THE ENVIRONMENTAL EFFECTS OF FLOATING MARICULTURE IN PUGET SOUND

Donald P. Weston, Ph.D.[1]

School of Oceanography, WB-10
University of Washington
Seattle, Washington 98195

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Washington Department of Fisheries
and
Washington Department of Ecology

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[1] Current address: Science Applications International Corporation, 13400-B Northup Way, Suite 38, Bellevue, Washington 98005

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Deborah Penry - University of Washington, Seattle, Washington
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ABSTRACT

Mariculture, particularly net-pen culture of salmon and suspended culture of shellfish, has grown rapidly in Puget Sound and the potential exists for this growth to continue. This review attempts to assess the probable magnitude of environmental changes that may result from mariculture operations in Puget Sound. The environmental changes which have been addressed can be summarized in four categories. First, there are some adverse changes which are highly probable for most salmon or suspended shellfish culture operations. These would include the accumulation of organic-rich sediments beneath the culture structure, and the consequent effects on the benthic macrofauna community. Secondly, the potential exists for mariculture effects on water circulation, water quality, phytoplankton productivity and the introduction of exotic species. However, the likelihood of these effects and their potential magnitude is highly dependent upon site-specific conditions or the species cultured. Thirdly, there are several issues for which available data are inadequate for a conclusive determination of significance. These include: 1) the environmental effects of antibiotic usage; 2) alteration of the wild gene pool; 3) the capacity for a mariculture operation to serve as a disease reservoir for the infection of wild organisms; and 4) the proliferation of human pathogens in the vicinity of mariculture sites. These potential effects of mariculture have not yet been demonstrated, and the existence of such effects remains largely speculative. Finally, there is little likelihood that mariculture would adversely affect local abundance of fish and megafauna.

Water circulation - A culture structure placed in the marine environment will reduce current velocity in the surrounding area, particularly in the down-current direction. This reduction in current velocity will impair dilution and dispersal of wastes downstream of the culture operation. However, this effect is not likely to be significant except in cases of intensive culturing in an area with very restricted natural circulation.

Water quality - Cultured organisms and culture practices alter the chemistry of the water passing through the culture structure, most notably increasing ammonia concentrations and decreasing dissolved oxygen concentrations. Greater

changes will occur with salmon net-pen culture than with mussel culture, given the relative production capacities of typical Puget Sound facilities.

The concentrations of nutrients and BOD in the water passing through a mariculture structure are generally very dilute compared to most other discharges to the marine environment. Field studies have typically observed little or no changes in water quality outside the culture structure in well-flushed areas. Adverse effects would be anticipated only in areas of extremely limited flushing or very intensive culturing activity.

Phytoplankton - Floating mariculture is unlikely to have a measurable effect on phytoplankton standing stock or productivity in most of Puget Sound. In the Main Basin of Puget Sound nutrients are not limiting to phytoplankton growth. Thus, additional nutrient input attributable to mariculture should have no effect on productivity. Nutrients may be periodically limiting in some vertically stratified area (e.g., Saratoga Passage), however, in many of these areas the dilution of nutrients which would occur prior to their utilization by phytoplankton would probably make any effect on productivity unmeasurable. A localized and measurable effect on productivity would be expected only in highly stratified and poorly flushed areas (e.g., some embayments of the southern Sound) in which the water passing through a culture structure could maintain its integrity with minimal dilution.

Sedimentation - Floating mariculture generates large amounts of solid wastes in the form of feces and unutilized feed (salmon culture) or feces, pseudofeces and shell debris (shellfish culture). These materials are generally deposited in the immediate vicinity of the culture structure. This deposition results in physical and chemical changes to the natural sediments including decreased redox potential, increased sediment oxygen consumption and increased concentrations of total volatile solids, total organic carbon, sulfides, nitrogenous compounds, and phosphates. While there are profound effects on sediment chemistry, and consequently the sediment biota, these effects are very localized. Visible accumulation of solids and the alteration of sediment chemistry typically extends no more than 30 m from the culture structure.

Accumulation of organic-rich sediments occurred around most culture facilities reviewed. The depth of this accumulation depends for the most part upon water depth and current velocity. In general, accumulation of sediments can be expected beneath any culture facility when less than 15 m exists between the bottom of the structure and the sea floor. Sediment accumulation is possible at even greater depths, but little data are available since few culture operations have been sited in deeper waters.

Benthic macroinvertebrates - The accumulation of organic-rich sediments beneath culture facilities and the consequent depletion of oxygen in the pore waters results in changes in the infaunal invertebrate community. Loss of species intolerant of organic enrichment (typically echinoderms, crustaceans and molluscs) often occurs. A few opportunistic species, most frequently polychaetes, attain numerical dominance in the community. In cases of extreme organic enrichment, there may be a total absence of benthic macroinvertebrates. Benthic community changes have been typically observed to be limited to an area within about 30 m of the culture structure. These changes can be expected to persist for the duration of culture activities and for at least several years following their cessation.

Fish and megafauna - Accumulation of organic material in the vicinity of a mariculture operation may result in the loss of nonmotile megafauna (e.g., geoducks) living in intimate contact with the sediments. However, fish and motile megafauna (e.g., crabs) living on or above the sediment surface are typically found in higher densities around floating mariculture structures than in the surrounding area. The attraction of fish and megafauna to the culture area is probably due to increased availability of food in the form of feed unutilized by the cultured fish, the high abundances of opportunistic macroinvertebrates, and epifaunal organisms living on the culture structure or which fall to the bottom.

Introduction of exotic species - If culture operations require the importation of live material into the state, the potential introduction of exotic species probably represents the greatest environmental threat posed by mariculture. Introduced species may establish self-sustaining wild populations, potentially becoming pests or eliminating native species. While there appears to be little risk of this occurring for those species currently being deliberately introduced for culture in Puget Sound, requests for future introductions should be carefully evaluated in this regard.

Accidental introduction of pests, parasites and diseases associated with imported organisms may also occur. Because of this risk the state has placed many restrictions on the type of organisms which may be imported and the steps which must be taken before live material destined for aquaculture may be placed in state waters. The adequacy of these regulations is currently being evaluated.

Diseases - Some concern has been expressed that the culture environment may serve as a reservoir for those diseases which are present in an environment but demonstrating no clinical symptoms in wild fish. There is a fear that the disease organism may proliferate among the cultured fish, become more virulent, and reinfect the wild stocks. However, there is no evidence to indicate that this scenario has ever occurred. The outbreak of a disease is often associated with some form of stress. In the culture environment, fish may be stressed by overcrowding, undernourishment, poor water quality and physical damage associated with handling and confinement. Thus, while fish held in culture are likely to show more frequent appearance of disease than wild fish, disease does not appear to be transmitted to the wild populations.

The bacterial diseases of salmonids in mariculture are not transmissable to humans. However, some investigators have questioned whether the organic enrichment of bottom sediments caused by mariculture could promote the growth of those species pathogenic to humans. Consumption of shellfish collected in the vicinity could then serve as a route for human infection. This is an issue where available scientific evidence is very meager, but experience to date has failed to show cause for concern. Increased bacterial abundance in sediments beneath a mariculture facility is quite probable, but it has not been demonstrated that this increased abundance is of any significance in terms of human health.

Genetic effects - The issue of the genetic effects of mariculture is largely speculative. Cultured organisms may be at a competitive disadvantage with respect to wild individuals. Thus, if escapes and interbreeding with the wild population occur, there may be some temporary loss of reproductive capacity in the wild population resulting from the production of less fit genotypes. The potential magnitude of this effect is dependent upon the proportion of the breeding population comprised of escaped animals.

The potential consequences of the interbreeding of escaped and wild organisms, if any at all, are unclear. However, for salmonids at least, the potential magnitude of the problem would seem minimal. For decades fisheries management agencies have routinely been transferring hatchery-reared salmonids between river systems to improve commercial and recreational fisheries. The number of fish which might escape from mariculture is negligable in comparison.

Toxicants - Salmon net-pen culture in Puget Sound requires the occasional usage of antibiotics, most frequently oxytetracycline. The potential environmental effects of this usage are minimized by the high water solubility of the compound, rapid dilution with the surrounding water and the infrequency of its use. Although, there is very little information available, the use of oxytetracycline does not appear to be a major problem at the present level of mariculture development in Puget Sound.

Modeling of Environmental Effects

Mathematical models are not yet available which provide reliable *a priori* estimates of the effect of mariculture on the receiving water body. As a short-term solution, a model is proposed to predict the changes in dissolved oxygen or metabolite concentration only in that parcel of water which passes directly through a culture structure. Since the model neglects the role of dilution by the surrounding water mass, it does not provide a definitive solution to modeling water quality. However, the model may have applications to site evaluation or the determination of maximum allowable culture intensity in a given area.

Sedimentation models would be valuable in predicting the depth and spatial extent of the accumulation of organic-rich sediments around a culture structure. Analytical models which predict this accumulation based entirely on properties of the settling particles and the moving fluid are beyond the current state-of-the-art. Empirical models are limited by site-specificity, but they represent the only modeling approach of immediate utility. A simple empirical model originally developed for net-pen culture of yellowtail in Japan is described. Given field measurements of particle settling velocity and current regime, the model is able to predict the depth of sediment accumulation as a function of distance from the culture structure.

Environmental Regulation of Mariculture

A review of environmental regulations pertaining to mariculture indicates that the policies of Washington State are generally comparable to those of many of the other states and countries surveyed. In general, the potential environmental consequences of mariculture are assessed on a site-specific and case-by-case basis. Applications for mariculture permits are usually subject to a review process which includes an opportunity for the responsible government agencies to evaluate potential environmental effects. There are typically few, if any, formalized criteria with regards to siting and operation.

Importation of eggs or live animals typically requires a permit from the responsible government agency. The permit will carry with it certain conditions which, depending on the particular state or country, may include restrictions on the country of origin, visual and/or pathological inspections, periods of quarantine, or disinfection requirements. Policies governing importation are tending to become more restrictive, and in several countries there is a total ban on the importation of eggs and/or live animals.

THE ENVIRONMENTAL EFFECTS OF FLOATING MARICULTURE IN PUGET SOUND

1.0 INTRODUCTION

Mariculture, the farming of plants or animals in marine waters, is undergoing a period of expansion in Puget Sound. For nearly a century, mariculture in Puget Sound has been largely limited to the production of clams and oysters by bottom culturing techniques. The commercial harvest of these species in the Sound is now at about 1,800 and 1,700 metric tons for clams (whole weight) and oysters (meat weight), respectively. Much interest has recently arisen in using the waters of Puget Sound for the culture of organisms other than clams and oysters. The culture of marine algae in the Sound has recently begun, primarily as a result of research by the Department of Natural Resources. The Department of Fisheries has been developing a hatchery for the production of geoduck seed which may be used to repopulate harvested beds. Mussel culture in the Sound began in the mid-1970s and is now practiced by a few private firms. Current annual production is about 140 metric tons. Several firms are also engaged in salmon culture, which first began in Puget Sound in 1969, currently yields about 1,500 metric tons per year, and now shows potential for rapid expansion.

Floating mariculture, or those types of culture in which organisms are suspended within the water column, shows the potential for the greatest growth in Puget Sound in the near future. Puget Sound lacks expansive areas of shallow water, thus the useable area for bottom culture is very limited. In addition, floating mariculture permits utilization of the three-dimensional nature of the water column, thus allowing a greater production per unit area. The types of floating mariculture with which this review is concerned are net-pen culture of salmon and suspended (i.e., raft or longline) culture of molluscs, particularly mussels. The culture of nori, a marine alga, is also a type of floating culture conducted in Puget Sound. It is not included in this review, however, since the technique is currently under extensive study by the Department of Natural Resources.

With the growth of mariculture in Puget Sound, increasing public attention has been focused on how culture activities may affect other uses of the Sound. This report provides a review of available information on the environmental changes which may occur as a result of floating mariculture. An effort has been made both to identify the potential effects and to assess their potential magnitude given the physical, chemical and biological conditions found in Puget Sound. The purpose of this study is to assist the public, regulatory agencies and the industry in planning the development of mariculture in Puget Sound. This report is intended to assist in the review of proposed mariculture ventures by identifying the issues of greatest concern and by providing the data base necessary to evaluate these issues. The information presented has been assembled through site visits to several mariculture operations, interviews with recognized authorities, and an extensive review of the scientific literature.

The placement of salmon net-pens or suspended mollusc culture in marine waters may affect the surrounding physical, chemical and biological environment in many ways. This report addresses the following potential environmental effects:

1) Changes in water circulation;
2) Sedimentation beneath the culture operation, particularly the accumulation of feces and excess feed;
3) Changes in water chemistry;
4) Alteration of phytoplankton biomass and productivity;
5) Effects on the benthic macrofauna;
6) Changes in species composition and abundance of fish and megafauna;
7) Introduction of exotic species;
8) Disease transmission from cultured to wild animals;
9) Proliferation of bacteria pathogenic to humans;
10) Changes in genetic fitness of wild stocks;
11) Use of antibiotics and effects on the surrounding biota.

Following a general description of salmon and shellfish culture practices (Section 2.0), each of the above potential effects is evaluated (Section 3.0). Each effect is discussed independently in order to simplify the presentation, but it must be recognized that many of the effects are interrelated. For example, changes in phytoplankton biomass and productivity are a function of water chemistry changes (e.g., input of nutrients). Benthic community changes are a result of the accumulation of sediments beneath the culture.

Section 4.0 describes mathematical models which may be useful in predicting the extent of environmental changes resulting from establishment of a mariculture operation. Models are presented which could be used to predict the extent of anticipated water quality changes and the dispersion of particulate material falling from the culture structure.

Section 5.0 reviews the environmental regulations of other states and countries which have been established to minimize the environmental effects of mariculture. These regulations include restrictions on siting, operational practices and the importation of live animals.

2.0 FLOATING MARICULTURE IN PUGET SOUND

2.1 SALMON NET-PEN CULTURE

The culture of salmon in floating net-pens in Puget Sound was begun in 1969 by the National Marine Fisheries Service (NMFS) at Manchester. Techniques were further refined in the early 1970s in cooperative experiments between NMFS and Ocean Systems, Inc. (now Domsea Farms). This early work demonstrated the feasibility of rearing both chinook and coho salmon to a marketable size within the confines of a net-pen.

There are presently 9 sites in Puget Sound where salmon are commercially grown to a marketable size (Figure 1, Table 1). A permit for an additional net-pen facility (Passage Silver at Bainbridge Island) has been granted, but pens are not yet in place. Many other net-pen applications are pending, particularly in Island, Jefferson, Kitsap and San Juan counties. Three net-pen operations in Puget Sound have failed (Aqua Seafarms, Weyerhaueser Co., Mariculture Northwest) because of market/finance problems, or the selection of sites with inadequate water exchange or recurrent phytoplankton blooms.

Some of the earlier net-pen operations in Puget Sound were located in sites that would now be quickly dismissed as unsuitable for salmon culture. Over the years operators have developed criteria to evaluate the physical, chemical and biological conditions at prospective sites. Some of the major criteria include:

Minimum current velocity - Current velocities adequate to supply oxygenated water to the net-pen and remove metabolic wastes, feces and excess feed are required. In general, a flow of at least 10 $\mathrm{cm \cdot sec^{-1}}$ outside of the net-pen is desirable throughout most of the tidal cycle (Kennedy, 1978; Leavens, 1983; Sutterlin and Merrill, 1978). Although occasional and short-term decreases below this velocity are acceptable (such as at slack tide), sites with consistently low current velocity are avoided.

Maximum current velocity - Excessive current velocities will cause the sides of the net-pen to distort and stress both the fish and the mooring system. Maximum current velocities of 50-100 $\mathrm{cm \cdot sec^{-1}}$ have been suggested (Kennedy, 1978; Leavens, 1983; Nyegaard, 1973; STOWW, 1974; Sutterlin and Merrill, 1978).

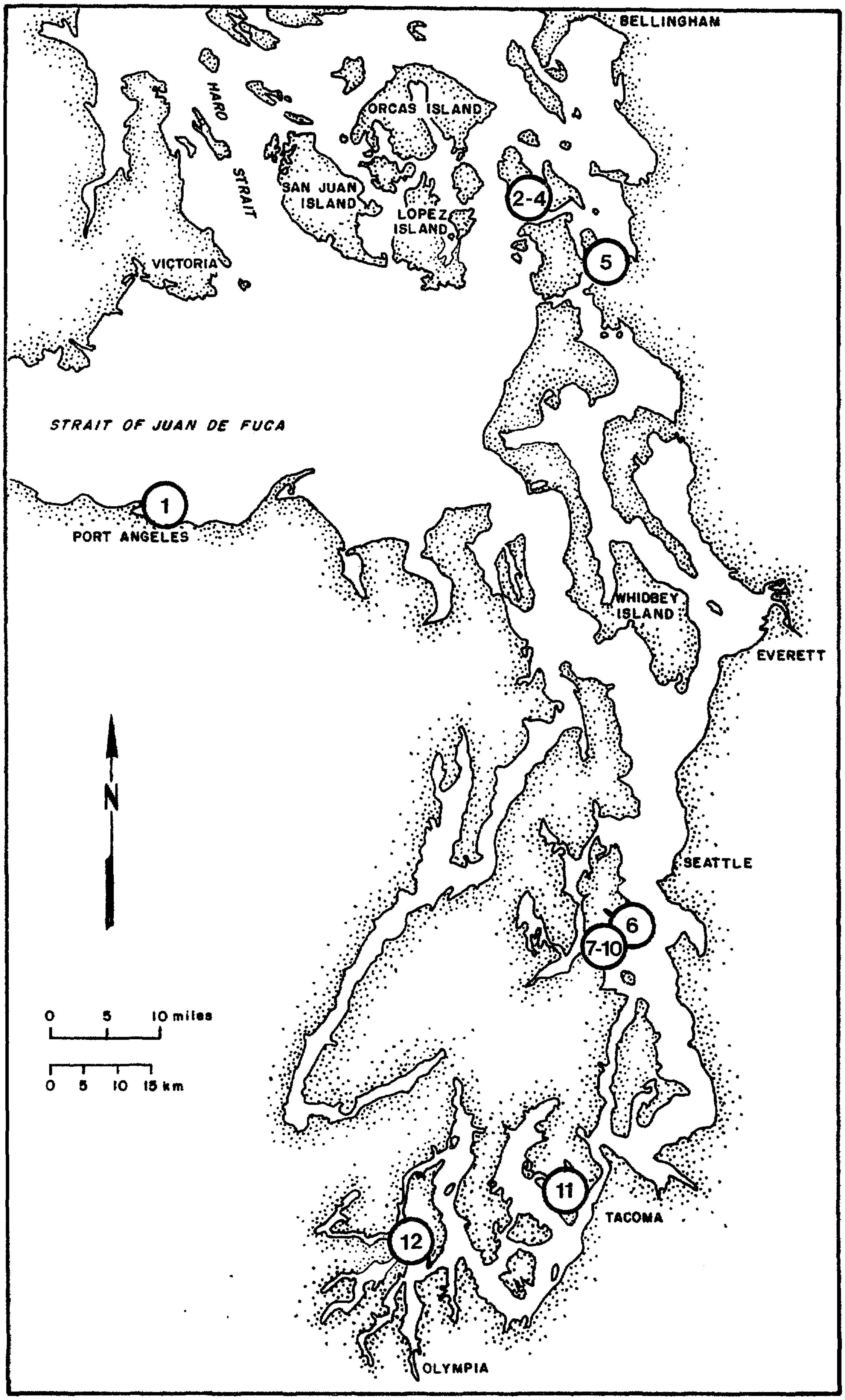

Figure 1 - Location of salmon net-pen facilities in Puget Sound

Table 1
Salmon net-pen facilities in Puget Sound
(Adapted from James, unpub.; Rensel, unpub.)

Map No.	Name	Location	Facilities
1	Sea Farm of Norway	Port Angeles	Culture of full-size Atlantic salmon (2-5 kg). Currently with 24 pens. Permitted for 50 pens.
2	Scan Am Fish Farms	Deepwater Bay, Cypress Island	Culture of Atlantic salmon. Originally located near Hadlock, Jefferson Co.
3	Cypress Salmon	Deepwater Bay, Cypress Island	Culture of coho and Atlantic salmon. Recently acquired by Scan Am.
4	Olympic Seafarm	Deepwater Bay, Cypress Island	Currently culturing coho. Culture of Atlantic salmon planned.
5	Skagit System Cooperative	Swinomish Channel	Currently culturing coho and Atlantic salmon. One net-pen and several seawater raceways.
6	Dirk Nansen and Tom Hamilton	Port Blakely, Bainbridge Is.	Culture of coho salmon. Recently received county permission for culture of Atlantic salmon at Port Townsend.
7	Passage Silver	Fort Ward, Bainbridge Island	Recently permitted for 16 pens of coho salmon.
8	Domsea Farms	Clam Bay, Manchester	Culture of pan-sized coho salmon. 160 net-pens moored in a single 4 acre array.
9	Domsea Farms	Fort Ward, Bainbridge Island	Culture of pan-sized coho.
10	NMFS	Clam Bay, Manchester	Salmon held for research purposes-only. No commercial culture.
11	WDF	Hale Passage, Fox Island	Coho and chinook salmon reared for fisheries enhancement. No commercial culture.
12	Squaxin Island Seafarm	Squaxin Island	Culture of coho to market size and for ocean ranching. Began Atlantic salmon culture in 1986. Experimental steelhead culture.

Five major and eight minor net-pen facilities used by Indian tribes or sportsmen's clubs for delayed release of salmon are not shown on Figure 1 nor listed individually here.

Water depth - The water depth should be sufficient to maintain the net-pen above the bottom throughout the tidal cycle in order to promote the dispersal of feces and excess feed. A clearance of at least 1-5 m beneath the net-pen has been suggested to minimize the possibility that these wastes could affect the health of the cultured fish (Kennedy, 1978; STOWW, 1974; Sutterlin and Merrill, 1978). Maximum depth is determined by mooring considerations.

Wind and waves - Areas sheltered from severe wind and wave action are preferred net-pen locations. Some of the earlier net-pen designs could withstand waves of up to 1 m in height (Kennedy, 1978; STOWW, 1974); net-pen systems capable of withstanding much greater wave heights are now available.

Dissolved oxygen - A supply of dissolved oxygen adequate to meet the respiratory needs of the fish is necessary. A dissolved oxygen concentration of 6-7 $mg \cdot l^{-1}$ is generally regarded as a minimum acceptable level (STOWW, 1974; Sutterlin and Merrill, 1978; Zook, et al., unpub.).

Temperature - Optimum growth of salmon occurs at temperatures of 10-15°C. A range of 5-16°C is acceptable (Kennedy, 1978; STOWW, 1974; Sutterlin and Merrill, 1978).

Salinity - There are no generally accepted standards for salinity in net-pen culture. Pacific and Atlantic salmon have been reared successfully in both marine and freshwater.

Pollution - Net-pens should be located far from polluted waters, such as industrial outfalls, densely populated areas or similar areas where water quality could threaten the health or marketability of the fish.

Permitting - Net-pen applications are being subject to increasing public scrutiny, particularly at the local level. Sites must be selected to comply with local zoning restrictions and state environmental policies, and to minimize conflict with other water uses.

Accessibility - If an operation is to be economically successful, the site must be readily accessible for the transport of staff, supplies, feed, and fish.

Currently, commercial net-pen operators in Puget Sound culture either coho (Onchorhynchus kisutch) or Atlantic (Salmo salar) salmon. While culture of chinook salmon (O. tshawytscha) is possible, the species is more susceptible to disease than the coho and less willing to accept pelleted dry feed (Mahnken, 1975). Steelhead (Salmo gairdneri) culture in net-pens is currently in an experimental stage at the Squaxin Island net pens in a cooperative venture between the Squaxin tribe and the Washington Department of Fisheries.

Fish are held in net enclosures with 10-30 mm mesh, depending on the size of the fish. The dimensions of the enclosure vary among facilities. A small net-pen may be only a few meters on each side, whereas a large net-pen may be up to 12x12 m square. The depth of the net-pen is typically 2-4 m. At most facilities many net-pens are moored together to form a single large unit, with the individual pens separated by walkways.

Eggs are hatched and the fry reared in a freshwater facility. Salmon smolts are generally transferred to the net-pens in the spring of each year. The timing of this transfer is deliberately spread over several months in order to provide a more consistent supply of product. The fish are held in the net-pens until they reach marketable size. Stocking density in net-pens depends on several factors (e.g., fish size) but is typically about 15 $kg \cdot m^{-3}$ in Puget Sound net-pen operations. Fish intended for the "pan-sized" market are held 6-11 months until they attain a weight of about 0.3 kg. Fish intended for the "full-size" market are held 18-24 months, attaining a weight of 2-5 kg.

Salmon may be fed on a variety of diets including pelleted dry or moist feeds and wet feed (e.g., minced fish). Growers in Puget Sound typically use a pelleted dry diet. The feed may be provided either by hand, through demand feeders (feed delivery triggered by fish behavior) or through automatic feeders (feed delivered at preset times and in predetermined quantities). Salmon are typically fed 2% of their body weight per day, although this may vary by an order of magnitude depending on size of the fish and water temperature. A feed conversion ratio of 2:1 is commonly achieved in Puget Sound, meaning that two kg of feed are required to produce 1 kg of salmon.

The net-pen operator must protect against loss of fish through both disease and predation. Mortality due to disease can be minimized by proper husbandry practices (e.g., reducing stocking density), vaccination or addition of therapeutic agents (e.g., antibiotics) to the feed. Predators include birds, otters and marine mammals. Birds and otters are excluded by the installation of nets over the top of the net-pen. Predation by seals and sea lions may be prevented by use of a double net around the cultured fish. Nonlethal seal and sea lion deterrents, such as acoustic devices, are also occasionally used.

2.2 SHELLFISH CULTURE

Most suspended shellfish culture in Puget Sound is dedicated to the production of the blue mussel, Mytilus edulis. With the exception of a few small operations, oysters are cultured on bottom tracts rather than by suspended techniques. Suspended scallop culture in the Sound is still in the experimental stage, and is not yet commercially feasible.

Culturing of mussels in the Sound began in the mid-1970s by Penn Cove Mussels. Although Penn Cove Mussels is still the largest firm, five other firms have entered the market (Figure 2, Table 2). Much of the culture activity is concentrated around Whidbey Island, particularly in Penn Cove, although there are culture operations in both the San Juan Islands and in the southern Sound.

Mussel culture of mussels may be conducted on the bottom, as in the Netherlands, on posts, as in the "bouchot" culture of France, or on strings suspended from a rack which rests on the bottom. Suspended culture from rafts or longlines has proven to yield the greatest production per unit area. In Spain, where mussels are grown suspended from rafts, a maximum production of 500 metric tons per hectare (in English units, 250 tons per acre) has been achieved. This figure is 1,000 times greater than any other form of aquaculture in which animals are grown without supplemental feeding (Ryther, 1969).

Suspended mussel culture in Puget Sound involves rafts or longlines. The size of these structures varies depending on the operator. Using Penn Cove Mussels as an example, rafts at this facility measure 10x12 m, and longlines are 91 m long. The mussels strings suspended from these structures extend about 7 m below the surface of the water. At the Penn Cove Mussels facility up to 400 strings may be hung from a single raft or longline, and the unit will typically support 9 metric tons of mussels (P. Jeffards, Penn Cove Mussels; pers. comm.).

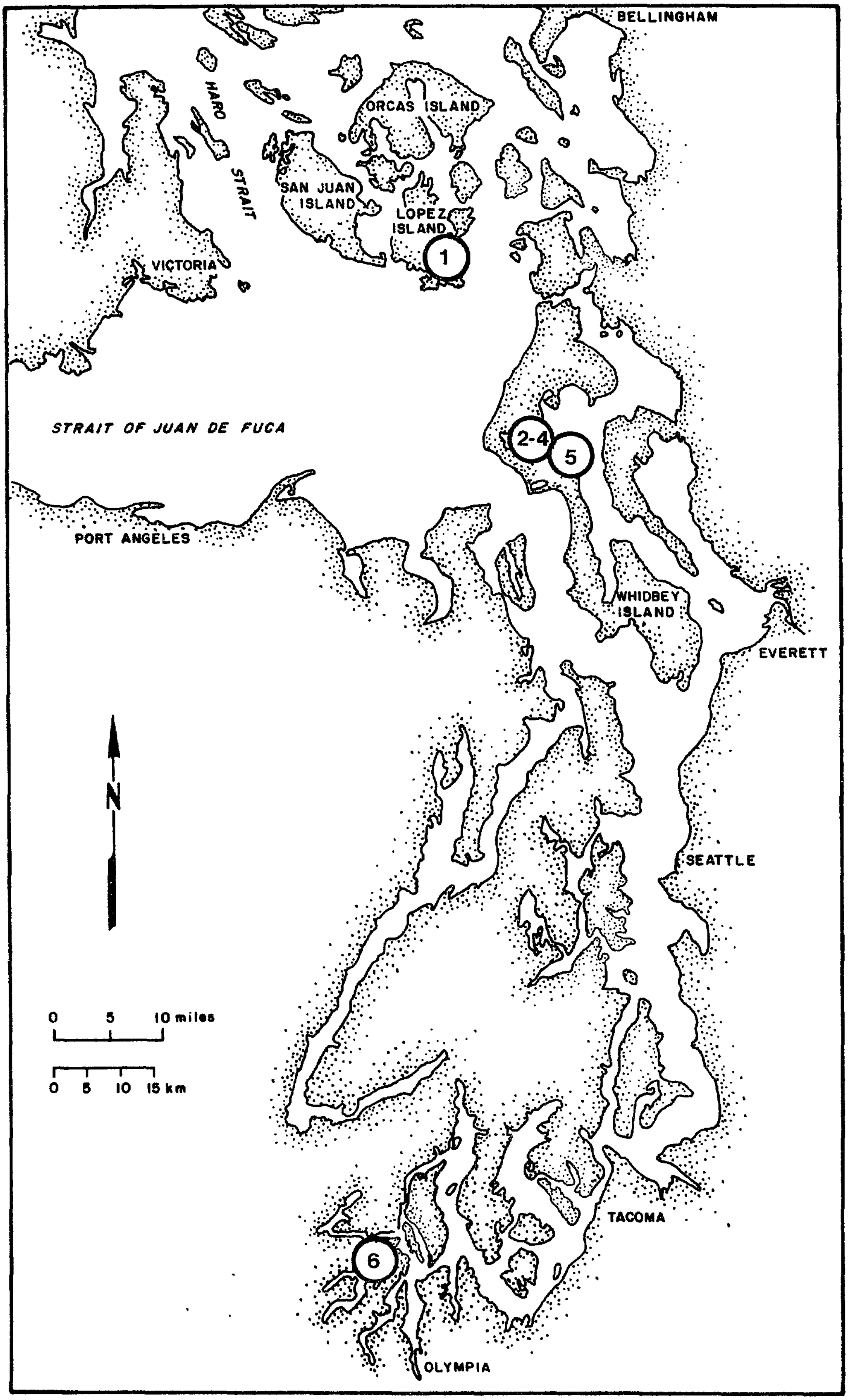

Figure 2 - Location of mussel culture facilities in Puget Sound

Table 2
Mussel culture facilities in Puget Sound

Map No.	Name	Location	Facilities
1	Scott McCullough	Lopez Island	One raft and two longlines as of 1984. Production that year of about 1000 kg.
2	Penn Cove Mussels	Penn Cove, Coupeville	Twelve longlines and four rafts. Annual production approx. 50,000 kg.
3	West Coast Blue Mussels	Penn Cove, Coupeville	Nine rafts
4	Sea Forms	Penn Cove, Coupeville	Ten acre site with twelve rafts.
5	Race Lagoon Mussels	Race Lagoon, Whidbey Island	Seven acre intertidal site with longlines.
6	Kamilche Sea Farms	Totten Inlet	Small facility - no specific data available.

Mussel seed for Puget Sound mussel culture comes entirely from natural populations. There are very few places in the Sound with a good, reliable seed set; Penn Cove is one of the best areas. The empty mussel strings are placed in the water in June or July, the major period of mussel set in Puget Sound. Following collection of the mussel seed, the strings may be either left in place or transferred elsewhere in the Sound for growth. The mussels are grown for 6-10 months until reaching a harvestable size, and may remain on the strings for almost 2 years until the last of a given set is harvested. Throughout the culture period it is necessary to periodically lift the strings from the water for removal of fouling organisms and thinning of the mussels.

3.0 POTENTIAL ENVIRONMENTAL EFFECTS

3.1 WATER CIRCULATION

Question

Water circulation is critical in minimizing sedimentation or promoting removal of metabolic wastes from a mariculture operation. To what extent will structures such as net-pens or mussel rafts reduce the current velocity in the culture structure and in the surrounding area?

Discussion

Effects on water circulation within the culture structure -

Any structure placed in a moving fluid will impede the flow of that fluid. The reduction in current flow induced by a net-pen is dependent upon the size and shape of the pen, the diameter of the twine used in the net, and the size and type of mesh (e.g., knotted or knotless, diamond or square). Textural differences in the type of material used for net construction can also affect current velocity (Milne, 1970). The effects of variables such as stocking density of fish and extent of fouling growth on the net are difficult to quantify, but they can have a dramatic impact on the resistance of the net-pen to water flow. Even the swimming movements of the fish can alter flow patterns (Hisaoka, et al., 1966).

There are several empirical studies of the effect of net-pens on water circulation; the most extensive being that of Inoue (1972). Current velocities inside floating net pens stocked with yellowtail were found to be 35-81% of the current velocities outside the pens. In addition, equations were developed to estimate the effect of multiple pens placed parallel to the current. As would be expected, current velocity was reduced with passage through each succesive pen. For pens having dimensions of 3x3x3 m, with 2.4 cm mesh and without fish, it was estimated that current velocities would be reduced to 70-80% of initial velocities after passage through the first pen, and reduced to 10-25% of initial velocities after passage through three pens. Comparable results were obtained with various stocking densities, cage sizes and mesh sizes.

Hisaoka, et al. (1966) measured current velocities associated with floating net-pens stocked with yellowtail in Daio Bay, Hiroshima Prefecture. Current velocity was reduced inside a net-pen with a 5 mm mesh to an average of 60% of upcurrent velocity, while a 3 cm mesh reduced inside velocity to 70% of outside velocity. These measurements were made after the net had been placed in the water only a few days prior to the investigation, thus providing insufficient time for growth of fouling organisms. Thus, the reduction in current velocities was attributable entirely to the net and the enclosed fish. Further reduction in water flow could be expected with growth of fouling organisms on the net.

Reduction of current velocity has also been observed in the vicinity of shellfish culture operations. Arakawa, et al. (1971) measured current velocities amidst culture strings of the Pacific oyster, Crassostrea gigas, under a raft in Hiroshima Bay. Within the raft current velocities were generally 12-14% of the velocity outside the raft, but 1 m below the lower end of the oyster strings there was no consistent effect on current velocity.

