quality or benthic conditions would be insignificant and that fish culture is technically feasible in the Strait. However, the high energy environment and challenging conditions will necessitate revised and novel management techniques to insure successful operations.

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Introduction

Though more than half the world's salmon and shrimp sold annually are now produced by aquaculture, very little of the marine white fish is farmed. As technical obstacles are overcome, many now believe that farming or stock enhancement of marine fish is a developing opportunity. It may be more than just a business opportunity; it potentially is the solution to a chronic problem of over-harvesting and resource depletion in many of the world's wild capture fisheries. But done improperly, mariculture could damage marine ecosystems and to deprive us of the seafood on which humans have come to depend. Modern, environmentally-sensitive aquaculture using low or no adverse environmental impact methods has been achieved at nearshore fish mariculture sites in Washington State (NOAA 2001, Rensel 2001) after environmental guidelines were adopted 20 years ago (SAIC 1986). A goal for the future of all mariculture is one in which our seafood harvests and the environment that supports them are in natural balance.

In recent years there has been increasing private and government interest in aquaculture "offshore" or in the "open ocean" in the nation's coastal waters. In some cases in the U.S. this could mean operating beyond the three mile State jurisdiction, in the Exclusive Economic Zone (EEZ) but in many cases, due to siting limitations of water depth, it would be nearer shore but in exposed locations. Advocates suggest that the only remaining opportunity for mariculture siting is offshore, due to space limitations and conflicting uses nearshore. Opponents raise several issues including nutrient enrichment and possible adverse benthic effects.

Already a few such offshore projects are operating in the U.S. as research or commercial businesses, mostly in Hawaii and Puerto Rico but more are being located overseas. Although not truly "offshore" in terms of distance from the coast, or being outside state or province jurisdiction, the Strait of Juan de Fuca (The "Strait") between Washington State and British Columbia is being considered for marine fish mariculture. The exposed, high energy nature of its waters means that offshore equipment and methods will have to be used if it is to be done successfully. Potential exists especially for the commercial culture and/or restoration of stocks of marine fish such as rockfish (*Sebastes* spp.), lingcod (*Ophiodon elongates*) or sablefish ("*blackcod*" *Anoplopoma fimbria*), culture techniques for which have now been developed (Ikehara and Nagahara 1980, Whyte *et al.* 1994, Clark *et al.* 1999, Rust *et al.* 2006).

The results of our study are reported in detail in a literature review and annual reports prepared for the U.S. NOAA Sea Grant Office that are all available via internet link in references (Rensel and Forster 2002, 2003, 2004). The literature review indicated that few multi-year hydrographic studies had been published for the western and central Strait and most were single year studies with monthly data collection. Studies conducted many decades ago, although done to high standards at the time, did not account for interannual and shorter temporal variation, which is known to be significant, as discussed below. Routine hydrographic monitoring of the eastern Strait began in 1999 and has shown some of this variability, such as occurred during a severe drought in 2000 and 2001 (Newton *et al.* 2003). Our sampling of the Strait began in the late summer of 2001, but as explained below, the system had apparently not returned to normal conditions by then. At that time we documented unusually low dissolved oxygen concentrations for surface and near surface waters in several locations. As a result, the subsequent years' work included a focus on dissolved oxygen conditions or surrogate measures, as discussed below.

Our study considered the siting of fish mariculture projects in the Strait in relation to key physical (water depth, tidal velocity and near-field circulation), biological (phytoplankton) and chemical factors (dissolved oxygen, water temperature and dissolved nutrient) conditions. Other biological issues such as effects of escapes, use of limited fish meal and oil or possible disease consequences are not discussed here. Socio-political aspects of mariculture siting such as competition with existing fisheries, avoidance of navigation lanes and concentrated fishing areas, maintenance of visual and auditory aesthetics for nearby shoreline owners, etc. are important too. However, they are not discussed in

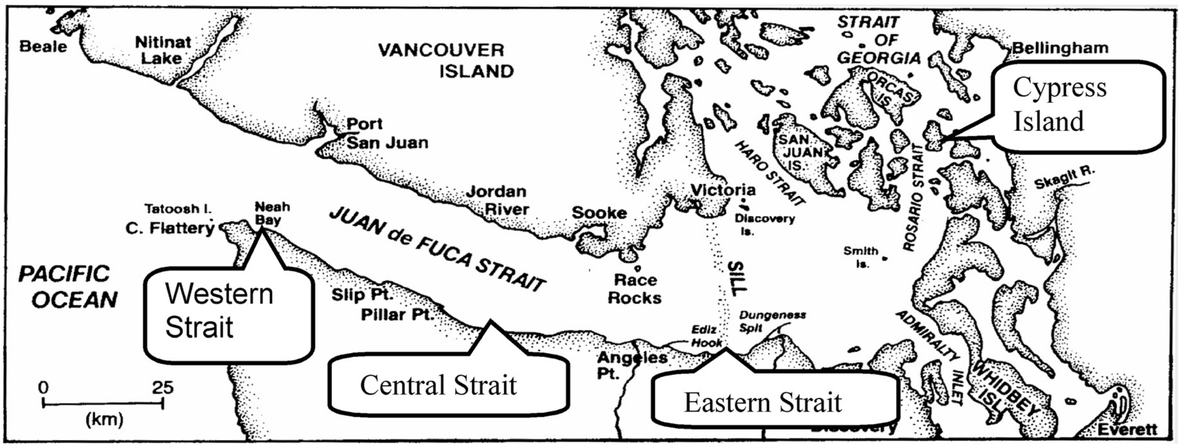

Fig. 1. Study area locations in western Strait (offshore of Neah Bay), central Strait (offshore of Whiskey Creek), Eastern Strait (offshore of Green Point to Morse Creek) and reference station at Cypress Island in North Puget Sound. Base figure from Thomson 1981, used with permission.

this paper except to the extent that our study areas were selected with prior knowledge that such areas were likely to be suitable with regards to these other considerations.

