

NOAA Technical Memorandum NMFS-NWFSC-49

The Net-pen Salmon Farming Industry in the Pacific Northwest

September 2001

**U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service**

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This document should be cited as follows:

Nash, C.E. (editor). 2001. The net-pen salmon farming Industry in the Pacific Northwest. U.S. Dept. Commer., NOAA Tech. Memo. NMFS-NWFSC-49, 125 p.

The Net-pen Salmon Farming Industry in the Pacific Northwest

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Acknowledgements

Thirty-five copies of this document in draft were circulated globally in April and May, 2001 for review and comment. The authors acknowledge the added contributions of the following individuals:

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Acronyms of Organizations and Common Terms

ACE	US Army Corps of Engineers
ADF&G	Alaska Department of Fish and Game
ALL	Aquatic Lands Lease
APHA	American Public Health Association
BC	British Columbia (Canada)
BCSAR	British Columbia Salmon Aquaculture Review
BCSGA	British Columbia Salmon Growers Association (Canada)
BMP	Best Management Practice
CFOI	Census of Fatal Occupational Injuries
CFR	Code of Federal Regulations (Food and Drug Administration)
COP	Code of Practice
DOC	United States Department of Commerce
DOI	United States Department of the Interior
DFO	Department of Fisheries and Oceans (Canada)
EAO	Environmental Assessment Office (Canada BC)
EEZ	Extended Economic Zone
EPA	United States Environmental Protection Agency
ESA	Endangered Species Act 1974
ESU	Evolutionarily Significant Unit
EU	European Union
FAO	Food and Agriculture Organization (United Nations)
FDA	United States Food and Drug Administration
FPC	Fish Passage Control (Oregon)
HACCP	Hazard Analysis Critical Control Point
HGMP	Hatchery and Genetic Management Plan
HIE	Highlands and Islands Enterprises (Scotland)
HPA	Hydraulic Project Approval
GDP	Gross Domestic Product
GDU	Genetic Diversity Unit
GESAMP	Joint Group of Experts on Scientific Aspects of Marine Environmental Protection (United Nations)
GLP	Good Laboratory Practice
GM	Genetically Modified
GMO	Genetically Modified Organism
ICOR	Interagency Committee for Outdoor Recreation (Washington State)
INAD	Investigational New Animal Drug
JSA	Joint Sub-Committee on Aquaculture
MLLW	Mean Low Low Water
NADP	National Aquaculture Development Plan
NBSGA	New Brunswick Salmon Growers Association (Canada)
NMFS	National Marine Fisheries Service (NOAA)
NOAA	National Oceanographic and Atmospheric Administration
NPAFC	North Pacific Anadromous Fish Commission

NPDES	National Pollution Discharge Elimination System Permit
NRC	Natural Resources Consultants
NSGCP	National Sea Grant College Program (NOAA)
NSSP	National Shellfish Sanitation Program
NWFSC	Northwest Fisheries Science Center
NWIFC	Northwest Indian Fisheries Commission
OAR	Office of Oceanic and Atmospheric Research (NOAA)
ODFW	Oregon Department of Fish and Wildlife
ODIN	Official Documentation and Information from Norway
OSU	Oregon State University
PCHB	Pollution Control Hearings Board (Washington State)
PNP	Private Non-Profit (Aquaculture Organizations, Alaska)
PNWFHPC	Pacific Northwest Fish Health Protection Committee
PSMFC	Pacific States Marine Fisheries Commission
PSEP	Puget Sound Estuary Protocols
PSGA	Puget Sound Gillnetters Association
PSWQAT	Puget Sound Water Quality Action Team
RCW	Regulatory Code of Washington
REUT	Resource Enhancement and Utilization Technologies Division (Northwest Fisheries Science Center)
SCAN	Scientific Committee on Animal Nutrition (European Union)
SEPA	(Washington) State Environmental Policy Act
SEPA	Scottish Environmental Protection Agency
SIC	Standard Industrial Classification (Index)
SMA	(Washington) Shoreline Management Act
SOAEFD	Scottish Office, Agriculture Environment and Fisheries Department
SSFA	Shetland Salmon Farmers Association (Scotland)
USCG	United States Coast Guard
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USOFR	United States Office of Federal Regulations
WAC	(State of) Washington Administrative Code
WDA	State of Washington Department of Agriculture
WDF	State of Washington Department of Fisheries (before 1991)
WDFW	State of Washington Department of Fish and Wildlife
WDL	State of Washington Department of Licensing
WDNR	State of Washington Department of Natural Resources
WDOE	State of Washington Department of Ecology
WFGA	Washington Fish Growers Association
WHO	World Health Organization (United Nations)
WMP	(BC Canada) Waste Management Policy
WRAC	Western Regional Aquaculture Center
WSGP	Washington Sea Grant Program

Abbreviations of Technical Terms and Symbols

AET	Apparent effects threshold
AVS	Acid volatile sulfides
BHA	Butylated hydroxyanisol
BHT	Butylated hydroxytoluene
BOD	Biological oxygen demand
DIN	Dissolved inorganic nitrogen
Eh	Redox potential
ER-L, ER-M	Effects range low and medium
FCR	Feed conversion ratio
H'	Shannon-Wiener diversity index
J'	Pielou's evenness index
MPN	Most probable number
NIS	Non-indigenous species
NIZ	Neutral impact zone
NOEC	No observed effect concentration
NOEL	No observed effect level
ORP	Oxidation-reduction potential
PCBs	Polychlorinated biphenols
PCA	Principal components analysis
PEC	Predicted environmental concentration
PEL	Probable effects level
PNEC	Predicted no-effect concentration
RPD	Reduction-oxidation potential discontinuity
S ⁼	Total sediment sulfides
SAC	Sediment assimilative capacity
SIZ	Sediment impact zone
TEL	Threshold effects level
TOC	Total organic carbon
TVS	Total volatile solids

Abbreviations of Diseases and Pathogens

BKD	Bacterial kidney disease
BSE	Bovine spongiform encephalitis
CS	Ceratomyxa
CWD	Coldwater disease
EIBS	Erythrocytic inclusion body syndrome
ERM	Enteric redmouth disease
FC	Fecal coliform
FC-MPN	Fecal coliform most probable number
FUR	Furunculosis
ICH	Ichthyophthirius
IHN	Infectious hematopoietic necrosis
IPN	Infectious pancreatic necrosis
MC	Whirling disease
PKD	Proliferative kidney disease
VHS	Viral hemorrhagic septicemia

EXECUTIVE SUMMARY

The US Government advocates a strong policy for national aquaculture development. The Department of Commerce (DOC) has set specific 25-year goals to offset the annual \$7 billion imbalance in seafood trade, and to double employment and the export value of goods and services. The policy is reflected in strategies proposed by the National Oceanic and Atmospheric Administration (NOAA) and its three line agencies responsible for certain aquaculture-related activities. With its broad mandate for stewardship of the nation's marine and coastal living resources, NOAA recommends that aquaculture development and environmental protection proceed hand in hand to meet public needs. Thus, in keeping with the Government's firm commitment to the United Nations Food and Agriculture Organization's (FAO) Code of Conduct for Responsible Fisheries, the line agencies of NOAA are encouraging the fisheries and aquaculture sectors to develop national Codes of Conduct, and their sub-sectors to develop and abide by Best Management Practices (BMPs).

The National Aquaculture Act of 1980 recognized that the principal responsibility for national development lay with the private sector. Therefore, to increase overall effectiveness of federal research, transfer, and assistance programs for the private sector, the Act created the Joint Subcommittee for Aquaculture (JSA). JSA published a National Aquaculture Plan in 1983, which has been recently updated. A review of all the current government policy statements and the National Aquaculture Development Plan 2000 reveals considerable verbal (but not financial) encouragement for private initiatives. The Plan recognizes that aquaculture is not a unique industry with unique hazards. Its systems and practices, and its products, parallel those of many other industries and human activities. Apart from the single and pandemic caveat of protection for the environment there are no directives which promote one aquaculture system or practice over another, elevate one genera or species above another, or forward or forbid the use of any specific technology. In summary, there is no political attempt to rate or rank a sub-sector, or to advance or suppress any specific activity because of any known risk.

The sub-sector of salmon farming in saltwater is a minor part of the national aquaculture industry, but it is a valuable economic asset contributing 11% to the total value of all aquaculture products. Only 45 commercial farms produce salmonids in marine net-pens directly for food, which is just 1% of all production facilities registered in the country, and <6% of all facilities in marine and coastal waters. Another 244 federal, state, or tribal facilities in the freshwater environment produce anadromous Pacific and Atlantic salmon for restoration of the commercial fisheries, recreational fisheries, or conservation, and another 362 freshwater facilities produce salmonids for both food fish and recreational fisheries. Because of its particular niche in marine and coastal waters, American net-pen technology has resulted in considerable growth of secondary producers in the aquaculture industry, and contributes a disproportionate share to the export of national goods and services.

Despite the economic success of net-pen salmon farming in the USA, this review of scientific and other literature reveals that there are many perceived and real issues with this industry which concern the American public. These areas of risk and uncertainty occur in many facets of the industry - from the effects of salmon farming on the environment, to competition with

other economies for the same resources, and the human health and safety of farming or consuming farm products. However, based on the evidence available in the existing literature and in ongoing research, it is apparent that the degrees of risk vary considerably from issue to issue.

Risk and Uncertainty in the Pacific Northwest Industry

A. Issues which carry the most risk

After a review of the available scientific literature, the following three issues of net-pen salmon farming in the Pacific Northwest appear to carry the most risk. All potentially impact the environment.

1. The impact of bio-deposits (fish feces and uneaten feed) from farm operations on the environment beneath the net-pens.

Bio-deposits from salmon farms settle onto sediments near the net-pens and can have definite effects on their chemistry together with their benthic and infaunal biota. Firstly, with regard to the chemistry, changes can be anticipated in total volatile solids and sulfur chemistry in the sediments in the immediate vicinity of operational net-pens, together with decreased redox potential. Sedimentation rates remain fairly constant irrespective of farm size, which currently is about 1,500 mt, and a typical total volatile solids (TVS) loading is 32.9 g/m²-day for the perimeter of such a farm near peak production. This value is reasonably close to a theoretical average of 25.7 g TVS/m²-day calculated for an entire 18-month production cycle. Reduced accumulation of volatile organic material under farms can extend to distances of 145 to 205 m from the net-pen perimeter during peak production. The magnitude of the change in any of these parameters is correlated with the degree of flushing in and around each farm site.

Secondly, with regard to the benthic biota, the accumulation of bio-deposits can enrich benthic communities but the actual affects depend on the hydrodynamics of each particular site. At poorly circulated sites these accumulations can exceed the aerobic assimilative capacity of sediments, leading to reduced oxygen tension and significant changes in the benthic community. Under extreme conditions sediments can become anoxic and depauperate. However, under any circumstances these effects are ephemeral and conditions have returned to normal within a period of weeks to years during fallow periods in all cases studied.

Thirdly, with regard to the infaunal communities, the accumulation of organic wastes in the sediments can change their abundance and diversity. But prolonged case studies reveal significant differences between poorly-flushed and well-flushed sites. At poorly-flushed sites benthic effects are highly dependent on farm management practices. Very high salmon production levels and other activities, such as cleaning nets *in-situ*, result in significant changes in both abundance and diversity of infauna to distances as great as 30 m from the net-pen's perimeter. At reduced production levels, and in the absence of *in-situ* net cleaning, the impacts are restricted to as little 15 m, or less, downstream from the net-pens. At well-flushed sites the abundance and diversity of infaunal organisms is positively correlated with total

organic carbon, suggesting that the farm stimulates the infaunal community throughout the area.

2. The impact on benthic communities by the accumulation of heavy metals in the sediments below the net-pens.

Both copper, from marine anti-fouling compounds used on net-pens, and zinc, from fish feeds, can be toxic in their ionic forms to marine organisms. Levels of copper are elevated around some net-pen farms which use government-approved anti-fouling paints on structures or, more likely, treat their nets with approved commercial compounds containing copper. The detected additions of copper in the water following the installation of newly-treated nets are biologically insignificant, except to organisms which settle on the nets. Zinc is an essential trace element for salmon nutrition, and it is added to feeds as part of the mineral supplement. Sediment concentrations of zinc are typically increased near salmon farms and the concentrations at a few farms in British Columbia have exceeded Washington State's sediment quality criteria (270 µg zinc/g dry sediment).

The degree of risk is dependent on several factors. Firstly, the concentration of sulfide in the sediment is important, as typically elevated concentrations near salmon farms reduce the bio-availability of both copper and zinc thus making the observed concentrations non-toxic. Long-term studies have demonstrated that the metal concentrations return to background during the period of chemical remediation, and there is no evidence of a long-term buildup of these metals under salmon farms. Secondly, the formulation of the feed is relevant, as the majority of feed manufacturers now use reduced amounts of a more bio-available proteinated form of zinc, or a methionine analog. Monitoring of zinc continues to determine the efficacy of this change in reducing even the temporary accumulation of zinc in sediments under salmon farms. Finally, management practices play a role, as the potential rate of accumulation of copper in sediments can be significantly reduced by washing the nets at upland facilities and properly disposing of the waste in an approved landfill.

3. The impact on non-target organisms by the use of therapeutic compounds (both pharmaceuticals and pesticides) at net-pen farms.

In European salmon farms therapeutic compounds are used for the control of sea lice, both for the health of the fish and to reduce their potential as vectors. The commonly used compounds are all non-specific within the Class Crustacea, and several are broad-spectrum biocides with potential to affect many phyla adversely.

The degree of risk is greatly reduced by government regulation for the use of specific therapeutic compounds following extensive research *in vitro* and *in situ* on their effects on marine organisms. Case studies show that some of these compounds can be detected in sediments close to the perimeter of net-pen farms, but the levels resulting from their authorized use do not show significant widespread adverse effects on either pelagic or benthic resources. In the Pacific Northwest the use of pharmaceuticals to control sea lice has not been practiced in Washington State for over 15 years because they have not presented significant

problems to growers, but some sea lice control agents have been used infrequently in British Columbia.

Note: One more issue might be included in this first category, although the degree of risk is uncertain as there is little scientific information available. This is the impact on human health through consumption of feed-borne organic toxicants. Farmed fish are exposed to dioxins through feed ingredients, and dioxins are found in virtually all feedstuffs of animal origin, especially those containing fish meal and oils. Dioxins can be accumulated and transferred up the food chain. But the degree of risk is uncertain, as the impact of dioxin and dioxin-like compounds on human health is a recent discovery. Currently the Codex Alimentarius Commission is making efforts to reduce the risk by specifying stringent quality control of the ingredients for all animal feeds, and the potential for substituting plant proteins and oils for fish meal and fish oil in salmon diets. Although observation of the Codex by the 165 member countries is voluntary, the USA is an active signatory (see the section on Managing Risk and Uncertainty, which follows).

B. Issues which carry a low risk

Puget Sound is a stressed ecosystem and one continuously being degraded by further human intervention. For the last 25 years it has been an area of intense annual population growth (1.5%) and is now home to 4 million people, with 1.4 million more projected by 2020. It is an area noted for recreational sailing and fishing, and there has been a corresponding growth in the number of support facilities for these water-borne activities. Salmon net-pen farming is another intervention competing for space and water-use, albeit minute by comparison. There are only 10 salmon net-pen farms active on sites in Puget Sound and unlike marinas, which deplete oxygen levels and elevate water temperatures, they are porous structures.

Nonetheless, there are a number of facets of the net-pen salmon industry in Puget Sound which appear to carry a low risk. The majority of these eight issues concern the environment in the immediate vicinity of the farms themselves.

4. The physiological effect of low dissolved oxygen levels on other biota in the water column.

Fish stocked intensively in contained areas are known to have a high oxygen demand. Decades of monitoring in Washington State have found a maximum oxygen reduction of 2 mg/L in water passing through salmon net-pens where large biomasses of fish were being fed. In most cases the reduction in dissolved oxygen has been ≤ 0.5 mg/L. Salmon are more sensitive than most other species to depressed oxygen levels and 6.0 mg/L is considered a minimum concentration for optimum health. Therefore, if there was a localized effect associated with net-pen culture, the farmed salmon would be the first organisms affected. At coastal (oceanic) sites, farmed salmon are infrequently subjected to low dissolved oxygen concentrations when oxygen deficient up-welled water naturally intrudes into the growing area. However, these are oceanographic events which have nothing to do with the culture of fish or shellfish. In even the most poorly flushed farm in Puget Sound the culture facility does not consume quantities of oxygen sufficient to affect other organisms.

5. The toxic effect of hydrogen sulfide and ammonia from the bio-deposits below a net-pen farm on other biota in the water column.

The accumulation of any highly-organic sediment produces ammonia and hydrogen sulfide once the oxygen is depleted. These gases most frequently cycle between oxidized and reduced states within superficial sediment layers where they modify the infaunal community. They are infrequently released into the water column. Although there is evidence from *in situ* studies that total sulfide concentrations in surface sediments in areas of high organic loading can exceed 20,000 μM , there is little soluble hydrogen sulfide in the water column even under poorly flushed sites. Less than 1.9% of the gases at the sediment-water interface are sulfide, and this can be reduced to 0.05% at a distance 3 m above the sediment. The majority of these gases are methane and carbon dioxide. In a well-sited farm concentrations of hydrogen sulfide gas rising through the water column are rapidly reduced by oxidation, diffusion, and mechanical mixing. For these reasons it is unlikely that toxic conditions caused by hydrogen sulfide will ever occur unless there were extremely large emissions at the sediment-water interface in shallow water.

6. The toxic effect of algal blooms enhanced by the dissolved inorganic wastes in the water column around net-pen farms.

Enhancement of a harmful algal bloom by the inorganic nutrients discharged from salmon farms in Puget Sound is feasible but highly unlikely to occur in the Pacific Northwest. First, apart from the summer months, the natural atmospheric and geographical parameters of the region reduce light availability for photosynthesis, and the waters are vertically well mixed which reduces the time phytoplankton spend in the euphotic zone. Second, the physical characteristics of locations permitted for salmon farming are not conducive to the accumulation of nutrients, even when the water body is nutrient limited. Decades of monitoring have shown minimal increases in inorganic nutrient concentrations downstream from even the few sites having restricted water exchange. Small increases observed at 6 m downstream during slack tide have been statistically insignificant at a distance of 30 m downstream. Nutrient-limited embayments in Washington State have been identified and salmon aquaculture activities in these locations are discouraged and carefully managed when allowed.

7. Changes in the epifaunal community caused by the accumulation of organic wastes in sediments below net-pen farms.

The effects on a wide variety of epifaunal communities have been studied in detail and the results are well-documented. One case study, with long-term (up to 10 years) monitoring, reveals significant numbers of fish, shrimp and other megafauna inhabiting the site, which appears to function as an artificial reef. Other salmon farms in close proximity all share the same characteristics, even attracting larger predators to the enhanced epifaunal communities.

8. The proliferation of human pathogens in the aquatic environment.

Wild salmonids carry genera of marine bacteria, such as *Vibrio*, *Acinetobacter*, and *Aeromonas*, some species of which are pathogenic to humans. The concern is that fish feces and waste feed might enhance populations of these pathogens. There is no evidence in the literature, or in the epidemiological records of Washington State, of any documented case in which the handling or consumption of farmed salmon has led to infectious disease in consumers or farm workers. There are many differences in the physical and chemical composition of salmon farm waste compared with human sewage discharge, and the former does not disperse over large areas but remains localized where it is metabolized by naturally-occurring marine bacteria and invertebrates. There is no credible evidence supporting a hypothesis that salmon farming increases the risk of infectious disease in humans or wild populations of animals.

9. The proliferation of fish and shellfish pathogens in the aquatic environment.

Public health concerns for the safety of fish and shellfish in the vicinity of discharges of industrial and residential waste are real, and vigilance is maintained by stringent regulations and monitoring programs. The accumulation of wastes from net-pen farms is perceived as another source of human and environmental pathogens. However, there is little evidence substantiating this hypothesis. Viruses pathogenic to fish have no documented effect on human beings because they are taxa-specific. Fecal coliform bacteria are unlikely to persist in net-pen sediments rich in total organic carbon as they are specific to warm-blooded animals. Sources of fecal coliform bacteria near salmon farms are more likely to be mammals (such as seals and sea-lions) or birds. *In situ* monitoring at some well-flushed net-pen farms revealed slightly more fecal coliform bacteria in water and shellfish tissues at stations closest to the farm perimeter. The sources of observed bacteria were not determined. However, all water and shellfish tissues examined were consistently of high quality and met all bacteriological requirements imposed by the National Shellfish Sanitation Program.

10. The increased incidences of disease among wild fish.

Maintaining animal or plant populations in intensive concentrations can be conducive to an outbreak of disease. The specific diseases and their prevalence in Atlantic salmon stocks cultured in net-pens in Puget Sound are not shown to be any different than those of the more numerous cultured stocks of Pacific salmon in hatcheries, which in turn are not known to have a high risk for infecting wild salmonids. All Pacific and Atlantic salmon stocks currently cultured in Washington are inspected annually for bacterial and viral pathogens, and the movement of fish from place to place is regulated by permit.

11. The displacement of wild salmon in the marketplace by farmed salmonids.

Salmon farmers and traditional Pacific salmon fishermen sell the same generic product, and therefore compete in the marketplace. Regulations specific to Washington State require farmed fish to be identified for the consumer. In terms of supply, salmon production by the net-pen salmon industry in the USA has been a counterbalance to the declining commercial

and tribal landings of Pacific salmon to meet increasing consumer demands for seafood. But in terms of demand there are distinct differences in the species produced by the two industries, and there are also differences in products available to consumers. Farmed fish are sold mostly as whole dressed fish and fresh fillets, while the typical disposition of the total annual wild catch (not by species) of the five Pacific species is whole fish, fresh and frozen, and canned products.

In terms of price and availability, Atlantic salmon has an all-year round advantage and therefore a competitive edge over Pacific salmon harvested in the commercial fisheries. They are also relatively cheap to produce for the market. Per harvested fish, the cost to the private producer of farmed Atlantic salmon is currently about \$1 per pound, head on, gutted weight. However, irrespective of its origin, production of salmon in Washington has little or no measurable effect on prices determined by global supply and demand, or reducing the large importation of farmed salmon from Norway and Chile.

C. Issues which carry very little or no risk

Despite the fact that two of the issues in this final category have many sub-sets, all three issues are deemed to carry very little or no risk. Two are specific to the environment of the Pacific Northwest, and the third concerns human health and safety in general.

12. The escape of Atlantic salmon - a non-native species.

Since a reporting regulation was imposed in 1996, the records show that some 600,000 farmed salmon escaped between 1996 and 1999. These were mostly fish between 0.5 - 1.5 kg in weight. Only 2,500 of these particular escapees were subsequently accounted for. In addition, between 1951 and 1991 the State made 27 releases of 76,000 smolts of Atlantic salmon of various sizes into the Puget Sound Basin in attempts to establish this prized species on the west coast. Many escapees were taken immediately by recreational fishermen angling close to the net-pen farms, and a few others were taken at random by commercial fishermen in Puget Sound and beyond. A few fish (which may have originated in either Washington or British Columbia) have been recovered as far away as the Alaskan Peninsula. However, the numbers recovered have always been small and the rest remain unaccounted for, and it is assumed that the domesticated existence and docile behavior of farm fish makes them easy victims of predators, especially the large populations of marine mammals which now exist throughout the Pacific Northwest.

The following list summarizes the sub-issues of concern regarding escaped Atlantic salmon in Puget Sound which appear to carry little or no risk.

(i) Hybridization with other salmonids

There is no evidence of adverse genetic impacts associated with escaped Atlantic salmon on the west coast of North America as they do not have congeneric wild individuals with which to interact. Hybrids between Atlantic salmon and the Pacific salmonid species can be produced *in vitro*, but with difficulty. Hybrids between Atlantic salmon and brown trout, another non-native species, are more easily produced *in vitro*, and occur readily in nature.

Atlantic salmon x Pacific salmonid hybrids are not observed in nature, whether for introduced Atlantic salmon in North America, or for introduced North American salmonids to Europe and the other continents. By comparison, successful hybridization between some North American salmonids is regularly recorded.

(ii) Colonization of salmonid habitat

Atlantic salmon are unlikely to colonize salmon habitat in the Pacific Northwest. Accidents occur, and farm fish of various sizes occasionally escape in large numbers. About 1 million Atlantic salmon have escaped from net-pen farms in Puget Sound and British Columbia since 1990. Only a few were accounted for in recreational and commercial fisheries. In addition to escapes, deliberate releases of Atlantic salmon to establish local self-sustaining populations have been made in the Pacific Northwest since the beginning of the century, with the last release in 1991. Although routine monitoring programs occasionally find naturally-produced juveniles, naturally-produced adults have yet to be observed.

(iii) Competition with native species for forage

Like all salmonids Atlantic salmon are high on the food chain. But few prey items of any sort have been found in the stomach contents of escaped Atlantic salmon which have been recaptured. As survival in the wild is extremely low for escaped farm fish, it is assumed that their domestic upbringing makes them poor at foraging successfully for themselves. Therefore, the few natural prey items any escaped fish might consume is negligible, especially when compared with the competitive food requirements of the juvenile Pacific salmon deliberately released into Puget Sound and its tributaries from hatcheries.

(iv) Predation on indigenous species

All salmonids are predators. However, all analyses of the stomachs of recovered farm Atlantic salmon, and of the few naturally-produced juveniles caught in the wild, have failed to show evidence of preying on native salmonid species. This is not the case of other introduced non-native species which are known to be voracious predators of juvenile Pacific salmonids. Some of these non-native predators have been deliberately and/or accidentally introduced and are now managed for sustained natural reproduction to enhance recreational fisheries and for their contribution to sport fishing revenues.

(v) Vectors for the introduction of exotic pathogens

Provided no new stocks or eggs of Atlantic salmon are introduced into the region, farm Atlantic salmon cannot be a vector for the introduction of an exotic pathogen into Washington State. The extensive movement of aquatic animals and plants globally is known to carry the risk of introducing exotic diseases but movement of fish into and within Pacific Northwest states is now well-regulated with the requirement for disease-free certification. No Atlantic salmon stocks have been transferred into the State of Washington since 1991.

13. The impact of antibiotic-resistant bacteria on native salmonids.

Drugs are used in all hatcheries and rearing facilities, and over-use of drugs is known to increase the resistance of many bacteria. Therefore there is the potential for development of antibiotic-resistant bacteria in net-pen salmon farms or Atlantic salmon smolt hatcheries

which could in time impact native salmonids. All drugs used in fish culture in the USA are scientifically safe and efficacious, and approved by the FDA. Drug resistance has been commonly observed in public fish hatcheries in Washington State for over 40 years and no resulting adverse impacts on wild salmonids have been reported.

14. Impacts on human health and safety.

The consumption of salmon farm products and/or working in and around the vicinity of net-pen salmon farms are perceived by some people to be concerns of human health and safety. The following list summarizes these sub-issues of concern regarding human health and safety which appear to carry little or no risk, either directly or indirectly.

(i) Heavy metal contamination of farm products

The three main sources of heavy-metal contamination found in coastal waters where fish and shellfish are farmed include industrial and municipal waste discharge, anti-fouling paints, and various organic pesticides, herbicides, and hydrocarbons. Problems with industrial and municipal waste discharges have long been recognized, and exposure to toxic chemicals from these sources are minimized by licensing farming areas away from sources of contamination. The hazards of heavy metal contamination, principally methyl mercury and tributyl-tin, are currently addressed by regulatory controls. As intensive farming relies on high quality formulated diets, the ingredients are regularly monitored to avoid possible contamination of feed with methyl mercury; and the use of tributyl-tin, once a common biocide used in anti-fouling bottom paints and for treating net-pens structures, is totally banned in North America.

(ii) Rendered animal products in animal feeds

The use of rendered animal proteins, once common in formulated feeds for many species of fish as well as other farm animals, has been curtailed by public concern over possible amplification of bovine spongiform encephalopathy (BSE), or 'mad cow disease'. Although not specifically prohibited by regulation, rules designed to prevent cross-contamination of feeds and feed ingredients at time of manufacture have effectively eliminated the use of these ingredients from salmon feeds. There are no scientific studies on the potential for BSE transmission to humans through discharge of BSE prions into the aquatic environment, but based on studies of the discharges from rendering plants to aquifers used for drinking water, the possibility of infection by this route is remote.

(iii) Genetically modified (GM) ingredients in fish feeds

Although safety concerns regarding the use of GM ingredients in animal feeds have not been substantiated scientifically, most feed suppliers continue to offer only GM-free feeds. The use of GM oilseeds and grains in animal and human foods has gained considerable public attention in North America because of uncertainties regarding their effects on human health and the environment.

(iv) Other ingredients and additives in animal feeds

The use of pigments, hormones, antioxidants, and vitamin/mineral supplements in animal feeds is strictly controlled by FDA regulations. Although growth hormones are given commonly to other farm animals, such as poultry and cattle, their use in food fish is

prohibited. Additives such as pigments, antioxidants, and other nutritional supplements have been proven safe and their use in fish feeds is permitted by FDA regulation.

(v) Residual medicines and drugs in farmed products

Antibiotic residues in any farmed animals, including fish, is of concern to consumers because they might induce allergic reactions, have toxic effects, or simply increase antibiotic resistance in human pathogens. All drugs used in aquatic species farmed in the USA have been proven safe and efficacious, and are undetectable at the time of harvest when withdrawal times prescribed by the FDA are followed. At present only two antibiotics are registered and sold for use in the USA as feed additives for disease control in farmed fish. The use of parasiticides and vaccines is similarly restricted by FDA regulation. There could be a risk to consumers if these chemical compounds and vaccines were misused or administered by untrained workers.

(vi) Biological hazards in farm products

Potential biological hazards include parasites, bacterial and viral infections, or naturally produced toxins. To date there have been no reported cases of any fish parasites or pathogenic organism from farmed fish causing disease in humans. Most hazards have been eliminated by strict adherence to BMPs on the farm and at harvest, and/or by HACCP regulations during processing.

(vii) Transgenic farm fish

The perceived hazards of transgenic farms products, such as human allergies or unnatural competitors in the ecosystem, are hypothetical issues for net-pen salmon farming in Puget Sound. There is no evidence in the literature that transgenic fish have been raised or are being raised in the Pacific Northwest, and there are no plans to raise them.

(viii) Workers' safety

Compared with commercial fishing, which is identified as one of the most hazardous of occupations, net-pen salmon farms provide a safe working environment. Some fatalities and injuries in the national aquaculture industry from physical accidents have been reported but not specifically among net-pen salmon farmers.

(ix) Public safety and navigational hazards

There is no evidence that floating net-pen structures in Puget Sound are a hazard to the safe navigation of Washington's large and diverse boating communities. Firstly, permits from the US Coast Guard and Army Corps of Engineers are required for each farm to ensure that it complies with navigation and water safety regulations. Secondly, the complexes are small in total area. The ten active sites, which range in size from 2 - 24 acres, occupy only 131 acres of navigable surface waters from the State. The actual surface areas of the net-pen structures themselves occupy only 21.2 acres in total, with each complex ranging from 0.48 - 3.9 acres. By comparison the State has 77 aquatic land sites leased for commercial shellfish production, with a total area of 81,500 acres.

(x) The impact on nearby property values

In the competition for coastal sites between the salmon farming industry (requiring access and good quality water conditions), and residential real estate (requiring access and industry-free views) there is no evidence that the sight and presence of net-pen operations has impacted the values of coastal properties in Puget Sound.

Managing Risk and Uncertainty

A. The environment

There is considerable evidence available in the scientific literature to evaluate any potential risk of net-pen salmon farming on the environment of the Pacific Northwest. Most issues have been studied in great detail for some 20 years, and in many similar environments in different parts of the world. The results are well documented, and a common denominator is that the potential for environmental impact depends primarily on the site of each individual farm. The most important rule in the management of risk is therefore the careful selection of the site.

Responsible permitting of each site is also playing an important management role. The National Pollution Discharge Elimination System (NPDES) permit has been effective in regulating the degree of allowable effect, but its impact must now be supplemented with the strict adherence by site operators to a well-defined set of industry BMPs which are based on good scientific information. These BMPs can be specific to a particular farm, or they can be overarching for the entire industry.

Scientific evidence in the literature indicates that the potential changes in the sediments below operating net-pen farms bear the most risk for the environment. Continuous monitoring of the sediments under and around farm sites for many years has produced an extensive database of chemical and biological information, and specific parameters are now being used to predict the environmental effects. Key parameters include, *inter alia*, sediment grain size, total volatile solids or total organic carbon, redox potential, free sulfide concentrations and ultimately invertebrate community assessment. Modeling programs are also beginning to provide insight into the environmental response to farm waste, but these are not yet adequate to make reasonable quantitative predictions.

Long-term monitoring of the sediments has also revealed that chemical and biological recovery of the substrate under and around farm sites occurs naturally without human intervention or mitigation. *In situ* data show that physicochemical recovery can occur within weeks or months at some sites, and within two or three years at others. Biological remediation of the sediments follows after a period of chemical remediation, and the speed of recovery depends on the seasonal recruitment of new infauna.

B. Human health and safety

Net-pen salmon farming is a relatively new global industry, but one which is very highly regulated in the USA. Atlantic salmon cannot be farmed in the Pacific Northwest or along the

Northeastern Atlantic coast under any conditions which might pose a hazard to human health by exposure to environmental contaminants, pathogens, or infectious disease organisms. Farm salmon cannot be treated with any chemo-therapeutic compounds not approved by the US Food and Drug Administration (FDA). The health and safety of the farm workers are protected similarly by labor and industrial regulations.

The United Nations Food and Agriculture Organization (FAO) in 1995 formally adopted a *Code of Conduct for Responsible Aquaculture*, which was followed in 1997 by a detailed document called *Responsible Aquaculture at the Production Level*. These documents detailed areas of concern regarding the responsible, safe, and effective use of feeds and feed additives, chemicals and chemotherapeutants, and other aquaculture practices which might reduce health and safety risks to humans. Food safety issues associated with farmed aquatic organisms have been subsequently evaluated by the World Health Organization in a working committee of the Codex Alimentarius Commission. The USA, which has agreed to abide by the intentions of all these international codes, has also developed national guidelines regulating the safety of all seafood, including farmed products. These are administered by the FDA.

The literature reveals that the net-pen salmon farming industry in the Pacific Northwest is integrating all these safety assurance and quality control measures at all levels of the farm-to-table food-safety continuum. It has been applying Hazard Analysis and Critical Control Point (HACCP) methods wherever possible since their inception, and is in the final stages of publishing its own BMP.

C. Farm escapes

Accidents have occurred enabling farmed salmon to escape. Such incidents are likely to continue following some unique meteorological event or human error. The possible negative consequences of such events have been limited in part by implementation of pre-prepared recovery plans, some of which have included deregulating catch limits for public fishing on escaped farm fish, and by programs to monitor the background populations of fish in nearby watersheds. These responses will continue to be effective management practices to minimize impact, together with further advances in the technology. Improvements in the design and engineering of net-pens and their anchorages, and the use of new net materials, are continuing to reduce the incidents of loss following structural failure or damage from large predators.

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FOREWORD

Many government regulators are now encouraging all intensive food production industries, including capture fisheries, to adopt and observe protocols and methodologies to make their activities more compatible with the environment. The majority of these industries are responsive to this challenge and are beginning to comply through self-developed codes of practice and best management practices.