Effects on water circulation beyond the culture structure -

No in situ measurements are available on alteration of water flow in the environment surrounding mariculture facilities, but principles of fluid dynamics can be used to estimate the magnitude of this effect. Much of the available information pertains to flow around solid objects rather than a porous structure, such as a net-pen or shellfish raft, however, a rough approximation of effects is possible. A large structure placed in the marine environment will reduce current velocity upcurrent of the facility for a relatively short distance. For a solid object this upstream distance is equal to about twice the dimension of the structure perpendicular to current flow (hereafter, a "diameter") (Nowell and Jumars, 1984). For a porous structure, such as a net-pen, the extent of upstream influence is probably on the order of about 1 structure diameter. To either side of the structure perpendicular to the current flow, alteration of flow can be observed for 2-5 diameters from a solid body (Eckman and Nowell, 1984; Nowell and Jumars, 1984). Since a mariculture facility is porous and since the effect of a structure on current velocity is a logarithimic function with distance, current velocity should be about 95% of the free stream value at distances of approximately 2 structure diameters. The influence of a structure on current velocity is measurable for the greatest distance downcurrent. Solid bodies will typically influence current velocity for up to 50 diameters downcurrent. For a porous structure current velocity should return to 95% of the mean unaffected value within 20 diameters downcurrent (A. Nowell, Univ. Washington, pers comm.). As an example of the potential areal extent of influence, if a net-pen 12x12x4 m were moored with a 12 m face perpendicular to the direction of water movement, there may be alteration of the flow field 12 m upcurrent of the pen, 24 m on either side and 240 m downcurrent. Multiple net-pens moored together would function as a single larger body, and the effects on circulation must be scaled upwards accordingly. These figures must only be considered as order-of-magnitude approximations, since important variables such as mesh size and extent of fouling are unspecified. It is also important to recognize that current flow patterns are rarely uniform and unidirectional as is implied in this discussion. The complex flow patterns actually found in most estuarine environments severely complicate efforts to quantify the effects of a mariculture structure.

Sedimentation -

One potential effect of a reduction in current velocity is sediment deposition in the area of the mariculture structure. Sedimentation resulting from current velocity reduction as discussed here is considered as distinct from sedimentation directly attributable to culture practices such as the deposition of feces and excess feed, potential effects of mariculture which are discussed separately in Section 3.4. The ability of flowing water to transport sediments is largely determined by current velocity. A reduction in current velocity may allow the sediment particles to settle out of suspension with the larger, denser particles settling first. This potential effect is not likely to be of significant magnitude for floating mariculture facilities in Puget Sound. First, floating structures are much less prone to problems associated with sedimentation than are bottom culture operations. Unless the structure is located close enough to the bottom to restrict flow of water beneath it, the current beneath the structure should prevent sedimentation of particles attributable to impedance of water flow by the structure. Secondly, the suspended sediment load of most Puget Sound waters is very low. Sedimentation would be expected to be greater in areas of major riverine inflow; areas that are generally unsuitable for mariculture for other reasons (e.g., phytoplankton blooms, variable salinity).

Circulation and water quality -

A reduction in current velocity caused by mariculture structures may affect water quality by preventing adequate supply of oxygenated water or inhibiting removal of metabolic wastes. The cultured organism is typically the first to show the effects of inadequate water exchange. Chinook salmon held in Squaxin Island net-pens experienced heavy mortalities when fouling of the nets prevented adequate exchange of water. Dissolved oxygen concentration in the pens dropped to as low as 2 $mg \cdot l^{-1}$, while concentrations outside the pens were 6.5-9 $mg \cdot l^{-1}$ (STOWW, 1974). When the nets were replaced the dissolved oxygen concentrations in the pens returned to near ambient levels. Thus, it is in the operator's best interest to minimize reduction in current speeds caused by his operation. A detailed discussion on mariculture effects on water quality is presented in Section 3.2.

Conclusions

Like any structure placed in the marine environment, a mariculture facility will alter water circulation. Within a net-pen itself, reductions in current velocity to 35-81% of the upcurrent velocity have been reported. There is also a "wake" associated with a mariculture facility which alters current patterns and velocities in the vicinity of the structure. The effect of this wake is observable in all directions from the structure but its influence extends for the greatest distance downstream. In some situations the effect of a mariculture structure may be considered beneficial if the facility functions as a breakwater, dampening wave action on inshore structures.

The reduction in current velocites induced by a mariculture structure could potentially promote sedimentation of suspended particulate matter or enhance degradation of water quality as a result of poor flushing. However, deposition of the suspended sediment load in the vicinity of floating mariculture facilities is likely to be of negligable importance in most of Puget Sound. The effect of reduced current velocity on water quality could be significant under certain conditions, such as a high density of mariculture units in an embayment with very restricted natural circulation. Such mariculture development is unlikely given the need of the operator to provide good water quality for the cultured organisms.

Operators of mariculture facilities can take certain measures to minimize the effect of their structures on water circulation. The fluid dynamics discussion above has implications for mooring arrangement of multiple pens or rafts. In strong currents, multiple pens or rafts should be arranged parallel to the direction of water flow. Not only would this arrangement minimize the alteration of water circulation, but it would simplify mooring requirements. Under weak current regimes, such a parallel arrangement would be undesirable because of potential reductions in water quality for those pens or rafts farthest downcurrent. Under these conditions, the individual units would be better arranged perpendicular to current flow with the optimal spacing between pens or rafts of 2 diameters or more. This spacing will minimize each unit's effects on water circulation, and consequently water quality, in neighboring units. These guidelines should be considered as optimal configurations strictly from the standpoint of minimizing effects on water circulation. Local conditions or operational considerations may dictate alternative arrangements.

Other mitigative measures which an operator might take include wide spacing of the strings in shellfish culture, use of the largest mesh possible for net enclosures, and frequent cleaning to remove fouling organisms. In most cases these measures would be in the best interest in the operator to minimize water quality degradation which could affect the health of the cultured organisms.

3.2 WATER QUALITY

Questions

How much organic matter and nutrients are introduced into the water during culture activities in the form of unutilized feed and metabolic wastes? Could these inputs result in a deterioration of water quality in the vicinity of the culture site, including high concentrations of substances such as of ammonia, nitrates and phosphates and reduced levels of dissolved oxygen?

Discussion

Characterization of wastes -

Dissolution of substances from unutilized feed and the metabolic breakdown of ingested food both result in some alteration of water quality. The general inputs are:

Ammonia - Ammonia is an end-product of protein metabolism and the principal nitrogenous excretory product of marine and freshwater organisms, both vertebrates and invertebrates. It is also released from sediments by the anaerobic microbial decomposition of nitrogen compounds. Ammonia can be present in either the ionized (NH_4^+) or unionized (NH_3) form. The unionized form, which comprises 2% or less of the total ammonia under typical marine conditions of temperature and pH, is the more toxic of the two.

Nitrite and Nitrate - These compounds are produced by microbially mediated conversion of other nitrogenous compounds. Elevated concentrations of nitrite (NO_2^-) and nitrate (NO_3^-) might be expected in the vicinity of mariculture facilities due to bacterial oxidation of ammonia.

Organic Nitrogen - Urea is typically the principal component of this group. Like ammonia, it is produced as an end-product of protein metabolism.

Phosphate - Phosphate is excreted in urine. A portion of the phosphate input from salmon culture facilities is also the result of leaching from feces and food.

Oxygen - Mariculture reduces dissolved oxygen in the water through both respiration by the cultured organisms and consumption of oxygen by decomposition of feces and excess feed. The latter utilization is quantified as the biochemical oxygen demand (BOD).

Waste loading from salmonid culture -

Much work has been attempted to quantify the nutrient load from freshwater fish hatcheries. In contrast, work in the marine environment is extremely limited: I can find no measurements of nutrient or BOD loading from marine net-pen culture. Freshwater systems have a number of characteristics that often make them more susceptible to adverse effects of nutrient enrichment, and therefore, these systems have been the subject of more attention. Freshwater systems are often characterized by high stability of the water column, lack of tidal-induced flushing, and culture discharge volumes which are relatively large in proportion to the volume of the total water body. Freshwater systems are also very different from marine environments in that the availability of phosphorus is often the factor which limits phytoplankton production. Nitrogen is typically the limiting nutrient in marine systems.

A summary of estimated nutrient and BOD loadings from freshwater salmonid hatcheries and net-pen aquaculture facilities is presented in Table 3. Loadings have been quantified on the basis of the weight of fish, annual fish production and amount of feed provided. This analysis does not discriminate between dissolved nutrients which will directly influence water quality and those nutrients which reach the bottom as feces or excess feed. The vast majority of the nitrogenous wastes will be released in the dissolved form, whereas most of the phosphorus will be incorporated into the particulate material (Enell and Löf, 1983b). Most of the BOD is generally associated with the solid material (Speece, 1973; Willoughby, et al., 1972).

It is readily apparent from Table 3 that loadings are extremely variable among or even within studies. This variation is attributable to many factors including type of feed provided, quantity and frequency of feeding, temperature, fish size, and proportion of suspended solids in the effluent. This variability makes it very difficult to predict the nutrient and BOD loading from any given facility. Attempts to estimate potential loadings from proposed facilities have been frustrated by the highly divergent results obtained

Table 3
Loading of nutrients and BOD from freshwater salmonid culture

Reference	Ammonia	Nitrite	Nitrate	Organic Nitrogen	Total Nitrogen	Phosphate	Total Phosphorous	BOD
Loading expressed as g·kg^{-1} fish·day^{-1}								
Bergheim and Selmer-Olsen, 1978	--	--	--	--	0.3-0.8	--	0.05	1.6-4.6[a]
Bergheim, *et al*., 1982	0-1.3	--	--	--	0.13-3.8	0.02-0.27	0.005-0.43	1.6-2.7[a]
Butz and Vens-Cappell, 1982	--	--	--	--	--	--	--	1.4-8.1[b]
Clark, *et al*., 1985	0.3-0.8	--	0.13-0.21	--	--	0.067-0.17	--	--
Korzeniewski, *et al*., 1982	0.032	--	0.053	0.040	0.12	0.033	0.10	--
VKI, 1976[c]	0.125	--	0.063	--	0.38	0.05	0.1	1.8[b]
Loading expressed as g·kg^{-1} fish produced·yr^{-1}								
Alabaster, 1982[d]	37-180	---- 0-548[e] ----		--	--	--	22-110	510-990[b]
Ackefors and Sodergren, 1985	--	--	--	--	71[f]	--	1.9[f]	--
Ackefors and Sodergren, 1985	--	--	--	--	87[g]	--	13.5[g]	--
Penczak, *et al*., 1982	--	--	--	--	100	--	23	--
Solbé, 1982	55.5	1.8	10.2	--	--	--	15.7	285[b]
Warrer-Hansen, 1982	45	--	--	--	83	--	11	350[b]

Table 3 continued

Reference	Ammonia	Nitrite	Nitrate	Organic Nitrogen	Total Nitrogen	Phosphate	Total Phosphorus	BOD
			Loading expressed as g·kg^{-1} feed provided·day^{-1}					
Butz and Vens-Cappell, 1982	--	--	--	--	--	--	--	80-300[b]
Clark, *et al.*, 1985	31-37	--	9-15	--	--	5.2-5.9	--	--
Liao and Mayo, 1972	0.3-4.0	--	0.06-15.0	--	--	0.04-0.94	--	6.4-25.0[b]
Liao and Mayo, 1974	28.9	--	24	--	--	16.2	--	600[b]
Querellou, *et al.*, 1982	26-34	0.04-7	3.8-118	--	9-64	2.6-19	43-75	33-121[b]
Speece, 1973	22-31	--	--	--	--	--	--	400[h]
Willoughby, *et al.*, 1972	32	--	87	--	--	5	--	340[b]

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[a] BOD$_7$

[b] Unspecified whether value is BOD$_5$ or BOD$_7$.

[c] Based on values for dry feed.

[d] Daily loadings of Alabaster (1982) multiplied by 365 days·yr^{-1}.

[e] Sum of nitrite and nitrate

[f] Dissolved fraction only.

[g] Total of dissolved and particulate fractions.

[h] Ultimate oxygen demand (UOD).

depending on the method of calculation employed (Tynan, unpub.). It is clear that loading values from any one aquaculture operation can not be used to accurately predict loadings from another. Thus *a priori* estimates are reliable only as order-of-magnitude approximations of actual values.

Waste loadings from mussel culture -

The discussion of nutrient loading has focused on quantifying the loading from fish culture in which the nutrients are added to the system through the feed provided to fish. Mollusc culture also has associated nutrient loads, but in this case such nutrient inputs are derived from the indigenous phytoplankton and particulate matter, rather than an external food source. Thus, the culture operation does not introduce any "new" nutrients into the marine environment, but only promotes the recycling of those which are already present. There is actually a net decrease in nutrient levels in the system since only about 40% of the total nutrients removed by the mussels are released directly to the water column, 30% fall to the bottom as particulate material and 30% are removed in the harvest (Ackefors and Grip, 1985; Ackefors and Södergren, 1985).

The nitrogenous excretory products of mussels are composed primarily of ammonia and amino-nitrogen, with ammonia accounting for 40-90% of the total excreted nitrogen (Bayne and Scullard, 1977; Bayne, *et al.*, 1976; Kautsky and Wallentinus, 1980). Oysters excrete a comparable percentage of ammonia, but the organic nitrogen component is urea rather than amino-nitrogen (Hammen, *et al.*, 1966). Excretion rates of the mussel *Mytilus* spp. have been estimated to be 1.4-75.5 ug inorganic N (Kautsky and Wallentinus, 1980), 5-40 ug NH_4-N (Bayne and Widdows, 1978 for 1 g mussel) and 2-30 ug NH_4-N (Bayne and Scullard, 1977), all on the basis of ug N (or NH_4)$\cdot g^{-1}$ shell free dry weight$\cdot hr^{-1}$. The wide variation in excretion rates within and among studies is primarily a result in differences in mussel size and study season, both of which dramatically affect nutrient production.

Mussels excrete phosphorus primarily as phosphate. Phosphate excretion rates of 0.4-24.1 ug PO_4-P (Kautsky and Wallentinus,1980) and 0.5-3.6 ug PO_4-P (Kuenzler, 1961), both on a ug $PO_4\cdot g^{-1}$ shell-free dry weight$\cdot hr^{-1}$ basis, have been reported.

Comparison of mariculture loadings with other discharges -

In order to put the changes in water quality induced by mariculture in perspective with other discharges to the marine environment, Tables 4 and 5 contrast nutrient and BOD releases from mariculture facilities with the releases from several rivers, wastewater treatment plants and industries in the Puget Sound area. Concentrations and loadings from mariculture have been based on expected releases from relatively large facilities. In the case of salmon net-pen culture, calculations are based on a facility with 50 net-pens, a holding capacity of 250,000 kg salmon and a current velocity of 8-16 $cm \cdot sec^{-1}$ outside of the nets at peak ebb tide. Data presented for mussel culture are based on a facility with 12 longlines supporting 108,000 kg of mussels. The reader is referred to the notes following the tables for an explanation of how the data were derived.

Several observations are readily apparent from Tables 4 and 5. First, the flow rate of water through either a net-pen or a longline system far overshadows most other discharges. The water flow through a net-pen is 5 orders of magnitude above that from a seafood processor and one order of magnitude above the flow of the West Point treatment plant. Only a major river system has a flow rate of comparable magnitude. Secondly, as a result of this heavy water usage the concentrations of nutrients and BOD from mariculture facilities are relatively small in comparison to the other discharges shown. This would suggest that near-field effects (e.g., effluent toxicity) would be much less of a problem at a mariculture facility than near the other outfalls. Thirdly, the nutrient load from a mussel culture is considerably less than from net-pen culture, and in fact is lower than all other discharges shown. It would seem unlikely that significant water quality deterioration would be found around any mussel culture of a size typical of Puget Sound facilities. Finally, the relative nutrient/BOD contribution of net-pen culture in comparison to the other discharges is highly variable depending on the particular parameter. In general, the nutrient or BOD loading from the net-pens is comparable to that of a small river or small dairy. The BOD load from the net-pens is comparable to that of the LOTT wastewater treatment plant but the nutrient load of the net-pens is considerably less.

Table 4
Concentration and loading of nitrogen compounds from various dischargers in the Puget Sound area

Discharge Source	Flow	Ammonia		Nitrates		Organic N		Total N	
	$(m^3 \cdot sec^{-1})$	$(mg \cdot l^{-1})$	$(kg \cdot day^{-1})$	$(mg \cdot l^{-1})$	$(kg \cdot day^{-1})$	$(mg \cdot l^{-1})$	$(kg \cdot day^{-1})$	$(mg \cdot l^{-1})$	$(kg \cdot day^{-1})$
Riverine discharge									
Chambers Creek (near Steilacoom)	3.44	0.037	11	1.53	450	ND	ND	ND	ND
Stillaguamish River (near Silvana)	112	0.043	360	0.27	2600	ND	ND	ND	ND
Skagit River (near Mt. Vernon)	496	0.02	857	0.15	6400	ND	ND	ND	ND
Wastewater treatment plants									
LOTT (Olympia)	0.39	14.4	490	2.6	88	1.7	57	19	650
Renton	1.9	14.8	2400	0.04	6	2.9	490	39	6400
West Point (Seattle)	5.0	16	6900	ND	ND	7	3024	ND	ND
Mariculture									
Salmon net-pen	72	0.01	75	0.004	25	0.002	10	0.02	150
Mussel culture	20	0.003	4.4	ND	ND	ND	ND	ND	ND

ND = No data available

Table 5
Concentration and loading of phosporus and BOD from various dischargers in the Puget Sound area

	Flow	Phospate		Total Phosphorus		BOD	
Discharge Source	$(m^3 \cdot sec^{-1})$	$(mg \cdot l^{-1})$	$(kg \cdot day^{-1})$	$(mg \cdot l^{-1})$	$(kg \cdot day^{-1})$	$(mg \cdot l^{-1})$	$(kg \cdot day^{-1})$
Riverine discharge							
Chambers Creek (near Steilacoom)	3.44	0.02	6	0.05	15	ND	ND
Stillaguamish River (near Silvana)	112	< 0.01	< 100	0.03	290	ND	ND
Skagit River (near Mt. Vernon)	496	< 0.01	< 430	0.03	1300	ND	ND
Wastewater treatment plants							
LOTT (Olympia)	0.39	4.7	160	4.97	170	16.6	560
Renton	1.9	2.79	460	3.41	560	9.4	1600
West Point (Seattle)	5.0	ND	ND	5.1	2200	87	38,000
Industries							
Universal Seafood (whitefish and crab proc.)	0.00055	ND	ND	ND	ND	300	14
Perfection Smokery (salmon processing)	0.00068	ND	ND	ND	ND	975	57
Vitamilk Dairy (milk processing)	0.0031	ND	ND	ND	ND	2975	800
Consolidated Dairy (milk processing)	0.0076	ND	ND	ND	ND	2500	1600
Rainier Brewing (beer brewing)	0.017	ND	ND	ND	ND	2925	4300
Mariculture							
Salmon net-pen	72	0.004	25	0.004	25	0.1	750
Mussel culture	20	0.001	2.2	ND	ND	ND	ND

Notes to Tables 4 and 5

1) Nitrite loadings are not shown since no reliable values are available for mariculture, and most other discharges shown either have no data on the parameter or found concentrations consistently below detection limits.

2) Riverine discharges - The data presented are from the WDOE water quality monitoring program and were obtained through Robert James of WDOE. The data are average values of monthly measurements taken from January 1984 through February 1986. The rivers shown were selected so as to encompass a wide range of flow rates. Chambers Creek has the lowest discharge rate of any riverine discharge to Puget Sound monitored by WDOE, while the Skagit River has the largest.

3) Wastewater treatment plants - The data presented include:
Lacey, Olympia, Tumwater, Thurston County - Grand mean of the mean values for 1984 and 1985. Data provided by Asha Mhatre.
Renton - Mean of monthly measurements from January 1984 through February 1986. Data provided by Richard Finger.
West Point - Mean of daily BOD and weekly nutrient measurements from January 1984 through December 1985. Organic nitrogen obatined by the difference between ammonia nitrogen and total Kjeldahl nitrogen (APHA, 1981). Data provided by Barry Uchida.

4) Industries - All industries listed discharge to Puget Sound via the Metro wastewater treatment system. Industry types which would be expected to have an organically enriched waste stream were selected, and then a range of plant sizes were chosen within each industry type. Flows represent the mean of the discharge rates over the last four quarterly measurements. BOD values are the mean of all measurements made since the last major process changes at the facilities. No data are available for water quality parameters of concern here other than BOD. Data provided by Bruce Burrow, Municipality of Metropolitan Seattle.

5) Salmon mariculture - The data presented are for a hypothetical net-pen operation, but are based on the permitted capacity of the Sea Farm of Norway, Port Angeles facility, a moderately large facility in comparison to other net-pen operations in Puget Sound. Plans call for expansion of the facility to 50 pens of 12x12x4 m in size. A maximum probable holding capacity of 250,000 kg of salmon has been assumed (J. Lindbergh, pers. comm.). In order to simplify the presentation and because of the uncertainty as to the alignment of the pens in relation to prevailing current at the site, it is assumed that the net-pens are arranged in a single row oriented perpendicular to the current direction.

Current velocity at peak ebb tide at the Sea Farm site ranges from 8-16 $cm \cdot sec^{-1}$ (existing and proposed locations - Milner-Rensel Assoc., 1986). Recognizing that the current velocity will be lower during other periods of the tidal cycle, and that the net-pens will further reduce currents in the pen to about one half of their upcurrent velocity (Inoue, 1972), a current velocity of 3 $cm \cdot sec^{-1}$ through the pens has been assumed. With 50 pens, each having a surface area of 12x4 m perpendicular to the direction of water flow, the volume of water which passes through the pens can be estimated as 72 $m^3 \cdot sec^{-1}$.

Loadings of nutrients and BOD have been estimated from Table 3 values on the basis of $g \cdot kg^{-1}$ $fish \cdot day^{-1}$. Based on the range of loading values reported, "typical" loadings have been estimated as: ammonia - 0.3; nitrate - 0.1; organic nitrogen - 0.04; total nitrogen - 0.6; phosphate - 0.1; total phosphorus - 0.1; and BOD - 3. These estimates should not be regarded as anything other than order-of-magnitude approximations. Concentrations shown on the tables were back-calculated from loadings and flow. Phosphate concentrations and loadings for mariculture are based on total phosphate-phosphorus, whereas data from the riverine discharges and wastewater treatment plants were reported as ortho-phosphate-phosphorus.

6) Mussel culture - The data presented are for a hypothetical mussel culture operation, but are are based on the longline culture of Penn Cove Mussels; the largest in Puget Sound. The facility is permitted for 12 longlines, each 91.4 m long. Each longline is comprised of 400 strings, 7.3 m in length, and supporting an average mussel weight of 9,000 kg (P. Jeffards, Penn Cove Mussels, pers. comm.). Given 12 longlines, the entire longline system could support 108,000 kg of mussels. Of the 9,000 kg on each longline, approximately 15% of the weight will be comprised of barnacles and other fouling organisms. No effort has been made to exclude the nutrient contribution of these organisms from the calculations, and it is assumed that they will release nitrogen and phosphate at the same rate as the mussels.

Lacking data on current velocity in the midst of the longlines, an estimate of 3 $cm \cdot sec^{-1}$ has been used as for the salmon net-pens. The longlines are assumed to be oriented perpendicular to the direction of current flow and placed directly behind one another. Thus, the surface area of the longline system on a plane perpendicular to the flow is 91.4x7.3 m.

Loadings are based on "typical" values given the ranges reported in the literature (see text). Ammonia and phosphate loadings of 20 and 10 $ug \cdot g^{-1}$ shell-free dry $weight \cdot hr^{-1}$, respectively, have been assumed. Concentrations shown have been back-calculated from loadings and flow.

To convert shell-free dry weight to wet weight with shell, the following factors can be used for Mytilus edulis: shell-free dry weight is 21% of dry weight with shell; dry weight with shell is 40% of wet weight with shell (Lappalainen and Kangas, 1975).

Oxygen consumption through respiration -

Oxygen consumption by cultured organisms and the decomposition of waste products could potentially affect water quality by decreasing dissolved oxygen concentrations. Salmonid respiration rate depends upon fish size, age, sex, activity, and temperature but an average value for routine metabolism is about 300 mg $O^2 \cdot kg^{-1}$ wet weight$\cdot hr^{-1}$ (Kils, 1979; Liao and Mayo, 1972). *Mytilus edulis* respiration rates are about 0.1-3 mg $O^2 \cdot kg^{-1}$ shell-free dry weight$\cdot hr^{-1}$ (Kautsky and Wallentinus, 1980). Applying salmon and mussel respiration rates of 300 and 1.5 mg $O^2 \cdot kg^{-1} \cdot hr^{-1}$, respectively, to the culture facilities discussed in Tables 4 and 5 (250,000 kg of salmon and 108,000 kg of mussels), it can be estimated that salmon respiration may consume 21,000 mg $O^2 \cdot sec^{-1}$ and the mussels may consume 45 mg $O^2 \cdot sec^{-1}$. This respiration would result in a reduction of 0.3 and 0.002 mg $O_2 \cdot l^{-1}$ in the oxygen content of the water which passed through the salmon and mussel culture facilities, respectively. Thus, a measurable change in dissolved oxygen would be anticipated around the net-pen culture, although with dispersion and dilution by the surrounding water concentrations should rapidly return to ambient levels. No measurable effect of the mussel culture on dissolved oxygen concentrations would be anticipated.

These estimates of oxygen consumption do not include the BOD of the feces and other metabolic wastes, which may consume about 1.5-3 times as much oxygen as respiration (Kalfus and Korzeniewski, 1982; Liao and Mayo, 1974; Willoughby, *et al.*, 1972). Since most of the BOD is associated with the solid wastes (Speece, 1973; Willoughby, *et al.*, 1972), most of the oxygen required to meet the BOD will be provided by bottom waters rather than the water which passes directly through the culture structure.

Field studies of effects of salmon net-pen culture on water quality -

Schools of wild fish have been shown to alter the chemistry of water bodies through which they pass. For example, increased ammonia and decreased dissolved oxygen concentrations have been observed around schools of menhaden (Oviatt, *et al.*, 1972). Thus, it is not suprising that mariculture has been shown to alter water quality. In freshwater environments, both lakes and rivers, there are many examples of water quality changes in the vicinity of fish hatcheries or net-pens. Increased concentrations of ammonia, organic and total nitrogen, phosphate, total phosphorus, and BOD and decreased dissolved oxygen have been observed (Bergheim and Selmer-Olsen, 1978; Beveridge, 1984; Eley, et al., 1972; Hinshaw, 1973; Korzeniewski, et al., 1982b; Mantle, 1982).

In marine waters measurable changes in water quality from fish culture are typically not as common or as great as in freshwater. Effects have been noted in some cases, such as an 8-9 fold increase in ammonia concentration around net-pens in Norway (Ervik, et al., 1985). Dissolved oxygen concentrations 0.2-2.5 mg $O_2 \cdot l^{-1}$ less than ambient were observed around yellowtail and sea bream net-pens in Japan, although immediately beyond the boundaries of the culture area there was no oxygen depletion (Kadowaki and Hirata, 1984; Kadowaki, et al., 1978a). However, alterations in marine water quality have not been reported with the same regularity as in freshwater. The principal reasons for differences between fresh and salt water systems are the generally greater degree of water-column mixing (and therefore, dilution of wastes) in marine systems, and the fact that in freshwater systems a large proportion of the water body is often routed through the culture operation (e.g., 70% of river flow in Bergheim and Selmer-Olsen, 1978). The dilution capacity of Puget Sound was clearly evident in studies of the Metro West Point sewage discharge. This discharge, which has ammonia concentrations over 1,000 times greater than the salmonid net-pen operation presented in Tables 4 and 5, increases the ammonia concentration of the receiving water for a distance of only 1.5 km (Collias and Lincoln, 1977).

Most studies in Washington and British Columbia have found little or no observable effects of mariculture on water quality. Two water quality surveys were conducted in 1982 in the vicinity of the Domsea Farms and NMFS net-pens in Clam Bay, Puget Sound (Anonymous, 1983a; D. Damkaer, NMFS, unpub. data). The Domsea Farms net-pen operation is by far the largest in Puget Sound. In 1982 it produced over 1 million kg of salmon per year (J. Lindbergh, pers. comm.). Despite the number of fish present, neither survey found any observable changes in turbidity, dissolved oxygen, particulate or dissolved nitrogen, or particulate or dissolved carbon that could be attributed to net-pen activities (Anonymous, 1983a).

In April of 1986 the Sea Farm of Norway, Port Angeles facility held approximately 27,000 kg of salmon (J. Forster, Sea Farm of Norway, pers. comm.). During a water quality survey done at that time ammonia concentrations inside the net-pens averaged 0.020 $mg \cdot l^{-1}$, approximately three times the concentrations found 30 m upcurrent (0.007 $mg \cdot l^{-1}$), but well below levels considered toxic to biota. Within 30 m downcurrent of the net-pens ammonia concentrations were 0.012 $mg \cdot l^{-1}$ (Milner-Rensel Assoc., 1986). No changes in ortho-phosphate, silica, nitrite or nitrate concentrations were observed, even within the net-pens themselves.

Water quality parameters have been monitored around four net-pen facilities in Sechelt Inlet, British Columbia. During a period of minimal tidal and wind mixing, elevated ammonia concentrations were observed around all net-pens and for a distance of at least 27 m from the sites. One net-pen contained no fish but increased ammonia concentrations were found in the surrounding water, suggesting that fouling organisms on the nets were at least partially responsible for the increase in ammonia levels (E. Black, British Columbia Ministry of the Environment, pers. comm.).

Net-pens in Henderson Inlet, Puget Sound have been shown to increase the ammonia concentrations and decrease the dissolved oxygen in surrounding waters (Pease, 1977). This effect was limited to periods of water column stratification and reduced mixing during the summer months. No measurable differences in water quality between reference and culture areas were found during the spring, fall or winter. The Henderson Inlet site could be regarded as a worst case situation since it was located in a poorly flushed area, with current velocities further reduced by surrounding log rafts. During a 24-hour observation period there was no measurable surface or bottom current in the vicinity of the culture area.

Field studies of effects of mussel culture on water quality -

No water quality data exist in conjunction with mussel cultures in Puget Sound, but information from a mussel farm in Sweden can serve as a close parallel. The Swedish culture area occupied 4500 m^2 and was designed to produce up to 200,000 kg Mytilus edulis every two years. Water depth was 10-15 m and the average current velocity in the culture area was 0-2 $cm \cdot sec^{-1}$ (Hagstrom and Larsson, 1982; Loo and Rosenberg 1983; Mattson and Linden, 1983; Rosenberg and Loo, 1983). Ammonia concentrations were two times greater and phosphate concentrations were four times greater in water samples taken among the longlines than in upcurrent samples. However, no changes in nutrients or dissolved oxygen were seen in samples taken about 100 m outside of the culture area (Hagstrom and Larsson, 1982; Larsson, 1985).

Similar water quality results were reported by Kaspar, et al. (1985) in their study of a New Zealand mussel farm. No differences in nutrients or other water chemistry parameters were found in comparisons of the culture site with a reference area. High current velocities (up to 110 $cm \cdot sec^{-1}$) at the site were responsible for the rapid dilution of metabolic wastes.

Conclusions

The culture of fish and molluscs results in release of nutrients and consumption of dissolved oxygen. A net increase in environmental nutrient levels may be expected in salmonid culture because of nutrient input in the form of feed. Culturing molluscs requires no addition of feed, so no input of "new" nutrients to the marine ecosystem results. However, molluscs do enhance the recycling of nutrients in the water column as they ingest phytoplankton and return a portion of the nutrients to the water column and sediments, making those nutrients available to primary producers again. The filtering activities of the molluscs also serve to concentrate nutrients from a wide area into the area of the culture (Ryther, 1969).

The effects of mariculture facilities on the water quality in the vicinity of the culture can be summarized as shown in Table 6. This table indicates the percentage change in several water quality parameters which could be expected in the parcel of water which passes directly through a large salmon net-pen and mussel longline culture. It is evident that the only parameters of potential concern are ammonia and dissolved oxygen from salmon culture and only ammonia from mussel culture.

It is possible to compare the concentrations of ammonia and dissolved oxygen in the vicinity of the culture to those levels which are considered toxic to aquatic life. Permissable levels of total ammonia are generally reported to range from 0.5-2.5 $mg \cdot l^{-1}$ (Ellis, 1948: Liao and Mayo, 1974), and it is obvious from Table 6 that the ammonia concentrations downcurrent of the culture facilities would not approach toxic levels. The toxicity of ammonia is usually attributable to the toxicity of the unionized fraction (NH_3), which at summer temperatures ($12^{o}C$) and a pH (8.0) typical of Puget Sound comprises approximately 2% of the total ammonia (Trussel, 1972). The maximum acceptable concentration of unionized ammonia for the protection of aquatic life is 0.02 $mg \cdot l^{-1}$

Table 6

Effects of mariculture on water quality

		Salmon culture		Mussel culture	
Parameter	Concentrations in Puget Sound[a] ($mg \cdot l^{-1}$)	Effect of culture facility[b] ($mg \cdot l^{-1}$)	Change[c] (%)	Effect of culture facility[b] ($mg \cdot l^{-1}$)	Change[c] (%)
Ammonia	0.002-0.04	+0.01	25-500	+0.003	8-200
Nitrate	0.3-1.9	+0.004	0.2-1	ND	ND
Phosphate	0.5-3[d]	+0.004	0.1-0.8	+0.001	0.03-0.2
Dissolved oxygen	6-14	-0.3	2-5	-0.002	0.01-0.03

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[a] Annual range in surface waters of the Main Basin from Collias and Lincoln (1977) and Friebertshauser, et al. (1971). For local conditions the reader is referred to Collias, et al. (1974), Friebertshauser, et al. (1971) and any available site specific studies.

[b] Data obtained from text and Tables 4 and 5 based on a 250,000 kg salmon net-pen culture and a 108,000 kg mussel culture. Values only apply given the current velocity and other conditions specified in the notes provided with Tables 4 and 5.

[c] Estimated change in water quality in the water mass which passes directly through the culture structure. The effects of dilution with the surrounding water are not considered.

[d] The Puget Sound concentrations provided are ortho-phosphate; total phosphate concentrations would be equal to or greater than this value. Therefore, the percent change attributable to salmon and mussel culture may be overestimated.

(Environment Canada, 1979; Roberts, 1978; U.S. EPA, 1976). Based on Table 6 the maximum concentration of unionized ammonia downcurrent of the net-pens would be 0.001 $mg \cdot l^{-1}$; far less than the toxic threshold. Unionized ammonia concentrations downcurrent of the mussel longlines would be even lower.

Minimum acceptable concentrations of dissolved oxygen have been reported to range from 5-6 $mg \cdot l^{-1}$ (Washington Department of Ecology, 1973; U.S EPA, 1976). The net-pen facility on which Table 6 is based caused a relatively small decrease in dissolved oxygen (0.3 $mg \cdot l^{-1}$, 2-5%). During the summer months dissolved oxygen concentrations in Puget Sound surface waters decrease to about 6 $mg \cdot l^{-1}$, a value which is at or close to the lowest acceptable limit. Therefore, the further decrease attributable to the net-pens could be significant if there is little or no mixing of the water which flows through the net-pens with the surrounding water mass. Inadequate mixing should be a significant problem only in very enclosed embayments.

It was demonstrated earlier that the nutrient and/or BOD loading from a net-pen facility is generally comparable to that of a small river or small milk processing plant. Loadings were greater than several seafood processors in the Puget Sound area and considerably less than that of a major brewery. In considering mariculture permit requests in Puget Sound, much attention has been given to comparisons of the water quality effects of mariculture with those of sewage discharge. In particular, nutrient and BOD loadings from proposed mariculture have been expressed in terms of their "population equivalents", and the siting of the proposed facility evaluated in terms of a comparable sewage discharge. For example the 250,000 kg salmon net-pen facility on which the loadings in Tables 4 and 5 are based would have loadings of nitrogen, phosphorus and BOD equivalent to untreated sewage from approximately 10,000 persons. The 108,000 kg mussel culture facility would have a loading equivalent to approximately 500 persons. While there may be some utility in this type of comparison, putting mariculture effects into some perspective with respect to a more familiar type of discharge, the determination of a population equivalency tends to reduce the issue to a single number, an oversimplification which may be misleading and unwarranted.