Fish mariculture is technically possible in many locations in the Strait but we selected three study areas, one each in the western, central and eastern Strait. These are referred to as 1) Offshore of Neah Bay, 2) Offshore of Whiskey Creek and 3) Offshore of Green Point (actually between Morse Creek and Green Point), respectively (Fig. 1). Also included for comparison was a reference area at Deepwater Bay, Cypress Island in north Puget Sound where fish mariculture has been practiced and environmentally monitored for several decades.

Additional details and literature reviews are reported in the underlying technical papers available from the primary author or from NOAA or at http://www.wfga.net/sjdf/index.html. Here we only include a partial overview of some of the results from our study in the 20 to 40 m depth zone of the subject area.

Current Velocities and Circulation

Current velocity is a primary consideration for fish culture in net pens both in regard to its effect on cultured fish and to potential impacts on the benthos and water column. Presently, sites considered optimal for fish mariculture in pens have current velocity in the range of 10 to 60 cm s^{-1} but varies within this range depending on size and species of fish, stocking density and pen design or configuration. Regular resuspension and dispersal of salmon farm wastes occurs at near-seabed current velocities in the range of $\sim$10 to 26 cm s^{-1} Cromey *et al.* 2002). Such dispersal allows the aerobic decomposition of wastes and avoids the extirpation of benthic infauna beneath of near net pens under optimum conditions.

At higher current velocity, fish may have to be sized appropriately and cage systems reinforced. At mean velocities lower than 5 to 10 cm s^{-1} (depending on the fish species and feed size) significant adverse sedimentation effects on the benthos are possible beneath or adjacent to the cages, although some sites in other areas may be episodically flushed by storm events. The minimal recommended average current velocity for near surface and midwater depths combined in Washington State is 5 cm s^{-1} (SAIC 1986). Other physical factors besides current velocity factors have a bearing on site suitability too, such as depth beneath pens, but in the Pacific Northwest and in Maine it is believed that current velocity is relatively more important than depth beneath cages to minimize benthic impacts (Cross 1993). Current and wave meters were deployed at all sites and acoustic Doppler current profilers with bottom tracking were used on vessels to survey during varying types of tidal amplitude cycles.

Drogue tracking was also used; see Rensel and Forster (2003, 2004).

Current velocity distributions for surface cage mean depth of 5 m in the western and central Strait locations were skewed with maximum velocity near 100 cm sec^{-1} (Fig. 2). Mean current velocity was ~32 cm sec^{-1} at both locations. At the location offshore Neah Bay, direction of flow was parallel to shore and equally distributed in both seaward (westerly) and easterly directions (50% each of total the 2,590 observations, directions within 180 degree arc of perpendicular bearing from shore) suggesting no net outflow during the winter time period. Net outflow at the nearshore locations sampled would be expected to increase in spring and early summer coincident with increasing river flow from the Georgia Strait-Puget Sound Basins. Periodic winter main channel and summer nearshore current reversals that last for several days are also not uncommon (Cannon 1978, Thomson et al. 2004).

A major difference between the Strait and inshore waters of Puget Sound is the temporal extent of slack tide between tidal phases periods, herein defined as periods of current velocity < 2 cm sec^{-1}. Offshore of Neah Bay slack tidal periods averaged only about one minute per day versus an estimated hour or more at a typical Puget Sound net pen site. In commercial fish mariculture, extended slack tide periods may result in depressed dissolved oxygen concentrations within the pens, sometimes causing damaging physiological stress on cultured fish. Offshore spar cages performed well in early trials offshore of Whiskey Creek in 1991 to 1993, as did the Atlantic salmon cultured within them (Loverich and Croker 1997). The strength and persistence of currents in the study areas are more than sufficient to prevent adverse benthic sedimentation effects, i.e., reduced benthic diversity and species composition changes. But such strong currents present challenges for mariculture operation and maintenance. Pacific Northwest fish farmers typically move cages, adjust anchoring systems and perform diving inspections outside of pens during slow currents or slack tides, conditions that are relatively infrequent in the Strait. The observed currents at our study sites, adjusted for deflection of currents (Inoue 1972), are also suitable for culture of appropriately-sized salmonids, but it is unknown how various sizes and species of marine fish species would respond to them. Effect of strong current velocity on marine fish culture is a topic requiring further research and experimentation.

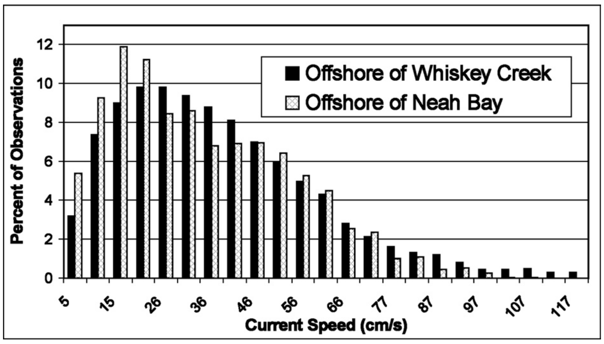

Fig. 2. Velocity distribution for 5 m depth (MLLW) current meter data offshore of Whiskey Creek and offshore of Neah Bay.

Wave Exposure

Wind waves and oceanic swell are major considerations for any form of mariculture. Oceanic swell is periodically encountered in the Strait, especially the west end, but large wind waves may be encountered anywhere in the Strait, depending on season and weather. Wind waves are particularly common in the afternoons from late spring through early autumn when westerly or sometimes easterly sea breezes funnel through the Strait (Renner 1993, Thomson 1994). Wave amplitude and frequency data offshore of Neah Bay were collected from December 2001 through January 2002 (Fig. 3). Significant wave height ranged from 0.2 to 2.2 m and was dominated by long period (~15 s) waves. These conditions do not exceed design criteria for several types of offshore cages. Moreover, wave frequency was not positively correlated with wave height (r^2 = 0.02), which means that large waves were not usually of short period that may be more destructive to mariculture facilities. Oceanic swell height estimates in the field were much less toward shore at 25 m depth, compared to further offshore at 50 m depth. This may be due to protection provided by Waadah Island, located immediately west of the study site.

