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AN EVALUATION OF KNOWLEDGE AND GAPS RELATED TO IMPACTS OF FRESHWATER AND MARINE AQUACULTURE ON THE AQUATIC ENVIRONMENT:

A Review of Selected Literature

PREPARED FOR:

Department of Fisheries and Oceans
Ottawa, ON

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FINAL REPORT

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GLOSSARY

Aerobic	oxygenated environment
Aetiology	study of the cause of a disease
Algae	non-vascular unicellular or multicellular plants which occur mainly in water
Anaerobic	de-oxygenated environment characterized by microbial metabolism which is based on sulfur reduction as an energy source and releases hydrogen sulfide
Anoxic	environment that does not contain molecular oxygen
Anthropogenic	originating from human activity
Aquaculture	cultivation of aquatic organisms such as fish, shellfish, crustaceans and algae
Assimilation	incorporation of food materials into tissue
Benthic communities	aquatic communities associated with the bottom substrate
Biocide	biological or chemical substance used to kill organisms
Biomass	total weight of a given category of organisms per unit of volume or area (e.g., g per m^2)
Bioturbation	disruption or mixing of sediment by organisms
BOD	*Biochemical Oxygen Demand*; amount of oxygen in water that is consumed by microorganisms during the process of decomposition; stated as mg O_2/L
Brackish water	dilute sea water
Chemotherapeutants	chemical compounds used to treat and control diseases (e.g., antibiotics and parasiticides)
Community	general term applied to groupings of organisms inhabiting a common environment

Crustaceans	arthropods of the subphylum Crustacea, including organisms such as crayfish, lobsters, shrimp, copepods, amphipods, etc.; generally characterized by an external chitinous exoskeleton
Deleterious	a substance that has the potential to be harmful to aquatic life or to degrade water quality
Denitrification	reduction nitrate and nitrite to nitrogen (N_2); typically accomplished by microorganisms in anaerobic or low oxygen environments
Ecology	study of interrelationships between living organisms and their environment
Ecosystem	community of organisms and their physical environment interacting as an ecological unit.
Enhancement programs	programs to increase productivity of existing habitats
Epibenthic	region occurring just above the lake or ocean bottom
Epizootic	widespread outbreak of disease
Eutrophic	waters having high primary productivity; waters rich in the mineral nutrients required for plant growth
Eutrophication	process of nutrient enrichment (usually by nitrates and phosphates) in aquatic ecosystems
Feed coefficient	ratio of the weight of food consumed per unit of weight increase
Halocline	zone associated with a rapid change in salinity
Hepatic	related to the liver
Hydrogen sulphide (H_2S)	a poisonous, odorous gas which is formed under anaerobic conditions by the bacterial decomposition of organic compounds containing sulphur or by the reduction of sulphate
Hypoxic	low concentrations of dissolved oxygen
Macroalgae	algae which are visible to the naked eye, often attached, e.g., seaweed belts along the coast

Macrofauna	organisms that are retained by a 0.5 mm screen
Mariculture	cultivation of marine plants and animals
Microalgae	generally free-floating microscopic phytoplankton; may be colonial; may also be found attached to stones, shells, other algae, etc.
Microfauna	organisms that are not retained by a 0.5 mm screen
Molluscs	taxonomic group comprised of gastropods, bivalves, squids, and octopuses, among others
Monoculture	cultivation of a single species
Net-pen farming	farming of fish (e.g., rainbow trout and salmon) in floating cages in lakes or coastal areas
Nitrification	microbial oxidation of ammonia to nitrite and then to nitrate
Offal	entrails and internal organs
Pathogenicity	the ability to cause a disease
Pelagic zone	open water, as opposed to nearshore and benthic zones
Pesticide	biological or chemical substance used for killing undesirable organisms
Photolysed	decomposed by the action of light
Plankton	organisms that are unable to maintain their position or distribution independent of water movement
Plasmid	genetic structure found in the cytoplasm of a cell that can replicate independently of the chromosomes
Population	group of individuals of one species occupying a defined area and sharing a common gene pool
Predator	free living organisms that kill and consume other animals
Proliferation	large and rapid increase in numbers

Recirculating system	system in which water is re-used for culture; usually involves some form of filtration and purification to remove waste products
Redox potential	measure of the oxidizing or reducing power of a water or sediment; negative values indicate reducing conditions and positive values indicate oxidizing conditions
Salinity	measure of the amount of dissolved inorganic minerals in water
Seaweed	marine macroalgae; usually found attached to substrate below high water mark
Sediment	the organic and inorganic matter accumulated on the bottom of a body of water
Shellfish	aquatic shelled molluscs and crustaceans
Smolts	juvenile salmonids which are in the process of leaving fresh water and migrating to the sea; characterized by physiological changes necessary for survival in the marine environment
Turbidity	measure of water clarity, or the degree to which water is opaque, due to suspended silt, sediments, and/or biological particles

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EXECUTIVE SUMMARY

This report presents a scientific review of the knowledge and gaps related to the environmental effects of marine finfish, marine shellfish and freshwater finfish aquaculture as it pertains to the Canadian context. The purpose of this report is to identify areas of knowledge based on scientific evidence; it is not to evaluate the environmental impacts or risks associated with the aquaculture industry. The project was completed as a joint effort between EVS Environment Consulting Ltd. and Canadian Fishery Consultants Ltd.

The report was prepared in support of activities of the Oceans Sector within the Department of Fisheries and Oceans (DFO). Specifically, it will be used as a guide for preparing a "State-of-Knowledge" report by DFO which, in turn, will be used to support responsibilities under the ***Fisheries Act*** and the ***Oceans Act***, identify strategic research directions, and communicate aquaculture science to broader audiences within and outside of DFO.

Areas of knowledge were identified based on a review of existing literature provided in a DFO reference database containing over 600 references. Each paper was evaluated based on standardized criteria to ensure relevance and acceptable scientific quality. Knowledge gaps were identified based on uncertainties recognized in the referenced literature.

EFFECTS KNOWLEDGE: MARINE FINFISH

Feed and Organic Waste

Waste production from marine net-pen finfish operations has been covered extensively in the literature referenced in the database, with studies originating from Canada, the United States, Europe, Africa, Asia, and Australia. These studies have found that, in general, inputs of organic waste material from aquaculture facilities can lead to changes in the physical, chemical and biological environment. However, these impacts are generally localized, with effects observed near the vicinity of the fish farm. Additional findings include:

- Industry practices (feed composition; feeding methodology; net-pen configuration; feeding behaviour of the stock; time of feeding; number of fish) and site-specific environmental factors (bottom topography, depth of water; current velocity; water column density and ability of the surrounding biota to assimilate the waste solids) are important factors determining waste accumulation.
- Physical evidence of waste accumulation is commonly observed beneath marine fish farms, including the presence of undigested feed pellets, fish fecal matter, patches of black reducing sediment and mats of the bacteria *Beggiatoa.*
- Accumulation of waste material below the net-pens often leads to organic enrichment of the underlying sediments resulting in chemical changes in the bottom sediments,

with the detrimental impact of organic pollution from fish farms generally limited to sediments in the immediate vicinity of the fish cages; however, some studies have also reported the absence of any effects on the sediment chemistry.

- Organic carbon levels in sediments beneath fish farms may increase to levels 4 – 5 times higher than background levels.
- Accumulation of organic waste below fish farms may lead to an increase in the oxygen demand of the underlying sediments, which may lead to depressed oxygen levels in the overlying water; however, a survey of several B.C. farms found that, in general, the entire water column remained well-oxygenated.
- While increased sedimentary hydrogen sulphide (H_2S) is sometimes observed, available literature appears to agree that H_2S toxicity in the water column is not a significant problem and is only likely to occur under certain conditions (i.e., sediment is extremely polluted, hydrographic conditions permit vertical currents, or in shallow water depths).
- Nitrification processes are often affected in organically enriched sediments located beneath fish farms.
- Increases in nutrient concentrations, especially ammonia, in the water column in the immediate vicinity of fish farms.
- Anoxic conditions that result from organic enrichment can enhance the exchange of nutrients between the sediments and the overlying water (phosphorus, in particular, is typically released from sediments at faster rates under anaerobic conditions).
- Nutrient enrichment of waters in the immediate vicinity of a fish farm has lead to increased phytoplankton growth in nutrient-deficient areas; however, there appears to be agreement that it is unlikely that marine fish farming will cause eutrophication on a large scale.
- An extreme case of eutrophication was reported in the southern Kattegat, where the observed changes to the environment included changes in macrophyte species, mortality of benthic macrofauna due to oxygen deficiency, and the disappearance of fish below the halocline.
- The incidence of harmful algal blooms and resulting fish mortality has been documented in many countries around the world, including Scotland, Norway, Canada and New Zealand.
- Elevated levels of zinc, copper, and manganese originating from aquaculture operations have been detected in underlying sediments.
- While one study did not detect any significant changes, it has been generally found that organic loading at marine fish farms has a detrimental effect on the benthic

community. Changes in benthic community structure have been reported in the sediment surrounding fish farming operations in Europe, Asia, US, and Canada. Changes in benthic community structure include:

- Macrofaunal species richness decreases near aquaculture operations; echinoderms are generally the first species to disappear and demonstrate the largest decrease in abundance; pollution-tolerant species, such as nematodes and/or polychaetes increase in species dominance.
- Elevated abundance of pollution-tolerant species may result in an increase in total benthic abundance; however, benthic abundance may also decrease and in extreme conditions, result in complete loss of organisms.
- Macrofaunal biomass is highly dependent upon the size and density of opportunistic species and no consistent relationship with levels of organic enrichment has been demonstrated.
- Impacts to benthic communities are relatively localized and confined to the immediate area surrounding the fish farm operation.
- Impacts to benthic communities generally occur quite quickly in the immediate vicinity of a fish farm (as soon as 3 months after farm establishment).
- Variable recovery rates of the macrobenthic community occur following farm removal.
- Responses of the benthic community are generally a better indicator of effects than sediment chemistry.

Use of Chemicals

One Canadian study was reviewed which examined the effects of antifoulants. This study measured water column concentrations and found no significant differences between concentrations of copper concentrations inside and outside of the fish farm net. Tidal exchange was identified as the likely factor responsible for maintaining the low copper levels. No other studies were reviewed which examined effects from antifoulants used in Canada. Several studies were reviewed that documented adverse effects of the antifoulant tributlytin (TBT). This compound is not used in Canada and is not discussed; however, there is extensive literature regarding its effects. Pesticides (dichloros, pyrethrum, hydrogen peroxide, azamethiphos and cypermethrin) and the drug ivermectin are used in the aquaculture industry to treat sea lice. Results from studies have found:

- Rapid dispersion of dichlorvos.
- Estimates of half-life for dichlorvos range from 1-30 days depending on temperature, pH, and salinity.

- Ivermectin is less readily dispersed than dichlorvos; persistence has not been measured directly but, based on its characteristics, researchers suggest that it could persist for weeks or months in sediments.
- No significant acute effects were found in shrimp when exposed to ivermectin in seawater, but mortalities observed when ivermectin was present in food.
- Pyrethrum degrades very quickly, but its impacts on the surrounding lobster and other crustacean populations needs to be evaluated.
- Shrimp and lobster were most sensitive to hydrogen peroxide.
- In toxicity tests, lobster and shrimp have been shown to be sensitive to azamethiphos and cypermethrin.

Oxytetracycline and two potentiated sulfonomides (Romet and Tribussen) are registered for use as antibiotics in Canada. No Canadian studies were reviewed which examined potential adverse environmental effects of these chemotherapeutants. Results from international studies have found:

- Localized spatial distribution of oxytetracycline in sediments beneath fish farms.
- Persistence of oxytetracycline in sediments, this varies depending upon site-specific environmental conditions and the amount of antibiotic administered.
- Persistence of sulfadiazone and sulfadimethoxine in laboratory sediments.
- Changes in sediment bacteria communities were associated with some antibiotics.
- Drug residues in wild fish and shellfish.
- Oxytetracycline-resistant bacteria in sediment, farmed fish, wild fish and blue mussels in vicinity of fish farms; however, researchers warn that caution needs to be applied when interpreting data on resistance frequencies in farmed fish and sediments because analytical methods and reporting of results have not been consistent.

Cultured and Wild Species Interactions

Disease transfer between cultured and wild salmon stocks is a significant concern of salmon aquaculture in Canada and worldwide, and may occur through a number of different mechanisms: 1) from the interaction of escaped farmed fish with wild stocks, 2) the transmission of pathogens present in fish farms through the water column, or from sediments, to local wild stocks, and 3) interaction with avian predators in coastal areas.

The majority of the studies included in the literature database are related to the pathogenicity of diseases affecting aquaculture. Limited information is provided on assessing the effects of diseases in farmed fish on wild populations. Canada does not have a structured disease surveillance program to assess the prevalence of disease in wild fish, which makes it problematic to determine any relationship regarding the transmittance of disease between farmed and wild finfish. Recent work in Canada has demonstrated that:

- Wild fish carry many of the same pathogens as cultured populations and, in some instances, more than farmed fish.
- All of the pathogens found in farmed fish in B.C. to date are endemic to the Pacific region and have existed in British Columbia for some time.

Only a select group of diseases in aquaculture have been found to transfer between farmed and wild salmonids. Bacterial kidney disease is one of these diseases. Results from relevant studies have shown:

- *Renibacterium salmoninarum* is capable of surviving outside the host for sufficient time to ensure successful horizontal transmission to nearby salmonids.
- *R. salmoninarum* has also been found to survive in sediment/fecal matter in fish tanks for up to 21 days in the absence of fish.

Studies have also documented the transmission of infectious pancreatic necrosis (IPN) from farmed stocks to wild stocks.

Sea lice is another pathogen of concern to wild fish populations. The literature in the database pertaining to sea lice reveals that:

- There is a lack of direct evidence of lice transfer from farmed to wild salmon populations; however, preliminary evidence from Norwegian studies suggests that transfer of sea lice to wild salmonids occurs.
- Major difficulties exist in determining the route of transfer and assessing the impact of highly pathogenic disease conditions, such as sea lice, in wild fish populations.
- Experimental studies reveal that copepodids, the main infective stage of sea lice, survive for less than 10 days in water, depending on local environmental conditions.
- Pulses in the occurrence of lice larvae depend on a variety of environmental factors including hatching cues, tide, photoperiod and time of year.
- Outbreaks of *Lepeophtheirus salmonis* are reported on both wild Atlantic salmon and sea trout smolts and have caused them to return to fresh water prematurely.

In Norway, furunculosis outbreaks have been documented in both wild and farmed populations of salmonids. This disease is now present in some 20 Norwegian salmon rivers due to the escape of farmed fish. Literature pertaining to the incidence of furunculosis in

Canada reveals that it has caused significant losses in cultured salmonids over most of its range and is widely distributed across the country. The issue of the transfer of furunculosis from farmed to wild salmonids is not directly addressed in papers in the database. A study conducted in Norway by Enger and Thorsen (1992) addressed the transmittance of this disease to the environment outside a farm area. However, the study does not report the direct transmittance to wild stocks. Another study in Puget Sound found transmittance of furunculosis between pens in seawater over distances of 24 km.

Vibriosis is another bacterial disease affecting populations of farmed salmonids caused by two different species. Classical vibriosis, caused by *Vibrio anguillarum*, has been found in both wild and farmed populations of salmonids. Historically documented in Norwegian waters, this disease is thought to be widely distributed in the marine environment, However, further information about this disease or its transmission between farmed and wild fish is not available from the papers included in the database. Additional research is required to support conclusions regarding the transmission of this pathogen from farmed to wild salmon. The second bacterial species causing vibriosis, *Vibrio salmonicida*, is represented by a greater number of papers in the literature database. However, this species has not been isolated from disease outbreaks in wild salmon populations.

Geneticists are developing new techniques and understanding at an extraordinary rate and this progress is being rapidly incorporated into aquaculture in Canada. Much data on potential genetic effects of aquaculture has become available in the past 5 years with the development of new types of molecular genetic markers such and microsatellite DNA polymorphism. For the most part this new information is not reflected in the papers in the database.

Although hypothetical discussions were found, none of the papers referenced in the database presented data on potential effects of inbreeding and loss of genetic diversity in wild populations in Canada or elsewhere. Recent observational papers not included in the database have generally found the genetic impact of escapes to be small, or at least not as great as has been feared.

Data on outbreeding depression is also not well represented in the papers referenced in the database. Recent work in Norway suggests that escaped farmed salmon are relatively unsuccessful in reproductive competition for wild mates, suggesting that the rate of introgression may be lower than feared. However, considerable introgression has been found in Ireland and Norway. Introgression has also been demonstrated in Denmark. The question of whether domesticated fish can cause outbreeding depression is likely location-specific and constitutes a Canadian knowledge gap.

Investigation of escaped farmed and wild fish using genetic markers is represented by several papers in the database. These studies have detected:

- Hybridization of escaped farmed Atlantic salmon with native brown trout in Scotland.
- Spawning of escaped salmon in Scottish, Icelandic and Norwegian rivers.
- A high proportion of farmed fish in some rivers, including one river in New Brunswick.

However, experimental and observational work on the effects of domestication on competitive and reproductive success of escaped fish (and by implication, on the fitness of hybrids and the rate of gene flow from cultured fish into wild populations) is not well represented in the database. Additional highly relevant papers do exist and should be reviewed.

None of the papers demonstrate effects from aquacultural transgenics. Several papers express concern and others predict reduced reproductive abilities based on characteristics in behaviour and physiological properties. A recent experimental study conducted in Canada concluded that transgenic salmon pose relatively low threat to wild salmon since they are likely to starve in nature.

Increased virulence has been found for non-native strains of pathogens introduced into new habitats. However, no documentation of genetic impacts from increased virulence of natural pathogens was provided in the papers referenced in the database.

Disturbance and Predator Control Activities

Limited information exists pertaining to the effects of aquaculture on birds and mammals. While disturbance as a result of aquaculture operations may have some effects, researchers generally suggest that predator control activities likely pose a greater impact. No studies were reviewed that documented the effects of using non-lethal predator control methods. Kills of harbor seals and sea lions, the major predators of farmed fish, were reported to be 3854 between the years of 1989 and 1996.

EFFECTS KNOWLEDGE: MARINE SHELLFISH

There has been increased emphasis on the production of cultured shellfish and other marine invertebrates worldwide to meet demand for human consumption and export. A variety of species are currently being cultured in Canada, including mussels, oysters, clams, urchins, scallops, and quahogs. As with finfish culture, there are numerous concerns associated with the culture of shellfish. However, limited papers pertaining to shellfish aquaculture were included in the reference database. A few of the papers that were included discussed the integration of shellfish aquaculture with fish farms as a mechanism to address concerns of organic enrichment. Other papers documented environmental degradation in Southeast Asia due to intensification of marine shellfish aquaculture. In contrast to the experience in southeast Asia, culturing of mussels (*Mytilus edulis*) in northwest Spain has shown generally positive environmental results, with increased seaweed production and healthy epifaunal community. Only one study referenced in the database examined the potential effects of chemical use on shellfish populations and this study evaluated the use of a compound (TBT) which is not currently used in Canada.

EFFECTS KNOWLEDGE: FRESHWATER FINFISH

As for marine aquaculture, a key concern related to freshwater aquaculture is the generation of organic wastes. Major environmental concerns include the production of anoxic sediments underlying the net-pens or at effluent discharge points, due to high loading of organic wastes and the nutrient-induced stimulation of local algal blooms in surface waters (eutrophication). Most of the published environmental studies for lake cage-culturing of temperate fish species, specifically salmonids, are from European waters where freshwater fish farming has been established and rapidly growing for more than two decades

All studies agree that there is a correlation between waste output and the quantity of feed applied. Much research has been conducted on feed formulations to reduce the dependency on fish meal-based diets, to enhance digestibility and reduce waste nutrients, and to reduce phosphorus levels in diets. Research has found that modern feed formulations have significantly reduced the quantity of wastes and represent highly digestible and nutrient-dense diets for farmed fish.

The release of nutrients from organic waste can lead to enhanced primary production; however, the correspondence between the magnitude of input and effect is not linear, and is affected by environmental variables and the other inputs and conditions associated with the aquaculture operation. Often, input of nutrients from aquaculture waste can cause an ecosystem-level shift towards higher system production and net heterotrophy by enhancing the long-term cycling of nutrients through primary production and biomass remineralization.

The ratio of several nutrients, rather than their quantities, may be a major factor influencing the species composition of the phytoplankton. The solid waste from fish farms (which is high in P) released over long time periods, can cause a persistent ecosystem-level shift to a dominance of cyanophytes. The cyanophytes modify the abundance of all other primary producers by reducing available light. The influences of environmental variables in mediating the interaction between N and P, the ratio of available nutrients, and species composition of the phytoplankton have not been adequately addressed.

Phosphorus release from fish pens is largely in the form of particulates, which sink and enrich the sediment community immediately below the fish pens. The leaching of soluble P from sedimenting food pellets can be significant, up to 12% in a 30 m water column.

Anticipated impacts of nutrient loading and sedimentation (in the limited number of studies provided) were found to be less severe than expected and within the assimilative capacity of the receiving water body. However, it is important to recognize that freshwater aquaculture operations have been relatively modest in size, especially in comparisons with marine net-cage. Consequently, it is difficult to predict the potential environmental impacts of larger systems based on the experience of the existing systems.

The effects of effluents on biotic systems are poorly represented with respect to freshwater aquaculture. Limited information suggests that effects on wild fish population abundance is variable, with some populations decreasing and others increasing as they capitalize on waste feed.

Fish farming, like most other forms of husbandry, has experienced disease problems, which arise out of increased holding density conditions and other conditions that may facilitate pathogens. No Canadian studies were included in the database that assessed the fate and effects of chemotherapeutants.

The antibiotic resistance of the microflora surrounding fish farms is poorly understood. However, one Danish study found resistance to oxytetracycline to be 15% higher in fish farm waters compared to a control stream. Studies have also demonstrated the importance of consistent methodology in evaluating the presence of resistant strains.

Research has also been conducted on detecting stress levels in order to gain a better understanding of fish stressors. Relevant studies referenced in the database were not successful in identifying useful parameters for detecting stress levels in cultured fish.

Limited information was provided on potential ecological effects of interactions between cultured and wild fish populations. One study referenced found that biological interactions between farmed and wild species may limit the rearing success of wild species in natural systems. The review of cultured and wild species interactions and genetic impacts was considered to apply equally to both fresh and marine environments as discussed above. No papers were identified in the reference database that examined the effects of disturbance or predator control activities on natural systems or animals.

KNOWLEDGE SUMMARY

The majority of the references cited in the database pertained to marine finfish. Several references were included that examined the effects of freshwater aquaculture. However, very few studies pertained to shellfish aquaculture. Impacts of organic waste on the water column, sediment chemistry and benthic organisms received the greatest attention. Some information on the effects of chemicals used in aquaculture was present but, in general, evidence of the fate and effects of chemicals used in Canadian ecosystems was not provided in the referenced literature. Several references identified concerns of disease and genetic impacts, but few provided documented evidence. Limited information was also available regarding effects on aquatic biota other than benthic invertebrate communities and wild fish populations.

Most studies assessed the effects on specific populations and in some cases, communities. The majority of relevant studies also examined near-field effects over relatively short time periods. Very few studies were identified that examined effects over longer terms or examined cumulative impacts of multiple farms or other human activities. Similarly, with one exception, comprehensive integrated assessments which examined ecosystems in their entirety were not found in the referenced literature.

1. INTRODUCTION

1.1 PROJECT OVERVIEW

Aquaculture was first used in Canada to enhance natural fish stocks. Commercial aquaculture production began in the 1950s, and has now become a large-scale industry across the country. The aquaculture industry provides benefits to many local and regional economies across the country. For example, in 1999, the Canadian commercial aquaculture industry generated over a hundred million dollars in revenue (DFO, 2000). All ten provinces and the Yukon Territory currently have a stake in commercial aquaculture and interest is increasing in the Northwest Territories (DFO, 2000).

The expansion of the aquaculture industry in Canada has led to an increased concern regarding potential impacts to marine and freshwater ecosystems. These include the accumulation of large amounts of organic and inorganic waste, the fate of antibiotics and other chemicals used in the industry, effects on wild stocks from interactions with cultured fish, and impacts to other wildlife through predator-control activities. While concerns have been raised for some time, a recent FAO newsletter identified a shortage of accurate and generally applicable information and scientific tools to support regulatory actions in the area of aquaculture-environment interactions (FAO, 1999). The article also identified "a growing and urgent need to create new knowledge and to synthesize information from a broad spectrum of disciplines so that decisions can be based on a much broader perspective and understanding (FAO, 1999)."