There are several factors which complicate comparisons between a sewage discharge and that of a culture facility. First, most wastewater treatment plants discharge industrial wastes or storm water along with domestic sewage. The effluent contains heavy metals, synthetic organics and other toxicants which pose a threat to the marine environment distinct from the effects of organic enrichment. With the possible exception of trace quantities of antibiotic drugs used for disease treatment (Section 3.10), the discharge from a mariculture faciliity contains no such toxicants. Secondly, sewage contains viral and bacterial pathogens which represent a public health hazard. Many state and federal effluent standards and restrictions on other water uses (e.g., shellfish harvesting) are a consequence of this health risk. In addition, the required disinfection of sewage results in the discharge of additional pollutants (e.g., chlorine). Thirdly, during primary treatment the large particulate material is removed from the sewage discharge so that the nutrient burden and resulting BOD are primarily associated with the dissolved phase. In contrast, most of the BOD and phosphates from a mariculture facility are associated with the solid wastes such as excess feed and feces. Thus, many of the effects of mariculture are more localized and gradual release of nutrients from the sediments may dilute effects over a longer time period. Finally, a sewage discharge is freshwater. Thus, depending on discharge conditions, the freshwater may promote stratification of the water column and inhibit mixing of the effluent with the receiving waters.

Aquaculture may use more water per unit of product than any other manufacturing process (Muir, 1985; Warrer-Hansen, 1982). The quantities of nutrients and associated BOD from the culture of 250,000 kg of salmonids (example discussed above) are comparable to those produced by about 10,000 persons, but the water which passes through the net-pens on a daily basis is equivalent to the domestic use of 25 million persons (based on 0.25 $m^3 \cdot day^{-1} \cdot individual^{-1}$; Muir, 1985). Thus, the concentrations of nutrients and BOD are very dilute compared to sewage and most other discharges to the marine environment.

Concerns that metabolites would increase or dissolved oxygen decrease to the point that water quality would be threatened beyond the immediate vicinity of mariculture operations in Puget Sound are generally unwarranted. Such conditions would be anticipated only in areas of extremely limited flushing or if culture intensity reached a magnitude far greater than can be expected in Puget Sound given the many competing water uses. In the few cases where measurable water quality changes have been noted, the effects have been largely confined within the culture structure. The cultured organisms would therefore be likely to first experience any toxic effects. Degradation of water quality resulting in toxic effects beyond the bounds of the culture area is unlikely in most of Puget Sound.

3.3 PHYTOPLANKTON

Questions

Could the input of nutrients associated with mariculture increase phytoplankton biomass and productivity, thereby inducing the occurrence of blooms which would have adverse effects on other water uses (e.g., shellfish harvesting)? Could culture of filter-feeding molluscs decrease phytoplankton standing stock to the point that inadequate food resources would be available to the natural suspension-feeding community?

Discussion

Enhancement of phytoplankton productivity -

Phytoplankton require nutrients, particularly nitrogen and phosphorus, for their growth and reproduction. In marine systems phosphorus is typically present in concentrations which exceed the demands of the phytoplankton, so the availability of nitrogen is one of the principal factors which often determines the growth rate. Mariculture provides nitrogen to the ecosystem principally in the form of ammonia, which may be used directly by the phytoplankton or indirectly following bacterial transformation of the ammonia to nitrate. In salmon culture, the feed provided to the fish causes a net increase of nitrogen in the system. In mollusc culture, there is a net decrease in total nitrogen because it is removed in the form of harvested animals.

Molluscs can, however, enhance phytoplankton productivity by increasing the rate of nutrient cycling; ingesting phytoplankton and then excreting a large portion of these nutrients, making them available again for use by other phytoplankton. The potential for stimulation of productivity by mussel culture has often been suggested (Campos and Mariño, 1982; Kaspar, et al., 1985; Tenore and González, 1975). It has been demonstrated in the laboratory (Rosenberg and Loo, 1983), but at least one study failed to find any effect of mussel culture on productivity in field measurements (Hagström and Larsson, 1882).

A phytoplankton bloom occurs when physical, chemical and biological factors interact to provide conditions ideal for a rapid burst of phytoplankton growth. Blooms are a common occurence in most coastal and estuarine marine environments including Puget Sound. Intense blooms usually appear in the Main Basin in late April or early May and recur throughout the summer months, each bloom lasting about 1-2 weeks (Winter, *et al.*, 1975). Most blooms pass unnoticed by Puget Sound residents, however, blooms of the diatom *Chaetoceros* sp. and the dinoflagellate *Ceratium fusus* have been responsible for fish mortalities and the subsequent closure of some net-pen operations in Puget Sound. Of greater public concern are blooms of *Gonyaulax catenella*, the organism responsible for paralytic shellfish poisoning (PSP).

Mariculture and other sources of nutrients (e.g., sewage discharges) have been implicated as potentially contributing factors in phytoplankton blooms outside of Puget Sound. While the input of nutrients may help sustain a bloom, it is important to recognize that this input may not necessarily trigger a bloom. In order for a bloom to occur many environmental factors must interact to provide suitable conditions for rapid phytoplankton growth. The availability of an adequate nutrient supply is one of these factors, but of equal importance are light, temperature, low wind velocities, reduced tidal mixing, and many other factors related to water column stability. The many interrelated environmental factors which trigger a bloom remain too poorly understood to permit prediction of bloom events. It is often tempting to implicate an obvious nutrient source without adequate understanding of hydrographic conditions and recognition of the many factors involved. Along Florida's west coast blooms were originally thought to be attributable to runoff, pollution and other land-derived nutrient inputs. Research activities were thus concentrated in the nearshore zone. Only after several years of research and observation was it found that the blooms originated 18-74 km offshore and moved shoreward (Steidinger and Haddad, 1981).

Although not conclusively demonstrated, mariculture may be responsible, in part, for phytoplankton blooms observed in other countries, with Japan being the most notable example. Arakawa (1973) correlated phytoplankton blooms with the culture of oysters in Hiroshima Bay. The frequency of the blooms closely paralleled historical trends in oyster production within the bay, however, it should be noted that correlations in time are often spurious. Bottom muds from shellfish culture have been found to accelerate the growth of red-tide organisms held in nutrient-free laboratory culture (Takagi, et al., 1980). Laboratory studies have also implicated yellowtail feces as a potential contributing factor in phytoplankton blooms (Nishimura, 1982), and yellowtail culture operations have been adversely affected by blooms, with consequent production losses. Although the causative factors have not been clearly demonstrated, the Japanese have found phytoplankton blooms appearing with greater frequency than in the past. In an effort to minimize the enrichment of nutrients in the culture areas, Japanese net-pen operators have been reducing the use of wet feed (which has a high percentage of waste) and moving culture operations from enclosed, well-protected bays into open coastal waters (Nose, 1985). Shellfish growers have also been forced to reduce culture densities (Takagi, et al., 1980).

Outside of Japan there are few reports of mariculture potentially contributing to phytoplankton blooms. At one site in Ireland (Doyle, et al., 1984) a bloom occurred that was localized around a culture operation, and the fish culture operation was believed to be a contributing factor. However, at another farm a phytoplankton bloom developed offshore and then moved into the culture area. Mortalities of the cultured fish occurred in both instances.

Field studies in Puget Sound (Weyerhaueser net-pens in Henderson Inlet, Pease, 1977; Domsea and NMFS net-pens in Clam Bay, D. Damkaer, NMFS, unpub. data) have failed to demonstrate any effect of mariculture on phytoplankton. Chlorophyll a concentrations (a measure of phytoplankton biomass) were measured in both studies and no effect attributable to the culture facilities was identified.

Under physical conditions typical of most of Puget Sound, it would be difficult to demonstrate any localized effect of mariculture on phytoplankton populations based on field sampling. Individual phytoplankton cells require several hours to divide even at rapid reproduction rates, and whole populations require a day or more to double in number (Parsons, et al., 1977). Phytoplankton populations require several days to increase to bloom proportions (Strickland, 1983). Therefore, by the time phytoplankton populations might be expected to show measurable responses to the nutrient enrichment in a parcel of water, that parcel is far from the culture site, and nutrient concentrations have been diluted many times over by mixing with the surrounding waters. Only in a static system such as a lake or an area with very poor flushing and intensive culture, would any measurable effect on productivity be expected.

There are several other reasons to expect Puget Sound mariculture to have minimal effect on phytoplankton productivity. As noted earlier, the unavailability of nitrogen is often a factor limiting phytoplankton growth in most marine systems. However, in much of Puget Sound nitrogen is usually present in concentrations which exceed the utilization capabilities of phytoplankton. Phytoplankton growth is instead often limited by low light levels and instability of the water column (Campbell, et al., 1977; Collias and Lincoln, 1977; Welch, et al., 1972; Winter, et al., 1975). Thus, additional input of nutrients already present in relatively high concentrations will have little or no measurable effect on primary productivity. It is only in areas with a high degree of water column stratification because of freshwater inflow or minimal tidal mixing would addition of nutrients be expected to influence productivity.

The danger of drawing direct parallels between the embayments of Japan and Puget Sound is demonstrated by examining nutrient levels in the Japanese culture areas. The Japanese culture areas are very poor in nutrients in comparison to Puget Sound waters, and thus additional nutrient input may have dramatic effects on phytoplankton productivity in those low nutrient areas. For example, various Japanese investigators have recommended upper limits for nutrient concentrations which, if exceeded, result in high potential for phytoplankton blooms. Murakami (1973) found that oyster production began to decrease when the average annual nitrate concentration exceeded 0.1 $mg \cdot l^{-1}$. It has been recommended that total nitrogen not exceed 0.1 (Iwasaki, 1976) and 0.35 $mg \cdot l^{-1}$ (Takagi, et al., 1980). In contrast, nitrate concentrations in the surface waters of the Main Basin of Puget Sound are typically about 1 $mg \cdot l^{-1}$ (Collias and Lincoln, 1977), far in excess of the recommended upper limits in Japan.

While nitrogen is abundant and not limiting to phytoplankton growth in the Main Basin, it should not be assumed that these conditions are found throughout the Sound. Certain areas of the Sound have been identified where stratification of the water column does occasionally permit depletion of available nitrogen (Yake, unpub.). These areas are Drayton Harbor, Bellingham Bay, Port Susan, Port Gardner, Possession Sound, Penn Cove, Holmes Harbor, Saratoga Passage, Hood Canal (lower three-fourths), Sequim Bay, Port Orchard, Dyes Inlet, Sinclair Inlet, Liberty Bay, Carr Inlet, Case Inlet, Budd Inlet, Eld Inlet, Totten Inlet and Oakland Bay. In these regions, nitrate concentrations in surface waters are reduced to less than 0.1 $mg \cdot l^{-1}$ for 2-3 months during the summer.

It is possible to obtain a crude estimate of the potential effects of mariculture on phytoplankton by estimating the maximum potential increase in phytoplankton standing stock should all nutrients supplied by a net-pen culture be used for phytoplankton growth. Tett (1981) estimated that about 3 mg nitrogen are required to produce 1 mg of chlorophyll, and Gowen, et al. (1985) used this factor to estimate the potential effect of salmon net-pen culture in Scotland. Applying the same calculation procedure to Puget Sound, we note that the net-pen operation described in Tables 4 and 5 increased the total nitrogen concentration of the water which passed through the pens by 0.02 $mg \cdot l^{-1}$ (or 20 $mg \cdot m^{-3}$). Assuming that nitrogen is a limiting nutrient, and that all of the nitrogen released from the net-pens was used for phytoplankton growth, the phytoplankton standing stock in the water passing through the net-pens could increase by about 7 mg chlorophyll $\underline{a} \cdot m^{-3}$, or about 30 mg chlorophyll $\underline{a}$ m^{-2} vertically integrated over the 4 m depth of the net-pens. Phytoplankton standing stock in the Main Basin of Puget Sound is typically about 10-30 mg chlorophyll $\underline{a} \cdot m^{-2}$ between blooms and in excess of 100 mg chlorophyll $\underline{a} \cdot m^{-2}$ during blooms (Strickland, 1983; Winter, et al., 1975 - standing stock expressed as a vertically integrated value through the water column from the surface to the 1% light depth). The additional 30 mg chlorophyll $\underline{a} \cdot m^{-2}$ attributable to net-pen culture would not initiate a bloom, and, in fact, would be completely unmeasurable given the natural spatial variability of phytoplankton biomass. These calculations have assumed no horizontal mixing, an implausible assumption given the time required before the phytoplankton population could fully utilize these nutrients. During this time period the enriched water would be thoroughly mixed with surrounding water under most conditions, and the increase in standing stock would be negligible. A bloom might be initiated or sustained only if the net-pens were placed in an enclosed and poorly-flushed embayment where dilution and dispersion were much reduced, or if local geomorphology and hydrography caused the same water mass to repeatedly pass through the culture area with each tidal cycle.

Reduction in phytoplankton standing stock -

Mussels and oysters feed by filtering seston (i.e., suspended particulate matter, both plankton and detritus), and thus the biomass of phytoplankton downcurrent of a mollusc culture site may be expected to be reduced. The effectiveness with which molluscs remove particulate material from the water is evident in the work of Imai (1971) (shown in Table 7). The concentration of seston in the water was measured after passage through oyster rafts, each

Table 7

Cumulative reduction in seston concentration with passage through oyster rafts: Kesen-numa Bay, Japan. (from Imai, 1971)

Raft Number	Percentage of initial seston concentration	
	June - Sept	Sept. - Nov.
Initial seston concentration outside culture ground	100	100
Passing through:		
Raft 1	88.9	77.4
Raft 2	78.9	60.0
Raft 3	70.1	46.4
Raft 4	62.3	36.0
Raft 5	55.4	27.8
Raft 6	49.2	21.6
Raft 7	43.7	16.7
Raft 8	38.8	12.9
Raft 9	34.5	10.0
Raft 10	30.7	7.7
Raft 11	27.2	6.0
Seston concentration inside culture ground	24.2	4.6

supporting 50,000-90,000 oysters. The seston concentration was reduced 76-95% after passage through 11 rafts (although some of this loss may be attributed to passive settling rather active removal by the oysters).

There is also anecdotal evidence of the filtering efficiency of mussels. Growers have found that mussels on the upcurrent side of a raft grow faster than those on the downcurrent side, presumably because of the reduction in food concentration as the water passes through the raft (Mason, 1976). Divers have reported the water clarity in the midst of mussel strings to be substantially improved over conditions beyond the perimeter of the raft, assumedly because the mussels have reduced the concentration of suspended material (Pease and Goodwin, unpub.).

While definitive data are lacking from Puget Sound, experiences from other mussel culture areas suggest that culture intensities anticipated in Puget Sound are far below the intensities that could be sustained. Changes in seston concentrations in the vicinity of the culture sites are therefore not likely to limit feeding of other organisms. Rosenberg and Loo (1983) examined the effects on seston of a mussel longline culture operation in Sweden that produced 200 metric tons of mussels every two years. On the basis of field experiments and theoretical calculations of seston concentration, current velocity and filtering efficiency it was estimated that the seston concentration was adequate to support a culture operation of twice the existing size. It was also considered unlikely that the culture would remove sufficient quantities of seston so as to impoverish other hard-bottom epibenthic animals in the vicinity.

The Ria de Arosa estuary in Spain has a surface area of 230 km^2 (slightly smaller than the area of Hood Canal), an average depth of 19 m and a phytoplankton biomass and productivity comparable to that of the Puget Sound Main Basin (Tenore and Gonzalez, 1975). The Ria is an area of intensive shellfish culture with 2,000 mussel rafts and 200 oyster rafts, with the established culture areas occupying 10% of the surface area of the entire estuary. The Ria produces about 100,000 metric tons of mussels per year. In comparison the annual production of mussels in all of Puget Sound is between 50 and 100 metric tons - the yield of one or two rafts in the Ria de Arosa. It has been estimated that the mussels filter at least 80% (and at times twice this) of the water volume of the Ria every day (Tenore, et al., 1982). Yet the seston concentration is adequate to support not only the needs of the mussels but the demands of a dense epifaunal community growing on the rafts. Extrapolating these observations to Puget Sound suggests that any reduction in seston concentration in the vicinity of the relatively (in comparison to the Ria de Arosa) small culture operations in Puget Sound would probably not be a limiting factor to the naturally occuring filter-feeding organisms.

Conclusions

Floating mariculture is unlikely to have measurable effects on phytoplankton standing stock or productivity in most of Puget Sound. With the exception of some stratified areas, such as some of the inlets of southern Puget Sound, there is little evidence that nutrients ever limit phytoplankton growth in much of the Sound. Even the West Point discharge, which releases about 100 times more ammonia and about 300 times more organic nitrogen than a large net-pen operation, has not been found to affect productivity, in part, because growth is limited by factors such as light and water column stability rather than by nutrient concentrations.

In areas where nutrients are limiting to phytoplankton growth, any input of nutrients would, by definition, stimulate phytoplankton growth. However, in most areas dilution of the nutrients released from a mariculture facility would minimize any potential localized effects on productivity. I calculated that, even if all nitrogen provided by a large net-pen operation to the water body passing through or under the pens were utilized by phytoplankton for growth, the phytoplankton biomass in this parcel of water would only be increased by about 30 mg chlorophyll $\underline{a}\cdot m^{-2}$. This increase in standing stock would not constitute a bloom, and, in fact, would be undetectable given the spatial and temporal "noise" of phytoplankton populations. Moreover, given the substantial dilution that would occur in the time before phytoplankton could use these nutrients, the actual increase in biomass would be negligible. A localized, measurable effect would be expected only if the culture operation were sited in a highly stratified and poorly flushed area where that parcel of water could retain its integrity for an extended period of time, or if the same parcel of water were repeatedly passed through the culture area with each tidal cycle.

The potential for changes in phytoplankton community composition as a result of mariculture activities has not been addressed. However, if observable changes in phytoplankton biomass and productivity are unlikely, observable changes in community composition seem unlikely as well. Based on observations in other marine areas, it also seems unlikely that any reductions in seston concentrations caused by the filter-feeding activities of mussels and oysters would limit the natural suspension-feeding community in Puget Sound.

3.4 SEDIMENTATION

Questions

Will solid wastes produced by mariculture operations, such as fecal material and excess feed, sink to the bottom and accumulate under the pens? In the event of this accumulation of organic matter, what physical and chemical changes will occur in the substratum? (The biological consequences of these changes are addressed separately in Section 3.5.)

Discussion

Quantity of solid waste produced by net-pen culture -

The culture of salmonids in Puget Sound generally results in the production of two types of waste: 1) excess food which passes through the pen without being ingested by the fish; and 2) fecal material. Smaller quantities of waste result from the sloughing of fouling organisms growing on the nets and associated structures.

The quantity of unutilized feed generated by mariculture is highly variable And depends to a great degree on culture practices including feed type, feeding methods and frequency. Wasteage is dependent upon type of feed used since differences in consistency affect capture efficiency and differences in digestibility affect utilization of the feed ingested. Sedimentation rates measured beneath net-pens vary up to 4-fold depending on the type of food supplied to the fish (fresh anchovies vs. frozen mackerel; Kadowaki, et al., 1980). For land-based trout farming, a wasteage of 1-5% has been estimated for dry feed, 5-10% for semi-moist feed and 10-30% for wet feed (VKI, 1976). Estimates of feed wasteage for net-pen rearing of trout or salmon in Europe include 15-20% (dry feed - Gowen, et al., 1985), 20% (primarily moist feed - Braaten, et al., 1983), and 30% (mixture of dry and wet feeds - Penczak, et al., 1982). The salmon culturists currently operating in Puget Sound typically use dry feed, which has a relatively low wasteage. It is estimated that no more than 5% of the feed is wasted in Puget Sound net-pen culture (C. Mahnken, National Marine Fisheries Service, pers. comm.).

Fish defecation is the second major source of organic matter to the sediments. Butz and Vens-Capell (1982) have shown that under laboratory conditions 25-38% of dry food ingested by rainbow trout is lost as feces. If these data are applied to net-pen culture of salmon and it is assumed that about one-third of the feed ingested is lost as feces, it is possible to estimate the quantity of solid waste which may be generated by a net-pen culture. Food conversion ratios for salmon raised in Puget Sound are typically about 2:1; the production of 1 kg of salmon requires 2 kg of feed. Assuming dry feed is used (the usual practice) approximately 0.1 kg (5%) of feed will be lost as waste with the remainder, 1.9 kg, ingested by the fish. With one-third of the ingested feed lost as feces, the ingestion of the 1.9 kg feed will result in the production of 0.6 kg of fecal material. The total solid waste (excess feed and feces) produced per kg of salmon will be about 0.7 kg (dry weight). A large operation (e.g., 250 metric tons of salmon per year) will generate about 175 metric tons of solid waste per year.

Quantity of solid wastes produced by mussel culture -

Mussel production generates solid wastes in the form of feces and pseudofeces (material which has been filtered from the water by the animal but not ingested). Shells which fall from the culture structure also accumulate on the bottom immediately under the raft or longline. Studies of oyster culture in Japan indicate that the amount of solid waste produced by shellfish culture can be considerable (Arakawa, et al., 1971; Ito and Imai, 1955; Kusuki, 1977a). A raft of oysters in Hiroshima Bay holds 350,000-630,000 oysters. During a nine month culture season a single raft will produce 16 metric tons (dry weight) of feces and pseudofeces, with an additional 4.5 tons attributable to feces of fouling organisms growing on the rafts. Approximately 20-30% of this material is deposited on the bottom under the raft.

Fecal and pseudofecal production by Mytilus galloprovincialis ranges from 14.3-149.3 mg dry weight$\cdot$day$^{-1}\cdot$individual^{-1} (Arakawa, et al., 1971). If a mean rate of 68 mg$\cdot$day$^{-1}\cdot$individual^{-1} is assumed for Mytilus edulis grown commercially in Puget Sound, it can be estimated that a typical raft supporting 700,000 individuals (P. Jeffards, Penn Cove Mussels, pers. comm.) will produce 17 metric tons of feces and pseudofeces per year.

Sedimentation rates -

Many investigators have attempted to quantify the rate of solid waste production from fish and shellfish culture facilities by placing sediment traps beneath the pens and rafts. Sedimentation rates beneath net-pens have been estimated for cultures of rainbow trout (Enell and Löf, 1983a; 1983b; Merican and Phillips, 1985; Phillips, et al., 1985), yellowtail (Hata and Katayama, 1977; Kadowaki, et al., 1978b; 1980), Atlantic salmon (Ervik, et al., 1985) and Pacific salmon (Pease, 1977). Sedimentation rates beneath mussel rafts or longlines have been measured by Dahlbäck and Gunnarson (1981) and Tenore, et al. (1982). Sediment traps are of questionable value in obtaining absolute measures of sedimentation rate since it is difficult to distinguish freshly deposited material from resuspended sediments, and the amount of material collected in a trap is highly dependent on trap size and shape (Butman, in press; Butman, et al., in press). Sediment traps are useful, however, in obtaining estimates of sedimentation relative to a reference area with a comparable current regime. Sedimentation rates beneath net-pens have typically been found to be 2-10 times greater than in reference areas (Enell and Löf, 1983a; 1983b; Pease, 1977). Sedimentation rates as high as 100-200 times rates in reference areas have been reported under net pens in some lakes (Merican and Phillips, 1985; Phillips, et al., 1985). Rates of deposition beneath mussel longlines have been observed to be 2-4 times those in reference areas (Dahlback and Gunnarson, 1981).

Fate of solid wastes -

The fate of solid wastes produced by a culture operation depends in large part on the current velocity, water depth and sinking speed of the material. The greater the current velocity or water depth, the greater the probability that the wastes will be dispersed. Dry feed which sinks more quickly than the other feed types will tend to accumulate immediately under the pen (Pedersen, 1982). Investigations of floating mariculture facilities have generally found significant accumulation of solid wastes beneath the pens, rafts or longlines. This deposit typically consists of a soft, flocculent layer on top of the natural sea bottom (Kaspar, et al., 1985; Morrison, unpub.; Pease and Goodwin, unpub.; Tenore, et al., 1982). Table 8 shows the extent of this accumulation

Table 8

Sediment accumulation beneath salmon net-pens or mussel culture facilities

Location (Reference)	Animal Cultured	Water[a] Depth (m)	Current[b] Velocity	Depth of Accumulation (cm)	Distance of Visible Accumulation from Facility (m)	Comments
Weyerhaeuser Co. Henderson Inlet, Puget Sound (Pease, 1977)	Coho salmon	5-7 (2-4)	Very weak[c]	ND[d]	At least 15	Sediments under pens covered by *Beggiatoa*
Scan Am Farms Hadlock, Puget Sound (Kyte, unpub.; pers. comm.)	Atlantic salmon	20 (13)	"Relatively strong"	2-8	3-5	Sediments under pens covered by *Beggiatoa*
NMFS Clam Bay, Puget Sound (Lindbergh, 1972)	Chinook and coho salmon	9-13 (0-8)	5-20 cm·sec^{-1}(e)	3-4	30	
Domsea Clam Bay, Puget Sound (Pease, unpub.)	Coho salmon	11-17 (7-14)	5-20 cm·sec^{-1}(e)	2-5	15	Sediments under pens covered by *Beggiatoa*
Domsea Fort Ward, Puget Sound (Pease, unpub.)	Coho salmon	8 (4)	"Strong"	see comments	see comments	Isolated pockets of fish feces and *Beggiatoa* around rocks and other protected areas. Visible up to 46 m from pens.
Suquamish tribe Agate Pass, Puget Sound (Pease, unpub.)	Coho salmon	8	"Weak to moderate"	see comments	directly under pens	Fish feces and *Beggiatoa* in small, scattered patches. Site used for delayed release; fish not in pens continuously

Table 8 continued

Location (Reference)	Animal Cultured	Water[a] Depth (m)	Current[b] Velocity	Depth of Accumulation (cm)	Distance of Visible Accumulation from Facility (m)	Comments
Nansen/Hamilton Port Blakely, Puget Sound (D. Nansen, pers. comm.)	Coho salmon	6 (0)	ND	5-8	Only directly under pens	Deposit consisting primarily of excess feed
Sea Farm of Norway Port Angeles, Str. Juan de Fuca (Milner-Rensel Assoc., 1986)	Atlantic salmon	23 (19)	8 cm sec^{-1}	0	0	Isolated small patches of *Beggiatoa*
Penn Cove Mussels Penn Cove, Puget Sound (Pease and Goodwin, unpub.)	Blue mussel	11-13	"Very weak"	7-30	Shell debris only directly under rafts. Organic enrichment extends less than 37 m.	Sediments under rafts covered by *Beggiatoa*
Hotham Sound, British Columbia (Morrison, unpub.)	Salmon	21 (12)	"Good flushing"	15	ND	Sediment under pens covered by *Beggiatoa*
Nanaimo, British Columbia (Kennedy, 1978)	Pacific salmon	ND	ND	ND	< 20	

Table 8 continued

Location (Reference)	Animal Cultured	Water Depth (m)[a]	Current Velocity[b]	Depth of Accumulation (cm)	Distance of Visible Accumulation from Facility (m)	Comments
Storebø, Norway (Braaten, *et al.*, 1983)	Atlantic salmon	10	ND	5-10	ND	Significant accumulation of sediment after 3 years of operation
Western Norway (Ervik, *et al.*, 1985)	Atlantic salmon	16-61	ND	up to 37	ND	
Tjarno, western Sweden (Dahlbäck and Gunnarson, 1981)	Blue mussel	8-13 (2-7)	"Weak-typically 3 cm·sec^{-1}"	10-15	ND	*Beggiatoa* under longlines. 10-15 cm sediment accumulation developed in 16 months.

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[a] Total water depth (at mean lower low water if available) and depth of water beneath lowest point of culture structure (in parentheses).

[b] Many studies lack quantitative data on current speeds. The authors' qualitative description is provided if available.

[c] No measurable surface or bottom current in the culture area during a 24-hr. period of observation.

[d] ND = No data available.

[e] Current velocity from Kramer, Chin and Mayo (undated). Reported to reach 100 cm·sec^{-1} at times (Lindbergh, 1972).

based on a review of the available literature. Several conclusions can be drawn from Table 8:

1) Most sites examined were in relatively shallow water with less than 15 m (and often less than 10 m) between the bottom of the culture structure and the sea floor, thereby increasing the likelihood of observable solids accumulation.

2) Many sites were located in areas of relatively weak currents decreasing the probability of solids dispersal. Most investigators provided no quantitative data on current speeds. This is a result of the fact that many of the studies identified in Table 8 were simply diver observations from a single survey.

3) Some accumulation of wastes associated with the culture operation was measured at all but one site examined. The accumulations ranged in depths from 2-37 cm. Even at the one site with no visible accumulation of solid wastes (Sea Farm of Norway), the presence of *Beggiatoa* spp., the odor of hydrogen sulfide in one sample and the elevation of ammonia concentrations in interstitial water indicated some organic enrichment of bottom sediments. It may be significant that the Sea Farm of Norway facility has been in operation only 1.5 years. It is unknown if greater accumulation will occur with continued operation.

4) Visible accumulation of wastes was localized, extending at most 46 m from the facility and typically much less.

5) White patches on the sediment surface consisting of colonies of *Beggiatoa* spp. bacteria were observed at most sites. This organism provides a readily visible indicator of organic enrichment of the sea floor.

The extent of solids accumulation is dependent on current velocity as well as depth, and both must be considered in project siting, but some of the investigators identified in Table 8 have used their observations of solids accumulation to suggest minimum depths for location of net-pens. Morrison (unpub.) recommended that pens not be located in less than 9 m of depth at low water, with a minimum of 3 m between the net and the sea floor. Braaten, *et al.* (1983) suggested that, in general, there should be a clearance of at least 10 m beneath the net-pen, and furthermore suggested that sites with strong currents (as indicated by a sand or gravel bottom) be selected. Table 8 suggests that localized solids accumulation is very likely if net-pens are located where water depth under pens is less than 15 m, and it should be noted that solids accumulation is possible at even greater depths. There are insufficient data provided by Table 8 to suggest optimal current velocities, although obviously the greater the current velocity, the less will be the extent of solids accumulation (Hata and Katayama, 1977).

Relatively little is known of the time required for observable accumulation of solids under culture operations or for dispersal of such accumulations following cessation of culture. Measurable accumulation (1-2 cm) of wastes did not develop until the third year of culture at one Norwegian net-pen site, but continued accumulation was rapid thereafter (Braaten, et al., 1983). After 16 months 10-15 cm of material had accumulated beneath mussel longlines in Sweden (Dahlback and Gunnarson, 1981).

The rate of removal of wastes after cessation of culture may be relatively rapid. Pamatmat, et al. (1973) found that benthic oxygen consumption under a net-pen in Clam Bay, Puget Sound, which had previously been about 6 times reference levels, had returned to reference levels within 2 months after removal of the pens. The pens had rested on the bottom at low tide, so dispersal of deposits was rapid after their removal. British Columbia salmon farmers report that deposits disappear within 4-6 months (Morrison, unpub.). Enell and Löf (1983a) found that wastes beneath a lake net-pen were reduced from 10 to 1 cm within one year after feeding rate was halved. Obviously the rates of both accumulation and removal are going to be highly dependent upon bottom current velocities at the culture site. Biological processes (both microbial decomposition and macrofaunal activity) will also affect the rate at which the sea floor returns to pre-culture conditions.

Sediment chemistry -

The solid wastes generated by fish or shellfish culture are enriched in carbon, nitrogen and phosphorus relative to natural sediments (Kusuki, 1977b; Merican and Phillips, 1985). Therefore, the accumulation of solid wastes beneath the culture operation alters the chemistry of the bottom sediments in a number of ways. There are changes in benthic oxygen consumption, Eh profile, total organic carbon, total volatile solids, sulfide concentrations, and nutrient concentrations (nitrogenous compounds and phosphates). Changes in all these parameters are typical of marine sediments enriched with organic matter, regardless of whether this organic matter is derived from a mariculture operation, sewage treatment plant, pulp mill, food processing plant, or any other comparable source.

Benthic oxygen consumption - The most extensive survey of oxygen uptake of bottom sediments in Puget Sound was by Pamatmat, et al. (1973). Typical oxygen consumption values throughout the Sound ranged from 4-56 ml $0_2 \cdot m^{-2} \cdot hr^{-1}$. The respiration of benthic organisms (bacteria, meio- and macrobenthos) generally accounted for 10-50% of the total with chemical oxidation accounting for the remainder. Sediments under salmon net-pens in Clam Bay had an oxygen uptake rate of about 125 ml $0_2 \cdot m^{-2} \cdot hr^{-1}$. Nearly two-thirds of this total was attributable to respiration. The organic enrichment was limited to the immediate vicinity of the net-pens. Oxygen consumption rates 15 m from the pens (31-42 ml $0_2 \cdot m^{-2} \cdot hr^{-1}$) were only slightly above reference conditions and no effect on benthic respiration was evident 30 m away. Rates of benthic oxygen consumption 2-3 times reference values have also been reported beneath net-pens or mussel longlines in Henderson Inlet, Puget Sound (Pease, 1977), New Zealand (Kaspar, et al., 1985) and Swedish lakes (Enell and Löf, 1983b).

Eh profile - The redox potential (Eh) is a measure of the oxygen content of sediments. In oxygenated (aerobic) environments the Eh is greater than zero. In anaerobic, reducing environments Eh is negative. The interface between the aerobic and anaerobic zones of the sediment (known as the redox-potential discontinuity) is a zone in which the oxygen demands of decomposing organic matter are in balance with the supply of oxygen from the overlying water. These chemical changes are also manifested by color changes of the sediment with oxygenated sediments appearing brown or yellow and anaerobic sediments appearing black. The depth of this interface can be used as a measure of the rate of organic material input (Fenchel and Riedl, 1970; Pearson and Stanley, 1979).

An example of the effect of floating mariculture on sediment Eh is shown in Figure 3 based on measurements made beneath mussel longlines in Sweden (Dahlbäck and Gunnarson, 1981). Eh values become more negative with depth in the sediment column in all marine sediments due to the limitations on diffusion of oxygen from the overlying water. However, there is generally a layer of

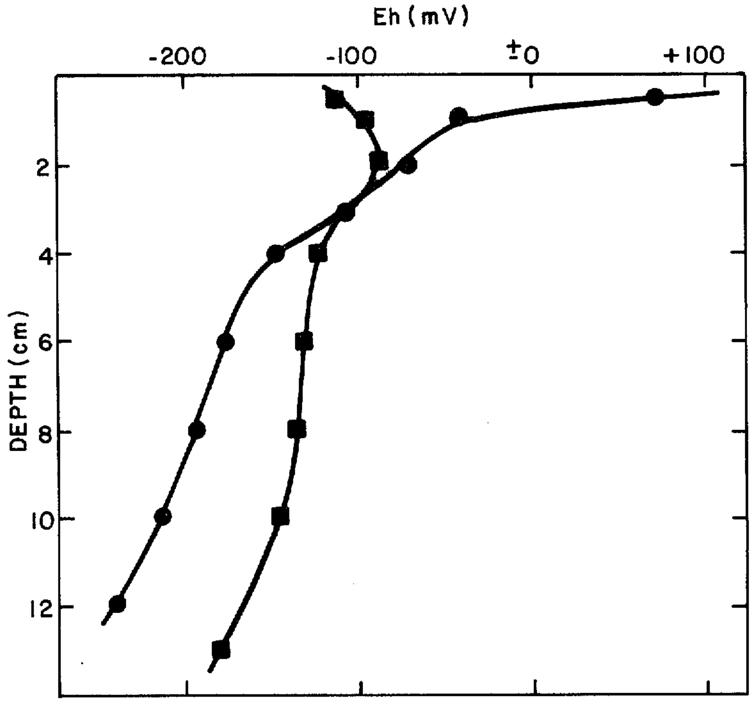

Figure 3 - Redox potential (Eh) profiles in the sediment column under a mussel culture (squares), and from a reference area (circles). From Dahlbäck and Gunnarrsson, 1981.

oxygenated sediments which overlies the anaerobic sediments. Such a pattern is seen at the reference site in Figure 3. Beneath the mussel culture the high input of organic wastes from the mussels prevents the establishment of a superficial aerobic sediment layer and negative Eh values are observed at the sediment surface. The fact that the reference sediment has a lower Eh than the sediment beneath the mussels at depths greater than 3 cm is not a typically observed condition and was not found in later measurements at the same site.