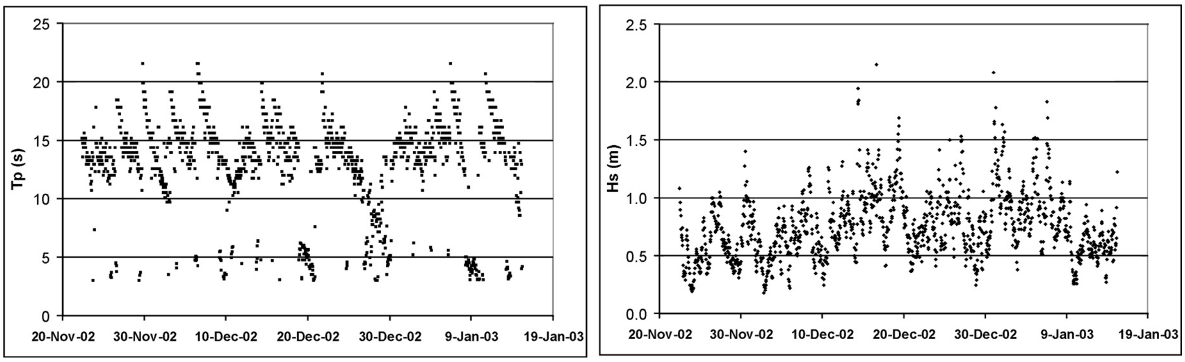

Fig. 3. Wave frequency (Tp, left) and significant wave height (Hs, right) offshore of Neah Bay during a two month period in the winter 2002-03.

Oceanic swell was also observed in the central Strait during our summer and fall field work but not in the eastern Strait on the same days. Significant wave height offshore of Whiskey Creek in a prior study in 1993 reached 3.6 m, but did not harm a prototype spar style offshore cage (Loverich and Croker 1997, Loverich and Forster 2000). Short frequency, choppy wind waves were relatively common during our field studies at all locations, particularly during afternoon hours. Modern offshore cage and anchoring systems should be able to survive all probable weather extremes at our study areas.

Water Temperature and Dissolved Oxygen Dynamics

The historical annual range of near-surface water temperatures in the Strait is approximately 7 to 12 C (e.g., Collias et al. 1974), more moderate than similar depths of north or central Puget Sound presently used for fish mariculture. The range is well suited to salmon and several other candidate marine fish species and is among the most moderate range of temperatures for all of temperate coastal waters of North America.

Dissolved oxygen concentrations in surface waters of the Strait follow previously documented seasonal and spatial cycles, peaking in late winter and declining during summer and early fall. In general, surface waters of the eastern Strait tend to have higher dissolved oxygen concentrations in the summer and fall than waters to the west, but at many times no consistent pattern is observable (Rensel and Forster 2002, 2003). We examined all available past surveys, studies and data reports, and could find no consistent trends within the central and western zones of the Strait at these times. Most prior studies were based on one year, once-per-month, multiple-day cruises or two year studies with less frequent cruises. Such monitoring is insufficient to describe the substantial change of dissolved oxygen that occurs in a few hours or a single tidal phase, as first noted by Herlinveaux and Tully (1961). Moreover, all prior published studies focused on deepwater areas, not in depths of 20 to 40 m as we did in our field studies.

A preferred approach to describe variability of dissolved oxygen in the Strait would have been to install moored instrument packages at several locations. But given the difficulties and cost of numerous such moorings, and the need to make repeated field observations of other factors, we chose two surrogate methods. The first was collection of vertical profiles of water quality during the potentially critical period of late summer and fall period in 2001 and 2002. The second utilized satellite sea surface temperature (SST) images, since it was shown that there is a strong positive correlation between near surface temperature and dissolved oxygen as described below. The former is reported in Rensel and Forster (2002, 2003) and indicated no significant differences among sampling locations. But the satellite SST approach yielded some interesting finds.

SST data was extracted from a transect located along the central longitudinal axis of the Strait between Neah Bay at the entrance to the Strait and Dungeness Bay at the eastern end of the Strait (Fig. 4d). In addition, the Strait was divided into 3 geographic regions (Western, Central, and Eastern Strait) for analysis purposes, and average transect temperatures for each region calculated from monthly composite satellite imagery.

Based on the SST satellite imagery analyzed, a persistent central Strait surface temperature reduction was noted for all months examined from May through October during 2001 and 2002. A persistent central Strait surface temperature reduction was noted for all months examined, when compared to the eastern and especially the western Strait (Figs, 4a and 4b). The feature is