A code of practice (COP) describes a set of general practices and standards to guide human conduct in a specific endeavor in order to maintain conformity and consistency. COPs are voluntary in principle but invariably the overarching organization, such as the Federation of European Aquaculture Producers (FEAP), makes them obligatory in universal interest (FEAP 2000). Best management practices (BMP), on the other hand, describe a specific (and often detailed) set of protocols, practices, or procedures to manage and carry out specific operations in a responsible manner, with respect to the social and ecological environment, based on the best available scientific information and an assessment of risk. BMPs are voluntary in principle but invariably the overarching organization makes them mandatory in the interest of the specific industry.

Each element in any code of practice is based on the best scientific information available or the most practical experiences. Consequently a code of practice is not a finite entity in itself but a never-ending dynamic process ready to incorporate each relevant scientific discovery and each new technical experience. In 1997 the Environmental Assessment Office of British Columbia (EAO) published the British Columbia Salmon Aquaculture Review (BCSAR). A section of this comprehensive document (EAO 1997) discussed key environmental issues based on reviews of over 750 scientific and technical papers, and many pertinent government documents. This background information greatly assisted the British Columbia Salmon Farmers Association (BCSFA) to develop its individual code of practice in 1999 (BCSFA 1999), and the New Brunswick Salmon Growers Association will complete its code in 2001 (N. Halse, NBSGA, personal communication). The same efforts have been made in other countries, and in 2000 the Shetland Salmon Farmers Association of Scotland produced its code of best practices (SSFA 2000).

Government and salmon farmers in the US on both the west and east coasts have not moved as quickly as those in Canada, or indeed as those in Norway, Scotland, and Ireland. This is because most of the sub-sectors of American aquaculture are very small, unlike those of US agriculture, and individual farmer's associations do not have the capacity or scientific information on which to develop appropriate codes. Consequently, research staff of the Northwest Fisheries Science Center (NWFSC) has prepared this scientific review to help salmon farmers in the Pacific Northwest codify their industry.

Research by scientists of the NWFSC first instigated the industry of net-pen salmon farming in saltwater in North America at the Manchester Research Station in the early 1970s. Subsequently salmon have been farmed extensively in the Pacific Northwest in

the protected waters of the Georgia Straits and Puget Sound. Therefore it is fitting that the NWFSC is guiding the local industry to be compatible with its ecological surroundings.

This document is the result of the efforts of the Resource Enhancement and Utilization Technologies Division (REUT) of the NWFSC. It is not a comprehensive review of the literature on net-pen salmon farming from its historical beginning, like the BCSAR, and it is not trying to update the BCSAR with citations to information after 1996. The document is intended to stand in its own right and fulfil a set of three objectives:

- First, from the perspective of the US and local stakeholders it annotates the best scientific information regarding local issues arising from or affecting development of net-pen salmon farming in the Pacific Northwest.
- Second, together with other literature reviews, it completes an information base for all stakeholders to make a qualified and quantified analysis and assessment of any risks associated with salmon farming in the area.
- Third, together with these risk assessment studies, it will assist salmon farmers to develop an appropriate COP for their industries, and in particular the salmon farm and hatchery managers in the Pacific Northwest, to develop a set of BMPs for their specific activity.

1. GENERAL DEVELOPMENT OF AQUACULTURE IN THE USA

The first chapter initially summarizes the national leadership for development and growth of the aquaculture sector by a range of government policies and legislation spread over half a century. It explains government direction was first to mitigate for displaced wildlife resources but now its objectives are to reduce imbalances in seafood trade, enhance commercial fisheries, and assist conservation of endangered species. It notes that national development has been guided for twenty years by the National Aquaculture Act of 1980, and a National Aquaculture Development Plan which has been continually under review and updated. The second part of the chapter summarizes the national salmon aquaculture sector. It provides current data for the two key pillars of the sector, specifically production for enhancement of commercial and recreational salmon fisheries, and production of food-fish for domestic and export markets. It explains briefly the different commercial end-products of salmon aquaculture, and the contribution to the national economy made by the industry's producers of good and services.

1.1 Federal Leadership for the National Aquaculture Industry

Modern aquaculture is not new technology to the USA. Early attempts to culture fish and shellfish in North America date back to the 1850s and 1860s, and it was the intensity of the early pioneers to raise fish to enhance the indigenous fisheries which persuaded the US Government to create the US Fish Commission in 1871. The Commission, in time, became the Bureau of Commercial Fisheries and subsequently the National Marine Fisheries Service (NMFS).

Early development of aquaculture in the US was continuously expanded by legislation. Predominantly it was federal legislation to compensate for salmon fisheries affected by federal water projects in the Columbia River Basin. The Federal Power Act of 1920 and the Fish and Wildlife Coordination Act of 1934 were responsible for over \$400 million spent on salmon hatcheries and fish passages constructed at that time, and in 1938 the Mitchell Act authorized appropriation of federal tax revenues annually to restore and enhance the salmon resources of the Columbia Basin as a whole. As a result, a substantial technical and scientific research and information base was established in the country on almost every aspect of the biology and culture of Pacific salmon. This knowledge and experience was a significant factor in the farming of both North American and European salmonids some 30 years later.

Encouraging development of aquaculture in the US was again the government's policy behind the National Aquaculture Act of 1980. Recognizing the growing diversity of modern aquaculture, and multi-agency responsibilities, the 1980 Act established a coordinating group, the Joint Subcommittee on Aquaculture (JSA) which continues in existence today. The JSA has been responsible for developing and updating the National Aquaculture Development Plan (NADP 2000), which identifies the relative roles of the

Department of Agriculture (USDA), the Department of Commerce (DOC), and the Department of the Interior (DOI).

Within DOC, the National Oceanic and Atmospheric Administration (NOAA) has a strong statutory base for the promotion and regulation of marine-related aquaculture. Historically this has been achieved through NMFS programs and the National Sea Grant College Program (NSGCP) in the Office of Oceanic and Atmospheric Research (OAR). In 1999 the Secretary of Commerce signed an Aquaculture Policy for DOC identifying seven specific objectives. Among quantified targets for the aquaculture sector to achieve by the year 2025, the policy strongly emphasized technological development and growth in harmony with the environment. The same message is evident in the NOAA policy on aquaculture, signed in 1998. The underlying goal is for development through environmentally sound production practices. Particularly noted is the use of aquaculture technologies for the enhancement of threatened populations but also avoiding negative impacts on any wild stocks. The policies of both DOC and NOAA are very evident in the draft National Marine Aquaculture Act of 1999 for further development of aquaculture into the exclusive economic zone (EEZ).

In conclusion, the federal government continues to encourage sector development through applicable legislation, funding programs, and agency policies. It has set 25-year targets for increased domestic production to help offset the large annual trade deficit in seafood, and to double employment and exports of goods and services. In addition, it wants new technologies for increased diversification of the industry, and for enhancement of wild stocks. Finally, it demands economic development with the necessary safeguards for the environment to be enforced through total compliance with industrial codes for responsible aquaculture.

NADP 2000 is not detailed regarding different aquaculture products or production technologies. Irrespective of any sub-sector, the Plan repeats the challenge for better knowledge about possible interactions between aquaculture and the natural environment to minimize, (i) the potential for habitat degradation, (ii) transmission of diseases, (iii) potential genetic dilution of wild stocks through interbreeding with cultivated strains, (iv) introduction of non-indigenous species into natural waters, and (v) discharges of wastes, toxins, and excess nutrients (JSA 1999).

1.2 The National Salmon Aquaculture Sector

The Census of Aquaculture recently published by USDA (USDA 1999) reports the value of salmon produced and sold for food or food/sport in 1998 was \$104 million, or about 11% of the total value of national aquaculture products. The Census notes that 244 farms produced salmon for restoration or conservation purposes. It defines these farms as mostly *non-commercial operations*, such as federal, state, or tribal facilities (which were mostly hatcheries), academic, and private research facilities with products valued above \$1,000 in the year of the Census. Within this total, the Census records that 238 farms produced 2.4 billion fish (288 million lb or some 130,000 mt), and 47 farms produced 71 million salmon eggs or seed for distribution. Another 362 farms produced trout for

restoration or conservation, of which 360 farms produced 177 million fish (32 million lb or 1,450 mt), and 72 farms produced 163 million eggs or seed for distribution.

In addition the Census notes that 47 farms in the country produced salmon commercially, of which 45 raised food-size fish. This number is about 1% of all the aquaculture farms recorded in the country. It is assumed that almost all these salmon farms are saltwater farms. The Census records that there are only 815 of the 4,028 recorded aquaculture facilities and/or farms in the country which operate with or within saltwater, and the majority raise mollusks or tropical fish.

The word '*farm*' in the literature can be confusing, as the definition adopted by the Census is specific to its own use. Typically, '*farm*' applies to a physical complex for production but this, in turn, can refer to a complex on a single registered site, or a number of complexes operated by a single business which owns or leases a number of registered sites close together. Using its definition of a commercial or non-commercial place from which \$1,000 of products were sold, the Census shows that the majority of salmon farms operate in the States of Alaska (19), Maine (12), and Washington (9). But Alaska prohibits private farming of all fish species, and therefore the number refers to salmon hatcheries operated by private non-profit corporations (PNPs) which rear to release and subsequently harvest – an aquaculture practice known as '*ocean ranching*.'

The word '*farm*' can in fact be applied to any location where primary production of aquatic animals and plants takes place. There are five primary producers in the salmon aquaculture sub-sector in the USA, and their end products are:

- (i) certified disease-free eggs from a freshwater hatchery,
- (ii) pre-smolted juveniles from a freshwater nursery farm,
- (iii) smolted juveniles from a saltwater nursery farm,
- (iv) marketable fish from the saltwater grow-out farm, and
- (v) marketable products after processing.

Active in these areas are both non-commercial and commercial enterprises. The non-commercial enterprises are all the federal, state, and tribal organizations that own and operate only hatcheries and other licensed rearing facilities to produce pre-smolts and smolts for release to enhance commercial and recreational fisheries. Commercial enterprises are private companies which invariably own or have controlling interests in at least four end-products, and possibly all five. The Western Regional Aquaculture Center (WRAC) noted that the State of Washington Department of Fisheries and Wildlife (WDFW) had close to 1,000 aquaculture licenses on file in 1995, of which 74 were for salmon and 187 for trout production (WRAC 1999). These numbers included both active and non-active licenses, as licenses are not required to be updated annually.

There are many secondary producers in the industry throughout the country. Their manufactured end products include, for example, (i) hardware, such as craned vehicles, service boats, floating cages, net-pens, feed silos, egg incubators, hatchery tanks, raceway tanks, pumps, pipes, etc., (ii) formulated feeds, (iii) technical apparatus and laboratory equipment, (iv) veterinary medicines and drugs, and (v) a variety of expert services. Again, many commercial enterprises active in primary production are active in secondary

production, particularly with ownership or controlling interest of subsidiaries in fish nutrition and health. Within the last 2 years several large companies in Europe and North America have spread their business risk throughout the global salmon industry by consolidating their hold on substantial lengths of the value chain.

Secondary producers are very important to the national economy. In a recent aquaculture policy statement, DOC recognized that the annual value of US exports of goods and services was \$500 million, and set a goal of \$2.5 billion by the year 2025 (DOC 1999).

2. SALMON AQUACULTURE IN THE STATE OF WASHINGTON

The second chapter is predominantly regional in scope and deals mostly with the pros and cons of salmon aquaculture in the State of Washington. The first section provides quantified data regarding aquaculture for restoration and conservation of salmon fisheries, and some economic costs and benefits. The second section provides data regarding the physical extent of the commercial salmon farming industry for food production, making comparisons with other parts of the US and overseas. The third section describes some of the interactions of the salmon farming industry in Puget Sound with commercial and recreational fishing activities, in particular with other fish populations and in the marketplace. The fourth section deals with economic benefits to the State, particularly at the regional and local levels. These include the contribution to seafood production, the impact on employment and wages, and the impact on coastal property values. The two final sections concern the current regulatory structure for commercial enterprises raising food fish in the State of Washington, and the regulatory structure for public and tribal hatcheries raising juvenile salmon for commercial and recreational fisheries.

2.1 Salmon Production for Restoration and Conservation

The State of Washington has one of the largest artificial production systems for salmonids in the world. Its hatcheries program operates 24 complexes (groups of hatcheries) with more than 90 rearing facilities (WDFW 2000). These include production hatcheries, net-pens, acclimation sites, and rearing ponds, as well as several remote egg-incubator locations and small-scale cooperative rearing programs with community and educational groups. Washington hatcheries produce approximately 75% of all coho and chinook salmon, and 88% of all steelhead trout harvested statewide. Trout hatcheries produce over 90% of the statewide harvest. Approximately 700,000 adult salmonids of several species return to hatcheries each year, and more than 300 million eggs are collected from them for future generations. All fish raised in State hatcheries are released into the open waters of Washington. In 1995 some 201 million salmon, 8.5 million steelhead, and 22.6 million trout and warm-water fish were released. In addition, there are 12 federal and 17 tribal rearing facilities which produce another 50 million salmonids for release (WDNR 2000a).

Between 1951 and 1991 WDFW also made 27 releases of Atlantic salmon in attempts to establish the species in State waters. A total of 76,031 parr and smolts were released varying in size between 0.25g and 450g (Amos and Appleby 1999). Until 1979 the origin of the stocks was Gaspé River in Canada, most of which came through broodstocks held in Oregon. From 1980 the stocks were a mix of origins, including Gaspé River, the Penobscot and St. John's Rivers (Maine), together with some landlocked stocks from Grand Lakes (Maine).

The State of Oregon, which shares the Columbia Basin with the States of Washington and Idaho, currently operates 34 hatcheries and 15 other rearing facilities. Annually these facilities release about 43 million Pacific salmon, 5.7 million steelhead, and 8.3 million trout. In the last decade about 80% of all trout, and 70% of all steelhead and coho harvested in Oregon were propagated artificially (ODFW 2000). More recently, net-pen complexes have been used for conditioning and releasing salmon in areas around the mouth of the Columbia River to create local commercial and recreational fisheries. The Clatsop County Economic Development project near Astoria released about 3.5 million coho, and 1.1 million chinook in 2000 (OSU 2000), and expected a return of 5,000 spring chinook from its previous releases.

Using 1990s data for the production, release, and survival of Pacific salmon from Columbia Basin hatcheries, where the juveniles may be retained for up to 18 months, Radtke (2000) calculated that the hatchery cost per harvested coho salmon was \$58.89, with an economic value per harvested fish (7 lb. at \$1.00/lb.) of \$76.07. For spring/summer chinook (12 lb. at \$1.50/lb.) the costs per harvested fish were \$404.55 and \$109.36, respectively, and for fall chinook (15 lb. at \$1.25/lb.) they were \$35.00 and \$114.5, respectively. For steelhead (9 lb. at \$0.60/lb.) the costs were \$292.86 and \$74.8, respectively. He also estimated the (fixed plus variable) cost per smolt from hatcheries in Oregon into the Columbia Basin for salmon (all species) to be between \$7.20–7.42 per lb of smolt. Current estimates by WDFW (K. Amos, WDFW, personal communication) put the cost at between \$3–4 per lb. of smolt. This is because outside the Basin hatcheries generally retain many stocks for a month or less, primarily chum salmon, which results in a lower cost per smolt.

Puget Sound has a large number of artificial propagation facilities releasing juvenile salmonids into its freshwater basin every year. Based on historical data over 30–40 years, a total of 30 facilities together released about 29 million coho every year (NMFS 1995). Some 43 facilities released 65 million chum (NMFS 1997a), and 69 rearing facilities released about 44 million chinook (NMFS 1998). There are also 10 facilities which release some 1.5 million-winter steelhead and 400,000 summer steelhead, mostly smolts, (NMFS 1996). Collectively, these facilities now release about 50 million juvenile salmon (equivalent to some 300 mt of fish) into the Puget Sound Basin on an annual basis. The reductions in number of fish released are due in part to changes in hatchery strategies to lessen the potential adverse impacts on wild salmonids.

Forster (1995), in his evaluation of cost trends in farmed salmon, reported the current (1994/95) production cost of an Atlantic salmon smolt (100 g in weight, or 3.5 oz) in Chile, Norway, and Canada was between \$0.75–1.25 each, which included \$0.5–0.15 for the eyed egg, and \$0.12–0.20 for the feed. Prices asked by smolt producers, however, might be \$1.50–4.00, depending on the size at sale, with \$2.00 being the average for a 100g fish. Grez (Salmones Camanchaca S.A. Chile, personal communication) reported that fixed and variable production costs for rainbow trout and coho salmon smolts in Chile in 1996 were \$0.21–0.26, and a little more for Atlantic salmon depending on the source and cost of eggs. Rainbow trout and coho salmon smolts were sold for \$0.55–0.65 each, and Atlantic salmon smolts for about \$1.00.

In his report to the State of Alaska Department of Commerce and Economic Development, Forster (1995) estimated that the cost to the private producer of farmed Atlantic salmon was \$1.14–2.03 per pound, head on, gutted weight. Based on advances in technology and increased farm efficiencies, he projected that production costs for the year 2000 would be between \$0.73–1.19 per pound, head-on, gutted weight. His current estimate is that it is about \$1.00 (J. Forster, Forster Consulting, personal communication).

2.2 Salmon Production for Food

A production site for salmon farming invariably consists of a complex of on-shore buildings and tanks, and offshore floating cages or net-pens. Floating cages are usually associated with the freshwater nurseries for smolt production, and net-pens are associated with grow-out and production of marketable fish in marine waters. The 1998 Census of Aquaculture (USDA 1999) defines cages as structures '*normally used in larger, open bodies of water such as lakes or rivers,*' while net-pens are '*enclosures usually placed in protected bays or inlets used to produce fish.*'

Weston (1986), in his study of the environmental effects of floating mariculture in Puget Sound, recorded nine sites where Pacific coho and/or Atlantic salmon were raised commercially in net-pen facilities. Another permit had been granted, and others were pending. There were also three more sites for non-commercial culture, which is for research or to enhance fisheries. In addition there were five major and eight minor net-pen facilities used by tribes or sportsmen's clubs for delayed release of coho and chinook salmon. By 1990 there were 13 commercial sites, each limited to a total surface area of less than 2 acres, or 8,100 m² (WDF 1990). In response to the listing of Puget Sound chinook salmon as threatened under ESA, chinook salmon releases from minor-net-pen sites have been reduced or terminated (NWIFC 2000).

In its summary of the status of aquaculture for 1997, WRAC (1999) reported that net-pen salmon farming in the Pacific Northwest only occurred in Washington. Earlier in the 1990s net-pen rearing of salmon had been practiced in Oregon, California, and Idaho but had since ceased. Atlantic salmon dominated production (99%) in Washington, with the remainder being coho, chinook, and steelhead trout.

All salmon production sites in Washington, whether on or off land, are licensed appropriately. Sites are owned outright or leased (tenured). Companies may own and/or lease several sites, and consequently some sites are continuously active; others are developed but not always in use, and a few may be inactive and undeveloped. WRAC (1999) reported six companies with leases to sites in Washington in 1997. These included Domsea Farms Inc. (5 sites), Global Aqua US Inc. (3 sites), Moore-Clark Co. (USA) Inc. (3 sites and a hatchery), Scan Am (3 sites), Sea Farm Washington (3 sites), and British Petroleum (1 site).

In the last five years there has been considerable restructuring in the salmon aquaculture industry worldwide with some companies consolidating their position through merger and/or purchase of smaller companies. Consequently, the global industry is now dominated by a few international companies, although individual farms may still operate

under the name of the registered leaseholder. In Washington four different companies now hold the leases to 12 licensed net-pen production sites. These are:

- Cypress Island Inc., which has three leases by Cypress Island outside Anacortes and one lease in Skagit Bay; and (once under Northwest Farms) three leases in Rich Passage, one in Port Angeles harbor (formed by combining two previous leases), and one by Hartstene Island currently not in use.
- Sunpoint Systems, which has one lease in Rich Passage.
- Jamestown S'Klallum Tribe, which has one lease in Discovery Bay but not in use.
- Ocean Spar Technologies, a sea-cage manufacturing company which has one lease by Whiskey Creek near Port Angeles for research and development trials, but not in use.

In the State of Washington, statistics provided by WDNR (2001) indicate there are 166.67 acres currently leased by companies for commercial salmon net-pens, and a further 38.67 acres currently leased by the State, tribes, and private enterprises for net-pens used for the delayed release of Pacific salmon, and 0.39 acres for herring net-pens. All these sites have a different limit for the water surface area leased (for anchorages and navigational protection) and the internal surface area for the net-pens in production. The 10 commercial sites currently operational in Puget Sound have a total of 131 acres under lease from the State (ranging from 2–24 acres in size), with 21.5 acres permitted for the internal pen structures (range 21,000–170,000 sq. ft) (K. Bright, WFGA, personal communication). This area is little more than the larger marinas located on State-owned aquatic lands, any of which can be 15–20 acres in size.

The number of commercial net-pen farms in Washington is small by comparison with that on the east coast (Maine) and other countries. Maine has 42 permitted sites for salmon, and two for steelhead, of which six are currently idle (J. McGonigle, Maine Aquaculture Association, personal communication). Producers in Maine, of which there are 14 companies, are in the process of moving to single-year-class cultivation over the next two years. This should result in about one-third of the sites lying fallow each year.

In eastern Canada the industry is largely confined to New Brunswick. In New Brunswick there are about 60 farming companies, each with one or more permitted sites. There are also a few sites in Nova Scotia and Newfoundland. In western Canada there are 122 registered net-pen sites in British Columbia (BC), of which 104 are active (BCSFA 1999). The Highlands and Islands Enterprise (HIE) of Scotland recorded 440 growing sites registered in 1997 with the Agriculture, Environment and Fisheries Department of the Scottish Office (SOAEFD). Of these, 128 were fully stocked all year round, 202 were in rotation, and 100 were classified as inactive (HIE 1999).

2.3 Interactions of Farming with Commercial and Recreational Fishing

In a commentary on regional fisheries, the Marine Advisory Services of the Washington Sea Grant Program (WSGP 2001) stated that commercial fishing was a significant industry in Washington State, with nearly 3 billion lb. of fish and shellfish harvested annually, with a wholesale value over \$1.6 billion. However, the report also added that commercial fisheries around the world were collapsing and efforts in fisheries science

were turning more to conservation of resources and finding ways to harvest fish stocks in a sustainable manner.

The commercial fisheries of Puget Sound reflect these global trends. WDFW (1994) reported that commercial salmon harvest levels in the State of Washington had declined from a peak of over 10 million fish in 1985 to about 7 million fish in 1993, with most of these fish produced in hatcheries. Similarly recreational salmon fishing levels had declined from a peak of 1,100,000 fish in 1979 to just over 600,000 fish in 1993. More recent data by Didier (1998) put preliminary estimates of commercial salmon catch in the State in 1998 as only 1,618,300 fish, together with 141,604 fish in the subsistence catch by the tribes; and the sport salmon (recreational) harvest in 1997 was down to 451,425 fish. Data for the 2000 landings and prices of salmon in Washington provided by Pacific Fishing (2001) gave figures of 1,475,315 fish (5,342 mt) that landed in the State, with a value of \$8.5 million. Both landings and prices were considerably above those for 1999.

Much of the decline in the commercial harvest can be attributed to the shift from a terminal harvest to a high catch-per-unit effort in the offshore fishery. Eriksson and Eriksson (1993) described the parallel of the Swedish salmon fisheries in the Baltic Sea in their study of wild and hatchery propagated stocks over the 40-year post-war period. They concluded that wild fish were unable to cope with the present exploitation rates, and without the effective compensatory program, a reduction in stock-size of the magnitude shown by wild salmon in the Baltic would decrease the catch-per-unit effort to such a degree that there would be no economic incentive for a commercial salmon fishery.

In addition to fluctuating changes in ocean conditions, declines in the commercial harvest can also be attributed to the increased interest in recreational fishing in Puget Sound, and competitive pressure on the habitat. Drinkwin and Ransom (1999) projected another 1.4 million people would settle in the Puget Sound Basin by 2020, which would further degrade the already-stressed ecosystem. Their indicators included continued declines in bottom-fish populations, restrictions on shellfish harvesting, and rapid loss of freshwater, estuarine, and near-shore habitats. All these indicators are impacted by the increase in aquatic recreational activities, particularly recreational boating (see Section 2.4).

The decline in some fisheries populations in Puget Sound has reached significantly low levels. For example, in 1999 chinook salmon in Puget Sound and summer chum salmon in Hood Canal were listed as threatened by NMFS under the federal Endangered Species Act of 1973 (ESA). However, not all aquatic species are in decline. In its current report on the health of Puget Sound, PSWQAT (2000) noted that the waters of the Sound were still home to over 220 species of fish, 26 different kinds of marine mammals, 100 species of sea birds, and thousands of species of marine invertebrates. Some species were migratory, while others remained in the Sound all year round. Some populations, such as harbor seals and California sea lions, were increasing rapidly. The trends in the counts of harbor seals indicated some 12,000 now living in the Puget Sound region, or double the number recorded in 1985. They attribute these increasing numbers to protection under the Marine Mammal Act of 1972, variable abundance of food resources, such as Pacific herring and Pacific hake, decreasing levels of contamination in the water, and tolerant

interaction with human interventions. As major fish predators in Puget Sound they must be contributing to the decline of some fisheries. In a study on the impacts of California sea lions and Pacific harbor seals on salmonids in the west coast States, NMFS (1997b) estimated that the total bio-mass consumption by these pinnipeds along the coasts (a minimum of about 217,400 mt) amounted to almost half of the commercial harvest of the three States.

There is no evidence in the literature that the presence of 10 operational net-pen salmon farms in Puget Sound has contributed to the decline of the fisheries populations. In fact Henriksson (1991), in his study on the effects of fish farming on natural fish communities in the Baltic Sea, described an overall recruitment by small fish around farms compared with reference areas, followed by the increased abundance of certain fish species such as, *inter alia*, perch, roach, white bream, and bleak. However, Crutchfield (1989) noted that fishermen opposed the growing salmon net-pen industry for encroachment on fishing grounds or transfer/over-wintering lay-up areas. He believed this was a legitimate complaint at the time but suggested it could be rectified easily by restricting net-pen farms in such sites, although this would add another site burden to farmers.

There is little evidence in the literature that deliberate releases or escapes of farmed fish from operational net-pen sites have resulted in the sustained natural production of a population providing a new commercial resource in Puget Sound. Rensel et al. (1988), in a 5-year tagging study with farmed coho salmon, showed that the annual estimated recovery (estimated catch plus escapement) averaged 17.1%, which was similar to recovery rates of coho salmon released from other facilities at about the same time. They estimated approximately only 0.2% of the released coho salmon survived to enter streams in the general vicinity of the net-pens. They concluded that the Puget Sound commercial net fishery benefited most from the program.

In Washington, in addition to the 27 releases of Atlantic salmon made by WDFW between 1951 and 1991, records by WDFW (Amos and Appleby 1999) indicated a total of 613,639 Atlantic salmon escaped from farms between 1996 and 1999. There had been escapes also in previous years (1990–1995), evidenced by the fact that fish were taken in the commercial and recreational catches, but at that time reporting was not a regulatory requirement. However, a sustained natural population has not been established.

Similarly attempts to establish Atlantic salmon in the waters of British Columbia were made between 1905 and 1935. These have also been supplemented with reported escapes of 286,885 farm Atlantic salmon between 1988 and 2000 (McKinnell et al. 1997, and A. Thomson, DFO, personal communication) but again no sustained natural production has been recorded. A total of 9,096 were recovered up to 1995, mostly in the area where the abundance of salmon farms was the highest. Wing et al. (1998) report that 89 Atlantic salmon which had escaped from marine aquaculture facilities in British Columbia and Washington were caught in Alaska fisheries between 1990 and 1995. New data by Thomson (DFO, personal communication) puts the number at 556 by 2001.

Losses of fish from net-pens are not always due to escapes. Moring (1989), in his documentation of unexplained losses of chinook salmon from small (5.5 m³) experimental saltwater cages with intact netting were on average 8–38% for individual locations, and 2.5–46.5% for individual cages. He attributed the losses to rapid decomposition of carcasses, scavenging by birds, mammals, and fishes, and to a lesser extent escapes. Actual unaccounted-for losses from commercial net-pens are currently in the order of ±2–5% (P. Granger, WFGA, personal communication). This is primarily because unexplained losses are few. In practice, fish arrive from hatcheries inventoried, and further inventories are taken each time they are moved for grading or changing nets. The accuracy of the inventory depends on how the fish are being handled.

Escapes have also occurred from net-pen salmon farms in Norway, Chile, and Tasmania. In Norway, Gausen and Moen (1990) reported that escaped fish entered Norwegian rivers in great numbers, but most (>20%) were found only in rivers having farms situated closer than 20 km from the outlet. Lura and Saegrov (1991) documented the successful spawning of farmed female Atlantic salmon in Norwegian rivers, where it is a native species, and Lura et al. (1993) recorded some differences in spawning behavior between a single farmed fish and wild fish. For example, the redd of the female farmed fish had more pockets (nine versus an average of two) but fewer eggs (459 compared with an average 707). Jonsson et al. (1991) described differences in life history and migratory behavior between wild and hatchery-reared Atlantic salmon. In the sea, wild salmon survived twice as well as hatchery fish, ascended the rivers earlier, and were injured less during spawning. Hatchery-reared fish, on the other hand, stayed for a shorter period in the rivers, and a larger proportion returned to sea without spawning.

Crutchfield (1989) reported that fishermen opposed the net-pen industry for adverse effects of farmed fish on market prices. He recognized that this was a complex point, but thought competition between farm and wild fish would broaden as farm salmon could be found year-round and wild salmon in relatively narrow windows – normally four months of the year, but much less in Washington where trollers and gill-netters were restricted. He concluded that farmed salmon would either moderate price increases or actually cut real-price increases for domestic wild salmon. However, he added that imports were much greater than the supplies of equal-quality troll-caught chinook and coho. Again, his conclusions proved to be correct, as evidenced by the imports of Atlantic salmon in 2000 which totaled over 130,000 mt with a value of \$741 million (USDA 2001), mostly from Chile and Canada.

From his economic and futuristic survey of the industry, Crutchfield (1989) indicated that 79% of wholesalers and distributors felt that fresh farmed Atlantic salmon were a direct substitute for fresh Pacific fish, and that 26% felt that farmed Atlantic salmon competed directly with frozen Pacific salmon. He said that exports of US wild salmon to Europe, which was about 10–15% by value of total production, would feel the impact of farmed salmon most severely. European smoked fish processors had all gone over to Atlantic salmon. However, he concluded that all the conjecture was insignificant as the output of farmed salmon in Washington in the long-term had little or no measurable effect on prices determined by worldwide supply and demand.

2.4 Interactions of Farming with Recreational Activities in Puget Sound

The State of Washington Department of Licensing (WDL) reported that the number of registered recreational boats in the State was about 250,000 (WDL 1997). This was double the number of boats registered in 1984. A more recent statistic (PSWQAT 2001) stated that people living in Puget Sound own more than 165,000 power boats, 21,500 sailboats, 43,500 canoes and kayaks, and numerous other watercraft. This had necessitated the installation of 43 new pump-out stations in the Puget Sound Basin since 1994, with the construction of 15 more on line.

Goodwin and Farrel (1991) published a directory of marinas and moorage facilities in the State in 1991, and listed 379. Kitsap County had 26 facilities and 2,968 wet moorage slips. The 20 facilities in Kitsap County which completed the survey data offered a total of more than 4 miles of dock and guest-dock space to recreational boats. The State's Interagency Committee for Outdoor Recreation (ICOR) made a comprehensive field inventory of motorized boat launches in the State in 1997 and identified 984 such sites (ICOR 2000). The typical marina or yacht club in Puget Sound leases between 2–20 acres of aquatic lands from the State (WDNR 2001). More importantly, these facilities displace areas which have probably been near-shore habitat for juvenile fish.

Based upon past studies of marinas for the State's Department of Fisheries, Cardwell et al. (1980) considered reduced dissolved oxygen (DO) and increased water temperature the greatest potential threat to aquatic life in Puget Sound marinas. Although coliform contamination of shellfish, the leaching of antifouling paints, and the introduction of hydrocarbons via the exhausts of outboard motors posed potential or real threats, they stated this could all be controlled if marinas were well managed and had sufficient flushing to prevent large temperature and DO changes. Although they recognized that the statistical relationship between flushing and changes in these parameters measured in the study was weak, they judged that a minimum flushing rate of 30% was adequate for the purpose. This value was based on a 1.82 m tidal range computed for a 24-hr period. If the marina was in an estuary where tidal ranges never attained 1.82 m, then the minimum overall flushing rate was about 15%.

Subsequently, Cardwell and Koons (1981) documented several water quality perturbations within marinas and moorage facilities. Pollutant inputs included runoff from parking lots and storm drains, hydrocarbons from outboard motor exhaust, heavy metals from antifouling paints, and biocides such as creosote and pentachlorophenol in wood piling and docks. Indirect effects resulted from nocturnal diminutions in dissolved oxygen due to respiration of phytoplankton blooms and diurnal elevations in water temperature due to solar radiation.

In an earlier study on the effects of hydrocarbons on marine organisms consumed by humans, Clark et al. (1974) exposed mussels and oysters to a diluted effluent from a two-cycle outboard motor in a running seawater system. The organisms displayed physiological stress, degeneration of gill tissue, and uptake of paraffin hydrocarbons from the effluent. Mussels showed an immediate response to the pollutant as well as a

significant delayed mortality after removal. The oysters were less affected as they had the capability of closing for longer periods of time.

Milliken and Lee (1990) carried out a comprehensive review of literature on recreational boating and pollution dating back over 40 years. They focused on four of the principal pollution problems associated with recreational boating, namely sewage, engine pollution, anti-fouling paints, and plastics debris. Regarding boat sewage, they found that, although the volume of wastewater discharged from recreational boats was small, the organic matter in the wastewater were concentrated, and consequently the biological oxygen demand (BOD) was much higher than that of raw municipal sewage or treated municipal sewage. Furthermore, the concentrations built up around the marinas as they were usually sheltered and poorly flushed. They also found that there was both a positive and negative correlation between the density of boats and fecal coliform concentrations in the water, but that background fecal coliform levels from overland storm-water runoff exceeded that caused by boats.

WDFW (1997a) reported that anglers took 1.5 million trips to Puget Sound and the coast in 1996 to catch 'food fish' – the State-designated category for salmon, sturgeon, carp, and most marine fish. Departmental statistics in the 1996–1997 Annual Report (WDFW 1997b) indicate that 358,954 fishing licenses for food fish were sold in 1996, together with 596,898 licenses for game fish (primarily freshwater species), and 89,393 licenses for steelhead. Zook (1999) estimated that recreational angling for non-native game fish contributed about \$735 million annually to the State's economy.

2.5 Economic Benefits of Salmon Farming to the State

Dicks et al. (1996), in a study on the economy-wide impacts of US aquaculture, concluded that, in 1992, the aquatic farming industry generated approximately \$5.6 billion in gross domestic product (GDP) and over 181,000 jobs. Production activities accounted for about 8% of the income and 16,500 jobs, while upstream activities, such as equipment, supplies, feed, seed, fertilizer, labor, and financing, accounted for about 23% of the income and 40,500 jobs. Downstream activities, such as transport, storage, processing, manufacture, distribution, and sale of products, etc., accounted for 69% of the income and approximately 125,000 jobs.