The Environmental Science Branch of Department of Fisheries and Oceans is developing a "State-of-Knowledge" report on the environmental effects of the aquaculture industry. This report will be used to identify strategic research directions, support responsibilities under the ***Fisheries Act*** and the ***Oceans Act*** (Section 1,2), and provide a knowledge-base for communicating aquaculture science.

In support of the "State-of-Knowledge" initiative, this report represents a scientific review of the relevant literature pertaining to the effects of aquaculture on the marine and freshwater environments. The intent of this "Knowledge and Gaps" report is to identify areas of knowledge and areas of uncertainty as documented in the scientific literature. The review focuses on "effects" information. Management strategies (e.g., husbandry practices), environmental interactions which may impact aquaculture activities (e.g., impacts of climate change on aquaculture; wild-farm disease transfer, etc.) and socio-economic impacts (e.g., user conflicts, employment) were not within the scope of this study.

A number of reviews have been conducted in the past. This review differs from those earlier efforts as it:

- Provides an "up-to-date" integration of available scientific evidence.
- Incorporates a broad coverage of environmental science pertaining to marine and freshwater aquaculture.
- Involves a transparent systematic approach for documenting supporting evidence for determining what is known, the associated level of uncertainty and where information gaps exist.
- Incorporates a peer-review process.

1.2 PROJECT CONTEXT: CLIENT'S NEEDS

As indicated, this review will be used to support research and communication activities within DFO, including supporting the agency in fulfilling it's responsibilities under the Canada ***Fisheries Act*** and ***Oceans Act***. Under the ***Fisheries Act***, DFO is responsible for the administration of the fish habitat protection provisions. The main provision dealing with the protection of fish habitat is Section 35 which states that: "No person shall carry on any work or undertaking that results in the harmful alteration, disruption or destruction of fish habitat". However, this prohibition can be lifted by regulation or authorization by the Minister of Fisheries and Oceans. Criteria for determining when harmful alteration, disruption or destruction of fish habitat (HADD) occurs as a result of aquaculture operations has been identified as an important research priority.

Under Canada's ***Oceans Act***, DFO is identified as the lead agency responsible for developing and implementing a National Oceans Management Strategy (OMS) for guiding marine conservation and development activities. The OMS is to be developed with the involvement of stakeholders and is to be based on the principles of sustainable development, integrated management and the precautionary principle. Implementation of the OMS is to occur through development and implementation of regional integrated management plans which take into account the interests of all users and all coastal activities. With respect to aquaculture, important research priorities as identified by DFO representatives for supporting its responsibilities under the ***Oceans Act*** include:

- Assessment information on ecosystem-level effects of aquaculture.
- Additional scientific evidence for guiding operation siting.
- Assessment information for determining assimilative capacity.
- Identification of tools and parameters for measuring marine environmental quality.

1.3 OBJECTIVES OF THE "KNOWLEDGE AND GAPS" REPORT

The purpose of this present study is to provide background material for supporting the development of a "State-of-Knowledge" report and subsequent identification of priority areas for research. This study reviews existing scientific data on the effects of aquaculture (freshwater and marine) on the environment and documents what information is known and where significant gaps in knowledge exist. The specific objectives of the "Knowledge and Gaps" report are:

- Integrate current knowledge on the environmental effects of freshwater and marine aquaculture using documents relevant to Canadian aquatic ecosystems.
- Identify gaps in knowledge based primarily on uncertainties or possible research avenues suggested in the literature.
- Discuss the scope of application of the results to the industry in general.
- Present this information in a scientifically credible document that will provide DFO with a solid basis for decision-making and action.

1.4 PROJECT METHODOLOGY

A reference database containing scientific information relevant to this project was developed by the DFO in January 2000. The database references information in Microsoft Access from a wide array of sources, including scientific-refereed journals, and open, or gray literature. The purpose of this study was to extract pertinent information from the literature cited in the database. The identification and evaluation of relevant literature and/or collection of papers not referenced in the database was outside the scope of work.

A number of additional fields were added to the database to expand the information provided for each paper. Specific information included the abstract, study location, species and water environment (i.e., marine, freshwater, brackish). A number of keywords were also entered to facilitate the extraction and integration of information for this report.

Articles and reports included in the database were evaluated according to their level of scientific quality and relevance to the Canadian aquaculture industry. A guidance document for evaluating the papers and entering key information into the DFO literature database was prepared to ensure that the evaluations were conducted using a standardized procedure. Criteria for defining relevance and scientific quality were developed in collaboration with the Project Authority and entered into the database for each paper. Relevance and scientific quality ratings are provided in Tables 1 and 2.

Table 1: Relevance Rating Scale.

RATING	LEGEND
1	Canadian study on species cultured in Canada with experimental or field conditions relevant to current aquaculture practices in Canada.
2	Study conducted outside of Canada on species that are cultured in Canada with experimental or field conditions relevant to current Canadian aquaculture practices.
3	Study on species cultured in Canada with experimental or field conditions no longer relevant to Canada.
4	Study on species not cultured in Canada, but the results have some relevance to Canada.
5	Study on species not cultured in Canada, but the study approach could be adapted to Canada.
6	Study on species not cultured in Canada and whose study approach could not be adapted to Canada.
7	Does not provide scientific data on the environmental effects of aquaculture.

High Relevance (1) - Zero Relevance (7).

Table 2: Scientific Quality Rating Scale.

RATING	LEGEND
1	Study which is representative (applicable to other sites and conditions), comprehensive (results and conclusions are well-supported by the data) and sound (uses valid research approach and methods) and is included in a peer-reviewed scientific journal.
2	Study which is included in a peer-reviewed scientific journal; content is sound (uses valid research approach and methods), but may be less representative and/or less comprehensive.
3	Study not included in a scientific journal, but is otherwise peer-reviewed; content is representative (applicable to other sites and conditions), comprehensive (results and conclusions are well-supported by the data) and sound (uses valid research approach and methods).
4	Non-reviewed materials that add substantial information to peer-reviewed material; content is representative (applicable to other sites and conditions), comprehensive (results and conclusions are well-supported by the data) and sound (uses valid research approach and methods).
5	Non-reviewed material that does not add substantial information to peer-reviewed material.
6	Material other than that described by ratings 1-5.

High Scientific Quality (1) - Low Scientific Quality (6).

Information from papers with high relevance (i.e., 1-3) and high scientific quality ratings (i.e., 1-4) was used to identify areas of knowledge and areas of uncertainty. Papers with low scientific quality ratings (i.e., 5, 6) were not included in the information review. References with relevance ratings of 4 or 5 were incorporated if they were of suitable scientific quality (i.e., 1-3) and had the potential for application in Canada or provided information in subject areas with limited documentation in the other papers. Papers with relevance ratings of 6 were deemed irrelevant in the Canadian context and were not included in the information review. Papers with relevance rating of 7 were also considered irrelevant to this study as they did not provide scientific information for evaluating the environmental effects of aquaculture on the environment. Generally, the reasons for excluding reports included the following:

- The paper does not pertain to effects on the environment (e.g., the use of aquaculture as a treatment method for domestic sewage).
- The paper is not science-based, but provides information pertaining to management, policies and regulations.
- The paper is not deemed scientifically credible (e.g., is comprised of conference presentation material such as overheads).
- Foreign papers with species not cultured in Canada and whose practices are not applicable to current Canadian aquaculture industry.
- The paper does not add anything to the general knowledge of aquaculture in Canada (i.e., too general or too basic).
- The focus of the paper is too specific and does not providing sufficient linkage for indicating or assessing potential effects (e.g., production rates of metabolic waste under different conditions without an indication of rates that lead to effects).

It is important to note that the relevance classification reflects the applicability of the contents to the specific objectives of this project (i.e., scientific review of areas of knowledge of the effects of aquaculture on the environment). Certainly, many papers considered irrelevant to this report provide useful and important information regarding other aspects of the aquaculture industry (e.g., industrial practices, general management practices, legislation and policy, etc.). Rationale for the exclusion of each paper is provided in a separate field in the database.

Note that a number of papers dealing with waste reduction and specific management practices that reduce environmental effects were included in the database. For example, 29 papers addressed some aspect of waste reduction (e.g., farm siting, feed formulation, waste treatment). Because the focus of these papers fell outside the scope of this report (i.e., the environmental effects of aquaculture), a discussion of these papers was not included in this final report.

Literature deemed of high scientific quality and relevance was compiled and integrated. Having established what is known about the environmental impacts, gaps in knowledge (based primarily on the uncertainties and possible research avenues suggested in the original papers) were identified. The results of this review are summarized in this "Knowledge and Gaps" report.

Where available, the information is provided on near-field (site-specific), far-field and cumulative effects. Information is also provided for different biotic scales, including effects on populations and communities.

As previously indicated, the information was extracted from a fixed database provided by DFO which attempted to compile references on a range of issues related to environmental effects. However, some areas were under-represented, and in other cases, more recent literature could have been included. While some improvements in the data base can be made, this report nonetheless provides a solid foundation (over 600 references reviewed) for integrating environmental effects information and identifying existing knowledge and areas of uncertainty.

1.5 REPORT FORMAT

This report is divided into six sections. This first section provides the project background, study objectives, and details on how the report was prepared, including how the literature assessment was conducted and how the information was assimilated and organized. Section 2 provides a general overview of environmental concerns that exist with respect to the aquaculture industry. The next three sections (Sections 3 to 5) summarize the scientific knowledge pertaining to environmental effects associated with marine fish, marine shellfish and freshwater aquaculture, respectively. Within each of these major divisions, the information has been organized according to the major issues identified in Section 2. Information gaps identified in the reviewed literature are provided in each of these sub-sections. The final section summarizes the areas of knowledge and where additional information is desirable.

2. ENVIRONMENTAL ISSUES OF CONCERN

This section provides an overview of the major environmental concerns regarding the marine and freshwater aquaculture industry. It is not part of the scientific review of material, but is a general introduction to the major issues of concern.

2.1 FEED AND ORGANIC WASTE

The generation of organic wastes from uneaten feed and fish fecal matter is a major concern in marine and freshwater aquaculture. Fin- and shell-fish aquaculture produces organic wastes, the bulk of which are in the form of feces and uneaten feed settling out of net-pens or effluent to the sediments (Beveridge, 1984). Soluble products of food and excretion are also present. Mortalities in cultured organisms further contribute to organic waste loadings.

In marine waters, aquaculture farms are often open rearing systems that permit the continuous exchange of water between the pens and the surroundings. This means that waste products easily pass through the nets into the surrounding environment. Similar concerns exist regarding the release of waste in the form of effluent and sludge from intensively managed fish farms in freshwater systems.

Much of the organic waste is directly linked to the quality and quantity of fish feed provided. Generated waste material may break down or become dissolved in the water column, be consumed by wild fish and other organisms, or settle on the bottom sediments. Dissolved organic carbon and other nutrients (nitrogen and phosphorus) may be released to surface waters surrounding the farm sites by solubilization of feed and feces and through the gill and urinary excretions of the fish. Large inputs of organic waste material from aquaculture facilities can lead to changes in the physical, chemical and biological environment.

Among the major environmental concerns are the production of anoxic sediments underlying the net-pens or at effluent discharge sites. High loading of organic wastes may elevate oxygen demand which may, in turn, deplete oxygen concentrations and lead to anoxia in the sediments and/or the overlying water column. Under anoxic conditions, degradation of organic materials shifts from aerobic processes to anaerobic processes and sulphate reduction by bacteria becomes the dominant energy process for the breakdown of organic carbon. Activity of methanogenic bacteria within the sediment can also be increased. The decomposition of organic material under these anaerobic conditions may produce gases, including carbon dioxide (CO_2), methane (CH_3) and hydrogen sulphide (H_2S). The release of these compounds from the sediments into the water column is known as sediment outgassing. All three of these gases may be toxic to fish and other aquatic organisms. Concerns also exist regarding potential impacts to benthic invertebrates due to sedimentation of waste material combined with the above changes in sediment chemistry. These processes may lead to smothering of the benthic community and alterations in the benthic environment that reduce its desirability as habitat.

High loadings of organic waste can also increase levels of nitrogen and phosphorus in the bottom sediment and surrounding water column. With increases in nutrient loading, concerns exist that fish farming may to lead to eutrophication of local waters. Eutrophication occurs when the conditions of a water body change towards a more nutrient-rich state (e.g., nutrient loading) and include a multitude of environmental alterations. Among these changes are increased phytoplankton and/or filamentous alga production and associated biomass that result in an increased flux of organic matter to the sediment surface. The biochemical decomposition of this organic matter subsequently causes an increased consumption of oxygen. A significant biochemical oxygen demand may cause a shift in the chemistry of the benthic environment to anaerobic conditions, as well as possible changes in the benthic community composition and diversity. An increase in turbidity may also result from higher phytoplankton abundance which, in turn, causes decreased light penetration into the water column and, therefore, a shallower zone of photosynthetic production. Concerns also exist that blooms of certain algal species may occur which are harmful to aquatic organisms.

Another issue regarding feed involves the utilization of wild fish stocks to manufacture fish meal for cultured fish. Concerns have been expressed that continued increases in aquaculture production and use of wild stocks for fish feed may result in the depletion of natural fish resources.

2.2 USE OF CHEMICALS

Concerns exist regarding the persistence and effects of chemicals used in the aquaculture industry. Chemicals commonly used in industry aquaculture include pesticides, disinfectants, antibiotics, and chemotherapeutants. These compounds are used to prevent and treat disease, control aquatic pests and protect farm infrastructure.

Due to the large-scale production and economic importance of salmon on both coasts of Canada, there has been a need to find suitable medicinals to keep salmon disease- and parasite-free. A common problem to the industry is the infestation of sea lice (parasitic copepods *Lepeophtheirus salmonis* and *Caligus elongatus*). Sea lice are natural parasites that can heavily infest farmed salmon. Sea lice feed on the mucus, skin and blood of salmon causing reduced growth, wounding and mortalities. Infestations of these parasites have been treated with baths of hydrogen peroxide, pyrethrins, dichlorvos or azamethiphos (Haya et al., 1999). Ivermectin, administered through fish feed, has also been used to address sea lice.

Many antibiotics are also currently being used in the aquaculture industry to prevent or control disease. The most commonly used antibiotic is oxytetracycline. Other antibiotics include oxolinic acid, furazolidone, flumequine, sarafloxacin, florfenicol, sulfadiazine and trimethoprim. The widespread use of antibiotics to combat disease in fish has led many to become concerned about the development of drug-resistant bacteria. In particular, there are concerns about the ability of bacteria to transmit resistance to other bacterial species (particularly fish and human pathogens) through transfer of DNA by means of plasmids and the ability of some bacteria to develop resistance to several drugs after being exposed to a single drug (i.e., cross-resistance).

Although not widely practiced, antifouling paints have also been used to control the growth of fouling organisms, such as algae, on farming equipment (Davies et al., 1986). The accumulation of fouling organisms on net-pens may interfere with the necessary water exchange between the pens and the sea, resulting in detrimental effects to cultured fish. Fouled nets are typically cleaned by pressure washing or scrubbing. However, paints containing biocides such as copper have been used to treat sea pens in order to prevent the accumulation of biological fouling organisms and, therefore, the need for net cleaning. These biocidal compounds slowly leach from the paint into the surrounding seawater, producing toxic concentrations near the treated surface that prevent fouling organisms from attaching to the nets. However, concerns exist that the leaching of biocides into the surrounding waters may also cause toxicity to non-target organisms.

2.3 CULTURED AND WILD SPECIES INTERACTIONS

Additional concerns exist regarding the effects of farmed species on wild stocks, especially with respect to natural salmonid populations. The incidence and transfer of disease is one key concern. A higher incidence of disease within farms often arises as a result of increased holding densities conditions and other conditions suitable for propagating pathogenic organisms. In addition to necessitating the use of antibiotics and therapeutants as discussed above, there is concern about the potential for disease propagation and transfer from cultured fish to wild stocks (Noakes et al., 2000; Subasinghe, 1997). The use of non-indigenous species for fish culture (e.g., Atlantic salmon on the Pacific Coast) also raises concerns regarding the introduction of new diseases to wild stocks. Another concern involving the interaction between wild and cultured fish is predation by the caged fish on wild stocks and aquatic invertebrates attracted to the pen structures.

The potential effects of escaped cultured fish also raise serious concerns. In addition to a potential increased exposure to disease, escaped cultured fish raise concerns of possible ecological effects, including competition with wild stocks for resources (e.g., spawning habitat and food) and predation on native species. Further concerns also exist regarding potential genetic changes in wild populations from inbreeding with cultured stocks.

2.4 PREDATOR CONTROL ACTIVITIES

Because they contain large densities of cultured fish and shellfish, aquaculture farms can attract several species of mammals and birds. Wild fish found near the pens and fouling organisms growing on pen structures are additional nutrient sources that can attract a variety of biota. To protect the cultured species and minimize equipment damage, aquaculture operators have utilized a variety of methods to deter wildlife from the pens. Methods have included scare tactics (dogs, guns, noisemakers, underwater acoustic deterrent devices), physical barriers (nets, electric fencing), as well as trapping and shooting. In addition to direct mortalities, there may also be potential effects on wildlife from disturbance. Potential effects on the migration behavior of marine mammals, including orcas, seals and porpoises, are a particular concern in Canada.

3. EFFECTS KNOWLEDGE: MARINE FINFISH

3.1 FEED AND ORGANIC WASTE

Waste production from marine net-pen finfish operations is covered extensively in the literature referenced in the database, with studies originating from Canada, the United States, Europe, Africa, Asia, and Australia. The bulk of waste discharged from fish farm operations is in the form of uneaten feed and feces (Brooks, 1996). The composition of organic waste from marine net-cage operations includes all of the compounds in fish food, together with fecal material and the by-products of metabolism. Waste may include unconsumed feed (carbohydrate [18%], lipid [14-17%] and protein [46-51%]), metabolic byproducts (ammonium, urea, bicarbonate), phosphate, pigments, vitamins, and therapeutants (Fivelstad et al., 1990; Gowen and Bradbury, 1987).

3.1.1 Amount of Waste Produced

Several studies report that the intensive cultivation of salmonids in sea-cages generates considerable amounts of solid organic matter and high levels of nutrient loading (Henderson et al., 1997; Johnsen et al., 1993; Ye et al., 1991: Thomson, 1987), with feed wastage one of the most important contributing sources (Seymour and Bergheim, 1991). The literature reviewed reported a range of 1 to 30% uneaten food generated due to overfeeding or to using feed methods that do not optimize ingestion (Beveridge et al., 1991; Gowen and Bradbury, 1987; Thomson, 1987). Dry food, which is the dominant type used on the Pacific Coast, has a loss of approximately 1 - 5% (Beveridge et al., 1991; Gowen and Bradbury, 1987). The upper range of uneaten food (30%) occurs when trash fish is fed; however, this method is not commonly used in Canada (Beveridge et al., 1991; Thomson, 1987). It is important to note that the data used to derive these conclusions is largely from tank and pond farms. Several authors suggest that the wastage at sea-cage farms is likely to be in excess of these values (Pillay, 1992; Gowen and Bradbury, 1987; Braaten et al., 1983). Braaten et al. (1983) estimated feed losses at approximately 20% for marine cage farming using salmon. Gowen and Bradbury (1987) noted that estimates of uneaten food have ranged from 20 - 31% for cage-reared salmonids. Gowen et al. (1991) suggest that without recourse to site-specific studies, the best estimates for organic waste production are estimates of total organic carbon based on feeding rate: 22% retention of carbon by the fish and total loss of 78% carbon (50% soluble) to the environment.

A few review papers cited in the database discuss the quantity of fecal material produced from marine net-pen operations; however, as these are review papers, limited data are provided to support the estimates. There appears to be agreement in the international studies reviewed which suggest that between 25 - 30% of food ends up as feces (Beveridge et al., 1991; Gowen and Bradbury, 1987; Ackefors, 1986). However, in his article on waste pollution in British Columbia, Thomson (1987) predicts the percentage of waste produced from farms is greater than the international studies, with fecal production as high as 50% of the feed consumed.

The total amount of waste produced from marine fish farm operations has been quantified in a number of documents. In a summary article on Canadian waste pollution, Thomson (1987) estimates the total amount of solid wastes (including unconsumed feed and feces) produced per kg of fish to be 0.7 kg. Brackett and Karreman (1998 as reported in Linehan 2000) report mortality at chinook and Atlantic salmon farms in B.C. at rates of 18% and 21% (e.g., 0.18 and 0.21 kg waste fish per kg of fish produced), respectively. Using these estimates, the total waste produced per kilogram of salmon produced in Canada can be calculated at approximately 0.9 kg. However, despite this high production of waste from fish farms, several authors note that significant organic loadings to the sediments from fish farms are usually localized to the area immediately below the pens (Hargrave et al., 1997; Wildish et al., 1993; Hall et al., 1990).

The addition of excess nutrients to the environment as a result of fish farms has also been studied. Nutrient losses of approximately 78% (55% as dissolved) carbon (C), 72% (51% as dissolved) nitrogen (N), and 78-82% (27-34% as dissolved) phosphorus (P) of food input from both freshwater and marine cage systems have been measured (Hall et al., 1990; Hall et al., 1992; Holby and Hall, 1991). One Canadian study adopted an ecosystem-level approach and examined loading of BOD, carbon, nitrogen and phosphorus from aquaculture and other sources to the Letang system in the Bay of Fundy (Strain et al., 1995). In this inlet, salmon aquaculture contributes the majority of the anthropogenic inputs of N, P, and BOD, and as much C as the fish processing plant. Despite comprehensive analyses of relative inputs, the authors concluded that impact analyses were not possible due to uncertainties in estimating the rate of net outward flushing of inlet waters and a limited understanding of biogeochemical processes within the inlet.

Several international studies have quantified the amount of nutrients added to the environment as a result of fish farming (Enell, 1995; Ackefors and Enell, 1994; Enell and Ackefors, 1992; Seymour and Bergheim, 1991; Ackefors and Enell, 1989; Gowen and Bradbury, 1987). Seymour and Bergheim (1991) reported pollution loading from a typical Norwegian net-pen farm as 500 kg BOD, 52 kg total nitrogen and 9 kg total phosphorus per tonne of fish produced (based on a feed conversion ratio of 1.5). Gowen and Bradbury (1987) estimated that a salmon farm with an annual production of 50 tonnes produces a total of 19.4 tonnes of organic carbon waste, 2.2 tonnes of organic nitrogen waste and 4.0 tonnes of soluble nitrogenous waste over a 12-month period. Enell (1995) reported that although the annual loads of nitrogen and phosphorus from a typical Nordic fish farm decreased significantly from 1974 to 1994 (N from 132 to 55 kg/t fish produced and P from 31 to 4.8

kg/t fish produced), the total load of N and P from the Nordic fish farming industry increased 6.6 fold and 2.4 fold respectively. This increase is explained by the growth of the industry due to the development of new farms; however, Enell (1995) reported that the overall total remains relatively small compared to other anthropogenic sources of nutrients to aquatic systems, including agriculture, atmospheric deposition, municipal sewage treatment plants, and industry, among others.

Several studies have found that the presence of fish pens leads to high rates of carbon burial in the sediments (Hargrave et al., 1997; Hargrave et al., 1995; Cranston, 1994; Hall et al., 1990). The remineralization of the organic load in under-cage sediments leads to efflux rates of total C that can be 50 times those of reference sites (Hall et al., 1990).

3.1.2 Amount of Waste Accumulation

Studies have demonstrated that organic matter from marine fish farms can accumulate on underlying sediment (Tsutsumi et al. 1991; Cross 1990). Cross (1990) reported evidence of waste accumulation at fish farms in British Columbia. This accumulation of waste was evident by the presence of organic components such as feed pellets on the bottom sediment and through the effects detected on the biophysical environment.