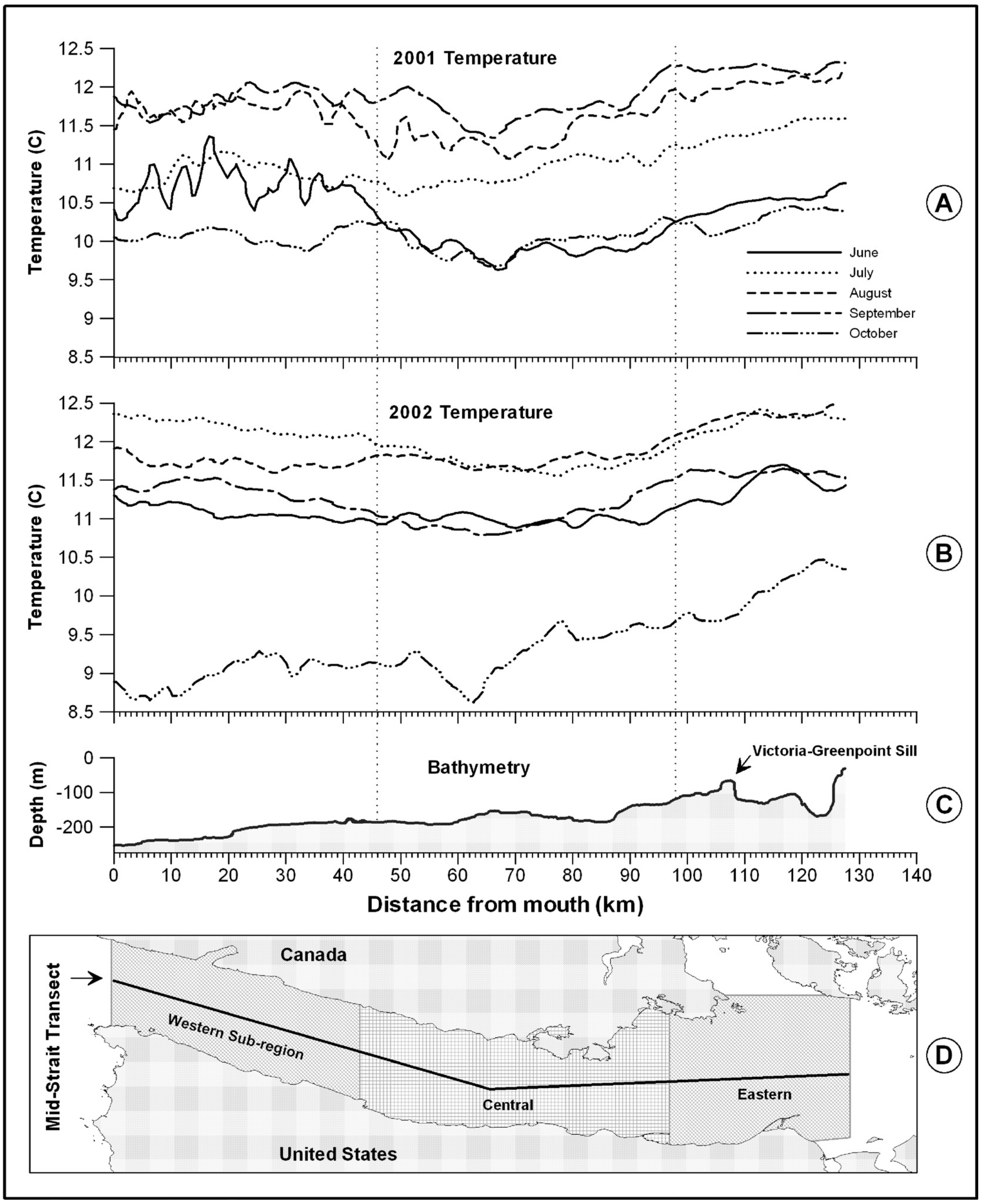

Fig. 4. AVHRR sea surface temperature imagery from the Strait of Juan de Fuca showing a lower temperature feature mid-Strait for a) 2001 and b) 2002 with c) bathymetry and d) transect sampled.

prominent in SST satellite imagery of the Strait and persistent to the extent of being visible in many daily and most weekly and monthly composites of the imagery (images not shown here due to color publication limitations). As much as a 1.5 to 3 ℃ temperature differential was observed in individual images, exceeding the 0.3 to 3 ℃ AVHRR SST error estimates noted above. In comparison, the eastern Strait had generally the highest SST results and the western Strait results were intermediate (Figs, 4a and 4b).

We compared temperature data from our field surveys using CTDs, previously discussed, to data from individual satellite images on the same days and same locations. There was an apparent lack of correlation between these data sources. There are several possible explanations for this. Satellite imagery provides an average temperature based on the pixel size of the imagery (1.1 km). A direct comparison between point data collected with the CTD and the average over a considerably larger area is necessarily going to yield differing results. In addition, the time differential between CTD data collection and satellite overpass was in some cases several hours, adding to the differential. Also, our field sampling locations were relatively close to shore where satellite imagery is less accurate due to interference from land. We would expect nearshore waters to be more variable and less vertically stratified due to more abrupt changes of bathymetry and the shoreline ruggedness that may enhance vertical mixing.

To our knowledge, there have been no prior published studies that have examined SST patterns in the Strait or mapped the extent of the surface temperature reduction we observed in the central Strait of Juan de Fuca persistently through the summer and fall months of our study in 2001 and 2002. The cause(s) of the temperature differential are unknown; however the bathymetry and cross channel profile of the central region may provide some insight. The single major bathymetric obstruction to deep flow in the Strait of Juan de Fuca is the Victoria-Green Point sill (Thomson 1994). The sill is located to the east of Ediz Hook in a region of slightly elevated surface-water temperatures (Fig. 4c). Circulation in the Strait is primarily estuarine, with cooler more saline oceanic water flowing inshore and eastward at depth, and warmer freshwater flowing seaward closer to the surface (Godin *et al.* 1980, Holbrook *et al* 1980, Thomson 1981). Supercritical turbulent flow over a shallow sill will cause deep water intrusions toward the surface during spring tides, particularly if density differences are minimal (Thomson 1994). Such phenomenon may be expected to vary on timescales similar or greater to a fortnightly schedule.

In addition to bathymetry, tidal cycle variation may influence the observed condition. Estuary to ocean exchange in the Strait is also thought to be modulated by tidal mixing and wind forcing that increases during neap versus spring tidal periods with greatest freshwater export during the neap tides (Griffin and LeBlond 1990). Monthly or bimonthly pulses of relatively warm fresh water have been documented traveling seaward from the western entry of the Strait (Hickey *et al.* 1991) although that particularly analysis was focused on the western entry to the Strait and adjacent oceanic waters off Vancouver Island. When we collated our data into neap vs. spring tide periods we did observe enhancement of the anomaly during spring tides and reduced intensity during neap tides, particularly during 2002 (the year with increased river flow).