Stokes (1988) concluded there were many economic net gains statewide from salmon farming in the State of Washington. In a study of 64 benefit-cost and sensitivity analyses for ratios of gross economic gains (household income) to potential losses (adverse property consequences), and reflecting a wide combination of data, the ratios all exceeded unity. Average results for all calculations and results calculated under assumptions favorable to the industry indicated substantial net economic gains. The study had three tasks, regional input-output analysis, state fiscal analysis, and property value analysis.

2.5.1 The contribution of salmon farming to seafood production

In its annual summary of national fisheries statistics, DOC estimated commercial aquaculture production in 1997 of 314,657 mt (693.7 million lb) with a value of \$886

million (DOC 1998). Total exports of edible fishery products were 915,000 mt (2.0 billion lb) valued at \$2.7 billion. The total imports of edible fishery products were 1.5 million mt (3.3 billion lb) valued at \$7.8 billion.

With regard to salmon, the DOC fisheries statistics estimated exports of fresh and frozen salmon in 1997 were 86,157 mt (189.9 million lb) valued at \$307.5 million. Canned salmon exports were 37,023 mt (81.6 million lb) valued at \$135.4 million. Imports of fresh and frozen salmon in 1997 were 73,847 mt (162.6 million lb) valued at \$344.4 million, and imports of canned salmon were 557 mt (28.8 million lb) valued at \$4.8 million. In an early review of the economics and future of salmon farming in the Pacific Northwest, Crutchfield (1989) concluded that a fully developed salmon industry in Puget Sound would make a positive contribution to the economies of the region but would do little to reduce the imbalance of international trade or even the trade in seafood. He estimated that salmon imports were less than one-tenth of one percent of the \$150 million international trade deficit, and a salmon farming industry would have little or no impact.

USDA more recently reported (USDA 2001) that Atlantic salmon imports in 2000 reached 289 million lb (131,000 mt), as shipments increased in all three main categories (fresh whole fish, frozen whole fish, and fresh and frozen fillets). Imports of fillets remained the fastest growing category and made up over 50% of imports. The majority of imports came from Chile (filleted products) and Canada (fresh fish), with Chile taking over as top supplier with shipments rising by 51%. The value of Atlantic salmon imports in 2000 was \$741 million, and the market continues to expand.

In a comparative review of 1999, Northern Aquaculture (2000) reported that actual production of salmon in Washington in 1999 was 5,500 mt, with a value C\$38 million (just below US\$30 at that time). Production was about the same as in 1998. In Maine production of Atlantic salmon was 12,100 mt (down 8%) with a value of C\$111 million. In Canada BC production was 47,000 mt of Atlantic and Pacific salmon (chinook and coho). This figure was up 19% over 1998. The value was C\$347, of which 86% was for Atlantic salmon. In New Brunswick production of Atlantic salmon and steelhead was about 27,000 mt, with a value of about C\$140 million.

The Washington Fish Growers Association FGA (WFGA) reported that total production in Washington in 1999 was 14 million lb. dressed weight (6,545 mt) of Atlantic salmon (99%) and steelhead (1%). The total value was about \$30 million. About 95% of the farmed products were sold on the national markets as whole dressed fish, and 5% were exported as fresh fillets (P. Granger, WFGA, personal communication).

2.5.2 The impact on employment and wages

Crutchfield (1989) predicted that a fully developed net-pen salmon industry in Puget Sound would be useful in contributing to employment in the area but would not be a significant factor. His prediction has proved to be very accurate.

Some earlier estimates regarding employment in the industry were rather optimistic. Inveen (1987) suggested primary employment in a typical net-pen operation in Puget

Sound was 8–10 persons with an average annual wage of \$19,000 (range \$14,500–30,000). Capital investment required was about \$750,000–1 million, with annual operating expenses of \$1.4 million (feed 30%, labor 14%, smolts 12%, other 44%). Assuming eight more jobs in secondary activities, the total contribution to employment by 10 farms would be 160–200 jobs. This was similar to employment profiles in Norway. Stokes (1988) in a report to WDFW estimated that the State economy would gain \$38–48 million in output, \$11–21 million in household income, and 257–303 jobs from the existence of five Atlantic salmon farms in the State, with typical production figures of 1 million lb/annum and \$5 million revenue. The average impact on the (Kitsap) County for one operational site would be \$5.8–6.8 million in output, \$1.1–2.1 million in household income, and 40–51 jobs.

For the state of the industry in 1999, with 10 operational sites, WFGA reported current employment in the local industry of 65 full-time positions, 5 part-time positions, and approximately 200 more employed indirectly down the line (P. Granger, WFGA, personal communication). By comparison, Young et al. (1998) reported 1,000 full and part-time employees in the net-pen salmon industry in Maine, with 38 operational sites, which equated to about 750 full-time jobs. In addition, about 500 full-time jobs in Maine were directly dependent on contracted employment with salmon farms, such as trucking, diving, health management, and other services. Indirect impacts of employment induced in the local communities by salmon farms represented another 1,000 jobs.

BCSFA (2000) reported that the salmon farming industry in Canada employed 3,400 people, mostly on the BC coast. In 1999 the BC salmon industry produced 47,000 mt of salmon valued at C\$347 million.

Estimated wages for a direct employee in the industry in Washington were up to about \$45,000, and for an indirect employee about \$35,000 (P. Granger, WFGA, personal communication). These wages continued to be above average for the collective agriculture sector (which includes forestry and fishing) in Kitsap County, which accommodates most of the net-pen sites. Kitsap County (2000b) reported that the annual average wage (1994) for this sector was \$16,268. This was higher than the statewide average of \$13,767 primarily, it noted, because of a small number of highly paid workers in aquaculture and fishing. However, about 70% of jobs in the collective agriculture sector were in agricultural services industries, with the largest industries being lawn and garden services, and non-livestock veterinarian services.

2.5.3 The impact on coastal property values

In a study of Puget Sound waters for coastal sites for net-pen fish farms, Weston (1986) provided interim tidal velocity and water quality guidelines to minimize their impact. Only 19 areas were identified as acceptable, relevant to specific farm capacity and the proximity of special habitats. Five more areas, in Puget Sound Basin and beyond, were acceptable without limitation.

Parameters relevant to the existence of shoreline industries or private properties, or any anticipated real estate developments, were not included in Weston's early guidelines,

although the Basin was in the middle of major population growth and property development. In its period summary on the health of Puget Sound, PWSWQAT (2000) noted the Sound was currently home to almost exactly 4 million people, or double the population of the 1960s. Annual growth was about 50,000 people (1.5%) and the population was expected to reach 5 million people by the year 2020.

The majority of preferred net-pen farm sites identified by Weston (1986) were located in waters around Kitsap County and Mason County. In the last 25 years (1970–1995) the population of Kitsap County, in the middle of the Sound, has increased 116.8%, compared with 59.1% across the State. Much of this was due to the immigration of 47,104 persons between 1980 and 1995 (Kitsap County 2000a). Property development was a priority and principal activity, as the collective finance, insurance, and real estate employment sector showed an increase in employment by 255% (1970–1995), of which real estate garnered one-third of the jobs (Kitsap County 2000b).

Alpine Appraisers (1988) undertook a comparative study of visual and market effects of net-pen fish farms on property values around Puget Sound. They concluded that floating net-pens had no effect on upland property values in the area studied (Mason County and Kitsap County), and that they had 'minimal', if any, visual impact at distances over 2,400 lineal feet. Stokes (1988), in a statistical analysis of 335 property listings and assessed value in water-front areas throughout Puget Sound in the vicinity of net-pen complexes, determined the average front footage price of \$409 had a standard deviation of \$290, half of which could be accounted for by general location (County), land type (high-low bank), and improvements (water, sewer, etc.). The remaining, or 'residual' price variation, was presumed to result, at least in part, from variations in visual aesthetic quality.

Parsons (1991) studied the effect of coastal-land-use restrictions on housing prices in the State of Maryland. He found that housing prices in the critical area with water frontage increased by 46–62% due to restrictions, compared with 14–27% without water frontage, 13–21% for those just outside the area, and 4–11% for those three miles away. The direct beneficiaries of coastal-land-use restrictions were the current owners of housing in the community, while the losers were owners of undeveloped or restricted land, renters, and future owners.

Garrod and Willis (1992) studied the effect of selected countryside characteristics on house prices in a rural area of England covering 4,800 km². They found that many variables (such as within 1 km proximity to woodland, river or canal, or rural settlement) had a positive influence on house prices of 7–10%, 4–9%, 8–12%, respectively. Furthermore, the characteristics of an open water view or gradient slope had no observable effect; and being close to wetlands or having woodland or urban views had the effect of reducing house prices.

2.6 The Regulatory Structure for Commercial Enterprises

The policies and regulations (and their enforcement) for aquaculture introductions in the State of Washington and the Province of British Columbia were reviewed and summarized in detail by Elston (1997) in his study of pathways and management of

marine non-indigenous species (NIS) into the shared waters of British Columbia and Washington. Aquaculture had been identified as one of six pathways for NIS introductions for the study, and in his final report to the Puget Sound Water Quality Authority, the US Environmental Protection Agency, and the Department of Fisheries and Oceans Canada, he stated that the adequacy of information available to assess the relative risks of introductions through aquaculture was good. This was because for more than a decade Washington and British Columbia had in place state/provincial (and federal) procedures specific to aquaculture. He noted that intentional introduction of aquaculture species was then far more restricted than in the past. He stated that technology could assist further in reducing the risk from exotic species introductions by, for example, culturing only strains of sterile organisms. Elston concluded that the risk from aquaculture introductions from aquaculture was well-defined, the industry was highly regulated, and active processes were underway for continuous review of aquaculture activities as they involved NIS.

Traditionally the policy of the State of Washington has been supportive of aquaculture. The State was one of the first to recognize that aquaculture was a form of agriculture and enacted legislation in 1985 which designated the Department of Agriculture as the lead agency, with WDF responsible for disease control and prevention regulations. The current policy of the State fosters the commercial and recreational use of the aquatic environment for production of food, fiber, income, and public enjoyment from state-owned aquatic lands, and identifies aquaculture among legitimate uses. In its policy implementation manual for the use of the State's aquatic resources (WDNR 2000b) aquaculture is specifically designated as an aquatic land use of statewide value. WDNR generally encourages this use, and it takes precedence over other water-dependent uses which have only local interest values. While commenting on the possible environmental impact on aquaculture by surrounding activities, and vice versa in a discussion on net-pens and floating rafts, the manual states again that aquaculture remains a favored use of state-owned aquatic lands. WDNR (1999) recently published a technical report on the potential offshore finfish aquaculture in the State.

Amos and Appleby (1999) summarized the roles and responsibilities of the regulatory authorities in the State of Washington with regard to the management of salmon farming in State waters, and particularly Atlantic salmon farming. Their summary forms the basis of the following annotations of the regulatory structure for commercial enterprises producing either Pacific or Atlantic salmon.

(i) WDFW has management and regulatory authority over all free-ranging fish in the State. The authority of WDFW over commercial fish culture in State waters is restricted to disease control and protection of wildlife in general.

- The Finfish Import and Transfer Permit (WAC 220-77-030) assures that diseases, pests, and predators are not introduced or transferred. In addition, under a legal settlement, WDFW is required to kill and conduct biological examination of any Atlantic salmon encountered by agency staff.

- Hydraulic Project Approval (RCW 75.20.100, WAC 220–120), or HPA, assures that all construction projects ensure protection of wildlife and habitats. However, the authority of WDFW to require HPAs of aquaculture workers at their sites is not clear.

WDFW, in association with the State of Washington Department of Ecology (WDOE) and Department of Natural Resources (WDNR), provides guidance to state and local agencies siting farms to avoid adverse impacts on the environment. In association with the State Department of Agriculture (WDA), it develops disease control regulations with regard to human health and safety.

(ii) WDOE has regulatory authority over discharges of pollutants into State waters for the protection, preservation, and enhancement of the environment.

- The National Pollution Discharge Elimination System Permit (40 Regulation CFR, Part 122.21), or NPDES, assures compliance with state and federal water quality laws.
- The Water Discharge Permit (RCW 90.48) assures that discharges and wastes do not adversely affect water quality and standards.

Under the Clean Water Act and the Water Pollution Control Act, WDOE can take regulatory action against net-pen operators who allow Atlantic salmon to escape. This follows the determination by the Pollution Control Hearings Board (PCHB) that Atlantic salmon are 'pollutants.' The PCHB also adjudicates appeals over permits issued by WDOE. In association with WDFW and WDNR, WDOE provides guidance to state and local agencies on siting farms to avoid adverse impacts on the environment.

(iii) WDNR has regulatory authority over state-owned aquatic lands, including all bedlands of Puget Sound, navigable rivers, lakes, and other waters. The authority also extends over lands covered and exposed by the tide, and most shores of navigable lakes and other fresh waters.

- The Aquatic Lands Lease (RCW 79.90–79.96), or ALL, assures the specification of all uses of the land and the proposed facilities.

WDNR, in association with WDFW and WDOE, provides guidance to state and local agencies on siting farms to avoid adverse impacts on the environment.

(iv) WDA is responsible for assuring the safety of the State's food supply, providing protection from diseases and pests, and facilitating movement of agriculture products in domestic and international markets. With WDFW it jointly develops disease control regulations with regard to human health and safety.

(v) Local counties in the State of Washington act as lead agencies for applying the environmental policies of the State, and the management of their respective county shorelines.

- The State Environmental Policy Act (RCW 43.21C, WAC 197–11), or SEPA, assures consideration of social and environmental impacts of proposed actions.

- The Shoreline Management Act (RCW 90.58), or SMA, assures appropriate and orderly development of state shorelines, management of their uses, and preservation of their natural character.

(vi) A number of federal agencies [NMFS, the US Army Corps of Engineers (ACE), US Fish and Wildlife Service (USFWS), US Coast Guard (USCG), and the Environmental Protection Agency (EPA)], together with respective State agencies, have management and regulatory authority over the use of all waters by the public.

- The Section 10 Permit assures protection of public interest, including navigation, water safety, and water quality.

(vii) NMFS administers the ESA for anadromous salmonids. It may require commercial salmon farmers to obtain permits to take fish for their use due to the impact on listed species. Jointly in collaboration with USFWS and WDNR, NMFS permits the use of predator control methods (non-lethal) for birds and mammals in accordance with permit restrictions.

(viii) The US Food and Drug Administration (FDA) is responsible for the protection of consumers by enforcing the Federal Food, Drug, and Cosmetic Act, and several related public health laws. It is also responsible for the safety of feed and drugs for pets and farm animals. Salmon farmers are restricted to the use and conditions of veterinary medicines, drugs, growth enhancers, and other chemical supplements licensed by FDA.

(ix) The Treaty Tribes of the State of Washington co-manage fisheries resources in the State with WDFW and thus have input into disease control regulations (see (i), above).

2.7 The Regulatory Structure for Public and Tribal Hatcheries

Public and tribal hatcheries producing Pacific salmon (and other fish) in the State of Washington must conform to the same general regulations regarding commercial hatcheries and farms. These regulations, as described, are all concerned with protection of the environment, or the health and safety of other plants and animals, including human consumers. However, since 1994, when a number of Pacific salmonid species in the region were listed for protection under ESA, there are some differences in regulations for public and tribal hatcheries. The production of listed fish in public and tribal hatcheries is now restricted to recovery purposes only, and not for subsequent commercial or recreational harvest.

Certain sections of the ESA pertain to the necessary taking of listed fish for public and tribal hatchery operations, and also for research. For example, in Section 7 of the Act, hatcheries in ESUs where there are single listed stocks are permitted a directed take of fish for recovery operations, and an incidental take in ESUs with mixed-stocks.

In an attempt to avoid further layering of regulations the NMFS is proposing to adopt a new approach. Through the so-called 4(d) Rules, public and tribal authorities (and the private sector) can develop their own conservation strategies to be approved by NMFS.

After approval of a specific conservation program, any activities appropriately implemented will automatically be in compliance with the ESA and will not require individual permitting.

As part of this approach the NMFS has been working with management agencies in the region to develop Hatchery and Genetic Management Plans (HGMPs). The HGMP procedure provides a thorough description of each hatchery operation, including the facilities used, methods employed to propagate and release fish, and measures of performance. There are also sections dealing with the status of listed stocks which may be affected by the plan, anticipated listed-fish 'take' levels, and a description of measures to minimize risk to listed fish. However, once completed, accepted, and followed, hatchery managers are assured that their activities are all in compliance with ESA and no further permitting is required.

3. POTENTIAL ISSUES FOR HUMAN HEALTH AND SAFETY

The third chapter is specific to the potential issues for human health and safety from net-pen salmon farming in the Pacific Northwest region. It is sub-divided into five parts. After a brief introduction to global and national responsibilities for food safety, the second part deals with the chemicals and chemical contaminants in materials used in farm production operations. Possible sources include metallic paints, feed ingredients, and chemo-therapeutants. The third part concerns the transmission of diseases, and the common pathogenic diseases are reviewed. The fourth part deals with the processing and quality of farm products, specifically the proximate composition of farm fish, and differences between farm and wild salmon species. The final part concerns worker safety.

3.1 General Food Safety

In 1995 the members of the United Nations Food and Agriculture Organization (FAO) formally adopted a *Code of Conduct for Responsible Fisheries*. The Code, which was then published (FAO 1995), advocated safe and high quality fisheries products. Article 9 of the Code, which was specific to aquaculture, was then broken out and detailed in a subsidiary document called, *Aquaculture Development* (FAO 1997). The section on *Responsible Aquaculture at the Production Level* called for the global aquaculture industry to make safe and effective use of feeds, feed additives, chemo-therapeutants, and other chemicals, and to promote the use of aquaculture practices and methods which reduced the hazards. As a signatory of the FAO Code, the US has ensured that its national aquaculture industry will abide by all the intentions contained in Article 9.

The terminology used in this Chapter is adopted from the World Health Organization (WHO) report on *Food safety issues associated with products from aquaculture* (WHO 1999). The terms '*hazard*' and '*risk*' have specific definitions. A '*hazard*' is a biological, chemical, or physical agent in food, or a condition of food, with the potential to cause harm. A '*risk*' is an estimate of the probability and severity in exposed populations of the adverse health effects resulting from a hazard(s) in food.

The greatest risk to human health from seafood occurs from post-harvest contamination and loss of product quality. However, this section confines its review to the risks to human health from hazards which might be incurred in the pre-harvest production of farm salmon raised in marine net-pens. When appropriate, it compares the risk with products from wild harvests, other forms of aquaculture, and agriculture.

Potential hazards to food safety by the consumption of farm salmon raised in net-pens, or by human contact with farm operations, may include:

- Toxic chemicals and chemical compounds which have been accumulated by the fish from their aquatic environment, or from their food, or as residues from veterinary medicines.

- Pathogenic organisms in the fish, such as parasites, viruses, and bacterial pathogens, which may also be harmful to humans.

The overall risks of feed-borne human illnesses from cooked seafood (wild and cultured) are low compared with risks from other animal products. Otwell (1989) pointed out that the estimated risk of disease from consuming a 4-oz serving of cooked seafood was 1 in 5 million servings, but for chicken it was 1 in 25,000 servings. However, unlike other meat products, seafood is often eaten raw or lightly cooked, and the estimated risk rises to 1 in 250 servings for the consumption of uncooked shellfish. The risk from consumption of uncooked fish is also higher than for cooked fish.

Primary responsibility for regulating all seafood safety, including farm products, rests with the FDA. The FDA performs its functions by adopting BMPs, approving hazard analysis and critical control points (HACCP) plans, and promulgating regulations. Enforcement is primarily through inspection of handling and processing plants to ensure compliance with BMPs, HACCP plans, and regulations. The FDA also approves and regulates the use of drugs and additives used in all domestic and farm animal feeds, which includes feeds used by the aquaculture industry.

3.2 Chemicals and Chemical Contamination

Toxic chemicals and chemical compounds are accumulated by fish and shellfish from their aquatic environment and from their food. Chemical contaminants which are potentially hazardous to humans through seafood consumption, including farmed salmon, are heavy metals, feed-borne toxicants, and chemo-therapeutics.

Human illnesses resulting from chemicals in the environment are more commonly associated with long-term exposure. Jensen and Greenlees (1997) found that illness associated with a single meal was rare. Moreover, areas of chemical contamination tended to be concentrated in space and sometimes in time. For the most part, sensible precautions and local regulations have ensured that fish farm facilities have been situated where risks of chemical contamination were minimized. Sites have always been far from industries associated with environmental pollutants and the out-fall of human sewage treatment plants.

3.2.1 Heavy metals

Metal ions enter fish by absorption through the gills or from food. The latter is more common. In general, fish regulate the concentrations of metal compounds in muscle tissue within tight limits. Consequently, concentrations of inorganic metals do not exceed regulatory limits even when the fish are harvested from environments with high metal concentrations. The exception to this rule is tin, in the organic form of tributyl-tin, and mercury in its organic form of methyl-mercury, which a number of sources (Cappon 1983, Jensen and Greenlees 1997, WHO 1999) indicate can be accumulated through the food chain.

Tributyl-tin was commonly used as a biocide in anti-fouling paints on recreational boats (Milliken and Lee 1990) in the marine environment. Subsequently it was used on net-pen structures. However, due to its rapid leaching, tributyl-tin and its breakdown products were found in the water, sediment, and in organisms where there are concentrations of recreational boats. Later it was demonstrated that salmon in treated pens could accumulate tin in their tissues. The use of tributyl-tin was consequently restricted in Europe and North America, and WHO set a limit of 3.2 µg/kg body weight for tin in humans (WHO 1999). Based on this figure, and levels of tin found in fish reared in cages treated with tributyl-tin, a daily consumption of 150 g of salmon by a 70 kg person would be necessary to exceed this level. At least 13 States in the US have enacted their own legislation on the use of tributyl-tin, in addition to that of the EPA.

Methyl-mercury bio-accumulates in the food chain, and is of particular concern for long-lived predatory fish. Farmed salmon live on a diet of prepared pelleted feeds, and are usually harvested before 3 years of age so there is less opportunity for methyl-mercury to accumulate. There are no records of farmed salmon accumulating methyl-mercury. However, there are examples of methyl-mercury accumulation in wild salmon. Cappon (1983) recorded mercury levels of 0.3–0.8 mg/kg in wild salmon from the Great Lakes, which is just below the maximum permissible limit of 1.0 mg/kg.

3.2.2 Manufactured feeds

The risks to human health from feed-borne toxins have long been known, and feed manufacturing standards, including the composition and labeling of fish feeds, are strictly regulated by the FDA. However, the ingredients for the compounding of animal feeds still come from a variety of suppliers, and some risks still remain. Of particular concern for human health are certain animal byproducts, oilseed meals, grains and byproducts, hormones, pigments, antioxidants, and most recently some organic compounds called 'dioxins.'

(i) Animal byproducts

Rendered animal protein ingredients, including various meat and bone meals, poultry byproducts, blood, and marine processing wastes have been used for decades to replace some fish meal in the diets of salmonids. However, the dietary inclusion levels for most of these products have been limited because of concerns of poor digestibility, nutritional value, palatability, and variable product quality. Efforts to avoid excessive phosphorous levels in hatchery effluents have also limited the use of some of animal byproduct meals, which may include relatively high levels of indigestible phosphorous from bone.

The use of rendered animal byproducts in animal feeds has been severely constrained since 1997 by new standards imposed by FDA in the Code of Federal Regulations (CFR) Title 21. Regulation 21 CFR, Part 589.2000 prevents the inclusion of certain mammalian proteins in feeds for cattle and other ruminant animals. This is intended to prevent the establishment or amplification of bovine spongiform encephalopathy (BSE) in the US by prohibiting the feeding of protein from ruminants (such as cattle, sheep, goats, deer, elk, buffalo, and antelope) to ruminants. Exempt from the ban is mammalian protein derived

from pure pork or horses slaughtered as single-species facilities, inspected meat products, blood and blood products, gelatin, and milk products.

Feeding of mammalian proteins to fish is not prohibited by the regulation. However, the final regulation requires feed manufacturers who handle both prohibited mammalian protein and non-prohibited mammalian /non-mammalian protein to follow strict measures to prevent cross contamination of feeds which may be fed to ruminants, label finished feeds appropriately, and maintain records of ingredient purchases and disposition of the finished feeds. Customer concerns and changes in market availability of many of these byproducts (e.g., meat and bone meal) have effectively eliminated these ingredients from salmonid feeds. The use of exempt products, including blood meal and byproducts of fish and poultry processing, still continues, although levels of dietary inclusion may be constrained by price and availability.

Studies regarding the potential for BSE transmission to humans through discharge of BSE prions into the aquatic environment via uneaten fish feed and feces have not been reported in the scientific literature. However, risks from a rendering plant disposing of cull cattle carcasses in the catchment area of a chalk aquifer used for drinking water have been examined by Gale et al. (1998). They calculated that the risk to consumers who drank the water was remote, and an individual consuming two liters daily for 45 million years would have a 50% chance of any infection.

(ii) Oilseed meals, grains, and byproducts

Fish meal in salmon feeds may be partially replaced by soybean, cottonseed, and canola meals. The dietary inclusion level is governed by available content of essential amino acids, palatability, and whether compounds toxic to the fish or anti-nutritional factors are present. Dabrowski et al. (1989) and Sanz et al. (1994) found that soybean meal products could replace a high percentage (25–40%) of dietary fish meal without affecting growth of rainbow trout. However, dietary levels of some soy products were limited by the presence of compounds which induced intestinal enteritis in Atlantic salmon (Baeverfjord and Krogdahl 1996) and rainbow trout (Refstie et al. 2000). Salmon feeds may also include low levels (<10%) of wheat and wheat byproducts, such as wheat middlings, as binding agents and sources of dietary energy.

In recent years, oilseeds and grains have been modified by genetic engineering to produce crops with increased yield and decreased reliance on herbicides and pesticides. Few published data are available regarding their safety and nutritional value as animal feed ingredients. Research by Hammond et al. (1996) has shown, however, that the feeding value (nutritional value) of soybeans to rats, chickens, catfish, and dairy cattle is not affected by genetic modifications which impart tolerance to mid-season application of the herbicide, glyphosate.

The use of genetically modified (GM) oilseeds and grains in animal and human foods has gained considerable attention in the US and the European Union because of uncertainties regarding their effects on human health and the environment. Of concern are modifications that introduce previously unknown allergens in food products, or affect

native plants through cross-pollination. The FDA is unaware at the present time of scientific data indicating that foods developed through genetic modifications differ as a class in quality, safety, or any other attribute from those developed by convention breeding techniques. In recognition of the importance of issues surrounding the safety of bio-engineered foods, the Codex Alimentarius Commission (established by WHO and FAO) in March 2000 appointed the Codex Ad-hoc Intergovernmental Task Force on Foods Derived from Biotechnology. Its mandate is to study the safety of such foods, their effects on the conservation and sustainable use of biological diversity, and also their effects on human health.

Safety concerns over the use of genetically modified ingredients in animal feeds have not been substantiated scientifically. However, consumer demand for GM-free fish in the marketplace has resulted in some feed companies producing and offering for sale only GM-free feeds. Suppliers are required to present documentation that all ingredients are free from any genetically modified organism (GMO).

(iii) Growth hormones

Exposure to steroids incorporated into the diet has been shown experimentally to affect sexual development, growth, and feed efficiency of several salmonids. Piferri and Donaldson (1989) found experimental feeding of low doses of 17- β -methyltestosterone to coho fry increased the proportion of males, whereas the estrogenic steroid 17- β -estradiol increased the proportion of phenotypic females. Baker et al. (1988) developed a technique for producing phenotypic male chinook salmon from mono-sex female-eyed eggs and fry by immersion in a solution of 17- β -methyltestosterone and water. Human food safety and environmental issues associated with the use of 17- β -methyltestosterone for sex control in fish have been reviewed by Green and Teichert-Coddington (2000).

Ostrowski and Garling (1986) found that dietary 17- β -methyltestosterone enhanced growth of fingerling rainbow trout without affecting feed utilization. In contrast, Yu et al. (1979) showed that low doses of androgenic steroids improved both growth and feed conversion of juvenile coho salmon. Some synthetic steroids have been approved by the FDA for use in the US to increase growth, feed efficiency, and milk production in cattle. However, the use of hormones has not been cleared for food fish.

(iv) Pigments

The characteristic red color of salmonid flesh from the deposition of dietary carotenoids is an important factor in determining product quality and consumer acceptance. In the wild, salmonids consume prey organisms containing small quantities of astaxanthin and other carotenoids which are deposited in the skin and muscle. Formulated feeds used in salmonid aquaculture are usually supplemented with astaxanthin, although a related carotenoid, canthaxanthin, is sometimes used. Astaxanthin is an approved color additive in the feed of salmonids (Regulation 21 CFR, Part 73.35 [USOFR 1995c]). The maximum permitted level of astaxanthin is 80 mg/kg (72 g/mt) of finished feed. The FDA requires that the presence of the color additive in the feed, or fish which have been colored with the feed additive, or any product which contains artificially colored salmon

as an ingredient, is declared on the label or ingredient list. However, this information is unlikely to pass to the consumer when the product is displayed out of its packaging.

(v) Antioxidants

Oxidation of lipids in feed ingredients can cause a reduction in their nutritional value and may produce compounds toxic to fish. Hung et al. (1981) found that feeds and/or ingredients containing high levels of unsaturated fatty acids, such as fish meal and fish oil, treated with synthetic antioxidants prevent nutrient loss and formation of toxic peroxide compounds. Synthetic antioxidants, such as BHA (butylated hydroxyanisole), BHT (butylated hydroxytoluene), and ethoxyquin (1,2-dihydro-6-ethoxy-2,2,4-timethylquinoline) are commonly used in animal feeds. Maximum levels permitted in the finished feed by the FDA is 0.2% of the fat content for BHA and BHT, and 150 mg/kg for ethoxyquin.

(vi) Organic toxicants

Organic compounds, such as polychlorinated biphenyls (PCBs), dibenzofurans, organic pesticides, and halogenated aromatic hydrocarbons, etc., have all been found in wild salmon from polluted areas, such as the Great Lakes (Cleland et al. 1987, Cleland et al. 1989, Daly et al. 1989, Seegal 1999) and the Baltic Sea (Svensson et al. 1991). Recently, media reports on the presence of 'dioxins' in farmed salmon have gained considerable attention, particularly among consumers in the United Kingdom and other EU countries. Dioxin exposure is of concern because of potential effects on the immune and endocrine functions and reproduction, as well as the development of malignant tumors (SCAN 2000).

The term dioxins describes three classes of toxic chemical compounds widely distributed and persistent in the environment. They tend to dissolve in lipids and thus can be accumulated in the food chain. The groups are polychlorodibenzo-p-dioxins (PCDDs), polychlorodibenzofurans (PCDFs), and dioxin-like or co-planar biphenyls (PCBs). PCDDs and PCDFs are by-products of certain industrial processes, such as high-temperature waste incineration, and/or those involving organic chlorine treatments (bleaching paper during manufacture, synthesis of herbicides). PCBs were used mainly in electrical equipment beginning in the early 1930s until their manufacture and use was stopped in almost all industrialized countries by the late 1980s. Of the 210 possible PCDF and PCDD congeners, 17 are considered toxic. Twelve of the 209 members of the PCB family show dioxin-like toxicity.

The overall toxicity of a dioxin-contaminated materials or food is an additive function of both the quantity of each congener present and its toxicity, relative to the most toxic compound 2,3,7,8-TCDD (Seveso-dioxin), expressed as total toxic equivalents (TEQ). WHO has proposed a tolerable daily intake (TDI) for humans of 1–4 pg WHO-TEQ/kg body weight (Van Leeuwen and Younes 2000), with the ultimate goal to reduce human intake levels below 1 pg TEQ/kg body weight per day. More than 90% of human dioxin exposure is derived from food, with food of animal origin as the predominant (*ca.* 90%) source. Consequently, recent efforts to reduce human dietary exposure to dioxin and PCBs has focused on evaluating the contribution of various feed ingredients given to

farmed animals, including fish, and the contamination of human food products of animal origin (SCAN 2000).

Data collected by the SCAN (2000) on basic feed ingredients (roughages, grains and cereals, vegetable oils, animal fat and other rendered by-products, fish meal and fish oil, as well as binders and trace element premixes) indicated that virtually all are contaminated with dioxin to varying degrees. Feedstuffs originating from plants generally contain low levels of dioxins (0.1–0.2 ng WHO-TEQ/kg dry matter), while fish meal and oil, particularly those originating from European sources are highly contaminated (fish meal 1.2 ng WHO-TEQ/kg dry matter, fish oil 4.8 ng WHO-TEQ/kg dry matter). European fish meals and oils are about 8-fold lower in total dioxin content than those produced from species caught in the coastal areas of less-industrialized regions of the world (Peru, Chile). Because of the high percentage of fish meal and oil in the diets of farmed carnivorous fish, such as salmon, the impact of using less contaminated feed materials of fish origin on whole diet dioxin burden is considerable. According to SCAN estimates, a typical diet for carnivorous fish containing 50% fish meal and 25% fish oil originating from Europe might contain 1.82 ng WHO-TEQ/kg dry matter, compared with 0.25 ng WHO-TEQ/kg dry matter if fish products from the south Pacific were used. Further reductions may be realized by partially replacing fish meal and oil with plant products, such as soybean meal and vegetable oils.

Little is known about transfer of dioxins from feed to fish. However, based on limited data on transfer rates for PCBs in fish, and assuming similar behavior of ortho and non-ortho chlorobiphenyls, SCAN estimated at least 60% of the total dioxin + PCB TEQ in fish feed is likely to be transferred to fish. At present, the level of dioxin contamination in farmed salmon has not been rigorously evaluated, and transfer rates to humans have not been determined. However, it is likely that guidelines for tolerable limits for dioxin in all human food products or animal origin will soon emerge.

While the potential for feed-borne hazards from organic compounds exists in farmed salmon, Jensen and Greenlees (1997) note that this public health issue is largely avoided in aquaculture by application of best management practices (BMPs) for site selection, and regulations for formulation and manufacture of feeds.

3.2.3 Chemotherapeutants

Toxic chemicals and chemical compounds may residualize in fish following protracted use of approved veterinary medicines. Aquaculture, like terrestrial animal agriculture, relies upon good husbandry and proper use of drugs and chemicals to combat infectious disease pathogens. Of the chemotherapeutants approved for use in aquaculture, certain antibiotics and parasiticides are used in salmon net-pen farming.

(i) Antibiotics

Antibiotic residues in farmed seafood products are possible hazards to consumers in that they might induce allergic reactions, have toxic effects, or modify the human gut flora. They might also increase resistance in aquatic bacteria to antibiotics, which in turn, might be transferred to human pathogens.

All drugs approved by the FDA must be shown to be safe and efficacious. Studies required to meet these requirements typically consist of field (clinical) and laboratory (non-clinical) trials (USOFR 1995a). Clinical studies are conducted under an investigational new animal drug (INAD) exemption issued by FDA under the same conditions expected under the proposed use of the drug. Laboratory studies under strictly controlled conditions in accordance with good laboratory practices (GLP) are specified under the Regulation 21 CFR, Part 58 (USOFR 1995b). Laboratory studies conducted for the approval of a new animal drug for use in US aquaculture have been reviewed in detail by Greenlees (1997).