Total organic carbon (TOC) and total volatile solids (TVS) - TOC and TVS are both measures of sediment organic enrichment. These two measures are highly correlated and both have been used in documenting organic enrichment which has occurred beneath mariculture facilities. Concentrations of both TOC (Dahlbäck and Gunnarson, 1981; Kaspar, *et al.*, 1985) and TVS (Kaspar, *et al.*, 1985; Mattson and Linden, 1983; Pease and Goodwin, unpub.) have been found to be elevated under mussel culture facilities. Pease (1977) found concentrations of total carbon (TOC unmeasured) to be approximately twice as great under salmon pens in Henderson Inlet in comparison to reference areas, but no enrichment of total carbon was found beneath the Sea Farm of Norway pens at Port Angeles (Milner-Rensel Assoc., 1986).

Sulfide concentrations - In the absence of oxygen, the microbial degradation of organic matter is accompanied by the reduction of the sulfate anion in seawater to hydrogen sulfide. Figure 4 illustrates the sulfate and sulfide concentrations in sediment pore waters beneath a mussel longline (Dahlbäck and Gunnarson, 1981). Due to the high input rate of organic material and the consequent development of anaerobic conditions, sediment pore waters were found to have low concentrations of sulfate, a high rate of reduction of sulfate to sulfide, and high concentrations of sulfides. Ito and Imai (1955) also reported high sulfide concentrations beneath oyster racks. Furthermore, they related an increasing sulfide concentrations with duration of culture at the site. Sediments beneath 2-year old rafts had sulfide concentrations approximately twice those in reference areas, whereas 6-year old rafts had sulfide concentrations nearly 10 times greater than reference areas. Lieffrig (1985) has shown hydrogen sulfide production beneath salmon net-pens to be 10 times greater than reference levels.

The generation of hydrogen sulfide beneath culture operations has been implicated as a cause of reduced productivity in shellfish culture (Arakawa, *et al*, 1971; Ito and Imai, 1955) or mortality in salmon net-pen culture (Braaten,

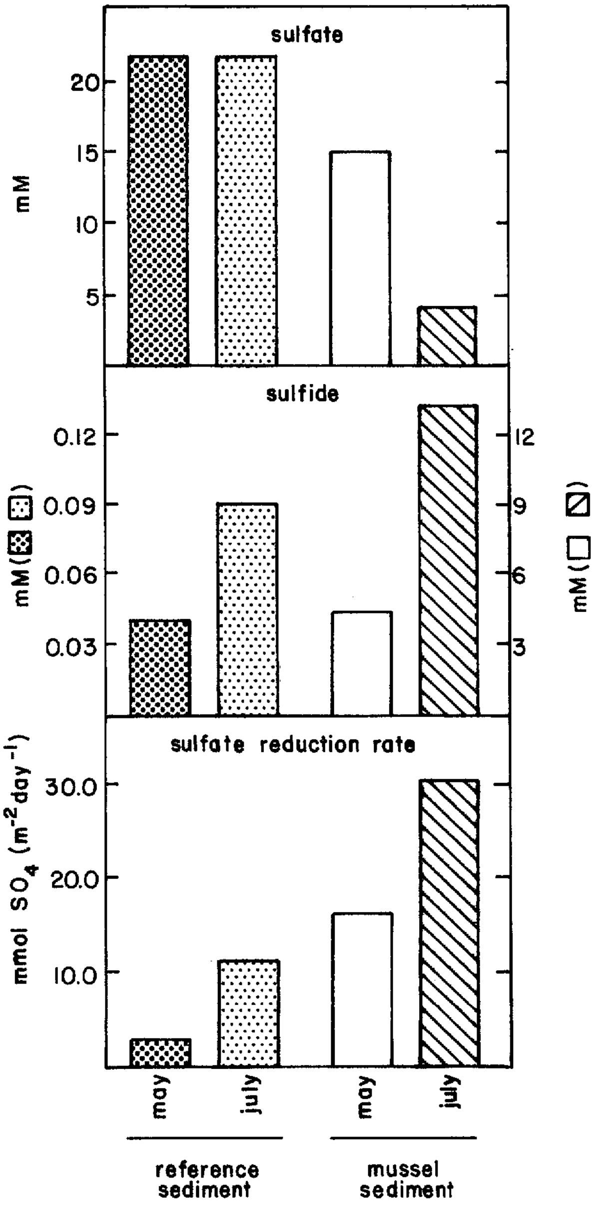

Figure 4 - Average pore water concentrations of sulfate and sulfide and sulfate reduction rate in sediments from beneath a mussel culture and from a reference area. From Dahlbäck and Gunnarsson, 1981.

et al., 1983; Pedersen, 1982). A relationship has also been found between concentration of sulfides in the sediments and incidence of disease in cultured yellowtail (Arizono, 1979). Periodic relocation of culture operations or rotation among several sites has been generally recommended as a means to prevent loss of productivity or mortality.

Nutrient concentrations - Feed, feces and pseudofeces all contain several times more nitrogen and phosphorus than natural sediments (Arakawa, et al., 1971; Kusuki, 1977b; Merican and Phillips, 1985) thus it is expected that there would be an enrichment of these elements in the solid wastes generated by mariculture facilities. This expectation is generally supported by the available data from both freshwater and marine culture:

1) Henderson Inlet, Puget Sound (Pease, 1977) - Total nitrogen content of sediment beneath salmon net-pens was approximately twice that of the reference area.

2) Port Angeles, Strait of Juan de Fuca (Milner-Rensel Assoc., 1986) - Ammonia nitrogen in interstitial and near-bottom water was elevated beneath salmon net-pens. No effect of pens on total nitrogen was observed.

3) Swedish lakes (Enell and Löf, 1983b) - Interstitial water concentrations of ammonia and molybdate-reactive phosphorus were approximately ten times greater beneath rainbow trout net-pens than in the reference area.

4) Lake Letowo, Poland (Trojanowski, et al., 1982) - Phosphorus and several nitrogenous compounds were enriched in sediments beneath rainbow trout net-pens.

5) Manchester, Puget Sound (Anonymous 1983a; D. Damkaer, NMFS, unpub. data) - No elevation of ammonia, total organic nitrogen, total inorganic nitrogen, or total Kjeldahl nitrogen attributable to salmon net-pens was observed. Concentrations of several of these parameters were elevated beneath a dock adjacent to the culture operation, and it was suggested that fouling organisms on the dock may be a source of some portion of the nitrogenous material.

Nitrogen and phosphorus are not retained equally in the solid wastes generated by net-pen culture. Most phosphorus consumed by a salmonid is lost as solid waste (66-84%). In comparison only 11-22% of the consumed nitrogen is lost in the solid phase, with the vast majority excreted in a dissolved form as ammonia or urea (Ackefors and Södergren, 1985; Enell and Löf, 1983b; Gowen, *et al.*, 1985; Merican and Phillips, 1985; Phillips, *et al.*, 1985). Over time the nutrients in the enriched sediments will be released to the water column, with the release of nutrients accelerated under anaerobic conditions (Enell and Löf, 1983b). In a freshwater environment where phosphorus concentration is typically the limiting nutrient controlling phytoplankton growth, the release of phosphorus from the sediments can contribute to eutrophication. However, in marine environments where nitrogen is typically the limiting nutrient, the principal nutrient effect of mariculture will be felt immediately with the excretion of dissolved metabolites.

Conclusions

Floating mariculture generates large amounts of solid wastes in the form of unutilized feed and feces (salmon culture) or feces, pseudofeces and shell debris (mussel and oyster culture). These wastes may accumulate on the bottom beneath the culture facility resulting in organic enrichment and associated dramatic changes in sediment chemistry. The changes which have been observed include decreased redox potential, increased sediment oxygen consumption and increased concentrations of TVS, TOC, sulfides, nitrogenous compounds and phosphates.

The areal extent of effect on bottom sediments is dependent upon the sinking speed of the waste, the current velocity and the water depth. Ideally, a culture operation should be sited so that currents would disperse the wastes over such a broad area that their deposition would not exceed the assimilative capacity of the marine environment and there would be no measurable effect on sediment quality. In practice, however, most mariculture facilites have been located in relatively shallow water (< 20 m), and there has been accumulation of solid wastes beneath the facility. From the literature reviewed, it appears that if less than 15 m of water is maintained under the lowest point of the culture structure there is a high probability that there will be visible accumulation of wastes on the bottom. These observations have implications in site selection and evaluation. For example, a culture operation with less than 15 m of water beneath it should not be located over a habitat of special significance or a habitat the loss of which would be considered unacceptable. Insufficient data were available for evaluation of sites in deeper water. Data on current velocity and its relationship to solids accumulation are also extremely limited. While most investigators have failed to provide quantitative data on current velocity, this is obviously a critical parameter if we are ever to obtain some predictive capabilities of the magnitude of effects.

However, even at sites in very shallow water, the areal extent of accumulation of solid wastes appears to be very limited. Visible accumulation of wastes typically are present only within about 30 m of the facility. This areal extent of effect is inferred from visible accumulation of wastes. Less information is available on the areal extent of alteration of sediment chemistry since most investigators on this topic established only distant reference stations rather than sampling along a transect at frequent intervals. However, it appears that the areal extent of effects on sediment chemistry is about the same as the extent of visible accumulation. As discussed earlier, Pamatmat, et al. (1973) found only a slight increase in benthic oxygen consumption 15 m from net-pens. Mattson and Linden (1983) found elevation of TVS under mussel longlines was limited to within 15 m of the culture site. In addition, most investigators (Dahlbäck and Gunnarson, 1981; Ito and Imai, 1955; Kadowaki, et al, 1980; Merican and Phillips, 1985; Pease, 1977; Pease and Goodwin, unpub.) have established reference stations within 100 m of the culture operation and frequently within 35 m, thereby implying that the expected areal extent of effect is very small.

There are several steps operators might take to minimize the accumulation of solid wastes beneath facilities. Not only may these efforts reduce the effect of the culture activities on the environment, but they may minimize mortalities of the cultured animals or decreases in productivity due to the generation of hydrogen sulfide by the waste deposits. Mitigative measures an operator might take include:

1) Siting in areas with the greatest current velocity and water depth permitted by anchoring and structural considerations and operational constraints.

2) Avoid siting the facility in areas where the bathymetry would promote the accumulation of wastes (e.g. within silled embayments).

3) Arrangement of culture units so as to disperse wastes over as broad an area as possible.

In other countries (e.g., Norway) operators have found a need to periodically rotate culture sites if the culture facilities are located in areas where currents do not provide sufficient waste dispersal. Some operators have employed submersible mixers to disperse wastes over a wider area. Other techniques to minimize solids accumulation which have been either proposed or tested include the use of waste catchment devices beneath net-pens, dredging or trawling of the sea bottom and the culture of shellfish around a net-pen in order to use the solid wastes to produce a harvestable product (Braaten, *et al*., 1983; Enell, *et al*., 1984; Pedersen, 1982; Rosenthal, 1985). None of these techniques have been tested in Puget Sound.

3.5 BENTHIC MACROINVERTEBRATES

Concern

Given that wastes which settle to the bottom beneath floating mariculture facilities can alter the physical and chemical properties of the substratum, how do these changes affect the benthic invertebrate community? Are there changes in community composition or abundance? Can there be complete mortality?

Discussion

Benthos live in or on the sediments. Macrobenthos are operationally defined as those invertebrates which pass through a 4 mm screen sieve but which are retained on a 0.5 mm mesh sieve (some investigators have used a 1.0 mm as the lower limit). The terms macrofauna, macroinvertebrates and macrobenthos are used interchangeably. Macrobenthic communities are often numerically dominated by polychaete worms, molluscs, and crustaceans. These groups serve as prey organisms for many species of bottom-feeding fish. With the exception of some bacteria (Section 3.8), invertebrates smaller than 0.5 mm are not discussed in this report because of the paucity of data; they are rarely sampled quantitatively. Invertebrates larger than 4 mm are considered as megafauna and are addressed in Section 3.6.

The effects of mariculture facilities on macrobenthic communities are largely attributable to organic enrichment of the substratum. With the exception of occasional use of antibiotics (Section 3.10), toxicants such as heavy metals or synthetic organics, which are present in many other discharges to the marine environment, are lacking in discharges from mariculture facilities. Effects of organic enrichment in the marine environment are better documented than effects of many other disturbances. An excellent review of the effects of organic enrichment on the macrobenthic invertebrate community can be found in Pearson and Rosenberg (1978), and much of the discussion in this section is based on their work.

Figure 5 illustrates typical qualitative changes in species number, biomass and species abundances along a gradient of organic enrichment. The abcissa is shown as an axis of decreasing organic input. However, the axis could

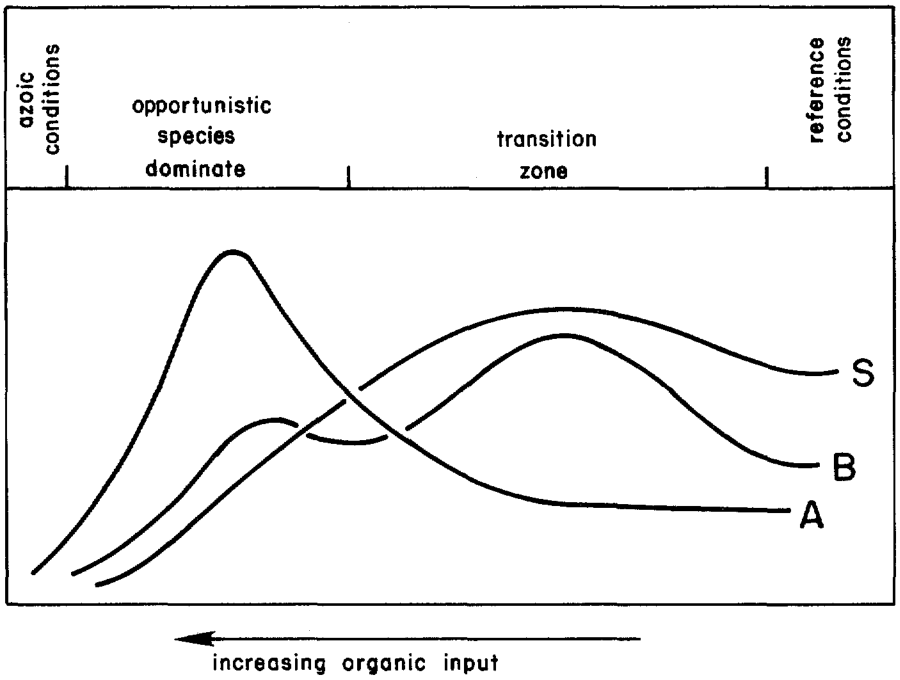

Figure 5 - Generalized trends in number of species (S), biomass (B) and total macrofaunal abundance (A) along a gradient of organic enrichment. From Pearson and Rosenberg, 1978.

also represent the changes which occur with increasing distance from the source of organic input, or temporal changes that occur at a given point following pollution abatement. The faunal zones shown on Figure 5 are not necessarily observed in all instances of organic enrichment. Depending on local environmental conditions certain zones may be lacking or others added. The presence of discrete zones is an oversimplification for illustrative purposes. There is actually a continuum of change, and boundaries between communities are generally indistinct. However, this model provides a useful summary of benthic community response to organic enrichment.

Regardless of the nature of the source (e.g., mariculture, sewage treatment, pulp mill, log handling, food processing, etc.), the response of the benthic community to organic enrichment is generally predictable. At low levels of organic input, a transition zone develops in which abundance, biomass and species richness gradually decrease from levels typical of the unpolluted environment. It may be noted on Figure 5 that an area within the transition zone exists in which species richness and biomass reach a value somewhat greater than in undisturbed conditions. This phenomenon has been termed "biostimulation" (Chen and Orlob, 1972). In this area the organic input provides a rich food source for both deposit and suspension-feeding organisms, yet the rate of input is not so great that it interferes with the mechanics of suspension feeding (e.g., clogging of filtering structures) nor causes serious oxygen depletion. The presence of a biostimulated zone is not universal, but the results of several studies have suggested its presence (Chen and Orlob, 1972; Christie and Moldan, 1977; Mackay, et al., 1972; Soule and Oguri, 1976; 1979).

At a somewhat higher rate of organic input, total macrofaunal abundance attains a maximum value. Biomass may also be slightly elevated, but the number of species is very low. The increased abundance and biomass results from the proliferation of only a few species. Pearson and Rosenberg designated this point as the "peak of opportunists". The polychaete Capitella capitata is the epitome of an opportunistic species. It is found throughout the world in organically enriched environments where few other species are able to survive.

With still higher rates of organic input, there is a complete absence of benthic macrofauna. The rate of organic input is so great and the rate of water exchange so low that oxygen levels in bottom waters and sediments decrease (or sulfide levels increase) to such an extent that aerobic organisms can not survive.

The extent of organic enrichment also affects the depth distribution of benthic invertebrates in the sediment column (Figure 6). The redox potential discontinuity layer (RPD) is the interface between aerobic and anaerobic zones within the sediments. The fact that the RPD is generally deeper in the sediment at lower rates of organic input is attributable to both physical-chemical and biological processes. The reduction in organic input reduces oxygen demand, thereby allowing oxygen from the overlying water to passively diffuse to greater depths in the sediment column. Animals accelerate this process. Burrowing, burrow ventilation, tube-construction and feeding activities promote movement of oxygen into the sediment and the transport of deeply buried anaerobic sediments to the sediment surface. At high rates of organic material input, the RPD is close to the sediment-water interface. The aerobic zone is limited to the top few millimeters or the entire sediment column is anaerobic. The macrofauna is characterized by species which live and feed very near the sediment-water interface. Deep-burrowing species are generally excluded.

Mattsson and Lindén (1983) observed the progression of community changes described above during a three year monitoring program beneath mussel longlines in Sweden. Three months after the culture was initiated communities beneath the longlines were similar in faunal composition to those at the reference station. Within six months after the start of culture, brittle stars had disappeared at the culture site. Species originally dominant in the community decreased in number and finally disappeared after 15 months. Opportunistic species became established in the culture area concurrently with the decline of the original fauna. Within six months, large populations of *Capitella capitata* were established, and the species later reached densities as high as 20,000 individuals m^{-2}. Other opportunistic polychaetes (*Scolelepis fulginosa* and *Microphthalmus sczelkowii*) appeared after about a year of culture. Total abundance and biomass decreased initially but then fluctuated widely depending on densities of the opportunistic polychaetes.

Mattsson and Lindén (1983) also monitored the recovery of the benthos after removal of a mussel culture facility that had been in production for three years. Six months after removal the bottom was still covered by 20-40 cm of mussel shells and sulfide-rich sediments. The benthos was numerically dominated by *C. capitata*, *S. fulginosa* and the amphipod *Corophium insidiosum*. Monitoring continued for a year and a half after mussel removal, during which only very limited macrobenthic recovery was observed.

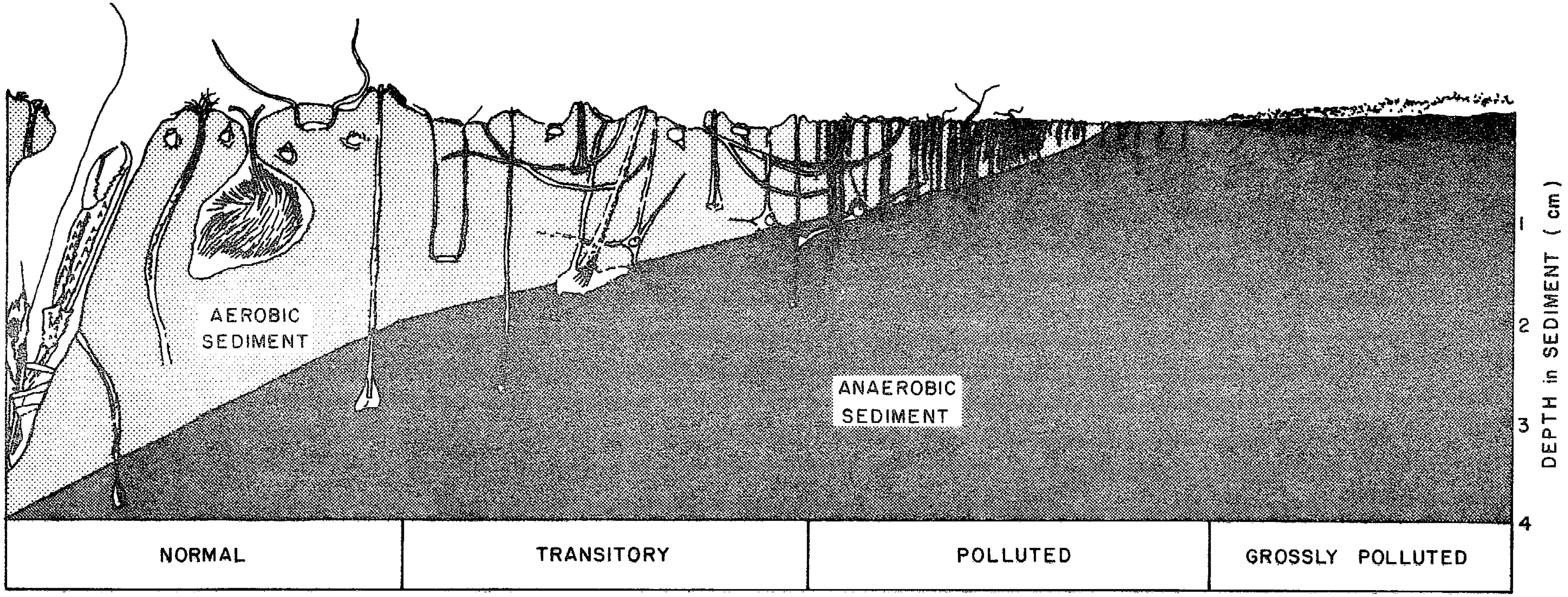

Figure 6 - Diagrammatic representation of faunal and sedimentary changes under increasing organic loading. From Pearson, 1976.

It is often difficult to distinguish the effects of mariculture related organic enrichment from other sources of organic material. The observations of Mattsson and Lindén (1983) highlight this difficulty. The initial reference station they established was 25 m from the culture site. When they found evidence of organic enrichment at the reference station, they assumed it was too close to the longlines, and established a second reference site 250 m away. When this site also showed evidence of community changes, a third reference site was established 1500 m away from the culture site. Mattsson and Linden later determined that the effects on the benthic community attributable to the culture operation were limited to within 20 m of the culture site. The changes in the communities at the reference stations resulted from organic input related to the decomposition of a regional phytoplankton bloom.

Table 9 presents the results of several studies which examined the effect of floating mariculture on marine benthic macrofauna. With one exception (a farm examined by Ervik, *et al*. in depths of 25-61 m) all studies demonstrated some effect on the benthos. The effects noted were very similar to those suggested by the Pearson and Rosenberg (1978) model. Directly beneath the culture operation there was, at some sites, a complete absence of macrofauna. As the rate of organic input decreased (or as one samples farther from the culture site), a community dominated by opportunistic species was observed. This community was generally characterized by high total abundance and low numbers of species. *Capitella capitata* was frequently a dominant community member.

With further reductions in the rate of organic input (or increasing distance from culture site), macrofaunal community composition gradually approached that characteristic of the reference sites. The area of effect of the culture operation on the macrobenthos generally corresponded to the area of altered sediment quality (Section 3.4), and typically was restricted to an area within a 30 m radius of the culture facility.

Only two investigators (Ervik, *et al*., 1985; Mahnken, *et al*., unpub.) have observed the presence of a biostimulated zone around mariculture facilities, and in both cases data to support the claim were not presented. The presence of a zone of biostimulation at some distance from a mariculture site does seem plausible, but this potentially "beneficial" effect should not be construed to mean that there is no net adverse effect of organic enrichment on the benthos (i.e., that the zone of biostimulation compensates for zones of mortality or zones of community degradation). As organic input increases, the extent of the

Table 9
Effects of floating mariculture on benthic macrofauna

Location (Reference)	Animal cultured	Observations
Weyerhaeuser Co. Henderson Inlet, Puget Sound (Pease, 1977)	Coho salmon	High macrofaunal abundance and low number of species beneath net-pens. Fauna numerically dominated by *Capitella capitata*
Sweden (Mattsson and Lindén, 1983)	Blue mussels	Area under raft dominated by opportunistic species. Diversity decreased, biomass and abundance fluctuated widely. Area of effects extended 20 m from culture.
Ria de Arosa, Spain (Tenore, *et al*., 1982) (López-Jamar, 1985)	Blue mussels	Macrofauna under raft dominated by opportunistic polychaetes. Biomass, abundance and diversity decreased in raft area. Tube-building species predominated.
Kenepuru Sound, New Zealand (Kaspar, *et al*., 1985)	Green-lipped mussel	Biomass unaffected by culture although diversity decreased. Only polychaetes found beneath culture. Infauna from reference area also included brittle stars, molluscs and crustaceans.
Ireland (Stewart, 1984)	Salmon	Macrofauna absent beneath net-pens. Zone around perimeter dominated by *Capitella capitata*.
Norway (Ervik, *et al*., 1985)	Atlantic salmon	Three farms were examined. Under one the number of species was low and the community was dominated by opportunistic species. Under the second the community was biostimulated. Under the third there was only minimal effect.
Bellacragher Bay, Ireland Doyle, *et al*. (1984)	Atlantic salmon	Highly localized zone under net-pens with no macrofauna. Unaffected community established within 25-45 m.
Uchiura Bay, Japan (Kitamori, 1977)	Yellowtail	As organic material accumulated there was an increase in abundance of opportunistic polychaetes and a decrease in the relative proportion of molluscs and crustaceans.

biostimulated zone increases as a function of the perimeter of the affected area (i.e., scales as a function of length), but the extent of adverse effects increases as a function of the entire affected area (i.e., scales as a function of length squared). Therefore, as the level of organic enrichment increases, the extent of potentially adverse effects increases much more rapidly than the extent of potential biostimulation.

Following cessation of organic input, such as after harvest or removal of the culture structure, a certain period of time will be required for the benthic population to recover from the disturbance to a point at which the affected community becomes similar in species composition and abundance to reference areas never affected by the organic enrichment. Although the Pearson and Rosenberg model suggests the sequence of benthic community recovery following the cessation of organic input, it does not predict the rate. As noted earlier Mattsson and Lindén (1983) found only slight community recovery 18 months after removal of mussel longlines. Recovery of the benthos following closure of a pulp mill has been found to require 3-8 years (Rosenberg, 1976). Vesco and Gillard (1980) reviewed the results of many investigations along the Pacific coast and found that recovery following disturbance typically requires 2 years and often 10 years or more. The time required for recovery will depend on many factors including the severity of the disturbance, the geographic location, the amount of disturbance to which a community is normally exposed and the life history of the species in the community (Vesco and Gillard, 1980).

Conclusions

The responses of benthic communities to organic enrichment fall along a continuum. As the level of enrichment begins to increase, the macrobenthic community begins a transition phase in which the background community is gradually altered. There may be biostimulation as the community undergoes this transition: a low rate of organic input may provide an enriched food source for the benthos without resulting in environmental degradation. As enrichment increases still further, sensitive species of the background community are replaced by a few opportunistic species tolerant of low dissolved oxygen, high sulfide concentrations and the other physical and chemical changes accompanying organic enrichment. At high rates of organic input, complete community mortality occurs. This continuum of change from background community to total community mortality may exist spatially as a function of distance from a culture site and temporally as a function of changes in organic input rates over time.

The extent of effects of floating mariculture on benthic communities is dependent on the magnitude of changes in sediment quality, which is in turn dependent upon the degree to which wastes are dispersed by water movements. The relationships between these variables is shown in Figure 7. As the potential for waste dispersal (e.g., high current velocities and deep water) increases, the likelihood that there will be significant effects on the benthos decreases. Most floating mariculture facilities established to date have been sited in relatively shallow water (< 20 m) and in areas of weak currents. Consequently major alterations of benthic communities immediately beneath culture facilities and for short (< 30 m) distances surrounding the sites have typically been observed. The effects of the mariculture operations on the benthos can be expected to persist for the duration of culture activities and for at least several years after their cessation.

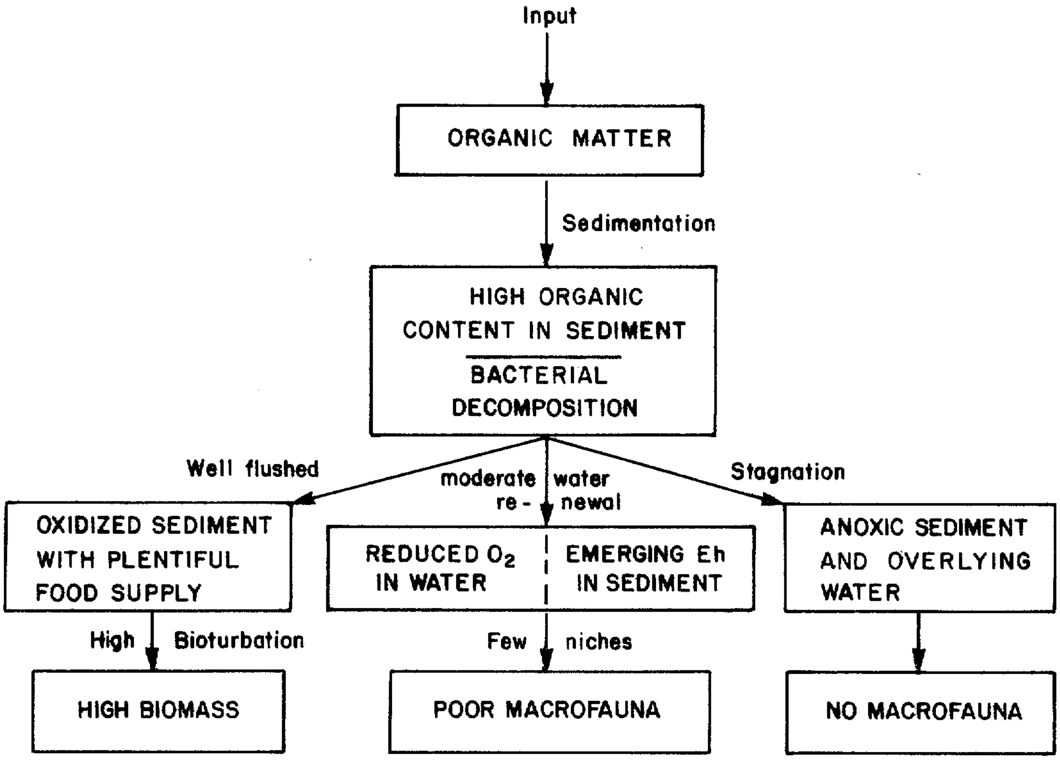

Figure 7 - Simplified diagram showing some pathways of organic input to the marine environment in relation to amount of water exchange. From Pearson and Rosenberg, 1978.

3.6 FISH AND MEGAFAUNA

Question

How do changes in water quality or the accumulation of organic material on the bottom affect natural fish and megafaunal populations in the vicinity of a mariculture operation? Of particular concern are fish and megafauna of commercial importance.

Discussion

Mariculture could potentially have adverse effects on nonmotile megafauna living in the sediment (e.g., geoducks and other large bivalves). Low dissolved oxygen concentrations and high sulfide concentrations shown to be detrimental to infaunal macrobenthos (Section 3.5), are also likely to prove harmful to megafaunal organisms which live in close contact with the enriched sediments. The severity of the effect will be somewhat reduced by the fact that many of these megafauna maintain contact with the overlying water through siphons (bivalves) or irrigated burrows (mud shrimp), but under conditions of high organic enrichment some mortalities are probable. The areal extent of impact would be expected to be limited to the immediate vicinity of the culture as has previously been shown for effects on sediment chemistry (Section 3.4) and macrofauna (Section 3.5).

Mariculture has been generally found to result in increased densities and diversity of motile megafauna (e.g., crabs, starfish) and fish in the vicinity of the culture operations. These organisms are able to exploit the enhanced food resources of the culture environment, but are not so intimately associated with the enriched sediments that toxic effects develop. Table 10 presents a summary of observed effects of mussel and net-pen culture. With very few exceptions, culturing activities resulted in increased abundance, species richness and/or biomass in the immediate vicinity of the culture facilities. Extreme organic enrichment of bottom sediments may reduce rather than enhance numbers of motile megafauna (e.g., the loss of starfish from the Japanese oyster grounds studied by Ito and Imai, 1955), but in the vast majority of cases culture activities result in enhancement of fish and megafauna populations, including enhancement of some species of commercial importance.

Table 10
Observations of fish and megafauna in the vicinity of mussel and salmon culture facilities

Location	Observations	Reference
Penn Cove Mussels Penn Cove, Puget Sound	Sea cucumbers and hydroids which had fallen from the rafts were found on the bottom. The crab *Cancer gracilis* was found in the area of the culture, presumably attracted by food in the form of mussels which had fallen from the strings. Mud shrimp were reduced in density under the culture, presumably because the shell debris inhibited burrowing. Octopus were attracted to the area.	Pease and Goodwin, unpub.
Weyerhaueser Co. Henderson Inlet, Puget Sound	The crab *Cancer gracilis* and three species of fish (rock sole, great sculpin and shiner perch) were more abundant at sampling sites under net-pens than in reference areas.	Pease, 1977
Scan Am Farms Hadlock, Puget Sound	Starry flounder, tubesnouts, buffalo sculpin and sailfin sculpin foraged around net-pens. Baitfish (probably Pacific herring) congegrated around pens. Fishermen have reported excellent Dungeness crab fishing in area.	Kyte, unpub.
Domsea Farms Clam Bay, Puget Sound	Surf perch, English sole and numerous sea anemones were present under net-pens. Geoducks were absent from area beneath pen, although they would have been expected based on sediment type.	Pease, unpub.
Domsea Farms Fort Ward, Puget Sound	Surf perch, flatfish and numerous sea anemones were present under net-pens. Kelp was absent from area under net-pens.	Pease, unpub.
Kenepuru Sound, New Zealand	Mussels which had fallen to the bottom provided substrates for the growth of epifaunal organisms and attracted predators such as fish and starfish. In comparison, the reference area was largely devoid of megafauna.	Kaspar, *et al.*, 1985
Sweden	The fish food lost in the form of infaunal mortalities was compensated compensated for by mussels and associated fouling organisms which fell to the bottom.	Mattsson and Lindén, 1983
Ria de Arosa, Spain	Biomass of crabs and starfish was greatly enhanced in raft areas because of the rain of mussels and epifauna from rafts. Fish biomass also was increased in raft areas but not to the same extent as the crabs and starfish. The primary fish prey organisms outside the raft area were infaunal invertebrates, whereas around the rafts fish fed primarily on epifaunal species.	Tenore, *et al.*, 1982 Romero, *et al.*, 1982 López-Jamar, *et al.*, 1984
Maine	Fish and shellfish densities were increased in the vicinity of net-pens and mussel rafts. Fishermen have reported that the sites are excellent for lobster fishing.	K. Honey, Maine Dept. of Marine Resources, pers. comm.