Whatever the cause of the anomaly, apparent reduced water temperature in the central Strait may be biologically significant because as pointed out above, even a small temperature variation equates to a significant variation in dissolved oxygen. For example, using the 2001 regression ($y = 1.5186x - 8.3368$ where y = dissolved oxygen in mg/L and x is water temperatures in degrees C and $r = 0.92$) a decline of only one degree C water temperature from 10 to 9 ℃ results in a reduction of dissolved oxygen of 1.5 mg/L from 6.8 to 5.3 mg/L. For wild and particularly cultured fishes, these are significant changes.

Dissolved oxygen cycles have been observed at our reference station at Cypress Island, generally, but not exactly, correlated with the spring-neap cycles (Rensel and Forster 2003). In the case of the mid Strait anomaly, westward, estuarine flow of the surface layer may result in the shift of the surface water temperature anomaly to the west of the Green Point-Victoria Sill into the central Strait. Displacement of the feature so far to the west of the sill by tidal excursion may not be the only factor involved. Narrowing of the cross channel profile to the west of the sill and turbulence of high velocity flow near the south end of Vancouver Island may contribute by elevating the degree of vertical mixing. Occasional reversals of flow pattern allowing eastern transport of surface waters occur in winter and even summer (Thomson *et al.* 2004), although no low SST zone is persistently located to the east of the sill in the images we reviewed during the study periods of 2001 and 2002.

The low temperature anomaly we have observed and measured in the central Strait warrants further investigation. Other studies in the past (Herlinveaux and Tully 1961, Collias *et al.* 1974) have measured vertical diversion of deepwater toward the surface by the Victoria-Greenpoint sill particularly on the ebb tide, however such results are typically sectional views and do not indicate regular breaching of the surface layer. The feature is highlighted in satellite imagery because of the greater temporal and spatial coverage of a feature in context to the surrounding water masses and topography. The seasonal and interannual nature of this feature and linkages to other parameters such as dissolved oxygen and salinity should be investigated to further understand basic water quality conditions and effects on marine resources.

Phytoplankton and Harmful Algae

Few studies have documented the spatial or temporal occurrence of phytoplankton in the Strait. Fish mariculture interests have a special interest in phytoplankton and harmful algae as the former is a primary source of fish-sustaining dissolved oxygen in surface waters while the latter may cause occasional fish mortality (see Anderson *et al.* 2001 for case histories, Rensel and Whyte 2003 for overview of harmful algae and mariculture). In the Pacific Northwest, two genera of harmful algae have been involved in kills of wild or cultured fish.

Large blooms of the raphidophyte microflagellate *Heterosigma akashiwo* have caused occasional fish losses of mariculture fish and also wild fish in shallow bays. Blooms of *H. akashiwo* are somewhat predictable in north Puget Sound on a time scale of days, typically occurring during especially warm, sunny periods marked by neap tides and calm winds (Rensel 1995, Anderson *et al.* 2001). Second, large-bodied diatoms of the genus *Chaetoceros* (subgenus *Phaeoceros including C. concavicornis* and *C. convolutus*) are capable of killing wild and cultured fish at relatively low concentrations (Bell 1961, Kennedy *et al.* 1976, Rensel *et al.* 1989). In acute exposures, fish death is due to clogging the gill secondary lamellae with cells and excessive gill mucus production that interferes with respiration (Rensel 1993).

For the present study we collected 1 and 10 m water sample composites from all three offshore stations during our 2001 field studies. For comparison, samples at the same depths were also collected in the approximate centers of adjacent bays included Neah Bay, Port Angeles Harbor and Inner Dungeness Bay (1 and 5 m composite). Samples were preserved to 1% final concentration of formalin and later identified and enumerated using settled subsamples and an inverted microscope (Hasle 1978).

Overall, diatoms were represented by 55 species or taxonomic groups, dinoflagellates by 27 species and taxonomic groups, and microflagellates by 15 species, taxonomic groups or size classes. At the offshore stations, total cell counts were relatively low compared to the bays. Total diatom counts offshore averaged 1.2 x 10^5 cells L^{-1}, about an order of magnitude less than in the nearby bays that averaged 1.3 x 10^6 cells L^{-1}. A few *H. akashiwo* cells were seen in October 2001 at very low concentrations at offshore stations (mean 0.5 x 10^3 cells L^{-1}, fish death sometimes occurs at 75 x 10^3 cells L^{-1}). No cells were seen in Neah Bay or Port Angeles Harbor but 5 x 10^3 cells L^{-1} were observed from samples inside Dungeness Bay. A large bloom occurred in Puget Sound in late June 2006 after the completion of this study and the bloom was observed in the Strait out to the Pacific Ocean. In the eastern Strait the bloom was visible from an airplane survey very near the south shore, but not as prevalent offshore (K. Bright, pers. comm.).

Non-harmful species of *Chaetoceros* were dominant at the offshore stations composing 60.4% of the diatoms, with *C. socialis* more abundant than other diatoms. Inshore in the bays, non-harmful *Chaetoceros* composed 79.7% of the diatoms, followed by 7 species of *Thalassiosira* (9.9%) and Skeletonema costatum (5.3%). Approximately 2,000 cells L^{-1} of the harmful species Chaetoceros convolutus were counted from offshore of Neah Bay in early September but none were seen in additional samples from offshore of Clallam Bay at the same time. Such patchiness may be common with the harmful Chaetoceros in most cases. In vivo chlorophyll a measurements and laboratory extractions for offshore stations ranged from 1 to 4 $\mu g\ L^{-1}$.

Overall, we expect the offshore waters of the Strait to be more suited for fish mariculture in regard to less frequency of fish-killing harmful algae. Increased phytoplankton in the bays does afford somewhat higher dissolved oxygen concentrations during the summer and fall, but if certain species of marine fish are selected this may not be a primary consideration due to their lower respiratory requirements for oxygen.

Water Column Effects Modeling

We have developed a simulation model of marine fish farms to assess water column and benthic effects, as summarized at http://netviewer.usc.edu/aquamodel/index.html.