A number of studies have found increased sedimentation rates resulting from aquaculture operations (Table 3). In a study examining several farm sites in B.C., Cross (1990) measured sedimentation rates between net-cages at the centre of each farm, as well as around the perimeter of the farm. The study found sedimentation rates from the centre of the farms ranged from 14.7 kg/m^2/yr to 35.4 kg/m^2/yr, with an average of 22.8 kg/m^2/yr. The organic component of this accumulated matter averaged 15.6 kg/m^2/yr. Cross reported a declining gradient of organic accumulation between the farm centre and the perimeter, with an average decrease to 4.9 kg/m^2/yr (Cross, 1990). Kupka-Hansen (1991) reported sedimentation rates from other studies ranging from 6 - 296 g/m^2/day. Sedimentation rates ranging from 30–52 kg/m^2/yr were detected in the vicinity of a fish farm located in Puget Sound, Washington (Weston and Gowen, 1988). Rates at a smaller farm in Puget Sound were estimated at 110 kg/m^2/yr (Weston and Gowen, 1988). However, neither of these two studies distinguished between natural sources and farm-related sedimentation.

It is evident that a large range of sedimentation estimates exists. Gowen et al. (1988) observed a three-fold difference in the quantities of material collected. The variability found is believed to be mostly due to differences in stocking density, feeding rate, and methodology (Gowen et al., 1991; Kupka-Hansen, 1991).

Table 3: Sedimentation rates resulting from marine aquaculture operations.

FARM LOCATION	SEDIMENTATION RATE ($kg/m^2/yr$)	CITATION
B.C.	14.7 – 35.4	Cross 1990
Washington, USA	110	Weston and Gowen 1988
Washington, USA	30 - 52	Weston and Gowen 1988
Not specified	2.2 – 108.0	Kupka-Hansen 1991

3.1.3 Variables Influencing Waste Production and Accumulation

The amount of waste produced and accumulated due to marine finfish aquaculture is dependent on a number of variables. These variables are briefly discussed in several international review documents (Pillay, 1992; Beveridge et al., 1991; Gowen and Bradbury, 1987), as well as two Canadian summary documents (Cross, 1990; Thomson, 1987). However, as these are summary documents, limited data were provided in support of study predictions. Of the variables discussed in these documents, those identified as most pertinent were feed composition, including digestibility and feed type (dry pellet vs. trash fish); feeding methodology; net-pen configuration; feeding behaviour of the stock; time of feeding; and number of fish (Pillay, 1992; Beveridge et al., 1991; Gowen and Bradbury, 1987; Thomson, 1987). Other external physical factors have been identified, including depth of water; current; and ability of the surrounding biota to assimilate the waste solids (Kupka-Hansen, 1991; Thomson, 1987).

In his study of 8 B.C. salmon farms, Cross (1990) concluded that bottom topography, depth, current velocity and water column density (temperature and salinity) are important physical attributes determining the potential for waste material dispersions, and thus, the degree to which these materials accumulate. Due to differences in these oceanographic conditions, Cross (1990) argues that waste impact characteristics will be different in Canada from those described in European and American studies. Salmon farming industries in European and American locations have generally been established in relatively shallow (<30 m) inlets or fjords characterized by flat bottoms. Conversely, much of the B.C. coastline is characterized by deep, well-flushed inlets and farms are often located in relatively deep water (30 to 65 m) positioned over steeply sloped bottoms. Therefore, these factors should be taken into consideration when investigating waste material dispersion in Canada.

3.1.4 Effects of Waste Production and Accumulation

3.1.4.1 Physical and Chemical Effects

Studies have found that the accumulation of waste material beneath net-pens may lead may lead to the organic enrichment of the underlying sediments (McCaig et al., 1999; Henderson and Ross, 1995; Axler et al., 1993). A number of studies have detected physical changes in sediment characteristics as a result of organic enrichment, including the presence of undigested feed pellets, fish fecal matter, patches of black reducing sediment and mats of the bacteria *Beggiatoa* (Findlay and Watling, 1994; Johannessen et al., 1994; Weston, 1991; Cross, 1990; Weston 1990). Studies have also found that the degradation of organically enriched sediments may result in chemical changes in the bottom sediments and in the overlying water column. These chemical changes may include increases in total organic carbon concentrations, depressed dissolved oxygen levels, changes in nutrients in sediments and the water column, and increases in H_2S concentrations. Each of these changes is discussed in greater detail in the following sections.

Organic Content

A number of studies have found increases in organic carbon levels in sediments beneath fish farms. Weston (1990) found sediment organic content directly beneath a Puget Sound farm to be approximately 4 times higher than levels measured 45 m away from the farm. A review conducted on monitoring data from fish farms located in southwest Scotland found sedimentary organic carbon levels to be 4 - 5 times higher than background levels at 5 of the 9 locations surveyed (Henderson and Ross, 1995). However, concentrations were variable with no consistent pattern associated with distance from the cage, site characteristics or fish farm size. A 1990 study of eight B.C. fish farms also found high variability in the total organic content of bottom sediments (Cross, 1990). Cross (1990) concluded that this variability, which ranged from 3-25% TOC, was indicative of the patchiness of waste material accumulation.

However, some studies have also reported the absence of any effects on sedimentary chemistry. Changes in sediment organic content were not observed following the establishment of a very large farm in Norway (annual production of 2200 tonnes) during its one year of operation (Johannessen et al., 1994). Weston and Gowen (1988) also did not detect any changes in sediment chemistry underneath a fish farm located in the Puget Sound, However, this farm was comparatively small (20-40 tons of fish on site) and had only been operating for a short period.

Oxygen Levels in Sediment and Water Column

A number of studies have reported an increase in oxygen demand of underlying sediments with increased organic waste accumulation (Wu, 1995; Tsutsumi et al., 1991; Kupka-Hansen et al., 1991). Oxygen consumption in sediment is reported to be a result of faunal respiration, bacterial consumption, and oxygen used in chemical oxidation of reduced compounds in the sediment (Kupka-Hansen et al., 1991). Wu (1995) found that the oxygen demand of bottom sediments beneath fish farming activities can be up to five times higher than at control sites. A study by Kupka-Hansen et al. (1991) also found a clear increase in overall oxygen consumption with increased organic waste accumulation. Tsutsumi et al. (1991) also determined that the chemical oxygen demand of underlying sediments continually increases with continual exposure to fish farm waste.

Some studies have documented the development of localized anoxic sediment conditions as a result of elevated sedimentary oxygen demand (Brooks, 1996; Cross, 1990; Gowen et al., 1991). Gowen et al., (1991) report a study that found the zero isovolt close to the sediment surface indicating the sediment was anoxic beneath the cage edge. At a distance of 25 m from the farm, the zero isovolt occurred at a depth of about 3.5 cm, indicating aerobic conditions in the upper 3.5 cm of the sediment. At the Clam Bay farm site in Puget Sound, redox measurements closely resembled gradients found in total organic carbon and total nitrogen, with values decreasing with increasing proximity to the farm (Weston and Gowen, 1990).

Increased sediment oxygen demand may lead to depressed oxygen levels in the overlying water. Deoxygenation of bottom water as a result of fish farming activity has been reported at several fish farms (Axler et al., 1993; Gowen et al., 1991; Kupka-Hansen et al., 1991; Tsutsumi et al., 1991; Thomson, 1987; Gowen et al., 1988 as reported in Gowen et al., 1991). Many of these studies found seasonal fluctuations in dissolved oxygen levels with very depressed levels occurring during summer months. Tsutsumi et al. (1991) found oxygen depletion in the bottom water at 5 stations adjacent to a fish farm in Japan every summer from 1978-1989. Rationale provided to explain the observed seasonal variation in dissolved oxygen levels included an accelerated degradation of organic matter, oxidation of reduced materials in the bottom sediment and overlying water, and stagnation of bottom water due to stratification of the water column (Tsutsumi et al., 1991). Seasonal fluctuations did not occur in sampling sites located 300 m from the farm (Tsutsumi et al., 1991).

Conversely, Cross (1990) found that, in general, the water column remained well-oxygenated at all 8 study farms surveyed in B.C. Dissolved oxygen concentrations were measured at various depths in the water column, including at the sediment-water interface. No difference in dissolved oxygen concentrations in the water column were detected at sampling stations located along the perimeter of the farm and those located more than 50 m away for 7 of the 8 farms surveyed. At the remaining site, there was no detectable reduction in upper water column dissolved oxygen concentrations, but near-bottom concentrations were significantly depleted, reaching concentrations of 3.1-3.5 mg/L. Cross (1990) attributed the marked depletion in dissolved oxygen levels at this one site to its shallow nature and limited tidal dispersion of waste material. Oxidation-reduction potential measurements also indicated that the sediment-water interface remained oxygenated. Acceptable oxygen levels ($\geq$ 4.9 mg/L) were also detected in the bottom water of a fish farm surveyed in Norway (Johannessen et al., 1994). During its one year operation, this farm produced 2417 tonnes of salmon (by comparison, 2200 tonnes of salmon were produced by all 138 farms in Norway in 1974 [Johannessen et al., 1994]). No depletion was detected in dissolved oxygen levels in water overlying the sediments beneath the Clam Bay fish farm in Puget Sound (Weston and Gowen, 1990). Brooks (1996) notes that anaerobic sediments are only likely to reduce the dissolved oxygen in overlying water at farms with very poor circulation. However, one study that adopted an ecosystem-level approach found that salmon aquaculture in the Letang system could reduce ambient oxygen concentrations by up to 12% in some bays (Silvert, 1994).

Production of Hydrogen Sulphide

Several studies have found the conditions in sediments under marine fish pens to be highly reducing and sulphidic (Wildish et al., 1999; Wildish et al., 1993; Tsutsumi et al. 1991; Wildish et al., 1990). Gowen et al. (1991) reports that the level of sulphate reduction can be sufficient to result in the release of H_2S, together with other gasses. Of the gases produced under reducing conditions, H_2S is of most concern as it is highly toxic to fish (Lumb, 1989). H_2S can be released into the water column directly from organically enriched sediments by diffusion from pore water, or by dissolving in the water column during its passage while entrained in methane bubbles (Black et al., 1996; Brooks, 1996).

A number of studies have examined the production of H_2S from organically enriched sediments (McCaig et al., 1999; Brooks, 1996; Wu, 1995; Johannessen et al., 1994; Kupka-Hansen et al., 1991; Partanen, 1986). Johannessen et al. (1994) detected the smell of H_2S and accumulation of fish feed on the sediment surface following the establishment of a Norwegian fish farm; however, changes in sediment characteristics were not observed at a station located 250 m away (Johannessen et al., 1994). Black et al. (1996) reports that there is much anecdotal evidence that the smell of H_2S has been detected at the surface around aquaculture operations but, in general, these reports have been from shallow sites with low currents. In a survey of 20 stations near the vicinity of two separate fish farms in Finland, Partanen (1986) found that, while there was no odour of sulphide, there was evidence of sulphide streaks.

Some studies that have found depressed dissolved oxygen in the water column beneath marine fish farms have also detected increased sedimentary H_2S concentrations (Tsutsumi et al., 1991; Jorgensen, 1980 as reported in Gowen et. al., 1991). Jorgensen (1980) found that depressed dissolved oxygen levels in the overlying water during the summer months were associated with an increase in sedimentary H_2S concentrations from below detection limits to 90 μmol (as reported in Gowen et al., 1991). Tsutsumi et al. (1991) found that sedimentary sulphide concentrations continually increased over a 15-year monitoring period (1975-1990) during farm operation.

Increased concentrations of H_2S in the sediment have in turn resulted in elevated levels of sulphide concentrations in the overlying water column in some instances. Brooks (1996) reports that 97.4% of the H_2S released from the sediments in bubbles is lost during passage through 3 m of water. Increased levels of water-soluble sulphide concentrations were detected directly beneath a Puget Sound farm (Weston, 1990). Conversely, as reported in Gowen et al. (1991), while Jorgensen (1980) detected increased sedimentary H_2S during summer months, the study did not find H_2S in the overlying water. This result was attributed to two factors: the growth of sulphur bacteria (*Beggiatoa* sp. and *Thiovulum* sp.), which formed a dense mat over the sediment surface, and the formation of iron sulphides by reaction between H_2S and ferric oxides.

Two studies have related the thickness of accumulated matter as a factor influencing the release of gases from enriched sediments (Kupka-Hansen et al., 1991; Lumb, 1989). Kupka-Hansen (1991) identified outgassing at sites with more than 5 cm of organically enriched accumulation. A study by Lumb (1989) found widespread acute organic enrichment and sediment outgassing under salmon farm cages and concluded that site location had a strong influence on the accumulation of organically enriched sediments. Sites located in sheltered seabeds accumulated more enriched sediments and, therefore, exhibited more sediment outgassing.

Studies have been conducted to examine fish toxicity related to H_2S released from underlying sediments. These studies have found that the bubbling of H_2S from the sediments does form a direct, negative coupling between sediment processes and fish health (Sorokin et al., 1999; Hargrave et al., 1993; Hall et al., 1990), with a probable link between H_2S outgassing and increased gill damage and mortality of farmed salmon (Lumb, 1989). However, these studies examined the toxicity to fish present in aquaculture operations and not wild fish. Burridge et al. (1999) conducted toxicity tests of sediments from four sites, three of which were directly below operational fish cages. The four sites differed in particle size, with increasing levels of silt associated with the aquaculture operations. The aquaculture sites were found to elicit the highest number of toxic responses, with sulphide and ammonia identified as the possible causes of toxicity.

However, the available literature generally agrees that H_2S toxicity in the water column does not constitute a significant problem as it is only likely to occur under certain extreme conditions (Black et al., 1996; Brooks, 1996; Lumb, 1989). These conditions include areas where the sediment is extremely polluted, where hydrographic conditions permit vertical currents (Black et al., 1996), or in shallow water depths (Lumb, 1989). Brooks (1996) also notes that if H_2S gas is being produced in sediments, those sediments are generally anaerobic and relatively depauperate. Therefore, Brooks (1996) argues that the presence of the gas imposes little additional stress because the infaunal community is already compromised. However, such conditions would likely result in loss of habitat for any associated fish communities.

Nutrients in Sediments

A recent study conducted by McCaig et al. (1999) in Scotland examined the effects of nitrification in bottom sediments due to organic waste loadings from marine fish farms. The results of the study indicated that nitrogen cycling beneath the fish cage was severely disrupted by the accumulation of nitrogen-rich organic material from the cage (McCaig et al., 1999). Other studies have also found altered nitrification processes in organically enriched sediments located below fish farms. Huettel (1990 in Wu, 1995) and Rublee (1982) both found a slow rate of nitrification in anoxic deposits underneath farms. A study by Kaspar et al. (in Wu, 1995) did not detect in-situ nitrification in sediment directly under a salmonid farm.

Where effects are detected, available literature indicates that impacts are generally localized. McCaig et al. (1999) concluded that the detrimental impacts were limited to sediments in the immediate vicinity of the fish cage (i.e., $\leq$ 10 m). Rensel (1989) also reported minor increases in dissolved nitrogen downstream of the pens.

Nutrients in the Water Column

The majority of the nutrients (>70%) supplied to finfish marine culture is lost to the environment (Kelly, 1995; Hall et al., 1992; Penczak et al., 1982). This loss is largely in the dissolved form, readily available for uptake by primary producers. In an intensive study of a marine fish cage farm in Sweden, Hall and his co-workers determined that the soluble nitrogen released from a cage was approximately 48% of the nitrogen added in food, while the sedimentation of solid nitrogen from the cage was 23% (Hall et al., 1992). In contrast to nitrogen, which is mostly in the dissolved form, phosphorus produced by fish farms are in particulate form (Holby and Hall, 1991; Hall et al., 1992). The proportions differed in the release of phosphorus to the environment, with 25 - 30% of the phosphorus added in food released as soluble phosphorus and 23% sedimented to the bottom as solid waste (Holby and Hall, 1991). Salmon aquaculture in the Letang system was found to increase phosphorus concentrations by up to 80% (Silvert, 1994).

Ammonium is the dominant form of dissolved inorganic nitrogen lost through fish excretion and through mineralization of organic nitrogen deposited in the sediments (Hatcher et al., 1995; 1994; Cranston, 1994; Hargrave et al., 1993; Wildish et al., 1993; Hall et al., 1992). A build-up of ammonium in the water is a potentially significant ecosystem-level impact. Ammonium can stimulate the production of some algal blooms, and is toxic to many animals (Hargrave, 1998). This toxicity can stress the caged fish as well as wild species. However, rapid flushing can ameliorate build-up of ammonium near the aquaculture site (Wildish et al., 1990, 1993; Stirling and Dey, 1990).

Kibria et al. (1997) conducted a study on the release of nutrients from feces into the marine environment. The study found a rapid release of phosphorus from feces, which gradually slowed down due to bacterial growth. The study concluded that the efficient and quick removal of solid waste is essential if phosphorus loading in the environment is to be controlled. It is important to note that this study was conducted at 25°C and it has been found that the rates of nutrient release increases at higher temperatures.

The anoxic conditions that result from organic enrichment may also enhance the exchange of nutrients between the sediments and the overlying water. Phosphorus, in particular, is typically released from sediments at faster rates under anaerobic conditions (Nurnberg, 1988 in Axler et al., 1993). Consequently, levels of carbon, nitrogen and phosphorus may increase in the surrounding water column as a result of soluble inputs and from nutrient exchanges with bottom sediments.

Nutrient enrichment of waters in the immediate vicinity of a fish farm may lead to increased phytoplankton growth in nutrient-deficient areas. In extreme cases, this increased phytoplankton productivity may result in an even greater flux of organic matter to the sediment and, thus, result in further changes in sediment chemistry (Baden et al., 1990). Increased growth rates and phytoplankton biomass are consequences of nutrient enrichment and eutrophication may be experienced in the vicinity of some fish farms (Pridmore and Rutherford, 1992; Aure and Stigebrandt, 1990; Pearson and Gowen, 1990). In general, there appears to be agreement that it is unlikely that marine fish farming will cause eutrophication on a large scale (Wu, 1995; Pillay, 1992; Aure and Stigebrandt, 1990). However, one study by Baden et al. (1990) depicts an extreme case of eutrophication in the southern Kattegat, where the observed changes to the environment included changes in macrophyte species, mortality of benthic macrofauna due to oxygen deficiency, and the disappearance of fish below the halocline. Lobsters and benthic infaunal species both emerged from burrows when oxygen concentration declined, and eventually died from hypoxia. Baden et al. (1990) also reports the recovery of flatfish and benthic infauna populations subsequent to reoxygenation of the bottom water, although neither lobster nor cod populations recovered.

Phytoplankton populations stimulated by nutrient enrichment may include harmful algal blooms. The incidence of harmful algal blooms and resulting fish mortality has been documented in many countries around the world, including Scotland, Norway, Canada, and New Zealand (Martin and Haya, 1999; Chang et al., 1990; Bruno et al., 1989). Many cases of these blooms have been documented at Scottish fish farms (Pearson and Gowen, 1990). Rapid and significant losses among farmed Atlantic salmon occurred on both the Shetland Isles and in Loch Torridon in Scotland which were attributed to phytoplankton blooms. In both incidents, the blooms were predominantly mixed diatom species, with *Chaetoceros* spp. being the dominant form observed. Bruno et al. (1989) also reports the occurrence of significant annual phytoplankton blooms on the west coast of Canada that have resulted in losses in farmed Pacific salmon. In this case, *Chaetoceros convolutum* was the cause of these fish deaths. Attempts have been made at Canadian fish farms to keep the fish cages below the water depth preferred by *Chaetoceros convolutum*; however this practice has generally failed due to the large diameter of the cages.

Wildish and Martin (1994) state that there has not yet been a harmful phytoplankton bloom experienced in the Bay of Fundy, as has been the case in other areas of the world. They outline a three-step method to proactively assess the likelihood of an occurrence. The steps include determining seasonal patterns of phytoplankton species, sublethal behavioral and physiological bioassays, and toxicity testing. This area of research is also supported in the findings of Stewart (1994) as one of 10 research priority areas outlined; specifically the 'influence of farming on enhancement of harmful algae and impacts of toxins on finfish and shellfish'.

In addition to measuring effects, the reviewed literature also describes equations for calculating nutrient loads from cage-fish farming (Ackefors and Enell, 1994; Aure and Stigebrandt, 1990; Ackefors and Enell, 1989) and predicting potential phytoplankton blooms from fish farming (Pridmore and Rutherford, 1992). Models such as these are useful for predicting the impact that a fish farm may have on the environment, especially since the impact will vary depending on the physical characteristics of the location of the farm (i.e., water circulation, turnover rate, etc.). For example, water with vertical stratification will confine the nutrients released during benthic decomposition to the sediment surface, which is usually below the photic zone. The stratification will, therefore, prevent the possibility of increased phytoplankton growth.

Sediment Metal Concentrations

Two studies referenced in the provided database examined the concentrations of metals in sediment beneath marine fish farms. In addition to toxicity testing, Burridge et al. (1999) conducted chemical analysis of underlying sediments. Elevated levels of organic carbon, ammonia, pesticides, and heavy metals were detected at the aquaculture sites. Copper and zinc were found in some samples at or above the threshold-effects level as prescribed by Environment Canada (1998 as reported in Burridge et al., 1999). This study recommended that protocols be established for standardized sampling and testing of sediments around aquaculture sites. A second study referenced in the database also examined the contribution of marine fish farms to metals in sediments. Uotila (1991) collected sediment cores in and around the fish farm cages in Norway, and analyzed the cores for metals, including zinc, copper, iron, manganese, chromium, lead and nickel. The results indicated that fish farming caused increased levels of zinc, copper, and manganese under the cages (Table 4).

Table 4: Concentrations of zinc, copper and manganese in sediments collected directly under a fish farm, and 20 m away (Uotila, 1991).

METAL	CONCENTRATION (ppm)		
	UNDER FISH FARM	20 m FROM FISH FARM	ISQG[1]
Zinc	400	150	124
Copper	120	20-30	18.7
Manganese	500	400	n/a

[1] Interim Sediment Quality Guideline (CCME, 1999)
n/a = not available

Sources of zinc and manganese were from fish food and copper likely originated from fish farm paint. Elevated concentrations were limited to within a radius of about 1.5 ha.

3.1.4.2 Biological Effects

Benthic Invertebrate Communities

Benthic communities in healthy areas are characterized by abundant and diverse populations (Tsutsumi et al., 1991). Heavy organic loading at marine fish farms has generally been found to have a detrimental effect on the benthic community. Changes in benthic community structure have been reported in the sediment surrounding fish farming operations in Europe (Henderson and Ross, 1995; Johannessen et al., 1994; Partanen, 1986), Asia (Tsutsumi et al., 1991), USA (Weston and Gowen, 1998; Weston 1990) and Canada (Cross, 1990). These studies include comparisons to reference sites during farm operation (Cross, 1990), as well as comparisons before and after farm establishment (Johannessen et al. 1994; Tsutsumi et al., 1991). However, one study conducted in Wales did not detect any impacts on the benthic community (Frid and Mercer, 1989). In macro-tidal environments such as the one studied, greater waste retention in the water column may reduce benthic waste accumulations. The authors also caution that farm wastes may be accumulating in nearby sink areas (Frid and Mercer, 1989).

Many of the studies reporting changes in benthic community structure as a result of organic enrichment have followed predictions made by Pearson and Rosenberg (1978 as reported in Weston 1990) (Figure 1). Their analysis predicts a low abundance of macroinvertebrates near the source of organic pollution (i.e., the aquaculture site). This low abundance occurs as a result of the depletion in oxygen levels in bottom waters and sediment due to the high rate of organic input. This study also predicts an increase in benthic abundance beyond these highly impacted areas where rates of organic enrichment are more moderate and, therefore, can provide an enriched food source for benthic organisms without depleting oxygen to harmful levels or impairing communities through physical sedimentation effects (i.e., burial). At far-field sites, the analysis conducted by Pearson and Rosenberg (1978 as reported in Weston 1990) predicts minimal levels of organic input and, as a result, the occurrence of benthic communities that reflect those found in undisturbed areas.

Several studies have reported a decrease in macrofaunal species richness near aquaculture operations (Henderson and Ross, 1995; Findlay and Watling 1994; Cross, 1990; Weston 1990 as reported in Gowen et al., 1991; Ritz et al., 1989; Weston and Gowen, 1988; Brown et al., 1987; Pease, 1977). These studies reported effect intensities ranging from minimal to severe (e.g., 90% reduction in species richness relative to undisturbed conditions: Weston 1990 in Weston et al., 1991), or even a total absence of all macrofaunal species (Brown et al., 1987 in Weston et al., 1991). Results from a number of studies reviewed are summarized in Table 5.