Similar observations have generally been reported in freshwater culture. Wild fish are frequently observed in high densities around cages containing cultured fish (Beveridge, 1984; Eley, _et_ _al_., 1972; Loyacano and Smith, 1976; Hays, 1980). Culture activities have also been shown to increase the number and biomass of native fish in lakes and reservoirs (Kilambi, _et_ _al_., 1976; Loyacano and Smith, 1976). This effect is due to both ingestion of excess commercial feed by the wild fish and increased nutrient levels in the lakes (Beveridge, 1974). However, adverse effects are possible in cases of intensive aquaculture development in freshwater systems. Penczak, _et_ _al_. (1982) reported that net-pen culure of rainbow trout is resulting in disappearance of the native Coregonidae in Lake Glebokie, Poland, presumably because of the increased nutrient input. In Laguna de Bay, Phillipines the pen culture of milkfish and _Tilapia_ has altered the density and species composition of the wild fish community (Ackefors, _et_ _al_., 1984). That such an effect was observed is not at all suprising since pens occupy about one-third of the surface area of the lake.

Conclusions

Accumulation of organic material may result in the mortality or exclusion of nonmotile megafauna which live in burrows or are otherwise in intimate contact with the sediment. This effect should be limited to the zone of organic enrichment in the immediate vicinity of the culture site. For megafauna living on or above the sediment surface and for fish in the surrounding waters, the effect of mariculture is more often positive than negative. Only in cases where very limited flushing permits development of near-bottom anoxia or other pronounced deterioration of water quality, would an adverse effect on fish or epibenthic megafauna be expected. This deterioration has rarely been observed. More often there is an increase in abundance, species number, diversity, and/or biomass of fish and megafauna in the vicinity of culture operations. Commercial and recreational fishing is typically enhanced in the vicinity of the culture (e.g., Dungeness crabs - Kyte, unpub.; lobsters - K. Honey, Maine Dept. of Marine Resources, pers. comm.; bluegills - Loyacano and Smith, 1976).

Wild fish or megafauna are attracted to the culture operations for several reasons. In part, there is a behavioral tendency for fish to congregate around floating objects (Gooding and Magnuson, 1967). A floating mariculture facility also increases the availablity of food in the area. This food may take several forms including excess feed unutilized by the cultured fish, epifaunal organisms growing on the culture structure or which fall to the bottom, or the high abundances of opportunistic macrofaunal species in the adjacent bottom sediments.

3.7 INTRODUCTION OF EXOTIC SPECIES

Questions

Could a species imported to Puget Sound for culture escape and establish a reproducing population in the wild? Would this pose a threat to native species or in any other way result in irreparable ecological harm? What are the dangers of other organisms and diseases being imported with the cultured animal?

Discussion

For many centuries man has been responsible for the accelerated spread of species from one area of the world to another. In some cases a species has been intentionally introduced because it possessed certain characteristics which were advantageous to man and which were not exhibited by indigenous species. It is probable that an even greater number of introductions have been unintentional. The transport of species on ship hulls and in ballast tanks provides the best example of unintentional introductions. Some introductions can be regarded as having largely positive results, at least from a commercial perspective. The Pacific oyster (*Crassostrea gigas*) and the Manila clam (*Venerupsis japonica*) were both introduced to Puget Sound from Japan in the early part of this century. The species now support the bulk of the Washington oyster and hardshell clam industries, respectively. Some introductions have had largely negative impacts. The Japanese oyster drill (*Ocenebra japonica*), which was probably accidentally introduced along with shipments of *C. gigas*, is now a major oyster predator in Puget Sound. Perhaps the greatest number of introductions involve species which have had no effect on commercial interests and whose ecological effects have been largely unrecognized. An evaluation of the role of mariculture in the introduction of exotic species requires that two separate issues be addressed: 1) the intentional importation of species for culture; and 2) the accidental introduction of organisms associated with the cultured species. These two issues are addressed individually below.

Intentional introduction of cultured species -

Intentional introductions are often made for purposes of culture, to establish a new fishery or to replace a declining native fishery. Intentional introduction of species is a common occurrence in the world today. It has been estimated that by 1978, intentional introductions of fish and shellfish involved 1,500 species worldwide (Rosenthal, 1978; Villwock, 1984). Introductions are so commonplace that the FAO Fish Culture Bulletin provides monthly updates on new introductions which have taken place around the world.

It is difficult to predict how a species will respond when it is placed in a new environment without the ecological checks and balances of its native habitat. In some cases, the species will be unable to survive and reproduce in the new environment. The species may be unable to establish a self-sustaining population, either dying if forced to live outside of the confines of the culture environment, or requiring a continuous flux of imported juveniles to maintain the population. For example, of 27 introductions of fish to the Netherlands, most of the species, including many salmonids, have failed to establish sustaining populations (DeGroot, 1985). At the other extreme, the species may thrive in the new environment, displacing native species through habitat alteration or competition for resources. Examples would include the introduction of Tilapia spp. throughout Southeast Asia and rainbow trout (Salmo gairdneri) into South Africa and South America (Rosenthal, 1980). In these cases, the introductions have led to the establishment of important fisheries or culture industries, but they have also led to the disappearance of native fish species.

Of those species which are currently raised in floating mariculture in Puget Sound, only the Pacific oyster (C. gigas), red alga ("nori" - Porphyra sp.), and the Atlantic salmon (Salmo salar) are not native to Puget Sound. None of these species appears to represent a threat to indigenous Puget Sound species. C. gigas was introduced to Puget Sound in 1902 to supplement dwindling stocks of the native Olympia oyster (O. lurida). Although the species grows well in the Sound and has established populations north to the Queen Charlotte Islands, water temperatures are usually too low for successful reproduction in most areas. Successful reproduction is limited to a few isolated areas such as Quilcene Bay and Dabob Bay in Hood Canal and Pendrell Sound in British Columbia. Good natural sets of oyster spat are not consistent even at these sites; in Dabob Bay commercial quantities of seed are produced 6-7 years out of 10 (Chew, 1984).

Nori culture in Puget Sound requires the importation of pathogen and parasite-free, unialgal cultures from Japan. Environmental conditions in Puget

Sound are not suitable to either the reproduction or dispersal of the species (Hurlburt, 1984). The reproductive cycle of nori includes a stage which bores into oyster shell. Given the long history of oyster importation to Puget Sound from Japan, it is probable that there has been extensive and repeated inadvertent introduction of nori. As no wild growth of nori has occurred in Puget Sound to date, it is unlikely that culture of the species would result in future establishment of the species.

The potential for S. salar to establish a self-sustaining population in Puget Sound has been thoroughly examined by Lindergh (unpub.). In Washington State there have been deliberate attempts to stock the species in Chambers Creek, Minter Creek and numerous eastern Washington lakes, some of which have access to the Pacific Ocean. There have also been several escapes of the species from the National Marine Fisheries Service facilities in Clam Bay, Puget Sound. Despite these numerous releases, no returning adults have been reported. Introductions have also been attempted in Oregon, California, British Columbia, New Zealand and Chile. In a few cases, self-sustaining, landlocked populations have been established, but most require continued hatchery support. No self-sustaining anadromous runs have been established anywhere in the world outside of the species' native range. Lindbergh (unpub.) estimated that about 5 million individuals of S. salar have been released in unsuccessful stocking attempts in the Pacific Northwest. Given the failure of these efforts, it would appear unlikely that future escapes from culture facilities in Puget Sound would result in the establishment of a wild population.

While those species currently employed in floating mariculture in Puget Sound seem unable to establish self-sustaining populations, future introductions of other species should be carefully evaluated on a case-by-case basis as they are proposed. It is never possible to rule out adverse effects until the introduction is an accomplished fact, and then, if successful, the introduction may be irreversible. Thus, any introduction should be carefully planned and thoroughly reviewed by the scientific community and appropriate government agencies (see Courtenay and Robins, 1973 for a suggested review protocol). It should be clearly demonstrated that the benefits to be gained by the introduction outweigh the potential ecological consequences.

Accidental introduction of associated organisms -

The transport of oysters throughout the world has been credited with contributing to the spread of more species throughout the world than any other human activity (Cronin, 1967). Oyster shells provide habitats for algae, hydroids, bryozoans, amphipods and a great variety of other marine life. Oysters may also serve as reservoirs for finfish pathogens (Meyers, 1984). The accidental introduction of the oyster drill to Puget Sound along with imported oysters from Japan was noted earlier. Other examples are provided by Quayle (1964), Rosenthal (1980) and Rosenfield and Kern (1979). Many introduced species currently in Puget Sound have come in with shipments of _Crassostrea gigas_. However, the danger of continued new introductions is not as great as it has been in the past. The escalating cost of obtaining oyster seed from Japan has stimulated the development of oyster hatcheries along the west coast of the United States. Since 1977, the importation of oyster seed from Japan has virtually ceased, and the demand is now met by hatcheries along the west coast and the collection of local natural seed from a few isolated areas (Chew, 1984). The west coast hatchery seed may still contain associated organisms (Carlton, 1981), but it is likely that those species which may establish themselves in Puget Sound have already done so by natural means of dispersal.

The importation of fish for culture has also frequently resulted in the introduction of associated organisms. Disease agents (including viruses, bacteria, fungi, and protozoan and metazoan parasites) are frequently of greatest concern in fish imports. Hoffman (1970) documented at least 48 species of freshwater fish parasites which have been established on other continents because of the importation of live or frozen fish. These species include 5 protozoa, 36 trematodes, 3 nematodes, 1 acanthocephalan and 3 copepods. Other examples of parasites and diseases introduced with fish include:

1) _Whirling disease_ - A disease in freshwater rainbow trout caused by the protozoan _Myxosoma cerebralis_. This organism has been spread throughout four continents by the transfer of live and frozen trout. However, outbreaks of the disease have been limited to cultured fish. The parasite is rarely detected in wild fish (Hoffman, 1970). Federal law and Washington state regulations now prohibit the importation of trout from areas where the disease is known or is likely to occur.

2) Infectious hematopoetic necrosis - This viral disease first appeared in sockeye salmon on the West Coast and later infected rainbow trout. Transfer of diseased trout and infected eggs has spread the disease throughout the northwestern and north central states (Amend, *et al.*, 1973). The disease was introduced to Japan by eggs imported from the United States (Egidius, 1984).

3) Furunculosis - This disease, which is caused by the bacterium, *Aeromonas salmonicida*, may have been introduced into Europe by the importation of rainbow trout from North America (Rosenthal, 1980).

The risk of introduction of disease and other organisms associated with cultured animals, both fish and molluscs, depends on the source of the animals to be cultured. There is no risk of introduction of diseases or other unwanted organisms in Puget Sound mussel culture, since growers use locally obtained, wild seed. The risks involved in oyster culture and net-pen culture of salmon depend on the source of seed, eggs or fish. However, if it is necessary to import animals into Puget Sound from outside Washington, the procedures for minimizing unintentional introduction of other organisms should be given very close scrutiny. An accidental introduction could have serious consequences not only to the cultured organisms but to native species as well.

Conclusions

The introduction of species, including pathogens, probably represents the greatest environmental threat posed by mariculture. However, the probability of an accidental introduction is considerably lower than it has been in the past. Many of the past introductions of unwanted species and diseases occurred in the past when scientists and environmental managers were unaware of the potential ecological repercussions and the various pathogens. The risks we face today are considerably reduced, in part, because the damage has already been done, and also because we are aware of potential problems and implement preventative measures.

For example, when *C. gigas* was first introduced to Puget Sound, the animals were collected from Japanese waters and packed directly into crates for shipment with little or no effort to inspect for associated organisms (Quayle, 1964). Only after many years of uncontrolled importation did high-pressure washing of the shells and careful inspection of each shipment become standard practice.

Many federal and state laws, rules and policies curently regulate the importation of live organisms for aquaculture or other purposes. A full review can not be presented here, but I have presented a few of the state requirements most pertinent to floating mariculture in Puget Sound:

1) Importation of food fish or shellfish into the state requires that the importer obtain a permit from the Department of Fisheries (WAC 220-20-038, 220-20-039).

2) Any request for the introduction of an exotic species is subject to the requirements of the State Environmental Policy Act. A report must be prepared outlining the potential benefits of the introduction as well as the potential environmental risks.

3) Department of Fisheries personnel or an approved pathologist must inspect, at the place of origin, any shipment of oysters, oyster shell or seed destined for state waters. A certificate must be obtained stating that the shipment is free of oyster drill and other pests (WAC 220-72-082).

4) Any fish to be transferred either within or from outside the state must be examined for disease by a state-approved inspector unless, in the case of intrastate transfers, the disease history of the stock alleviates the need for inspection.

5) No live salmonids or their reproductive products may be imported from Europe except eyed Atlantic salmon eggs. For the importation of these eggs, the parent stock must be certified as disease-free, a health history of the stock and hatchery must be submitted to the state, the eggs must be disinfected, and the eggs must be held in a quarantine facility for 90 days following swim-up.

As a result of the recent passage of the Aquaculture Disease Control law (RCW 75.58) the requirements pertaining to importation of live animals for culture may change in the near future. Under this law, the Washington Department of Fisheries now has disease prevention/control responsibility for all cultured organisms, both plant and animal. The Department of Fisheries, in cooperation with other state and federal authorities, is currently developing a comprehensive program of disease inspection, prevention and control specifically for aquaculture operators.

3.8 DISEASES

Questions

Do the confined and crowded conditions of the culture environment increase the probability of a disease outbreak? Can the disease be transmitted from cultured fish to wild fish? Can mariculture promote the growth of bacteria capable of causing disease in humans?

Discussion

Transmission of disease between cultured and wild fish -

Mariculture could potentially introduce a disease to an area where it had not previously occurred, and potentially lead to the infection of native populations (see Section 3.7). This discussion is concerned with those disease organisms already present, but demonstrating no clinical symptoms in the wild fish. It has been suggested that culture conditions may provide an environment where these disease organisms could initiate an outbreak, become more virulent and then reinfect the native fish populations (Mills, 1982; Odum, 1974).

It is generally recognized that many diseases in fish, whether cultured or wild, are often associated with some form of stress (Sindermann, 1984). In a culture environment fish may be subjected to stress by overcrowding, undernourishment or poor water quality. Such factors have been directly correlated to the frequency of disease outbreaks in cultured fish (Arizono, 1979). In addition, cultured fish are also subject to physical damage (e.g., handling, abrasion against the net). Thus, there may be a greater frequency of surface lesions which provide a route for infection. Cultured fish may therefore be more susceptible to diseases than wild fish, with the degree of susceptibility determined, in large part, by the extent to which good husbandry practices are followed by the culture operator.

Despite the potential for disease in a culture environment, there is little evidence to suggest that this potential represents a threat to wild fish. In fact, there are several examples of diseases which have had more than adequate opportunity to infect wild fish, but have failed to do so. For example, viral hemorrhagic septicemia (VHS) is a disease of cultured rainbow trout in

Europe. It is believed that the VHS virus has always been present in Europe, although the wild fish have failed to show any symptoms of the disease. Rainbow trout imported to Europe and held in culture are very susceptible to the disease and many mortalities have been reported. However, the disease does not appear in free-living rainbow trout even if they harbor the virus, and the native brown and brook trout show no signs of the disease even though they have been infected experimentally (Egidius, 1984).

A second similar example is provided by whirling disease, a disease of cultured freshwater rainbow trout caused by the protozoan *Myxosoma cerebralis*. *M. cerebralis* is a parasite which causes no apparent disease in native European trout. Rainbow trout imported from North America are very susceptible to infection and disease. Despite many outbreaks of whirling disease and devastating losses of rainbow trout in culture throughout Europe, the infectious parasite is only rarely reported in wild fish (Hoffman, 1970).

A third example, and one of direct relevance to Puget Sound, involves bacteria of the genus *Vibrio*. *Vibrio* spp. are natural components of the marine microbial community throughout much of the world, and are dominant components of the normal microbial community of salmonids (Colwell and Grimes, 1984). In a survey of 12 fish species in Puget Sound, 88% of the gill samples, 61% of the skin samples and 32% of the gut samples contained *Vibrio* spp., including a common salmonid pathogen, *V. anguillarum* (Baross, 1973). Most *Vibrio* bacteria, including potentially pathogenic species, are not normally virulent unless the host animal is stressed. *Vibrio* disease outbreaks are frequently reported in net-pen culture in Puget Sound, particularly during the summer months, but there is no evidence that these outbreaks have had any effect on unstressed fish beyond the confines of the culture facilities. While *Vibrio* disease does occur in wild fish, outbreaks frequently have been associated with environmental degradation (e.g., oil spills, municipal sewage) or some other form of stress (Grimes, *et al*., 1984; Hada and Sizemore, 1981; Larsen, *et al*., 1978; Minchew and Yarbrough, 1977; Robohm, *et al*., 1979). There is no evidence that mariculture has contributed to an increased incidence of vibriosis in wild fish.

Mariculture and the proliferation of human pathogens -

It has been suggested that mariculture may potentially lead to increased numbers of bacteria that cause disease in humans (Baross, 1973). If environmental alterations associated with a mariculture operation promoted growth of human pathogens, these pathogens might then be accumulated in filter-feeding bivalves (e.g., mussels, clams, oysters), and infect man upon ingestion of the contaminated bivalves. These concerns have been directed specifically towards the bacteria genus *Vibrio*, since the genus is common in marine systems and includes fish, shellfish and human pathogens.

The genus *Vibrio* includes approximately 20 species (Baumann, *et al.*, 1980). Five of the species, *V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*, *V. alginolyticus* and *V. mimicus*, are known human pathogens, and the pathogenicity of two other species, *V. fluvialis* and *V. metschnikovii*, is unclear (Spira, 1984; West and Colwell, 1984). *V. anguillarum* and *V. ordalii* infect salmonids in Puget Sound net-pen culture. There is no evidence that these species are human pathogens.

In humans, *Vibrio* infections most frequently cause gastroenteritis. The clinical symptoms include diarrhea, abdominal cramps, nausea, and vomiting. The disease is normally mild to moderate in severity, and symptoms typically persist for a few days (Blake, *et al.*, 1980). Exposure to *Vibrio* spp. in seawater can also cause infection of wounds. Primary sepsis, caused by *V. vulnificus*, is the most serious of the *Vibrio* diseases. Infection occurs most frequently in persons with chronic liver disease (Tacket, *et al.*, 1984). The *V. vulnificus* infection causes fever, chills and nausea, and results in death in about half the cases.

Vibrio-related illnesses are reported infrequently in the Puget Sound area. In all the counties bordering Puget Sound there were only three reported cases of *Vibrio parahaemolyticus* gastroenteritis between 1982 and 1986 (excluding 4 cases contracted out-of-state) (G. Potter, Washington Dept. of Social and Health Services, pers. comm.). Two of the three reported cases were acquired after consumption of raw oysters from Hood Canal. The cause of the third case was not established. It is possible that there may be additional undiagnosed infections, but medical authorities are confident that the disease is rare in the Puget Sound region (C. Nolan, Seattle-King County Health Department, pers. comm.; G. Potter, pers. comm.). No *Vibrio* infections other than *V. parahaemolyticus* have been reported in Washington state (excluding those contracted elsewhere and brought into the state by travellers).

Vibrio bacteria, including both pathogenic and nonpathogenic species, are common members of the microbial community in estuarine environments throughout the world. They play significant roles in nutrient recycling, and are probably the principle bacterial group responsible for the mineralization of refractory organic material like chitin (Baross, 1973). Surveys of Puget Sound microbial communities have indicated that *Vibrio* spp. are widely distributed in the water, sediments and biota (Baross, 1973; Colwell and Liston, 1960). *Vibrio parahaemolyticus* is commonly found in Puget Sound sediments and biota, particularly during the summer (Baross and Liston, 1970). A survey of seafoods marketed in the Seattle area found *V. alginolyticus* in half of the seafood products tested (Baross, 1973). Such results are not unique to Puget Sound. A survey of market-level seafood in Louisiana indicated that 10.7% of the products contained *V. parahaemolyticus*, 7.7% contained *V. vulnificus* and 5.4 % contained *V. fluvialis*, all of which are known or potential human pathogens (Barbay, *et al*,, 1984).

The fact that potentially pathogenic *Vibrio* species are widespread, but the incidence of infection is relatively low is probably attributable to three factors. First, not all strains of a pathogenic species are virulent. *Vibrio parahaemolyticus* is widespread in Puget Sound, but most of the strains are incapable of causing infection in humans (Baross, 1973). The factors that cause a small proportion of the strains to become virulent are unknown. Secondly, while *Vibrio parahaemolyticus* may be isolated for environmental samples at temperatures as low as 5-10°C (Ayres and Barrow, 1978), rapid growth of the species (and many other pathogenic vibrios) does not occur until water temperatures reach 15°C (Baross, 1973; Kaneko and Colwell, 1973). The cool temperatures which persist throughout the year in much of Puget Sound prevent the species form reaching the densities necessary to cause infection. Finally, the frequency of *Vibrio* infections is also minimized by cooking seafood and killing the bacteria. *Vibrio* infections are contracted by eating raw seafood, inadequately cooked seafood, or cooked seafood which is subsequently left in contact with raw seafood.

Suggestions that mariculture could lead to increased incidence of *Vibrio* infections are based on two circumstances. First, *Vibrio* spp. have frequently been found in greatest abundance in areas characterized by high inputs of organic matter and/or particulate material (Baross, 1973; Colwell, *et al*., 1984; Joseph, *et al*., 1982). Such conditions may exist in the vicinity of mariculture operations. Secondly, filter-feeding molluscs concentrate bacteria through normal feeding activities (Greenberg, *et al*., 1984). Thus, there is a potential route for human infection if a mariculture operation promotes increased *Vibrio* spp. abundances in the vicinity of harvestable shellfish.

Our knowledge of marine microbial ecology is too limited to conclusively establish how mariculture will affect the abundances of pathogenic or nonpathogenic bacteria. In freshwater systems, bacterial abundance has been shown, in some cases, to be increased in the vicinity of aquaculture operations (Eley, *et al*., 1972). The elevated rates of biological oxygen consumption observed in sediments under net-pens in Puget Sound (Pamatamat, *et al*., 1973) suggest that bacterial abundances are high in those sediments. Since *Vibrio* spp. are facultative anaerobes and prominent components of marine microbial communities, increased abundances might occur in the organically enriched sediments associated with mariculture operations, although data are inadequate to establish this.

There have been no indications to date that mariculture contributes to the proliferation of bacteria species and strains pathogenic to humans. In fact, the mariculture industry is moving towards the concept of polyculture (i.e., culturing several species in the same area). Specifically, the feasibility of growing mussels adjacent to salmonid net-pens is being investigated since the mussels are able to utilize the particulate material from the net-pen as a food source (Wallace, 1980). The Norwegians are actively experimenting with such techniques. There are no reports indicating that mariculture has increased the occurrence of gastroenteritis or other *Vibrio* related diseases anywhere in the United States (P. Blake, Center for Disease Control, pers. comm.) or elsewhere in the world (based on this literature search). The Washington Department of Fisheries prohibits siting of most floating mariculture facilities over a harvestable shellfish bed in order to avoid the adverse effects of sedimentation on the shellfish. Should there be any risk that mariculture would promote transfer of pathogenic bacteria to humans via shellfish, this siting restriction should minimize this risk.

Conclusions

There are many examples of wild fish transmitting disease to cultured fish (Harrell and Scott, 1985; Jarrams, *et al*., 1980; Johnstone, 1984; Munro and Waddell, 1984; Wooten, 1979). While it is more difficult to document disease transmittal to wild fish, there are no known examples of a culture operation providing a site for disease organisms to multiply, become more virulent and reinfect the wild populations. It can not be conclusively demonstrated that such a scenario can not occur, but both this literature review and another (Odum, 1974) failed to document any instance of disease transmittal of this nature. Prevailing scientific opinion on the subject is best stated by Egidius (1984): "Very little is known about diseases in the wild stocks of cultured species, but it is not likely that culture creates new infectious diseases. However, culture accentuates infectious diseases by crowding, environmental stress etc., although most probably the disease potential as such originates from the wild stocks".

The potential proliferation of human pathogens because of mariculture is also an issue where conclusive scientific evidence is lacking, but experience to date has failed to show cause for concern. There is no evidence that mariculture, either in this country or elsewhere, has resulted in increased incidence of human disease. It is quite likely that mariculture would increase total bacterial abundance in the organically enriched sediments below the culture structure. However, it is not known if these bacterial species are likely to be human pathogens, if the particular strains would be virulent, or if consumption of shellfish in the vicinity would pose a health risk. The current policy of the Washington Department of Fisheries of prohibiting floating mariculture development over harvestable shellfish would minimize the risk, if any, of disease transmission.

3.9 GENETIC EFFECTS

Question

For those operations which culture species native to Puget Sound, could interbreeding of cultured and wild animals alter the genetic fitness of the wild population?

Discussion

It should be stated at the outset that the potential for adverse effects by the interbreeding of cultured and wild animals is largely speculative. Despite decades of hatchery-rearing and release, transplantations and other fishery enhancement programs, the genetic consequences of these actions remain largely unknown. While there is evidence that hatchery-reared fish interbreed with wild populations (Allendorf, *et al.*, 1980; Campton and Johnson, 1985), it has yet to be shown that this interbreeding has threatened the survival of any population.

The potential for genetic alteration of wild populations by cultured populations does not exist for all floating mariculture currently practiced in Puget Sound. It can only be an issue if species are native to Puget Sound and the juveniles for the culture operation are not supplied by the wild population, or if species not native to Puget Sound can hybridize with the native species. The Pacific oyster *Crassostrea gigas* and the mussel *Mytilus edulis* are the only molluscs commercially grown by suspended culture in Puget Sound. *C. gigas* is an introduced species to Puget Sound. The species has shown no evidence of hybridization with native oysters, and in fact, *C. gigas* rarely, if ever, hybridizes with native oyster species wherever it is been introduced (Newkirk, 1979). *M. edulis* is native to the Sound, but the seed for culture is collected from wild populations so the difference between the genetic composition of the cultured organisms and the wild populations can be no greater than the genetic variation between the individual wild populations.

Among finfish, only the Atlantic salmon (*Salmo salar*) and the coho salmon (*Onchorhynchus kisutch*) are currently cultured in Puget Sound net-pens (excluding experimental culture of steelhead at Squaxin Island). The history of Atlantic salmon introductions to the west coast was discussed in Section 3.7.

Despite numerous deliberate releases to attempt to establish wild populations, there are no reports of hybridization of the Atlantic salmon with any of the Pacific salmon species (Lindbergh, unpub.). The fact that the Atlantic and Pacific salmon belong to different genera (i.e., *Salmo* and *Onchorhynchus*) would suggest a low probability of successful hybridization. Three attempts have been made to produce hybrids between Atlantic salmon and the rainbow trout or steelhead (*Salmo gairdneri*), but all have proven unsuccessful (Lindbergh, unpub.; Refstie and Gjedrem, 1975).

Thus, the potential for interbreeding with wild fish populations exists only for the coho salmon. Operators of coho net-pens in Puget Sound maintain their own brood stock (e.g., Domsea Farms) or obtain smolts from Puget Sound or Columbia River hatchery stocks.

There are theoretical grounds for avoiding interbreeding of cultured and wild populations. First, salmonids tend to evolve genetically discrete and ecologically specialized subpopulations (see Stahl, 1983 for references). If a population has remained in a particular habitat for a sufficient length of time, natural selection may have led to the development of characteristics optimally adapted for that habitat. These same characteristics are unlikely to be equally adaptive if these individuals are placed in another habitat, as happens, for example, when individuals for culture are obtained from distant sources.

Secondly, cultured individuals may have been selectively bred to promote the development of one or more characteristics desirable in the culture environment. Selective breeding of salmonids for high fecundity, large egg size, high hatching percentage, rapid growth, altered rates of maturity, high temperature tolerance, disease resistance and other characteristics has been very successful (Ackefors and Rosen, 1979). Domsea Farms in Clam Bay currently raises coho salmon which have been selectively bred for improved growth efficiency. Selective breeding of molluscs is still in its infancy, although there is great potential (Newkirk, 1980). Efforts are in progress to improve resistance to summer mortality of oysters grown in Washington (Hershberger, *et al.*, 1984). While such traits may be desirable to improve the profitability of culture operations, these individuals may be less able to survive the rigors of the natural environment beyond the confines of the culture facility.

Thirdly, the maintenance of a high degree of genetic variability may be critical to the survival of a wild population since this variability provides the plasticity needed to respond to changing environmental conditions. For a variety of reasons (founders' effect, genetic drift, genetic bottlenecking, intentional and unintentional selection) genetic variability may be reduced in cultured populations. Many studies have documented a lower genetic variability in hatchery trout stocks than in wild populations (Allendorf and Phelps, 1980; Ryman and Stahl, 1980; Stahl, 1983), and there are indications of the same phenomenon in cultured oysters (Wilkins, 1976). This loss of variability, often through inbreeding, has resulted in the development of deleterious traits in some hatchery-reared rainbow trout and Atlantic salmon stocks (Aulstad, et al., 1972; Kincaid, 1976a; 1976b; Ryman, 1970). However, there is no indication at present that this loss of variability has occurred in Pacific salmon (specifically chinook). About 65 genetically distinct stocks have been identified along the west coast of North America, and there is no evidence that stocks of hatchery origin have any less variability (as measured by relative heterozygosity) than wild stocks (C. Mahnken, NMFS, pers. comm.).

This discussion has been derived primarily from the literature pertaining to hatchery rearing and release programs. With floating mariculture operations, however, fish are held until they reach a marketable size and then harvested. Interbreeding with the wild populations becomes an issue only if cultured fish escape. Since there are no data available on the extent of escapes from Puget Sound facilities, it is impossible to evaluate the significance of the issue. Obviously a critical variable in evaluating potential genetic effects is the number of cultured fish that escape relative to the size of the wild population.

The greatest potential for genetic alteration of a wild population would exist if escaped fish congregated to spawn in one particular area, and therefore comprised a larger proportion of the total breeding population in that area. The likelihood of congregation depends upon how strongly cultured fish imprint to the culture area. Cultured fish are typically placed in net-pens at about the time of smolting when the tendency to imprint is the greatest. Even if placement in salt water is delayed beyond smoltification, there appears to be a long-term imprinting process if the fish are held in the net-pens for an extended period. To evaluate homing ability of net-pen cultured fish, coho salmon were intentionally released from net-pens in Clam Bay. Some of these fish returned to Beaver Creek, the nearest freshwater stream to the net-pen site (C. Mahnken, NMFS, pers. comm.).

There is also a question of potential for survival of cultured fish in the wild. Cultured fish have become accustomed to a predator-free environment with regularly-provided pelleted feed. It is unknown how well these fish adapt and survive outside of the culture environment, but they would appear to be at a competitive disadvantage, at least in the short-term. Hatchery trout have been found to have a lower survival rate than wild fish (Chilcote, et al., 1985; Reisenbichler and McIntyre, 1977). Of particular interest have been studies on the growth and survival of the progeny of crosses between hatchery and wild steelhead (Reisenbichler and McIntyre, 1977). In hatchery conditions, hatchery/hatchery crosses showed the highest growth and survival. However, when placed in natural streams the wild/wild fish showed the highest survival and the hatchery/wild fish had the highest growth rate when significant differences were found.

In general, cultured fish would appear to be at a competitive disadvantage, but the relative extent to which selective pressures operate on the escaped fish (thereby preventing interbreeding) or on their progeny is unclear. In the worst case, there may be a temporary reduction of reproductive capacity of the wild population since reproductive effort may be wasted in producing less fit genotypes against which selection may occur. The potential for such an impact depends upon the number of fish escaping, and may be significant only when the proportion of escaped fish is large in comparison to the wild breeding population.

Conclusions

Assessment of the potential for genetic alteration of wild populations by escapes from mariculture facilities is difficult given the lack of reliable field data and the speculative nature of the whole issue. However, to put the potential problem into perspective, one must consider the history of fisheries enhancement programs, particularly for salmonids. For nearly a century, fisheries management agencies in Washington have routinely been transferring hatchery-reared fish between river systems to improve commercial and recreational catches. In addition, many net-pen facilities are used for delayed release, and the number of fish released in these programs is substantial (e.g., 3 million smolts per year at the Squaxin Island facility alone). Hatchery and net-pen releases are not permitted in a few areas (e.g., Skagit Bay) because of concern for potential effects on wild stocks. However, large parts of the Puget Sound Basin are managed for one or more species on a hatchery basis. The numbers of fish that could escape from mariculture facilities is dwarfed by the number of fish intentionally released in fisheries enhancement programs.

Cultured organisms may be at a competitive disadvantage in comparison to wild organisms for several reasons: 1) they are not pre-adapted to the habitat; 2) they may have been bred for characteristics desirable under culture conditions, but maladaptive in the wild; and 3) they may have reduced genetic variability, thus limiting their abilities to cope with environmental change. Hatchery steelhead, for example, appear to have poorer survival than wild steelhead (Reisenbichler and McIntyre, 1977), may be more susceptible to disease (Allendorf and Phelps, 1980) and their spawning cycle may not be attuned to the local environment resulting in release of offspring under suboptimal conditions (Chilcote, et al., 1985). Thus, there may be some selective pressure against fish which escape from mariculture facilities. In the event of escapes, the greatest effect, if there is any effect at all, may be a temporary loss of some reproductive capacity in the wild population. The magnitude of this effect depends upon the relative size of the breeding population of escaped fish in comparison to the wild breeding population.

The measures which a culture operator might take to minimize interbreeding between cultured and wild populations are very limited. First, the number of escapes should be minimized, obviously standard procedure for any successful operator. Secondly, an operator could choose a cultured stock that is either: 1) genetically similar to the wild population so that interbreeding would entail minimal risk of introduction of maladaptive traits; or 2) poorly adapted to survival in the wild so that reproduction of the cultured individuals under natural conditions would be unlikely. Finally, continued research should be directed towards development of sterile stocks for cultivation through procedures such as hybridization, hormonal sterilization or creation of triploid animals (Chevassus, 1983; Purdom, 1983; Stanley, 1979).

3.10 TOXICANTS

Question

Does the use of chemicals for disease control in culture facilities pose a threat to the surrounding environment?

Discussion

In the event of a disease outbreak among net-pen cultured salmon, it is necessary to use an antibiotic to stop the spread of the disease and minimize fish mortalities. There are presently three antibiotics licensed by the Food and Drug Administration (FDA) for use on food fish: oxytetracycline (also known by the trade name of Terramycin), sulfamerizine and Romet 30 (a potentiated sulphonamide). Of these three, oxytetracycline is the most widely used in Puget Sound, therefore the remainder of the discussion will be focused on this chemical. No chemicals are used for disease treatment in suspended mollusc culture.

Oxytetracycline (OTC) is a broad spectrum antibiotic useful in the treatment of many fish diseases including general and hemorrhagic septicemia, furunculosis, bacterial gill diseae, columnaris, vibriosis and enteric redmouth (Austin, 1985). It is not used on a routine basis for disease prevention, but only as needed for disease therapy. In Puget Sound its use is generally required in the summer months, typically 2-3 times a year (C. Mahnken, NMFS, pers. comm.). It is provided to the fish in the feed at a concentration of 50-75 $mg \cdot kg^{-1}$ body $weight \cdot day^{-1}$ for a period of 10 days (Austin, 1985; Herman, 1969). The FDA does not allow food fish to be sold with detectable concentrations of the antibiotic in the tissue, therefore a 21 day waiting period is required after cessation of usage before the fish may be harvested.

OTC is widely used in human medicine because of its low toxicity, clinical flexibility in dosage and administration, and its effectiveness against a wide variety of bacteria, viruses and even some protozoa and metazoa. The antibiotic is also widely used in agriculture as a feed supplement in the diet of animals such as cattle, chickens and pigs. However, unlike its use in mariculture and human medicine, in which the antibiotic is used only in disease treatment, it is given to livestock on a continuous basis to prevent diseases and improve growth rate.