The model was imported into a marine, geographical information system called EASy (Environmental Analysis System www.runeasy.com developed by one of us, DAK), which provides a 4 dimensional framework (latitude, longitude, depth, and time) to run simulation models as well as to analyze field measurements as graphical and statistical outputs. Although several species of marine fish are candidates for future culture in the Strait, salmon were selected for this simulation since their physiology has been well studied, and they may be more sensitive to low dissolved oxygen. This salmon farm model is conveniently described in terms of 3 components: a growth and metabolic submodel of salmon within the farm, a plankton submodel that provides a description of the response to nutrient and oxygen perturbations caused by the farm and a 3 dimensional circulation submodel. The simplified version of the model is available on line for demonstration at http://netviewer.usc.edu/mariculture/mariculture.htm

The metabolic submodel of AquaModel is budgeted for the fate of carbon ingested by the fish; these include calculations of the rates of ingestion, egestion, respiration, and growth. Specifically, these rates are functions of the average weight of fish, the feed ration, the ambient temperature, oxygen concentration within the farm, and advective flow speed. The system of equations that describe rates of metabolism were obtained by fitting functions to the data found in the extensive literature on the growth and respiration of *Salmo salar* (Atlantic salmon) and *Onchorhynchus nerka* (sockeye) dealing with metabolic scope for activity including Fry (1947), Brett (1964, 1976), Brett *et al.* 1969, Brett and Zala (1975) and Smith, 1982.

Key features of the model are:

- The growth rate of the fish is determined by difference in the rate of assimilation of organic carbon (food) and the rate of respiration.
- The rate of carbon ingestion and assimilation is determined by a single most limiting factor: either the size of the fish, the temperature of the water, the food ration, the concentration of dissolved oxygen, or the swimming speed required of the fish within the farm.
- Because water temperature of Strait is slightly below the optimal temperature range for growth, the maximum growth rate of a 0.5 kg Atlantic salmon is calculated to be 0.01/ day, similar to that actually achieved in Puget Sound net pens for similar-sized Atlantic salmon and significantly below the maximum rate of 0.021 reported by Brett et al. (1969) for smaller sockeye salmon. In our model, the growth rate of the fish is reduced as conditions vary from near optimum.
- Respiration rates increase with swimming speed. Such increases in respiration cause decreases in growth rate when swimming speed exceeds the optimum range of ～ 1 to 2 body lengths per second.

- The supply of oxygen to the fish is described mathematically as the product of the rate of flow of water across the gills (respiratory pumping at low speeds and ram ventilation at high speeds) and the ambient concentration of dissolved oxygen.
- The rate of oxygen consumption by the fish is linked to the rate of carbon dioxide production by a constant flux ratio of 1 mole O_2/mole CO_2, and the rate of nitrogen excretion by the fish is linked to the rate of carbon dioxide production by a constant flux ratio of 1 gm-at N/7 moles CO_2.

The ideal rate of flow for culturing Atlantic salmon is not known precisely, but is probably about 1 to 1.5 body lengths per second. In a literature review, Davison (1997) concluded that training at 1.5 body lengths per second (bl s^{-1}) or less improved growth rate and food conversion for many teleost species, but cited some exceptions in the literature showing conflicting information for Atlantic salmon and other species. It can also be concluded with certainty that above optimum swimming speeds do not result in better food conversion and growth and we would estimate that this means above 2 bl s^{-1} for larger (> 500 g) Atlantic salmon. Salmonids do not require a rest period for optimum growth, survival and food conversion, continual exercise results in better growth than intermittent swimming (e.g., Azuma 2001).

A plankton submodel 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 (consisting of the sum of concentrations for nitrate, nitrite and ammonia as well as urea as oxidized to nitrate), organic nitrogen in phytoplankton, and organic nitrogen in zooplankton.

The three biological transforms consist of:

- photosynthetic assimilation of inorganic nitrogen by phytoplankton which is a function of temperature light levels, DIN concentration, and dissolved oxygen concentration
- grazing by zooplankton on phytoplankton which is a function of temperature and concentrations of dissolve oxygen concentration, zooplankton, and phytoplankton
- excretion of DIN by zooplankton, which is solely a function of the concentration of zooplankton

It is assumed that all three compartments 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 12 mg-at N-at m^{-3}, 2 mg-at N m^{-3}, and 3 mg-at N m^{-3}, 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 7 moles O_2 per gm-at N, consistent with the Redfield ratio. As indicated in the accompanying table, the inputs to this model consist of the time series of exchange coefficients produced by the circulation 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, and zooplankton.

The inputs to the fish farm model are the dimensions and location of the farm in the array, daily feed ration, the initial average weight and density of the fish, as well as the water temperature, and the time series of outputs from the circulation and plankton models. The outputs consist of a time series of the average rates of growth, nitrogen excretion, and respiration. The dispersion and BOD of egested, solid material (fish feces) is not considered since, as discussed above, the study areas are not depositional zone and the BOD is distributed widely in the deep layer or on the bottom.

The physical dimensions of the model are set by the user, and in our simulations the transport and transformations of variables was calculated for rectangular region or array that is aligned parallel to the coastline. The modeling domain is 10,000 meters in length, 2,500 meters in width, and 30 meters in depth. Figure 5 shows only the center of this domain. This region consists of a 3 dimensional array of rectangular elements each of which is 50 meters in length, 25 meters in width, and 5 meters in depth. The farm itself with dimensions of 50m x 25m x 10m occupies 2 of the elements, both in the center of the array with one at the surface and one immediately below. Water as well as the chemical and biological variables of the model are transported between adjacent elements of the array by advection and turbulent dispersion. The region is bounded by the air-water interface at its surface, by the 30 meter bottom, and by ambient waters along its 4 sides.