Most species experience a decrease in abundance following an increase in organic loading (Weston, 1990). However, changes in individual abundance vary depending on the benthic species. Echinoderms are generally the first species to disappear and demonstrate the largest decrease in abundance (Tsutsumi and Kikuchi, 1983). Conversely, densities of pollution-tolerant species such as nematodes and/or polychaetes tend to increase (Weston, 1990). The polychaete species, *Capitella capitata*, is a commonly occurring benthic organism inhabiting enriched sediments within the vicinity of marine fish farms (Weston and Gowen, 1990; Cross, 1990). Elevated abundance of pollution-tolerant species may result in localized increases in total benthic abundance (Weston, 1990).

Macrofaunal biomass is highly dependent upon the size and density of opportunistic species. Therefore, no consistent relationship has been demonstrated with respect to changes in macrofaunal biomass and levels of organic enrichment. Some studies have detected little effect on macrofaunal biomass (Kaspar et al., 1985). Other studies have reported an increased biomass corresponding to high densities of opportunistic species, followed by an abrupt decrease with further increases in enrichment (Brown et al 1987 in Weston et al., 1991). Studies have also reported a decrease in biomass relative to controls in the vicinity of the farms (Weston 1990 as reported in Weston et al., 1991; Lopez-Jamar, 1985; Tenore et al., 1982). Total biomass of the benthic communities decreased by more than 90% in 22 years in a survey of a fish farm located in Hong Kong (Tsutsumi et al., 1991). Weston (1990) also found a decrease in total benthic biomass despite the occurrence of a greater number of

Figure 1: Trends in benthic community changes along gradients of organic enrichment (modified figure of Pearson and Rosenberg (1978) by Weston and Gowen (1988).

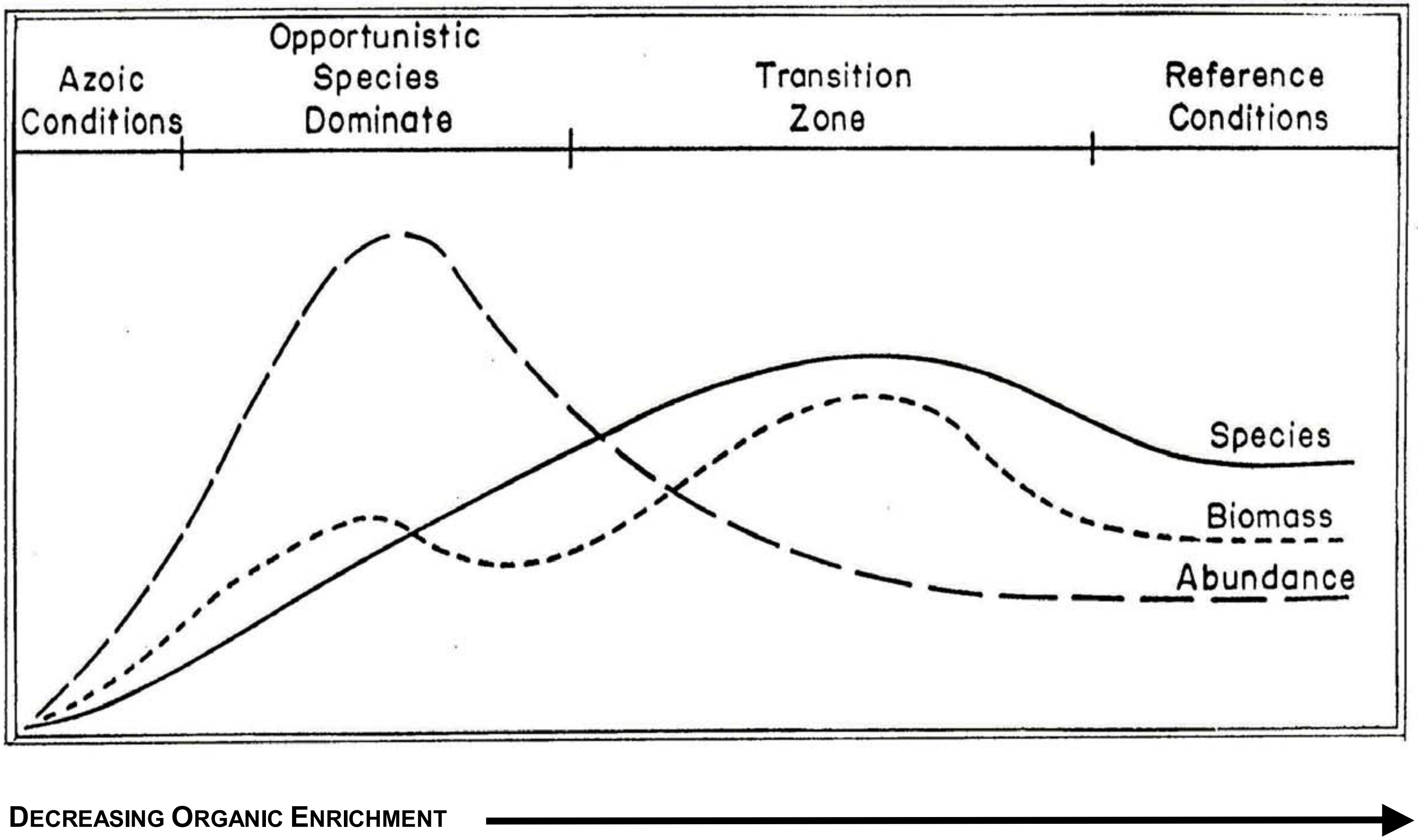

Table 5: Benthic Community Impacts.

SITE	FARM SIZE	DISTANCE FROM PERIMETER	OBSERVATIONS OF IMPACT	SURVEY DATE	CITATION
B. C. farm	320 t	Extensive	Very high (regular fallowing; extensive accumulations; azoic areas; *Beggiatoa* mats; *Capitella* dominant)	Summer 1989 (one assessment visit/per farm)	Cross 1990
B. C. farm	306 t	Areal extent indeterminate	Low (deposits below net-pens; extent depth dependent; wastes drift; patchy impacts; normal biota)		
B. C. farm	300 t	Areal extent indeterminate	High (entire area impacted with other organics; *Capitella* dominant)		
B. C. farm	272 t	≤30 m	High impact (localized deposits beneath farm; *Capitella* dominant)		
B. C. farm	215 t	Perimeter of net-pens	Moderate (some patchy *Beggiatoa; Capitella* dominant)		
B. C. farm	200 t	Perimeter of net-pens	High (*Beggiatoa* mats, *Capitella* dominant)		
B. C. farm	180 t	≤20 m	Moderate (some back-eddy accumulations to within 20 m)		
B. C. farm	103 t	≤20 m	High impact (some *Beggiatoa*; *Capitella* dominant),		
Japanese farm	Prior to farm establishment in 1973	-	Natural benthic community (bivalves and gastropods dominate)	April 1966	Tsutsumi et al., 1991.
	Not specified	-	Marked change in benthic community (polychaetes including *Capitella* dominate)	April 1978	
		≤600 m	Increased dominance of *Capitella* and other polychaetes	April 1989	
		≤300 m	Benthic communities almost disappear at stations nearest the farm (repeated annual cycle of temporary defaunation in summer)	August 1989	
Finnish farm	25 000 kg/a	1.6 km [1]	Polluted bottom (dominance of pollution tolerant species)	September 1984	Partanen 1986

SITE	FARM SIZE	DISTANCE FROM PERIMETER	OBSERVATIONS OF IMPACT	SURVEY DATE	CITATION
Finnish farm	7000 kg/a	1.8 km[1] (other sources of pollution were also likely contributing; 460 m is likely due to fish farm alone)	Polluted bottom (small number of species, absence of indicators for unaffected conditions, abundant occurrence of pollution indicator species for area, *Chironomus plumosus*, reduced total biomass)	September 1984	
Norwegian farm	2417 t	Prior to farm establishment	No evidence of pollution impact	March 1998	Johannessen et al. ,1991
		Not determined – although no impacts were detected at a station 250 m away	Impact (appearance and dominance by *Capitella capitata* decreased abundance of *Malacoceros fuliginosa*)	September 1989 April 1990	
		After farm establishment	Improved conditions (presence of bivalve species although in low abundance) but *C. capitata* still dominant	March-April 1991	
Scottish farm	664 t	<25 m	No measurements taken.	mid-late summer 1991	Henderson and Ross 1995
		25-50 m	Measurable impact (reduced species richness and dominance by 3 species)		
Scottish farm	460 t	≤30 m	No data		
		30-35 m	Highly impacted (cumulative dominance of *C. capitata* and 2 was 92%; however, species richness was 44)		
Scottish farm	550 t	≤25m	Severe impact recorded at cage edges and at 25 m (one station was afaunal and others were heavily dominated by *C. capitata* and other opportunistic species	mid-late summer 1990	

SITE	FARM SIZE	DISTANCE FROM PERIMETER	OBSERVATIONS OF IMPACT	SURVEY DATE	CITATION
Scottish farm	444 t	≤25m	After 3 months following, severe impact recorded at cage edges and 25 m away	mid-late summer 1992	
		50m and 75m	Impact less (diversity higher) but community still dominated by a few species		
Scottish farm	332 t	≤50 m	Severe impact at some sites along cage edges with *C. capitata* comprising >50% population. Less impacted stations located at 10-50 m. A variety of echinoderm species were recorded at some stations	mid-late summer 1993	
Scottish Farm	321 t (max)	<25 m	Heavy impact (dominated by *C. capitata*)	mid-late summer 1992	
		25 –50 m	Reduced species variety		
Scottish farm	298 t	≤25m	No stations showed severe impact but perturbation of fauna observed by dominance of some species	mid-late summer 1992	
		25-50m	Less impact but differences from control community composition still apparent		
Scottish farm	187 t	<25 m	Severe impact at cage edges (one station afaunal, extremely low densities and number of species at other stations)	mid-late summer 1991	
		25-50	Moderate impact with dominance by 3 species.		
Scottish farm	187 t	≤25 m	Severely impact (reduced species richness and faunal density, *C. capitata* was dominant)	mid-late summer 1991	
US farm (Clam Bay Puget Sound, Washington)	620 t (160 net-cages)	≤45 m	High impacted (reduced species richness and biomass; increased density of *C. capitata*)	June 1987	Weston and Gowen 1988; Weston 1990
		45-150 m	Moderate impact		
		450 m	No evidence of disturbance		

SITE	FARM SIZE	DISTANCE FROM PERIMETER	OBSERVATIONS OF IMPACT	SURVEY DATE	CITATION
US farm Squaxin Island Puget Sound, Washington)	20-40 t	Prior to farm establishment	No evidence of pollution impact	January 1987	Weston and Gowen 1988
		≤ 6 m	No evidence of pollution impact	August 1987	
		≤ 6 m	High impact (depauperate community, presence of *C. capitata*)	January 1988	
		≤ 6 m	Heavy impact with further degradation evident	August 1988	
US farm (Maine – depositional site)	250 000 kg	Areal extent indeterminate	Sediments under site aerobic; presence of abundant macrofauna	1991 - 1992	Findlay and Watling 1994
US farm (Maine – erosional site)	41 500 kg	Areal extent indeterminate	Few detectable effects		
US farm (Maine)	22 200 kg	Areal extent indeterminate	Developed *Beggiatoa*-type bacterial mats		

individuals as a result of the smaller individual size of the dominant species present in the enriched condition. In his survey of B.C. farms, Cross 1990 reported a biomass reduction in 6 farms, although one farm demonstrated the opposite trend and another exhibited no apparent change in biomass.

In addition to abundance, richness and biomass, a few studies have examined other community and population effects in the benthos as a result of organic enrichment. Weston (1990) found an increase in individual body size with increasing enrichment for some species (Weston 1990 in Weston et al., 1991). This study found that individuals of *C. capitata* and other enrichment tolerant species may be 3 to 5 times larger in enriched areas than individuals from populations at undisturbed sites, indicating a tendency for the occurrence of large individuals for some species at enriched sites. While individual size may increase, inter-specific measures of animal size decreased with increasing enrichment, predominately a reflection of changes in benthic species composition. This results because organic enrichment tends to selectively eliminate the largest species among the macrobenthos, resulting in a decrease in the mean individual size in the community (i.e., total sample biomass divided by total sample abundance).

The amount and rate of waste material lost in conjunction with the physical properties unique to a site will govern the areal extent and magnitude of impacts to the surrounding benthic environment. Cross (1990) argues that bottom topography, depth, current velocity and water column density (temperature and salinity) are important physical attributes determining the potential for waste material dispersion around marine fish farms and, thus, the degree to which these materials accumulate and impact the benthic environment. More serious, long-term effects may occur in low energy marine environments, such as the deep basins of some fjords and inlets of Canada (Gowen et al., 1991) One study reviewed assessed the importance of locality on determining the effects of fish farming on bottom fauna. This study hypothesized that locations with a high percentage of accumulation bottoms would be more severely affected than locations characterized by erosion bottoms. To test this hypothesis, four different locations were assessed. The study's results did not show any connection between the type of bottom and its sensitivity to fish farms (Lauren-Maatta et al., 1991). However, the authors concluded that the methodology was insufficient to distinguish between the effect of location and other factors such as the farm size and presence of other loading sources (Lauren-Maatta et al., 1991).

Studies have generally found that impacts to benthic communities are relatively localized and confined to the immediate area surrounding the fish farm operation (Table 5). In his review, Gowen et al. (1991) reports on studies that detected benthic community changes at distances of 15 to 50 m from the farm perimeter (Lumb, 1989; Aure et al., 1988; Weston and Gowen, 1988), with more limited effects at greater distances. Gowen et al. (1991) also references Brown et al. (1987) who detected benthic community changes 15 m from a farm and undisturbed conditions at a distance of 120 m. Weston (1990) found effects only extended 45-90 m from the farm (as reported in Weston et al., 1991). Henderson and Ross (1995) found that, although the results varied, species richness generally increased dramatically away from cage edges. In a survey of B.C. farms, Cross (1990) found that the areal extent of waste material impacts on resident benthic communities was dependent on the magnitude and direction of local tidal current. However, impacts typically extended only to the cage edges, although effects were detected at 25 m for some farms. Conversely, some studies have detected larger far-field impacts. Weston (1990) detected changes in benthic community effects at a sampling station located 150 m away from a fish farm located in Puget Sound, USA. The environmental influence of a Norwegian fish farm was not detectable at a station about 250 m away from the pens (Johannessen et al., 1991). Most studies referenced in the database examined impacts from a specific farm. One survey was found that examined cumulative impacts to an entire marine basin receiving inputs from fish farms and other pollutant sources. This study found that a 3 km long basin located in Finland was polluted in its entirety (Partanen, 1986).

Impacts to benthic communities have generally been found to occur quite quickly in the immediate vicinity of a fish farm (Gowen et al., 1991; Johannessen et al., 1991; Ritz 1989; Lumb 1989; Gowen et al., 1988), and as soon as 3 months after farm establishment (Bergheim et al., 1991). A few studies in the database compared conditions of the benthic community before and after farm establishment. At a farm located in a cove along the coastline of Japan, Tsutsumi et al. (1991) found a marked change in the faunal composition of benthic communities. Five years after the farm establishment, the majority of benthic fauna was replaced by pollution-tolerant species (i.e., polychaetes). Nine years after farm establishment, the numerical dominance of polychaetes continued to increase, with percentages reaching between 50 to 95%. Johannessen et al. (1991) examined conditions at a fish farm in Norway before, during and after farm establishment. This study found distinct decreases in species richness one year following the establishment of the farm. Weston and Gowen (1990) also evaluated the benthic community underneath a small farm in Puget Sound. This study did not detect any changes in species richness or faunal composition after 6 months of farm operation. However, after 12 months, a dramatic decrease was detected in species richness and abundance directly beneath the pens and, to a lesser extent, 6 m away. Further deterioration of the benthic community was apparent in the next 6 months (i.e., 18 months following farm establishment).

Studies have found variable recovery rates of the macrobenthic community following farm removal. Johannessen et al. (1994) found improvements in the benthic community a year after a Norwegian fish farm was moved. Species richness increased from only 11 during farm operation to 29. However, the benthic community had not returned to the status measured (richness = 65) prior to farm operation. In another study, the benthic community beneath a farm showed no recovery after 8 months following cessation of culture (Gowen et al., 1988 as reported in Gowen et. al, 1991). Ritz et al. (1987 as reported in Gowen et al., 1991) detected a partial recovery of the benthos 10 weeks after fish feeding was stopped.

Various studies have reported that the response of the benthic community is a better indicator of effects than sediment chemistry. Weston (1990) found that sediment chemistry results indicated changes at a distance of 45 m from the farm and alterations were evident in the benthic community to a distance of least 150 m. This result suggests that benthic fauna are sensitive to enrichment levels not detectable with conventional sediment chemistry analysis (Weston, 1990). Gowen et al. (1991) reports that conventional chemical parameters which measure sediment conditions (e.g., organic carbon, and nitrogen, reduction-oxidation potential) are poor indicators for assessing biological effects. Gowen et al. (1991) reference two studies in which chemical measurements detected no enrichment, but changes in the faunal community demonstrated evidence of effects from fish farm culture (Gowen et al., 1988; Weston and Gowen, 1988). Cross (1990) found that redox potential and dissolved oxygen measurements both indicated that conditions at the sediment-water interface were oxygenated even in highly impacted benthic environments. Other studies also found inconsistent relationships between sediment chemistry and benthic communities (Henderson and Ross, 1995; Brown, 1987).

3.1.5 Identified Research Gaps

There have been several comprehensive analyses of organic loading associated with marine finfish aquaculture. However, there are few mass balance studies for nutrients in fish farms (Hall et al., 1990). This is considered to be a significant gap, leading to uncertainty in estimating the amount of environmental loss of nutrients from added food (Silvert, 1992).

The effect of organic enrichment on the benthic community within the vicinity of the fish farm has been well studied. In general, a decrease in species richness along with an increase in the abundance of a few opportunistic species is the characteristic response. Weston (1990) recommends further work be conducted on assessing the effects of organic enrichment on benthic animal size and distribution to determine whether patterns found in his study of a US farm are applicable to other areas. Weston (1990) also recommends that research be directed at developing a greater understanding of the underlying community response processes and how accompanying benthic functional changes could affect other natural processes (e.g., rates of nutrient regeneration and bioturbation). Additional areas recommended for further research include:

- The development of meaningful sediment quality standards to apply to the fish farming industry (Henderson and Ross, 1995).
- Long-term monitoring and refinement of assimilative capacities of bays (Tlusty et al., 1999).

- Further integrated biological and hydrological studies to develop stronger connections between bottom type and the sensitivity of the biological community to fish farming (Lauren-Maatta et al., 1991).
- Assessing the impacts of materials mobilized from sediments and in the water column on surrounding organisms, with emphasis on benthic cycles (Stewart, 1994).

The reviewed literature is limited with respect to eutrophication around Canadian fish farms, and, thus, identification of possible gaps in our knowledge is difficult. However, one area of research recommended for investigation involves the potential influences that farming operations have on the production of harmful algae from eutrophication or hypernutrification, and effects of their associated toxins on finfish and shellfish (Gowen and Ezzi, 1992).

3.2 USE OF CHEMICALS

Concerns exist regarding the persistence and environmental effects of chemicals used in the aquaculture industry. Chemicals commonly used in industry aquaculture include pesticides, disinfectants, antibiotics, and chemotherapeutants. These compounds are used to prevent and treat disease, control aquatic pests and protect farm infrastructure.

Due to the large-scale production and economic importance of salmon on both coasts, there has been a demand to find suitable medicinals to keep salmon disease- and parasite-free. A common problem to the industry is the infestation of sea lice (parasitic copepods *L. salmonis* and *C. elongatus*). Sea lice are natural parasites that can heavily infest farmed salmon. Sea lice feed on the mucus, skin and blood of salmon causing reduced growth, wounding and mortalities. Infestations of these parasites have been treated with baths of hydrogen peroxide, pyrethrins, dichlorvos or azamethiphos (Haya et al., 1999). Ivermectin, administered through fish feed, has also been used to treat sea lice.

Many antibiotics are also currently being used in the aquaculture industry to prevent or control disease. The most commonly used antibiotic is oxytetracycline. Other antibiotics include oxolinic acid, furazolidone, flumequine, sarafloxacin, florfenicol, sulfadiazine and trimethoprim. The widespread use of antibiotics to combat disease in fish has led many to become concerned about the development of drug-resistant bacteria. In particular, there are concerns about the ability of bacteria to transmit resistance to other bacterial species (particularly fish and human pathogens) through transfer of DNA by means of plasmids and the ability of some bacteria to develop resistance to several drugs after being exposed to a single drug (i.e., cross-resistance).

Although not widely practiced, antifouling paints have also been used to control the growth of fouling organisms such as algae on farming equipment (Davies et al., 1986). The accumulation of fouling organisms on net-pens may interfere with the necessary water exchange between the pens and the sea, resulting in detrimental effects to cultured fish. Fouled nets are typically cleaned by pressure washing or scrubbing. However, paints containing biocides have been used to treat sea pens in order to prevent the accumulation of biological fouling organisms and therefore, the need for net cleaning. These biocidal compounds slowly leach from the paint into the surrounding seawater producing toxic concentrations near the treated surface that prevent fouling organisms from attaching to the nets. However, concerns exist that the leaching of the biocides into the surrounding waters may also cause toxicity to non-target organisms.

3.2.1 Antifoulants

Cupperous oxide is a registered compound in Canada for use as an antifoulant in the aquaculture industry. The database contained one study that evaluated the environmental effects of using copper within the marine fish aquaculture industry (Lewis and Metaxas, 1991). This study measured the total dissolved copper concentrations in seawater inside and outside a copper-treated net-pen in Blind Bay, British Columbia. Results indicated that copper concentrations inside and outside the net were similar and did not change over a one month period of time. The study also found that copper concentrations were not significantly different than those found in the middle of the bay where there was no influence from any fish farm operation. The authors suggested that tidal exchange was responsible for maintaining the low copper levels. No studies were reviewed that measured effects on aquatic biota.

Another antifoulant of environmental concern is tributylin (TBT). However, it is not registered for aquaculture use in Canada and is not discussed, although there is extensive literature regarding its effects (Thrower and Short, 1991; Short and Thrower, 1991; Balls, 1987; Bruno and Ellis, 1988; Davies, 1987; Davies and McKie, 1987).

3.2.2 Pesticides and Drugs Used to Treat Sea Lice

Toxicity tests have been conducted on the impact of various pesticides on several crustaceans and bivalves (Abgrall et al., 2000; Haya et al., 1999; Burridge et al., 1999; Burridge and Haya, 1997, 1998; Chang et al., 1996). However, the distribution and fate of chemical used as pesticides in aquaculture operations is largely unknown (Haya et al., 1999).

Dichlorvos is an organophosphorus pesticide used to treat sea lice in the aquaculture industry. It is applied as a bath treatment for 1h at 1 mg/L solution. Only one paper was in the database that specifically measured concentrations of dichlorvos in the water column near fish farms (Dobson and Tack, 1991). This paper reports on a study of two Scottish fish farms treated with dichlorvos. Results found that dichlorvos dispersed very rapidly to below detection (2 μg/L). Varying levels of dichlorvos were detected within 25 m of the fish pens and no dichlorvos was detected outside of 25 m at any time. However, Ross (1989) cautions on the use of dichlorvos, stating that there are extensive gaps on information regarding its environmental fate and effects. Ross (1989) also mentions that dichlorvos could potentially be toxic to marine invertebrates. The breakdown rate of dichlorvos is reported to vary with temperature, pH and salinity, and estimates of its half-life in seawater range between 1 to 30 days (Ross, 1989).

Adding to the potential impact of dichlorvos in the treatment of sea lice is di-n-butylphthalate (DBP), which is used as the solvent carrier in its formulation. DBP is lipophilic, persistent in sediments and is listed as a priority pollutant in Canada and the U.S. (Burridge and Haya, 1995). Burridge and Haya (1995) reviewed the presence and effects of DBP in the aquatic environment of North America, Japan and Europe. Based on the limited data available, the authors concluded that DBP is sparingly soluble in water, is readily metabolized by fish and has a high lethal threshold for aquatic organisms.