The FDA permits certain antibiotics to be added at sub-therapeutic levels to the feeds of poultry, swine, and cattle as growth promoters. It does not permit the use of antibiotics as growth promoters for fish. In contrast with the results obtained with higher vertebrates, Wagner (1954), Sniezko and Wood (1954), and Sniezko (1957) reported that sulfonamide, tetracycline, and other antibiotics added to the diets of several salmonid species (brook trout, brown trout, and rainbow trout) had no stimulatory effect on growth.

At the present time three antibiotics are registered in the US as feed additives for disease control under Regulation 21 CFR, Parts 558.450, 558.575, and 558.582. Respectively, these are oxytetracycline (terramycin), sulfadimethoxine plus ormetoprim (@Romet-30), and sulfamerazine, although sulfamerazine is no longer marketed. For salmonids, oxytetracycline (terramycin) has a 21-day withdrawal period before harvest, and @Romet-30 has a 42-day withdrawal period. Stoffregen et al. (1996) stated that levels in flesh tissues were undetectable if these withdrawal times were followed. Fong and Brooks (1989) determined that the tolerance levels of salmon for each of these antibiotics were 0.1 ppm.

(ii) Parasiticides

JSA reviewed the use of chemical compounds and vaccines in aquaculture and published their findings in a guidebook (JSA 1994). Seafood producers operating by the JSA guidelines introduce no hazards from residual drugs. The risk is the misuse of chemical compounds and vaccines by untrained workers.

Formalin is the only parasiticide approved at present for farm salmon operations (JSA 1994). It is applied topically, and Fong and Brooks (1989) were unable to detect it in salmon flesh after treatment, concluding that it was not a hazard to consumers. Other substances with putative activity, including acetic acid, garlic, hydrogen peroxide, onion, and sodium chloride, are currently classified by FDA as '*unapproved drugs of low regulatory priority*.' The FDA is unlikely to object to use of these substances if the following conditions are met: (a) the drugs are used for the prescribed indications, including species and life stage where specified, (b) they are used at the prescribed dosages, and (c) are used according to good management practices. Also, (d) the product is of an appropriate grade for use in food animals, and (e) an adverse effect on the environment is unlikely. However, the use of such substances under these conditions is not approval or affirmation of their safety and efficacy, and the FDA may take a different position on their use in the future based on further information.

3.3 Biological Safety

Potential biological hazards to human health from the consumption or contact with contaminated farm products include parasites, bacterial infections, viral infections, or naturally produced toxins. The majority of human pathogens associated with aquaculture products are to be found at freshwater farms, farms in tropical countries, and among shellfish operations.

Specific hazards to human health which might be associated with net-pen farming of salmon are anisakiasis, diphylobothriasis, rickettsialosis, vibriosis, aeromoniasis, salmonellosis, and pleiomoniasis. To date there have been no reported cases of any of these hazards being associated with farmed salmon, and WHO (1999) states that the risk of contracting these illnesses from farmed fish is considered to be low.

(i) Anisakiasis

Anisakiasis is caused by larval ascaridoid nematode parasites which normally infect marine mammals as the definitive host, and an invertebrate as the primary host. Marine fish are secondary hosts, and are infected when they consume infected fish or invertebrates. Roderick and Cheng (1989) indicated that the parasite inhabits the viscera of live fish but relocated to the musculature upon death. They concluded that the parasite is not likely to be a problem in farmed fish, as the viscera are removed quickly after harvest. The parasite is killed by proper cooking or proper freezing, and only infrequently infects humans. Human infection of this and other parasites primarily occurs when wild fishery products are consumed raw, as in Japanese maguro (tuna) or sake (salmon) sashimi, or after only mild processing, such as cold smoking.

Studies by Angot and Brasseur (1993), Bristow and Berland (1991), and Deardorff and Kent (1989) have indicated that farmed salmon do not have nematodes. Consequently the European Union (EU) exempts farmed salmon from a directive (91/493/EEC) which requires that all (wild) Atlantic and Pacific salmon to be processed with minimal cooking (i.e. cold smoking <60°C) must be frozen prior to sale. This is to protect the consumer from anisakiasis and other parasites. The reason that farmed salmon are apparently free of nematodes is that they are fed with manufactured feeds. If farmed salmon were fed with fresh trash fish, WHO (1999) believes that the potential for anisakiasis from farmed salmon would exist.

(ii) Diphylobothriasis

Diphylobothriasis is caused by the broad fish tapeworm, *Diphyllobothrium latum*. While the majority of human infections of this parasite come from freshwater fish, Roderick and Cheng (1989) described cases caused by the consumption of uncooked wild salmon. They assumed that the salmon contracted the tapeworm in freshwater and carried the parasite throughout the marine phase before capture. Diphylobothriasis is commonly found among Eskimos of Alaska and Canada and inhabitants of Finland, all of whom consume large quantities of wild caught salmon. There have been no reports of this tapeworm associated with farmed salmon.

(iii) *Rickettsialosis*

Rickettsialosis, or '*salmon poisoning*,' is caused by a digenean troglotrematid and is primarily a problem for dogs, which have eaten uncooked wild salmon entrails. Rodrick and Cheng (1989) described reports of this parasite in humans but rarely with serious disease consequences. There have been no reports of this parasite associated with farmed salmon.

(iv) *Vibriosis and other bacterial diseases*

Vibriosis, aeromoniasis, salmonellosis and plesiomoniasis are caused by bacterial infections of *Vibrio* spp., *Aeromonas* spp. *Salmonella* spp. and *Plesiomonas* spp., respectively. All of these bacteria are a part of the normal aquatic flora, except for *Salmonella* spp. which are associated with human and animal wastes.

The greatest potential for contamination of wild or farmed fish occurs post-harvest when the muscle, which is sterile in healthy living fish, is exposed to external contamination. The practice of delivering net-pen reared salmon alive to the processing plant, where strict BMPs and HACCP practices are followed, significantly reduces the risk to public health from bacteria and parasites. Wild caught salmon, which are landed headed and gutted, have a slightly higher risk of contamination *en route* to the processing plant. Ward (1989) noted that all these bacteria were killed by thorough cooking, and concluded that the greater risk for the consumer was uncooked or undercooked fish, or if the product was incorrectly handled and processed after harvest.

3.4 Quality and Safety of the Products

The public perception of seafood has traditionally been one of high quality, with a range of products all beneficial to individual health. However, there are subtle differences between species, and many of the positive healthy qualities can be destroyed or contaminated by poor post-harvest handling and processing.

The proximate composition of farmed salmon (percent protein, lipid, ash and water) is generally similar to wild salmon, except that the lipid and fatty acid composition can differ. In general, wild salmon have a higher concentration of n-3 fatty acids as a percent of total fat, while farmed salmon have a higher level of total fat. Sargent (1995) found there was a similar overall level of n-3 fatty acids as a percentage of the total fillet, which was important for human health. The fatty acid composition of farmed fish reflects the fatty acid of the lipid source in the feed. Many authors (Nettleton 1990, Haard 1992, Nettleton and Exler 1992) have experimented with an array of variables and all report that it is possible to control the fatty acid composition of farmed fish.

Many food nutritionists have worked on the various sensory measures of farmed salmon, such as taste, texture, and color of the final product. Haard (1992) reported that farmed salmon, in general, were milder in flavor, softer in texture, and paler in color than their wild counterparts. Sylvia et al. (1995) and Wessells and Holland (1998) noted that consumers were able to detect differences between wild and cultured salmon, with preferences related to regional experience with each product. The greatest determinant of product quality for salmon from either source was freshness. Consistency in quality and

quantity, consistent price, and year-round availability were all considered by consumers to be advantages of farmed salmon.

3.5 Worker Safety

According to the Bureau of Labor Statistics Census of Fatal Occupational Injuries (CFOI) commercial fishing was the single most deadly occupation in the US between 1992 and 1996 (CFOI 1999). This is likely to still be the case. Drudi (1998) concluded that fishers face a risk of death 20–30 times higher than all other occupations. Between 1992 and 1996 inclusive, 380 fishermen fatalities were recorded in the USA. During the same period the occupation classified as '*Animal aquaculture*' (SIC 0273) had eight fatalities, and '*Fish hatcheries and preserves*' (SIC 0921) had five fatalities (D. Drudi, personal communication, 2000). It was not possible to isolate salmon fishers and salmon farmers from within these numbers.

Fish farm workers face chemical hazards from mishandling drugs and chemicals used in aquaculture. Guidelines for the use and safe handling of chemical compounds and vaccines in the aquaculture industry in the US have been published by JSA (JSA 1994), and many of these guidelines are being reflected by the COPs and BMPs being prepared by individual industries for the protection of their workers.

4. SALMON FARMING AND THE ENVIRONMENT

The fourth chapter reviews current information on the effects of the many activities associated with salmon aquaculture on the environment. Where possible the review attempts to deal with these effects in quantitative terms, and the measures which are currently used to reduce them. The chapter has seven identified sub-sets. The first sub-section reviews the potential effects of the organic wastes emanating from net-pen salmon farming. The origins of such effects are uneaten or waste feed, feces from the fish, and bio-fouling organisms on the structures. The second sub-section reviews the inorganic wastes, specifically nitrogen and phosphorus, and heavy metals. The third sub-section deals with the pathogenic organisms, which might be in the vicinity of fish farms, and the risks to human health from wastes, which might contain such pathogens. The next sub-section deals with the therapeutic compounds which might be used to control parasites and diseases. The fifth sub-section reviews the biological and chemical changes in the sediments and in the water column both beneath the farm and downstream. Where possible, quantitative information is provided and then applied collectively in terms of an operating farm with reference points. The sixth sub-section reviews information on the chemical and biological recovery of sediments under salmon farms. The final sub-section reviews alternatives being used for management of all these environmental effects. These include monitoring experiences with a number of indicators and models, followed by a review of other government policies and methodologies.

4.1 The Effects of Organic Wastes from Net-pen Salmon Farms

4.1.1 Waste feed

Early diets for farmed Atlantic salmon contained 45–50% protein, 16–22% lipids, and 17% carbohydrates. Technology now permits the production of high-energy salmon diets containing about 30–35% lipids and 40% protein, and the minimum level of digestible carbohydrate (about 10%) necessary to bind the pellets. These high-energy diets more closely resemble the composition of the natural prey of salmon. More recent salmon feeds were reported by Einen et al. (1995) and Rosenthal et al. (1995) to contain 7% nitrogen and 1% phosphorus. Mann (EWOS Canada Ltd., personal communication) estimates that current salmon diets contain 38–39% crude protein, 6.5% nitrogen, and 1% phosphorus. Lipid content in current high-energy diets is 33–35%, of which half is fish oils and half plant oils, such as flax and linseed oils, high in omega-3 fatty acids.

The amount of waste feed depends on feeding efficiency, which is principally influenced by feed composition, feeding methodology, water currents at the site, and net-pen configuration. Beveridge et al. (1991) stated that up to 30% of feed was lost. Rosenthal et al. (1995) noted higher losses (up to 35%) for wet feeds, which might contain greater than 30% moisture, than dry feeds. Weston (1986) suggested that less than 5% of dry feed was lost at Puget Sound salmon farms. This is consistent with research by Gowen

and Bradbury (1987), who reported losses were least (1–5%) with dry feeds, which contained less than 10% moisture. Findlay and Watling (1994) reported maximum feed loss rates of 5–11%, with an average feed wastage of <5%. Dry and semi-moist feeds are now used exclusively in the Pacific Northwest and current feed loss rates are estimated between 3–5 % (J. Mann, EWOS Canada Ltd., personal communication).

The amount of feed loss is also dependent on feeding methods and strategies. Cross (1990) reported that feed wastage at a commercial salmon farm in Sooke Inlet, British Columbia (BC) was 3.6% delivered by hand and 8.8% delivered by automatic feeders. This was probably due to the abrasion of feed pellets in some automatic feeders, which can result in the disintegration of 4–5% of the pellets. Other automated feeding systems, with short delivery distances and operated by compressed air valves, may disintegrate <0.5% of the pellets (J. Mann, EWOS Canada Ltd., personal communication).

New technologies, such as feedback cones and underwater video or acoustical devices described by Mayer and McLean (1995), are now commonly used to monitor feeding behavior in efforts to minimize losses of uneaten feed from net-pens. Sutherland et al. (2000) conducted a study at a salmon farm in the Broughton Archipelago, Canada BC, to quantify suspended particulates during peak feeding times and to make point-in-time estimates of organic loading. Based on stable carbon isotope analysis, they concluded that very little feed was not consumed by the fish at the farm under study. In a series of video reports to the BC Ministry of Environment documenting the environmental conditions on the perimeter of several salmon farms in the Province, Brooks (2000a–f) recorded no observable wasted feed pellets.

The results of this review are reasonably consistent and indicate that, as at this time, 5% or less of the dry feed delivered to cultured salmon in net-pens is lost to the environment. The low proportion has been due to the combination of improved feedback technologies and the practice of quickly feeding the fish to satiation once or twice each day (mean feeding). Improvements in feed delivery systems to minimize pellet disintegration will probably reduce losses further well below 5%, a figure much less than the 20–30% numbers used in many aquaculture models (see Section 4.7.2).

4.1.2 Fish feces

Weston (1986) estimated that 25–33% of feed consumed by the fish was ejected as feces. Modern diets are approximately 87–88% digestible (J. Mann, EWOS Canada Ltd., personal communication). The remaining ash consists primarily of calcium and inorganic phosphate, and represents 8.0–8.5% of the feed. This implies approximately 12.5% of the weight of ingested feed will be ejected in feces. Subtracting 87.7% for digested protein and 8.25% for ash, this leaves about 4% of the feed ingested to be ejected as labile organic material in the feces. If 5% of the feed is uneaten (Findlay and Watling 1994) and feces contribute organic matter equivalent to 4% of the feed weight, then approximately 8.8% of the labile organic carbon delivered in feed is discharged from the net-pen structure in particulate form, contributing to the BOD of the sediments.

Feed conversion ratios (FCRs) of farmed fish are frequently quoted in literature, but have not been adequately defined. They are typically measured as the ratio of the dry weight of feed provided to the wet weight of salmon produced. They are considered an essential metric by the aquaculture industry for assessing producer program efficiency. The FCR is affected by genetic and environmental factors. The quality and composition of the feed, to include palatability and nutrient balance, is also important together with fish health and feeding methodologies. In short, the FCR integrates all aspects of the culture operation into one simple metric.

Two types of FCR are typically defined by industry:

- The economic feed conversion ratio (EFCR) is defined as the amount of feed supplied to a farm divided by the round dressed weight of fish produced for market. This metric is easy to calculate and is useful in determining the economic efficiency of a farm.
- The biological feed conversion ration (BFCR). This metric is biologically and environmentally more meaningful but more difficult to determine. It is equal to the feed actually consumed by the fish (feed provided less the uneaten portion) divided by the total fish biomass produced on the farm, including escapes and mortalities. Robinson (Stolt Sea Farm, personal communication) noted that the head-on processed weights must be corrected for the approximate 16% loss of fish weight during starvation, bleeding and removal of offal.

Enell and Ackefors (1992) reported that marine FCRs in Norway declined from 2.25 in 1974 to an average of 1.2–1.3 in 1992. The authors calculated that improvement resulted in a 23% decrease in nitrogen and a 50% decrease in phosphorous loading associated with farm operations. Rosenthal et al. (1995) estimated FCRs for Atlantic salmon to be 1.2, while Levings (1997) estimated an even lower FCR of 1.17 for operations in BC. FCRs have probably advanced to a point where significant additional improvement will be difficult.

4.1.3 Fish carcasses as wastes

Winsby et al. (1996) reviewed and analyzed the mortality of fish at BC net-pen salmon farms in 1994. Their data suggested approximately 2,000 mt of salmon died at farms that year, or approximately 9% of the total production of 22,000 mt. They concluded that most of the salmon carcasses were removed to approved compost disposal locations.

No inappropriate disposal of salmon carcasses has been documented in the literature. Losses of fish on net-pen salmon farms are restricted to individual fish, which may have been attacked and killed by a predator, and numbers of fish which died as a consequence of an algal bloom or disease epidemic. BMPs of net-pen salmon farms require physical removal of any carcasses on a daily basis, and therefore they do not contribute to any biological loading on the environment.

4.1.4 Bio-fouling organisms as wastes

Biological fouling is a significant factor in coastal environments and large masses of mussels, barnacles, ascidians, and bryozoans can weigh down nets and restrict water flow

through a net-pen complex. Heavily fouled nets can also compromise the structural integrity of the complex.

Weston (1986) concluded that bio-fouling organisms on net-pens, and the debris which was released by net cleaning, were not significant sources of organic input to sediments beneath salmon farms. Winsby et al. (1996) discussed the mechanics of removing fouling organisms from nets associated with salmon farms. There is no literature quantitatively describing the mass of bio-fouling which builds up on nets and floating structures of salmon farms, or other similar marine structures.

Brooks (1994a) defined a neutral impact zone (NIZ) as that distance from the perimeter of a salmon farm at which there was neither an apparent increase nor decrease in the abundance and diversity of the benthic infaunal community when compared with a local control site. In annual observations at a poorly flushed farm site, he noted that the NIZ was influenced by several factors, including, for example, deposits of debris following the pressure-washing of nets *in situ*. He observed a 30-cm deep layer of mussel debris in sediments from the perimeter of the farm stretching a distance of 6 m downstream. The downstream location of the NIZ increased from 12 m in 1993 to approximately 22 m in 1994, after *in situ* cleaning. He concluded that it was not possible to establish a cause and effect relationship but the presence of the mussel shells undoubtedly had an effect on the benthos.

4.1.5 Measurement of organic wastes

Brown et al. (1987) compared the areal extent of benthic impacts associated with organic wastes from fish farms in Sweden with that from sewage treatment plant and pulp mill effluents. They found reducing (anaerobic) sediments covering 0.6 km² around a poorly flushed (mean current velocity = 3.7 cm/sec) salmon farm located in shallow water (20 m below MLLW). Significant changes in the benthic community were observed within 15 m of the perimeter of the farm. In comparison, they cite Stanley et al. (1980) in noting that a pulp mill in Loch Eil, Scotland had created reducing conditions in sediments extending over an area of 5 km². Pearson (1986) observed reducing sediments covering 23 km² associated with a sewage disposal site at Garroch Head, Firth of Clyde, Scotland. The impact associated with this single sewage discharge covered an area 38 times as large as that impacted by the salmon farm.

Ellis (1996) suggested that waste feed and feces from salmon farms in BC were equivalent to the human sewage from a city of 500,000 people, and Folke et al. (1994) compared the waste from 100 mt of salmon with a human settlement of 850 to 3,200 persons. Ackefors and Enell (1990) criticized the assumptions upon which such comparisons were made. Their argument was based on differences in the form of nitrogen released from sewage treatment plants and fish farms and differences in the ratio of carbon, nitrogen and phosphorus discharged from the two activities.

Taylor et al. (1998) found that organic enrichment adjacent to the Macaulay and Clover Point outfalls in the city of Victoria BC, was similar to that expected at a productive salmon farm. Adverse effects on benthic infauna associated with organic enrichment by

sewage treatment plants were generally restricted to distances less than 100 m from the diffusers. They also found significantly elevated levels of 1,4-dichlorobenzene, polycyclic aromatic hydrocarbons and mercury within 100–400 m of the same two outfalls. These concentrations exceed Washington State Sediment Quality Standards. Sediment toxicity associated with these outfalls was limited to adverse effects on growth and development in laboratory bioassays. The authors concluded that the magnitude and extent of the observed effects (<400 m from the outfalls) indicated little cause for concern for human health. The effects at these outfalls extend four times further from the source than is allowed at salmon farms complying with the BC Draft Waste Management Policy. Salmon farm wastes do not contain toxic levels of metals and industrial hydrocarbons associated with sewage treatment plants, and there are no reasonable sources of these common contaminants on farms other than the minor exhaust from boats.

Ackefors and Enell (1994) estimated the total organic output from salmon farms on the order of 2.5 mt wet weight per metric tonne of fish produced. Gowen et al. (1991) cited three studies assessing the flux of carbon through salmon net-pens. In all three cases the harvested fish retained 21–23% of the carbon in feed and it was estimated that 75–80 % of the carbon was lost to the environment mostly in a dissolved form as CO₂. Merican and Phillips (1985) estimated that 35.6% of the carbon, 21.8% of the nitrogen, and 65.9% of the phosphorus were lost to the environment in solid form. Other estimates of the total suspended solids output from intensive net-cage culture of fish by Kadowaki et al. (1980), Warrer-Hansen (1982), Enell and Lof (1983), and Merican and Phillips (1985) range from 5–50 g suspended solids/m²-day. All these publications are more than 15 years old and therefore these values do not reflect recent improvements in fish feed and feeding technologies.

Gowen and Bradbury (1987) estimated organic waste sedimentation rates of 27.4 g/m²-day under Irish salmon farms, and an average of 8.2 g/m²-day immediately adjacent to the perimeter of the net-pen. Gowen et al. (1988) measured average rates of 82.2 g dry weight/m²-day on the perimeter of a net-pen in Washington, and Cross (1990) estimated an average overall sedimentation rate of 42.7 g TVS/m²-day with a maximum of 94.5 g total volatile solids (TVS)/m²-day at seven salmon farms in BC. More recent work by Findlay and Watling (1994) in Maine measured sedimentation rates on the perimeter of salmon farms at between 1.0–1.6 g carbon/m²-day, and Hargrave (1994) summarized sedimentation rates from less than one to over 100 g carbon/m²-day from salmon cage operations described by a number of authors.

Brooks, using his published data from many original sources (Brooks 2000a–f), derived a theoretical estimate of contemporary TVS loading near fish farms. Given a feed with 11% moisture content and FCR of 1.2, the feed provided (1.2 kg x 89 % dry matter) or 1.07 kg dry feed/kg of fish produced. This:
– [(1.07 kg dry wt. feed/kg salmon produced) x 8.8% labile organic waste/dry weight] –
was in turn equal to 0.094 kg of labile volatile solids/wet weight kg of fish produced. Thus he estimated that a salmon farm producing 1,500 mt of salmon during a 16 to 20-month production cycle would discharge 141 mt of organic waste on a dry weight basis.

Furthermore, assuming a fish density of 10 kg/m³ in cages 15 m deep and a grow-out cycle of 18 months, the annual sediment load on average would be:

$$\frac{(10 \text{ kg fish/m}^3 \times 15 \text{ m deep} \times 0.094 \text{ kg TVS/kg fish})}{(548 \text{ days})}$$

which is equal to 25.7 g TVS/m²-day. The load would, in reality, be lower at the beginning of the grow-out cycle and increase towards maximum biomass.

Brooks (2000e) analyzed sediments collected in canisters deployed 5 m above the bottom at varying distances from two farms in BC and at reference stations. The mean loading of volatile solids on the perimeter of these farms was 39.2 g TVS/m²-day. The mean deposition of volatile material at the control stations was 6.3 g TVS/m²-day and the contribution by the farm was approximately 32.9 g TVS/m²-day. These studies were completed near peak salmon biomass and the observed values would therefore be greater than the theoretical average of 25.7 g TVS/m²-day calculated above. Nonetheless, these observed and theoretical values are reasonably close.

In summary, sedimentation rates on the perimeter of salmon net-pens have remained fairly constant in the range 15.1–100 g TVS/m²-day despite the typical increase in farm size from 200–300 mt in the 1980s and early 1990s to the 1,500 mt of recent years. A recent study by Brooks (2000e) found a TVS loading of 32.9 g/m²-day on the perimeter of a salmon farm at peak production. This value is reasonably close to a theoretical average of 25.7 g TVS/m²-day calculated for an entire 18-month production cycle.

4.2 Dissolved Inorganic Wastes

4.2.1 Dissolved nitrogen and phosphorus

Salmon excrete 75–90% of their ammonia and ammonium waste across gill epithelia (Gormican 1989) or in concentrated urea (Persson 1988, and Gowen et al. 1991). Brett and Zala (1975) reported a constant urea excretion rate by sockeye salmon of 2.2 mg N/kg per hour. Nitrogen and phosphorus are also dissolved from waste feed and feces during and after descent to bottom sediments. All these dissolved forms of nitrogen are readily available for uptake by phytoplankton. Silvert (1994a) suggested that 66–85% of phosphorus in feed is lost in a dissolved form to the environment at salmon farms.

Winsby et al. (1996) reported significant variation in observable increases in soluble nitrogen and phosphorus levels in the water column at salmon farms. Johnsen and Wandsvik (1991) and Johnsen et al. (1993) estimated that 20.5–30.0 g of nitrogen and 6.7 g of phosphorus are released per kilogram of Atlantic salmon produced when fed modern high-energy diets containing 30% lipid. Levings (1997) used these estimates to conclude that 844 mt of nitrogen and 188.6 mt of phosphorus are released to marine environments in BC each year by salmon farms. These values do not include nitrogen and phosphorus associated with uneaten feed.

Statistically significant increases in soluble nutrients at salmon farms have infrequently been observed in Puget Sound (Rensel 1989, and Brooks 1994a, 1994b, 1995a, and 1995b). Aquatic Lands Leases (ALLs) for salmon farms in Washington State have required monitoring of NO₃, NO₂, and total ammonia (NH₃ + NH₄) in water samples

taken within one hour of slack tide at stations located 30 m up-current, and 6 m and 30 m downstream at all permitted farms at a depth equal to one-half the depth of the containment nets. In general, the variability between replicate samples taken at the 6 m downstream station was as great, or greater, than any observed increase in nitrogen between upstream and downstream stations. No significant increases in nitrogen were observed at any of the 30 m downstream stations.

The highest observed level of toxic unionized ammonia (NH₃) was 0.0004 mg-L⁻¹. This is lower (by a factor of 87.5) than the EPA chronic exposure (4-day) concentration limit of 0.035 mg-L⁻¹ at pH = 8 and T = 15°C when sensitive salmonid species are present.

Rensel (1989) studied dissolved nitrogen production at two poorly flushed farms in Washington. He compared dissolved nitrogen and unionized ammonia concentrations within the salmon pens with upstream and downstream levels during early ebb tides. Upstream dissolved nitrogen levels of 0.0003 mg-L⁻¹ were increased to 0.0023 mg-L⁻¹ at the center of the net-pen complex, but decreased to background levels at downstream stations. He also observed maximum unionized ammonia levels equivalent to 6% of the EPA criteria in the center of these net-pen complexes during slack tide.

Weston (1986) reported ambient levels of dissolved inorganic nitrogen (DIN) in Puget Sound at 0.3 to 1.9 mg-L⁻¹, indicating high variability. The greatest increase in DIN reported by Brooks (1991, 1992, 1993a, 1994a, and 1995a) was 5.29 µmoles-L⁻¹ (0.09 mg-L⁻¹), or 8% of the mean value reported by Weston (1986).

The literature indicates that the concentration of dissolved inorganic nitrogen added to marine water at salmon farms is very low on the perimeter of net-pen farms, and essentially immeasurable at distances greater than 9 m from the farm perimeter.

4.2.2 Heavy metal accumulation in sediments

(i) Zinc

Zinc is an essential metal important for insulin structure and function and as a co-factor of carbonic anhydrase. Historically it has been added to salmon feeds in trace amounts equal to 30 to 100 mg-kg⁻¹ of feed (see Chow and Schell 1978, and Anderson 1998).

Long et al. (1995) provide an effects range-low (ER-L) of 150 µg zinc/g dry sediment weight, an effects range-moderate (ER-M) of 410 µg/g and an overall apparent effects threshold (AET) of 260 µg/g. The Washington State sediment quality criterion for zinc is 270 µg Zn/g dry sediment (WAC 1991). Other available benchmarks include the (TEL + PEL)/2 or 197.5 µg Zn/g dry sediment. Information on the development of the threshold effects level (TEL) and the probable effects level (PEL) can be found in MacDonald (1994). The published sediment benchmarks (in µg Zn/g dry sediment) are summarized below. It should be noted that only the WA State AET is a statutory criterion.

Contaminant	NOAA AET	(TEL + PEL)/2	WA State AET
Zinc	260.0	197.5	270.0

Brooks (2000b) summarized 193 analyses for zinc in sediments collected near 27 salmon farms in BC. Nineteen samples from eight farms exceeded the AET of 260 µg Zn/g dry sediment. All of the high zinc samples also contained significantly elevated sediment sulfide and TVS concentrations. There was a statistically significant correlation between zinc and both TVS and total sediment sulfides (S⁻).

In response to the observed high sediment zinc concentration at some farms, fish feed manufacturing companies in BC have reduced the amount of zinc in feed to the minimum necessary to maintain salmon health. They have also changed the form of zinc from zinc sulfate to a methionine analog, which is more bio-available.

Di Toro et al. (1992) described the relationship between sediment acid volatile sulfides, metal concentrations, and toxicity to infauna. Acid volatile sulfides (AVS) is a reactive pool of solid-phase sulfide that is available to bind metals and render them biologically unavailable and non-toxic to biota. The AVS method is useful in predicting when sediments with elevated metal concentrations are potentially toxic. Metal toxicity is considered additive, and each must be added to obtain a sum of toxic units. This methodology has been validated for copper and zinc (EPA 1994). None of the zinc concentrations observed by Brooks (2000a) was toxic, as they were all associated with sediments containing high concentrations of sulfide.

Furthermore, Brooks (2000a) reported that initially high sediment concentrations of zinc under one salmon farm declined to background during a post production fallow period. At the peak of production at the studied farm, sediment zinc concentrations were elevated to 200 µg/g on the perimeter. They declined exponentially and reached a background concentration of ca. 25 µg/g at a distance of between 30–75 m from the net-pen perimeter on the downstream transect. Sediment-zinc concentrations were well correlated with TVS throughout the study ($r = 0.76$). Sediment-zinc declined during chemical remediation and was at background concentrations after six months of fallow. He hypothesized that zinc was bound by sulfides in the sediments. Sediment sulfides decrease with decreasing biological oxygen demand during chemical remediation. When the sediments become aerobic, the sulfide is oxidized back to sulfate releasing the zinc, which is diluted in the overlying water column. This hypothesis is consistent with chemical theory and with evidence collected earlier by Brooks (2000b). Given that these hypotheses stand the test of further scrutiny, no biological effects should be anticipated from the observed concentrations of sediment zinc under salmon farms.

(ii) Copper

Levels of copper may be elevated in the environment around net-pen farms, which use preventative treatments for bio-fouling. Several anti-fouling paints and solutions are approved for use in the marine environment, and are therefore used on salmon farms.

Anti-predator nets and fish containment nets are increasingly treated with a copper anti-fouling solution to inhibit the settlement of organisms and bio-fouling. The practice benefits the environment by reducing carbon inputs to the benthos. However, if cleaning is accomplished *in situ* the displaced organisms can exacerbate organic loading to the

benthos under the farm. BMPs should require that nets first be removed and then washed by hand or machine on a barge or at an upland facility.

Copper is a micronutrient. At moderately low levels the cupric ion is toxic to marine organisms – particularly the larval stages of invertebrates. Until 1995 the EPA marine chronic water quality criterion for copper was $2.5 \mu\text{g-L}^{-1}$ (EPA, 1986). Based on new information that level is now being increased to $3.1 \mu\text{g-L}^{-1}$ dissolved copper (EPA, 1995).

Lewis and Metaxas (1991) examined copper concentrations immediately adjacent to newly installed copper-treated nets at net-pen salmon farms in BC. They measured ambient copper concentrations of $0.38 \mu\text{g-L}^{-1}$ in July and $0.37 \mu\text{g-L}^{-1}$ in August. The concentration inside the pen was $0.54 \mu\text{g-L}^{-1}$ in July after a freshly treated net was installed, and $0.54 \mu\text{g-L}^{-1}$ one month later in August. The small addition of copper in the water from the treated net (0.16 to $0.17 \mu\text{g-L}^{-1}$) was not biologically significant except to organisms which tried to settle on the net.

Peterson et al. (1991) compared copper levels in muscle and liver tissue from chinook salmon grown in pens treated with ®Americoat 675, a copper based antifoulant, with those in a pen with untreated nets. No statistically significant differences in the copper levels in like-size fish from these two farms were observed, suggesting that the copper released from the treated nets was not significantly concentrated by chinook salmon.

Brooks (2000d) conducted *in vitro* studies on the leaching of copper from ®Flexgard XI, the most commonly used antifouling product on the west coast of North America. Initial losses of $155 \mu\text{g Cu/cm}^2\text{-day}$ declined exponentially during the period of the study. Brooks (2000d) used the data to develop a spreadsheet model that predicts copper concentration in the water as a function of the maximum current speeds observed at a site, and the net-pen configuration and orientation of the complex to the currents. His model predicted that containment nets treated with ®Flexgard XI would not exceed the US EPA copper water quality criteria when fewer than 24 cages were installed in two rows oriented parallel to currents flowing with a maximum speed greater than 20 cm/sec. The model predicted that unless the configuration of net-pens or their orientation with the currents was changed, the use of ®Flexgard XI treated nets would result in exceeding the chronic water quality copper criterion at a small percentage of existing farms. The author noted that assumptions used in his model were conservative, and probably predicted higher copper concentrations than would actually be observed in the field. The model has not been yet been tested in the field but it clearly demonstrated the need to manage the use of antifouling products.

Brooks (2000d) compared sediment copper concentrations at salmon farms in BC using ®Flexgard XI treated nets with those at farms using untreated nets and reference stations. Farmers in BC typically treat their nets at the beginning of each production period and treat them again only after the fish are harvested. The mean concentration of copper in the sediments of 117 farm stations using treated nets was $48.24 \pm 27.00 \mu\text{g Cu/g}$. This level was not significantly different than the mean concentration of 12.01 ± 2.77

measured at the reference stations, or mean concentration of 26.3 observed at farms not using copper treated nets (ANOVA $F = 0.73$; $p = 0.49$).

Brooks (2000d) found a great deal of variability in sediment copper concentrations at farms using copper treated nets. The concentration of copper in 2 of these 117 samples collected at 14 farms using copper treated nets exceeded the NOAA ER-M of 270 $\mu\text{g Cu/g}$ dry sediment, and the State of Washington sediment quality criterion of 390 $\mu\text{g Cu/g}$. Thirteen of the samples (11%) exceeded the mean of the TEL and PEL used as a regulatory benchmark in BC. All samples exceeding the lower benchmark were collected at 5 of the 14 farms using copper-treated nets. Discussion with the producers revealed that these farms washed their nets in barges during fallow periods. The fouling debris cleaned from the nets was not retained but washed over the side. Consequently, the concentrations observed at 5 of the 14 farms were not directly associated with the copper treatment itself but some ancillary activity, like net washing. Other anecdotal information revealed also that the copper – latex paint was abraded from the nets during washing and that significant quantities of the latex chips (with copper imbedded) were then washed over the side of the barge with the fouling organisms. The copper bound in the latex would then leach out over time. Brooks (2000d) concluded that all copper-treated nets should be removed after harvesting the fish, and washed and retreated at upland stations. Furthermore, all debris should be buried at an approved landfill site.

4.3 Pathogenic Organisms in the Vicinity of Net-pen Salmon Farms

4.3.1 Fecal coliform bacteria

The National Shellfish Sanitation Program (NSSP) certifies commercial shellfish beds in the US and their harvest is governed by some very specific regulations (NSSP 1997); for example, harvesting shellfish is forbidden within one mile of any out-fall from a sewage treatment plant. This is because of public health concerns associated with toxicants (heavy metals, PCBs, polycyclic aromatic hydrocarbons, etc.) released in industrial and residential waste, and because many human pathogens (including viruses and bacteria) are associated with treated human sewage. Shellfish sanitation is not adversely affected by nutrients (carbon, nitrogen or phosphorus).