Assessment of the environmental consequences of OTC usage in net-pens is severely hindered by a lack of available information on fate and effects of the antibiotic in the marine environment. In addition to the literature reviewed for this study, a computerized literature search on the drug (provided by J. Forster, Sea Farm of Norway) has been reviewed, the Washington Department of Agriculture has attempted to obtain information from the Food and Drug Administration and I have made inquiries with the manufacturer (J. Hilton and C. Downing of Pfizer, Inc.). All efforts have met with little or no success to date. Thus, all conclusions below must be regarded as tentative, having been based on limited and in some cases conflicting data.

Despite extensive use of OTC in treatment of fish diseases both in the United States and elsewhere, as of yet there has been no demonstration of significant environmental effect. Many investigators have raised the issue of potential effects of antibiotic use in mariculture, although almost without exception the discussions have been entirely speculative, with no evidence of observed effect and little or no data provided to argue against an effect (Anonymous, 1983b; Beveridge, 1984; Midtlying, 1985; Pedersen, 1982; Solbé, 1982). I am aware of only one publication (Austin, 1985) which addressed the issue through field studies at a fish farm, and in this case the potential environment effects were left largely unresolved. There appears to be three potential environmental effects of concern: 1) inhibition of microbial decomposition of organic wastes; 2) development of OTC-resistant bacteria; and 3) accumulation of antibiotic residues in shellfish. These three issues are addressed individually below.

Inhibition of microbial decomposition of wastes -

OTC retards bacterial growth not only of the target bacterial pathogens, but of a wide spectrum of marine microbes. The natural bacterial community involved in nutrient cycling can also be affected by the antibiotic, but the limited evidence available suggests that these organisms can tolerate relatively high concentrations of OTC with little loss of activity. Marine bacteria responsible for sulfur oxidation and the oxidation of ammonia to nitrite/ nitrate are unaffected by concentrations of OTC up to at least 10 $mg \cdot l^{-1}$. Almost complete loss of activity occurs at a concentration of 100 $mg \cdot l^{-1}$ (Carlucci and Pramer, 1960). Bacteria responsible for production of ammonia have shown about a 30% loss of activity at concentrations of OTC between 1 and 100 $mg \cdot l^{-1}$.

The issue of OTC effects on the natural microbial community becomes a question of the concentration and persistence of the antibiotic. Given the rapid dilution of dissolved substances that occurs in a net-pen environment, it would seem that the only opportunity for OTC to remain at concentrations high enough to elicit a bacteriostatic effect would be if the substance remained associated with the particulate material (e.g., feces and excess feed). However, OTC is readily soluble in seawater (Musselman, 1956). At a pH and temperature typical of the marine environment, 4-20% of the OTC leaches from dry feed pellets within 15 minutes; a leaching rate constrained by the surface area of the pellet rather than the solubility of OTC (Fribourgh, et al., 1969). Thus, it seems unlikely that significant quantities of OTC would persist around a net-pen site. The effect of the antibiotic on the non-pathogenic bacteria community would probably be, at most, a very short-term phenomenon.

Development of OTC-resistant bacteria strains -

Use of an antibiotic will encourage proliferation of those strains of bacteria having a natural resistance to the substance. The presence of antibiotic-resistant bacteria has been demonstrated in the vicinity of effluent discharge from antibiotic manufacturing plants (Cornelson, et al., 1958), hospitals (Peou, et al., 1981) and domestic sewage treatment plants (Bell, et al., 1981). Use of antibiotics in fish culture has resulted in the appearance of resistant bacterial strains in the vicinity of the culture (Aoki, et al., 1980; Austin, 1985; Bullock, et al., 1974).

Austin (1985) studied the development of antibiotic-resistance in bacteria isolated form trout farm effluents, and monitored the duration of this resistance. Before treatment with OTC there was no OTC-resistance among the bacterial community. During OTC treatment 90% of the bacteria strains examined showed resistance to the antibiotic. However, within 9 days after cessation of the treatment, all OTC-resistance had been lost. Austin suggested this may indicate that antibiotic-resistance is a short-term phenomenon, and that this resistance is lost when antibiotic usage ceases. There is limited evidence of this from human evidence (Forfar, et al., 1966), but there are insufficient data at the present time to draw such a conclusion. Since Austin's studies were conducted in a flow-through system, there is some question as to whether he was monitoring anitbiotic resistance in the same population over time.

In agriculture, antibiotics are supplied to the animals on a routine basis for disease prevention and growth enhancement. The limited, therapuetic usage of antibiotics in net-pen culture would tend to lessen the likelihood of significant, long-term effects resulting from antibiotic usage. Net-pen operators typically use OTC only 20-30 days out of the year (2-3 treatments of 10 days each), thus lessening the selective pressure for development of antibiotic resistance in the microbial community.

The issue of microbial resistance has always provoked debate over antibiotic usage whether in human medicine or agriculture (see for example Solomons, 1978; Van Houweling and Gainer, 1978). On the one hand, there are immediate and obvious benefits of antibiotic usage. However, the more they are used, the less likely they are to be effective. Generally, the course which has been followed in medicine is to use antibiotics as judiciously as possible. There are still many unanswered questions regarding antibiotic usage in human medicine: the unknowns are even greater in fish culture.

Accumulation of OTC residue in shellfish -

Since the FDA prohibits sale of organisms having measurable residues of OTC in their tissue, accumulation of the antibiotic in shellfish could prevent their harvest. However, the probability of this presenting a problem appears remote. First, dilution would probably reduce the concentration of OTC to immeasurable levels within a very short distance of the culture facility. As an example, one may make a rough approximation of the OTC concentration in the water passing through the 250,000 kg net-pen operation discussed in Section 3.2. If the fish are treated with 75 mg $\mathrm{OTC \cdot kg^{-1}}$ body $\mathrm{weight \cdot day^{-1}}$, a daily total of 19 kg OTC would be introduced into the net-pens. Assuming no retention by the fish, and all OTC being dissolving in the parcel of water which passes directly through the pens during the day (72 $\mathrm{m^3 \cdot sec^{-1}}$, see Tables 4 and 5), the OTC concentration in that parcel of water would be only 0.003 $\mathrm{mg \cdot l^{-1}}$.

Secondly, OTC shows little potential to bioaccumulate so it is unlikely that shellfish would concentrate the antibiotic in their tissues above its concentration in the surrounding water. The potential for bioaccumulation of a compound is directly correlated with its water solubility (Kenaga and Goring, 1980). Given the fact that OTC is readily water soluble, it is unlikely to be concentrated in shellfish tissue. The fact that OTC-treated organisms lose their OTC body burden within a matter of a few days to one month (Corliss, 1979; Herman, *et al*., 1979), provides further evidence of little bioaccumulation potential.

Conclusions

Very little data were available with which to evaluate the environmental consequences of OTC usage in net-pen culture, thus, all conclusions must be considered tentative. However, on the basis of the available evidence OTC usage does not appear to be of major environmental concern given the infrequency of its use, its high water solubility, the rapid dilution which could be expected, and the limited mariculture development anticipated in Puget Sound.

4.0 MODELING OF ENVIRONMENTAL EFFECTS

4.1 INTRODUCTION

Models capable of predicting the environmental effects of mariculture would be extremely valuable both to environmental managers and the industry. With such models one might describe *a priori* the extent of changes in water chemistry or phytoplankton productivity which may occur should a proposed culture operation be permitted. The carrying capacity of a region could be determined, and steps taken to insure that the number of culture units allowed in this area does not exceed this capacity. The culture operator could use similar models to determine the maximum stocking density given the limitations of waste removal and oxygen supply.

Unfortunately, models capable of predicting the environmental effects of mariculture are, at best, only in very preliminary stages of development, and, in general, have not been tested. The development of new models or the refinement and testing of existing models require major research efforts, far beyond the scope of this study. It is not the intent of this report to provide definitive models, for they do not exist. However, the types of models currently available are reviewed and evaluated in order to provide a basis for further work. Primary emphasis has been given to those models specifically developed for, or applied to, mariculture, but several models developed for other situations are also evaluated with respect to their potential applicability to mariculture. Two environmental effects of mariculture which may be amenable to modeling are changes in water quality and the accumulation of organic-rich sediments under the culture facility.

4.2 WATER QUALITY MODELING

Many models have been developed to predict effects of nutrient inputs on water quality and productivity in the receiving water body (see Jorgensen, 1979; O'Connor, 1981; and Russell, 1975). Some investigators have applied these models to aquaculture in lake systems (Beveridge, 1984; Beveridge and Muir, 1982). However, the modeling of nutrient inputs to a lake is a far easier task than modeling inputs to Puget Sound. In a lake the system boundaries can readily be established, and the surface area and the volume of the affected water mass are easily defined. In Puget Sound, most suspended culture sites are located in open, unconfined areas, and tidal exchange complicates quantification of the affected water body.

Without the convenience of a relatively small, defined body of water like a lake, the simplest approach to modeling water quality effects from net-pens or suspended shellfish culture is to quantify effects on the parcel of water which passes directly through the culture structure. Water flow is assumed to be laminar, and no mixing of the water passing through the culture structure with the surrounding water mass is assumed to occur. These two assumptions are most assuredly always violated, and, therefore, severely limit the validity and utility of the models as they are presently formulated. However, in the absence of any better approach, this approach was used in Section 3.2 and has been used by many other investigators (Beveridge, 1984; Inoue, et al., 1966; 1970; Incze and Lutz, 1980; Kils, 1979) to obtain estimates of water quality changes.

Most investigators modeling the water chemistry changes occurring in a parcel of water as it passes through a culture structure have done so to maximize production. For example, the technique can be used to determine the maximum culture intensity achievable given the oxygen or food content of the incoming water (e.g., Beveridge, 1984; Incze and Lutz, 1980; Kils, 1979). The same approach can be adapted for purposes of environmental protection.

A model to determine the number of mussel longlines which could be supported by a given seston concentration was developed by Incze and Lutz (1980) and modified by Rosenberg and Loo (1983). The longline system modeled has a depth (h), and a width (w) equal to the length of the longlines. The longlines are oriented perpendicular to the current. The following terms are used:

A: (m^2), area of the culture system normal to the flow, $A=w \cdot h$
V: ($m \cdot hr^{-1}$), velocity of water mass entering normal to face A
N: ($l \cdot hr^{-1}$), volume of water entering face A per unit time, $N=V \cdot A \cdot 10^3$
S_k: ($mg \cdot l^{-1}$), seston concentration flowing into longline k, $k=1,2,\ldots,n$
M: (individuals), number of mussels suspended on each longline
F: ($l \cdot hr^{-1} \cdot individual^{-1}$), filtration rate of a mussel

The mussels will filter water at a rate of $F \cdot M$ $l \cdot hr^{-1}$ with passage through each longline, thus, $S_1 \cdot F \cdot M$ $mg \cdot hr^{-1}$ is the rate at which the first longline will filter seston from the water. The rate at which seston enters the first longline is $S_1 \cdot N$ mg·hr^{-1}. Therefore, the rate at which seston leaves the first longline is the rate at which it enters minus the rate at which it is filtered by the mussels, or $(S_1 \cdot N)-(S_1 \cdot F \cdot M)$ mg·hr^{-1}. This is equivalent to the rate at which seston is available to the second longline, $S_2 \cdot N$ mg·hr^{-1}. Thus:

$$S_2 \cdot N = (S_1 \cdot N) - (S_1 \cdot F \cdot M) \qquad \text{(Equation 1)}$$

Rearranging this expression to obtain the concentration of seston entering longline 2 yields:

$$S_2 = \frac{S_1 (N - F \cdot M)}{N} \qquad \text{(Equation 2)}$$

Likewise, the concentration of seston entering longline 3 is:

$$S_3 = \frac{S_2 (N - F \cdot M)}{N} \qquad \text{(Equation 3)}$$

Substituting Equation 2 for S_2 in Equation 3 yields:

$$S_3 = S_1 \left[\frac{N - F \cdot M}{N}\right]^2 \qquad \text{(Equation 4)}$$

The concentration of seston entering longline k is:

$$S_k = S_1 \left[\frac{N - F \cdot M}{N}\right]^{k-1} \qquad \text{(Equation 5)}$$

The same model can be used to approach the problem from a different perspective. If the size of the culture operation and the minimum acceptable seston concentration are known, one can determine the current velocity needed to support such a system and suitable sites may be identified. Rearranging Equation 5 yields:

$$\sqrt[k-1]{\frac{S_k}{S_1}} = \frac{N - F \cdot M}{N}$$

$$N \sqrt[k-1]{\frac{S_k}{S_1}} = N - F \cdot M$$

$$N \left[1 - \sqrt[k-1]{\frac{S_k}{S_1}}\right] = F \cdot M$$

$$V = \frac{F \cdot M}{A \cdot 10 \left[1 - \sqrt[k-1]{\frac{S_k}{S_1}} \right]}$$

$$V \cdot A \cdot 10^3 = N = \frac{F \cdot M}{1 - \sqrt[k-1]{\frac{S_k}{S_1}}} \qquad \text{(Equation 6)}$$

Rosenberg and Loo (1983) used Equations 5 and 6 to develop the relationships shown in Figure 8. Given the current velocity and the desired number of longlines, the model can predict the seston concentration needed to support the operation (Equation 5). Alternatively, if the seston concentration and number of longlines are known, the required current velocity can be determined (Equation 6).

This approach represents the best modeling tool currently available for managing the water quality in the vicinity of floating mariculture operations. Environmental managers and mariculture operators may find the approach useful to model depletion of dissolved oxygen or accumulation of ammonia. If threshold concentrations for these parameters can be established (either from the perspective of protecting the aquatic environment or the health of the cultured fish) and current velocities are known, one could predict the size of the culture operation which could be established without violating these standards. It should be recognized that these standards are applied to the parcel of water passing through the culture structure and not the receiving water body as a whole, since the effects of dilution are not considered. Alternatively, for an operation of known size, one could determine if a site was suitable, i.e., had sufficient current velocity or adequate dissolved oxygen to support the operation. The approach was developed for mussel longlines, but could readily be adapted for net-pen farming of salmon.

While the approach may eventually provide first-order approximations of the water chemistry changes that occur in water bodies with passage through culture structures, it should be recognized that it is untested. An evaluation of the approach in the marine environment is recommended before the model is used as a basis for decisions pertaining to siting or facility operation.

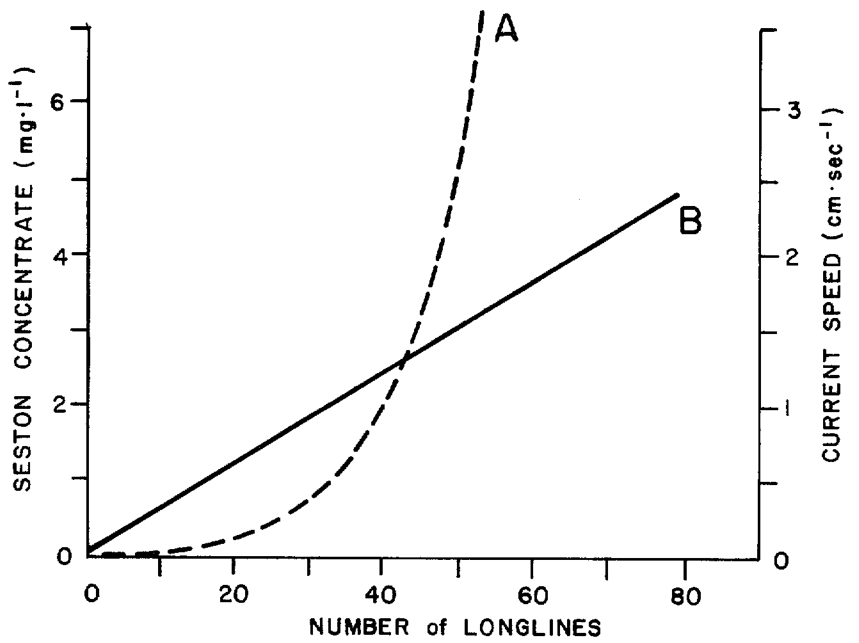

Figure 8 - The seston concentration (A) and current speed (B) needed to support a given number of mussel longlines. From Rosenberg and Loo, 1983.

Model parameters

	A	B
w: (m), length of longline	180	180
h: (m), depth of mussel strings	6	6
V: $(m \cdot hr^{-1})$, current velocity	36	Y
M: (individuals) mussels per longline	1,120,000	1,120,000
F: $(l \cdot hr^{-1} \cdot indiv.^{-1})$ filtration rate	3.2	3.2
S_1: $(mg \cdot l^{-1})$ initial seston concentration	Y	1.1
S_{k+1}: $(mg \cdot l^{-1})$ minimum acceptable seston concentration after passage through all longlines.	0.05	0.05
k: number of longlines (k+1 should be substituted for k in Equations 5 and 6)	X	X

4.3 SEDIMENTATION MODELS

The general goal of modeling sedimentation associated with mariculture is to determine the depth, rate and areal extent of accumulation of feces, pseudofeces or excess feed on the sea floor. Such models might be used in siting culture facilities to minimize effects on the benthos or to establish adequate distances from certain critical habitats. While the objective of sedimentation modeling is relatively straightforward, the accomplishment of this goal is not an easy task. The development of a sedimentation model requires the inclusion of many parameters that are very difficult to quantify at present. The parameters necessary may be grouped into the general categories of particle characteristics and fluid flow characteristics.

Particle characteristics

When a particle is placed in a non-moving fluid it accelerates toward the lower boundary of that fluid in response to gravity. However, as the velocity of the particle increases, so do the drag forces opposing the downward movement. When the gravitational and drag forces are in balance the particle falls at its terminal velocity, known as the settling velocity. Quantification of particle settling velocity is critical to any sedimentation model.

Settling velocity may be determined theoretically by Stoke's or Newton's equations, or empirically in the field or laboratory. Each approach has inherent advantages and disadvantages. The theoretical approaches (i.e., analytical equations) based on physical properties are preferred, but at present are well-developed only for solid, spherical particles. The empirical approaches are costly and the results do not generalize to conditions or sites other than those for which the data were collected. However, given the complex nature of the particles produced by mariculture operations, empirical determination of settling velocities is the only feasible approach at present.

Estimates of the sinking speed of particulate material from trout and yellowtail culture have ranged from 2-12 $cm \cdot sec^{-1}$ (Collins, 1983; Hagino, 1977; Iigura, 1974). However, these estimates of settling velocity were empirically derived and are not necessarily applicable to other sites wherre flow conditions may be very different. The use of a single number to quantify the settling velocity of the particles from a mariculture facility is misleading and inaccurate, since these particles are likely to encompass a wide range in settling velocities. In still water the standard deviation of the settling velocity may be half as great as the mean, and may exceed the mean value when currents are present (Hagino, 1977).

The determination of particle settling velocity by an analytical model will require quantification of the many individual parameters affecting settling velocity. The settling velocity of an individual particle is a function of particle shape, size and density. The concurrent settling of multiple particles is also affected by cohesive or adhesive forces between the particles and by the concentration of the particles in suspension.

Shape - Settling velocity is dependent upon particle shape, and most analytical sedimentation models assume the settling particles to be perfect spheres. Feed and fecal material are particle aggregates whose shapes are not accurately described by spheres. Nevertheless, most existing analytical models require that their shape be approximated as such.

Density - The densities (i.e., mass to volume ratio) of individual particles also affects their settling velocities. Aggregate densities are extremely difficult to determine, and one mean value is not likely to be an adequate representation for the complex mix of particles from mariculture. These aggregates are also porous. The porosity of fecal material affects determinations of both particle density and settling velocity. Both effects are difficult to quantify. In order to apply analytical sedimentation models it will probably be necessary to model the particles as solid objects, but the potential artifacts introduced must be recognized.

Size - Given constant particle density, settling velocity increases with particle size. Modeling the transport of particulate material from mariculture is complicated by the fact that the size of the particles encompasses a very broad range. Furthermore, the size of a given particle may change throughout the descent as aggregates disintegrate or reform.

Cohesion/Adhesion - Particle aggregates may be formed by either cohesion (electrostatic interactions) or adhesion ("gluing" of particles by a binding agent). The organic aggregates from mariculture are both cohesive and adhesive, although most sedimentation models are incapable of addressing these particle interactions.

Concentration - The rate at which particles settle in a fluid is dependent upon their concentration. Therefore, it is necessary to determine the concentration of particles beneath a culture operation in order to chose the appropriate model. At low concentrations the individual particles are sufficiently far from one another that no interactions occur. As concentrations increase a phenomenon known as "hindered settling" occurs in which interaction between particles reduces the settling velocity from that of the particles settling independently. At still higher concentrations "group settling" causes the particles to fall much faster than they would independently. Group settling is not likely to occur given the particle concentrations anticipated in mariculture.

Input rate - Models may be developed either for a pulsed input of particulate material or a continuous input. The later type would probably be most appropriate for application to mariculture, although there is a pulse component (i.e., feeding intervals) in the particulate input.

Fluid flow characteristics

Flow regime - Flow may be described in one, two or three dimensions, depending on the desired complexity of the model. At a minimum the model should account for bi-directional tidal flow in one dimension. Two dimensional models would permit the contouring of sediment accumulation around a culture facility. Water movement in the third (vertical) dimension may be important in sediment transport under some conditions, but is ignored in most models.

The forces on a particle and its movement in a fluid are highly dependent on the viscosity and density of the fluid. Both parameters are dependent upon temperature and salinity, and are two of the few necessary model parameters that are easily quantified. The water column may be stratified by density and a sedimentation model should be capable of quantifying sediment transport in a vertically stratified density gradient if it is to have broad application.

The simpler sedimentation models assume that water depth is constant within the area of potential deposition. However, it would be preferable to use a more complex model capable of predicting particle accumulation on a sloping or uneven bottom.

Benthic boundary conditions - The probabilities of deposition and resuspension are determined by boundary layer structure and bed shear stress, both of which are functions of the near-bottom flow regime. The bed shear stress is in turn dependent upon bottom topography, bottom roughness and other factors.

In order to demonstrate how particle and fluid characteristics are incorporated in sedimentation models, and to assess the types of models currently available, various sedimentation models are evaluated with respect to their applicability to modeling of sediment input and transport from mariculture. A review of all available models has not been attempted. Instead, several model types representing alternative applications are discussed. The models reviewed have been developed for ocean dumping, manganese nodule mining, estuarine sediment transport and aquaculture.

Ocean dumping

Many models have been developed for ocean disposal of wastes including dredged material (Brandsma and Divoky, 1976; Stoddard, et al.,1985), mining wastes, (Bigham, 1986), drilling muds (Brandsma, et al., 1983) and sewage sludge (Koh, 1971; Koh and Chang, 1973). Ocean dumping typically incorporate two phases of particle descent. The first phase is convective descent. When the material is released to the ocean, the particle concentration is high, and the density of the plume is likely to be much greater than that of the surrounding seawater. Because of "group settling" the plume tends to settle as a single, large mass. The settling velocity of the plume may be several orders of magnitude greater than the settling velocities of individual particles acting independently. As the plume descends it becomes less dense through entrainment of the ambient ocean water. If the water column is density-stratified, the convective descent of the plume may terminate at some point of neutral bouyancy at which the density of the diluted plume is equal to that of the surrounding seawater.

The second phase of particle transport is passive dispersion. At this point the plume is assumed to have reached a point of neutral bouyancy. Further particle dispersion occurs as a result of currents and turbulence. Typically, most models will consider only two dimensions in this phase where, other than particle settling, vertical water movement is neglected.

The phenomenon of convective descent is entirely inapplicable to the modeling of particle transport from suspended mariculture. If ocean dumping models are to be applied to mariculture, this phase of particle settling can be ignored.

An additional problem with most of the ocean dumping models is that they are based on a single input of particles over a very short time period (e.g., the release of dredged material from a barge). These models would be inappropriate to the long-term, essentially continuous release of particulates from mariculture. Trajectory models have been used to predict the dispersal of drilling muds when the discharge has negligible initial momentum or bouyancy and the discharge continues for long periods with variable currents (Brandsma, 1984; Runchal, 1978), and might be applicable.

Manganese nodule mining

Lavelle et al. (1981) developed a model to predict dispersion of the sediment plume generated during manganese nodule mining in the deep sea. As the nodule collector moves across the bottom, it resuspends silts and clays. The model predicts the depth of redeposition as a function of lateral distance from the collector track.

One advantage of this model to those discussed previously is that a convective descent phase is not included in the model. The mining process does create a high density plume which goes through a stage of gravitational collapse immediately behind the collector. However, the model only attempts to predict the passive dispersion which occurs following the convective descent stage.

The model has a number of assumptions and limitations which make it unsuitable for application to mariculture without substantial modification. First, it assumes a constant, unidirectional current and a uniform settling velocity for all particles. Both assumptions may be reasonable in the deep sea but inappropriate in coastal environments. Secondly, the model utilizes an empirically-determined settling velocity. While this does not preclude its applicability to mariculture, it should be recognized that an appropriate empirically determined settling velocity must be obtained whenever the model is used. Thirdly, there is no provision for continuous sediment input. It is assumed that any given point on the bottom is subject to accumulation from only a single sediment pulse. Fourthly, sediment input to the model is in the form of a concentration gradient of particles near the bottom, with no particles more than 5 m above the sea floor. Such a sediment distribution would not be expected in the case of floating mariculture, and the input conditions must be modified as appropriate for mariculture. Finally, there is no provision for resuspension of particles once deposited. Such a simplifying assumption may be necessary in a first generation model, but the limitations should be recognized, and the possibility of resuspension and redistribution of sediments from mariculture should be considered.

Estuarine sediment transport

Complex numerical (i.e., empirical) models have been developed to describe sediment transport in estuarine environments (e.g., Ariathurai, et al., 1977; Sheng, 1983). The modeling of estuarine sediment transport is considerably more difficult than modeling of sediment dispersion from floating mariculture. Given the input of fresh water, fluid density differences are of particular concern in estuarine modeling. Unlike mariculture, sediments are introduced into an estuary within a fluid (the river) having a very different density than the receiving (marine) waters. This density difference has profound consequences on the time and path of particle descent. In addition, as salinity increases the fine particles tend to aggregate. The effective particle size, and consequently the settling velocity, may be increased. Finally, estuarine sediment transport models must take into account the influence of wind forcing. This factor will probably be neglected in initial mariculture models.

Despite the added complexities of estuarine sediment transport models, they can serve as patterns for development of numerical models for mariculture: 1) sediment input is continuous rather than single or pulsed events; 2) sediment concentration is low in comparison to other inputs such as dredged material disposal, thus avoiding the modeling problems associated with group settling; and 3) the settling behavior of cohesive sediments must be considered. No single estuarine sediment transport model currently in use is readily available for application to mariculture, and the modification of existing models would require substantial effort.

Aquaculture

Hagino (1977) developed a simple model to predict the dispersion of feces and unutilized feed from net-pen culture of yellowtail in Japan. Rather than modeling the complex physical processes involved in determining settling velocity, this parameter was determined empirically by the use of sediment traps placed around the net-pens. The settling velocity of particles from the net-pens was found to encompass a very broad range. The range of settling velocities was quantified as a normal distribution with a mean and standard deviation of 7.5 $cm \cdot sec^{-1}$ and 10-13 $cm \cdot sec^{-1}$, respectively.

The extent of sediment accumulation as a function of distance was determined based on the formula:

$$x_i = \frac{u \cdot h}{w_i}$$

where x_i equals the horizontal distance from the net-pen traversed by the particle, u equals the current speed, h equals the water depth and w_i equals the particle sinking speed. Using a probability function of settling velocity in place of w_i, and assuming a constant, unidirectional current, an estimate of sediment accumulation as a function of distance was obtained (Figure 9 a). The extent of sediment accumulation in two directions from the net-pen (Figure 9b) was estimated by modeling tidal currents as a sine function. With field data on the current regime in the vicinity of the net-pens, contours were developed to predict the accumulation of feces in all directions. The distribution of accumulated sediment predicted by the model was found to resemble the actual depth of accumulations measured in the field.

The model of Hagino (1977) is a very simplified approach to a complex problem. The major limitation of the approach is that it is empirical, and therefore, site-specific. No attempt was made to determine the many variables affecting settling velocity. Values were derived empirically with no knowledge of how settling may have been influenced by site-specific conditions of current and turbulence. Therefore, the estimated settling velocities are not necessarily applicable to other sites and conditions. The process of sediment resuspension also was not considered by the model.

It is clear that the development of analytical models is a monumental task. Certain simplifying assumptions (e.g., no vertical water movement, no particle interactions during settling, particles modeled as solid spheres) may approximate actual sediment transport processes. This development of analytical models is an active field of research, but has not yet reached the point where sediment transport related to mariculture can be modeled realistically.

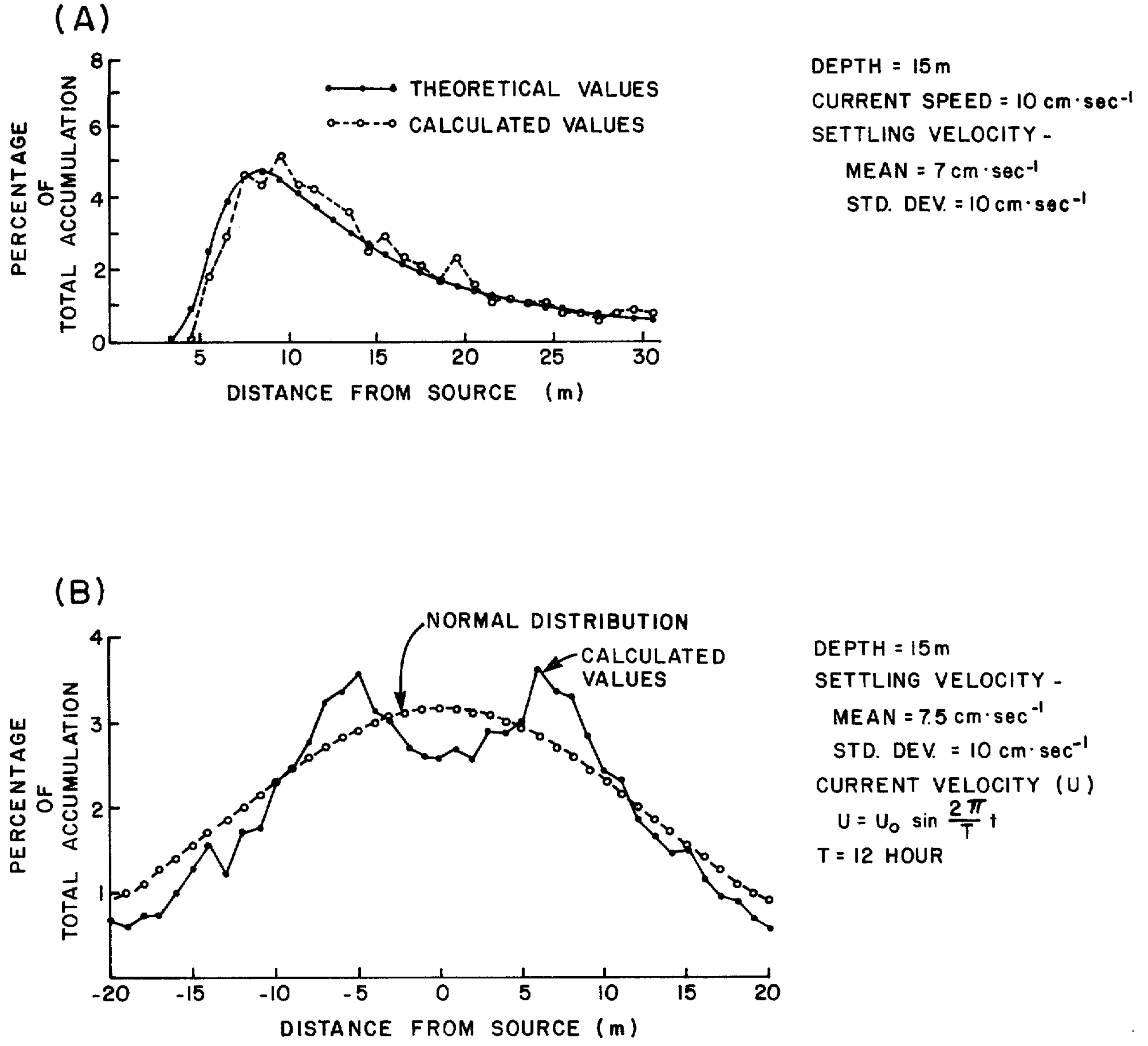

Figure 9 - Bottom accumulation of feces and excess feed from a net-pen facility predicted by a one-dimensional empirical model. (A): Constant unidirectional current. Theoretical values determined by a probability density function of sinking speed. Calculated values based on empirical settling velocities. (B): Simulated bidirectional tidal current. From Hagino, 1977.

The presently available empirical models like that of Hagino (1977) may provide reasonable approximations of actual deposition. Given the present state of our knowledge of sediment transport processes, the simple, empirical Hagino model is probably as valid and as useful as any of the more mathematically complex models, whether analytical or empirical. Empirical models are limited by site-specificity, but they represent the only approach of immediate applicability. The Hagino model, or any other empirical model should be used cautiously, and efforts should continue towards development of models with better predictive capabilities.

Concurrent with the development of models should be further efforts to relate the rate of sedimentation with the consequent biological effects. It is not yet possible to determine what biological changes will occur with any given rate of sedimentation or organic enrichment. The magnitude of the effect will be determined largely by the rate of oxygen supply to the sediments and the tolerances of the specific benthic community to burial, oxygen depletion, etc. Further studies of benthic communities exposed to varying rates of sedimentation and organic enrichment are necessary to quantify the relationship. If "acceptable" rates of sedimentation/enrichment can be established, these rates can then be integrated into the appropriate sedimentation model.

5.0 ENVIRONMENTAL REGULATION OF MARICULTURE

5.1 INTRODUCTION

Mariculture is practiced much more extensively in other countries than it is in the United States. Therefore, the laws and regulations developed elsewhere to minimize environmental effects of mariculture may provide valuable insight into management of mariculture development in Puget Sound.

A survey of mariculture regulations in other states and countries was conducted. No attempt was made to identify mariculture regulations pertaining to issues such as navigational rights, property access, recreational or commercial fishing interests, or sale and public consumption of products. Emphasis was placed on identifying those laws and regulations intended to minimize alterations to the physical, chemical and biological environment resulting from establishment of the culture operation. Such regulations can be grouped into two general categories: regulations which attempt to minimize environmental degradation through siting and operational restrictions, and regulations which are intended to prevent the spread of disease or introduction of exotic species. Siting and operational restrictions may include requirements regarding water depth, distance between culture operations, the exclusion of specific habitats, stocking density, production limits and feeding restrictions. Regulations minimizing opportunity for the spread of disease or the introduction of species may include inspection of shipments, quarantining, pathological examinations, restrictions on the country of origin or bans on the importation of certain species.

The states and countries in which marine net-pen culture of salmon and/or suspended culture of shellfish is practiced were surveyed, since the regulation of these two industries is most relevant to mariculture development in Puget Sound. The states surveyed were Washington, California and Maine. Extensive culture of shellfish, particularly oysters and scallops, is practiced in California. Maine is the only other state with significant suspended mussel culture. There are also several operations in Maine for net-pen culture of Atlantic salmon. The countries surveyed were Canada (specifically British Columbia), Chile, Faroe Islands, Japan, New Zealand, Norway, Scotland, Spain and Sweden. These countries are either major producers of mussels (by suspended culture) and/or net-pen reared salmon, or which have adopted particularly stringent requirements to minimize the environmental effects of mariculture.

5.2 STATE REGULATIONS

Washington

Sources: Eric Hurlburt, Washington Department of Fisheries, pers. comm.