The drug ivermectin is not currently registered for use in Canada as the required research and testing has not been completed. However, it can be used under a prescription from a veterinarian. Ivermectin is incorporated into feed which means that much of it remains in particulate form. As a result, ivermectin is less readily dispersed. Although ivermectin is rapidly photolysed, this will not occur when it is incorporated in food or feces, or when buried in sediments. Grant and Briggs (1998) suggest that, based on available information, ivermectin could persist for weeks or months in sediments, prolonging its potential availability to aquatic organisms. Furthermore, uneaten food and feces present a significant danger to non-target organisms

Burridge and Haya (1993) determined the effects of ivermectin in water and food on a non-target organism, the shrimp, *Crangon septemspinosa*. The results showed that no significant mortality occurred when ivermectin was exposed in seawater, but shrimp mortality was observed when ivermectin was present in food.

Another pesticide, pyrethrum, is a mixture of six different extracts naturally occurring in an East African Chrysanthemum. It is used to treat sea lice and is applied as a bath treatment at 10 μg/l for 1 hour (Burridge and Haya, 1998). It was found that earlier stages of lobster larvae are more resistant to this pesticide (Burridge and Haya, 1998), in contrast to the finding that the earlier life stages are less resistant to other types of compounds (Burridge and Haya, 1997). Although pyrethrum degrades very quickly in the aquatic environment, there are numerous factors influencing its dissipation, so it cannot be conclusively stated what impact the use of this chemical will have on surrounding lobster and other crustacean populations.

Hydrogen peroxide is added to cages as a 50% formulation called ‘Salartect’, using a 20 minute bath. It is not currently registered for use in Canada. Sensitivity testing among crustaceans and bivalves showed that shrimp and lobster were the most sensitive (Burridge and Haya, 1998). Hydrogen peroxide was used extensively in Atlantic Canada under emergency registration in 1995, but farmers were concerned with its high cost and low efficacy. DFO initiated a research project in 1995/96 to investigate other alternatives to the treatment of sea lice (Chang, 1997).

Azamethiphos is an organophosphate insecticide and the active ingredient in the formulation Salmosan (Burridge and Haya, 1998). It is the only product currently registered for use in the treatment of sea lice. It is applied as a 1 hour bath at concentrations of 100 μg/L. Toxicity tests demonstrate that lobster and shrimp are sensitive to this chemical (Burridge et al., 1999; Burridge and Haya, 1998). Based on acute lethal tests (Burridge et al., 1999) and lobster behavioral response (Abgrall et al., 2000), it was concluded that adverse impacts might occur to lobster populations, depending on concentrations and exposure times (Abgrall et al., 2000).

'Excis' (cypermethrin) and 'Salmosan' (azamethiphos) are products which are used by aquaculturists to control the growth of sea lice (Burridge et al., 2000; 2000a) in marine finfish culture. It has been found that adult lobsters exposed repeatedly to concentrations approximately 10% of the recommended treatment level for both of these compounds were affected. However, the predicted concentrations in field situations are generally low enough to expect no significant impact. Under the current knowledge base, little is known about the sublethal or cumulative impacts of these chemicals to wild species (Burridge et al., 2000; 2000a).

3.2.3 Chemotherapeutants

Many researchers have expressed concerns over the use of antibiotics and in particular, their fate and effects in the environment (GESAMP, 1997; Weston, 1996; Samuelsen, 1994; Bjorklund, 1991; Hansen, 1991; Lunestad, 1991; Austin, 1985). Grave et al. (1990) caution that an increase in resistant bacteria in the marine environment may lead to the risk of transferring the resistance to human pathogens.

Three antibiotics are licensed in B.C. for use in marine finfish aquaculture: Terramycin Aqua (oxytetracycline), Romet (sulfadimethoxine and ormetroprim), and Tribrissen (trimethoprim and sulfadiazine) (B.C. Environmental Assessment Office, 1998). These antimicrobial drugs are administered in the feed. Although a veterinarian prescription is not required, the use of oxytetracycline must be done in accordance to label instructions. Use of the other two drugs, Romet and Tribrissen, must be prescribed by a veterinarian.

Diseased fish usually exhibit reduced appetites and, as a result, much of the drugs intended to treat the disease pass directly into the environment as a result of uneaten feed (GESAMP, 1997). In addition, it has been shown that some antibiotics (i.e., oxytetracycline) are poorly absorbed in the intestinal tract of fish (Samuelsen, 1994), possibly due to complexation with Ca^{2+} and Mg^{2+} ions in seawater (Lunestad and Goksoyr, 1990). Therefore, much of the oxytetracycline ingested by the fish enters the environment unchanged and is in the active form in the fish feces. Most of the drug ends up in the bottom sediment under the fish farm, dissolved in seawater, or eaten by wild fauna (GESAMP, 1997). No Canadian studies were identified in the referenced database. Extensive studies conducted in Norway, Finland and Ireland have reported on the following findings:

- Antibiotics accumulate and persist in sediment under fish farms, even after medication has stopped (GESAMP, 1997; Weston, 1996; Hektoen et al., 1995; Le Bris et al., 1995; Coyne et al., 1994; Samuelsen, 1994; Samuelsen et al., 1994; Bjorklund et al., 1992; Samuelsen et al., 1992; Bjorklund, 1991; Kupka-Hansen et al., 1991; Samuelsen et al., 1991; Bjorklund and Bodestam, 1990; Jacobsen and Berglind, 1988; Samuelsen et al., 1988).
- Antibiotic residues have been found in non-target organisms (Weston, 1996; Samuelsen et al., 1992; Samuelsen, 1992; Bjorklund et al., 1991; Lunestad, 1991; Bjorklund and Bondestam, 1990).
- Antibiotics may induce bacterial resistance which could potentially be transferred to fish pathogenic bacteria (Kerry et al., 1996; Weston, 1996; Austin, 1995; Kerry et al., 1995; Smith et al., 1995; Kerry et al., 1994; Samuelsen, 1994; Smith et al., 1994; Nygaard et al., 1992; Samuelsen et al., 1992; Bjorklund, 1991; Kupka-Hansen et al., 1991; Grave et al., 1990; Samuelsen et al., 1988).
- Antibiotics could cause changes in sediment bacterial communities (Austin, 1985).

Each of these areas is discussed in more detail below.

Kerry et al., (1996) investigated the spatial distribution of oxytetracycline in sediments beneath a marine salmon farm in Ireland following oxytetracycline therapy and found that oxytetracycline was confined to an area of sediment under the cages. Similarly, Capone et al. (1996) showed that sediments containing oxytetracycline residues were very localized with residues detectable to a 30 m distance from the farm.

Table 6 provides summaries of the residence time (persistence) of some antibiotics in seawater. Lunestad (1991) reported that oxytetracycline was very stable when kept in the dark, but when exposed to light, the half-life was 30 hours in seawater. However, the author also found that there was a significant decrease in antibacterial performance of oxytetracycline due to complexation with Mg^{2+} and Ca^{2+} in seawater. Residence time for the other two antibiotics used in Canada was not found in the referenced literature.

Table 6: Residence time of several antibiotics in seawater.

ANTIBIOTIC	RESIDENCE TIME	REFERENCE
Oxytetracycline	Stable in the dark; Half-life of 30 h in light	Lunestad, 1991
Oxolinic acid	2 months in light	Lunestad, 1991
Furazolidone	10 days in light	Lunestad, 1991

Generally, studies show that oxytetracycline and oxolinic acid are persistent in sediment (Samuelsen, 1992; Bjorklund et al., 1991; Kupka-Hansen et al., 1991) and that marine sediments serve as long-term reservoirs for residues of some antibacterial drugs (Hektoen et al., 1995; Samuelsen, 1994; Samuelsen, 1992; Bjorklund, 1991; Kupka-Hansen et al., 1991; Samuelsen et al., 1991; Bjorklund et al., 1990; Jacobsen and Berglind, 1988) (Table 7). In a laboratory mesocosm experiment, Kupka-Hansen et al. (1991) found that half of oxytetracycline and oxolinic acid in sediment disappeared two weeks after the addition of drugs, but that 5-10% remained even after six months. Studies by Bjorklund et al. (1991) and Samuelsen (1992) also showed that oxytetracycline rapidly degraded during the first few weeks, but persisted at lower concentrations for much longer. Jacobsen and Berglind (1988) and Bjorklund et al. (1990) have shown that oxytetracycline, under stagnant anoxic conditions may be very persistent. Residues at the top layer were found to dissipate more rapidly than deeper layers and was probably due to leaching, outwashing or redistribution rather than degradation (Smith and Samuelsen, 1996; Hektoen et al., 1995; Bjorklund et al., 1990). In Ireland, Coyne et al. (1994) reported low concentrations of oxytetracycline in sediment under a salmon farm after use of the drug. They suggested that factors which influenced the measured concentration and persistence of oxytetracycline were: the amount of oxytetracycline administered, the amount that reached the sediment, the area of sediment over which it was deposited, and the depth to which it was distributed. In addition, current speed and bioturbation may affect the release or persistence of the chemical in the sediment. The range of values shown in Table 7 indicate that the residence time of antibiotics in sediment are site specific and vary depending on local environmental conditions.

Sulfadiazine and sulfadimethoxine have also been found to persist in sediment in laboratory experiments (Hektoen et al., 1995; Samuelsen et al., 1994). Sulfadiazine was found to be stable for 180 days in a laboratory experiment while sulfadimethozine decreased by 20% over the same period (Samuelsen et al., 1994). Hektoen et al., 1995 reported a half-life of about 90 days for sulfadiazine in a 6-7 cm layer of sediment. Persistence of antibiotics used in other regions (e.g., flumequine, florfenicol and sarafloxac) has also been reported (Hektoen et al., 1995; Samuelsen et al., 1994).

Table 7: Residence time of several antibiotics in sediment.

ANTIBIOTIC	RESIDENCE TIME	REFERENCE
Oxytetracycline	Half-life of 70 days	Jacobsen and Berglind, 1988
	Half-life of 32 to 64 days	Samuelsen, 1989
	Half-life of 2 weeks; 5-10% remained after 6 months	Kupka-Hansen et al., 1991
	Several months	Bjorklund, 1991
	Half-life of 28 days	Capone et al., 1994
	Half-life of 16 days	Coyne et al., 1994
Oxolinic acid	Half-life of 2 weeks; 5-10% remained after six months	Kupka-Hansen et al., 1991
Furazolidone	4 days	Kupka-Hansen et al., 1991
	Half-life of 18 hours	Samuelsen, 1994

Investigators have also shown that antibiotics in the sediment can affect sediment bacterial communities (Kupka-Hansen et al., 1992; Samuelsen et al., 1991; Austin, 1985). Kupka-Hansen et al. (1992) examined the effects of oxytetracycline, oxolinic acid, flumequine and furazolidone in marine sediments and found that there was a dramatic initial reduction in the total number of bacteria. There was an elevated number of bacteria resistant to oxytetracycline and oxolinic acid present for at least 11 weeks and there was a strong decrease in bacterial activity (measured as sulphate reduction), followed by a return to control levels within ten weeks. Samuelsen et al. (1991) investigated furazolidone and its effects on bacteria in marine sediments in the vicinity of marine aquaculture sites. Results showed that furazolidone remains in the sediment for only a very short time and is actively metabolized by microorganisms in the sediment. The metabolite had no detectable antibacterial activity. However, despite its short residence in sediment, furazolidone has been shown to reduce the total number of bacteria in sediment (Samuelsen et al., 1991).

Studies conducted in Norway have also found bacteria resistant to antibiotics in sediment, farmed fish and wild fauna (Samuelsen et al., 1998; Samuelsen, 1994; Samuelsen et al., 1992; Bjorklund, 1991; Kupka-Hansen et al., 1991; Bjorklund et al., 1990). In one study, elevated numbers of bacteria resistant to antibiotics were found in the sediment and were detected for at least 11 weeks (Kupka-Hansen et al., 1991). Samuelsen et al. (1988 and 1992) also found oxytetracycline resistant bacteria in sediment following the end of the drug treatment period. Several other studies have reported on the occurrence of bacteria resistant to several antibiotics (oxytetracycline, oxolinic acid, flumequine, furazolidone) isolated from farmed fish, and wild fish and blue mussels collected in the vicinity of fish farms (Samuelsen, 1994; Samuelsen et al., 1992; Bjorklund, 1991; Bjorklund et al., 1990).

Nygaard et al. (1992) examined the frequency of bacterial resistance to oxytetracycline and oxolinic acid in marine sediment and also examined the cross-resistance between oxytetracycline, oxolinic acid and furazolione. Results showed that there was a significant increase in the percentage of drug-resistant bacteria in sediments containing antibacterial agents relative to untreated sediment. Cross-resistance between antibacterial drugs was also observed.

Studies conducted in Ireland have also shown an increase in frequency of oxytetracycline-resistant bacteria in sediment (Kerry et al., 1994, 1995 and 1996). However, the researchers did not believe that the observed resistance was associated with an increase of oxytetracycline in the sediment. Instead, their data suggest that there is a possibility that resistant microbes in fish feed or other unknown factors may contribute to resistant microbes detected in sediments under fish cages. Furthermore, Smith (1995) and Smith et al. (1995) warn that caution needs to be applied when interpreting data on resistance frequencies in farmed fish and sediments because analytical methods and reporting of results have not been consistent.

Since aquaculture structures can potentially provide shelter and ecological niches for wild fauna, concerns exist that wild fauna could be exposed to the antibiotics during their use in treating bacterial diseases of farmed fish. In particular, wild fish would take advantage of excess uneaten food near the net cages and filter-feeding molluscs nearby could also be exposed to antibiotic-contaminated particulates. A number of studies have reported on drug residues detected in wild fish, mussels and oysters collected in the vicinity of aquaculture operations in Norway and Finland (Samuelsen, 1994; Samuelsen et al., 1992; Lunestad, 1991; Bjorklund et al., 1990). Bjorklund et al. (1990) found oxytetracycline residues in wild fish captured close to an aquaculture site. Drug residues declined rapidly within the first week after drug treatment, but traces were found in specimens caught 13 days later. A similar study by Le Bris et al. (1995) in France, found increased concentration and persistence of oxytetracycline in shellfish which may have been related to the availability of oxytetracycline in the sediment. Samuelsen (1994) examined wild fish in the vicinity of fish farms treated with oxolinic acid and found that 166 out of 189 fish contained residues of oxolinic acid. Similarly, Lunestad (1991) reported residues of oxolinic acid in wild fish caught up to 400 m from the fish farm. Residue levels exceeded acceptable levels for human consumption, but decreased below detection levels 12 days after treatment was terminated. A study by Samuelsen et al. (1992) found residues of oxolinic acid in wild fish and in blue mussels retrieved near two Norwegian salmon farms.

Ervik et al. (1994) tested two feeding devices, the Lift-Up feed collector system and a hydroacoustic feed detector, in Norway. Both devices were found to be effective in minimizing feed waste in fish farms relative to the more traditional feeding methods and also contributed to a reduction in antibiotic (oxolinic acid and flumequine) residues in the muscle of nearby wild fish. A reduction of feed waste with a concurrent reduction of antibiotic resides found in tissue of wild fish, provides further evidence of waste feed as the source of antibiotics to the wild fish.

3.2.4 Identified Research Gaps

Based on the available literature, it is apparent that more data is needed regarding the fate and effects of the chemical agents used in Canadian ecosystems. Areas of further interest for research identified in the reviewed literature include:

- Comprehensive listing of materials used in aquaculture and the amounts added to the water column and sediments (Stewart, 1994).
- More toxicological studies of aquaculture chemicals on a wider range of species (Haya et al., 1999).
- More detailed chemical dispersion studies (Chang et al., 1996).
- Additional data on the fate and acute and chronic effects of dichlorvos and DBP in the aquatic environment (Burridge and Haya, 1995; Ross, 1989).
- Additional data on the fate and effects of ivermectin in the aquatic environment (Grant and Briggs, 1998; Burridge and Haya, 1993).
- Research on alternative methods to control sea lice, such as the use of light traps (Pahl et al., 1999).
- Sublethal effects of anti-sea lice compounds on lobster biochemistry and reproduction (Burridge and Haya, 1998).
- Development of analytical methods for the measurement of pesticides currently used in aquaculture (Burridge et al., 1999).
- Research on alternative or improved feeding techniques to reduce the amount of excess food treated with antibiotics entering the environment (Ervik et al., 1994).
- Data of background frequencies of antibiotic resistance in bacteria in unpolluted sediments (Smith, 1995; Smith et al., 1995).

In conducting this review, it is also evident that more data would beneficial in the following areas:

- There are much data available on fate and effects of oxytetracycline, however, more data are required on the amounts, fate and effects of other types of antibiotics used in Canada.
- Data are needed on how other aquatic communities are impacted due to changes in sediment bacteria.
- Research on alternative methods to treat disease or prevent outbreaks of disease.
- Data on whether bacterial resistance has been transferred to fish pathogens.

The other risk of drug use in aquaculture is the uptake by the fish and subsequent risk to human health. In a review of the use of drugs in aquaculture, Johnson and Rainnie (1989) state that there is little known about the pharmacokinetics of drugs in fish but, based on knowledge of fish physiology and anatomy, the fate of drugs in fish can be identified. No papers were present in the database on this topic.

3.3 CULTURED AND WILD FISH INTERACTIONS

Cultured fish may act as an environmental stressor both within farm cages and upon escape from farms. Potential effects include the transmission of disease, predation on wild juveniles, competition for resources (food sources and habitat) and genetic alteration of wild stocks.

3.3.1 Escape of Farmed Fish

A number of articles in the database report on the incidence of farmed Atlantic salmon in Pacific waters (McKinnell et al., 1997; Thomson and McKinnel, 1996), Norwegian and Faroese waters (Hansen et al., 1997; Jacobsen et al., 1992; Gausen and Moen, 1991; Lund et al., 1991) and Scottish waters (Hislop and Webb, 1992). Tagging experiments suggest that the rate of escape from marine salmon cages under normal circumstances is low (Browne, 1990). However, Browne (1990) reports that large-scale escapes also occur from cage facilities in every country. Escapes occur from farms for any number of reasons, including damage to net pens from storms, tides, currents, predators, vandalism, boats and farming equipment, accidental spills during transport form hatcheries, or handling during harvest or grading. Larger escapes (thousands to tens of thousands of fish) are usually associated with extreme environmental events, while smaller escapes result from routine farming operations (McKinnell et al., 1997). Recoveries of farmed fish in local drift net catches in Ireland have been reported as high as 3% of the annual production.

3.3.2 Disease Transmission to Wild Stocks

Disease transfer between cultured and wild salmon stocks is a key concern of salmon aquaculture in Canada and worldwide. Concerns of the reviewed literature relate to the introduction of exotic pathogens to both British Columbian and other waters, the amplification of pathogens in cultured fish, as well as the use of antibiotics and therapeutants to control diseases as discussed in Section 3.2. Pathogens causing disease in aquaculture can result in fish mortality or, in less extreme cases, lesions, ulcers, discolouration, and other sublethal effects which may not cause immediate death. Moreover, the presence of the disease may also increase the susceptibility of the fish to secondary infections that may in turn lead to death.

The transfer of disease from farmed to wild stocks may occur through a number of different mechanisms: 1) from the interaction of escaped farmed fish with wild stocks, 2) the transmission of pathogens present in fish farms through the water column, or from sediments, to local wild stocks, and 3) interactions involving avian predators in coastal areas. The majority of papers in the database that discuss the transfer of disease to wild stocks involve transfer via interaction with escaped infected fish. Transmission through the water column or from the sediments are described to a lesser extent (Evenden et al., 1993; Husevåg, et al., 1991; Enger et al., 1989).

The immediate fate of escaped diseased fish and their associated pathogens will greatly influence the level of risk from cultured fish to wild stocks. It is generally understood that the manifestation of disease in fish farms is closely related to the concentration of infective agents, as well as fish density in confined conditions (McVicar, 1998). These conditions enhance the frequency of interaction between pathogen and host, as well as increase the susceptibility of hosts to infection through the effects of stress on the defense mechanisms of caged fish. In the natural environment, these factors aiding the spread of infection are reduced considerably, and are further ameliorated by the effects of predation on weaker infected fish that have escaped. Therefore, the risk of wild fish becoming infected by escaped farmed fish is most likely substantially reduced in comparison to the possible spread of infection between fish inside cages. However, although the presence of disease in fish farms does not necessarily make wild populations more susceptible, or increase the probability of effective contact, it does increase the possibility of infected hosts in the natural environment upon the escape of infected fish. This probability will largely influence the spread or incidence of disease in wild populations. There are major difficulties in determining which infections are actually causing significant effects in wild fish populations and their origins (McVicar, 1998).

Concerns also exist that avian predators may transfer disease from fish farms to wild stocks (Pillay, 1992). For example, herons appear to be the final host for fish tapeworms (cestodes) and gulls and grebes are the final hosts for fish flukes (trematodes) (Pillay, 1992). These organisms infect both wild and farmed fish in their larval stages (Pillay, 1992).

Birds can also act as passive carriers of viruses, including infectious pancreatic necrosis (IPN) and viral haemorrhagic septicaemia (VHS), which have been isolated from regurgitated food and feces after ingestion (Pillay, 1992). Price and Nickum (1995) examined the transfer of disease by avian predators through regurgitated fish, fecal transmission and their feet. Their review found that birds have transmitted 3 fish viruses including, Spring Viraemia of Carp (SVC), VHS and IPN. Both VHS and IPN occur in North America. However, their review focused predominately on impacts to cultured fish with most of the data based on European studies. The authors identify gaps in available information and state that information on disease and parasite transmission to aquaculture operations is unquantified. McAllister and Owens (1992) also examined disease transmission, focusing on the feces of piscivorous birds. The study found IPN virus in the feces of herons, mallards, and other birds, and demonstrates that wild birds can become contaminated with IPN virus under natural conditions and excrete the virus in their feces. However, this study did not demonstrate that the disease can subsequently be transmitted to wild fish populations.

The database includes several overview reports that summarize the different types of diseases involved in fish farming (Brackett, 1991; Håstein and Lindstad, 1991; McArdle, 1990), and their incidence in the history of aquaculture (McVicar, 1998; St. Hilaire et al., 1998; Kent, 1994). The majority of the studies included in the literature database are dedicated to furthering our knowledge of the pathogenicity of diseases affecting aquaculture. No studies were reviewed that exclusively assessed the transfer of disease to wild salmon populations. A number of studies touch on the issue of disease transfer, although it is apparent that there is a general lack of understanding regarding the processes involved in disease transfer (McVicar, 1998; Evenden et al., 1993; Johnson *et al*., 1993; Håstein and Lindstad, 1991). The literature referenced in the provided database also predominately pertains to disease in aquaculture of European origin and not Canadian. According to St.-Hilaire (1998), Canada does not have a structured disease surveillance program to assess the prevalence of disease in wild fish. Without such a program, it is difficult, if not impossible, to determine any relationship regarding the transmittance of disease between farmed and wild finfish.

Work in Canada has demonstrated that wild fish carry many of the same pathogens as cultured populations and, in some instances, more than farmed fish (McArdle, 1990). Noakes et al. (2000) also reports that all of the pathogens found in farmed fish to-date are endemic to the Pacific region and have existed in British Columbia for some time. An interesting point extracted from the literature addresses the public perception of disease that “wild” implies “pristine” which is not necessarily true, as exemplified by Pacific salmon. Wild fish act as reservoirs for a number of different diseases, and new hosts are being found on a regular basis. In fact, parasites carried by this species are used as natural tags to distinguish different stocks (Noakes et al., 2000).

The pathogens found to transfer between both wild and farmed fish populations, from the articles provided in the database, include bacterial kidney disease (BKD), sea lice, infectious hematopoietic necrosis (IHN), IPN, papillomatosis, furunculosis, and vibriosis (McVicar, 1998; Evenden et al., 1993; Johnson et al., 1993; Brackett, 1991; Margolis and Evelyn, 1987). Each of these diseases are considered in detail below.

Bacterial Kidney Disease (BKD) caused by *Renibacterium salmoninarum* was initially described in 1930 in connection with disease outbreaks in Scottish rivers. Since that time, BKD has been reported in at least 13 salmonid species from many countries around the world, and represents one of the most persistent and prevalent diseases in fish farming, especially to the farming of Pacific salmon (Håstein and Lindstad, 1991). Up to 80% of the losses in Pacific salmon stocks, and 40% of the losses among infected Atlantic salmon have been caused by this bacterium. BKD is widespread in Canada and is a particularly important problem for salmon farming in both Pacific and Atlantic regions (Margolis and Evelyn, 1987). In the Pacific region specifically, BKD is known as one of the single biggest problems in sea-farmed salmon, especially for chinook salmon. In fact, in 1987, Margolis and Evelyn reported that most of the marine salmon farms on the coast of British Columbia were infected with this pathogen.