Viruses are generally taxa-specific, and viruses pathogenic to fish, such as infectious pancreatic necrosis (IPN), viral hemorrhagic septicemia (VHS), and infectious hematopoietic necrosis (IHN) have no documented effect on human beings. However, fecal coliform (FC) bacteria persist in sediments high in total organic carbon (TOC) for varying periods. These bacteria are specific to warm-blooded animals (mammals and birds) and are not a normal part of the microflora found in fish intestines. However, mammals and birds are strongly attracted to fish farms increasing the potential for increased fecal coliform levels in the sediments near salmon farms. There is no potential for an increase in fecal coliform bacteria associated with cultured fish.

NSSP defines water quality standards for shellfish growing areas and has a methodology for assessing and classifying shellfish harvest grounds. Approved growing areas must have a most probable number or geometric mean (FC MPN) of $<14 \text{ FC}/100 \text{ ml}$, with not

more than 10% of the samples exceeding an MPN of 43/100 ml in a 5-tube decimal dilution test (APHA, 1992).

Brooks (2000a) analyzed 33 water samples from the vicinity of an operating salmon farm during every quarter of the year. The MPN for all stations was less than the NSSP requirements for an *Approved Shellfish Harvest Classification* (14 FC/100 ml), and all stations met NSSP requirements. He also examined shellfish tissues for FC bacteria. NSSP has established an allowable upper limit of 230 FC/100 g of tissue for product entering interstate (or international) commerce. Average clam tissue levels at the closest station located 200 m from the farm were 130 FC/100 g tissue. At 500 m the average level dropped to 50 FC/100 g, and at the reference station it was 20 FC/100 g. All of the shellfish samples tested met the NSSP requirement for shellfish tissues in commerce. In summary, he observed slightly more FC bacteria in water and shellfish tissues at stations closest to the farm perimeter. The sources of observed bacteria were not determined, but potential sources include farm workers themselves and, more probably, the birds and mammals which congregate around salmon farms. Water and shellfish tissues were consistently of high quality and met all bacteriological requirements imposed by NSSP.

4.3.2 Farm wastes

Ellis (1996) postulated that waste feed and feces might enhance populations of a variety of ubiquitous marine bacteria pathogenic to humans. There is no direct evidence in the scientific literature that salmon farm wastes enhance pathogenic marine bacteria. In an extensive review of the epidemiological records for shellfish in the waters of Washington State spanning 20 years, Brooks (1993 unpubl. data, Aquatic Environmental Sciences, Port Townsend, WA 98368) did not find one documented case of *Vibrio vulnificus*-induced disease. This, he concluded, was because thermophilic bacteria, like *V. vulnificus*, required a high water temperatures in addition to a rich source of organic material to thrive. Elevated ambient water temperatures would likely be a requirement of most bacteria that are pathogenic to homoeothermal humans. Bacteria which flourish in warm-blooded animals are unlikely to proliferate in cold Pacific Northwest waters under salmon farms. Also, as salmon are poikilotherms, FC and other disease-causing bacteria which flourish in warm-blooded animals would not likely multiply in the gut of salmon, whose intestinal flora is determined primarily by ambient bacterial concentrations. He concluded there was no basis for assuming the feces of caged salmon would contain more than ambient concentrations of those bacteria pathogenic to humans.

In another comparison of microbial levels in the tissues of farmed and wild salmon, Calderwood et al. (1988) examined the kidney, liver, spleen, heart, and muscle tissues for the presence of viruses and 16 bacterial species, including several later hypothesized as risks by Ellis (1996). They compared 68 adult wild steelhead trout at Robertson Creek and 50 wild adult coho from Chehalis, Washington with cultured chinook salmon from Sechelt and Sooke Basin in British Columbia. Their results were as follows:

(a) *V. vulnificus*, a potentially serious human pathogen in immune-compromised individuals, was not detected in the cultured fish. However, 44% of wild fish returning to Chehalis were positive for this bacterium. Other vibrio species, including the potential

human pathogen, *V. parahaemolyticus*, were not found in the farmed salmon, but were found with a prevalence of 9 and 44% in the wild fish.

(b) *Acinetobacter calcoaceticus* var. *anitratus*, which is a common bacterium found in water and soil, and has been associated with pneumonia, meningitis, and septicemia in humans, was observed with an average prevalence of 14% in cultured fish, and five times higher (76%) in wild fish.

(c) *Aeromonas hydrophila* was observed in over half of the wild fish from both Robertson Creek and Chehalis. Both *A. hydrophila* and *A. salmonicida* are common fish pathogens (Roberts 1978) but neither was isolated from tissues of cultured chinook salmon.

This early work by Caldewood et al. (1988) suggests that wild fish are far more likely to be a source of disease-causing bacteria than farmed fish. Their data do not support any hypothesis that environmental conditions on farms with healthy chinook salmon are enhancing populations of pathogenic bacteria.

Furthermore, in their search for human diseases epidemiologists most frequently examine the population having the greatest exposure to the suspected etiologic agent. On salmon farms, the populations most exposed to the fish are the farm workers and processors. If farms are a significant source of human pathogens, then farm workers and fish processors should show some history of such diseases. There are no epidemiological records, which show evidence of any infectious outbreaks of disease.

Collectively, an understanding of productive environments and fish and human physiology, and the lack of supporting epidemiological evidence, show that salmon farms in the Pacific Northwest are unlikely to increase any risk to human health from marine bacteria. Because of differences in its physical and chemical composition fish farm wastes do not disperse over large areas. They remain localized where they are metabolized by naturally occurring marine bacteria and opportunistic invertebrates. There is no evidence that salmon farms create conditions leading to a proliferation of pathogenic bacteria. Furthermore, from a perspective of human health there appears to be no basis for suggesting fish farm wastes are comparable with human sewage from either large cities or even small towns.

4.4 The Effects of Therapeutic Compounds

The majority of therapeutic compounds used at salmon farms are for the control of sea lice. Sea lice, particularly *Caligus elongatus*, *Lepeophtheirus salmonis*, and *Ergasilus labracis*, have caused extensive losses of fish, particularly at farms in the northeastern Atlantic. They have not presented significant problems to producers in the Pacific Northwest, and salmon produced in Washington have not been treated for lice for the last 15 years (A. Mogster, Northwest Seafarms, personal communication). Both ivermectin and emamectin have been used infrequently to control sea lice in BC.

Costello (1993) and Roth et al. (1993) describe the physical, chemical, and biological methods used to control sea lice on fish farms in other areas. Current practices rely

primarily on the administration of chemo-therapeutic compounds in food or as a bath. The following treatments have been authorized for use.

(i) *Ivermectin*

Ivermectin (22, 23-dihydroavermectin B1) has been used widely in agriculture for many years to control parasites, and was reported by Smith et al. (1993), and Johnson and Margolis (1993) to be effective in controlling sea lice on caged salmon. It is administered as a coating on feed at a rate of 0.025 mg ivermectin/kg of fish at 10°C twice per week for 4 weeks. The dose is increased by 10% for every 1°C decrease in ambient temperature. In Scotland the maximum number of weekly treatments is three per year (SEPA 2000).

Ivermectin is a broad-spectrum biocide which has low water solubility and a moderately high affinity for binding to particles. The compound is reported by SEPA (1998a) to concentrate in *Mytilus edulis* by a relatively low factor of 752. Grant and Briggs (1998a) stated that it did not appear to accumulate or concentrate in the food chain.

Dissolved concentrations of ivermectin are lethal to a number of marine organisms, ranging from a 96 hr LC₅₀ of 0.022 µg ivermectin/L for *Mysidopsis bahia* (Davies et al. 1997) to >10,000 µg/L for nematodes (Grant and Briggs 1998b). Most of the 96 hr LC₅₀ values are less than 1000 µg/L. Collier and Pinn (1998) and Grant and Briggs (1998b) have shown that crustaceans and polychaetes are more susceptible to ivermectin than mollusks. Annual studies in Scotland by ERT Ltd. did not detect ivermectin in the water column (detection limit = 0.5 µg/L) at a Scottish farm undergoing treatment (ERT 1997, and ERT 1998).

Burridge and Haya (1993) found that ivermectin-coated waste feed affected non-target species, such as the shrimp (*Crangon septemspinosa*) at concentrations of 8.5 µg ivermectin/g food. Ivermectin toxicity was demonstrated in laboratory sediments at concentrations ranging from a 10 day LC₅₀ of 23 µg ivermectin/kg dry sediment for *Arenicola marina* by Thain et al. (1997), and to 180 µg/kg for *Asterias rubens* by Davies et al. (1998). Black et al. (1997) documented significant mortality of polychaetes at ivermectin accumulations >81 µg ivermectin/m². This is equivalent to a concentration of approximately 25 µg/kg if the ivermectin is mixed into the top 2-cm of sediments having a density of 1.6 g/cm³. Of particular interest was the adverse effect on the organic carbon tolerant opportunist *C. capitata*, whose abundance was significantly reduced at ivermectin concentrations above the calculated value of 25 µg/kg. The paper by Black et al. (1997) did not discuss the increased chemical and biological remediation times that might result from a significant reduction in the abundance of *C. capitata*.

The fate of ivermectin not absorbed by Atlantic salmon appears to be sedimentation followed by slow degradation. Collier and Pinn (1998) noted that the breakdown of ivermectin in marine sediments was dependent on light and temperature. Davies et al. (1998) determined a half-life of ivermectin in marine sediments to be >100 days under the tested conditions.

ERT (1997 and 1998) detected ivermectin at concentrations ranging from 5–11 µg/kg (wet sediment weight) in only 3 of 54 sediment samples at a farm undergoing treatment. Ivermectin was also detected in sediment traps deployed on the perimeter of farms undergoing treatment at 42 g/kg. Ivermectin was detected in 2 of 108 mussel samples at concentrations of 5 and <5 µg/kg collected from caged mussels deployed around farms undergoing treatment. The active ingredient was not detected in wild shrimp (*Nephrops norvegicus*) collected in the vicinity of the treated farm. According to a report by the Canadian Department of Fisheries and Ocean (DFO), ivermectin (with a detection limit of 1 to 2 µg/kg) was not found in American lobsters (*Homarus americanus*) around salmon farms (DFO 1996); however, the same document noted detection of ivermectin in sediments at distances up to 50 m from a farm in the Bay of Fundy where the compound was used. Concentrations varied between 13.7 and 17.3 µg/kg dry sediment at distances <10 m from the farm perimeter. Traces (between 2 and 6 µg/g) of ivermectin were detected at distances up to 100 m from the farm.

These results suggest that ivermectin is most likely to be detected in sediments and not in the water column. DFO has set a predicted no-effect sediment concentration (PNEC) of 1.8 µg ivermectin/kg dry sediment. Empirical evidence has demonstrated sediment concentrations exceeding this value to 50 m from the perimeter of one farm, but not beyond. In general, significant sediment concentrations of ivermectin have not been observed at distances beyond 10–20 m. The half-life of sedimented ivermectin is approximately three months (DFO 1996). Permission to use ivermectin on farms in Scotland has been withdrawn by the Scottish Environmental Protection Agency (SEPA).

(ii) *Emamectin benzoate*

SEPA reviewed the proposed use in Scotland of the pharmaceutical emamectin benzoate under the proprietary name @Slice (SEPA 1999a). Emamectin has low water solubility and is expected to accumulate in sediments. However, based on laboratory bioassays SEPA stated that emamectin was about ten times less toxic than ivermectin, at least for the genus *Crangon*. However, SEPA noted that the PNEC level of 0.763 µg emamectin/kg wet sediment was lower than the PNEC of 1.8 µg ivermectin/kg proposed by DFO (DFO 1996). Field studies failed to detect emamectin in water, and maximum observed sediment concentrations were just above the level of quantification (1.0 µg/kg wet weight). The sediment half-life of emamectin was 175 days. No adverse effects on infaunal communities were observed following treatment with emamectin benzoate. SEPA used the deposition model (DEPOMOD) to suggest that the ratio of the predicted environmental concentration (PEC) to the PNEC was low, and there was little risk that treatment would pose a threat to sediment-dwelling organisms, even in the worst-case scenario tested. Currently @Slice is in use in Chile, Ireland, and Norway, and has been approved in Scotland by SEPA in January 2000 (SEPA 2000) but to-date no permits have been issued.

(iii) *Calicide*

Calicide (teflubenzuron) has been licensed by SEPA for the control of sea lice in Scotland (SEPA 2000), and is being licensed in Canada, Chile, Ireland, and Norway. This therapeutic compound is administered as a 2-g/kg coating on feed. It is a chitinase

inhibitor effective against juvenile sea lice on salmon at a dose of 10 mg/kg-day⁻¹ for seven consecutive days. It has reduced effectiveness after lice become adults and stop molting.

SEPA (1999b) noted that calicide had a long half-life of 115 days in sediments, and could be detected at distances up to 1,000 m downstream from farms being treated. However, no adverse effects were detected in benthic communities (including crustaceans) and SEPA concluded that any residual teflubenzuron was not bio-available. Calicide inhibits the production of chitinase and therefore is not toxic to phyla other than the Crustacea.

For teflubenzuron, SEPA (1999b) permitted an allowable sea-water quality standard of 6.0 ng/L for the annual average, and a maximum allowable concentration of 30 ng/L. In Scotland there is an '*allowable effects area*' of 100 m from salmon farms. A sediment quality standard of 2.0 µg calicide/kg dry sediment in a 5-cm deep core has been established outside this area. Sediment concentrations at all distances within 25 m of a treated farm must be maintained at less than 10 mg calicide/kg dry sediment (5 cm core).

Calicide is approved only for interrupting the life cycle of sea lice. It is not approved for treating adult lice infestations. Its use is based on computer-modeling of specific sites and it is not approved for general use. Predicted sediment and water column concentrations of the active ingredient must be lower than the water and sediment quality standards described above.

(iv) Cypermethrin

®Cypermethrin (dichlorvos) is a pesticide being used in investigative programs, and under some form of temporary registration in Canada, Ireland, Norway, UK, and US. It is administered in a 5 µg/L bath for 60 minutes within a confined and covered area.

Dichlorvos is toxic to crustaceans, with a LC₅₀ of 0.006 µg/L and a no-observed-effect concentration (NOEC) of 0.003 µg/L for *Mysidopsis bahia*. It is adsorbed by sediments where it degrades with a half-life of 35 days in high TVS sediments and 80 days in low TVS environments. It has a 10-day NOEC of 1000 µg/kg in *Arenicola*, and 64 µg/kg in amphipods of the genus *Corophium*. Concentrations greater than about 10 ng/L are acutely toxic to some crustaceans, and modeling suggests that this value can be exceeded in the immediate vicinity of pens being treated with this product. SEPA (1998b) concluded that toxic effects to non-target species could occur within a few hundred meters of a treated farm and that these effects might last for several hours.

High mortality of shrimp and lobsters has been observed when they are exposed to a bath of dichlorvos, but the effect has not been observed outside net-pens. Field trials have observed peak water concentrations of 187 ng/L 25 m downstream from salmon net-pens following removal of the tarpaulin covers.

Based on an absence of demonstrated deleterious effects on non-target animals, SEPA (1998b) recommended authorization of ®Excis (containing dichlorvos) for a 2-year period initially. Individual permits are issued by SEPA. Modeling must predict that the

proposed treatment will not result in exceeding a 3-hr environmental quality standard of 16 ng/L in the dispersing plume following removal of the covers. Post-treatment monitoring is required.

(v) *Azamethiphos*

Azamethiphos (or ®Salmosan) is a pesticide administered in a bath at 0.1 mg/L. The active ingredient degrades with a half-life of approximately 11 days at neutral pH. Larval lobsters were the most sensitive organism tested with a 96 hr-LC₅₀ of 0.52 µg/L and a no-observed-effect level (NOEL) of 0.156 µg/L. A toxicity threshold to lobster larvae was estimated by SEPA (1997) at 0.078 µg/L. Azamethiphos is very water-soluble and is not expected to accumulate in sediments. Compared with dichlorvos, azamethiphos is considered more toxic to crustaceans. SEPA (1997) restricted its use in aquatic environments where modeling predicted that:

- 3 h after treatment the mean residual concentrations in the dispersion zone will not exceed 160 ng/L.
- 24 h after treatment the mean residual concentrations in the receiving water will nowhere exceed 80 ng/L.
- 3 days after treatment the residual concentrations in the receiving water will nowhere exceed 5 ng/L.

Post-application monitoring was required by SEPA to ensure compliance.

The control of sea lice is important to the health of farmed salmon and to reduce the potential for salmon farms to act as vectors for the infestation of wild stocks of salmon and sea trout. A review of the available treatments suggests that great care must be exercised in the use of these therapeutic compounds. They are all non-specific, at least within the Class Crustacea, and several are broad-spectrum biocides with potential to affect many phyla adversely. However, field studies have not found significant widespread adverse effects to either pelagic or benthic resources associated with the authorized use of these pharmaceuticals or pesticides.

4.5 Farm Sediments

4.5.1 Monitoring environmental effects on sediments

Infaunal community analysis, as demonstrated by Pearson and Rosenberg (1978), Mahnken (1993), and Brooks (2000a), is ultimately the most direct and sensitive methodology for assessing the biological response to organic loading from salmon farming. However, benthic communities are not stable, as shown by Mills (1969) and Eagle (1975), and their structure is influenced by many natural processes unrelated to human influence. These processes include seasonal factors (Crisp 1964, Arntz and Rumohr 1982, and Brooks 2000a) and physicochemical factors (Striplin Environmental Associates 1996). Skalski and McKenzie (1982) pointed out that this variability typically requires large numbers of samples to achieve reasonable test powers.

The international Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) noted that the taxonomy required in support of infaunal analysis was expensive and time consuming (GESAMP 1996). This cost, when

coupled with high internal variability, detracted from infaunal analysis as a routine method for evaluating environmental effects as part of regulatory programs. Therefore physicochemical endpoints, including TVS, TOC, redox potential (Eh) and total sediment sulfides (S^{2-}) were being used increasingly as rapid and inexpensive surrogates for assessing biological response. GESAMP (1996) concluded that the visually determined depth of the reduction-oxidation discontinuity was of low value because it was semi-quantitative. They did not consider emerging physicochemical endpoints, such as sulfide analysis using ion specific probes (Wildish, et al. 1999), or TVS (Hargrave et al. 1995, Brooks 2000e and 2000f).

Brooks (2000c and 2000e) discussed the relative merits of TVS, TOC, S^{2-} , and Eh for evaluating the environmental response to salmon farms. He noted that organic carbon, whether measured as TOC or TVS, had only a moderate correlation with biological effects, particularly infauna. He hypothesized that sediment carbon comes in many forms including woody debris, which is refractory to microbial catabolism resulting in low BOD. Drift macroalgae and eelgrass form an intermediate class of sediment carbon broken down within a few months to one year. Fish feces on the other hand was very labile and created high BOD, more frequently leading to anaerobic conditions than woody debris or macroalgae. Therefore 15% TVS may not exceed the assimilative capacity of the sediment if it was in the form of woody debris, whereas 15% TVS associated with salmon farm waste in the same sediment would be more likely to create anaerobic conditions with significant biological effects. It was recognized that when finely divided woody debris exceeded the assimilative capacity the effect could last for centuries as the wood deteriorated very slowly. Salmon farm waste, on the other hand, because it was catabolized very quickly had rather ephemeral effects lasting from months to two or three years in extreme cases.

Redox potential (Eh) was identified by GESAMP (1996) and Wildish et al. (1999) as a valuable endpoint for evaluating sediment chemistry near salmon farms because it is rapid, low cost, and permits extensive spatial surveys. Brooks (2000f) found low sediment redox (20.68 ± 22.29 mV) and low sulfide concentrations (29.83 ± 11.59 μ moles) in the same samples from reference stations located in areas with greater than 80–90% silts and clays comprising the sediment grain size distribution. He noted low Eh and high sulfide concentrations in sediments were not always well correlated, and that low Eh could be the result of physical processes, especially in fine-grained sediments. This limited its usefulness in evaluating the effects of carbon input from salmon farms.

Wang and Chapman (1999) described the response of laboratory bioassay test animals to sediment sulfides. However, despite attempts by Brown et al. (1987), Henderson and Ross (1995), and Hargrave et al. (1997), the literature does not provide a good quantitative description of the response of natural infaunal communities to sediment sulfide concentrations or redox potential.

In summary, benthic infaunal and epifaunal analysis appears to be the most sensitive indicator of environmental health in sediments around salmon farms. However, benthic communities are not stable across environments and depend on the physical environment,

including water depths, current speeds, sediment grain size distribution, and the availability of organic carbon (Striplin Environmental Associates 1996). In addition benthic communities vary by season, as influenced by food input and water temperature, etc. (Arntz and Rumohr 1982).

4.5.2 Biological changes in the water column and sediments

The environmental changes associated with salmon farms are superimposed on natural changes. These potential effects have been examined in numerous studies during the last two decades. Despite significant site-specific variability there is a consistent thread binding this literature.

(i) Water column changes

Possible changes in the water column associated with the intensive culture of fish could be associated with intoxication due to hydrogen sulfide and ammonia production in underlying sediments, decreases in dissolved oxygen associated with salmon respiration and/or the oxidation of sedimented waste, and eutrophication associated with nitrogen released across gill epithelia and in urine and feces. The magnitude and consequences of environmental changes associated with these factors is dependent on environmental parameters such as water depth, current speeds, background nutrient availability, salinity, rainfall, wind, etc., which in aggregate constitute the local environment.

(ii) Nitrogen and phosphorous loading to the water column

Marine environments along the west coast of North America are especially productive because cold, upwelling, nutrient rich water replaces surface waters driven offshore by prevailing northwesterly winds. In addition, the relatively high geographic latitude of BC and Washington results in reduced light penetration in water compared with more southerly latitudes. Lastly, moisture laden onshore winds create significant cloud cover throughout much of the year. These factors combine to limit light availability significantly in most temperate marine environments, except during summer months. Furthermore, it should be noted that in most marine environments, nitrogen is the limiting nutrient and not phosphorus. The remainder of this review will focus on nitrogen inputs.

In the Pacific Northwest, wind-driven vertical-mixing drives a significant proportion of the phytoplankton crop below the compensation depth where cell respiration equals photosynthesis and where they no longer multiply. Where water freely circulates, flood tides replenish nutrients from water upwelling offshore. When coupled with the atmospheric and geographical factors that reduce light availability, the result is that primary productivity in the Pacific Northwest is generally light limited, not nutrient limited. This is especially true during winter months. In other words, there is insufficient light to use the nutrients already available in the water column. Adding more nutrients in a light limited system does not increase plant growth.

There are sheltered, poorly flushed, shallow embayments where salinity and temperature induced stratification results in a stable water column that allows phytoplankton to remain above the compensation depth. When these conditions occur in the spring or summer, significant blooms can occur following several days or weeks of clear sunny

weather. These blooms eventually wane because winds increase vertical mixing; cloud cover reduces the available light; or nutrients are depleted in the surface water. In this last situation, nutrient input from a salmon farm could further stimulate plant growth, exacerbating the problem. In addition, shallow bays having significant freshwater input and minimal flushing, are not considered good sites for net-pen grow-out operations. However, they might be deemed appropriate as smolt introduction sites.

The last point to consider in this general discussion is that nitrogenous compounds are released from fish farms into currents that generally average greater than 4 to 12 cm-sec⁻¹ and acoustic Doppler current meter studies at British Columbia salmon farms have revealed net transport speeds of 1.0 to 5.0 cm-sec⁻¹. At temperatures of 10–15°C, it takes one to two days for an algal cell to divide, even if all of its photosynthetic needs are met (Brooks 2000g). An algal bloom may result in cell densities increasing from a few thousand cells per ml to perhaps a million. That requires eight or nine cell generations, which requires a minimum of 8–16 days. In open bodies of water, moving with a net speed of even 2 cm-sec⁻¹, a phytoplankton population would move 14 km from the location at which nutrients were added during creation of a bloom. Recall that the barely significant increases in nitrogen observed 6 m downstream from farms in Puget Sound were generally not detectable at 30 m downstream. Therefore it appears reasonable to conclude that, within a single algal cell division (one to two days), the water passing through the farm would have traveled at least 1.7 km. It is difficult to conclude that the nutrient additions from the farm, generally undetectable at 30 m downstream would have any effect at all on primary production even if the water body was nutrient limited.

Pease (1977), Rensel (1988 and 1989), and Parametrix Inc., (Parametrix 1990) documented small increases in dissolved nitrogen within and on the perimeter of salmon farms. However, all of these authors agreed that the quantity of dissolved nitrogen added by even several farms would have no measurable effect on phytoplankton production. Gowen et al. (1988) studied a Scottish loch with very restricted water exchange to the open sea and a large salmon farm. The authors concluded that the farm had no measurable effect on phytoplankton density.

Weston (1986) conducted a quantitative assessment of the effects of five hypothetical farms located in a small embayment with poor flushing. His analysis suggested that the nitrogen added by five farms could not be expected to adversely affect the phytoplankton abundance in the embayment. He did address the issue of nutrient sensitive embayments and recommended that these areas should be identified and carefully managed.

Banse et al. (1990), Parsons et al. (1990), Pridmore and Rutherford (1992), Taylor (1993), and Taylor and Horner (1994) all examined phytoplankton production and blooms of noxious phytoplankton in the Pacific Northwest. They concluded that nitrogen levels and phytoplankton production at salmon farms were determined by ambient conditions. Furthermore, they found that salmon farms had little or no effect on ambient levels of either nutrients or phytoplankton density.

The literature is consistent with the previous general discussion and strongly supports a thesis that, with the exception of a few shallow, very poorly flushed embayments, the potential for net-pen enhancement of phytoplankton populations is remote, or non-existent. Based on similar arguments and ten years of monitoring dissolved nutrients at salmon farms, Washington State eliminated any requirement for water column monitoring in compliance with NPDES permits issued to all salmon farms in 1996.

4.5.3 Hydrogen sulfide gas production in sediments

When the assimilative capacity of the benthos is exceeded, oxygen is depleted and sulfur-reducing bacteria continue to degrade organic carbon. During the process either ammonia or hydrogen sulfide gas may be produced. These gases, particularly the latter, are highly toxic and can significantly compromise infauna. They are not unique to fish farms and other sources of anthropogenic carbon, and are frequently found in natural environments where organic debris (leaves, macroalgae, eel-grass, etc.) accumulates. Hydrogen sulfide is the cause of the 'rotten egg' smell emitted from many pristine estuarine sediments at levels $>2 \mu\text{g/L}$ (EPA 1986).

Hargrave et al. (1997) examined a suite of physicochemical parameters under 11 salmon farms and 11 reference stations located >50 m from net-pens in the Western Isles region of the Bay of Fundy on the east coast of Canada. Sediment concentrations of hydrogen sulfide were found to be significantly different ($P = 0.00001$) under net-pens when compared with reference sediments. Total sulfide concentrations in surface sediments at all cage sites were $>180 \mu\text{M}$ while values at all but one reference location were $<200 \mu\text{M}$. They noted sulfide concentrations $>2000 \mu\text{M}$ were indicative of high organic loading under some net-pens and were generally associated with negative Eh potentials.

Ammonia and hydrogen sulfide are lighter than water and when significant quantities of these gases accumulate in sediments, they can escape and rise to the surface (out-gassing). As the bubbles rise the soluble H_2S is dissolved in the water column. Samuelsen et al. (1988) analyzed gas released from sediments underlying poorly flushed salmon farms. They found that 98% of the gas was CH_4 and CO_2 . Less than 1.9% of the gas at the sediment-water interface was sulfide (S^-). Furthermore they found that, after rising 3 m in the water column, the S^- was reduced to 0.05% of the total gas. The resulting concentration would be $1.54 \times 10^{-6} \text{ g S}^- / (58.9 \text{ ml} \times 1.025 \text{ g/ml})$ or $25.5 \mu\text{g S}^- / \text{L}$ seawater (25 ppb). Water quality standards are based on the undissociated sulfide (H_2S) which is ca. 10% of S^- at $\text{pH} = 8.4$. Applying this factor predicts an undissociated H_2S level of 2.55 in the 0.5 cm diameter column through which the gas bubble passes. This is approximately equal to the $2 \mu\text{g/L}$ chronic water quality criteria established by the EPA (1986) for freshwater and marine environments. In reality oxidation, diffusion, and mechanical mixing significantly reduce concentrations further by a factor of 100 or more.

Samuelsen et al. (1988) found that the fraction of the less soluble CH_4 did not appreciably change during transit of the bubbles through the water column. The low concentration of H_2S in the bubbles at the sediment-water interface, and the low water concentrations predicted during ascent, suggests that very large gas emissions would be required before sufficient H_2S could be dissolved in the water column to create toxic conditions.

4.5.4 Dissolved oxygen

Weston (1986) reviewed the effects of salmon culture on ambient dissolved oxygen levels and concluded that farms could decrease these levels by 0.3 ppm. Brooks (1991, 1992, 1993a, 1994a, 1994b, 1995a, and 1995b) observed decreases of as much as 2 ppm in water passing through a large, poorly flushed farm in Puget Sound. Significant reductions in dissolved oxygen (DO) were not observed by Brooks (1994a and 1994b) at farms in well-flushed passages. In no case were DO levels within 6 m of the downstream farm perimeter depressed below 6 ppm, a minimum level for optimum culture of salmonids. Winsby et al. (1996) reported a range of results from the literature. However, his discussion in general suggested that depressed oxygen levels are associated with the water column immediately overlying anaerobic sediments. Cross (1993) concluded that salmon farms in BC have minimal effects on ambient DO levels.

Depressed oxygen levels (3 to 6 ppm) are infrequently encountered at salmon farms along the Pacific coast. These depressions result from the upwelling of cold, nutrient rich but oxygen deficient water to the surface. Conditions favoring depressed DO are most frequently encountered in the Pacific Northwest during the summer and fall when northwest trade winds increase oceanic upwelling. Deep fjords, like Hood Canal in Washington State, can also experience depressed concentrations of DO when winds bring anoxic water to the surface from deep stagnant pools. Feeding is suspended and compressors used to increase DO when these naturally occurring masses of water with low DO levels flow into salmon farms. This phenomenon is imposed on the farm, not caused by the farm. However, the frequency of occurrence of these oxygen deficient water masses should be assessed in siting a farm. In addition, it could be considered good management on the part of operators to measure DO in bottom water under their farms in an attempt to predict periods of depressed surface oxygen.

In summary, based on the literature it appears that net-pens create only minor depressions in surface water DO concentrations. When sediments under a farm become anaerobic the overlying water to a depth of perhaps a meter may experience some reduction in DO. This is most likely to occur under farms with very poor circulation (<3 to 5 cm-sec^{-1} maximum current speeds).

4.5.5 Changes in the local fish community

Salmon farms are known to function as fish aggregating devices. The structures attract numerous fish species, which frequently take up residence between the containment and predator nets. There are no published reports as yet which document this community of aquatic animals, and its abundance. Brooks (1994b and 1995b), at a well-flushed net-pen site in Washington identified pile perch (*Rhacochilus vacca*), shiner perch (*Cymatogaster aggregata*), herring (*Clupea pallasii*), lingcod (*Ophiodon elongatus*), bay pipefish (*Syngnathus leptorhynchus*) and several species of sole (*Pleuronichthys* spp.) all in abundance. At another site nearby, located over a sandy bottom, sea cucumbers (*Parastichopus californicus*) and geoducks (*Panopea abrupta*) had proliferated. All of these populations are closely associated with the farm (within 30 m). It should be added that one of these facilities is located in shallow water (15–18 m MLLW) and fast currents

(115 cm-sec⁻¹). The second facility is located in a moderately well flushed environment with maximum currents of 30 cm-sec⁻¹ and water depths of 22–30 m MLLW.

4.5.6 Physicochemical changes in the sediment near salmon farms

The chemical and biological effects associated with fish farms have been documented and reviewed by Pease (1977), Braaten et al. (1983), Earll et al. (1984), Ervik et al. (1985), Ackefors (1986), Weston (1986), Aure et al. (1988), Rosenthal et al. (1988 and 1995), Weston and Gowen (1988), Hansen et al. (1990), Parametrix (1990), Gowen et al. (1991), Johannessen et al. 1994, Winsby (1996), Mazzola et al. (1999) and Morrissey et al. (2000). It is possible to model rates of organic loading from net-pen operations described by Weston and Gowen (1988), Findlay (1992), Einen et al. (1995), Silvert and Sowles (1996), and Ervik et al. (1997). The fate and transport of those wastes is a far more complex problem. However, the effects of farm wastes on the benthos in a variety of environments have been well documented. Brooks (1992, 1993a, 1994a, 1994b, 1995a, and 1995b) studied sediment chemistry (redox, TOC, nitrogen, and sediment grain size) and benthic infaunal response at two farms which represented two very different environments in Puget Sound, Washington. In terms of negative environmental effects associated with intensive net-pen fish culture, organic loading to the sediments is most significant. Goyette and Brooks (1999) observed statistically significant changes in the composition of the benthic infaunal community in Sooke Basin, BC associated with small natural changes in sediment organic carbon content of <1% change across the 500-m study area. In general, the literature suggests a lack of appreciation of the sensitivity of the benthos to small additions of organic carbon, particularly labile forms like fish feces.

Hargrave et al. (1995) documented sediment total sulfide concentrations under salmon farms in the Bay of Fundy that were $\leq 6,600 \mu\text{moles S}^-$. In contrast, Brooks (2000c and 2000f) observed significantly higher sediment sulfide concentrations (<16,000 μmoles) on the perimeter of salmon farms in Canada BC, and Wildish (1999) reported sediment concentrations up to 36,000 $\mu\text{moles S}^-$ in Bay of Fundy sediments under operating farms.

4.5.7 Biological effects

The biological response of infauna to the sediment physicochemical changes occurring as a result of organic loading from salmon farms has been assessed by Hargrave (1994), Henderson and Ross (1995), and Hargrave et al. (1997). The toxicity of sulfide to infauna is documented for a few species (Bagarinao 1993; Wang and Chapman 1999), but despite the efforts of Henderson and Ross (1995), quantitative relationships between infauna and physicochemical endpoints (S^- , Eh, TVS) remain elusive. Brooks (2000a) observed a significant enhancement in infauna during the early stages of production and at the end of the fallow period. However, at the peak biomass there was a significant reduction in the number of invertebrates observed at downstream stations located between 20 m and about 70 m from the farm perimeter. Near-field invertebrate numbers were supplemented by allochthonous input from the fouling community on farm nets. In addition, a significant portion of the invertebrate community associated with near-field sediments during periods of high organic farm input were the TOC tolerant species *C. capitata* and *Ophryotrocha cf. vivipara*.

Species richness, the number of species observed in biological samples, is frequently a more sensitive indicator of environmental stress than abundance. Brooks (2000a) observed significant reductions (<2.0 standard deviations below the mean) in the number of taxa within 45 m of the farm during peak production. It did not appear that significant effects extended beyond 75 m during this production period. Biological remediation began as soon as harvest was initiated in April of 1997 and was essentially complete within four months of fallow. A slight enhancement in taxa richness was evident five months following the completion of harvest.