The circulation model is a simple finite element description of the movement of water and suspended and dissolved materials caused by advection and turbulent dispersion. Such circulation is described in terms of a box model in which flow occurs across 5 sides of those elements found at the surface and bottom and across all 6 sides of all other elements at intermediate depths deeper elements. Advective flow in the Strait is largely driven by semidiurnal tides that are oriented along the central axis of the array. Advection is constant with depth and occurs principally in the horizontal direction. We are able to run two types of simulation, one in which the time series of advective velocity was determined by the current meter records discussed above and another in which velocity was described by a sine function of 6-hour periodicity. Inputs to this model consist of the time series for advective flow, the depth of the surface mixed layer, and the dimensions of the region and location within the Strait. Outputs consist of exchange coefficients for advective and turbulent flow for all elements of the array.

Turbulent dispersion was parameterized as an exchange velocity whose value was some fraction of the speed of advective flow. Horizontal dispersion was assumed isotropic, thus the exchange coefficients of the 4 vertical sides of element were of the same value, 1/10th the advective velocity. However, vertical dispersion varied depending upon whether the element lies within the surface mixed layer or within the underlying water column. The vertical turbulent exchange velocity within the surface mixed layer was 10 times greater that its value in deeper waters, and the horizontal exchange velocity was 5 times greater than the vertical exchange velocity within the mixed layer. We have run simulations for winter conditions when the mixed layer extends to 30 meters, and summer conditions when the mixed layer extends only to 5 meters. The vertical exchange coefficients at the surface and the bottom of the water column are zero.

AquaModel provides several types of graphic displays of the dynamic 3-dimensional fields produced by the simulation model. These include plane 2-dimensional views of the waste plume produced by the farm at selected depths, 2-dimensional vertical transects or slices through the plume, 1-dimensional depth profiles at a given location, and time series plots of current speed, the mean growth rate of fish, and the concentration of any variable of within the farm.

Fig. 5 is a representative screen of selected outputs for the farm simulation model with oxygen selected as one of several available main screen views. It is a computational array for a virtual fish farm placed in surface waters offshore of Neah Bay at our study location.

The location of a virtual farm, which initially contains a concentration of 90 fish m^{-3} whose average weight is 0.5 kg, is marked by a central orange-colored rectangle. The resulting density of 45 kg m^{-3} is approximately triple the maximum loading achieved for S. salar in the past, but is used here intentionally to illustrate worst-case possible effects. Total biomass is set at about 0.6 metric tons for this single large pen simulation. Larger amounts of fish may be cultivated in an area, but presently offshore pens such as the Ocean Spar system are placed and moored separately, not in a series as with some nearshore pens. We show here a "snapshot" of the time series for a summer-time simulation during which the mixed layer is shallow, irradiance is sufficiently high to drive driving optimal rates of photosynthesis and grazing within near surface waters. The orange to green plume shows the horizontal distribution of waters with concentrations of dissolved oxygen that are below ambient concentrations. Such a plume is caused by the passage of water through the farm and subsequent mixing with surrounding waters. During a simulation the plume will spread toward the east during the flood tide and then recede and spread to the west during ebb tide. The magnitude of the oxygen reduction within the plumes will vary with tidal flow; highest during slack flow and lowest during peak tidal flow. These changes are complex and not only depend upon cumulative effects of the near-term history of advective and turbulent transport within the array but also depend upon the cumulative effects of the near-term response of the fish to the changing conditions.

The longitudinal red line is a transect placed (and easily moved) to measure conditions through the centerline of the plume; it yields a vertical transect of oxygen vs. depth that is shown in the lower left. At this time in the simulation the graph shows the concentration of oxygen is lowest within the pen which extends to a depth of 10 m. The other X-Y plots display a vertical profile of oxygen within the center of the farm (at the red dot, also moveable), the time series of the rate of advection (current velocity), and the instantaneous rate of growth of the fish over time.

Similar dynamic 3-dimensional views of the "farm's waste plume" may also be displayed concurrently for other variables of interest such as nitrogen, phytoplankton and zooplankton. Since the excretion of dissolved inorganic nitrogen and urea by the fish in the farm is proportional to the rate of consumption of oxygen, the "waste plume" is enriched in nitrogen, and its spatial distribution closely resembles that of the oxygen-deficit waters. The distribution of phytoplankton and zooplankton are unaffected by the farm as discussed below.

Analyses of Model Simulations

We have run the fish mariculture model for summer and winter conditions, and examined the results in terms of three key questions.