Only two papers in the database specifically discuss this disease, one of which simply describes the first case of *R. salmoninarum* detected in wild chum salmon populations in eastern Asia (Sakai *et al*., 1992). The chum salmon had migrated into a bay containing cultured coho salmon infected with *R. salmoninarum.* The second paper states that although research has increased our knowledge of the prevalence, pathology, diagnosis, and treatment strategies, many aspects of this disease in both wild and cultured salmon are still poorly understood (Evenden et al., 1993).

An overview of various diseases in aquaculture by Håstein and Lindstad (1991) describes the present threat of BKD to fish farming, especially to the farming of Pacific salmon. This paper reports that this disease is only occasionally found in wild fish populations. However, a heavy infestation of BKD in farmed fish may pose considerable infectious pressure on wild fish populations.

Five species of parasites are collectively known as **sea lice**: *L. salmonis*, *C. clemensi*, *C. curtus*, *C. elongatus* and *L. cuneifer* (Johnson et al., 1993). These copepods remain one of the most important parasite problems worldwide, in salmon farming and in wild populations (Håstein and Lindstad, 1991). Although infestations have become more severe in recent years, the transfer of this disease from farmed to wild fish stocks is still not fully understood. McVicar (1998) reports not only a lack of direct evidence of lice transfer from farmed to wild salmon populations, but also that major difficulties exist in determining the route of transfer and assessing the impact of highly pathogenic disease conditions, such as sea lice, in wild fish populations. Research continues in an attempt to find other evidence of this transfer to wild populations, such as recognizable features of lice on farmed salmon which could be recorded when these infect wild salmon. This would provide an accurate quantification of any level of pathogenic transmission between the two groups of fish. Genetic markers are also being explored by scientists at the Universities of St. Andrews and Stirling in Scotland to identify transfer of lice to wild populations. Other markers, such as the occurrence of carotenoid pigment in lice that has been acquired from the feed of farmed salmon, have also been considered (Noack et al., 1997; in McVicar, 1998).

The report on the effects of sea lice on farmed salmon by McVicar (1998) also addresses the occurrence of this parasite before the development of fish farming, and currently in wild populations. This report also details possible contributions from escaped farmed salmon, evidence for lice transfer from farmed to wild stocks, the potential for contact between salmon and lice, consequences of lice infection on wild salmon and other infections transmitted by lice. Jacobsen and Gaard (1997; in McVicar, 1998) found that escaped farmed salmon caught north of the Faroe Islands had a significantly higher level of lice infection than wild stocks in the same area. The risk of spreading lice infections was therefore assumed to increase with increasing incidence of escaped of farmed fish. In addition, recent research has revealed that these parasites have developed an effective and economic way of locating and infecting a new host, and thus facilitating disease transfer. (McVicar, 1998).

Another report written for the Ministry of Agriculture, Fisheries and Food (Johnson *et al*., 1993) summarizes proceedings from the sea lice symposium of the first European conference on crustacea, and also highlights current international research on the biology and control of sea lice. Outbreaks of *L. salmonis* are reported on both wild Atlantic salmon and sea trout smolts, causing them to return to fresh water prematurely. Researchers in both Norway and Ireland are investigating the source of these infections and their effects on wild salmon populations.

Another study is being developed to look at the transfer of sea lice to wild stocks by monitoring sea lice numbers on wild smolts returning to rivers in fjords with and without fish farms (Johnson et al., 1993). Preliminary results indicate higher infections of sea lice on smolts returning to rivers from fjords with fish farms, or caught in the fjord itself (average 389 copepods per fish). Although sea lice infections were not found on smolts in areas without fish farms in this study (with the exception of one fish), many other studies provide evidence of salmonids with appreciable levels of lice infection in non-farming areas. McVicar (1998) documents a number of studies that have found an abundance of sea lice (approximately 8 – 28 lice per fish) on wild fish. However, these natural abundances may not cause mortality of the fish. Preliminary laboratory results suggest that 50 chalimus larvae or preadults are sufficient to kill smolts, and may cause death in up to 85% of wild smolts within 12 days of entering the sea. Johnson et al. (1993) attributes the source of these infections most likely to fish farms.

A high level of mortality of sockeye salmon reported in Alberni Inlet on Vancouver Island in 1990 was attributed to a natural heavy *L. salmonis* infection (mean intensity of 300 per fish) (McVicar, 1998) and demonstrates the potential of sea lice to be highly pathogenic in the natural environment, even in non-farming situations. A similar situation was found in western Ireland, where heavy infections of *L. salmonis* occurred at several sites on wild sea trout within 3 weeks of their migration to sea (Johnson et al., 1993). Infections of epizootic proportions occurred at some sites, resulting in significant damage to the sea trout. This study attributed the source of the infection to farmed salmon, and that estimated up to 38 million nauplii of *L. salmonis* were released per day from cultured fish in the vicinity of the study sites during the period encompassing sea trout migration.

Recent research has also been directed at methods for controlling sea lice infestations, especially through the use of cleaner-fish, such as corkwing and goldsinny wrasse as an alternative to chemical treatments (Deady et al., 1995; Costello, 1993). These cleaner-fish were found to successfully control sea lice infestations on farmed Atlantic salmon smolts on two commercial fish farms off the west coast of Ireland (Deady et al., 1995). Wrasse were able to clean both diseased and healthy fish stocks with equal efficiency, whereas orally administered chemotherapeutants have been less effective with diseased stocks.

Canadian efforts to continue research initiatives to understand the cleaning behavior of these fish are supported, as well as further developing cleaner-fish technology. In British Columbia, several fish species have been identified as having the potential for acting as cleaner fish, such as kelp perch (*Brachyistius frenatus*), pile perch (*Rhacochilus vacca*), and white sea perch (*Phanerodon furcatus*) (Johnson et al., 1993). The use of small scale tank trials has been suggested to determine the effectiveness of these fish in controlling sea lice infestations in cultured fish.

A number of **viral diseases** have also been recognized and range in their virulence on both wild and cultured fish stocks. Literature from the late 1970s and early 1980s, in both Europe and Canada, describe outbreaks of both **infectious hematopoietic necrosis** (**IHN**) and **infectious pancreatic necrosis (IPN)** in salmon populations. IHN has been reported at numerous net-pen farm sites in British Columbia, and has become a major disease of concern to Atlantic salmon farm operations in the province since the first report of the disease in 1992. In farmed salmonids, this disease occurs only in the Pacific region of Canada, but has also been detected in wild chinook salmon and rainbow trout (Margolis and Evelyn, 1987). Studies have documented the transmission of IPN from wild to farmed stocks and vice versa, and investigated the survival of these diseases in treated water (as reported in Håstein and Lindstad, 1991).

Papillomatosis of Atlantic salmon was first recorded in wild stocks from Sweden in 1971 and has more recently been observed in cultured rainbow trout. This condition, known as salmon wart disease, causes benign, neoplastic lesions of the epidermis that do not cause immediate death, but secondary infections with prolonged wound-healing that may lead to fatalities. Bylund et al. (1980) describes observations of papillomata in both free and captive Atlantic salmon in Finland, although the wild salmon affected by the disease were in a river completely unaffected by human influence. Methods of transfer of this disease from farmed to wild stocks were not identified, although the report discusses this possibility and its importance as a focus of future research. Some of the gaps in knowledge for this disease include:

- Aetiology of papillomatosis.
- Research for a causative or predisposing agent of papillomatosis before outbreaks occur.

Furunculosis is a condition characterized by the production of boil-like raised lesions on the skin of affected fish, and is caused by an organism known as *Aeromonas salmonicida*. Several studies have investigated the incidence of furunculosis, dating back to Plehn (1909) that documented the rapid spread of the disease in European farmed fish and wild stocks (Heggberget et al., 1993; Håstein and Lindstad, 1991). Wild Atlantic salmon populations can be seriously affected by furunculosis attacks. Although transfer between farmed and wild stocks is highly likely and discussed in many of the reviewed papers, none of these reports provide direct evidence of this transfer. Enger and Thorsen (1992), for example, addressed the transmittance of this disease to the benthic environment and water column outside a farm area, but did not report the direct transmittance to wild stocks. This report also cites another study in Puget Sound where the transmittance of furunculosis between pens was found over distances of 24 km but, once again, direct transfer to wild stocks was not evidenced. Overall, the papers included in the database primarily address the ecological implications and incidence of furunculosis, but the mechanism of transmission between farmed and wild salmon remains unclear (Heggberget et al., 1993; Håstein and Lindstad, 1991).

Literature pertaining to the incidence of furunculosis in Canada reveals that it has caused significant losses in cultured salmonids over most of its range and is widely distributed across the country (Margolis and Evelyn, 1987). The disease is now reported to be controlled with antibiotics and vaccines. The issue of disease transfer is not directly addressed in the database literature, but is alluded to in the observations that mature salmon become infected upon return to hatcheries one or more months prior to spawning.

Vibriosis is another bacterial disease affecting populations of farmed salmonids and is caused by two different species. Classical vibriosis, caused by *Vibrio anguillarum*, results in deep red ulcers in the skin of infected fish, and has been reported in both wild and farmed populations of salmonids (Håstein and Lindstad, 1991). Historically documented in Norwegian waters, this disease is thought to be widely distributed, but in only marine environments. Further information about this disease or its transmission between farmed and wild fish is very limited in the papers in the database.

On the other hand, information on *Vibrio salmonicida*, the causative agent of coldwater vibriosis in Atlantic salmon, is better represented in the database literature. However, this species has not been isolated from disease outbreaks in wild salmon populations (Håstein and Lindstad, 1991). Literature in the database include studies from Norway that have focussed on the possibility of a sediment reservoir for this pathogen, and found a simultaneous occurrence of coldwater vibriosis with bacteria resistant to oxytetracycline in sediments at aquaculture sites abandoned for more than one year (Husevåg, et al., 1991; Enger et al., 1989). Håstein and Lindstad (1991) reported that the only *Acinetobacter* spp. infection in wild migratory broodstock of Atlantic salmon is believed to have been caused by *Vibrio* spp., although they did not specify the species responsible. In the absence of such data, additional research is required to support a conclusion regarding the transmission of this pathogen species from farmed to wild salmon.

In Canada, vibriosis is found on both the Pacific and Atlantic coasts where it is present in sea-farmed salmonids. Margolis and Evelyn (1987) consider this to be the second most important disease in cultured Pacific salmon, infecting chinook salmon to a greater degree than coho salmon. If the number of studies included in the database can be used as a measure of research effort, more work has been conducted in foreign waters compared to Canadian. Future work would therefore be necessary to identify the incidence and environmental effects of vibriosis on farmed and wild salmon stocks in Canada.

The issue of exotic disease introduction to Canadian waters was also addressed in some of the database literature. In an attempt to minimize the risk associated with introducing exotic diseases to local waters, an eggs-only importation policy was adopted in British Columbia and has proven effective (Carey and Pritchard, 1995). Various authors have recommended additional strategies for reducing the risk of disease transfer. St.-Hilaire et al. (1998) recommended:

- The establishment of a surveillance system to monitor trends in the occurrence of disease pathogens in both wild and cultured fish.
- Studies to determine the extent of interaction between wild and farmed populations, and use of this knowledge to develop a management plan to minimize this interaction.
- Improving the state of health of salmonids on fish farms using an action plan based on reducing the risk of transmission of diseases.

- Re-assessment of management practices for wild fish stocks to ensure they do not increase susceptibility to disease.

From Pillay (1992), preventative measures recommended for fish disease control include:

- Improvement in design, operation and inspection of fish farm establishments.
- Inspection, quarantine and certification of transferred, traded or imported stocks.
- Development of a disease registry, reporting and information system.
- Adoption and enforcement of adequate and comprehensive legislation.

McVicar (1998) also provides suggestions towards the reduction of disease in Canadian farms involving farm water quality, stock densities, selection of tolerant fish species, and use of advanced vaccines to reduce disease occurrence. Stewart (1991) also describes a dozen similar methods to address the problem of disease in Canadian aquaculture.

A greater number of papers pertaining to disease in aquaculture exist in the database than have been discussed here, but they do not address the issue of disease transfer to wild stocks (e.g. Bruno, 1992; Bristow and Berland, 1991a; Bristow and Berland, 1991b; Deardorff and Kent, 1989; Bylund et al., 1980). These papers primarily deal with the pathogenesis and incidence of diseases in aquaculture. Kent and Poppe (1998) provide a comprehensive report detailing diseases found in seawater netpen-reared salmonid fishes in Canada, which includes such information as the clinical signs, gross pathology, microscopy, diagnosis, and control and treatment of the variety of diseases discussed. It is evident from these reports that a great amount of research has been conducted on disease in aquaculture, but also that future work is still required to fully understand the ecological ramifications of these diseases and their transfer to wild stocks.

3.3.3 Establishment of Exotic Species, Predation and Resource Competition

Two issues often raised by concerned parties include whether it is possible for escaped farmed Atlantic salmon to establish self-sustaining breeding populations of an exotic species in British Columbia, and whether they could displace native stocks? For example, Browne (1990) identifies a number of potential problems from the interaction of escaped farmed fish with wild populations, including competition with wild stocks for spawning habitat and food. While Atlantic salmon is an exotic species on the west coast of Canada, evidence presented at the British Columbia Environmental Assessment Review suggests that this species has a low overall risk to Pacific salmon (Noakes et al., 2000). Brown trout (*Salmo trutta*) from Europe is the only successful inter-continental introduction of a salmonid species in North America (Krueger and May, 1991), although introductions of native salmonids within North America, but outside their native ranges, have been common. Pink salmon were introduced to the Great Lakes in Canada in the 1950s and established self-sustaining populations in many streams. After a 20-year period, the species had greatly extended its range, from a tributary of Lake Superior to streams as far as the eastern end of Lake Ontario (Thorpe, 1994). Needham (1995) questions the viability of farmed salmon in open waters. In the cages, farmed salmon feed on pellets and may not adapt well to feeding strategies required for survival in the natural environment (Needham, 1995). Escaped Atlantic salmon caught in commercial nets are generally in a starved and emaciated condition. The environmental conditions in net-pens also cause the fish to become accustomed to light and overhead movement, making them easy prey to the large population of harbour seals in British Columbian waters. Needham (1995) concluded that all the scientific evidence shows that Atlantic salmon are uncompetitive with the diverse range of species occupying the rivers of British Columbia. Similarly, Noakes et al. (2000) states that overall, scientific evidence indicates that salmon farming, as currently practiced in British Columbia, poses a low risk to wild salmon stocks particularly when compared to other potential factors. Recently, however, in spite of the conclusions of low risk (Noakes et al. 2000; Needham, 1995), it has been found that Atlantic salmon are reproducing in British Columbian streams (Volpe et al., 2000).

Migration, spawning behaviour and competition with wild stocks for resources are some of the causes of concern regarding the interactions between farmed fish (exotic and indigenous) and their wild counterparts. Migration behaviour of escaped farmed salmon compared to wild stocks, and the spawning behaviour of escaped farmed female Atlantic salmon have been well-documented (Økland et al., 1995; Lura et al., 1993; Quinn, 1993; Jonsson et al., 1991; Hansen et al., 1987).

Hansen and Jacobsen (1997) conducted an in-depth tagging experiment in the Faroe Islands comparing the origin and migration of wild and escaped farmed Atlantic salmon. Results from this study suggest that Atlantic salmon caught in Faroese waters originate from at least 10 different countries including Norway, Scotland, Russia, Ireland, Sweden, Denmark, England, Iceland, Spain, and Canada. This study also confirmed that adult Atlantic salmon can cross the north Atlantic ocean in at least 5 months. The farmed fish caught were mostly from Norway and Sweden. In the tagging experiments, the rate of recapture of farmed origin was significantly lower than for wild fish.

Another study by Økland et al. (1995) tracked the migration of farmed Atlantic salmon in North Norway using radio telemetry. Farmed females were found to move significantly more than their wild counterparts, whereas no difference was found between the wild and farmed males. Wild salmon remained at the spawning areas for longer than farmed fish (8.1 days versus 5.2 days for farmed fish). Overall, the authors suggest that escaped farmed salmon had reduced spawning success compared to wild stocks.

Smolts that have escaped from a marine locality tend to return as adults to the same area from which they escaped (Hansen and Bakke, 1989). Upon maturity, these fish will enter rivers in the area without a defined home stream as they are not imprinted to a stream. Therefore, they will have no motivation to enter freshwater before physiological reasons force them to do so, likely resulting in a lower proportion of fish farm escapees among the spawners far upstream than in the lowermost part of the river system (Browne, 1990). In the event that escape occurs at the post-smolt or adult stage, these fish stray to rivers farther away from the site of escape when mature (Hansen and Bakke, 1989).

In an investigation on the importance of olfactory sense in migrating farmed adult Atlantic salmon released on the Norwegian coast, Hansen et al. (1987) found that olfactory sense was not mandatory for salmon to enter freshwater. The homing behaviour of farmed Atlantic salmon is not a direct consequence of imprinting at the smolt stage, and there is not a direct genetic link for these fish to return to a particular river.

Spawning behaviour, researched by Lura et al. (1993), was found to differ between wild and farmed stocks of Atlantic salmon. Redds of farmed fish contained more egg pockets, with fewer eggs per pocket, than their wild counterparts. However, the basic components of spawning behaviour seemed to be intact in female escapees. Needham (1995) was of the opinion that escaped farmed Atlantic salmon do not pose a threat large enough to displace Pacific species from their spawning redds, but also noted that farmed salmon have been found to successfully spawn with brown trout (Needham, 1995). In view of the depressed numbers of Pacific salmon stocks in many streams, it should be noted that escaped Atlantic salmon may not face significant competition for spawning areas and rearing habitat.

In addition to competition for spawning habitat, concerns exist regarding predation by farmed salmonids both within cages and in the natural environment, and their feeding behaviour upon escape. Black et al. (1992) reports observations made by farm workers of caged salmon feeding on wild fish passing through the web of the cage structure. Among the three species studied, chinook, steelhead and coho salmon, coho had the highest level of predation on fish. The areas studied included the northern part of the Strait of Georgia as well as southern Queen Charlotte Strait, in British Columbia. This report also refers to several studies that document the aggregation of wild fish around cages at salmon farms. No studies were reviewed which examined the possible predation by escaped salmonids on juvenile wild stocks.

Another key question pertaining to the escape of farmed fish involves the impact of the predation of cultured fish on natural prey populations, and subsequent effects on wild stocks. Hislop and Webb (1992) investigated the feeding behaviour of escaped farmed Atlantic salmon in Scotland. Results from stomach contents of 54 escaped fish showed the predominant prey to be juvenile whiting, *Merlangius merlangus* (L.), unidentified Gadidae and sandeels (*Ammodytidae*), as well as other fish and invertebrates, including post-larval hermit crabs. This study thus confirmed that escaped salmon feed on natural prey in coastal waters.

3.3.4 Genetics Effects on Wild Populations

Geneticists are developing new techniques and new understanding at an extraordinary rate and this progress is being rapidly incorporated into aquaculture genetics in Canada. The most important technical developments are procedures for direct gene transfer to generate new aquaculture strains (genetic engineering) and procedures for identifying individuals and populations (microsatellite and other DNA markers). The application of these techniques is very poorly represented in the database - only 9 of the approximately 50 genetics-related papers in the database were published after 1995, and most of those are review papers that cover work at least two years older than that. Consequently, the database *seriously* under-represents the current level of Canadian and worldwide knowledge of the genetic impact of aquaculture. To attempt to fill this gap in this review in a small way, a number of additional references published during the past 18 months (in 1999 and 2000) which contribute directly or indirectly to Canadian knowledge, plus a few important earlier papers have been incorporated. Citation of additional papers are included in Appendix A.

Impact of Escapees on the Genetic Fitness of Natural Populations

Aquaculture escapees can affect the genetic fitness of wild populations in three principal ways:

- By reducing genetic diversity of wild populations by massive hybridization with genetically homogeneous domesticated fish.
- By inducing inbreeding depression in wild populations which are supplemented by hatchery fish, if the latter have undergone generations of matings among close relatives.
- Causing outbreeding depression or maladaptation by hybridization between populations with different local adaptations, in particular wild-adapted fish hybridizing with domesticated escapees from aquaculture.

A number of the overview papers in the database express *hypothetical* concerns, unsupported by data from Canada or elsewhere, over potential genetic impacts to natural populations from escaped cultured species (Peterson, 1999; Ritter et al., 1999; Verspoor, 1998; Lacroix and Fleming, 1998; Hutchings, 1991; Saunders, 1991). Several of these papers mention the possibility that maladapted genes from aquaculture will be promptly selected out again in nature so we might not have to worry about them (Peterson, 1999; Verspoor, 1998).

Data on these potential effects have become available in the past 5 years or so with the development of new types of molecular genetic markers, such as microsatellite DNA polymorphism. For the most part, this new information is not reflected in the papers in the database. The few exceptions will be noted below.

None of the papers in the database present data on the concern with loss of genetic diversity and inbreeding in Canada or elsewhere, although hypothetical discussions can be found in the overview papers mentioned above. Data on the rate of random loss of genetic diversity during cultivation, and the impact of this loss on supplemented and wild populations are examined in relevant, recent papers by Primmer et al., (1999); Norris, Bradley, and Cunningham (1999); Tessier, Bernatchez, and Wright (1997), which are not included in the database. For the most part, these recent observational papers have found the genetic impact of escapees to be rather small, or least not as great as had been feared.

Several of the overview papers in the database mention the concern of outbreeding and maladaption of hybrids or escapees and some cite possible instances (e.g., declines in supplemented populations of Pacific salmon species (Waples, 1991)). A large number of instances in which cultured salmonids may have affected the fitness of indigenous populations of the same or related species are noted by Heen et al., (1993) and Hinder et al., (1991); these influential papers are, however, too old to have included the more powerful types of direct genetic information on fitness effects as opposed to simple mixing. The preferred use of local broodstocks for hatchery supplementation to reduce outbreeding is frequently emphasized.

A number of papers in the database deal with the genetic changes in growth, behaviour and morphology which occur during domestication (Fleming et al., 1994, Hershberger et al., 1990, Webb et al., 1991), and which would be involved in the fitness breakdown of wild-aquaculture hybrids following an escape. For example, domesticated Norwegian salmon are less streamlined (Fleming et al., 1994), growth is faster (Hershberger et al., 1990), and escaped farmed salmon spawn lower down in Scottish rivers and later than wild fish (Webb et al., 1991). For the most part, these observations have been confirmed by later work, which is not in the database.

None of the papers directly demonstrate the outbreeding depression which may occur when hatcheries mix and release fish adapted to different natural habits (rivers), as demonstrated by Berg and Moen (1999). Recent work in Norway suggests that escaped farmed salmon are relatively unsuccessful in reproductive competition for wild mates, and the rate of introgression may be lower than was feared until recently (Fleming et al., 2000). Considerable introgression has, however, been found in Ireland and Norway (Norris, Bradley, and Cunningham, 1999). Recent work in Denmark also showed that farmed brown trout do introgress genes into the native population (Hansen et al., 2000). The question of whether or not the release or escape of domesticated fish actually does cause outbreeding depression is probably location-specific and constitutes a Canadian knowledge gap.

The detection of mixing of farmed and wild fish (without necessarily interbreeding) using genetic markers is represented by several papers in the database (Lacroix and Flemming, 1998; Crozier, 1993; Heggberget et al., 1993; Youngson et al., 1993; Webb et al., 1993; Gudjonsson, 1991). Lacroix and Flemming (1998) include an excellent and relatively up-to-date overall review of the mixing of farmed and natural salmon. Hybridization of escaped farmed Atlantic salmon with native brown trout has been detected in Scotland (Youngson et al., 1993). Escaped salmon do spawn in Scottish (Webb et al., 1993; 1991), Icelandic (Gudjonsson, 1991) and Norwegian (Heggberget et al., 1993) rivers. It has been suggested (Heggberget et al., 1993) that escaped salmon are preferentially attracted to the larger rivers in Norway. It has been found that the proportion of farmed fish in some rivers is very high: above 90% in some Norwegian and Irish rivers and also in the Magaguadavic river in New Brunswick (Ritter et al., 1999).