Polychaete abundance was enhanced as sediment organic carbon built up at the beginning of the production cycle. Abundance declined within 80 m of the farm perimeter during peak biomass when farm waste exceeded the assimilative capacity of the sediments, which became anaerobic. Polychaete abundance began increasing again during the winter of 1996–1997, approximately six months after harvest began. Polychaetes proliferated with the improving benthic conditions and exceeded reference abundance during the last 6 months of the study. The enhanced area extended from the farm perimeter to a distance of at least 75 m during the October 1997 evaluation.

Brooks (2000a) found that crustaceans were adversely affected at near-field stations earlier (and therefore possibly in association with smaller increases in sediment organic carbon) than polychaetes. A steady increase in the number of crustacean taxa was observed as soon as the fish biomass began decreasing during harvest. The salmon farm had little effect on the overall abundance of crustaceans. In part that was because the benthos in the immediate vicinity of the farm was supplemented by allochthonous input from the net-pens, such as the amphipods *Metacaprella kennerlyi* and *Jassa falcata*. Arthropods were supplemented by mobile crustaceans, such as the megalope of *Cancer magister* which were very abundant in the vicinity of the farm during June 1996.

Brooks (2000a) found that mollusks were an abundant and diverse part of the infaunal invertebrate community in reference sediments from the study area. Statistically significant decreases in the numbers of mollusks were not observed in this study. However, the number of molluskan taxa was significantly reduced at all farm stations during the production cycle. An increase in the number of molluskan taxa was evident at the end of the study, but the number of taxa observed within 50–75 m from the net-pen perimeter had not recovered to reference conditions.

Brooks (2001) has determined the biological response to varying concentrations of sediment TVS, sulfides, and Eh as a function of farm production, overlying currents, and sediment grain size distribution. Preliminary results indicated that reference sulfide concentrations were generally low (10–100 μmoles) but could be as high as 250–300 μmoles . Reductions in the number of taxa from >20 species to 12–14 species, with significantly increased abundance and biomass of infauna, were noted with sulfide concentrations in the range of 300–2,000 μmoles . Sediments containing >2000 micromoles S^- had a reduced infaunal community dominated by *C. capitata*, and those containing greater than 6,000 μmoles were generally sparse. His findings were consistent

with the reports of Wildish (1999), Poole et al. (1978), and Pearson and Rosenberg (1978), which are tabulated below.

Endpoint	Classification				Reference
	Normal	Oxic	Hypoxic	Anoxic	
Microbial	Normal	Oxic	Hypoxic	Anoxic	Poole et al. 1978
Macrofaunal	Normal	Transitory	Polluted	Grossly polluted	Pearson and Rosenberg 1978
Sulfides	<300	300–1300	1300–6000	>6000	Wildish et al. 1999

4.5.8. Case histories describing benthic responses to salmon farming.

Brooks (1991a, 1992, 1993a, 1994a, and 1995a) evaluated a salmon farm located in a poorly circulated bay with maximum current speeds of less than 8 to 10 cm-sec. This farm is situated in deep water (30–33 m MLLW) over fine-grained substrates containing 820–50% silt and clay mixed with sand. The farm has produced as much as 863 mt of Atlantic salmon in one year. TOC remained constant near the baseline mean of 1.067% at all stations until 1990 when production increased. By 1990, TOC at the periphery of the farm increased to 2.48% and remained within a range of 1.85 to 2.95 from 1990 until 1995 while significant quantities of salmon were being produced. This level of TOC in sediments containing less than 50% fines (silt and clay) resulted in a significant change in the benthic community.

Reductions in the infaunal community were generally restricted to distances less than 22 m, and in 1992 and 1993 a normal benthic community was observed at distances as close as 6 m from the farm perimeter. The biomass of salmon on site during the period immediately preceding the survey was significantly greater in 1995 (453,229 kg) than in previous years (134,577 kg in 1994). The effects of this were seen in the increased TOC at all far-field stations. Sediment organic carbon was very sensitive to farm operations and highly correlated with management practices.

The number of infaunal species was determined at the same stations used to measure TOC. The results indicated a reasonably homogeneous benthic community over the 60 m sampling transect during the baseline survey. Infaunal diversity decreased at stations less than 6 m from the perimeter of the farm very shortly after operations began in 1989. Species diversity was variable at stations >15 m from the perimeter of the farm following start-up. In general infaunal diversity exceeded baseline values at stations >30 m in all years except 1989, which was probably due to a 1,250 m³ oil spill in the harbor several months prior to the survey. In years following that accident, infaunal diversity at all stations greater than 15 m from the farm perimeter were elevated above the 1987 baseline value. However, the 15 m station suffered a significant decline in species during 1995 when production peaked.

Total invertebrate abundance was more sensitive than diversity to organic carbon input. Except for the year of the oil spill, and 1995 when production peaked, infaunal abundance was generally equal to or greater than baseline values at all stations greater than or equal to 30 m from the perimeter of the farm. There was a consistent amplification of abundance at the 60 m station in all years. Benthic impacts were restricted to 15 m and less, except when production peaked. This reinforces the diversity

data and demonstrates that both abundance and diversity were sensitive to organic carbon input. Over the history of this farm the distance at which adverse effects on benthic community were observed varied between 6 m and 30 m downstream from the farm perimeter. These effects were dependent on the biomass of fish being raised and the resulting sediment concentrations of organic carbon.

Sediment organic carbon was reduced to less than baseline values between 30–60 m downstream where there was a significant increase in the number of species (average of 106 species per station) and their abundance (9,367 animals per station, which was over twice the baseline average of 4,552). No cause and effect relationship between this amplification and the reduced TOC at stations 30 m and 60 m was investigated. Brooks hypothesized that the increased infaunal biomass was consuming the missing TOC.

In contrast, Brooks (1994b and 1995b) documented sediment chemistry and infauna downstream from a salmon farm located in a well-flushed passage with maximum current speeds in excess of 125 cm-sec^{-1} . The water was shallow (15–18 m MLLW) and the bottom consists of large gravel, cobble and rock mixed with small amounts of sand, silt, clay and broken shell. The site was used for final grow-out as part of a complex, which produced approximately 3,000 mt of Atlantic salmon per year. Monitoring results demonstrated the positive environmental effects associated with this farm, which had been operating continuously for more than 10 years in the same location. A total of 3,953 infaunal organisms distributed in 116 species were observed at the 60 m control station in 1994. The abundance and diversity of benthic infauna was enhanced at all stations closer to the farm with a maximum of 7,350 animals distributed in 173 species observed at the 30 m station. On the periphery of the farm 4,207 animals were observed, distributed in 142 species. Annelids dominated the infaunal community and the annelids *C. capitata* (16%) and *Prionospio steenstrupi* (17%) were abundant in the immediate vicinity of the farm. However, arthropods and surprisingly mollusks (*Mysella tumida* and *Macoma* spp.) were well represented in these samples. The abundance and diversity of infaunal organisms was positively correlated with sediment TOC, suggesting that organic carbon was limiting the infaunal community throughout the area. Significant numbers of fish, shrimp and other megafauna were observed during each annual survey at this site, which appeared to function as an artificial reef. Three salmon farms located in close proximity all shared the same characteristics. They appeared to attract megafaunal predators and to enhance the infaunal and epifaunal communities.

4.6. Recovery and Remediation of Sediments

Chemical and biological recovery of sediments under salmon farms has been documented by, *inter alia*, Ritz et al. (1989), Anderson (1992), Mahnken (1993), Brooks (1993b), Brooks (2000a), Lu and Wu (1998), Karakassis et al. (1999) and Crema et al. (2000).

4.6.1 Chemical remediation

Brooks (2000a) defined chemical remediation as the reduction of accumulated organic carbon with a concomitant decrease in hydrogen sulfide and an increase in sediment oxygen concentrations under and adjacent to salmon farms to a level at which aerobic organisms can recruit into the area. At the farm being studied sediment concentrations of

volatile solids declined rapidly as soon as harvest was started in June of 1996 and they were close to control values when the harvest was completed in April of 1997. By the end of the 10-month harvest, significant differences ($\alpha = 0.05$) in TVS were not observed between the mean for all reference area data and farm stations located at 5, 10, and 15 m from the net-pen perimeter. Chemical remediation resulted in increased levels of oxygen in sediment pore water and decreased levels of H₂S and/or ammonia. H₂S was evaluated organoleptically. High levels of sediment H₂S were evident to 20 m during peak production. Moderate levels of H₂S were observed as far as 37 m on the downstream transect. H₂S was detectable at low levels to distances less than 50 m from the net-pen perimeter at the peak of production. It was moderately well correlated with other physicochemical parameters ($r = 0.68$ to 0.69).

4.6.2 Biological remediation

Biological remediation was defined by Brooks (2000a) as the restructuring of the infaunal community to include those taxa representing at least 1% of the total invertebrate abundance observed at a local reference station. Recruitment of rare species (those representing <1% of the reference area abundance) into the remediation area is not considered necessary for biological remediation to be considered complete.

Brooks (2000a) observed the beginning of biological remediation during the harvest period. Biological remediation appeared to be nearly complete 5 months following harvest. Several infaunal series are apparent in his data. These were initially identified using principal components analysis. The results are presented in Figure 1.

Farm inputs (fish biomass and 30-day feeding rate) associated in Group I were positively correlated with several sediment physicochemical variables including percent fines, total volatile solids and the presence of hydrogen sulfide. There was also a significant and positive correlation between the opportunistic polychaetes *C. capitata* and *O. vivipara*, and farm inputs.

Species identified in Group II were not strongly negatively correlated with farm inputs. However these species all shared at least one of two characteristics. Larval shrimp (LSHRIMP), and crab megalope larvae (BRACHMEG) are mobile organisms which live on top of the sediments, enabling them to avoid the anaerobic conditions associated with high organic loading. The amphipods, *Jassa falcata* (JASFAL) and *Metacaprella kennealyi* (METKEN), and barnacles in the Class Cirripedia (CIRRI), were found in great abundance on the farm structure. Their presence on anaerobic sediments containing high amounts of volatile solids probably represented an ephemeral benthic community derived from the net-pen structure.

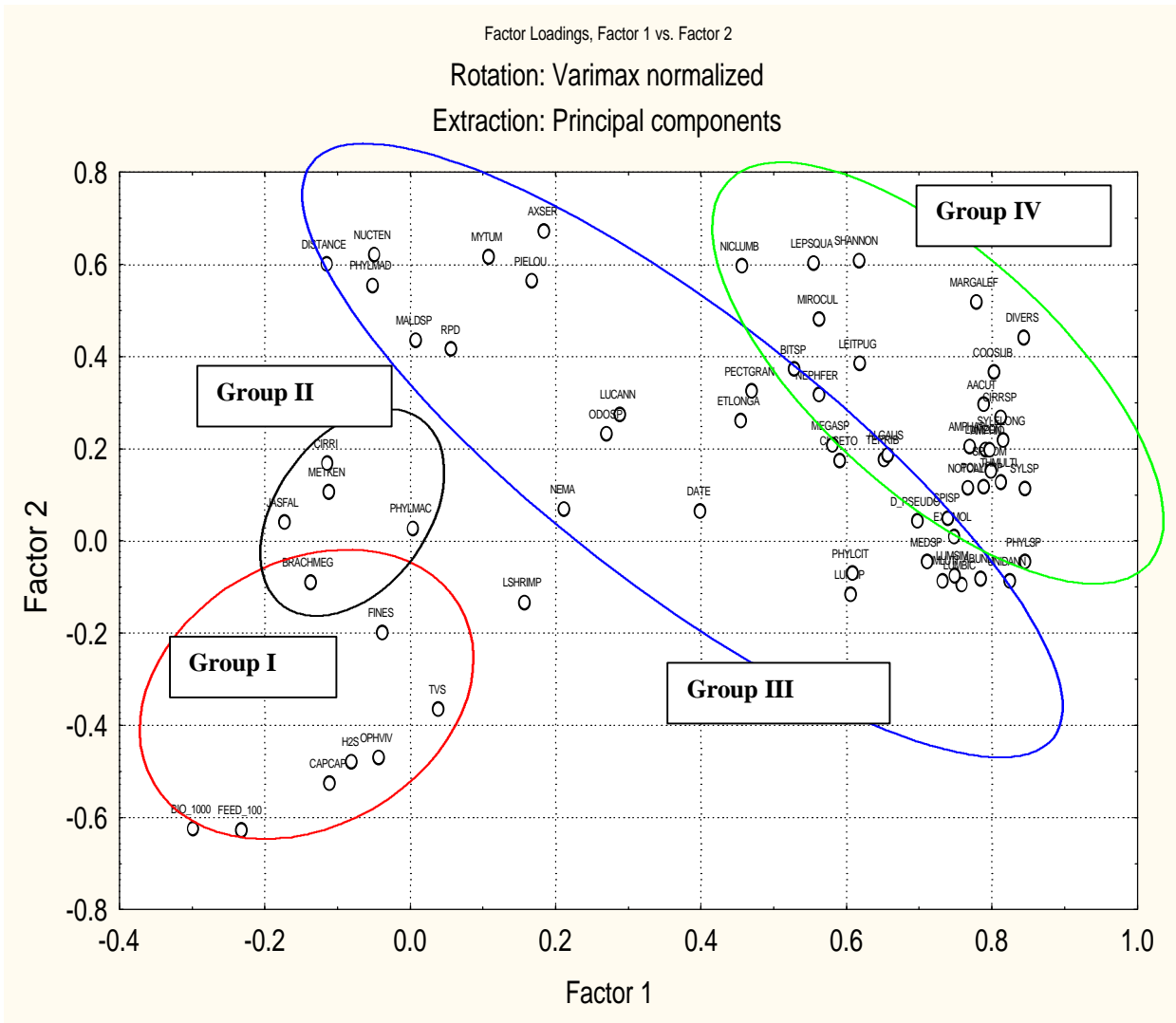


Figure 1. Output from a Varimax normalized principal components analysis of the dominant infauna, farm inputs, and sediment physicochemical parameters. (From Brooks 2000a).

Key for Group II organisms

LSHRIMP – Larval shrimp

BRACHMEG – crab megalope larvae

JASFAL – the amphipod *Jassa falcata*

METKEN – the amphipod *Metacaprella kennerlyi*

CIRRI – barnacles in the Class Cirripedia

Group III organisms were early colonizers following chemical remediation. Organisms in this group demonstrated a range of tolerance to sedimented organic carbon. Chemical remediation occurred very quickly at this site and the order of recruitment into the area was more likely a function of when the various taxa spawned than of sediment TVS concentrations. Finally, the organisms in Group IV were strongly negatively correlated with farm inputs. These organisms were least tolerant of sedimented carbon, or recruited late in the year. It is also worthy of note that Shannon's diversity index, Margalef's index, and infauna-diversity were more negatively correlated with farm inputs than any of the individual taxa. These data suggested at least three invertebrate series, as follows:

Concentrations of organic carbon		
High	Medium	Low
<i>Capitella capitata</i>	<i>Nematoda</i>	<i>Lepidonotus squamatus</i>
<i>Ophryotrocha vivipara</i>	<i>Mediomastus sp.</i>	<i>Cooperella subdiaphana</i>
	<i>Eteone longa</i>	<i>Syllis elongata</i>
	<i>Lumbrineris sp.</i>	<i>Notocirrus californiensis</i>

Other measures of biological integrity (Shannon's diversity index and Margalef's index) were also evaluated. Striplin Environmental Associates (1996) found that Shannon's index varied between 1.09 and 1.53 at Puget Sound reference stations where the percent fines (silt and clay) was less than 20% and water depths were <45 m. Brooks (2000a) found relatively high values of Shannon's index (2.6 ± 0.4) at the reference station. These values suggest that the undisturbed infaunal community was diverse and evenly distributed. Low values of Shannon's index suggest a community dominated by a few species. This condition was evident to 50 m and possibly as far as 100 m from the perimeter of the net-pens on the down current transect during the peak of the production period. Shannon's index increased steadily following the initiation of harvest and an enhancement of the invertebrate community was suggested by this index at the end of the 5-month fallow period.

Anderson (1992) aggregated the taxa identified in three replicate Ponar grab (0.05 m²) samples at each station at fallow farms in Canada BC, and found H' values varying from 0.108 to 1.465. The lowest values were found at stations with high TOC loading dominated by *C. capitata*, *Nephtys cornuta*, and the gastropod *Mitrella gouldi*. The higher values were generally associated with undisturbed reference stations. He used principal components analysis (PCA) to observe that factors fallow time, biomass, percent fines, total taxa richness and Shannon's index (H') were positively correlated with each other and negatively correlated with TVS, coarse sand, gravel, and sulfide. He concluded that high values of TVS and sulfide were indicative of unhealthy ecological conditions. Anderson (1992) observed recovery times that varied between several months at sites with low initial impact to an estimate of two years for severely impacted sites during which physical, chemical and microbial processes acted on sediments to make them hospitable to macrofaunal colonization. This refractory period was referred to as *chemical remediation* by Brooks (2000a). Once macrofaunal colonization began Anderson (1992) observed an increased rate of recovery.

In Washington State Brooks (1993b) found recovering sediments dominated by *N. cornuta*, *Glycera*, and *Lumbrineris*, with few *C. capitata* in the vicinity of a fallow salmon farm in Port Townsend Bay, Washington. He hypothesized that, following cessation of production in October 1992, an initial period of chemical remediation was followed by a proliferation of opportunistic *C. capitata*. As the organic load was dispersed and catabolized by microbes, and the oxidation-reduction potential increased, predatory polychaetes in the genera *Nephtys*, *Glycera*, and *Lumbrineris* flourished by preying on the large standing crop of smaller prey species.

Mahnken (1993) studied the succession of invertebrates at a depositional environment in Clam Bay, Puget Sound, for two years during a fallow period at a salmon farm and observed two distinct 'stanzas' of biological recovery. The first was a three month period of rapid recovery in abundance and species diversity followed by a 3–25-month period when community recovery proceeded more slowly. Species which were numerically dominant in samples from the reference station showed rapid colonization. Rare species were slow to recruit to the area. He identified four successional series including:

- A pre-successional series comprised of species tolerant of sediments having high TOC.
- A pioneering group of early colonizers containing several species of organic-tolerant opportunists.
- An intermediate group of colonizers associated with reduced numbers of deposit feeding opportunists.
- A group of late colonizers consisting of a group of more conservative and persistent species.

A fifth group of rare species identified at the reference station were still absent from the farm sediments at the end of the 20.5 month study. Mahnken (1993) observed that succession was most clearly defined in the Order Polychaeta. At the Clam Bay site biological recovery was initiated by *C. capitata* and followed in successive series characterized in turn by *Armandia brevis*, *Phyllodoce maculata*, *Pectinaria granulata*, *Platynereis bicanaliculata*, and finally by more generalist species like *Leitoscoloplos pugettensis*. He concluded that the sequence was best described as a response to changing organic content in the sediments, resulting from biogenic reworking by changing guilds of benthic organisms.

Brooks (2000a) conducted an exhaustive study of a salmon farm in BC during production and fallow periods over a period of two years. This was the first study documenting the relationship between salmon farm biomass, fish feed inputs, and the physicochemical and biological response of the benthos. The study design focused on quarterly samples collected on the downstream transect from the net-pen perimeter to a distance of 75 m, and at a local reference station located approximately 1,200 m from the farm. A maximum Atlantic salmon biomass of 1,199 mt was raised at the farm under study. His data clearly depicted the accumulation of volatile organic material under the farm and out to distances of ca. 40 m from the net-pen perimeter during the peak of production. The physicochemical data (TVS, TOC, hydrogen sulfide, zinc, and depth of the reduction-oxidation potential (RPD) discontinuity) were well correlated and internally consistent.

Organic carbon accumulations (TOC or TVS) were sensitive indicators of biological effects. The regression approach taken in the experimental design allowed for the three-dimensional mapping of these parameters describing the spatial (as a function of distance from the net-pen perimeter on the downstream transect) and temporal (as a function of both season and production cycle) trends in the data.

In all of these cases chemical and biological recovery of the benthos occurred within weeks or months at some sites, and within two to three years at others. These benthic recoveries have occurred naturally with no need for intervention or mitigation.

4.6.3 The assimilative capacity of the local environment

Brooks (2000a) provided a methodology for estimating the assimilative capacity of sediments adjacent to salmon farms. The upper 90th percentile TVS observed at the local reference station was 3.4%. In Figure 2 this value is represented by the boundary between dark green and light blue. Based on the assumption that the 90th percentile TVS observed at the reference station represents the sediment assimilative capacity (SAC), this analysis suggested that a maximum salmon biomass of ca. 170 mt could be raised at this site without exceeding the SAC on the perimeter of the farm. That is 14% of the actual farm production. A similar methodology could be applied to other physicochemical benchmarks including sediment sulfides or Eh.

4.7 Managing the Environmental Effects Associated with Salmon Farms

4.7.1 Monitoring experiences

From 1987 until 1996 the Washington State DNR required monitoring of sediment chemistry (carbon, nitrogen, redox and sediment grain size), water chemistry (dissolved oxygen, pH, nitrate, nitrite, total ammonia and unionized ammonia), and the benthic community (quantitative infaunal surveys and qualitative scuba surveys) as a condition in ALLs for salmon farms. That monitoring experience provided an extensive database upon which to evaluate the effectiveness of each measured parameter in predicting environmental effects. Several lessons were learned from those studies, as follows:

(a) Sediment grain size and water depth were primary factors determining the structure of an undisturbed infaunal community.

(b) Absent any anthropogenic inputs, i.e., in reference areas, the TOC content of undisturbed sediments was significantly correlated with the proportion fines (silt and clay) contained in superficial sediments (<2 cm depth). Depositional areas associated with slow current speeds and gyres accumulate both fine sediments and particulate organic materials at higher rates than high-energy areas.

(c) The redox potential and health of the infaunal community associated with a particular sediment grain size distribution appears well correlated with the level of TOC in the sediments (Striplin Environmental Associates 1996, Goyette and Brooks 1999). This is evident in Figure 3, which depicts the relationship between infaunal abundance, diversity, redox potential, and percent TOC. Note that the significant depressions in infaunal diversity and abundance observed at distances of zero and 6 m from the perimeter of the net-pens was associated with TOC levels averaging 2.8% and an RPD

$$z=0.021-0*x+5.859e-8*y+2.25e-6*x*x-6.028e-10*x*y-1.415e-14*y*y$$

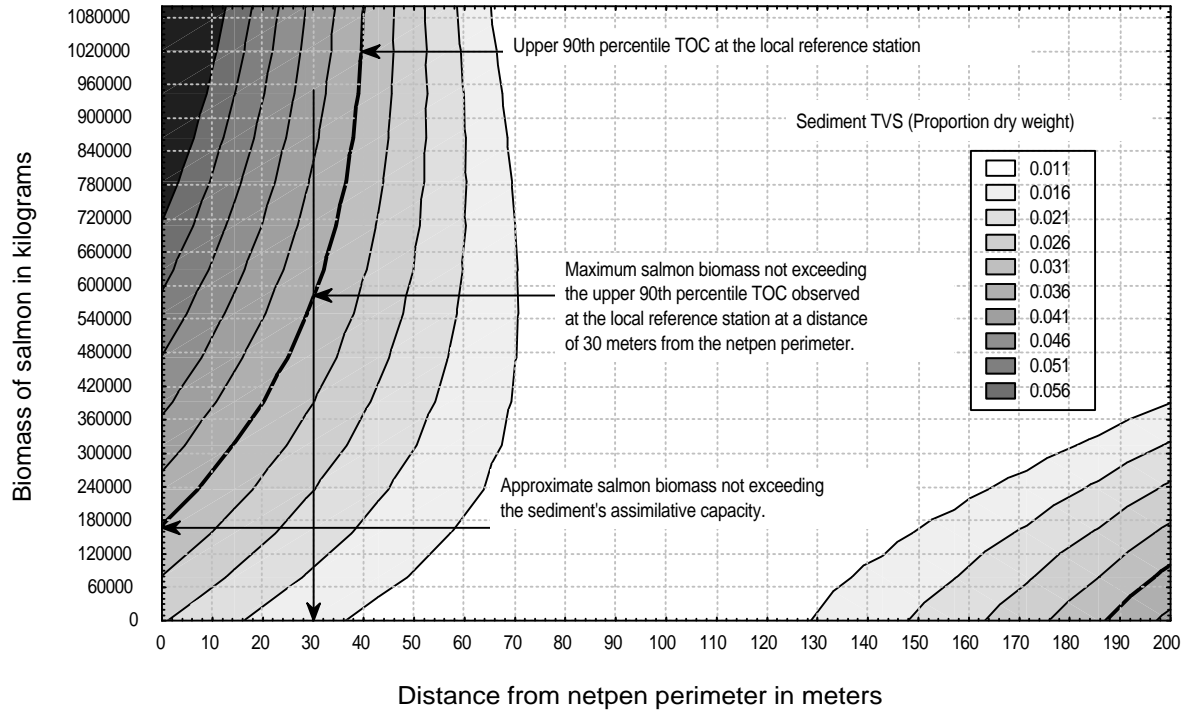


Figure 2. Surface contour plot describing the relationship between salmon biomass (kg), distance from the farm perimeter on the downcurrent transect in meters, and TOC expressed as a proportion of dry sediment weight.

that was very close to the sediment surface. These sediments smelled strongly of hydrogen sulfide. Beyond 6 m the TOC declined rapidly to 1.8% and the depth of the RPD increased to approximately 1.0 cm. Conditions remained constant to 24 m from the farm perimeter where TOC slowly declined to background levels of ca. 1.25%. Infaunal samples were not collected at all TOC stations during this study. However, sediments were depauperate from the perimeter of the farm to 6 m downstream. The abundance and diversity of infauna slowly increased between 6 and 30 m downstream but remained depressed to a distance of 30 m from the net-pen perimeter. A normal community was observed in samples collected 60 m downstream from the perimeter of this farm.

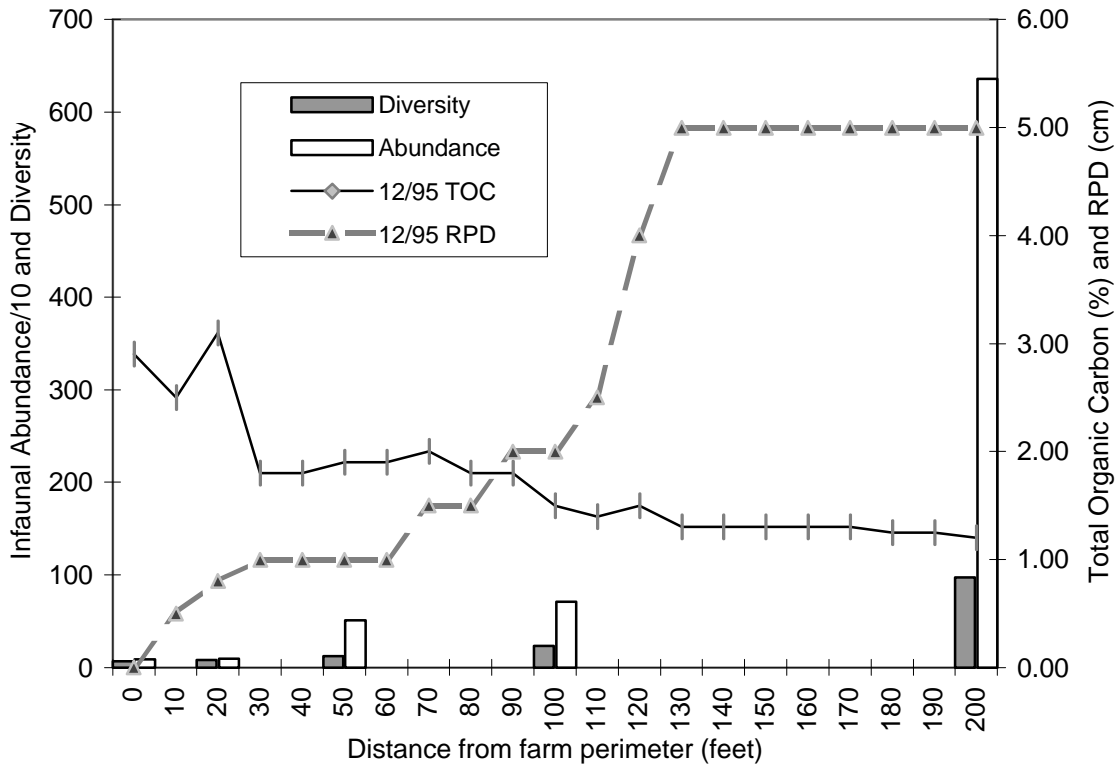


Figure 3. Relationship between percent total organic carbon, depth of the reduction-oxidation potential discontinuity (cm), Washington State TOC triggers, and abundance and diversity of infaunal organisms at a major salmon farm located in a deep (33 m MLLW) bay where maximum currents speeds were less than $10 \text{ cm}\cdot\text{sec}^{-1}$.

Based on these monitoring reports, it appears that TOC can be used as a screening tool to evaluate benthic health indirectly. This is not unlike the use of bioassays as a screening tool in evaluating the effects of toxic industrial and municipal effluents in fine-grained sediments. The use of TOC (or TVS) as a screening tool has the advantage of being fast. Analyses can be completed in a few days, whereas infaunal community analysis takes months. In addition, the lower cost of TOC/TVS analysis allows more frequent monitoring. When combined, these factors allow TOC/TVS to be used as a real-time parameter useful to farm managers.

Sediment total sulfides and oxidation-reduction potential measured with ion specific probes immediately following sample collection are emerging as more biologically relevant physicochemical endpoints in ongoing studies in BC. The results of these studies will be available in May 2001.

(d) Invertebrate community analysis has been a traditional and direct way of evaluating the effects of organic loading (see Pearson and Rosenberg 1978, Lunz and Kendall 1982, Weston 1990, Brooks 1993 and 1993b, Henderson and Ross 1995, Brooks 1994a, 1994b, 1995a, and 1995b). In Washington State invertebrate infaunal community analysis is used as a primary endpoint for evaluating benthic sediment quality (WAC 173-204-320).

(e) Salmon farms located in well-flushed (>50 to 100 cm-sec^{-1}) environments frequently increase both the abundance and taxa richness of infaunal communities, even at high levels of salmon production (Brooks 1994b and 1995b).

(f) Salmon farms located in poorly flushed ($<10 \text{ cm-sec}^{-1}$) environments can result in the deposition of significant amounts of carbon to the benthos – even when located in water as deep as 30 m MLLW. Adverse effects are generally restricted to an area within 15–22 m from the perimeter of farms located in these poorly circulated environments. Increases in both the level of TOC and the distance at which adverse effects are observed are sensitive to farm management practices (Brooks 1994a). However, in these poorly flushed environments the negative effects can be managed so that they remain within 33–100 m of the farm perimeter, even during intensive production of fish.

(g) Indicator invertebrate taxa have been identified at several of the farms studied in the ALL Program of DNR. These indicator taxa and groups of taxa appear temporally consistent but are specific to different environments (Brooks 1995a and 1995b). Other authors (Weston 1990, Tsutsumi et al. 1991, Mahnken 1993, and Henderson and Ross 1995) have identified similar suites of indicator species in response to organic loading.

4.7.2 Management by modeling salmon farm wastes

There is significant interest in modeling salmon farm waste as a management tool for regulatory agencies. Some of these models are qualitative (Sowles et al. 1994) and others attempt to quantify the dispersal and accumulation of particulate organic matter in sediments (Fox 1990, Gowen et al. 1994, and Silvert 1994b). It appears that the more basic the model inputs, the more room there is for error. Silvert (1994a) used a simple carbon budget to model salmon farm waste and concluded that 40% of the feed was not consumed by the fish. There is no evidence in the literature substantiating feed loss rates this high. None of these models has been tested to compare predictions with observed carbon deposition rates or sediment physicochemical responses to salmon farm waste.

Findlay and Watling (1994) modeled sediment organic carbon decay rates and developed nonlinear regression equations relating oxygen delivery ($\text{mmoles/m}^2\text{-hr}$) and maximum oxidizable organic matter ($\text{grams carbon/m}^2\text{-day}$) to sediments as a function of current speed (cm/sec). They concluded that the maximum carbon flux not exceeding the assimilative capacity of the sediment is highly dependent on the minimum 2-hour average bottom current speed.

Silvert and Sowles (1996) developed several algorithms considered useful in modeling the environmental response to salmon farming. They concluded that models exist which can help to assess impacts and make reasonable management decisions, but this is not substantiated in the existing literature.

These models provide some insight into the environmental response to salmon farm waste. However, they are not adequate for making reasonable quantitative predictions regarding the degree or spatial extent of salmon farm waste.

4.7.3 Risk management through NPDES permit standards

In 1996 Washington State developed sediment management standards for marine net-pens (WAC 173–204). The Washington State rule is based on the following assumptions:

- (a) Salmon farming provides significant benefit to the State and its people.
- (b) The negative benthic effects associated with net-pen operations in poorly flushed environments will remediate naturally following cessation of operation or initiation of a fallow period.
- (c) The spatial extent of these effects can be managed. The sediment rule for net-pens authorizes a sediment impact zone (SIZ) extending 33 m from the perimeter of the farm structure. This distance was chosen because it corresponds to the SIZ provided for other industrial discharges. From a biological point of view, it would seem more appropriate to develop site specific SIZs which reflect the biological productivity of the site's benthos and the presence of adjacent valuable resources. In that context, SIZ widths could extend considerably further from the perimeter of a farm, perhaps to a distance of 100 m or more.
- (d) TOC can be used as a screening tool in evaluating the health of the benthos. TOC 'triggers' have been defined as a function of the proportion of silt and clay in the sediment matrix. TOC triggers used to screen sediments for adverse biological effects at salmon farms in Washington State are tabulated below. If sediments located 33 m from the perimeter of the net-pen structures at salmon farms exceed these trigger values, then an evaluation of the health of the infaunal community is required.

Proportion (%) silt-clay in the sediments	TOC trigger (%)
0 – 20	0.5
20 – 50	1.7
50 – 80	3.2
80 – 100	2.6

(e) Biennial monitoring of sediment TOC is required at seven stations at each permitted farm. Four of these stations are located at a distance of 30 m from the perimeter on each side of the farm. Three replicate sediment samples are collected at each station. No further monitoring is required if sediment TOC is not statistically elevated (t-test) above the TOC trigger corresponding to the observed percent fines at each 30 m station. If the measured TOC is significantly higher than the corresponding trigger, then repeat sampling is required in the summer of the next year together with the collection of five benthic infaunal samples at each station failing the TOC trigger, and at a suitable control. Benthic infaunal analysis is required for any station at which elevated TOC is observed during the second round of sampling.

(f) Each farm is required to manage its production such that there are no significant negative effects on benthic resources beyond the boundary of this 33-m SIZ. WAC 173–204 states that biological resources in sediments are considered adversely impacted if the mean numbers of crustaceans, mollusks or polychaetes in the test sediment at the boundary of the SIZ are reduced to significantly less than 50% of the number of animals belonging to the same taxa living in an undisturbed reference sediment. Evaluation is based on a one tailed t-test at $\alpha = 0.05$ for five replicate 0.1 m² samples. It should be pointed out that populations of benthic organisms are frequently found in patchy distributions with many animals of the same species confined in groups separated from each other. Infauna are seldom found regularly distributed in sediments. For that reason, if three samples were collected from the same general area, the individual samples would likely contain very different numbers of any one of these taxa. The reason that the rule relies on a 50% reduction in the number of any taxa is not that it is acceptable to kill 50% of the crustaceans, mollusks, or polychaetes outside the boundary of the sediment impact zone, but to acknowledge that the collection of a reasonable number of random samples may produce two means which vary by as much as 50%, even though the sediments are not impacted at all, or share the same level of impact.