Proposed mariculture facilities are subject to permit reviews by a variety of government agencies. These reviews include, among many other considerations, the potential effect of the operation on nearby habitats (e.g., kelp and eelgrass beds, spawning areas). The counties have taken an active role in this review process, and each has adopted its own approach to project siting. There are currently no state regulations on permissible depths for mariculture operations, stocking densities, or proximity to other culture operations. There are, however, some state agency policies which would affect project siting. The Department of Social and Health Services prohibits the sale of shellfish from decertified areas (as determined by fecal coliform counts) or from within 0.5 miles of a sewage outfall. The Department of Fisheries has a policy of prohibiting net-pens over harvestable shellfish beds.

Introductions of exotic species must comply with the State Environmental Policy Act (SEPA), through which they are reviewed for possible impacts on native species and habitats. The importation of fish, shellfish and aquatic plants, or the transfer of fish within the state is subject to the issuance of a permit, for which the potential accidental introduction of diseases and undesirable organisms is assessed. Department of Fisheries policy prohibits the importation of all live salmonids or their eggs from Europe, except for eyed Atlantic salmon eggs. The importation of these eggs requires that they originate from a disease-free facility, they must be surface disinfected, and they must be held in quarantine for 90 days following swim-up.

California

Sources: Bowden, 1979; Smith, 1985; Earl Smith, Marine Resources Supervisor, Marine Resources Division, California Department of Fish and Game, pers. comm.

There is presently no net-pen salmon culture in California. There are two salmon growers, one which holds the fish until they attain marketable size and the other which is involved in ocean ranching, but both hold the fish in land-based containment structures (e.g., tanks, raceways). There is, however, extensive suspended mollusc culture in the state including oysters, scallops and mussels.

Applicants for an aquaculture permit are required to go through a review process in which the California Department of Fish and Game evaluates the environmental acceptability of the proposed operation. There are, however, no formal siting or operational criteria intended to minimize environmental effects. The Marine Resources Division of the Department of Fish and Game is unaware of any adverse environmental effects resulting from operation of suspended shellfish culture in California (E. Smith, pers. comm.).

Written permission from the California Department of Fish and Game is required to import live fish and shellfish into the state. Salmon eggs must originate from an approved source and be accompanied by a disease-free certification. Imported oysters are inspected for drills and other pests. A culturist wishing to introduce an exotic species must demonstrate that a sound reason exists for the introduction and that the species will not cause harm to native species. The state has recently adopted guidelines for the importation of exotic species proposed by the International Council for the Exploration of the Sea (ICES, 1982; Rosenthal, 1985). Complete reviews of California policy regarding importation of live animals for aquaculture can be found in Bowden (1979) and Smith (1985).

Maine

Sources: DMR, 1985; Ken Honey, Maine Department of Marine Resources, pers. comm.

Both net-pen culture of salmon and suspended culture of mussels are practiced in the state of Maine. An applicant for either type of operation must submit an aquaculture lease application to the Department of Marine Resources. While there are no specific criteria designed to minimize environmental effects, the Department does consider potential environmental consequences during application review. However, while permit requests have been denied by the state for a variety of reasons, no mariculture permit has ever been denied because of concerns of environmental degradation. The Maine Department of Marine Resouces is unaware of any adverse environmental changes in the vicinity of mariculture operations within the state (K. Honey, pers. comm.).

5.4 REGULATIONS OF OTHER COUNTRIES

Canada (specifically British Columbia)

Sources: Frances Dickson, Aquaculture Co-ordinator, Field Services Branch, Fisheries and Oceans, pers. comm.; Edward Black, Ministry of the Environment, pers. comm.; Bruce Kay, Environmental Protection Service, pers. comm.

Salmon net-pen culture is rapidly expanding in British Columbia. For example, in Sechelt Inlet alone there are currently four net-pen facilities currently in operation, and applications in review for an additional 25 farms. Such dramatic growth is typical for much of the marine waters within the province. About 200 net-pen farms are expected to be in operation in the province by 1987.

Federal and provincial authorities have begun developing siting criteria, although because the industry is relatively new, the criteria are frequently refined and updated. Some of the major siting criteria currently under consideration for adoption include:

1) A new net-pen facility will not be permitted within 0.5 nautical miles of a major salmon spawning stream or within 0.5 nautical miles of an existing net-pen operation. This minimum distance is intended to minimize deterioration of water quality and the potential for disease transmission. The exact distance is a somewhat arbitrary "best guess", and is not based on firm scientific data. Provincial authorities are allowing a new farm to locate within 0.5 n.m. of an existing farm if approval of the existing farm's owner can be obtained, but federal authorities are not generally advocating this practice.

2) A new facility may not be located closer than 125 m from a shellfish bed, and there is some consideration being given to increasing this distance.

3) New net-pens may not be located in less than 10 m water.

4) Net-pens may not be located near eelgrass beds, herring spawning areas or other habitats of special significance.

British Columbia also has relatively restrictive policies regarding the importation of salmon into the province. These regulations include:

1) Pacific salmon may not be imported. Only Atlantic salmon and non-anadromous rainbow trout may be brought into the province.

2) Smolts may not be imported. Eggs brought into the province must be quarantined for a minimum of 12 months, during which the young fish must be inspected at least four times by a pathologist. The last inspection must occur after smolting.

3) Imported eggs must originate from approved, disease-free hatcheries. No importation of eggs is permitted from Europe, the southern hemisphere, or other countries where viral hemorrhagic septicemiae has been reported or is likely to be present. All eggs must be surface-disinfected prior to importation.

4) Consideration is being given to halting all Atlantic salmon importation after March 31, 1989.

Chile

Sources: Ron Zebal, WDF, pers. comm.; Jon Lindbergh, pers. comm.

There are no regulatory restrictions imposed on salmon growers with respect to number of net-pens, stocking density, spacing between operations or similar siting and operational considerations. The government does not require any formal review of the potential for environmental alterations in the vicinity of a proposed culture site.

The only regulations intended to minimize environmental effects are those pertaining to the introduction of exotic species and diseases. The importation of live fish is prohibited, although eggs may be imported if certified to be disease-free. Applications for the introduction of exotic species are reviewed on a case-by-case basis. For example, review of a proposal to introduce the oyster Crassostrea gigas took five years. The introduction was finally allowed with the restriction that they not be placed near natural or cultured beds of the native oyster.

Faroe Islands

Sources: Tommy Petersen, Secretary of the Faroese Sea Breeding Commission, pers. comm.

The Faroe Islands are not major producers of net-pen grown fish; 1985 production was only 1,100 metric tons of Atlantic salmon and sea trout. The environmental policies of this country pertaining to mariculture were chosen for review because environmental concerns have were reported to have resulted in strict regulation of the industry (NOAA, 1985). However, the information I obtained from the Faroese Sea Breeding Commission, the government agency responsible for licensing fish farms, does not indicate that environmental policies are any more restrictive than in many other countries.

The most restrictive government policies pertain to the importation of live material and the potential introduction of disease organisms. No live fish can be imported for culture purposes, nor has the importation of eggs been permitted since 1984.

Applications for a net-pen facilities are carefully scrutinized with respect to the education, experience and economic status of the operator. Environmental concerns have played a minor role in permit reviews to date because the industry is relatively new and few farms are currently in operation. However, as the industry expands the Faroese government is becoming increasingly aware of environmental issues, and siting criteria may be developed in the near future.

Japan

Sources: Kunihiko Fukusho, National Aquaculture Research Institute, pers. comm.

There are no national standards regarding siting or operation. Instead, standards are established by each individual prefecture. The prefectures set standards as necessary for environmental protection, but primarily from the standpoint of preventing deterioration of the culture grounds to the point where the health of the cultured animals is threatened. Guidance of the culturists is followed in establishing the maximum culture intensity achievable in a given area, optimal spacing between operations, maximum stocking densities, etc.

Since each prefecture has its own siting and operational standards, it is not possible to provide a thorough review of these requirements here. However, a few examples are provided.

Kagoshima Prefecture - The culture grounds have been divided into several subareas as determined by the minimum annual dissolved oxygen concentration. In Zone A, where oxygen concentrations outside the net-pens reach as low as 5.5 $mg \cdot l^{-1}$ (4.5 $mg \cdot l^{-1}$ inside the pens), stocking densities can not exceed 11 $kg \cdot m^{-3}$ and culture intensity can not exceed 40 metric $tons \cdot hectare^{-1}$. Zones B and C experience lower dissolved oxygen concentrations, and consequently, permissible stocking densities and culture intensities are reduced. In Zone C (oxygen concentration undetermined) stocking densities must be 7 $kg \cdot m^{-3}$ or less and the culture intensity can not exceed 20 $tons \cdot hectare^{-1}$.

Mie Prefecture - Stocking density in net-pens is limited to 10 $kg \cdot m^{-3}$. Only one 7x7x7 m net-pen is permitted per 700 m^2. The use of moist feed is encouraged over the use of wet feed because of the proportionately lower amount of wasteage.

Kagawa Prefecture - Phytoplankton blooms are a frequent occurrence in this area, thus net-pens must be at least 20 m deep to provide the fish a refuge from dense phytoplankton populations in the surface waters. Stocking density is limited to 7 $kg \cdot m^{-3}$.

New Zealand

Sources: John Galat, New Haven Salmon Ranch, pers. comm.; Jon Lindbergh, pers. comm.

An applicant desiring to establish a salmon net-pen operation in New Zealand must submit a permit request and operations plan to the Ministry of Agriculture and Fisheries for review and approval. While potential environmental effects are one consideration in this review process, there are no specific siting or operational requirements. There are no water depth requirements and, in fact, some operators have net-pens which rest on the sea bottom. Siting and operational practices which can affect environmental quality are generally left to the discretion of the culture operator, since deterioration in environmental quality would be reflected in decreased productivity of the culture operation itself.

There is also minimal regulation of suspended mussel culture with respect to potential environmental effects. Marlborough Sound, a major culture center for the green-lipped mussel (Perna canaliculus), is divided into contiguous lease tracts. There are no restrictions on the number, size or spacing of longlines or rafts within each tract.

New Zealand has one of the most restrictive policies regarding importation of fish and shellfish into the country. Concerned about the introduction of diseases, the government allows no importation of live, fresh or frozen fish. Only processed seafoods (e.g., canned goods) are allowed into the country. While there are regulatory pathways through which one may apply for special exemptions, the stringent requirements (e.g., two years holding time in a quarantined facility) render the importation of live animals unfeasible in practice.

Norway

Sources: Anonymous, 1984; Edwards, 1978; Hurlburt, unpub.; NOAA, 1985; NOU, 1985; Knut Senstad, Sea Farm of Norway at Bergen, pers. comm.

Norway is the world's largest producer of net-pen reared salmon. In 1985 the country produced 35,500 metric tons of Atlantic salmon. As of 1984, 575 licences to operate salmon and trout fish farms had been granted and 1,700 more applications had been submitted.

Many of the early net-pen operations established in Norway were sited in silled fjords with little water exchange. This siting has resulted in accumulation of so much organic matter beneath the pens that the health of the cultured fish is threatened. Some operators have moved their pens to sites with better water exchange, while others have begun periodic rotation of net-pen sites or adopted the use of submersible mixers to disperse the accumulated solids.

The Norwegians have since become more cognizant of protecting environmental quality when siting new net-pen operations. The government will not license a proposed facility in an area where flushing is considered inadequate because of the presence of a sill or other physical factors. A water depth of 10-15 m beneath the pens is considered desirable, although this criterion has not adopted as a formal requirement.

The Norwegian government also sets standards for minimum distance between culture operations. New fish farms in Norway were previously required to maintain a minimum distance of 1000 m from established farms, although this distance has recently been reduced to 500 m. This minimum distance has been established with the intent of minimizing the possibility of disease transmission between facilities.

Norway imposes a maximum size limit of 4,000 m^3 on new net-pen operations (K. Senstad, pers. comm.; elsewhere quoted as 3,000 m^3 and 5,000 m^3). If, after several years, the grower is able to demonstrate a successful operation, he may be granted a license to add additional net-pens and expand holding capacity to 8,000 m^3. With the exception of operations in place prior to passage of the law in the mid-1970s, no net-pen operation in Norway is allowed to exceed the 8,000 m^3 limit. While the imposition of this limit may have the effect of lessening environmental disturbance, it was adopted for socioeconomic rather than environmental reasons. It was the intent of the Norwegian government to exclude the large companies and promote development of the industry by small growers, thereby alleviating the unemployment in small, isolated fishing villages along the coast.

The importation of eggs and live fish into the country is allowed after receipt of the necessary permits. All shipments must be accompanied by a disease-free certification.

Scotland

Sources: Anonymous, 1984; Marvyn Eddie, Marine Harvest Limited, Edinburgh, pers. comm.

As of 1983 there were 41 freshwater and 62 marine salmon farms in Scotland producing 2500 metric tons of Atlantic salmon. By 1985 the production increased to 7,000 tons, and a production of 10,000 tons is projected for 1986.

Applications for new net-pen operations in Scotland must be approved by the Department of Agriculture, Fisheries and Food. This agency consults other regulatory bodies, fishermen, yachtsmen and other interested parties prior to granting an operating license. The potential environmental effects of the operation are considered in this review, although there are no established criteria for siting or operation. Pollution-related issues have not been of major concern to date, in part because many of the farms are small in size.

The Scottish government prohibits the importation of live fish. A license for the importation of eggs may be obtained if steps have been taken to minimize the potential for introduction of disease with the shipment (e.g., eggs may not originate from restricted areas, the disease history of the hatchery is known).

Sweden

Sources: Anonymous, 1982.

Mussel culture operations with annual production in excess of 50 metric tons and salmon culture operations are regulated under the Swedish Environmental Protection Act. The County Administration examines applications for new aquaculture facilities or modification of existing facilities in accordance with the provisions of this Act. While there are no standardized siting or operational criteria, the County Administration does assess the potential for environmental alteration, and may require the operator to take actions to minimize environmental disturbance.

Application for an aquaculture permit must also be made to the Swedish National Board of Fisheries. This agency reviews the potential for spread of fish diseases and the introduction of exotic species. In a few cases it has also been necessary to submit the application for review by a third agency, the Water Rights Court. This body reviews the proposed facility if it will transgress public or private rights.

In summary, this review of environmental regulations pertaining to mariculture indicates that the policies of Washington are generally comparable to those of many of the other states and countries surveyed. There are usually few, if any, formalized siting or operational criteria designed to minimize environmental effects. Instead, each application is handled on a case-by-case basis through a review process which includes an opportunity for the responsible government agencies to evaluate potential environmental effects. Such is generally the case in Washington as well as in California, Maine, Chile, Faroe Islands, New Zealand, Scotland and Sweden. Of the countries surveyed, only Norway and Canada (specifically British Columbia) have developed specific numerical criteria regarding water depth, distance between operations and similar siting requirements.

Importation of eggs or live animals typically requires a permit from the responsible government agency. The permit will carry with it certain conditions which, depending on the particular state or country, may include restrictions on the country of origin, visual and/or pathological inspectios, periods of quarantine, or disinfection requirements. There appears to be a growing tendency to completly ban importation of eggs or live animals for culture. Chile and Scotland ban the importation of live fish for mariculture, but allow the importation of eggs if certain steps have been taken to minimize the introduction of disease. The Faroe Islands and New Zealand prohibit the importation of both eggs and live animals.

6.0 RECOMMENDATIONS

This report has evaluated the likely environmental consequences of floating mariculture development in Puget Sound based on the best information currently available. However, some unanswered questions remain which complicate assessment of environmental effects and frustrate attempts by regulatory agencies to develop defensible siting and operational criteria. Work in progress will provide some of the needed information. For example, the National Marine Fisheries Service is currently analyzing benthic samples collected over a 2.5 year period after removal of a net-pen. These samples will provide information on the time required for recovery of the benthic community following cessation of culture operations. The Washington Department of Fisheries and other agencies are currently reviewing state policies pertaining to the importation of plants and animals for aquaculture in order to insure that adequate safeguards are in place to prevent disease transfer.

Three additional avenues of research appear to have the greatest priority:

Factors affecting the accumulation of organic-rich sediments beneath floating mariculture facilities

This review has indicated that most floating mariculture operations have resulted in substantial alteration of sediment chemistry and the benthic invertebrate community in the immediate vicinity of the culture. Environmental managers have recognized this fact, and have endeavored to site new operations distant from benthic habitats that are considered critical or sensitive.

Rather than accepting accumulation of organic-rich sediments as an unavoidable consequence of mariculture, it would be preferable to find the means to avoid this accumulation. It may be possible to establish conditions of current velocity and water depth at which the rate of organic input to the bottom would not exceed the assimilative capacity of the benthos. Determination of the maximum allowable rate of organic input, or the conditions of water depth and currents necessary to achieve it, will require the following steps be taken:

1) Field studies at numerous net-pen and mussel culture sites in Puget Sound are needed to better quantify the chemical and biological gradients in surrounding sediments. These field surveys should include measurements of the current regimes at the sites. This information is critical, but is generally lacking from studies to date.

2) Based on the field studies and a literature review some estimate of an "acceptable" rate of organic input may be obtained. It is not anticipated, however, that one estimate of loading rate will be applicable to all conditions since it will depend on sediment porosity, bottom current velocity, BOD of the natural sediments, oxygen content of the overlying water, biological community structure and other factors. Site by site evaluations will be necessary until our understanding of benthic processes increases to the point that predictive capabilities are developed.

3) Sediment transport models are needed to describe the behavior of particulate material falling from the culture structure. Modeling sediment transport is a very active area of research, but we are still far from realizing the types of predictive models needed for mariculture applications. We can begin with development of empirical models that attempt to quantify the interdependence of water depth and current velocity in determining the rate of sediment accumulation on the bottom. Data collected in the field studies can be used to evaluate and refine these empirical models.

The environmental effects of antibiotic usage in salmon net-pen culture

The use of antibiotics in mariculture does not appear at present to be an environmental threat given the characteristics of the antibiotic most commonly used, the infrequency of its use and the limited development of mariculture in Puget Sound, but the data available on potential effects are extremely limited. As mariculture continues to develop in Puget Sound, the need for more information on environmental release of antibiotics grows in importance. The following information is needed:

1) Additional data are needed on environmental fates of antibiotics currently in use or of potential use in Puget Sound. Literature pertaining to metabolism of the compounds in fish (e.g., retention time and metabolic breakdown products) and the persistence of the compounds in the marine environment (e.g., half-life, light sensitivity, susceptibility to chemical or biological degradation) should be reviewed. Laboratory studies may be needed to supplement existing information.

2) Antibiotics are currently in use in mariculture operations in Puget Sound. This on-going use provides an excellent opportunity to monitor environmental fates. Monitoring of antibiotic concentrations in water, sediments and biota should be performed by sampling before antibiotic treatment, during and immediately after treatment, and continuing for at least several weeks thereafter. Monitoring for the development of antibiotic resistance in microbial populations should also be included.

Determination of environmental carrying capacity

This review suggests that toxic effects attributable to accumulation of metabolites and depletion of dissolved oxygen are not likely to occur if mariculture operations are sited in well-flushed areas, and if the intensity of mariculture (i.e., number of operations in an area) remains low. Unfortunately, the quantification of adequate flushing and determination of a maximum allowable culture intensity are very difficult.

The determination of the environmental carrying capacity for mariculture has typically been done by trial and error. A preferable approach would be the development of mathematical models to predict changes in water chemistry parameters as a function of mariculture development. No such a predictive capability currently exists, although some investigators have begun to explore the concept of carrying capacity (e.g., Beveridge, 1984; Sakamoto, 1977). The objective of these past studies has typically been the maintenance of the health of the cultured animals rather than environmental protection (not necessarily mutually exclusive objectives). Most work on the subject has been done by the Japanese, where intensive culture in shallow, enclosed embayments has, in some cases, exceeded the carrying capacity of the culture grounds.

Given the many competing priorities for use of Puget Sound, it is difficult to envision mariculture development to the extent practiced in Japan. However, should the industry show continued expansion, and development occur in areas of marginal suitability, a need may arise to determine how many operations in a given area are "too many" and how little water exchange is "too little". At present the best we can do is to learn from past mistakes and evaluate each case on a site-by-site basis. However, the development of carrying capacity models is recommended as a long-term goal.

Literature Cited

Ackefors, H. and K. Grip. 1985. Musslor och Ostron. Swedish Council for Planning and Coordination of Research (FRN). 84 pp.

Ackefors, H., K. Murray and H. Rosenthal. 1984. A European view on the Asian approach to modern aquaculture development. International Council for the Exploration of the Sea C.M. 1984/F:3. 38 pp.

Ackefors, H. and A. Södergren. 1985. Swedish experiences of the impact of aquaculture on the environment. International Council for the Exploration of the Seas C.M. 1985/E:40. 7 pp.

Alabaster, J.S. 1982. Survey of fish-farm effluents in some EIFAC countries. In J.S. Alabaster (ed.), Report of the EIFAC Workshop on Fish-farm Effluents. Silkeborg, Denmark, 26-28 May 1981. pp. 5-20. EIFAC Tech. Pap. 41.

Allendorf, F.W., D.M. Espeland, D.T. Scow and S. Phelps. 1980. Coexistence of native and introduced rainbow trout in the Kootenai River drainage. Proc. Montana Acad. Sci. 39:28-36.

Allendorf, F.W. and S.R. Phelps. 1980. Loss of genetic variation in a hatchery stock of cutthroat trout. Trans. Am. Fish. Soc. 109:537-543.

Amend, D.F., W.T. Yasutake, J.L. Fryer, K.S. Pilcher and W.H Wingfield. 1973. Infectious hematopoietic necrosis (IHN). In W.A. Dill (ed.), Symposium on the Major Communicable Fish Diseases in Europe and Their Control. pp. 80-87. EIFAC Tech. Pap. 17, Suppl. 2.

Anonymous. 1982. Får Jag Lov? Vattenbrukets juridik. [May I have permission? Legal concerns in aquaculture]. Swedish Council for Planning and Coordination of Research (FRN). 73 pp.

Anonymous. 1983a. Water quality surveyed in Clam Bay. Quarterly Report, Jan.-Mar. 1983, pp. 11-12, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, National and Oceanic Atmospheric Administration, Seattle, Washington.

Anonymous. 1983b. The Environmental Impact of Aquaculture. Report no. 83:5, Swedish Council for Planning and Coordination of Research (FRN). 74 pp.

Anonymous. 1984. Review of Salmon Aquaculture. Prepared by the Senate Advisory Council, Alaska State Legislature.

Aoki, T., Y. Jo and S. Egusa. 1980. Frequent occurrence of drug resistant bacteria in Ayu (Plecoglossus altivelis) culture. Fish Path. 15(1):1-6.

APHA. 1981. Standard Methods for the Examination of Water and Wastewater. Fifteenth edition, 1980. American Public Health Association, Washington, D.C.

Arakawa, K.Y. 1973. Yoshoku kaki seisan no suii narabi ni kaisan seibutsu gunshu no seni kara mita [Aspects of eutrophication in Hiroshima Bay viewed from transition of cultured oyster production and succession of marine biotic communities]. Nihon Kaiyo Gakkai-Shi 11(2):43-48. (Translated by the Multilingual Services Division, Dept. of the Secretary of State of Canada).

Arakawa, K.Y., Y. Kusuki and M. Kamigaki. 1971. Kaki yoshokujo ni okeru seibutsu gentaiseki gensho no kenkyu (I) yoshoku tekisei mitsudo ni tsuite [Studies on biodeposition in oyster beds (I) economic density for oyster culture]. Venus 30(3):113-128.

Ariathurai, R., R.C. MacArthur and R.B. Krone. 1977. Mathematical model of estuarial sediment transport. Technical Report D-77-12. Waterways Experiment Station, Vicksburg, Mississippi.

Arizono, M. 1979. Disease control in mariculture, with special reference to yellowtail culture. *In* G. Yamamoto (ed.), Proc. Seventh Japan-Soviet Joint Symposium on Aquaculture, September 1978, Tokyo and Tsuruga, Japan., Tokai University. pp. 79-88.

Aulstad, D., T. Gjerdrem and H. Skjerold. 1972. Genetic and environmental sources of variation in length and weight of rainbow trout (*Salmo gairdneri*). J. Fish. Res. Bd. Canada 29:237-241.

Austin, B. 1985. Antibiotic pollution from fish farms: effects on aquatic microflora. Microbiol. Sci. 2(4):113-117.

Ayres, P.A. and G.I. Barrow. 1978. The distribution of *Vibrio parahaemolyticus* in British coastal waters: report of a collaborative study 1975-6. J. Hyg. Camb. 80:281-294.

Barbay, J.R., H.B. Bradford, Jr. and N.C. Roberts. 1984. The occurrence of halophilic vibrios in Louisiana coastal waters. *In* R.R. Colwell (ed.), Vibrios in the Environment. pp. 511-520. John Wiley and Sons, New York.

Baross, J.A. 1973. Some influences of temperature, bacteriophage, and other ecological parameters on the distribution and taxonomy of marine vibrios. Ph.D. thesis, University of Washington, Seattle. 451 pp.

Baross, J.A. and J. Liston. 1970. Occurrence of *Vibrio parahaemolyticus* and related hemolytic vibrios in the marine environments of Washington state. Appl. Microbiol. 20(2):179-186.

Baumann, P., L. Baumann, S.S. Bang and M.J. Woolkalis. 1980. Reevaluation of the taxononmy of *Vibrio*, *Beneckea* and *Photobacterium*: abolition of the genus *Beneckea*. Curr. Microbiol. 4:127-132.

Bayne, B.L. and C. Scullard. 1977. Rates of nitrogen excretion by species of *Mytilus* (Bivalvia: Mollusca). J. mar. biol. Ass. U.K. 57:355-369.

Bayne, B.L. and J. Widdows. 1978. The physiological ecology of two populations of *Mytilus edulis* L. Oecologia (Berlin) 37:137-162.

Bayne, B.L., J. Widdows and R.J. Thompson. 1976. Physiology II. *In* B.L. Bayne (ed.), Marine Mussels: Their Ecology and Physiology. pp. 207-260. Cambridge Univ. Press, Cambridge.

Bergheim, A. and A.R. Selmer-Olsen. 1978. River pollution from a large trout farm in Norway. Aquaculture 14:267-270.

Bergheim, A., A. Sivertsen and A.R. Selmer-Olsen. 1982. Estimated pollution loadings from Norwegian fish farms. I. Investigations 1978-1979. Aquaculture 28:347-361.

Beveridge, M. 1984. Cage and pen fish farming. FAO Fisheries Technical Paper 255. 131 pp.

Beveridge, M. and J.F. Muir. 1982. An evaluation of proposed cage fish culture on Loch Lomond, an important reservoir in central Scotland. Canadian Wat. Res. J. 7(2):181-196.

Bigham, G.N. 1986. Chapter 23: Oceanic disposal of wastes from manganese nodule processing. In M.A. Champ and P.K. Park (eds.), Oceanic Processes in Marine Pollution. Vol. 3: Marine Waste Management: Science and Policy. R.E. Kreiger Publ. Co., Malabar, Florida. (in press).

Blake, P.A., R.E. Weaver and D.G. Hollis. 1980. Diseases of humans (other than cholera) caused by vibrios. Ann. Rev. Microbiol. 34:341-367.

Bowden, G. 1979. Law, politics and biology: aquaculture in the primordial ooze. In R. Mann (ed.), Exotic Species in Mariculture. pp. 306-330. MIT Press, Cambridge, Massachusetts.

Braaten, B., J. Aure, A. Ervik and E. Boge. 1983. Pollution problems in Norwegian fish farming. International Council for the Exploration of the Sea C.M. 1983/F:26. 11 pp.

Brandsma, M.G. 1984. Simulation of drilling mud and cutting discharges in Gainesville area block 707 and Apalachicola area block 1003. Prepared for Continental Shelf Associates, Tequesta, Florida under contract to Sohio Petroleum, Inc. 23 pp.

Brandsma, M.G. and D.J. Divoky. 1976. Development of models for prediction of short-term fate of dredged material discharged in the estuarine environment. Prepared by Tetra Tech, Inc., Pasadena, California for the U.S. Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.

Brandsma, M.G., T.C. Sauer and R.C. Ayers. 1983. Mud discharge model. Report and user's guide model version 1.0. A model for predicting the fate of drilling fluid discharges in the marine environment. Exxon Production Research Company, Houston, Texas.

Bullock, G.L., H.M. Stuckey, D. Collis, R.L. Herman and G. Maestrone. 1974. *In vitro* and *in vivo* efficacy of a potentiated sulfonamide in control of furunculosis in salmonids. J. Fish. Res. Bd. Canada 31:75-82.

Butman, C.A. in press. Sediment trap biases in turbulent flows: results from a laboratory flume study. J. Mar. Res.

Butman, C.A., W.D. Grant and K.D. Stolzenbach. in press. Predictions of sediment trap biases in turbulent flows: a theoretical analysis based on observations from the literature. J. Mar. Res.

Butz, I. and B. Vens-Cappell. 1982. Organic load from the metabolite products of rainbow trout fed with dry food. In J.S. Alabaster (ed.), Report of the EIFAC Workshop on Fish-farm Effluents. Silkeborg, Denmark, 26-28 May 1981. pp. 73-82. EIFAC Tech. Pap. 41.

Campbell, S.A., W.K. Peterson and J.R. Postel. 1977. Phytoplankton production and standing stock in the Main Basin of Puget Sound. Prepared by the Universtiy of Washington, Dept. of Oceanography for the Municicpality of Metropolitan Seattle, Seattle, Washington.

Campos, M.J. and J. Mariño. 1982. Comparison of phytoplankton species composition and abundance in the Rias Arosa and Muros (NW Spain). Mar. Ecol. 3(1):1-12.

Campton, D.E. and J.M. Johnston. 1985. Electrophoretic evidence for a genetic admixture of native and nonnative rainbow trout in the Yakima River, Washington. Trans. Am. Fish. Soc. 114:782-793.

Carlton, J.T. 1981. Caveat indigenae: The unintentional introduction of exotic species with target species in mariculture operations, and the potential ecological impact on the adjacent environment. International Council for the Exploration of the Sea C.M. 1981/F:17. 5 pp.

Carlucci, A.F. and D. Pramer. 1960. An evaluation of factors affecting the survival of Escherichia coli in sea water. Appl. Microbiol. 8(4):251-254.

Chen, C.W. and G.T. Orlob. 1972. The accumulation and significance of sludge near San Diego outfall. J. Wat. Pollut. Control Fed. 44:1362-1371.

Chevassus, B. 1983. Hybridization in fish. Aquaculture 33:245-262.

Chew, K.K. 1984. Recent advances in the cultivation of molluscs in the Pacific United States and Canada. Aquaculture 39:69-81.

Chilcote, M.W., S.A. Leider and J.J. Loch. 1985. Hatchery summer-run steelhead natural reproductive success in the Kalama River. Washington Dept. of Game, Report No. 85-24, Olympia, Washington.

Christie, N.D. and A. Moldan. 1977. Effect of fish factory effluent on the benthic macrofauna of Saldanha Bay. Mar. Poll. Bull. 8:41-45.

Clark, E.R., J.P. Harman and J.R.M. Forster. 1985. Production of metabolic and waste products by intensively farmed rainbow trout, Salmo gairdneri Richardson. J. Fish. Biol. 27:381-393.

Collias, E.E. and J.H. Lincoln. 1977. A Study of the Nutrients in the Main Basin of Puget Sound. Prepared by the University of Washington, Department of Oceanography for the Municipality of Metropolitan Seattle, Seattle, Washington.

Collias, E.E., N. McGary and C.A. Barnes. 1974. Atlas of Physical and Chemical Properties of Puget Sound and its Approaches. Washington Sea Grant, Univ. of Washington Press, Seattle. 235 pp.

Collins, I. 1983. A study on the environmental impact of particulate matter, derived from a salmonid cage culture system on L. Fad, Isle of Bute, Scotland. B.Sc. Thesis, University of Stirling. (not seen - cited in Gowen, 1985).

Colwell, R.R. and D.J. Grimes. 1984. *Vibrio* diseases of marine fish populations. Helgolander Meeresunters. 37:265-287.

Colwell, R.R. and J. Liston. 1960. Microbiology of shellfish -- Bacteriological study of the natural flora of Pacific oysters (*Crassostrea gigas*). Appl. Microbiol. 8:104-109.

Colwell, R.R., P.A. West, D. Maneval, E.F. Remmers, E.L. Elliot, and N.E. Carlson. 1984. Ecology of pathogenic vibrios in Chesapeake Bay. *In* R.R. Colwell (ed.), Vibrios in the Environment. pp. 367-387. John Wiley and Sons, New York.

Corliss, J.P. 1979. Accumulation and depletion of oxytetracycline in juvenile white shrimp (*Penaeus setiferus*). Aquaculture 16:1-6.

Cornelson, D.A., I. Sechter, E. Balteanu and V. Avram. 1958. Specific bacteriological pollution of streams by waste waters from penicillin plants. Arch. roum. Path. exp. 17:271-278.

Courtenay, W.R., Jr. and C.R. Robins. 1973. Exotic aquatic organisms in Florida with emphasis on fishes: a review and recommendations. Trans. Am. Fish. Soc. 102(1):1-12.

Cronin, L.E. 1967. The role of man in estuarine processes. *In* G. Lauff (ed.), Estuaries. pp. 667-689. Amer. Assoc. Adv. Sci., Washington, D.C.

Dahlbäck, B. and L.A.H. Gunnarson. 1981. Sedimentation and sulfate reduction under a mussel culture. Mar. Biol. 63:269-275.

De Groot, S.J. 1985. Introductions of non-indigenous fish species for release and culture in the Netherlands. Aquaculture 46:237-257.

DMR. 1985. Maine Marine Resouces Laws. Prepared by the Maine Department of Marine Resources, Augusta, Maine.

Doyle, J., M. Parker, T. Dunne, D. Baird and J. McArdle. 1984. The impact of blooms on mariculture in Ireland. International Council for the Exploration of the Sea, Special Meeting on the Causes Dynamics and Effects of Exceptional Marine Blooms and Related Events, Copenhagen, 4-5 October 1984.

Eckman, J.E. and A.R.M. Nowell. 1984. Boundary skin friction and sediment transport about an animal-tube mimic. Sedimentology 31:851-862.

Edwards, D.J. 1978. Salmon and Trout Farming in Norway. Fishing News Books Limited, Farnham.

Egidius, E. 1984. Diseases of salmonids in aquaculture. Helgoländer Meeresunters. 37:547-569.

Eley, R.L., J.H. Carroll and D. DeWoody. 1972. Effects of caged catfish culture on water quality and community metabolism of a lake. Proc. Okla. Acad. Sci. 52:10-15.

Ellis, M.M., B.A. Westfall and M.D. Ellis. 1948. Determination of water quality. U.S. Fish and Wildlife Service, Res. Rept. 9. 122 pp.

Enell, M. and J. Löf. 1983a. Miljökonsekvenser av akvakultur. Sedimentation från fiskkasseodlingar. Report for the National Swedish Environment Protection Board. 46 pp. (not seen - cited in Anonymous, 1983b)

Enell, M. and J. Löf. 1983b. Miljöeffekter av vattenbruk - sedimentation och narsaltbelastning från fiskkasseodlingar [Environmental impact of aquaculture - sedimentation and nutrient loading from fish cage culture farming]. Vatten 39:364-375.

Enell, M., J. Löf and T.-L. Bjorklund. 1984. Fiskkasseodling med Rening, Teknisk Beskrivning och Reningseffekt. Institute of Limnology, Lund. (not seen - cited in Ackefors and Sodergren, 1985)

Environment Canada. 1979. Water quality sourcebook, a guide to water quality parameters. Inland Waters Directorate, Water Quality Branch, Ottawa, Canada.