Several papers deal with the use of allozyme (protein) and mitochondrial DNA molecular markers to distinguish natural (non-aquaculture) populations from each other. Genetic differentiation of European and North American Atlantic salmon stocks is described in the database (Davidson et al., 1989), but this work has been superseded by much more powerful analyses using newer techniques. Genetic mixing and erosion of both farmed and wild salmon affected by escaped salmon from farms has been documented in Ireland using microsatellites (Norris, Bradley, and Cunningham, 1999). For the most part, these papers do not reflect the state of the art in this fast-moving field. A paper that does so is Allendorf and Seeb (2000). Recent Canadian studies on differentiation of natural population of cultivated species do exist (Volpe et al., 2000; Tessier, Bernatchez, and Wright, 1997). Additional, highly relevant European studies (Clifford, Mcginnity, and Ferguson, 1998; Clifford, McGinnity, and Ferguson, 1997) also exist.

Experimental and observational work on the effects of domestication on competitive and reproductive success of escapees (and by implication, on the fitness of hybrids and the rate of gene flow from cultured into wild populations) is not represented in the database. Highly relevant papers do however exist; a representative sampling of the literature on species relevant to Canada is (Hansen et al., 2000; Rhodes and Quinn, 1999; Ruzzante, 1993; Leider, 1990).

Impact of Aquacultural Transgenics

Transgenic aquacultural species, also known as "genetically modified organisms" or GMOs, are fish or shellfish into which foreign genes have been inserted by direct manipulation of DNA. The products of more conventional techniques for transferring genes between species, such as hybridization, are not usually included in the definition of GMOs. The rising public anxiety about GMOs is based on two major fears, one being the possible consequences of the transgenic gene products for public health, and the other the ecological and genetic impact of transgenic fish if they escape to interact with the wild relatives of the GMOs. It is the latter impact that is most relevant to the present survey.

Species of principal interest to Canada are salmon (both Atlantic salmon and several west coast species) and rainbow trout. Transgenic work on other aquacultural species such as tilapia, is being conducted in Canada, but will not impact natural Canadian populations. Transgenic work on cultured bivalves, crustaceans, bass and carp is underway elsewhere in the world and *may* be underway in Canada. Although this work will become relevant if the GMOs are brought into Canada, there is no information about it in the database.

A number of papers in the database are concerned at the hypothetical and policy levels with the impact of escaped transgenic fish, as distinct from problems posed by ordinary domesticated fish (Dunham, 1999; Devlin, 1998; Hallerman and Kapuscinski, 1992; Kapuscinski and Hallerman, 1990). Some papers in the database deal with the reduced reproductive (mating) impact of transgenics as predicted from their behaviour and physiological properties (Devlin, 1999; Farrell et al., 1997). Work on salmon which is directly relevant to Canada is described by Cook et al. (2000); Hill, Kiessling, and Devlin (2000); and Devlin et al. (1994). Community and ecosystem level impacts may occur because of, for example, the destabilizing effects of transgenics with greatly increased food requirements and acquisition capabilities. The very important, recent Canadian experimental study by Cook et al. (2000) concludes that transgenic salmon (using at least one possible gene construct) are likely to starve to death in nature and therefore pose a relatively low threat to wild salmon.

Genetic Impact of Aquaculture on the Virulence of Natural Pathogens.

Routine Canadian aquacultural practices, including antibiotic feed supplements, dips and immunization can increase the genetic virulence of natural pathogens. This indirect effect comes about because hosts and pathogens are a co-evolving system, engaged in what is called an "evolutionary arms race". The presence of a resistant (domesticated) subpopulation of fish in the environment can select for pathogens which are more virulent. Wild subpopulations coexisting with the aquacultural populations in the same environment will be exposed to these extra-virulent pathogens. Theoretical analyses have been conducted by Gandon and Michalakis (2000); and Roy and Kirchner (2000). This hypothetical, indirect but potentially serious genetic impact of aquaculture has not yet been documented in Canada and no relevant papers are included in the database.

Another related impact on natural populations which *has* been documented is the increased virulence of non-native strains of pathogens when they are introduced into new habitats for aquaculture. Burreson, Stokes, and Friedman (2000) use genetic procedures to demonstrate that the greatly increased virulence of *Haplosporidium nelsoni* (MSX), a serious pathogen of the Eastern Oyster *Crassostrea virginica*, has been caused by transplantation of a Pacific species of oyster (*C. gigas*) from California and probably, ultimately from Japan.

Risk Assessment of Genetic Impacts

Several papers in the database (Ritter et al., 1999; Verspoor, 1998; Hutchings, 1991) emphasize the importance of formal risk assessment procedures for assessing the genetic impact of stock supplementation, but do not undertake such an analysis. One early analysis Hutchings (1991) concludes not unsurprisingly, that the extinction probability of native genomes is greatest when introgression is from large numbers of frequently intruding cultured salmon. More recent theoretical work incorporates genetics into ecological models of population viability analysis. For example, McKenna (2000) predicted strong, negative impacts on the survival of native salmon stocks in Maine induced by inbreeding and outbreeding in the supplemental hatchery releases.

Mitigating the Genetic Impact of Aquacultural Escapes and Releases

The most commonly considered mitigation procedure for aquaculture escapees is containment (i.e., preventing escapes from occurring). When escapes do occur despite containment efforts, the proposed fall-back strategy for mitigating genetic impacts is usually some sort of sterilization of the cultivated population. The favoured procedure for doing this is chromosome manipulation such as triploidization. Excellent Canadian work on chromosome manipulation in salmon and trout is being done (Benfey, 1998). The effectiveness of triploidization for mitigating both the genetic and the ecological (competitive) impact of escaped Atlantic salmon has been demonstrated in Ireland (Cotter et al., 2000). Dillon, Schill, and Teuscher (2000) have shown that triploidization of released rainbow trout does not negatively affect their attractiveness to anglers in the US.
Special biological containment procedures, such as "terminator" genes have been mentioned for use with GMOs (Anonymous, 2000). This introduction of lethal or sterilizing transgenes to block gene transmission to wild relatives has been proposed for use in aquaculture, and potentially suitable inducible promoter sequences have recently been identified in fish (Molina et al., 2000). This controversial work constitutes a gap in the database, if not in Canadian knowledge.

As alternatives to containment, various "anti-domestication" selection and breeding procedures have been proposed for reducing or mitigating the loss of genetic diversity and/or maladaptation when gene transfer from aquaculture does occur. These procedures are especially appropriate when aquaculture escapes are practically inevitable (as in sea-cage aquaculture) or there is a program of deliberate release as in stock supplementation from hatcheries. No papers in the database deal explicitly with these possibilities.

Recent work does help to fill the knowledge gap. A breeding programme that successfully prevented random gene loss in a supplemented stock of Pacific salmon is described in a recent paper by Hedrick et al. (2000). Theoretical procedures for genetic mitigation when recovering totally extinct populations using foreign or captive breeders are discussed by Young (1999) and Frankham (1999) among many others. These discussions revolve around the uses of DNA-marker-based pedigrees to maximize the genetic diversity of sources, and the question whether or not inbreeding should be undertaken to selectively "purge" small populations of the deleterious recessive alleles that cause inbreeding depression. Both issues are highly controversial. Doyle et al. (1995) discussed DNA-based hatchery breeding strategies for reducing or mitigating the domestication selection and maladaptation of fish released into the wild.

3.3.5 Identified Research Gaps

Information provided in the referenced literature reports on the incidence of finding cultured fish in natural waters. However, estimates of the rate of escape and total numbers of cultured fish in natural waters were not provided. Chang (1998) reports that there is a lack of data on the numbers and causes of escapees from salmon cages.

The impacts of escaped cultured finfish in the natural environment are also not understood well. Further studies need to be conducted to advance understanding of salmonid behavior upon escape, in terms of migration and behaviour at spawning habitats.

As previously mentioned, the majority of our research on disease in aquaculture pertains to understanding how a disease operates and its occurrence. More recent work has focused on developing strategies to better control or avoid these diseases. Less information was available in the literature provided that addressed concerns of disease amplification, transmission and subsequent impacts to wild populations. Additional research is required to fully understand the transfer of disease via exposure of wild salmonids to cultured stocks and furthermore, to use this knowledge in effective assessment and risk management procedures (McArdle, 1990; Margolis and Evelyn, 1987).

Evenden et al. (1993) identified several specific gaps with respect to *R. salmoninarum* infection. These include:

- The exact route of entry of this pathogen via horizontal transmission into salmonids.
- The minimum infective dose for horizontal transmission. (In terms of vertical transmission, egg studies suggest that only a few organisms, possibly a single bacterium, are needed for infection to the ovum.)
- The development of a standardized laboratory model infection system in order to make further progress with pathogenicity studies. Knowledge of the number of *R. salmoninarum* cells required to initiate infection would help in designing control and

treatment strategies and, particularly, for the evaluation of vaccine trials and chemotherapeutic regimens.

A number of gaps with respect to sea lice infection were identified in the literature. Recommended areas for future research include:

- Studies to increase understanding of the behavior of both salmon smolts and returning adults in inshore waters in the vicinity of farms (McVicar, 1998).
- Studies to investigate the trends of infection levels in both farmed and wild salmon occurring in the same area (McVicar, 1998).
- Studies to evaluate correlations between levels of sea lice in farmed and wild salmon and studies to provide evidence for the transfer of lice from farmed to wild fish populations (McVicar, 1998).
- Studies to provide more information on the dispersion of the infective stages of lice from farms (McVicar , 1998).
- Studies to determine the distribution and behavior of the infectious copepodid stage of sea lice using more sophisticated laboratory techniques and subsequent field investigations to confirm laboratory results (Johnson et al., 1993).
- Small-scale tank trials to determine the potential of cleaner fish for use in the control of sea lice (Johnson et al., 1993).
- Research into the development of either fishing management strategies or wrasse-rearing facilities to supply salmon farms with certified, disease-free cleaner-fish in an attempt to enhance the use of wrasse in sea lice control (Deady et al., 1995).

Other recommended areas for future research on disease include:

- Research into the origin of infectious salmon anemia (ISA) in Atlantic salmon, and the connection between ISA and EIBS-virus particles (Håstein and Lindstad, 1991).
- Studies on assessing the potential impacts of ISA on wild stocks (Håstein and Lindstad, 1991).
- Studies to further understand the processes involved in the transmittance of *Aeromonas salmonicida* between fish farms and to wild stocks.

As indicated, the database seriously under-represents the current level of Canadian and worldwide knowledge of the genetic impacts of aquaculture. It is recommended that additional further papers be incorporated to ensure that gaps identified are areas requiring additional research and not areas under-represented in the database.

3.4 Disturbance and Predator Control Activities

3.4.1 Effects to Birds and Mammals

Pillay (1992) discusses the effect of disturbances due to the aquaculture operations (i.e., noise, boats, habitat alteration, etc.) on birds. Pillay suggests that disturbances from aquaculture may cause birds to leave the farm area, but notes this has not been substantiated, and that predatory birds attracted to farms by the easy availability of feed appear to become accustomed to the noise and other disturbances. The most important impact on birds is likely deliberate killing and entrapment (Pillay, 1992).

There appears to be very limited information pertaining to the effects of aquaculture on mammals. Pillay (1992) states that the effects of aquaculture on mammals have not been sufficiently investigated to arrive at reliable conclusions. However, one recent Canadian review paper by Nash et al. (1999) examines the interaction of wildlife with marine aquaculture operations. The paper notes the three most common predators are harbor seals, California sea lions, and Steller sea lions. The killing of offending pinnipeds that cannot be deterred by non-lethal predator control methods is permitted by DFO, with reported kills of these 3 species between 1989 and 1996 numbering 3854 (unpublished data in Nash et al., 1999).

Nash et al. (1999) also notes a change in behaviour of some marine mammals located around aquaculture operations. Increased aggression has been observed and is attributed to social hierarchies that are established in small feeding areas (such as net-pens). This may lead to dominant behaviour in some individuals, which is displayed as aggression (Nash et al., 1999).

Several solutions to prevent marine mammal attacks on aquaculture operations are also addressed by Nash et al. (1999). Suggested short-term solutions mainly involved net cage improvements to separate the prey from the predators, such as increased tension in nets to make them rigid; installing heavy duty predator nets around aquaculture units; as well as the use of better deterrents around the floats. Proposed long-term solutions included moving aquaculture operations away from coastal haul-outs and rookeries of marine mammals, as well as offshore relocation. In addition, a reduction in the number of marine mammals through animal relocation, shooting and a regional culling program is discussed.

3.4.2 Identified Research Gaps

Further research is needed on the transmission of disease and parasites through avian carriers to wild communities (Price and Nickum, 1995). The effects of aquaculture on mammals have also not been sufficiently investigated (Pillay, 1992). In particular, more information about social behaviour of sea lions and seals is necessary to gain a better understanding of potential effects (Nash et al., 1999). It is also necessary to gain further understanding on the effects to orcas and other marine mammals.

3.5 EFFECTS PREDICTION

3.5.1 Modeling

Models have been developed and widely used in the determination and estimation of environmental impacts from aquaculture in the marine environment. Models are useful tools for predicting impacts based on known or assumed variables. The inherent limitation is that models are dependant upon the present knowledge of biological, chemical and physical interactions and pathways. As ecological systems are complex, the application of models is constrained by inherent assumptions, algorithms and input variables.

Models have been developed and used for nutrient loading, dispersal, benthic accumulation, waste transport and fate, chemical interactions in sediments and a variety of sub-categories within the evaluation of aquaculture wastes (Findlay and Waitling, 1997; Silvert, 1995; Silvert and Sowles, 1995; Sowles et al., 1994; Turrell and Munro, 1988).

Quantitative estimates of the possible environmental consequences of aquaculture development have been routinely modeled (Silvert and Sowles, 1996) and are now used to provide data to environmental managers and policy makers. The report of the conference on modeling environmental interactions of mariculture in 1995 (Silver and Hargrave, 1995) recommends that:

- Modeling should be viewed as an essential component of understanding and controlling the environmental interactions of mariculture.
- Modeling should be dealt with in the context of coastal zone management, and not as an isolated field.

Large-scale or regional modeling has been less developed. However, 3D models of the tidal flows of the Passamaquaddy Bay, New Brunswick have been developed (Greenberg et al., 1997). These types of models are useful in understanding the dynamics of a body of water and in predicting waste transport and dispersion of aquaculture operations.

3.5.2 Identified Research Gaps

Further research areas as recommended by the reviewed literature include:

- Modeling of bays and estuaries re: loading and general performance of models (Stewart, 1994).
- Development of a computer application to combine data, models, and expert advice for input into decision making process (Hargrave et al., 1995).

4. EFFECTS KNOWLEDGE AND GAPS: MARINE SHELLFISH AQUACULTURE

4.1 EFFECTS KNOWLEDGE

There has been increased emphasis on the production of cultured shellfish and other marine invertebrates worldwide to meet the increasing demands for human consumption and export (Chua et al., 1989). A variety of species are currently being cultured in Canada, including mussels, oysters, clams, urchins, scallops, and quahogs. As with finfish culture, there are numerous concerns associated with the culture of shellfish. However, limited papers pertaining to shellfish aquaculture were included in the database. The following is a summary of the papers referenced in the database. These papers address environmental issues of concern regarding shellfish aquaculture practices in southeast Asia, Scotland and Spain. Consequently, they are included in the absence of direct Canadian information to provide an indication of issues that may be of concern.

Environmental degradation in southeast Asia due to intensification of marine coastal aquaculture is well documented (Chua et al., 1989; Fung-Smith and Briggs, 1998). In addition to finfish, shrimp, oysters, mussels, clams and blood cockles are intensively cultured in southeast Asia. Although aquaculture conducted in Asia is very different to the industry practiced in Canada, studies conducted in Asia illustrate the potential for adverse cumulative impacts. Impacts due to shellfish aquaculture activities in southeast Asia include:

- Conversion of mangrove forests and wetlands leading to a loss of critical habitats for some commercially important species.
- Changes in hydrologic regimes in enclosed waters (restricted water movement) due to a proliferation of mollusc culture beds and fish cages.
- Discharge of high levels of organic matter from fertilizers, excess food and waste.
- Increased frequency of red tides.
- Increased sedimentation from mollusc farming due to excretory products and trapping of suspended particles.

In contrast to the experience in southeast Asia, culturing of mussels (*Mytilus edulis*) in the Rias Bajas on the Galician coast of northwest Spain has shown generally positive results (Tenore et al., 1985). Studies on the effects of intense mussel culture indicate that they affect food chain patterns and production in generally positive ways and can be summarized as follows:

- Detritus from mussels support a dense epifaunal community which supply food to fish and crabs.
- Epifaunal larvae, instead of copepods, dominate the zooplankton community.
- Recycling of nutrients by mussels contributes to high seaweed production.
- Sedimentation from mussel deposits changes the sediment regime and lowers infaunal populations.

One study referenced in the database examined effects of chemical toxicity to shellfish populations in Scotland (Davies et al., 1986). However, this study only examined effects of TBT on cultured species (Pacific oyster, *Crassotrea gigas*, scallops, *Pecten maximus* and salmon). This study found that:

- Total tin concentration in oysters increased rapidly at the beginning of the study, then fell steadily over time and decreased rapidly after transfer to untreated nets to twice the concentration of control oysters located 200 m away.
- Juvenile scallops showed a similar pattern, but contained twenty times the amount of tin compared to the control scallops, also located 200 m away.
- Oysters depurated 90% of accumulated tin and TBT after transfer to untreated nets over 41 weeks.
- Scallops retained 60-80% of accumulated tin and TBT over the same period.
- TBT led to moderate mortalities and slightly reduced growth in juvenile scallops, but enhanced survival of adult scallops.
- Oysters showed decreased growth and thickening of the shells.

However, the use of TBT is not currently permitted in Canada.

4.2 IDENTIFIED RESEARCH GAPS

Areas recommended in the reviewed literature for further research include:

- Additional scientific data to develop policies for environmental management (Chua et al., 1989).
- Environmental baseline studies to establish benchmarks on environmental quality (Chua et al., 1989).
- Studies to determine the effects of high sediment loads on oyster growth and survival (Jones and Preston, 1999).

5. EFFECTS KNOWLEDGE AND GAPS: FRESHWATER AQUACULTURE

5.1 FEED AND ORGANIC WASTE

As with agriculture, aquaculture involves feeding of confined animals in order to realize an increase in saleable product. A key concern related to aquaculture is the generation of organic wastes. All salmonid aquaculture produces organic wastes, the bulk of which is in the form of fish feces and uneaten feed settling out of the netpens or effluent pipe to the sediments (Beveridge, 1984). Dissolved organic carbon and nutrients (nitrogen and phosphorus) are also released to surface waters surrounding the farm sites by solubilization of feed and feces and through the gill and urinary excretions of the fish. Among the major environmental concerns are the production of anoxic sediments underlying the netpens or at effluent discharge sites, due to high loading of organic wastes and the nutrient-induced stimulation of local algal blooms in the surface waters (eutrophication). Ultimately, waste loads in aquaculture are a direct result of feeding (Axler et al., 1997).

Organic wastes are directly linked in quality and quantity to the feed used. As fish meal is still the primary source of protein in aquaculture feeds, there is a global concern that the required increase in aquaculture production to meet demand will result in depletion of fish resources required to manufacture fish meal for fish feeds. As such, research has been conducted in diet formulations to reduce dependency on fish meal based diets, to enhance digestibility and reduce waste nutrients, and to reduce phosphorus levels in diets. Achievement of better food conversion ratios through better holding conditions, feeding regimes, and diet formulations have also been evaluated as a means to reduce the nutrient contents of waste streams.

A total of 20 papers were reviewed that dealt with feed for species cultured in freshwater environments. Of these papers 9 were conducted in Europe, 4 in the United States, and 7 in Canada. Most of the diet formulation studies have involved salmonids, primarily Atlantic salmon and rainbow trout (Heinen and Hankins, 1996). Replacement of fish meal with alternative sources of protein has been a well-studied area (Luzier et al., 1995, Kim et al., 1998, Medale et al., 1998, Gomes et al., 1995). Partial replacement of fish meal with soy meal (Gomes et al., 1995), showed that up to 50% of trout feed could be replaced without adverse effects on growth or food conversion ratios (FCR). Similarly, Luzier et al. (1995) found that replacing approximately 23% of fish meal with blood meal reduced phosphorus concentrations in feed and effluent by 38% and 47%, respectively. However, it has been demonstrated that fish fed soy meal-based diets have a higher soluble phosphorus profile in their effluent (Kim et al., 1998; Medale et al., 1998). Kim et al. (1998) hypothesize that this might be due to an excess of total available phosphorus supplied mainly in the inorganic form. They also demonstrated that soy-based diets were not as efficient in terms of growth, especially for small fish.

The total replacement of protein by a soy-based concentrate was not recommended by Medale et al. (1998) but levels of up to 75% SPC did not impair growth or food conversion. Medale et al. also found that diets with soy-based protein had higher nitrogen and phosphorus releases to the effluent. Robinson and Meng (1998) found that channel catfish showed no difference in weight gain on total soy-based diets when protein contents were between 20% and 32%. At higher protein levels, animal-based protein diets resulted in increased weight gain and food conversion ratio, compared with total soy-based diets.

Vielma and Lall (1998) showed that diets high in calcium do not interfere with the utilization of phosphorus. However, diets containing plant-based protein sources may benefit from high calcium ratios.

The use of treated feeds with antibiotics and its impact on digestibility of lipids was studied by Cravedi et. al. (1987) who reported that total lipid deposits were not affected, but the use of antibiotics significantly enhanced the digestibility of some unsaturated fatty acids.

Studies have been conducted on diet formulations to reduce phosphorus (Weismann and Pfeffer, 1988; Jacobson and Borresen, 1995; Lanari et al., 1995) or to improve nutritional quality based on bioenergetic knowledge and models of fish assimilation (Cho et al., 1994; Cho et al., 1998; Azevedo et al., 1998; Bureau and Cho, 1999). Most of the feeding guides and diet formulations used in the aquaculture industry are based on meal-meat mixture diets of the 1950-60's (Cho et al., 1998). In contrast, the new feeding standards are being based on principles of nutritional energetics in which digestible protein and energy ratio and the amount of digestible energy required per unit of live weight gain are taken into account (Cho et al., 1998). The overall goal is to produce a feed so well-suited to the nutritional needs of the fish that maximum growth can be achieved with the minimum waste, specifically phosphorus and nitrogen. Azevedo et al. (1998) showed that feed efficiencies in rainbow trout were not influenced by the feeding level. Merely reducing the protein level in diets is a means of reducing nutrient loading, but also results in decreased food conversion ratios and growth rates (Lanari et al., 1995). Culturing conditions and factors such as temperature and oxygen influence the digestibility of protein in fish (Rodrigues, 1995). Models developed by Cho and Bureau (1998), such as Fish-PrFEQ software can now be used to estimate production, feeding ration and waste output for aquaculture operations. In addition to dietary information, the models include oxygen and temperature as variables in their calculations. Modern feed formulations have the potential to significantly reduced the quantity of wastes and are highly digestible and nutrient-dense diets for salmonids that result in outputs of less than 150 kg of solids and 3 kg of phosphorus per metric ton of fish produced (Cho and

Bureau, 1997). These formulations are being developed and used by the Ontario Ministry of Natural Resources in their fish culture stations, but widespread adoption of this approach to feed formulation has not yet been taken up by the major feed manufacturers.

5.1.1 Characterization of Fish Wastes

Of the papers reviewed, there were 27 that dealt with effluent and sludge from freshwater fish farms. These do not include feed-related studies that are reviewed separately above. There is undoubtedly cross-over between the two categories. Of the 27 papers reviewed, the following general topics were covered:

- Characterization of quantity and quality of effluent and sludge – 10 papers (2 Canadian).
- Impact of wastes on biota (2 papers), general impacts (3 papers – 2 Canadian).
- Remediation and treatment of wastes - 12 papers (1 Canadian).

Freshwater environmental impacts from effluent are a result of waste loading from net-pen culture in lakes and rivers as well as land-based (hatchery and growout) systems that discharge into these water bodies. Unlike the marine system, freshwater cage and land-based systems have been relatively modest in size. However, there has recently been interest in more intensive and higher production volumes for freshwater facilities. It is difficult to predict the potential environmental impacts of larger systems based on the experience of the existing modest sized systems.