(g) Benthic conditions at each of the four orthogonal 30 m SIZ stations must be photographically documented every two years and whenever sediment samples cannot be collected and analyzed in conformance with the requirements stipulated in the Puget Sound estuary protocols (PSEP 1986).

(h) Well-managed salmon farms recognize the benefits of vaccination and BMPs in controlling disease. While not examined in this review, records of antibiotic use in Washington indicated a sharp decline at permitted farms between 1992 and 1996. Similarly, Kontali (1996) reported that the use of vaccines in Norway had resulted in reductions in the use of antibiotics from a high of 592 mg/kg salmon produced in 1987 to 5, 9 and 3 mg/kg in 1994, 1995, and 1996, respectively.

Based on the current low use, Washington regulations (WAC 173–204–412) do not require routine monitoring for bacterial resistance at marine net-pen sites. All farms are required to maintain an operational log that specifies the date and nature of application of all disease control chemicals used. In addition, farms are required annually to report the amount of each therapeutic used on each farm.

Based on the absence of adverse effects observed during 10 years of monitoring the water column adjacent to salmon farms in Washington State, the WDOE eliminated all

requirements for nutrient and dissolved oxygen monitoring in the water column from the NPDES permits.

This approach by the State of Washington regulatory agencies is appealing for several reasons:

- It recognizes the value of net-pen culture while requiring that any negative impacts be restricted to the immediate vicinity of the farm
- It invokes a realistically achievable performance standard that can (must) be met through proper management practices
- It is a relatively inexpensive approach as long as TOC levels at the boundary of the SIZ remain below trigger levels. This provides a real incentive to maintain carbon levels below specified triggers
- The immediate endpoint (TOC) can be measured quickly and is useful as a real time management tool
- The performance standard encourages future siting in environments that either have fine grained sediments that support high TOC levels, or in high current areas where TOC will not accumulate

On the other hand there have been some problems in implementing the State's NPDES permit system. For example, sediment samples collected from coarse bottoms cannot be analyzed for TOC because the matrix must be ground to a fine consistency. Sediments from erosion environments are generally composed of coarse gravel and cobble.

Opponents of aquaculture have argued that the WDOE biological performance standard defined in WAC 173-204-320 (3)(c) is inappropriate because it allows for up to a 50% reduction in the abundance of arthropods, mollusks, or annelids, and because it does not include some measure of species richness (PCHB Nos. 96-257 through 96-268). This criterion applies to all discharges in the State of Washington and not just to salmon farms.

Application of the criterion requires analysis of these major taxa in five 0.1 m² infaunal samples. A one-tailed t-test is then applied with $\alpha = 0.05$. Alpha is the probability of finding an effect when it does not exist (the probability of making a Type I error or of rejecting the null hypothesis when it should not be rejected). That means that approximately 1 in 20 tests will indicate a statistically significant difference in the means of the populations when in fact the populations are identical. Brooks (2001, unpubl. data, Aquatic Environmental Sciences, Port Townsend, WA 98368) has tested this hypothesis using a Monte Carlo approach for analyzing benthic data from reference sites at two farms located in Puget Sound. He found that the null hypothesis was in fact rejected in 22% of the analyses on samples collected from the same reference station. Obviously, absent the allowable error of 50% incorporated in the WDOE rule, the criterion would be too conservative.

The consequences to the permittee of failing the benthic biological criteria are significant, requiring reductions in the number of fish raised, or the amount of food provided, or actually following the farm for a period. That is a significant penalty when there is a half

chance that failure is simply a matter of chance with $\alpha = 0.05$. There are at least three ways to address this issue:

(a) The value of α could be decreased to 1% or 0.5%. When $\alpha = 0.1\%$, there is only a one in 100 probability of obtaining a false positive (Type I error). That would require a larger difference between the mean number of animals in any of the taxa observed at the reference site and the SIZ boundary – in other words it would not provide any more protection for the environment,

(b) The DOE has defined an allowable error term of 50%,

(c) The number of endpoints at each station could be increased by evaluating both the abundance and the number of species observed in each of the major taxa. This would provide six endpoints (abundance and richness of arthropods, mollusks and annelids) for evaluation. By requiring failure of two of these endpoints before considering the station failed, the probability of a false positive would be decreased to $0.05 \times 0.05 = 0.0025$.

4.7.4 Risk management practices in British Columbia

Following the exhaustive review of the scientific literature by EAO (EAO 1997), the Provincial Government of Canada BC has been developing a performance-based waste management policy (WMP) to insure that adverse benthic effects associated with salmon farming are managed. The following are essential elements likely to emerge.

(a) Only single year-classes of fish will be grown at BC salmon farms. The purpose of this restriction, as practiced also in Norway and Chile since the mid-1990s, is to reduce the potential for disease transfer between year-classes and to provide for a fallow period between production cycles sufficient to insure that sediments chemically remediate to within 30 m of the farm perimeter prior to restocking.

(b) Prior to restocking a new year-class, the farm must remain fallow until the level of volatile residue in sediments at a distance of 33 m from the net-pen complex perimeter returns to baseline or local reference station values. The length of fallow is not specified, but farm management must certify to the Ministry of Environment that this condition has been met before restocking fish.

(c) At no time will adverse benthic effects be allowed at distances ≥ 100 m from the perimeter of the net-pens. This performance standard will be evaluated annually during the months of August through November. This distance is under review and will likely be set by the BC Government during 2001.

(d) Based on the problems encountered with the analysis of TOC in Washington State, BC is using TVS as a primary screening tool. TVS (as a percent of dry sediment weight) must not statistically exceed (one-tailed t-test, $\alpha = 0.05$, $N = 3$) the upper 90th percentile value observed at a local reference station. Samples are collected for this analysis at a distance of either 30 m (for the pre-stocking certification) or 100 m (for the annual monitoring) from the midpoint on each of the sides of the net-pen's perimeter. These points are referred to as the 'inner' and 'outer' sediment impact zones (ISIZ and OSIZ). If no local reference station is available, then farm samples will be compared against TVS triggers which represent the upper 90th percentile of historical TVS levels observed at reference stations throughout BC.

(e) Hargrave et al. (1997) examined the biological and physicochemical attributes at 11 salmon farm and 11 reference stations in the Western Isles region of the Bay of Fundy on the east coast of Canada. They found that organic carbon, sediment sulfides,

and redox potential were effective endpoints for evaluating the benthic effects associated with salmon farming. The results of this study have been incorporated in the WMP by requiring quantitative evaluation of sediments for total sulfides (S^{2-}) and oxidation-reduction potential (ORP). Protocols developed by Hargrave et al. (1995) were adopted for these analyses. Specific performance standards for sulfides and Eh will be developed pending the outcome of a series of focused studies designed to determine the biological response to varying concentrations of these endpoints.

Stations failing the screening tests will probably be evaluated against the biologically-based performance standard which states that, *'Adverse Sediment Biological Effects will be evaluated by comparing abundance and diversity (number of species) in the Class Crustacea, Class Polychaeta and the Phylum Mollusca at farm sample stations defined in the performance standards with the abundance and diversity of the same taxa found at a local reference station. This test will establish six endpoints for evaluation (abundance and diversity in each of three major taxa). These differences shall be evaluated using a one-tailed t-test with a probability of observing an effect when one does not exist of five percent ($\alpha = 0.05$). Because one in twenty of these tests are expected to produce a false positive (indicates an adverse effect when one does not exist), this performance standard defines adverse biological effects when two or more of the six endpoints are statistically decreased compared to levels observed at a local reference station. This procedure will still result in one false positive in 400 tests.*

This biological standard will be determined by comparing the three major taxa, observed in five 0.1 m² grab samples at each farm station with the abundance and diversity of these taxa observed at a local reference station sharing similar depth and sediment grain size characteristics. This may require more than one local reference station per farm. Identification of all taxa in this evaluation will be to the level of species, or the lowest practical level. Ammann et al. (1997) used the results from 28 previous studies to examine the Taxonomic Sufficiency of various levels of biological organization to determine adverse impacts in aquatic environments. They found that for 89% of the experiments evaluated, phyla counts were as sensitive as any of the metrics evaluated. Community metrics (Shannon-Weiner's, Simpson's, and Brillouin's diversity and evenness and richness) were never found to be more sensitive than count data. Amman et al. (1997), and the citations included therein, support British Columbia's choice of major taxa (Phylum Mollusca, Class Crustacea and Class Polychaeta) as appropriate metrics in developing their regulatory policy. The identification of organisms to species will allow for future analysis using a variety of additional metrics.

Farms with stations failing the Sediment Biological Effects Standard will be required to develop a remediation plan that brings the farm back into compliance.'

The BC Provincial Government has stated a desire to establish a final performance based salmon farm management program in the fall of 2001. In addition, the DFO, which has the responsibility to enforce the Fisheries Act is participating at the technical level in developing the BC program.

5. ATLANTIC SALMON AND THE LOCAL ECOSYSTEMS

The fifth chapter is very specific to the pros and cons of salmon species in the local ecosystem of the Northwest (Puget Sound). It has seven identified subsets. The first subsection reviews the issue of the introduction of Atlantic salmon into the Pacific ecosystem and the potential interactions. Specific sections review possible hybridization between Atlantic and Pacific salmon, the genetic dilution and alteration of the gene pool, the colonization of the aquatic environment by Atlantic salmon, and finally the interactions of wild salmon and genetically altered transgenics. The second subsection concerns epidemics and transmission of waterborne disease, and reviews the potential for cultured Atlantic salmon, an exotic species, to introduce new diseases into the local ecosystem. There are nine specific items, from the diseases which might be involved, to potential interactions, and current policies for disease control. The third subsection concerns the potential ecological impacts in the Pacific Northwest, specifically the interaction with Pacific salmon and predation. The following sections review the effects of artificial propagation practices in the region in general, the impacts of the introduction of non-indigenous species, and a comparison of escapes or releases of propagated Atlantic and Pacific salmon. The last section examines the NMFS Biological Status Reviews of west coast Pacific salmon stocks.

5.1 General Issues of Artificial Propagation of Salmonids

Ellis (1996) and Alverson and Ruggerone (1997) comment that the artificial propagation of salmon and trout in the Pacific Northwest had come under increasing scrutiny in recent years. This was due to the recognition that hatchery cultured salmon and trout may have the potential to adversely impact natural populations. Although the weight of attention has been focused on the extremely large complex of federal, state, tribal, and cooperative hatcheries in Alaska and the western States, concerns about the potential adverse impacts of private trout and salmon culture in Washington have also been expressed.

Concerns about genetic interactions, the transmission of disease, and ecological interactions are most commonly voiced. The secondary source for this unpublished study is Gross (1997), who stated that Atlantic salmon had the potential for hybridization with Pacific salmon. Quinn (1997) stated that it was possible that the 369,000 Atlantic salmon which escaped into Puget Sound in 1997 would produce 10 million healthy smolts in local rivers. The Alaska Department of Fish and Game (ADF&G) has expressed concern that escaped Atlantic salmon from west coast salmon farms will compete with wild salmon and spread diseases and parasites for which Pacific salmon have little resistance (ADF&G 1999). For example, a letter sent to Alaska Senator Stevens (April 25, 1997), by a constituent, read, in part, *'The continued introduction of Atlantic salmon to the marine habitat of British Columbia and Washington State will inevitably have negative biological impacts. These will include displacement, hybridization, and the introduction of alien....disease.'* (Gilbertsen 1997).

5.2 Genetic Interactions of Artificially-Propagated Pacific and Atlantic Salmon

A major concern with artificial propagation in general and farming of Pacific salmonids and Atlantic salmon in particular are the potential genetic effects of inadvertent escapees on the native salmonids. For the salmon farming industry in BC, where both Pacific and Atlantic salmon are extensively farmed, the BCSAR study listed four major areas of concern (EAO 1997):

- Hybridization between Atlantic and Pacific salmon
- Genetic dilution and alteration of the wild salmonid gene pool
- Colonization by Atlantic salmon
- Interactions between wild salmon and genetically altered transgenics

These concerns are both geographically and species specific. For the Puget Sound, the primary concern is with Atlantic salmon, as Pacific salmon, with rare exception, are not cultured by private enterprises.

5.2.1 Hybridization

No genetic interactions between Atlantic and wild Pacific salmon have been reported in the Pacific Northwest. Similarly, under controlled and protected laboratory conditions where survival of hybrid offspring should be optimized, viable hybrids between Atlantic and Pacific salmonid species are difficult to produce. Refstie and Gjedrem (1975), Sutterlin et al. (1977), and Blanc and Chevassus (1979, 1982) found that crosses between Atlantic salmon and rainbow trout failed to produce any viable progeny. A similar lack of vitality was observed in pairings of Atlantic salmon and coho salmon (Chevassus 1979) and Atlantic salmon and pink salmon (Loginova and Krasnoperova 1982). Gray et al. (1993) attempted to produce diploid and triploid hybrids by crossing Atlantic salmon with chum and coho salmon, and rainbow trout. All embryos died in early developmental stages, leading to the conclusion that hybridization of Atlantic salmon with Pacific salmon species was unlikely to happen.

The secondary source of these two unpublished BC studies by Alverson and Ruggerone (1997) have provided more data regarding the relative genetic compatibility between Atlantic and Pacific salmon (R. Devlin, DFO Canada, reported in Alverson and Ruggerone 1997). In the first, using a small number of eggs, Atlantic salmon produced no viable hybrids with coho, chum, chinook, sockeye salmon, and rainbow trout. In the same experiment, each species of Pacific salmon readily produced hybrids with between two and five other Pacific salmon species, and confirmed previous observations in this genus by, *inter alia*, Foerster (1935), and Seeb et al. (1988). These results were cited as evidence of '*rampant hybridization potential*' in hearings before the Washington State PCHB (96–257–266, and 97–110, 1998). However, the Board found the statement not supported by the study, and there was no reasonable potential for hybridization between escaped Atlantic salmon and native Pacific salmon in Puget Sound based on current knowledge and behavior (PCHB 1998).

In the second study using a much larger number of eggs, viable hybrids to hatch involving rainbow and steelhead trout, coho, chum, chinook, and pink salmon were produced. Approximately 6.1% of the steelhead x Atlantic salmon, and 0.01% of the

pink salmon x Atlantic salmon hybrids survived to the hatching stage. The inter-specific crosses between *Oncorhynchus* species produced hybrids with survivals to hatch ranging from 10–90% in 15 of the 42 crosses. Despite these high survivals to hatch among the Pacific salmon hybrids, compared with the fractional survival to hatch observed between an Atlantic salmon x pink salmon cross, no concerns over the introduction of hatchery stocks of Pacific salmonids into natural habitats were addressed to the PCHB.

The '*successful*' Atlantic x steelhead hybrids were carefully controlled experiments *in vitro*, and actual Atlantic/steelhead hybridization would probably not happen under natural conditions in Washington State. The Atlantic salmon stocks used in Washington have finished spawning by the end of November (W. Waknitz, NMFS, unpublished data), and wild steelhead in western Washington spawn between mid-March and mid-June (Freymond and Foley 1985). Therefore, there is virtually no opportunity for Atlantic salmon to spawn with local wild, native steelhead outside the laboratory.

While viable hybrids between Atlantic salmon and the Pacific salmonid species have been difficult to produce in the laboratory and do not occur under natural conditions, hybrids between Atlantic salmon and a sympatric species, the brown trout are relatively successful. Viable Atlantic salmon x brown trout hybrids have been produced in the laboratory by, *inter alia*, Suzuki and Fukuda (1971), Refstie and Gjedrem (1975), Blanc and Chevassus (1982), and Gray et al. (1993).

Successful hybridization under natural conditions has been reported for Europe where brown trout are native, and also in North America where the brown trout has been introduced (Verspoor and Hammar 1991). The frequency of natural hybridization in Europe and North America ranges from 0.1 to 13.2% of juveniles in river systems (Jordan and Verspoor 1993) and appears to be increasing relative to pre-aquaculture levels (Hindar et al. 1998). McGowan and Davidson (1992) cite the breakdown in pre-reproductive isolating mechanisms (abundance of mature Atlantic parr) as the principal mechanism for natural hybridization. Hindar et al. (1998) reported that although a disproportionate number of hybrids were the product of matings involving Atlantic salmon females, there was no evidence that escaped farmed Atlantic salmon females produced more hybrids than wild females. Youngson et al. (1993), on the other hand, had previously reported that escaped female in western and northern Scotland rivers hybridized with brown trout more frequently. Wilkins et al. (1993) found that male hybrids were fertile and when back-crossed with female Atlantic salmon produced about 1% diploid progeny. Galbreath and Thorgaard (1995) reported that back-crosses between male diploid, male triploid, and female diploid Atlantic salmon x brown trout hybrids and both parental species produced either non-viable or sterile progeny.

No natural hybrids between Atlantic salmon and Pacific salmonids have been reported in Europe. This is despite the fact that introduced rainbow/steelhead trout, brook trout, coho salmon, and pink salmon have all established naturalized populations within the native range of Atlantic salmon throughout the European continent (MacCrimmon and Campbell 1969, MacCrimmon 1971, Berg 1977, and Lever 1996). Similarly, no hybrids between Atlantic salmon and brown trout, rainbow trout or brook trout have been

reported in South America or New Zealand, even though all four of these species are not native to those locations (MacCrimmon 1971, Lever 1996).

The propensity of Atlantic salmon to produce successful hybrids with brown trout and not with the Pacific salmonids may be related to the phylogenetic distances that exist between the two groups. Neave (1958) postulated that the putative ancestors of the *Salmo* group migrated to the Pacific 600,000 to 1,000,000 years ago, were subsequently isolated by land bridges, and evolved to the ancestral *Oncorhynchid* form. The ancestral *Oncorhynchid* form subsequently developed to form the separate *Oncorhynchus* species (Simon 1963). McKay et al. (1996), based on DNA sequence analysis of growth hormone type-2 and mitochondrial NADH dehydrogenase subunit 3 gene, estimated that, at a minimum, the major divergence between the genus *Salmo* and the genus *Oncorhynchus* occurred 18 million years ago, while speciation within the genus *Oncorhynchus* began about 10 million years ago. Benfey et al. (1989) also noted that the evolutionary differences between the Pacific and Atlantic salmonids were reflected by immunologically detectable forms of vitellogenin.

Attesting to their phylogenetic similarity, interspecific hybrids within the *Oncorhynchids* are relatively successful. Foerster (1935) was among the first to report successful hybrids between controlled mating of sockeye, chum, pink and chinook salmon. Since then, limited occurrences of natural hybrids have been reported among anadromous salmonids. Bartley et al. (1990) reported on natural hybridization between chinook and coho salmon in a northern California river, and Rosenfield (1998) reported a natural pink x chinook hybrid from the St. Mary's River in Michigan. On the other hand, hybridization between introduced rainbow trout and native cutthroat trout appears to be almost ubiquitous throughout the interior part of western North America, and has been enormously detrimental to the latter species according to Gresswell (1988) and Behnke (1992).

5.2.2 Genetic dilution and alteration of the wild salmonid gene pool

Adverse genetic and ecological effects due to releases or escapes of artificially-propagated Atlantic salmon from public hatcheries and private net-pens on wild Atlantic salmon populations in Norway, Scotland, Ireland, and the Canadian Maritimes have been reported. For wild Atlantic salmon these include a reduction in their genetic adaptability and capacity to evolve as a result of interbreeding with artificially-propagated fish, and direct competition for food and space (Einum and Fleming 1997, Gross 1998).

Such adverse effects only happened in those locations because both the cultured and wild fish were Atlantic salmon. Escaped Atlantic salmon on the west coast of North America do not have congeneric wild individuals with which to interact. In the Pacific Northwest region, the release of hatchery Pacific salmon has the greater potential to produce impacts on native Pacific salmon which are analogous to those found between cultured and wild Atlantic salmon in Europe and eastern North America.

Adverse genetic and/or ecological interactions on local wild salmon populations from artificially-propagated Pacific salmon have been well documented by Weitkamp et al. (1995), Busby et al. (1996), Hard et al. (1996), EAO (1997), Gustafson et al. (1997),

Johnson et al. (1997), Myers et al. (1998), and Johnson et al. (1999). No detrimental effects related to Atlantic salmon have been reported in western North America.

Compared with the evidence in the literature of genetic alterations of Pacific salmonid populations as a consequence of salmonid enhancement and supplementation programs in the Pacific Northwest, there is little or no evidence in the literature of adverse impacts associated with escaped Atlantic salmon in the region.

5.2.3 Colonization by Atlantic salmon

In the past century there have been numerous attempts in the US and elsewhere to establish Atlantic salmon outside their native range. These attempts involve at least 34 different States, including Washington, Oregon, and California. None of these efforts was successful. MacCrimmon and Gots (1979) subsequently reported that no reproduction by Atlantic salmon was observed in the waters of these States, and twenty years later this was reconfirmed by Dill and Cordone (1997) and Alverson and Ruggerone (1997).

It also appears difficult to reintroduce Atlantic salmon to their native rivers. In the last 100 years, Atlantic salmon populations in New England have declined precipitously, despite the large-scale introduction of locally derived hatchery fish (Moring et al. 1995). The Penobscot strain of Atlantic salmon (which is used in net-pen farms in Puget Sound) is now under consideration for listing under the US Endangered Species Act 1974 (USDOI/USDOC 1995).

Between 1905 and 1934 the government of BC released 7.5 million juvenile Atlantic salmon into local waters, primarily on the east coast of Vancouver Island and the lower Fraser River in Canada (MacCrimmon and Gots 1979; Alverson and Ruggerone 1997). These releases were not successful in establishing Atlantic salmon populations in the Province, although some natural reproduction may have occurred according to Carl et al. (1959). Emery (1985) noted that even in historic Atlantic salmon habitat, such as the lower Great Lakes, attempts to re-establish Atlantic salmon populations have not been successful, although Brown (1975) had earlier stated that introduced Pacific salmonids had succeeded in establishing self-reproducing populations in that area.

Lever (1996) noted that, worldwide, no self-sustaining populations of anadromous Atlantic salmon have been established outside the natural range of this species, although a landlocked population appears to have become established in the mountains of New Zealand. Reproduction by Atlantic salmon was also observed subsequent to introduction in Chile and Australia, but these transfers also failed to create self-sustaining populations.

The failure of early introductions of Atlantic salmon to produce self-sustaining populations could have been due to the rather primitive hatchery methods used in the early 1900s. However, the same primitive methods that failed to establish Atlantic salmon anywhere in North America proved to be remarkably successful in establishing European brown trout, brook trout, and rainbow trout almost everywhere in the earliest days of fish culture, usually on the first attempt. With these particular salmonids, the

success or failure of introduction appears to be associated with attributes inherent to the species, not from the hatchery methods employed. Atlantic salmon are virtually the only non-native salmonid not successfully introduced to Washington, with the exception of Arctic char and Masu salmon (Wydoski and Whitney 1979).

The initial transfer of Atlantic salmon to Washington occurred in 1904, according to MacCrimmon and Gots (1979), and Coleman and Rasch (1981) noted that attempts to introduce runs of this species continued until about 1980. Occasional releases of Atlantic salmon into high mountain lakes have since been made. Sea-run and landlocked strains were used, but neither life-history form succeeded in establishing self-perpetuating populations. Attempts to establish Atlantic salmon in Canada BC took place during this period, with similar results, although successful spawning may have occurred in the Cowichan River, Canada as specimens thought to have resulted from the planting of Atlantic salmon were taken until May 1926, according to Dymond (1932), Carl et al. (1959), and Hart (1973). The DFO has been carrying out a long term monitoring study on the catches and sightings of individuals and to see if self-sustaining populations are becoming established but without results (Thomson and Candy 1998). Recently Volpe et al. (2000) reported that Atlantic salmon had successfully produced offspring in BC.

Several Atlantic salmon farmers in Washington rear juveniles in the Chehalis River basin prior to transfer to seawater in Puget Sound. Since the mid-1980s escaped Atlantic salmon smolts have been captured in traps designed to monitor the outmigration of juvenile Pacific salmon (Seiler et al. 1995). However, as of 1998, no returning adult Atlantic salmon have been encountered at adult salmon traps on several tributaries of the Chehalis River system, or been caught in tribal gillnet fisheries, which capture about 10% of all upstream migrants in the main stem of the Chehalis River (D. Seiler, WDFW, personal communication).

The risk of anadromous Atlantic salmon establishing self-perpetuating populations anywhere outside of their home range is extremely remote, given that substantial and repeated efforts over the last hundred years have not produced a successful self-reproducing population anywhere in the world. In the Pacific Northwest Atlantic salmon introductions also have not succeeded in producing self-sustaining populations, even though a few naturally produced juveniles may have been observed from time to time, according to Dill and Cordone (1997).

5.2.4 Interactions of wild salmon and transgenic fish

As with other agricultural sectors, there is considerable interest within the fish farming sector to improve growth or survival of fish or shellfish through genomic manipulations. In recent years the role of transgenics (descendants of genetically engineered parents whereby introduced DNA has been incorporated and inherited) in traditional farming has been a controversial topic.

The potential exists that transgenic fish, should they escape from fish farms, may reproduce successfully with wild or other transgenic fish and produce offspring which may eventually adapt to their local environments. This is a topic which will receive

considerable debate in the years to come. There is no evidence in the literature that transgenic fish have been raised or are currently being raised in Puget Sound waters, and there are no plans to raise them in the future.

5.3 Epidemics and the Transmission of Waterborne Disease

5.3.1 The origin and disease status of Atlantic salmon stocks in Puget Sound

In 1971 scientists from the NMFS Northwest Fisheries Science Center began testing the feasibility of rearing New England stocks of Atlantic salmon in seawater net-pens in Puget Sound to provide 3.5 million eyed eggs annually for restoring depleted runs in southern New England (Mighell 1981, Harrell et al. 1984). Between 1971 and 1983 NMFS received eggs from many North American stocks, including the Grand Cascapedia River in Quebec (via Oregon State), and the Penobscot, Union, St. John, and Connecticut rivers in the USA.

All Atlantic salmon eggs sent to the NMFS Manchester Research Station were examined according to the code of federal regulations (Regulation 50 CFR) and certified by federal pathologists to be free of bacterial and viral pathogens prior to transfer from New England to Washington. However, few eggs were ever sent back to New England due to the reluctance of east coast fisheries managers to accept eggs from Atlantic salmon which had been grown in waters inhabited by Pacific salmon. A panel of New England state and federal fisheries officials met at Newton Corner, Massachusetts in March, 1984 and determined that raising Atlantic salmon in Puget Sound had rendered the eggs unfit for transfer back to the east coast because the risk of introducing Pacific salmon diseases to New England Atlantic salmon populations was too great.

As a result of this decision, millions of Atlantic salmon eggs originally meant for New England restoration programs were available for distribution to salmon farmers in Washington. These eggs proved to be a boon to the local industry as, by this time, it was clear from work in Norway and Scotland, that Atlantic salmon were superior to Pacific salmon in all aspects of culture, including survival to hatching, growth rate in fresh and sea water, and, contrary to east coast opinion, resistance to infectious diseases (Mighell 1981, Waknitz 1981).

5.3.2 Disease of salmonids

Freshwater salmonid diseases observed in Pacific salmon hatcheries in the Pacific Northwest include furunculosis, bacterial gill disease, bacterial kidney disease, botulism, enteric redmouth disease, cold water disease, columnaris, infectious hematopoietic necrosis, infectious pancreatic necrosis, viral hemorrhagic septicemia, erythrocytic inclusion body syndrome, and a large number of parasitic infections, such as gyrodactylus, nanophyetus, costia, trichodina, ceratomyxosis, proliferative kidney disease, whirling disease, and ichthyophonis. All these diseases are described in works by, *inter alia*, Wood (1979), Leitritz and (1980), Foott and Walker (1992), and Kent and Poppe (1998).

The frequency of occurrence of these pathogens in hatcheries appears to vary geographically. For example, between 1988 and 1992, a greater percentage of hatcheries in Alaska tested positive for infectious hematopoietic necrosis, viral hemorrhagic septicemia, furunculosis, and ceratomyxosis than hatcheries located elsewhere in the western States, whereas the same hatcheries in Alaska tested positive at the lowest rate for several other salmonid pathogens (PNWFHPC 1993) (Table 1).

In the Pacific Northwest, hatchery diseases associated with freshwater organism can also occur in natural sea water environments after salmon are released from hatcheries or transferred to net-pens for further rearing. Some pathogens, such as *V. anguillarum* and various parasites, are unique to the marine environment and are normally encountered by wild and hatchery-reared salmonids only after they leave rivers for the sea (Wood 1979, Harrell et al. 1985 and 1986, Kent and Poppe 1998). Salmonid diseases observed in salmon and trout reared in public and private net-pens in sea water in the Pacific Northwest include; vibriosis, furunculosis, bacterial kidney disease, enteric redmouth disease, myxobacterial disease, infectious hematopoietic necrosis, infectious pancreatic necrosis, viral hemorrhagic septicemia, erythrocytic inclusion body syndrome, rosette agent, and a large number of parasitic infections. Kent and Poppe (1998) listed and described infections currently observed in salmonids in marine waters.

Like other animals, salmon can carry pathogen organisms without themselves being infected. For example, numerous bacterial species were observed in tissues of chinook salmon which had returned from the ocean to a hatchery in the lower Columbia River Basin, although the fish displayed no clinical signs of disease. Some bacteria observed were *Listeria* sp., *Aeromonas hydrophila*, *Enterobacter agglomerans*, *E. cloacae*, *Staphylococcus aureus*, *Pseudomonas* sp., *Pasteurella* sp., *V. parahaemolyticus*, *V. extorquens*, *V. fluvialis*, *Hafnia alvei*, and *Serratia liquefaciens* (Sauter et al. 1987). Several of these organisms found in hatchery salmon are known to be infectious for humans but it does not infer they pose any risk.

Table 1. Facilities (%) testing positive for various salmonid pathogens (July 1988–June 1993). (Data from PNWFHPC 1993)

State or Agency	IHN	IPN	VHS	EIBS	BKD	FUR	ERM	CWD	PKD	MC	CS	ICH
AK	47.3	0.0	1.2	0.0	75.2	42.5	10.9	27.5	NS	NS	50.0	0.0
CA	24.2	0.0	0.0	0.0	31.2	2.2	23.0	19.4	27.9	12.0	12.8	56.3
ID	20.2	8.7	0.0	15.5	48.4	1.8	12.3	23.6	4.3	15.6	20.4	20.7
MT	0.0	0.0	0.0	0.0	5.6	2.5	0.8	4.2	7.7	0.0	0.0	0.0
OR	18.1	0.3	0.0	24.6	53.1	35.9	17.8	84.8	0.0	2.9	33.3	26.2
WA	11.5	0.7	0.1	34.2	52.6	20.1	17.0	60.3	3.5	0.0	11.9	24.4
USFWS	37.5	1.0	0.0	27.2	84.9	23.7	20.0	34.9	0.0	0.6	30.6	24.0
NWIFC	2.9	0.0	0.6	NS	51.5	14.0	18.1	39.9	56.3	0.0	0.0	15.0
Average	20.2	1.3	0.2	14.5	50.3	17.8	15.0	36.8	12.5	4.4	18.8	20.8

NS = Not surveyed

Key:

(a) Viral Diseases

- IHN Infectious hematopoietic necrosis
- IPN Infectious pancreatic necrosis
- VHS Viral hemorrhagic septicemia
- EIBS Erythrocytic inclusion body syndrome

(b) Bacterial Diseases

- BKD Bacterial kidney disease
- FUR Furunculosis
- ERM Enteric redmouth disease
- CWD Coldwater disease

(c) Parasites

- PKD Proliferative kidney disease
- MC Whirling disease
- CS Ceratomyxa
- ICH Ichthyophthirius

5.3.3 Infectious disease therapy

Fish diseases and subsequent antibiotic therapy have been normal occurrences at state, federal, and tribal Pacific salmon hatcheries since the 1940s (WDF 1950, PNWFHPC 1993). For example, an examination of the disease histories of Puget Sound area Pacific salmon hatcheries (data from 45 hatcheries) during the 1980s showed that on average each hatchery commonly experienced disease outbreaks from about 4 different pathogenic organisms during this period, frequently on an annual basis (PNWFHPC 1988a–d).

Cumulatively, salmon hatcheries in the Pacific Northwest (Alaska, Washington, Oregon, and Idaho), including those located in Puget Sound, experience hundreds of disease outbreaks every year, according to Wood (1979) and PNWFHPC (1988a–d). For example, Michak and Rodgers (1989) reported that, between 1983 and 1986, the WDFW Cowlitz Hatchery experienced *Costia* sp. infections on 11 different occasions, bacterial hemorrhagic septicemia 4 times, cold water disease 9 times, bacterial kidney disease 8 times, and furunculosis once. Disease outbreaks have been observed in hatchery salmon reared in saltwater in Washington since the first attempts at seawater rearing in the 1950s (WDF 1954, PNWFHPC 1998). However, the occurrence of fish diseases and their treatment with chemotherapeutics at public hatcheries has not been shown to have deleterious effects on wild salmonids.

Diseases in public trout and salmon hatcheries (Table 1) are normally treated with a variety of antibiotics and chemical baths including, *inter alia*, oxytetracycline, @Romet-30, formalin, iodophores (Wood 1979; PNWFHPC 1988a–d, 1998). Drug therapy in federal, state, and tribal hatcheries in Washington State is conducted in line with FDA guidelines (K. Amos, WDFW, personal communication). Antibiotic-resistant strains of bacterial fish pathogens have been observed in Pacific salmon hatcheries in the Pacific Northwest for over 40 years (WDF 1954, Wood 1979, PNWFHPC 1993), but no adverse impacts on wild salmonids have been reported as a result of drug use or the occasional development of antibiotic-resistant bacteria.

Schnick (1992) reported that only three therapeutants (formalin, oxytetracycline, and @Romet-30) and one anesthetic (MS-222) were currently approved by the federal government for use with food fish in public and private artificial propagation facilities. However, the use of antibiotics in the US is far more restrictive than in other countries. For example, Weston (1996) stated that 26 different antibacterials were approved for use in Japan. This compares currently with three in Canada, according to EAO (1997) and two in the US (Schnick 1992).

Given that Pacific salmon hatcheries rear thousands of metric tons of fish each year, the amount of antibiotics used to treat bacterial salmon diseases is not insignificant, amounting to hundreds of tons of medicated feed each year. Michak et al. (1990) stated that WDF hatcheries located in the Columbia River Basin used about 200 mt of feed containing antibiotics. Since WDF (now WDFW) hatcheries in the Columbia River Basin represented only about 25% of the number of all salmon and trout hatcheries (albeit many of the largest facilities are in the Columbia River Basin) in Washington State at that

time (Myers et al. 1998), it is reasonable to estimate that the total amount of medicated feed used by the public hatchery system in the State was about 450 mt in 1990. However, no adverse impacts to wild salmonids have been reported as a result.

Actual or estimated annual amounts of medicated feed used in private fish culture of Atlantic salmon in seawater and rainbow trout in freshwater are not available at this time for the USA. However, the amount of drugs used elsewhere in salmon farming has greatly declined, mostly as a result of improved husbandry practices, including development of effective vaccines. EAO (1997) noted that salmon farmers in Norway used 48.7 mt of antibacterial drugs in 1987, and the figure had fallen to 6 mt by 1993. In 1998 it was only 679 kg (Intrafish 2000). During the same ten year period, the production of salmon increased from 50,000 mt to 400,000 mt, and the quality of product was considerably improved (ODIN 2001). A similar pattern of reduced drug use has occurred in BC. With few salmon farms in Washington the annual use of antibiotics in the net-pen farms will be minimal.