Ervik, A., P. Johannessen and J. Aure. 1985. Environmental effects of marine Norwegian fish farms. International Council for the Exploration of the Sea C.M. 1985/F:37. 13 pp.

Fenchel, T.M. and R.J. Reidl. 1970. The sulfide system: a new biotic community underneath the oxidized layer of marine sand bottoms. Mar. Biol. 7:255-268.

Forfar, J.O., A.J. Keay, A.F. Maccabe, J.C. Gould and A.D. Bain. 1966. Liberal use of antibiotics and its effect in neonatal staphylococcal infection, with particular reference to erythromycin. Lancet ii:295-300.

Fribourgh, J.H., F.P. Meyer and J.A. Robinson. 1969. Oxytetracycline leaching from medicated fish feeds. U.S. Bur. Sport Fish. Wildlife, Tech. Pap. 40. 7 pp.

Friebertshauser, M., K. Krogslund, V. Wong, J. McCulloch and P. Stoops. 1971. Puget Sound and Approaches Seasonal Variations of Oceanographic Parameters in Near-surface Waters. Washington Sea Grant, Univ. of Washington, Seattle. 235 pp.

Gooding, R.M. and J.J. Magnuson. 1967. Ecological significance of a drifting object to pelagic fishes. Pac. Sci. 21:486-497.

Gowen, R.J., N.B. Bradbury and J.R. Brown. 1985. The ecological impact of salmon farming in Scottish coastal waters: a preliminary appraisal. International Council for the Exploration of the Sea C.M. 1985/F:35. 13 pp.

Greenberg, E.P., H.B. Kaplan, M. DuBoise and B. Palhof. 1984. In R.R. Colwell (ed.), Vibrios in the Environment. pp. 479-493. John Wiley and Sons, New York.

Grimes, D.J., S.H. Gruber and E.B. May. 1984. Experimental infection of lemon sharks, Negaprion brevirostris (Poey), with Vibrio species. J. Fish. Dis. 8(2):173-180.

Hada, H.S. and R.K. Sizemore. 1981. Incidence of plasmids in marine Vibrio spp. isolated from an oil field in the Northwestern Gulf of Mexico. Appl. Environ. Microbiol. 41:199-202.

Hagino, S. 1977. [Physical properties of the pollutants]. In Japanese Society of Scientific Fisheries (ed.), Senkai Yoshoku to Jika Osen [Shallow-Sea Aquaculture and Self-Pollution], Suisan-gaku Shirizu 21 [Fisheries Series 21]. pp. 31-41. Koseisha Koseikaku, Tokyo. (In Japanese - translated by Madelon and Louis Mottet).

Hagstrom, A. and A-M. Larsson. 1982. Pelagiska bakterier och musselodling [Pelagic bacteria and mussel culture]. Meddelande Havsfiskelaboratoriet Lysekil, No. 286. 21 pp. (In Swedish - partial translation by Daniel Olsen)

Harrell, L.W. and T.M. Scott. 1985. Kudoa thyrsitis (Gilchrist) (Myxosporea: Multivalvulida) in Atlantic salmon Salmo salar L. J. Fish. Dis. 8(3):329-332.

Hata, Y. and H. Katayama. 1977. [Chemical processes of the pollutants]. In Japanese Society of Scientific Fisheries (ed.), Senkai Yoshoku to Jika Osen [Shallow-Sea Aquaculture and Self-Pollution], Suisan-gaku Shirizu 21 [Fisheries Series 21]. pp. 52-66. Koseisha Koseikaku, Tokyo. (In Japanese - translated by Madelon and Louis Mottet)

Hays, T. 1980. Impact of net pen culture on water quality and fish populations on Bull Shoals Reservoir. Completion Rep. Arkansas Game Fish. Comm. 10 pp. (not seen - cited in Beveridge, 1984)

Herman, R.L. 1969. Oxytetracycline in fish culture -- a review. U.S. Bur. Sport Fish. Wildlife, Tech Pap. 31. 9 pp.

Herman, R.L., D. Collins and G.L. Bullock. 1969. Oxytetracycline residues in different tissues of trout. U.S. Bur. Sport Fish. Wildlife, Tech. Pap. 37. 6 pp.

Hershberger, W.K., J.A. Perdue and J.H. Beattie. 1984. Genetic selection and systematic breeding in Pacific oyster culture. Aquaculture 39:237-245.

Hinshaw, R.N. 1973. Pollution as a result of fish cultural activities. EPA-R3-73-009. U.S. Environmental Protection Agency, Washington, D.C.

Hisaoka, M., K. Nogami, O. Takeuchi, M. Suzuki and H. Sugimoto. 1966. Studies on sea water exchange in fish farm. II. Exchange of sea water in floating net. Bull. Naikai Reg. Fish. Res. Lab., Contr. No. 115, pp. 21-43.

Hoffman, G.L. 1970. Intercontinental and transcontinental dissemination and transfaunation of fish parasites with emphasis on whirling disease (Myxosoma cerebralis). In S.F. Snieszko (ed.), A Symposium on Diseases of Fishes and Shellfishes. pp. 69-81. American Fish. Soc., Spec. Publ. No. 5.

Hurlburt, E.F. 1984. Aquaculture in Puget Sound - Its potential and its possible environmental impact. State of Washington, Department of Fisheries, Olympia, Washington.

ICES. 1982. Proposed guidelines for implementing the ICES Code of Practice concerning introductions and transfers of marine species. International Council for the Exploration of the Sea. CM 1982/F:33.

Iigura, T. 1974. [Sinking speed of feces and uneaten food in hamachi culture]. Suisan zoshoku 22:34-39.

Imai, T. 1971. Aquaculture in Shallow Seas: Progress in Shallow Sea Culture. Koseisha Koseiku, Tokyo. Translated by the National Marine Fisheries Service and republished in 1977 by Amerind Publishing Co. Pvt. Ltd., New Dehli.

Incze, L.S. and R.A. Lutz. 1980. Mussel culture: an east coast perspective. In R.A. Lutz (ed.), Mussel Culture and Harvest: A North American Perspective. pp. 99-140. Developments in Aquaculture and Fisheries Science, 7. Elsevier Scientific Publ. Co., Amsterdam.

Inoue, H. 1972. On water exchange in a net cage stocked with the fish, hamachi. Bull. Japanese Soc. Sc. Fish. 38(2):167-176. (In Japanese - translated by Madelon and Louis Mottet)

Inoue, H., Y. Tanaka and K. Fukuda. 1970. On water exchange in a shallow marine fish farm - II. Hamachi fish farm at Tanoura. Bull. Jap. Soc. Sci. Fish. 36(8):776-782.

Inoue, H., Y. Tanaka and M. Saito. 1966. On the water exchange in the shallow marine fish farm - I. Hitsuishi fish farm of hamachi. Bull. Jap. Soc. Sci. Fish. 32(5):384-392.

Ito, S. and T. Imai. 1955. Ecology of oyster bed. I. On the decline of productivity due to repeated cultures. Tohoku J. Agric. Res. V(4):251-268.

Iwasaki, H. 1976. [Red tides - Questions concerning their outbreaks]. Ocean Publications Co., Ltd., Tokyo. (not seen - cited in Takagi, et al., 1980).

James, W. unpub. Internal memorandum dated November 8, 1985 from Bill James to Eric Hurlburt, Washington Department of Fisheries.

Jarrams, P., A. Starkie, K. Easton and R.G. Templeton. 1980. Salmonid rearing in floating net cages in freshwater reservoirs owned by the Severn Trent Water Authority. Fish. Mgmt. 3:101-117.

Johnstone, A.K. 1984. Pathogenesis and life cycle of the myxozoan Parvicapsula sp. infecting marine cultured coho salmon. Ph.D. thesis. University of Washington, Seattle.

Jorgensen, S.E. 1979. State-of-the-art in Ecological Modelling. Pergamon Press, Oxford. 891 pp.

Joseph, S.W., R.R. Colwell and J.B. Kaper. 1982. Vibrio parahaemolyticus and related halophilic vibrios. CRC Crit. Rev. Microbiol. 10(1):77-124.

Kadowaki, S. and H. Hirata. 1984. Oxygen distribution in the coastal fish farm. I. Effects of feeding on the distribution patterns. Suisan zoshoku 32(3):142-147. (In Japanese - translated by Madelon and Louis Mottet)

Kadowaki, S., T. Kasedo and T. Nakazono. 1978a. Continous records of DO contents by cruising in the coastal culture farm. I. Relation between DO content and fish density in cages. Mem. Fac. Fish., Kagoshima Univ. 27(1):273-280.

Kadowaki, S., T. Kasedo, T. Nakazono and H. Hirata. 1978b. Continuous records of DO contents by cruising in the coastal culture farms. II. Diffusion of suspended particles by feeding. Mem. Fac. Fish., Kagoshima Univ. 27(1):281-288.

Kadowaki, S., T. Kasedo, T. Nakazono, Y. Yamashita and H. Hirata. 1980. The relation between sediment flux and fish feeding in coastal culture farms. Mem. Fac. Fish., Kagoshima Univ. 29:217-224.

Kaneko, T. and R.R. Colwell. 1973. Ecology of Vibrio parahaemolyticus in Chesapeake Bay. J. Bacteriol. 113:24-32.

Kaspar, H.F., P.A. Gillespie, I.C. Boyer and A.L. MacKenzie. 1985. Effects of mussel aquaculture on the nitrogen cycle and benthic communities in Kenepuru Sound, Marlborough Sounds, New Zealand. Mar. Biol. 85:127-136.

Kautsky, N. and I. Wallentinus. 1980. Nutrient release from a Baltic Mytilus-red algal community and its role in benthic and pelagic productivity. Ophelia, Suppl. 1:17-30.

Kenaga, E.E. and C.A.I. Goring. 1980. Relationship between water solubility, soil sorption, octanol-water partitioning, and concentration of chemicals in biota. In J.G. Eaton, P.R. Parrish and A.C. Hendricks (ed.), Aquatic Toxicology. pp. 78-115. ASTM STP 707, American Society for Testing and Materials.

Kennedy, W.A. 1978. A handbook on rearing pan-size Pacific salmon using floating seapens. Fisheries and Marine Service Industry Report No. 107, Pacific Biological Station, Nanaimo, British Columbia. 111 pp.

Kilambi, R.V., et al. 1976. Effects of cage culture fish production upon the biotic and abiotic environment of Crystal Lake, Arkansas. Prepared by the Department of Zoology, University of Arkansas for the Arkansas Game and Fish Commission and U.S. Dept. of Commerce. 127 pp. (not seen - cited in Beveridge, 1984)

Kils, U. 1979. Oxygen-regime and artificial aeration of net-cages in mariculture. Meeresforsch. 27(4):236-243.

Kincaid, H.L. 1976a. Inbreeding in rainbow trout (Salmo gairdneri). J. Fish. Res. Bd. Canada 33:2420-2426.

Kincaid, H.L. 1976b. Inbreeding depression in rainbow trout. Trans. Am. Fish. Soc. 105:273-280.

Kitamori, R. 1977. [Changes in the species composition (principally benthic organisms)]. In Japanese Soc. Scientific Fisheries (ed.), Senkai Yoshoku to Jika Osen [Shallow-Sea Aquaculture and Self-Pollution], Suisan-gaku Shirizu 21 [Fisheries Series 21]. pp. 67-76. Koseisha Koseikaku, Tokyo. (In Japanese - translated by Madelon and Louis Mottet)

Koh, R.C.Y. 1971. Ocean sludge disposal by barges. Water Resources Res. 7(6):1647-1651.

Koh, R.C.Y. and Y.C. Chang. 1973. Mathematical model for barged ocean disposal of wastes. EPA 660-2-73-029. U.S. Environmental Protection Agency, Washington, D.C.

Korzeniewski K., J. Trojanowski and B. Mrozek. 1982a. Effect of intensive trout culture on contents of nutrients in water. Pol. Arch. Hydrobiol. 29(3-4):625-632.

Korzeniewski, K., Z. Banat and A. Moczulska. 1982b. Changes in water of the Uniesc and Skotawa Rivers, caused by intensive trout culture. Pol. Arch. Hydrobiol. 29(3-4):683-691.

Kramer, Chin and Mayo. undated. An environmental impact assessment for the NOAA/UW Regional Fisheries Laboratory. Prepared for the National Oceanic and Atmospheric Administration and University of Washington, Seattle, Washington.

Kuenzler, E.J. 1961. Phosphorus budget of a mussel population. Limnol. Oceanogr. 6:400-415.

Kusuki, Y. 1977a. Fundamental studies on the deterioration of oyster growing grounds - I. Production of faecal materials by the Japanese oyster. Bull. Japanese Soc. Sci. Fish. 43(2):163-166.

Kusuki, Y. 1977b. Fundamental studies on the deterioration of oyster growing grounds - II. Organic content of faecal materials. Bull. Japanese Soc. Sci. Fish. 43(2):167-171.

Kyte, M.A. unpub. Report on a geoduck survey performed for the Scan Am fish farm off Crane Point, Indian Island, Washington.

Lappalainen, A. and P. Kangas. 1975. Littoral benthos of the Northern Baltic Sea II. Interrelationships of wet, dry and ash-free dry weights of macrofauna in the Tvärminne area. Int Revue ges. Hydrobiol. 60(3):297-312.

Larsen, J.L., N.J. Jensen and N.D. Christensen. 1978. Water pollution and the ulcer syndrome in the cod _Gadus_ _morhua_. Vet. Sci. Commun. 2:207-216.

Larsson, A-M. 1985. Blue mussel sea farming - effects on water quality. Vatten 41:218-224.

Lavelle, J.W., E. Ozturgut, S.A. Swift and B.H. Erickson. 1981. Dispersal and resedimentation of the benthic plume from deep-sea mining operations: a model with calibration. Mar. Min. 3(1-2):59-93.

Leavens, K. 1983. An overview of netpen rearing as an enhancement technique. Prepared for the Department of Fisheries and Oceans, Vancouver, British Columbia.

Liao, P.B. and R.D. Mayo. 1972. Salmonid hatchery water reuse systems. Aquaculture 1:317-335.

Liao, P.B. and R.D. Mayo. 1974. Intensified fish culture combining water reconditioning with pollution abatement. Aquaculture 3:61-85.

Lieffrig, D.V.M. 1985. The effects of hydrogen sulfide (H_2S) on aquaculture production. MSc thesis, University of Stirling. (not seen - cited in Phillips, et al., 1985)

Lindbergh, J.M. 1972. Pacific salmon aquaculture program - incubation and cultivation phases. Univ. of Washington Sea Grant Final Report, Prepared by Ocean Systems, Inc., Domsea Farms, Inc., Reston, Virginia. 52 pp.

Lindbergh, J.M. unpub. Potential interaction between net pen farmed Atlantic salmon and native salmonid species in the Pacific Northwest. Prepared for Sea Farm of Norway, Inc., Greenwich, Connecticut.

Loo, L-O. and R. Rosenberg. 1983. Mytilus edulis culture: growth and production in western Sweden. Aquaculture 35:137-150.

López-Jamar, E. 1985. Distribución espacial del poliqueto Spiochaetopterus costarum en las Rias Bajas de Galacia y su posible utilización como indicador de contaminación orgánica en el sedimento. Bol. Inst. Esp. Oceanogr. 2(1):68-76.

López-Jamar, E., J. Iglesias and J.J. Otero. 1984. Contribution of infauna and mussel-raft epifauna to demersal fish diets. Mar. Ecol. Prog. Ser. 15:13-18.

Loyacano, H.A., Jr. and D.C. Smith. 1976. Attraction of native fish to catfish culture cages in reservoirs. Proc. Ann. Conf. Southeast. Assoc. Game Fish. Comm. 29:63-73.

Mackay, D.W., W. Halcrow and I. Thornton. 1972. Sludge dumping in the Firth of Clyde. Mar. Poll. Bull. 3:7-10.

Mahnken, C.V.M. 1975. Status of commercial net-pen farming of Pacific salmon in Puget Sound. In Proceedings of the Sixth Annual Meeting World Mariculture Society, Seattle, Washington, January 27-31, 1975. pp. 285-298. Louisiana State Univ., Baton Rouge, Louisiana.

Mahnken, C.V.W., D.M. Damkaer and J. Vidal. unpub. Impact of intensive marine net-pen culture on water quality and benthic community structure. Unpublished research proposal, August 1982.

Mantle, G.J. 1982. Biological and chemical changes associated with the discharge of fish-farm effluent. In J.S. Alabaster (ed.), Report of the EIFAC Workshop on Fish-farm Effluents, Silkeborg, Denmark, 26-28 May 1981. pp. 103-112. Food and Agricultural Organization of the United Nations, EIFAC Tech. Pap. No. 41.

Mason, J. 1976. Cultivation. In B.L. Bayne (ed.), Marine Mussels: Their Ecology and Physiology. pp. 385-410. Cambridge Univ. Press, Cambridge.

Mattsson, J. and O. Linden. 1983. Benthic macrofauna succession under mussels, Mytilus edulis L. (Bivalvia), cultured on hanging long lines. Sarsia 68:97-102.

Merican, Z.O. and M.J. Phillips. 1985. Solid waste production from rainbow trout, Salmo gairdneri Richardson, cage culture. Aqua. Fish. Mgmt. 1:55-69.

Meyers, T.R. 1984. Marine bivalve mollusks as reservoirs of viral pathogens: significance to marine and anadromous finfish aquaculture. Mar. Fish. Rev. 46(3):14-17.

Midtlyng, P.V. 1985. Bruk av medikamenter og desinfeksjonsmidler i norske fiskoppdrettsanlegg. [Use of drugs and disinfectants in Norwegian fish farms]. Vann 3:177-180.

Mills, S. 1982. Britain's native trout is floundering. New Scientist 25:498-501.

Milne, P.H. 1970. Fish farming: a guide to the design and construction of net enclosures. Dept. Agric. and Fish. for Scotland, Marine Research, No. 1.

Milner-Rensel Assoc. 1986. Aquatic conditions at the Seafarm of Norway net-pen site in Port Angeles harbor in April, 1986. Prepared for Sea Farm of Norway, Port Angeles, Washington.

Minchew, C.D. and J.D. Yarbrough. 1977. The occurrence of fin rot in mullet (Mugil cephalus) associated with crude oil contamination of an estuarine pond ecosystem. J. Fish. Biol. 10:319-323.

Morrison, J.A. unpub. Memorandum dated July 16, 1985 from J.A. Morrison to other staff of the Canada Department of Fisheries and Oceans.

Muir, J.F. 1985. The role of aquaculture in the industrial regions of the temperate zone. GeoJournal 10(3):277-298.

Munro, A.L.S. and I.F. Waddell. 1984. Furunculosis: experience of its control in the sea water cage culture of Atlantic salmon in Scotland. International Council for the Exploration of the Sea C.M. 1984/F:32. 9 pp.

Murakami, A. 1973. [Eutrophication of the hydrosphere and the increase of fisheries culture]. In [Water Pollution and Eutrophication]. pp. 37-48. Japanese Fisheries Society, Koseisha Kosei Kakuhan. (not seen - cited in Arakawa, 1973)

Musselman, M.M. 1956. Terramycin (Oxytetracycline). Medical Encyclopedia, Inc., New York. 144 pp.

Newkirk, G.F. 1979. Genetic aspects of the introduction and culture of nonindigenous species for aquaculture. In R. Mann (ed.), Exotic Species in Mariculture. pp. 192-211. MIT Press, Cambridge, Massachusetts.

Newkirk, G.F. 1980. Review of the genetics and the potential for selective breeding of commercially important bivalves. Aquaculture 19:209-228.

Nishimura, A. 1982. Effects of organic matters produced in fish farms on the growth of redtide algae Gymnodinium type-'65 and Chattonella antiqua. Bull. Plankton Soc. Japan 29(1):1-7.

NOAA. 1985. The outlook for salmon and shrimp aquaculture products in world markets. Prepared for the NOAA Assistant Administrator for Fisheries by the Aquaculture Project Group, National Oceanic and Atmospheric Administration. 109 pp.

Nose, T. 1985. Recent advances in aquaculture in Japan. GeoJournal 10(3):261-276.

NOU. 1985. Akvakultur i Norge. Norges Offentlige Utredninger 1985: 22. 153 pp. (In Norwegian - partial translation by Leslie Grove).

Nowell, A.R.M. and P.A. Jumars. 1984. Flow environments of aquatic benthos. Ann. Rev. Ecol. Syst. 15:303-328.

Nyegaard, L. 1973. Coho salmon farming in Puget Sound. Washington State University, Cooperative Extension Service, College of Agriculture. Extension Bull. 647. 14 pp.

O'Connor, D.J. 1981. Modeling of eutrophication in estuaries. In B.J. Neilson and L.E. Cronin (eds.), Estuaries and Nutrients. pp. 183-223. Humana Press, Clifton, New Jersey.

Odum, W.E. 1974. Potential effects of aquaculture on inshore coastal waters. Envir. Cons. 1(3):225-230.

Oviatt, C.A., A.L. Gall and S.W. Nixon. 1972. Environmental effects of Atlantic menhaden on surrounding waters. Ches. Sci. 13(4):321-322.

Pamatmat, M.M., R.S. Jones, H. Sanborn and A. Bhagwat. 1973. Oxidation of organic matter in sediments. EPA-660/3-73-005. U.S. Environmental Protection Agency, Washington, D.C.

Parsons, T.R., M. Takahashi and B. Hargrave. 1977. Biological Oceanographic Processes. Second edition. Pergamon Press, New York. 332 pp.

Pearson, T.H. 1976. A comparative study of the effects on the marine environment of wastes from cellulose industries in Scotland and Sweden. Ambio 5:77-79.

Pearson, T.H. and R. Rosenberg. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr. Mar. Biol. Ann. Rev. 16:229-311.

Pearson, T.H. and S.O. Stanley. 1979. Comparative measurement of the redox potential of marine sediments as a rapid means of assessing the effect of organic pollution. Mar. Biol. 53:371-379.

Pease, B.C. 1977. The effect of organic enrichment from a salmon mariculture facility on the water quality and benthic community of Henderson Inlet, Washington. Ph.D. Dissertation, Univ. of Washington, Seattle, Washington.

Pease, B. unpub. Memorandum dated May 7, 1984 from B. Pease to R. Westley, Washington Department of Fisheries.

Pease, B. and L. Goodwin. unpub. Memorandum dated February 27, 1986 to Dick Burge, Washington Department of Fisheries.

Pedersen, A. 1982. Miljøpåvirkning fra fiskeoppdrett [Environmental effects from fish farming]. Prosjektrapport FP 80802 (F.430) NIVA:153 pp. (In Norwegian - partial translation by A. Bohn)

Penczak, T., W. Galicka, M. Molinski, E. Kusto, and M. Zalewski. 1982. The enrichment of a mesotrophic lake by carbon, phosphorus and nitrogen from the cage aquaculture of rainbow trout, Salmo gairdneri. J. Appl. Ecol. 19:371-393.

Peou, S., M.F. Blech and P. Hartemann. 1981. Study of the frequency of antibiotic resistant microbial indicators in hospital and urban sewage. Envir. Tech. Letters 2(8):347-356.

Phillips, M.J., M.C.M. Beveridge, and J.F. Muir. 1985. Waste output and environmental effects of rainbow trout cage culture. International Council for the Exploration of the Sea C.M. 1985/F:21. 17 pp.

Purdom, C.E. 1983. Genetic engineering by the manipulation of chromosomes. Aquaculture 33:287-300.

Quayle, D.B. 1964. Distribution of introduced marine Mollusca in British Columbia waters. J. Fish. Res. Bd. Canada 21(5):1155-1181.

Querellou, J., A. Faure and C. Faure. 1982. Pollution loads from rainbow trout farms in Brittany, France. In J.S. Alabaster (ed.), Report of the EIFAC Workshop on Fish-farm Effluents. Silkeborg, Denmark, 26-28 May 1981. pp. 87-97. EIFAC Tech. Pap. 41. 166 pp.

Refstie, T. and T. Gjedrem. 1975. Hybrids between Salmonidae species. Hatchability and growth rate in the freshwater period. Aquaculture 6:333-342.

Reisenbichler, R.R. and J.D. McIntyre. 1977. Genetic differences in growth and survival of juvenile hatchery and wild steelhead trout, Salmo gairdneri. J. Fish. Res. Bd. Canada 34:123-128.

Rensel, J. unpub. Marine farms in Washington State - Existing farms: March 1986.

Roberts, R.J. 1978. Fish Pathology. Balliere and Tindall, London.

Robohm, R.A., C. Brown and R.A. Murchelano. 1979. Comparison of antibodies in marine fish from clean and polluted waters of the New York Bight: relative levels against 36 bacteria. Appl. environ. Microbiol. 38:248-257.

Romero, P., E. González-Gurriarán and E. Penas. 1982. Influence of mussel rafts on spatial and seasonal abundance of crabs in the Ria de Arousa, North-west Spain. Mar. Biol. 72:201-210.

Rosenberg, R. 1976. Benthic faunal dynamics during succession following pollution abatement in a Swedish estuary. Oikos 27:414-427.

Rosenberg, R. and L-O. Loo. 1983. Energy-flow in a Mytilus edulis culture in western Sweden. Aquaculture 35:151-161.

Rosenfield, A. and F.G. Kern. 1979. Molluscan imports and the potential for introduction of disease organisms. In R. Mann (ed.), Exotic Species in Mariculture. pp. 165-189. MIT Press, Cambridge, Massachusetts

Rosenthal, H. 1978. Bibliography on transplantation of aquatic organisms and its consequences on aquaculture and ecosystems. Spec. Publ. European Mariculture Soc. 3:1-146.

Rosenthal, H. 1980. Implications of transplantations to aquaculture and ecosystems. Mar. Fish. Rev. 42(5):1-14.

Rosenthal, H. 1985. Constraints and perspectives in aquaculture development. GeoJournal 10(3):305-324.

Runchal, A.K. 1978. Drilling fluid dispersion and biological effects study for the lower Cook Inlet C.O.S.T. well. Dames and Moore, Anchorage, Alaska. 309 pp.

Russel, C.S. (ed.). 1975. Ecological Modeling in a Resources Management Framework. John Hopkins Univ. Press, Baltimore, Maryland.

Ryman, N. 1970. A genetic analysis of recapture frequencies of released young of salmon (Salmo salar L.). Hereditas 65:159-160.

Ryman, N. and G. Stahl. 1980. Genetic changes in hatchery stocks of brown trout (Salmo trutta). Can J. Fish. Aquat. Sci. 37:82-87.

Ryther, J.H. 1969. The potential of the estuary for shellfish production. Proc. Nat. Shellfisheries Assoc. 59:18-22.

Sakamoto, I. 1977. [Discussion. Estimating the carrying capacity for culturing fish]. In Japanese Society of Scientific Fisheries (ed.), Senkai Yoshoku to Jika Osen [Shallow-Sea Aquaculture and Self-Pollution]. Suisan-gaku Shirizu 21 [Fisheries Series 21]. pp. 119-129. Koseisha Koseikaku, Tokyo. (In Japanese - translated by Madelon and Louis Mottet)

Sheng, Y.P. 1983. Mathematical modeling of three-dimensional coastal currents and sediment dispersion: model development and application. U.S. Army Corps of Engineers, Washington, D.C. Tech. Rep. CERC-83-2.

Sindermann, C.J. 1984. Disease in marine aquaculture. Helgoländer Meeresunters. 37:505-532.

Smith, E.J. 1985. Marine resources - information leaflet: regulations governing marine aquaculture. Prepared by the California Department of Fish and Game, Sacramento, California.

Solbé, J.F. de L.G. 1982. Fish-farm effluents; a United Kingdom Survey. In J.S. Alabaster (ed.), Report of the EIFAC Workshop on Fish-farm Effluents. Silkeborg, Denmark, 26-28 May 1981. pp. 29-55. EIFAC Tech. Pap. 41.

Solomons, I.A. 1978. Antibiotics in animal feeds - human and animal safety issues. J. Anim. Sci. 46(5):1360-1368.

Soule, D.F. and M. Oguri (eds.). 1976. Bioenhancement studies of the receiving waters in outer Los Angeles harbor. Marine Studies of San Pedro Bay, California, Part 12. Allan Hancock Foundation, Los Angeles.

Soule, D.F. and M. Oguri (eds.). 1979. Ecological changes in outer Los Angeles-Long Beach harbors following initiation of secondary waste treatment and cessation of fish cannery waste effluent. Marine Studies of San Pedro Bay, California, Part 16. Allan Hancock Foundation, Los Angeles.

Speece, R.E. 1973. Trout metabolism characteristics and the rational design of nitrification facilities for water reuse in hatcheries. Trans. Amer. Fish. Soc. 102(2):323-334.

Spira, W.M. 1984. Tactics for detecting pathogenic vibrios in the environment. In R.R. Colwell (ed.), Vibrios in the Environment. pp. 251-268. John Wiley and Sons, New York.

Stahl, G. 1983. Differences in the amount and distribution of genetic variation between natural populations and hatchery stocks of Atlantic salmon. Aquaculture 33:23-32.

Stanley, J.G. 1979. Monosex and sterile fish for transplantation and aquaculture. International Council for the Exploration of the Seas C.M. 1979/F:32.

Steidinger, K.A. and K. Haddad. 1981. Biologic and hydrographic aspects of red tides. Bioscience 31(11):814-819.

Stewart, K.I. 1984. A study on the environmental impact of fish cage culture on an enclosed sea loch. M.Sc. thesis, University of Stirling. (not seen - cited in Gowen, et al., 1985)

Stoddard, A., R. Wells and K. Devonald. 1985. Development and application of a deepwater ocean waste disposal model for dredged material: Yabucoa Harbor, Puerto Rico. Mar. Tech. Soc. J. 19(3):26-39.

STOWW. 1974. Salmon pen culture at Squaxin Island Indian Reservation. Prepared by the Small Tribes Organization of Western Washington, Federal Way, Washington for the Economic Development Administration, U.S. Office of Economic Opportunity and the Bureau of Indian Affairs. Washington, D.C. 68 pp.

Strickland, R.M. 1983. The Fertile Fjord. Washington Sea Grant Publication, Univ. of Washington Press, Seattle. 145 pp.

Sutterlin, A.M. and S.P. Merrill. 1978. Norwegian salmonid farming. Department of Fisheries and Environment, St. Andrews, New Brunswick. Fisheries and Marine Service, Tech. Rep. 779.

Tacket, C.O., F. Bremer and P.A. Blake. 1984. Clinical features and an epidemiological study of Vibrio vulnificus infections. J. Infec. Dis. 149(4):558-561.

Takagi, M., H. Kamada and A. Tazaki. 1980. A consideration on the occurrence of Protogonyaulax sp. at the scallop ground in Funka Bay. Bull. Fac. Fish. Hokkaido Univ. 31(2):215-221. (In Japanese - translated by Madelon and Louis Mottet)

Tenore, K.R., L.F. Boyer, R.M. Cal, J. Corral, C. Garcia-Fernandez, N. González, E. González-Gurriarán, R.B. Hanson, J. Iglesias, M. Krom, E. López-Jamar, J. McClain, M.M. Pamatmat, A. Perez, D.C. Rhoads, G. deSantiago, J. Tietjen, J. Westrich and H.L. Windom. 1982. Coastal upwelling in the Rias Bajas, NW Spain: contrasting the benthic regimes of the Rias de Arosa and de Muros. J. Mar. Res. 43:701-772.

Tenore, K.R. and N. González. 1975. Food chain patterns in the Ria de Arosa, Spain: an area of intense mussel aquaculture. Tenth European Symposium on Marine Biology, Ostend, Belgium, Sept. 17-23, 1975, Vol. 2:601-619.

Tett, P. 1981. Modelling phytoplankton production at shelf-sea fronts. Phil. Trans. R. Soc. London A 302:605-615.

Trojanowski, C.Trojanowska and H. Ratajczyk. 1982. Effect of intensive trout culture in Lake Letowo on its bottom sediments. Pol. Arch. Hydrobiol. 29(3-4):659-670.

Trussel, R.P. 1972. The percent un-ionized ammonia in aqueous ammonia solutions at different pH levels and temperatures. J. Fish. Res. Bd. Canada 29:1505-1507.

Tynan, T. unpub. Letter dated April 11, 1985 from T. Tynan, Squaxin Island Tribe to G. Cloud, Washington Department of Ecology.

U.S. EPA. 1976. Quality Criteria for Water. U.S. Environmental Protection Agency, Washington, D.C.

Van Houweling, C.D. and J.H. Gainer. 1978. Public health concerns relative to the use of subtherapeutic levels of antibiotics in animal feeds. J. Anim. Sci. 46(5):1413-1424.

Vesco, L.L. and R.M. Gillard. 1980. Recovery of benthic marine populations along the Pacific coast of the United States following natural and man-made disturbances including pertinent life history information. POCS Ref. Pap. No. 53-4. Bureau of Land Management, Los Angeles, California.

Villwock, W. 1984. Some remarks on genetic influences of mariculture practices, realized or potential ones, on the natural resources of populations. In Report of the Working Group on Genetics, 1984, St. Andrews, Canada, 13-15 June 1984. Appendix 1. International Council for the Exploration of the Sea C.M. 1984/F:4.

VKI. 1976. Vandkvalitetsinst. & Jydsk Teknologisk Inst.: Forskellige driftsparameters indflytelse på forureningen fra dambrug. [The influence of different operational parameters on the pollution from fish farms]. Rapport til Teknologiradet. Horsholm, Denmark. (not seen - cited in Ackefors and Södergren, 1985; Warrer-Hansen, 1982)

Wallace, J.C. 1980. Growth rates of different populations of the edible mussel, Mytilus edulis, in north Norway. Aquaculture 19:303-311.

Warrer-Hansen, I. 1982. Evaluation of matter discharged from trout farming in Denmark. In J.S. Alabaster (ed.), Report of the EIFAC Workshop on Fish-farm Effluents. Silkeborg, Denmark, 26-28 May 1981. pp. 57-63. EIFAC Tech. Pap. 41.

Washington Department of Ecology. 1973. Water quality standards, June 19, 1973. Washington State Department of Ecology, Olympia. 17 pp.

Welch, E.B., R.M. Emery, R.I. Matsuda and W.A. Dawson. 1972. The relation of periphytic and planktonic algal growth in an estuary to hydrographic factors. Limnol. Oceanogr. 17(5):731-737.

West, P.A. and R.R. Colwell. 1984. Identification and classification of Vibrionaceae -- an overview. In R.R. Collwell (ed.), Vibrios in the Environment. pp. 285-363. John Wiley and Sons, New York.

Wilkins, N.P. 1976. Genic variability in marine Bivalvia; implications and applications in molluscan mariculture. In G. Persoone and E. Jaspers (eds.), Tenth European Symposium on Marine Biology, Ostend, Belgium, Sept 17-23. Vol. 1:549-563. Universal Press, Welteren.

Willoughby, H., H.N. Larsen and J.T. Bowen. 1972. The pollutional effects of fish hatcheries. Amer. Fish. U.S. Trout News 17(3):6-7, 20-21.

Wooten, R. 1979. Tapeworm threat to trout in floating freshwater cages. Fish Farmer 2(3):5.

Winter, D.F., K. Banse and G.C. Anderson. 1975. The dynamics of phytoplankton blooms in Puget Sound, a fjord in the northwestern United States. Mar. Biol. 29:139-176.

Yake, B. unpub. Internal memorandum dated December 27, 1981 from B. Yake to D. Cunningham, Washington Department of Ecology.

Zook, W.J., J. Rensel, J.M. Gearheard, J.C. Grover, B. Hopley, S. Rainey, L. Rutter, T. Scribner, H. Senn and M. Stratton. unpub. Recommendations for proposal and evaluation of salmonid production facilities. May 20, 1984.