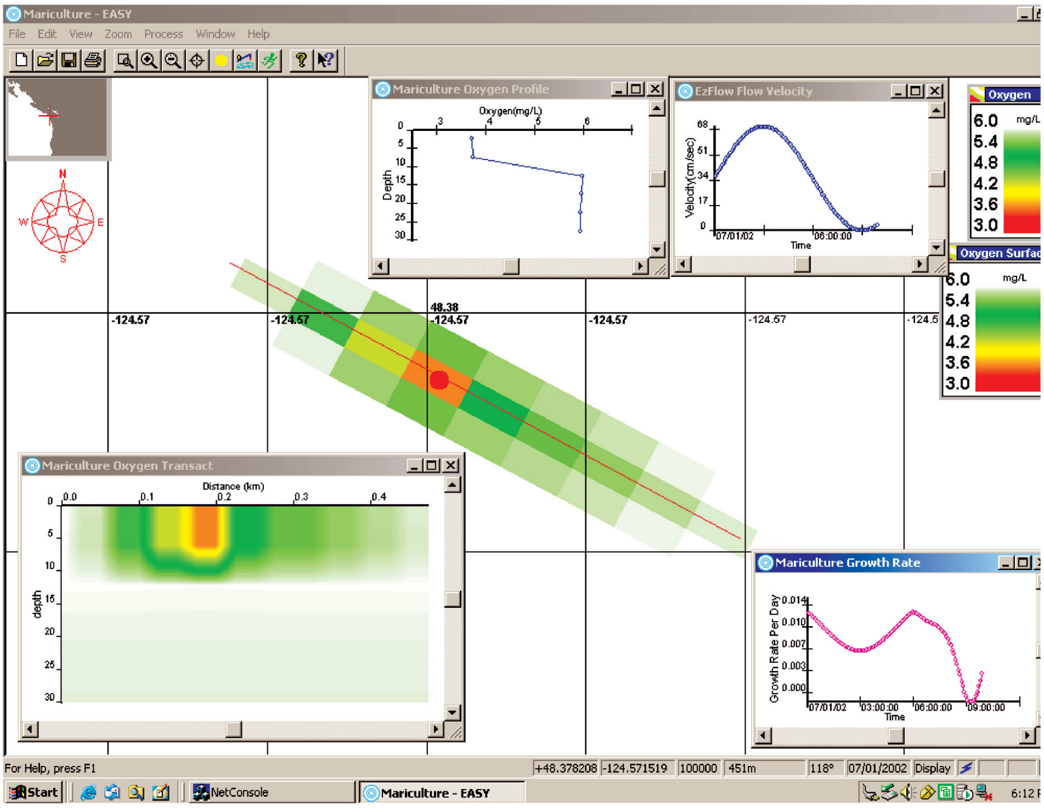

Fig. 5. Screen view of outputs from the simulation model showing just a few of the possible plots or profiles available for display and output to file. See text for explanation.

First, will the operation of a single farm stimulate algal blooms within the farm's nutrient enriched waste plume? Our simulations produced no phytoplankton enrichment much less a bloom. This result is easily explained by the fact that the ambient concentration of the limiting nutrient in the Strait, dissolved inorganic nitrogen, is much higher than the concentrations that are know to limit phytoplankton growth (Bowie et al. 1985, Rensel Associates and PTI Environmental 1991, Mackas and Harrison 1997). Even though the concentration of dissolved inorganic nitrogen is higher in the waste plume than in the surrounding waters, there is no increase in the growth rate of phytoplankton, because their growth rate is already nutrient saturated. In addition, because rates of turbulent dispersion in the Strait are high, the residence time of the phytoplankton within the waste plume is relatively short, a few minutes to less than a day.

The second question is: will the operation of a single farm form an oxygen-depleted waste plume that is of significant ecological concern? Our simulations showed that during times in the tidal cycle when flow is slow the concentrations of oxygen within the farm are much reduced, sufficient to temporarily reduce the metabolic rate of the fish. However, the simulation also revealed that the oxygen-deficit plume extended less than 50m downstream. Both the short duration of slack water and horizontal dispersion once flow accelerates limits the spatial extent of the plume. Many measurements up and downstream of commercial salmon farms by Rensel (1989) and more extensively by Heinig (1998, summarized by Normandeau Associates and Battelle 2003) indicate that reduction of downstream dissolved oxygen is extremely infrequent beyond about 5 m downstream, usually less than 0.1 mg/L at 30 m distance and non-existent at 100 m downstream. Such oxygen and nitrogen production data and horizontal dispersion measurements from drift objects are used for model validation, along with other types of data.

Third, is the growth rate of salmon within the farm significantly affected by environmental conditions? Our simulations indicate that the growth rate of the fish in the farm is sensitive to both ambient and operating conditions. Specifically, growth rates decline as ambient current velocities exceed ~60 cm s^{-3} for fish of the size modeled here. The metabolic cost of swimming against the increased current diminishes the reserves that support growth. Furthermore, growth rates decline when oxygen concentration declines within the farm falls. This occurs during slack water when water exchange within the farm is diminished, and the condition is exacerbated when the tidal flow reverses direction, thereby sweeping water from the oxygen-depleted waste plume through the farm. It is also exacerbated by decreases in the low concentrations of oxygen of ambient waters that occur during summer and early fall when cold, oxygen-depleted water is upwelled or advected to the surface of the Strait.

Discussion and Conclusions

This study indicates that the high energy study zone near the south shore of the Strait of Juan de Fuca is suitable for finfish mariculture with minimal or even no measurable adverse effects on benthic or plankton components. Dissolved nitrogen concentrations are constantly high, while standing stock of phytoplankton is relatively low. Light limitation and some grazing are the factors that limit phytoplankton growth in the Strait. Benthic impacts from fish mariculture facilities will be transient and limited in extent, as resuspension and fast transport rates will rapidly spread fish fecal matter for long distances downstream of the pens where it can be decomposed and biologically assimilated. AquaModel simulations provided a useful tool to examine probable effects.

Although environmental impacts discussed above should be very limited, rigorous conditions found in the Strait during storms will challenge fish culturists and demand use of offshore technology and methods. Operation, maintenance, grading and harvesting procedures in the cold waters of the Strait will demand innovation and careful consideration. The species of fish likely to be reared in such cages may include marine fish that have not been cultivated in offshore cages in the past. They may have an advantage over salmonids with regards to oxygen requirements (e.g., Sullivan and Smith 1982), but their physiological performance and stamina in high current conditions is not known in some cases. Creative configuration and arrays of pens to reduce surface currents or stocking of relatively large fish may be means to deal with elevated current velocity effects.

There are other factors besides those considered here in siting of fish mariculture in the coastal zone of the Strait. For example, the south shore of the central Strait has very prolific kelp beds that generate large rafts of floating, senescent material in the late summer and fall. Test versions of offshore cages placed offshore of Whiskey Creek in 1991 where able to withstand forces generated by this material impinging on the nets for long periods. Other regions of the south shore have much less kelp and resulting flotsam. Mariculture siting must also consider native Tribal fishing, sport fishing and commercial fish and shellfish areas, recreational and commercial navigation use, habitats of special significance, marine bird and marine mammal habitat and shoreline residents' view and aesthetic concerns. There is precedence for dealing with site-specific topics such as these. Washington State government has promulgated monitoring requirements, operation guidelines, a programmatic impact statement and 2 sets of NPDES permits (SAIC 1986, WDF 1990, WDOE 1996, WDOE 2002) to document impacts based on ten years of annual impact monitoring that led to strict impact limits and rules. This regulatory experience and set of rules can be applied to fish mariculture in the Strait of Juan de Fuca, an area that appears to have several notable advantages for marine fish mariculture.

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