5.3.4 Disease interactions between wild and propagated salmonids

Documented examples of pathogen transmission between wild and artificially-propagated fish are not common, yet have been known to occur (Brackett 1991). For example, the planting of infected Atlantic salmon smolts from Norwegian federal salmon hatcheries into rivers in Norway was responsible for the introduction of the freshwater parasite *Gyrodactylus salaris*, which caused the extirpation of Atlantic salmon in many river systems (Johnsen and Jensen 1986, 1988). The salmonid viral pathogen IHN (infectious hematopoietic necrosis) was introduced to Japan from a shipment of infected sockeye salmon eggs from a hatchery in Alaska and subsequently caused epizootic mortality in Japanese chum salmon and in two species of landlocked salmon which occur only in Japan (McDaniel et al. 1994). In these two cases, the indigenous salmonids in Norway and Japan were exposed to novel pathogens to which they had little or no immunity. In Washington the pathogens found in cultured salmonids are identical to those known to occur in wild salmon (Amos and Appleby 1999).

PSGA (2000) and Carrel (1998) assert that local Atlantic salmon stocks are more likely to carry pathogens than hatchery stocks of Pacific salmon, but this is not supported the scientific literature. Salmonids, including Atlantic salmon, can only carry diseases to which they have been exposed. The New England Atlantic salmon stocks used by Washington growers were certified by federal pathologists to be pathogen-free prior to shipment from east coast hatcheries between 1980 and 1986, inclusive, and have been reared exclusively in the Pacific Northwest for many generations. Their diseases, if any, would be no different than the diseases found in nearby Pacific salmon hatcheries. In addition, Washington regulations require that all broodstocks of hatchery salmon, including Atlantic salmon broodstocks, are examined for pathogens each year (WAC 220-77; RCW 75.58). Non-indigenous salmon diseases transmitted into the Pacific Northwest by North American stocks of Atlantic salmon have not been reported.

Pacific salmonids do not seem to be put to any increased risk of pathogen transmission when exposed to water in which Atlantic salmon have been reared. For example, Rocky

Ford Creek near Ephrata, in eastern Washington, is considered one of the premier trout streams in the State but its entire flow consists of effluent from an Atlantic salmon hatchery (J. Parsons, Troutlodge Inc., personal communication). There are no reports of diseased trout in this stream in either the scientific literature or in 'gray' literature.

There is no evidence to suggest that hatchery-reared Atlantic salmon have introduced or spread non-indigenous pathogens to native fishes in Washington. With Pacific salmon, Griffiths (1983) observed that outbreaks of serious contagious diseases were normally associated with the intensive culture of fish in a hatchery environment. There are no recorded observations to suggest this would be any different for artificially-propagated Atlantic salmon or rainbow trout.

5.3.5 The scale of artificial propagation

Based solely on the enormous number of hatchery-reared salmonids released into rivers and lakes in the Pacific Northwest, the potential for transmission of disease to wild stocks from hatchery-reared Pacific salmon and trout greatly exceeds that of accidentally-escaped farmed Atlantic salmon and rainbow trout in Washington State. This is because escaped Atlantic salmon and rainbow trout constitute an insignificant percentage of all artificially-propagated salmon which end up in natural waters in the area. However, the millions of Pacific salmon which enter the marine waters of Washington each year have not been shown to impose adverse impacts on wild salmonids. Carrel (1998) described escaped Atlantic salmon as 'smart bombs, delivering disease right into the bedrooms of wild salmon' in the Pacific Northwest, but this is not supported in the scientific literature.

Because Atlantic salmon are propagated in only a few facilities in the Pacific Northwest, compared with the several hundred federal, state, tribal, and cooperative hatcheries rearing Pacific salmon and trout, the primary difference in the disease incidence between artificially-propagated Atlantic and Pacific salmon is one of scale. Mahnken et al. (1998) reported that, since 1980, the number of Pacific salmon released from west coast hatcheries was about two billion fish annually. This number is 4 or 5 orders of magnitude larger than the number of Atlantic salmon which may have escaped from net-pens since 1980 (Table 2).

Table 2. Number (in millions) of salmon released or escaped by species and location along the west coast of North America, 1980–1995 (Data from NRC 1995 and 1996; Thomson and McKinell 1993–1997; Mahnken et al. 1998; Thomson and Candy 1998).

State or Region	Atlantic	Sockeye	Chum	Steelhead	Pink	Coho	Chinook
Alaska	0	978	3,885	2	8,610	193	98
Canada BC	~0.4	3,930	2,870	17	533	300	721
Pacific Northwest	~0.6	52	1,081	359	21	726	4,320
Total	~1.0	4,960	7,836	377	9,164	2,219	5,139
Total (%)	0.0003	16.7	26.4	1.2	30.9	7.5	17.3

Comparing only the number of Pacific salmon released from salt-water net-pens, then the magnitude and geographic distribution of these artificially-propagated Pacific salmon is still much greater than the number and magnitude of Atlantic salmon reared in farms.

For example, NRC (1995, 1996) reported that coho salmon were released annually from 18 different marine net-pen sites, chinook salmon from 13 different sites, and chum salmon from 10 different sites in Puget Sound between Olympia and Bellingham. The annual release from these marine sites between 1980 and 1992 averaged about 10 million fish. These fish had sometimes been exposed to various salmonid pathogens while in seawater, including bacterial kidney disease, vibriosis, and furunculosis. Infections in these fish were often treated with antibiotics prior to their release (PNWFHPC 1988a–d), yet no adverse impacts on wild salmonids have been reported as a result.

5.3.6 Disease control policies in Washington and the USA

In Washington all public and private growers of salmon, including Atlantic salmon hatchery operators, are required to adhere to strict disease control policies which regulate all phases of fish culture, from egg take to harvest and/or release (NWIFC/WDFW 1991; NWIFC/WDFW1998). Each year at spawning time, adult salmon at public and private hatcheries must be sampled for viral, bacterial, and parasitic organisms. If any of several reportable organisms are detected in fish at a hatchery, or have been detected within the past five years, transfer of eggs or fish from that facility is prohibited.

The movement of fish and eggs across state or international borders is regulated by the USFWS under Title 50 of the CFR, which has stipulations and controls in accord with State regulations (Regulation 50 CFR, Part 16.13). For the case in point, all Atlantic salmon stocks distributed to local growers by NMFS were federally certified by federal pathologists before transfer from New England, and have been annually certified since then under Washington guidelines and procedures.

Most of the cumulative body of information pertaining to salmon farming developed in the last several decades has already been integrated into the regulatory processes of Washington State. This scientific information has been incorporated into State regulations relating to farm fish escapes, antibiotic residues in sediments, accumulation of organic wastes on the seabed, importation of non-native and non-local species, and disease management. These and other important regulations and documents pertaining to private salmon farming include:

- Final programmatic EIS for fish culture in floating net-pens (WDF 1990)
- Recommended interim guidelines for the management of salmon net-pen culture in Puget Sound (WDOE 1986)
- Environmental effects of floating mariculture in Puget Sound (Weston 1986)
- Environment fate and effects of aquacultural antibacterials in Puget Sound (Weston et al. 1994)
- Disease control policies of Washington (NWIFC/WDF 1991)
- Disease control policies of the United States (USFWS 1984)
- Fish health manual of the Washington Department of Fish and Wildlife (WDFW 1996)

5.4 Potential Ecological Impacts of Atlantic Salmon in the Pacific Northwest

In areas where Atlantic salmon are indigenous, such as Scandinavia, Great Britain, and eastern North America, adverse genetic and ecological impacts for natural populations of Atlantic salmon have been reported by, *inter alia*, Gibson 1977; Gross 1998; Hearn and Kynard 1986; Jones and Stanfield 1993; Beall et al. 1989; Heggberget et al. 1993, following programmed releases or escapes of artificially-propagated Atlantic salmon from public hatcheries and private net-pens. The impacts included reduction in genetic adaptation and capacity to evolve in wild Atlantic salmon resulting from interbreeding with artificially-propagated Atlantic salmon, and competition for food and space between wild and hatchery stocks of Atlantic salmon.

These adverse effects occurred because both the artificially-propagated and wild salmonid species were Atlantic salmon. Escaped Atlantic salmon on the Pacific coast of North America do not have congeneric wild individuals with which to interact. In the Pacific Northwest region it is the introduction of hatchery stocks of Pacific salmon which have the potential to produce impacts on native Pacific salmon comparable to those found between propagated and wild Atlantic salmon in Europe and eastern North America.

Adverse genetic and/or ecological interactions on local wild salmon populations resulting from plants of artificially-propagated Pacific salmonids have been well documented in the Pacific Northwest in papers by Nickelson et al. (1986), Behnke (1992), Kostow (1995), Campton and Johnston (1985), WDFW et al. (1993), and Leider et al. (1997). A series of papers by Thomson and McKinnell (1993, 1994, 1995, 1996, and 1997), Thomson and Candy (1998), and Amos and Appleby (1999) have reported no detrimental effects in the region which can be related to deliberate or accidental Atlantic salmon introductions.

5.4.1 Social interactions between Pacific and Atlantic salmon

Gibson (1981) reported that, from laboratory studies in New England, introduced Pacific steelhead juveniles were more aggressive than Atlantic salmon. In turn Atlantic salmon fry appeared to be more aggressive than coho salmon fry when introduced into open pools, although it was recognized that open pools are not the preferred habitat of coho salmon fry. Beall et al. (1989) in a similar experiment reported that the survival of Atlantic salmon was reduced in the presence of older coho salmon fry.

In trials of inter-specific combative behavior in New England, Hearn and Kynard (1986) observed that rainbow trout juveniles initiated three to four times more aggressive encounters than did Atlantic salmon, and concluded that it would take very large numbers of Atlantic salmon juveniles to displace or even disrupt native species. Jones and Stanfield (1993), in a study conducted in a Lake Ontario tributary once inhabited by Atlantic salmon, reported that their attempts to reintroduce hatchery strains of Atlantic salmon were significantly impaired in the presence of naturalized Pacific salmon juveniles, compared with reintroduction in stream sections where Pacific salmon juveniles had been removed.

5.4.2 Predation by Atlantic salmon

In a study on farmed fish in Canada BC by Black et al. (1992) stomach analyses revealed that <1% of farmed salmon in net-pens (in this case coho and chinook salmon) contained the remains of fish. Since 1992 scientists of the Canadian federal government have examined the stomach contents of escaped Atlantic salmon recovered in the open waters of BC. Fish remains of any sort were rarely observed, and no confirmed salmonid remains were reported (see Thomson and McKinnell 1993, 1994, 1995, 1996, 1997; Thomson and Candy 1998). This confirms earlier work by Tynan (1981) who examined the stomachs of 93 coho salmon captured after release from a net-pen near Squaxin Island, in South Puget Sound, and reported that only three stomachs contained fish remains, which were identified as smelt.

At the NMFS Manchester Research Station in Puget Sound many species of forage fish have been observed seeking refuge from predators in net-pens containing large Atlantic salmon. Among the species observed are known prey of salmonids, such as herring, smelt, candlefish, shiner perch, and tube snouts. These prey species enter the net-pens voluntarily and then grow too large to exit. A report by Alverson and Ruggerone (1997) noted that many thousands of these small fish had been observed in Atlantic salmon net-pens, and had to be removed by hand.

Buckley (1999) showed that cannibalism and predation on other salmonids by chinook salmon when feeding was uncommon in Puget Sound waters. It is difficult to imagine that escaped Atlantic salmon, conditioned to a diet of artificial feed pellets and trained to be fed by humans, could have greater predation impacts on juvenile native salmonids than the low impact observed with free-swimming Puget Sound chinook salmon.

In the Cowichan River in Canada BC, non-native brown trout became established soon after its first introduction in 1932. Idyll (1942) observed that native salmon and trout, and their eggs, were a significant dietary component of newly-established Cowichan River brown trout, and were the primary food item of large brown trout. Recent evaluations by Wightman et al. (1998) of steelhead populations on the east coast of Vancouver Island showed that the Cowichan River was one of only two rivers (out of 27 evaluated) with a relatively healthy steelhead population. Therefore the successful colonization of the Cowichan River by a highly piscivorous species such as the brown trout has apparently had no adverse impact on steelhead abundance for more than 60 years, whereas concurrent attempts to establish Atlantic salmon in the Cowichan River basin were failures.

5.5 Potential Impacts of Propagated Pacific Salmon

Adverse genetic and ecological effects from artificially-propagated Pacific salmon have been documented by, *inter alia*, Weitkamp et al. (1995), Busby et al. (1996), Hard et al. (1996), Gustafson et al. (1997), Johnson et al. (1997), Myers et al. (1998), and Johnson et al. (1999) in a number of coast-wide status reviews of Pacific salmonids. These status reviews were conducted by NMFS in fulfillment of their responsibilities under ESA. The reviews contained information from the scientific literature which documented known

adverse ecological impacts sometimes associated with the artificial propagation and release of Pacific salmon. In recent years, west coast management agencies have eliminated many of the policies which contributed to these adverse effects. However, examining some of the known adverse impacts of Pacific salmon hatchery programs which have not been observed to be a result of Atlantic salmon hatchery programs on the west coast offers an effective demonstration that the ecological and genetic risks associated with Atlantic salmon farming are small in the waters of Puget Sound. The following paragraphs provide a brief review by species of adverse effects of artificial propagation which occurred under the old Pacific salmon hatchery policies.

(i) Steelhead trout

Hatchery stocks of steelhead have been widely distributed. Few native steelhead stocks exist in the contiguous US which have not had some influence from hatchery operations. For example, Busby et al. (1996) cite the summer steelhead program at the Nimbus Hatchery in Central Valley, California was established with fish from a distant coastal tributary hatchery which was itself earlier established with Lower Columbia River summer steelhead.

Howell et al. (1985) reported that over 90% of the 'wild' steelhead spawning in the Cowlitz River originated in a hatchery, and some of these fish exhibited genetic characteristics of Puget Sound steelhead due to previous transfers of Puget Sound stock to the Cowlitz Hatchery.

Chilcote (1997) reported that, since 1980, the percentage of non-native stray hatchery steelhead (from upper Columbia River and Snake River hatcheries) spawning in the Deschutes River had increased to over 70% of the run, while the percentage of native, wild steelhead spawning in the Deschutes River decreased to less than 15%. Phelps et al. (1997) postulated that introductions of non-native steelhead stocks in Washington, primarily Chambers Creek winter steelhead and Wells and Skamania summer steelhead, may have changed the genetic characteristics of some populations sufficiently so that the original genetic relationships between stocks may have been obscured. Finally, Leider et al. (1987) concluded that the genetic fitness of the wild Kalama River population had been compromised by maladaptive gene flow from excess hatchery escapement. By comparison, no documented adverse effects on steelhead have been reported to result from escapes of Atlantic salmon in Washington or elsewhere.

(ii) Chinook salmon

About 2 billion hatchery chinook salmon have been released into Puget Sound since 1953, with the stock from the Green River Hatchery being the dominant stock as far back as 1907. Concerns that this strategy may erode genetic diversity was raised by Myers et al. (1998). As recently as 1995, 20 hatcheries and 10 marine net-pen sites throughout Puget Sound regularly released Green River-stock chinook salmon. Busack and Marshall (1995) reported that the extensive use of this stock had an undoubted impact on among-stock diversity within the South Puget Sound, Hood Canal, and Snohomish summer/fall genetic diversity unit (GDU), and may also have impacted GDUs elsewhere in Puget Sound and the Strait of Juan de Fuca.

Rogue River chinook salmon were recently released on the Oregon side of the Lower Columbia River to produce a south-migrating stock to avoid interception in commercial fisheries in Canada BC and Southeast Alaska. However, chinook salmon exhibiting Rogue River fall chinook salmon genetic markers were subsequently observed by Marshall (1997) in several lower Columbia River tributaries, and were estimated to comprise about 13% of the Lower Columbia River naturally-produced chinook salmon sampled in 1995. Marshall et al. (1995) had earlier stated that most of the naturally-spawning spring chinook salmon in Lower Columbia River tributaries were hatchery strays. Adverse impacts resulting from the introduction of artificially-propagated fish into native populations of chinook salmon were identified as a primary concern by the NMFS Biological Review Team during the recent review of the status of west coast chinook salmon populations (Myers et al. 1998). There is no documented evidence of adverse effects on chinook salmon resulting from escaped Atlantic salmon in Washington or elsewhere.

(iii) Chum salmon

Johnson et al. (1997) reported that five hatchery stocks and several wild populations of chum salmon outside the Hood Canal, but which received eggs from Hood Canal hatcheries for several years, exhibited genetic frequencies more similar to those in Hood Canal hatchery populations than to populations in nearby streams not receiving Hood Canal hatchery stocks. Their analyses of gene frequency patterns were consistent with the hypothesis that egg transfers between hatcheries and out-plantings of Hood Canal stock fry had genetically influenced the receiving populations. According to Phelps et al. (1995) such transfers were terminated because of the potential jeopardy to wild gene pools through interbreeding. However, there is no documented evidence of adverse effects on chum salmon resulting from escaped Atlantic salmon in Washington or elsewhere.

(iv) Coho salmon

Weitkamp et al. (1995) noted that the NMFS Biological Review Team was unable to identify any remaining natural populations of coho salmon in the lower Columbia River below Bonneville Dam, due in large part to persistent and extensive hatchery programs. A recent survey by NRC (1999) of coho salmon spawning habitat in the lower Columbia River estimated that about 97% of recovered spawned-out carcasses originated from hatchery releases. Hatchery fish were observed in high percentages in streams up to 45 miles from the nearest hatchery. In many streams, wild, native coho salmon were not observed at all. In an earlier similar survey by NRC (1997) in Hood Canal, over 50% of all spawning coho in streams within a 10-mile radius of a net-pen release site were fish released from the net-pen as juveniles 18 months earlier.

Kostow (1995) stated that hatchery programs in Oregon may have contributed to the decline of wild coho salmon by supporting harvest rates in mixed-stock fisheries which were excessive for sustained wild fish production, and by reducing the fitness of wild populations through interbreeding of hatchery and wild fish. Furthermore, they may have reduced survival of wild coho salmon juveniles in Oregon through increased competition

for food in streams and estuaries, through attraction of predators during mass migrations, and through initiation of disease problems.

Weitkamp et al. (1995) also reported that artificial propagation of coho salmon had appeared to have substantial impact on native coho salmon populations to the point where it was difficult for the NMFS Review Team to identify self-sustaining native stocks in Puget Sound, as over half the returning spawners originated in hatcheries. Spawn-timing had been advanced by selective breeding so that most hatcheries met their quotas for eggs by early November, and fish arriving at the hatchery with the later run (which would be coincidental with the spawn-time of the wild or native fish) were not propagated. As a result of such practices, according to Flagg et al. (1995), segments of hatchery coho salmon populations which historically returned as late as January through March have disappeared from many river systems, resulting in a significant loss of life history diversity. Again, for comparison, there is no documented evidence of adverse effects on coho salmon resulting from escaped Atlantic salmon.

(v) Trouts

Long-term introductions of rainbow trout into western streams originally inhabited only by cutthroat trout have resulted in widespread extinctions of native cutthroat trout through introgressive hybridization, according to Leary et al. (1995). They noted that hybridization between introduced brook trout and bull trout is widespread in the western USA, and usually produces sterile hybrids. Behnke (1992) noted that introduced brown trout had commonly replaced interior subspecies of cutthroat trout in large streams throughout the same region, and introduced brook trout were the most common trout to be found in many small streams.

The situation regarding attempts to establish Atlantic salmon populations in the West is much different. In summary, MacCrimmon and Gots (1979) described frequent attempts and failures to introduce Atlantic salmon to the western States, many of which occurred in the same river systems and at the same time as the introductions noted above. Since then no recent introductions, accidental or not, have succeeded and, most importantly, no known adverse impacts on indigenous species by Atlantic salmon have been reported in the literature.

5.6 Adverse Impacts of Non-indigenous Fish Introductions

As many as 50 species of non-native fish are successfully established in the western US (Table 3). The Atlantic salmon is not one of those listed. Some adverse impacts associated with the establishment of these species are discussed below. None of these negative impacts has been associated with the artificial propagation of Atlantic salmon in the Pacific Northwest.

Table 3. Status of non-native fish introductions in the Pacific Northwest vis-à-vis their behavior relative to Pacific salmonids (Data after Behnke 1992, Lever 1996, ODFW 1999, WDFW 1999, Dill and Cordone 1997)

Non-Native Species	Naturalized in Washington	Naturalized in Oregon	Naturalized in California	Predator	Competitor	Hybridize
Atlantic salmon						
Non-native rainbow	X	X	X	X	X	X
Non-native cutthroat	X	X	X	X	X	X
Lahotan cutthroat	X					X
Westslope cutthroat	X		X		X	X
Brown trout	X	X	X	X	X	X
Brook trout	X	X	X	X	X	X
Lake trout	X	X	X	X		X
American shad	X	X	X		X	
Threadfin shad			X			
Lake whitefish	X					
Arctic grayling	X		X			
Grass pickerel	X			X		
Northern pike	X		X	X		
Striped bass		X	X	X		
White bass			X			
Common carp	X	X	X		X	
Grass carp	X		X			
Tench	X		X			
Brown bullhead	X	X	X	X	X	
Black bullhead	X	X	X	X	X	
Yellow bullhead	X	X	X	X	X	
Flathead catfish	X		X	X	X	
Blue catfish	X			X	X	
Channel catfish	X	X	X	X	X	
White catfish		X	X	X	X	
Largemouth bass	X	X	X	X	X	
Smallmouth bass	X	X	X	X	X	
Warmouth bass	X	X	X	X	X	
Rock bass	X			X	X	
Redeye bass			X			
Northern spotted bass			X			
Alabama spotted bass			X			
Black crappie	X	X	X	X	X	
White crappie	X	X	X	X	X	
Green sunfish	X	X	X	X	X	
Bluegill	X	X	X	X	X	
Pumpkinseed	X	X	X	X	X	
Redear sunfish			X			
Bigscale logperch			X			
Yellow perch	X	X	X	X	X	
Walleye	X	X	X	X	X	

ODFW/NMFS (1998) documented that many introduced non-native species were harmful to native salmon. For example, walleye, bass, perch, sunfish, brown trout, and brook trout, among others, are all now well-established in Northwest waters and are well-known predators and/or competitors of native salmon and trout. Beamesderfer and Nigro (1988) and Beamesderfer and Ward (1994) estimated that walleye and smallmouth bass introduced into the John Day Reservoir of the Columbia River consumed an average of 400,000 and 230,000 juvenile salmonids, respectively, each year.

Daily et al. (1999 in prep.) reported that juvenile salmonids from seven ESUs currently listed as threatened or endangered under ESA must migrate through the John Day Reservoir; and in some coastal lakes in Oregon the summer rearing of coho salmon fry no longer occurred due to predation by introduced largemouth bass. Seiler (WDFW, personal communication) has observed that introduced bass eat out-migrating salmon, including juvenile chinook salmon, as they pass through the Lake Washington Ship Canal in Seattle, WA. There is no documented literature which shows that Atlantic salmon in western states prey on juvenile native salmonids.

In 1997 and 1999, in response to the escape of some net-pen Atlantic salmon, WDFW suspended fishing regulations concerning size and bag limits for these fish. Licensed anglers fishing in open management zones were permitted to keep all Atlantic salmon they could catch, of whatever size (WDFW 1997c, 1999). Suspension of fishing regulations for an introduced, non-native species in waters inhabited by native salmonids at some period of their life cycle is an appropriate management which WDFW has used before. For example, freshwater angling regulations for non-native brook trout in Washington were recently relaxed to increase harvest of this species, and regulations for non-native shad, perch, crappie, and carp have long-since been dismissed entirely.

Catch limits and close seasons for non-native salmonids in Washington (such as brown trout, golden trout, lake trout, landlocked Atlantic salmon, California-strain rainbow trout, and grayling) have given these species many of the same protections given to native salmonids. Furthermore, several non-native species known to prey on salmonid juveniles (such as smallmouth and largemouth bass, walleye, and channel catfish) are currently managed for sustained natural reproduction through regulations which limit the take of large individuals which have the greatest reproductive potential (WDFW 2001). From a review of the literature, Atlantic salmon have far less potential for adverse impacts than all the non-native species noted above. Therefore, to decrease unnecessary adverse impacts on listed native salmonids by non-indigenous fish, it would not be an inconsistent strategy for states in the Pacific Northwest to suspend regulations for the harvest of all non-indigenous fish by licensed anglers.

5.7 A Perspective of Salmon Culture in Northwest Waters

Most of the concerns for the negative impacts of Atlantic salmon on native salmon in the Pacific Northwest are hypothetical. They are associated with the belief that artificially-propagated fish are bigger, stronger, and more vigorous than wild fish. Although this opinion has been generally disproved in a multitude of studies, many studies and reviews, among them WDFW et al. (1993) and the NMFS Status Reviews, have shown that adverse impacts from hatchery stocks of Pacific salmon are likely to occur if and when hatchery fish comprise a large portion of the total population. Therefore, it is instructive to compare the numbers of artificially-propagated Pacific salmon released each with the number of Atlantic salmon estimated to escape each year to give a perspective as to where and when the greatest risks actually occur, and to what degree, keeping in mind recent changes in hatcheries strategies in the Pacific Northwest which will likely reduce the impact of hatchery fish on wild fish.

Mahnken et al. (1998) reported that several billion Pacific salmon were released from freshwater hatcheries and marine net-pens in North America each year (see Table 2). Although Washington, Oregon, Idaho, and California had more salmon hatcheries, the total number of fish released in the contiguous States of the Pacific Northwest was dwarfed by the vast number of hatchery salmon released in Alaska each year. McNair (1997, 1998, and 1999) documented the annual release of about 1.4 billion hatchery salmon into natural rearing areas since 1996.

Pacific salmon have been released from hatcheries with the understanding that they must compete for food and habitat in common with native wild salmon to survive. Until recently the capacity of the ocean pastures were thought to be limitless. Recent investigations by Heard (1998), Cooney and Broder (1998), and Beamish et al. (2000) show that food availability in the ocean fluctuated over time and might be limiting salmon abundance. Bisbal and McConah (1998) proposed fishery managers planning to release vast numbers of fish from hatcheries should take these fluctuations into account. Compared with the great numbers of Pacific salmonids released each year into the marine ecosystems, there is no evidence in the literature that the few Atlantic salmon which escape pose any competitive threat to native Pacific salmon for forage or habitat.

The majority of Atlantic salmon escapes have occurred in Puget Sound. However, the number of escapees is extremely low compared with the number of Pacific salmon deliberately introduced into the ecosystem. NRC (1995, 1996) documented that the total number of cultured chinook, coho, and chum salmon released into Puget Sound tributaries by various fisheries agencies between 1980 and 1992 exceeded 2.2 billion in number. Although data are not yet available through the year 2000, it is predictably over 3 billion. For comparative purposes, if the total number of Atlantic salmon which escaped into Puget Sound since 1980 was represented on a histogram by a bar one inch high, the total number of Pacific salmon released into Puget Sound and its river basins since 1980 would be a bar about 250 feet high. Comparison with the 13.5 billion hatchery fish released into Alaskan waters since 1990, using annual data published by

ADF&G between 1991 and 2000, is even more dramatic, and would require a bar almost one quarter of a mile high.

The adverse ecological and genetic interactions associated with abundant releases of hatchery-reared Pacific salmon are well-documented and present a more serious risk for native salmonids. There is no evidence in the literature which associates adverse impacts with the escape of Atlantic salmon in the Pacific Northwest, or that they even pose a serious threat.

NRC (1995) reported that over 240 million small, non-migratory, hatchery coho salmon were released into Puget Sound tributaries between 1980 and 1992, which averaged about 18 million annually. FPC (1999) since reported that the number of unsmolted coho salmon was reduced by over half, due to the previously mentioned changes in hatchery strategies. Nonetheless, these artificially-propagated fish have to survive by competing for natural food and rearing space with native salmon for about 18 months. Using typical wild coho salmon life history data (ODFW 1982), such as egg-to-fingerling survival levels of 10% and a fecundity of 4000 eggs per female, it would take every year about 92,000 mature, successful Atlantic salmon spawners (1:1 female:male ratio) to produce enough fry to equal the numbers of artificially-propagated non-migrant coho salmon planted in Puget Sound rivers every year.

Applying the same calculations on a more local scale, FPC (1999) reported that about 7,500,000 coho salmon fry of hatchery origin were planted in the Green River between 1993 and 1996. To produce an equal number of Atlantic salmon juveniles, it would be necessary for over 9,000 mature Atlantic salmon adults to escape and spawn successfully in the Green River each year. However, Thomson and Candy (1998) recaptured fewer than 20 mature Atlantic salmon in all Washington rivers systems during 1997, although some were not surveyed completely. BMPs for net-pen salmon farming continue to stress the importance of preventing escapes (BCSFA 1999), but any potential adverse impacts associated with escaped Atlantic salmon cannot begin to approach the potential impacts of fish released from Pacific salmon hatchery programs, even when recent changes in hatchery strategies are considered

Volpe et al. (2000) recovered less than 100 naturally-spawned juvenile Atlantic salmon during counts of salmon juveniles in the Tsitika River in Canada BC. Noakes (1999) noted more than 10,000 juvenile Pacific salmonids were observed in this river in the same survey. The juvenile Atlantic salmon made up approximately 1% of the juvenile salmonids in the river and presented no competition to native salmonids for food or rearing space. No naturally-produced Atlantic salmon have been observed in Washington rivers to-date, although surveys have not been as vigorous as those in Canada.

The success of a hatchery or net-pen facility, as well as the degree to which hatchery fish potentially impact wild fish, is largely determined by how well fish survive in the wild after release. Some hatchery programs are very successful at producing fish for harvest. Johnson et al. (1997) noted that hatcheries in Alaska, through extremely successful early-rearing strategies, produced prodigious numbers of adult chum and pink salmon, two

species which normally have juvenile to adult survival rates of <0.5%. The Hidden Falls Hatchery in Southeast Alaska has consistently experienced survivals of 3–8% with chum salmon (Bachen 1994), resulting in this single facility producing more than 22% of all the chum salmon, wild and hatchery, caught in the fisheries of southeast Alaska (Johnson et al. 1997). McNair (1998) reported that 93.6% of all pink salmon caught in Prince William Sound in 1997 were artificially propagated, and that for all salmon harvested in common property fisheries throughout Alaska that year, 22% of the coho salmon, 30% of the pink salmon, and 65% of the chum salmon originated in hatcheries. Overall, she reported that hatcheries contributed 26% of all salmon harvested in Alaska in 1997. In 2000, McNair (2001) reported that 34% of the total salmon catch in Alaska was produced in Alaskan hatcheries. Additional contributions to Alaska's commercial harvest from hatcheries in British Columbia, Washington, Oregon, and Idaho were not included in this analysis. In Washington, WDFW (2000) estimated that hatcheries provide about 75% of all coho and chinook salmon harvested, as well as 88% of all steelhead harvested. As west coast hatcheries put enough artificially-propagated salmon into the natural environments to produce a significant proportion of the harvest in Alaska, and the overwhelming proportion of fish harvested in Washington, it is not possible that the relatively inconsequential competition for natural resources from present levels of escaped Atlantic salmon could even be evaluated.

Given that it is necessary for millions of hatchery Pacific salmon to compete successfully with wild salmon in natural environments to survive and contribute to the economies of Alaska and Washington, expressions of concern by ADF&G (1999) regarding competition for food from relatively small numbers of escaped Atlantic salmon appear misdirected. A review of the literature reveals that the potential for artificially-propagated Pacific salmon released from public hatcheries to pose adverse impacts with wild Pacific salmon through competition for food is far greater than the potential for competition posed by escaped Atlantic salmon.

5.8 NMFS Biological Status Reviews of West Coast Pacific Salmon Stocks

Since 1991 14 Biological Status Reviews have been published by NMFS as part of its federal obligation under ESA. These Reviews are individual scientific studies of the current status of all anadromous salmonid populations on the west coast of the USA. These are generally regarded as the most complete scientific reviews of their kind ever published. They form the basis for NMFS actions concerning ESA listing determinations, as well as the scientific basis for NMFS testimony for litigation and courtroom challenges to proposed and implemented listings under ESA.

In these Reviews, experienced federal scientists have identified many factors which have adverse effects on the Pacific salmonids of the west coast. The potential biological impacts of cultured salmon have continuously been identified as a primary factor (see Hard et al. 1992, and Waples 1991). Atlantic salmon farms have not been identified as the cause of adverse effects in any of the 14 Reviews conducted to-date, which cover 58 separate ESUs for Pacific salmon species, or factors in the decline of west coast populations of chinook salmon or steelhead (NMFS 1996, 1998).

6. POST SCRIPT

In 1996 a group of organizations brought suit before the PCHB in the State of Washington against WDOE, WDFW, and salmon farmers in the State. The suit (PCHB Nos. 96–257 through 96–268) challenged the issuance of NPDES permits to the salmon farmers. The basis of the suit by the appellants was a series of allegations regarding conflict with other resources and unacceptable environmental risks associated with the culture of Atlantic salmon, the effects of waste on the water column and benthos, and damage to other resources, including fish and shellfish.

Following months of testimony by experts, on May 27, 1997 the PCHB denied partial summary judgement to the appellants because of a genuine issue of material fact as to whether escaped Atlantic salmon 'shall cause or tend to cause pollution' under State law, and whether they constitute 'a man-made change to the biological integrity of State water' under federal law (PCHB 1997). The PCHB found that, *'the Permittees' facilities do not create unresolved conflicts with alternative uses of Puget Sound resources as contemplated by RCW 43.32C.030(2)(e). The existence of commercial salmon farms as permitted uses does not preclude other beneficial uses in Puget Sound, such as shellfish harvesting, commercial or sport fishing, navigation or recreational boating. Likewise, the existence of the salmon farms does not operate to the exclusion of available resources, such as native salmon runs, sediment and water quality, or marine mammals. In short, salmon farming in Puget Sound does not present the citizens of the State of Washington with an "either/or" choice with respect to other beneficial uses and important resources.'*

The Board issued its Final Order on the matter on November 30, 1998 (PCHB 1998) and found: *' no evidence that Permittees' facilities have impacts that effectively exclude other beneficial uses of available resources of Puget Sound. The escapement of Atlantic salmon from Permittees' facilities absent large regular releases in the future does not pose an unacceptable risk to native Pacific salmon in terms of competition, predation, disease transmission, hybridization or colonization.'* This decision by the PCHB was not substantially different from that of the authors of the *British Columbia Salmon Aquaculture Review* (EAO 1997) which concluded that salmon aquaculture, as currently practiced in BC, did not pose unacceptable risks to the environment. The PCHB finding in favor of the *'performance standard'* on which the NPDES permit system in Washington State is based also supports the decision by the BC government to work towards similar standards.

Organic and inorganic loading of the benthos, the transport, fate and biological effects of pharmaceuticals, and dissolved nutrient effects on phytoplankton are important public concerns which have long been recognized and studied. Responsible publications by Weston (1986), Parametrix Inc. (Parametrix 1990), Winsby et al. (1996), and the BC government (EAO 1997) have reviewed all these issues in depth, and in the context of the environment of the Pacific Northwest.

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