Beveridge (1984) summarized the history and diversity of methods used in temperate and tropical fish culture, described many of the environmental effects on fresh waters, and proposed some preliminary models to predict the carrying capacity of lakes and ponds for fish culturing. Persson (1991) similarly looked at salmonid farming in Scandinavian fresh and marine waters. Most of the published environmental studies for lake cage culturing of temperate fish species, specifically salmonids, are from European waters where freshwater fish farming has been established and rapidly growing for more than two decades (Kelly et al., 1997, Bergheim et al., 1984, Kelly et al., 1994, Oberdorff and Porcher, 1994, Hennessy et al., 1994).

There has been a considerable effort to estimate the quantity of effluent that can be expected based on the nature of operations of specific fish farms. All studies agree that there is a correlation between waste output and the quantity of feed applied. Clark et al., 1985 found that waste production varied inversely with fish size and that the main pollutants per kg of fish produced per day were ammonia (0.3 – 0.8 g); phosphate (0.067 – 0.17 g), nitrate (0.13 – 0.21 g), and suspended solids (0.8 – 0.94 g). Other studies investigating the quantity of waste products have similar findings (Axler et al., 1997, Hennessy et al., 1993, Enell, 1983).

Siddiqui and Al-Habari, 1999 examined nitrogen and phosphorus budgets in land-based tilapia systems and found similar waste outputs for this warm water species. They also determined that 21.4% of nitrogen and 18.8% of phosphorus was retained by the fish. Chen (1998) states that of the total nitrogen and phosphorus in the feed, approximately 70% and 80% respectively will be lost to the aquatic environment. Wei and Laws, 1989 demonstrated that there are important temporal and spatial variations in nutrient levels in the water column in ponds. This characteristic is common to most static or semi-static freshwater bodies and must be considered in sampling design.

Chemical composition of fish solids was evaluated from commercial trout farms in Ontario (Naylor et al., 1999) and it was found that fresh fish manure is similar to other livestock manure in its chemical composition and, therefore, could be considered for agricultural fertilizer application. Parameters evaluated included N, P, K, Ca, Mg and metals. Kelly et al. (1997) looked at the differences between particle size of fish wastes and their respective water quality parameters. It was found that filtration at 60-100 μm during tank cleaning was effective at reducing BOD, suspended solids and, to a lesser degree, total phosphorus. No significant differences were found in the effectiveness of 100 vs. 60 μm filtration. Filtering during non-peak periods was found to be approximately half as effective as during peak periods. Thus, filtration alone cannot be looked at as the sole solution to reducing loadings, except during periods of high discharge. In addition, as the majority of phosphorus loading from farms is in the dissolved form, filtration would have little impact on its reduction.

Chen (1998) in his review of waste management, compared the waste generated for a ton of catfish to other agricultural land animals. Although the volume of waste is upwards of 2000% higher, the waste parameters of BOD, solids, and nitrogen are at, or below, the levels for the other animals. Compared to municipal sludge, aquaculture sludge has a lower solid and BOD concentration.

Several authors have undertaken studies to predict or calculate waste outputs. Bergheim et al. (1984) relate ammonia output to direct feed input; Kelly et al. (1994) draw a further correlation between ammonia output, feed, and water temperature; and Bureau and Cho (1999) offer calculations for estimating dissolved waste outputs based on feed quantity, digestibility and retention by the fish. Legislation in Denmark has stipulated the actual amount of feed on a national basis that can be used by the freshwater aquaculture industry in a year, in order to reduce nutrient inputs and remediate freshwaters (Iversen, 1995).

5.1.2 Impacts of Fish Wastes

The impacts of effluents on other biotic systems is poorly represented with respect to freshwater aquaculture. The impacts of organic enrichment, as well as sedimentation and resultant anoxic conditions, can reduce or eliminate biota in the sediments and water column downstream of the effluent source. Biotic indices have been developed and evaluated with respect to their use as indicators of impacts. Oberdorff and Porcher, 1994 evaluated the 'Index of Biotic Integrity' (IBI). When the IBI was applied to fish assemblages, it was found that it correlated well with measured chemical parameters associated with fish farm effluent. As expected, "habitat specialist" species tend to disappear as a result of sedimentation effects, whereas "habitat generalists" are not affected or increase in biomass as food availability increases as a result of higher organic loading. Gabrielsen (1999) studied the impact of four fish farms in Scandinavian lakes on the community structure of brown trout and Arctic charr and found that the trout population declined and the charr population increased largely as a result of the diet choices of the two species. Phillips et al. (1985) describes several other studies that have demonstrated that wild fish populations, including brown trout, can increase and become reliant on waste feed from net-pen cages. A comparison of several different indices for invertebrate species in a freshwater stream receiving fish effluents was conducted by Camargo (1992). This study found that there was significant variation in the sensitivity of the indices for species richness. This implies that the use of biological indices and/or the incorporation of biological indices into models must be tempered by the choice of index used.

Three studies (2 in Canada and 1 in Scotland) were conducted on site-specific assessments of the impacts of salmonids reared in net-pens in a lake (MacIssac and Stockner, 1995; Cornel and Whoriskey, 1993; Beveridge and Muir, 1982). In all of the studies, it was found that the anticipated impacts of nutrient loading and sedimentation were not severe nor were they perceived to exceed the capacity of the water body. Beveridge and Muir (1982) determined that, although the nutrient loading was far in excess of that prescribed by limnological studies published in 1968, the water quality was not experiencing eutrophication effects. The studies conclude that, although an understanding of the present status of a lake can be obtained by a synoptic evaluation, it is of little use in understanding environmental degradation. Long-term environmental impacts are the more critical factors in assessing impacts from lake aquaculture (Cornel and Whoriskey, 1993).

5.1.3 Nutrient Enrichment

The release of nutrients from an aquaculture facility can lead to enhanced primary production. The correspondence between magnitude of input and effect is not linear, and is affected by environmental variables and the other inputs and conditions associated with the aquaculture operation (Holeck et al., 1998; Dobrowolski, 1987; Munro et al., 1985; Selong and Helfrich, 1998). Often, input of nutrients from aquaculture waste can cause an ecosystem-level shift toward higher system production and net heterotrophy by enhancing the long-term cycling of nutrients through primary production and biomass remineralization (Sorokin et al., 1999, Munro et al., 1985). Various environmental conditions influence the relationship between added nutrients and primary production. Sufficient N must be available to allow phytoplankton to benefit from added P (Kelly, 1993). However, the temporal scales of degradation of C, N and P in solid aquaculture waste are decoupled, with P being the longest in marine and freshwater systems (Hall et al., 1992; Enell, 1983; Shrestha and Lin, 1996). Environmental adjustments, such as proliferation of nitrogen-fixing organisms (Stirling and Dey, 1990; Sorokin et al., 1999) may occur that amplify the impact of added nutrients, such as P.

The ratio of several nutrients, rather than the quantity, may be a factor influencing the species composition of the phytoplankton. For example, in fish ponds, diatom production is favoured by high N P ratios of available nutrients (Boyd, 1997). Low N:P ratios in lakes produce blooms of cyanophytes (Stirling and Dey, 1990; Foy and Rosell, 1991) and in coastal waters high N and P relative to silica produce blooms of toxic dinoflagellates (Holby and Hall, 1994). Fish farm discharges often have low N:P ratios in soluble nutrients (Foy and Rosell, 1991), which would impact the phytoplankton communities by producing a condition of N limitation and by encouraging the growth of nitrogen-fixing species (Foy and Rosell, 1991). The solid waste from fish farms, which is high in P, released over long time periods, can cause an persistent ecosystem-level shift to a dominance of cyanophytes. The cyanophytes modify the abundance of all other primary producers by reducing available light. This phenomenon has been documented in a Scottish freshwater loch due to finfish culture (Stirling and Dey, 1990) and in estuaries subjected to organic inputs from various sources. The influences of environmental variables in mediating interactions between the N:P ratio of available nutrients and species composition of the phytoplankton have not been adequately addressed.

The burial rate of silica in sediments underlying fish pens is high, and the uptake by fish of added silica in artificial diets is low. Biogenic flux from the sediments, however, can be high, providing a niche for silica-utilizing diatoms (Holby and Hall, 1994). There has been little work done on this subject, an obvious gap.

Phosphorus (P) is considered to be a limiting nutrient in many freshwater systems, and the addition of P can lead to alterations of ecosystem structure and function at all levels of integration. Because of concerns in the early 1980's that P loading from fish culture was negatively impacting freshwater lakes, there have been many research projects that focus on P metabolism in fish, P loading to the environment from fish cages, and P cycling in the water and benthos of systems that receive aquaculture waste. Approximately 32 papers in the database deal with some aspect of phosphorus enrichment due to aquaculture. The majority of studies concentrating on phosphorus enrichment from aquaculture facilities have been done in Europe and the U.K., but the findings are of general relevance to the Canadian context for fish hatcheries in freshwater and finfish cage installations in estuaries and some enclosed bays.

Phosphorus enrichment of the environment due to aquaculture largely results from leaching of soluble P from sedimenting food and feces, and deposition of particulate P to the sediments. The leaching of soluble P from sedimenting food pellets can be significant, up to 12% in a 30 m. water column (Garcia-Ruiz and Hall, 1996; Phillips et al., 1993). The feces are enriched in labile P relative to total P when compared to the food, and the rates of leaching of the labile P are high and variable (Pettersson, 1988; Phillips et al., 1993; Garcia-Ruiz and Hall, 1996), because of the mineralization of total P in the fish guts (Foy and Rosell, 1991). The rates of leaching of phosphorus from fish food during incubations ranged from 5 to 180 ug P/g dw/min, varying as a function of incubation conditions and diet formulations (Garcia-Ruiz and Hall, 1996; Phillips et al., 1993; Pettersson, 1988). Rates of leaching of phosphorus from feces were higher, varying from 54 to 251 ug P/g dw/min, largely as a function of diet formulation (Phillips et al., 1993). As well as dissolved labile P leaching from fish feces, it has been suggested that high levels of free alkaline phosphatase are directly released by the feeding fish (Carr and Goulder, 1990; Massik and Costello, 1995). The implications of this release are far-reaching. Free alkaline phosphatase carried downstream of a fish farm could transform organic phosphorus from the fish farm effluent as well as naturally-occurring forms into labile, dissolved reactive phosphorus which would be readily available to support enhanced primary production at some distances from the aquaculture facility (Car and Goulder, 1990). We need to have a better understanding of the environmental significance of this release (Car and Goulder, 1990).

Phosphorus release from fish pens is largely in the form of particulates which sink and enrich the sediment community immediately below the fish pens (Kelly, 1993, 1992; Hall et al., 1992; Trojanowski et al., 1985; Trojanowski et al., 1982; Shrestha and Lin, 1996; Holeck et al., 1998;Wildish et al., 1993). Release of this P over time can result in enhanced primary production (Kelly, 1993; Trojanowski et al., 1985) which may result in the proliferation of toxic algal species (Trojanowski et al., 1982) in both freshwater and marine systems. The connection between phosphorus release from these sediments and the enhancement of primary production is affected by many factors. The interactions among these factors are poorly understood. For example, the enhancement of chlorophyll-a by P enrichment from any source, including sediment release, may be affected by the availability of nitrogen (Kelly, 1993; Boyd, 1997; Foy and Rosell, 1991), the presence of humic substances (Kelly, 1993), water clarity (Trojanowski et al., 1985; Massik and Costello, 1995), alkalinity (Shrestha and Lin, 1996), physical events leading to sediment resuspension (Wildish et al., 1993; Foy and Rosell, 1991; Stirling and Dey, 1990) and temperature (Massik and Costello, 1995, Pettersson, 1988). Understanding the interrelationships among these variables is an area where there is a clear gap. For example, a negative feedback occurs between oxygen concentrations in the overlying water and phosphorus release from the sediments, with highest P release rates occurring in low oxygen conditions (Wisniewski and Planter, 1987). In benthic environments subjected to organic inputs such as the solid waste from fish pens, decreasing oxygen concentrations near the sediment surface result from the decomposition of the labile organic material. Thus, a feedback occurs between the organic loading, the quantity of deposited total P and its lability. This feedback is temperature-dependent (Wisniewski and

Planter, 1987), a function of the availability of reduced iron and manganese (Enell and Lof, 1983; Hatcher et al., 1994) and poorly characterized, a clear gap in our knowledge as described by the papers in the database.

The magnitude of the impact of phosphorus in fish farm waste is a function of its bioavailability. Borum et al. (1995), Massik and Costello (1995), and Foy and Rosell (1991) commented on the lack of knowledge of the bioavailability of the P in feces of farmed fish. We do know that feces of salmonids are enriched in bioavailable P relative to the added food (Pettersson, 1988; Foy and Rosell, 1991; Massik and Costello, 1995). This changes with temperature and with the growth stage of the fish, but we know little about the mechanisms (Foy and Rosell, 1991). This is a gap. Of particular relevance to the Canadian context, it has been suggested that decreasing temperature can enhance both the P metabolism of cultured fish (Kibria et al., 1998; Pettersson, 1988) and the release of soluble reactive P from fish farm waste (Hatcher et al., 1994). The work that has been done on P release from sediments has been largely performed at warmer temperatures, so the influence of cold Canadian temperatures, when P mobilization could be accelerated (Hatcher et al., 1994), is not well known.

There are several reasons that the bioavailability of P in feces is significant in terms of assessing impacts. The degree of bioavailability can affect the spatial and temporal extent of the impact. For example, uptake of dissolved bioavailable P enhances primary production in the short term in the immediate vicinity of the fish pens. Recalcitrant, bound P is sedimented to the bottom or transported to other parts of the system and is either buried or released over longer temporal and broader spatial scales due to biogeochemical processing in the sediments. Transport from the point source can either be through physical removal of resuspended contaminated sediments during higher energy conditions (Wildish et al., 1993) or through biological transport (Johansson et al., 1998; Hakansson et al., 1998; Borum et al., 1995). Feces of cultured fish in lakes are ingested by wild species of fish (Johansson et al., 1998; Hakansson et al., 1998; Borum et al., 1995), which can act as a mechanism for widespread application of phosphorus. The magnitude of the impacts of this diffusion of nutrients from the point-source input are a function of the bioavailability of the nutrients in the feces. No information on wild species around Canadian aquaculture facilities was found in the database, but this information is critical in assessing environmental impacts in general and the potential transport of phosphorus and other nutrients through this mechanism in particular.

5.1.4 Identified Research Gaps

Identified research gaps identified in the reviewed literature include:

- Additional studies on the relationship between diet, rearing unit hydraulic characteristics and management practices as related to waste characteristics (UMA Engineering, 1988).

- Field testing and development of technology to capture settleable solids of freshwater net-pens (Behmer et al., 1993; Enell, 1983).
- Long term and holistic monitoring of freshwater lakes with respect to aquaculture impacts (Cornel and Whoriskey, 1993; MacIssac and Stockner, 1995).
- Relationship between energy levels in diets, energy retention in fish and temperature (Azevedo, et al., 1998).
- Studies to evaluate dietary supplements such as calcium (Vielma and Lall, 1998) and sulphur amino acids (Kim et al., 1998) to augment plant protein based diets.
- Studies on appetite regulating factors (Medale et al., 1998) and additional studies on feeding strategies (Cho et al., 1994, Cho and Bureau, 1998).
- Feeding strategies with respect to diet formulation and desired body composition at harvest (Lanari et al., 1995).
- The mechanisms involved in fatty acid uptake and influence by antibiotics requires investigation (Cravedi et al., 1987).

5.2 DISEASE AND USE OF CHEMOTHERAPEUTANTS

Fish farming like most other forms of husbandry has experienced disease problems, which arise out of increased holding density conditions and/or providing suitable conditions to facilitate pathogens. Fish disease has been an important constraint to aquaculture development and there has been concern about the transfer of disease from cultured fish to wild stocks focused on the introduction of new diseases. This has largely been addressed by controlling fish transfers and certifying juvenile stock. The greater concern for the aquaculture industry is the onset of disease from indigenous opportunistic pathogenic organisms (Phillips et al., 1985). As such, farmers have adopted widespread use of chemotherapeutants to reduce the impacts of disease. The propagation and spread of disease to other populations is a concern, as is the impact of the chemicals being used to treat the diseases. Within the freshwater aquaculture sector, issues relating to disease involve use of therapeutants in general, fate of chemicals within the aquatic environment, effectiveness and resistance to therapeutants, and regulation and approval of aquaculture drugs for use, risk to humans.

Thirteen papers were reviewed pertaining to the use of chemotherapeutants, 5 of which were generated in Canada (Burridge and Haya, 1990; Brooks, 1989; Thorburn and Moccia, 1993; Haya et al., 1997; Burridge, 1998). Studies conducted in Canada dealt with determination of fish stress level using insulin levels as an indicator (Burridge, 1998), determining a stress and growth inhibitor indicator (Haya et al., 1997), use of chemotherapeutants by Ontario trout farmers (Thorburn and Moccia, 1993), lethality of a biocide to juvenile Atlantic salmon

(Burridge and Haya, 1990), and regulatory issues of drug use in aquaculture (Brooks, 1989). Foreign papers dealt with fate and reduction of antibiotics in effluents (Vaughn et al., 1996; Smith et al., 1994; Spanggaard et al., 1993; Cazabon et al., 1991), regulatory review of ecotoxicological risk assessment (Redshaw, 1995), and parasite profiles of farmed and wild salmon and eels (Bristow, 1993; Koops and Hartman, 1989). The lack of Canadian studies on fate of these chemicals in freshwater systems illustrates a gap in the database, even though similar studies of therapeutant fate have been conducted in the marine environment.

Appropriate use of drugs in aquaculture will depend upon having standardized criteria for approving the use of any chemical, controlling the use of it by limiting the amounts than can be applied in fixed periods of time, and developing standardized application methods. This approach dictates that there is a knowledge base on the potential risks to aquatic flora and fauna, that chemical fate pathways are understood including risks of bio-accumulation and human health risks, and treatment systems are effective. Papers covered near-field studies as well as general overviews and risk associated with chemical use. The papers were within 4 to 11 years old. The Canadian regulatory review of aquaculture drugs was 11 years old and could be considered out-of-date, given the changes in drug use in Canada since that time. The Canadian papers were exclusive to New Brunswick and Ontario.

Redshaw (1995) outlines potential impacts from the use of chemicals in freshwater environments, including:

- Induction of antibiotic resistance in aquatic microorganisms.
- Killing of non-target species.
- Uptake of contaminants by wild species.
- Inhibition of microbial activity below fish cages.
- Contamination of potable water supply.

Of the literature reviewed only two of the above impacts are represented.

Fish pathogenic bacteria constitute only a small percentage of the total bacterial flora in fish farms and the development of antibiotic resistance in the bacterial population may have serious environmental consequences. In addition, with most fish farms having a free exchange of water to a river or ocean, resistant bacteria can spread with water circulation (Spanggaard et al., 1993). The environmental impact of effluent from hospitals, farms and communities has been well studied, whereas the effects of fish farm effluents on the antibiotic resistance of the microflora surrounding fish farms is poorly understood (Spanggaard, et al., 1993). Spanggaard, et al., (1993) delineated resistance profiles of two antibiotics, oxytetracycline and oxolinic acid for 296 bacterial strains from three fish farms and an unpolluted stream in Denmark. Two types of resistance curves were observed. One showed an instant inhibition at a given concentration of antibiotic. The other curve showed a slow decrease in growth with increasing concentration of antibiotic. It was determined that resistance to oxytetracycline was higher in the fish farm waters (15%) vs. the unpolluted stream (6%). Similarly, resistance to oxolinic acid was also higher in the fish farm waters (27%) vs. the unpolluted stream (16%).

Vaughan et al. (1996) found that the frequency of antibiotic resistance in effluent microflora of fish farms was dramatically different at samples taken at two different locations in the farm outflow. In oxytetracycline-free laboratory mesocosms studies, it was demonstrated that in the presence of anaerobically decomposing fish feed, river sediments, and river water, the frequency of oxytetracycline-resistant strains increased rapidly at 18^{o}C. In the presence of feed, resistance increased from 1% to 25% after 14 days. When feed was not present, the frequency of resistance remained below 1%. This information has importance in the design of these types of studies.

A survey of the use chemotherapeutants by trout farms in Ontario indicated that gill disease was the primary reason for treatment. Prophylactic treatments were more frequent than post disease treatments. There was a common occurrence of treatment failure indicating incorrect application.

One study conducted in Ireland (Smith et al., 1993), indicates that the correct design of effluent treatment systems could significantly reduce the environmental impact of land-based fish farms by the capture and removal of antibacterial agents from the waste stream. This statement is true of most constituents of land-based fish farm effluents. Cazabon et al. (1991) showed that a sediment trap and drum filter were effective at removing over 90% of oxytetracycline from a land-based fish farm.

Bristow (1993) conducted a review of the 40 known parasites of wild freshwater Norwegian Salmonidae, of which over 20 are known to affect cultured salmonid species. Wild Salmonidae are, in most cases, the only reservoirs for these parasites in Norwegian waters (Bristow, 1993). There is concern over the host-parasite relationships that are being found in aquaculture conditions and how this will impact the development or spread of parasites. The importation of live eels from the Far East in the early 1970's is attributed for the parasitic nematode (*Anguillicola*), which now infests the swim bladders of eels throughout Europe (Koops and Hartman, 1989). Glass eels were not affected as the parasite does not propagate in saline waters (Koops and Hartman, 1989).

5.2.1 Identified Research Gaps

Areas requiring further research as identified in the referenced literature include:

- Additional studies on the resistance characteristics of microflora strains to antibiotics (Vaughan et al., 1996).
- Studies to address the link (or risk) between antibiotic resistance of aquatic microflora and human health (Vaughan et al., 1996).
- Additional studies to acquire better understanding of the processes involved with respect to chemicals in sediment.
- More studies to identify relationships of chemical impacts on biota in surrounding water and sediments required for improving environmental fate models (Redshaw, 1995).
- Further research on the epidemiology of the parasites of wild Salmonidae, particularly charr and trout (Bristow, 1993).
- Studies on the development of a routine and on-going epidemiological program for chemotherapeutant use in freshwater in Canada (Thorburn and Moccia, 1993).

5.3 CULTURED AND WILD SPECIES INTERACTIONS

5.3.1 Establishment of Exotic Species, Predation and Resource Competition

Jones and Stanfield (1993) examined the interactions of juvenile Atlantic salmon and brown trout, rainbow trout, and coho salmon in a tributary and found that biological interactions between these species may limit the rearing success of Atlantic salmon in natural systems.

5.3.2 Genetic Interaction

The review of cultured and wild species interactions and genetic impacts was considered to apply equally to both fresh and marine environments. The review of this subset of literature is presented in the 'Marine Finfish' section.

5.3.3 Identified Research Gaps

Phillips et al., 1985 comments on the need for additional research on the behavioral interactions of freshwater species, specifically brown and rainbow trout and Atlantic salmon and rainbow trout. Please refer to the 'Marine Finfish' section regarding recommended research priorities as identified by the referenced literature.

5.4 DISTURBANCE AND PREDATOR CONTROL ACTIVITIES

The database reviewed did not contain any papers on predator control activities or their impacts on natural systems or animals.

6. KNOWLEDGE SUMMARY

This report incorporated the review of over 600 scientific references. The majority of these references pertained to marine finfish. A considerably smaller number of references were included that examined the effects of freshwater aquaculture, and very few studies were included in the database that pertained to shellfish aquaculture.

Impacts of organic waste on the water column, sediment chemistry, and benthic organisms received the greatest attention. Some information on the effects of chemicals used in aquaculture was present but, in general, information regarding the fate and effects of chemicals used in Canadian ecosystems was not provided in the referenced literature. Several references identified concerns of disease and genetic impacts, but few provided documented evidence. Limited information was also available on effects on aquatic biota other than benthic communities and wild fish populations.

Most studies assessed the effects on specific populations and in some cases, communities. The majority of relevant studies also examined near-field effects over relatively short time periods. Very few studies were identified that examined effects over longer terms or examined cumulative impacts of multiple farms or farms in conjunction with other human activities. Similarly, comprehensive integrated assessments which examined ecosystems in their entirety were poorly represented in the referenced literature.

APPENDIX A

Citations Not Referenced in the Database

APPENDIX A
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APPENDIX B

Database Bibliography – Non-excluded References[1]

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