Canada

SCOPING SCIENCE ASSESSMENT OF THE IMPACTS OF FRESHWATER AQUACULTURE ON THE CANADIAN ENVIRONMENT

S.L. Walker, S.S. Dixit, D. Andersen,
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L.A. Howes, L. Kingsley

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S.L. Walker[1,5], S.S. Dixit[2,5], D. Andersen[1,5], P.Y. Caux[3,5], P.A. Chambers[1,6], M.C. Charlton[1,6], L.A. Howes[4,5], L. Kingsley[4,5]

[1]National Water Research Institute
[2]Water Policy and Coordination Directorate
[3]Conservation Programs Integration
[4]Canadian Wildlife Service
[5]Environment Canada, 351 St. Joseph Blvd., Gatineau, Quebec, K1A 0H3, Canada
[6]867 Lakeshore Blvd, Burlington, Ontario, L7R 4A6, Canada

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Abstract

Commercial aquaculture in Canada has rapidly expanded in the last 20 years and is expected to grow further in coming years. In 2000, the federal government implemented a Program for Sustainable Aquaculture in Canada, led by Fisheries and Oceans Canada. Under this program, Environment Canada was given responsibilities to develop science assessment tools and conduct research to assess the effects of aquaculture operations on freshwater ecosystems. Freshwater aquaculture involves growing a large number of fish in a small space, similar to livestock in feedlots. Types of waste produced from feeding fish include solid (feces, uneaten feed, and organic matter) and soluble (dissolved phosphorus, ammonia, dissolved organic carbon, and lipids) material. As well, there are inputs of drugs, disinfectants and other chemicals as part of the ongoing operation and maintenance of the aquaculture operations. Aquaculture operations across Canada vary greatly. Some land-based operations use recirculation and wastewater treatment technology, thereby reducing input of nutrients and other chemicals. However, net cage operations generally disperse waste directly into public waters.

Environmental impacts of aquaculture vary from minimal to severe impairment depending upon the site characteristics, the type, size and practices of the operation, and the nature of the wastes in the aquaculture effluent. The most common impact of aquaculture is nutrient enrichment potentially resulting in eutrophication. Other potential changes include deterioration of water quality, changes in physical and chemical characteristics of the sediment, shifts in algal and invertebrate communities, increase of birds around net cages, and increased interactions, disease transmission, and competition between farmed and wild fish. A review of the existing environmental monitoring programs indicates a lack of consistency across Canada. Similarly, Canadian Environmental Quality Guidelines are lacking for many chemicals used in aquaculture. This report identifies information gaps and recommends the development of science-based tools and research to improve the scientific basis for sustainable management of freshwater aquaculture in Canada.

Resumé

Au Canada, le secteur de l'aquaculture commerciale connaît depuis deux décennies une croissance rapide, que l'on s'attend à voir se poursuivre au cours des années à venir. En 2000, le gouvernement fédéral a lancé le Programme d'aquaculture durable, sous la responsabilité de Pêches et Océans Canada. Dans le cadre de ce programme, Environnement Canada s'est vu confier la responsabilité d'élaborer des outils d'évaluation scientifique et de procéder à des recherches afin de connaître les effets de l'aquaculture sur les écosystèmes dulcicoles. L'aquaculture en eau douce consiste à élever un grand nombre de poissons dans un espace restreint; en cela, on peut la comparer à l'élevage de bétail en parcs d'engraissement. Cette industrie produit des déchets solides (matières fécales, reliefs de nourriture et matières organiques) et solubles (phosphore en solution, ammoniac, carbone organique dissous et lipides). De plus, les activités d'exploitation et d'entretien supposent l'administration de médicaments ainsi que l'emploi de désinfectants et autres produits chimiques. Au Canada, les fermes aquacoles diffèrent beaucoup entre-elles. Dans certaines installations continentales, on a recours à des techniques de recirculation et de traitement des eaux usées, ce qui permet de réduire les quantités de nutriments et autres substances chimiques rejetées. Par contre, les exploitations où l'on utilise des cages en filet répandent habituellement les déchets qu'elles produisent directement dans les eaux publiques.

Les répercussions de l'aquaculture sur l'environnement vont de dommages minimes à des dégâts graves, selon les caractéristiques du site, la taille et le type d'exploitation aquacole et les pratiques qu'on y adopte, ainsi que la nature des déchets rejetés dans les effluents de la ferme. L'incidence la plus courante de l'aquaculture sur l'environnement est un enrichissement en éléments nutritifs pouvant entraîner une eutrophisation. On peut aussi craindre d'autres changements comme la détérioration de la qualité de l'eau, la modification des caractéristiques physiques et chimiques des sédiments, des changements dans les communautés d'algues et d'invertébrés, l'accroissement du nombre d'oiseaux aux alentours des cages en filet, ainsi qu'une intensification des échanges, de la transmission de maladies et de la compétition entre les poissons d'élevage et les poissons sauvages. Lorsqu'on examine les programmes de suivi environnementaux en place, on constate un manque d'uniformité d'un endroit à l'autre au Canada. On remarque également que de nombreux produits chimiques utilisés en aquaculture ne sont pas visés par les Recommandations canadiennes pour la qualité de l'environnement. Dans le présent rapport, on identifie les lacunes et on recommande des travaux de recherche et la création d'outils scientifiques afin d'améliorer les fondements scientifiques de la gestion de l'aquaculture en eau douce dans une optique de durabilité.

Preface

The *Scoping Science Assessment of the Impacts of Freshwater Aquaculture on the Canadian Environment* was conducted under the direction of the Environment Canada Freshwater Aquaculture Science Working Group consisting of scientists from the National Water Research Institute, the Canadian Wildlife Service and the Water Policy and Coordination Directorate within the Environmental Conservation Service. This assessment reviews the available literature on the environmental impacts of freshwater aquaculture in Canada, monitoring programs, and environmental quality guidelines. Information gaps are identified and recommendations are made for future science needs for aquaculture. This assessment was undertaken by the Freshwater Aquaculture Science Working Group from the Environmental Conservation Service of Environment Canada (EC) as a first step under the Program for Sustainable Aquaculture (PSA), implemented in August 2000. This report is intended to provide background information needed for Environment Canada to fulfill its responsibilities under this program with the goal of improving the environmental and biological knowledge base to assess and understand the effects of aquaculture operations on the quality of freshwater ecosystems. This assessment is a scoping exercise and is not intended to be an exhaustive review of the literature as recent reviews are available elsewhere (e.g., BC Environmental Assessment Office 1996; Black 2001; US EPA 2002; Fisheries and Oceans Canada 2003a; Podemski et al. in prep.). Members of the working group included:

Sherry L. Walker (Chair)
Environmental Effects Monitoring Office
National Water Research Institute
Environment Canada

Dr. Sushil S. Dixit
National Guidelines and Standards Office
Water Policy and Coordination Directorate
Environment Canada

Don Andersen
Environmental Quality Monitoring Office
National Water Research Institute
Environment Canada

Dr. Pierre Yves Caux
Conservation Program Integration
Environment Canada

Dr. Patricia A. Chambers
Human Impacts on Aquactic Ecosystem Processes
National Water Research Institute
Environment Canada

Dr. Murray C. Charlton
Lake Management Research
National Water Research Institute
Environment Canada

Lesley-A. Howes
Program Analysis and Coordination
Canadian Wildlife Service
Environment Canada

Louise Kingsley
Program Analysis and Coordination
Canadian Wildlife Service
Environment Canada

Lise Trudel
Environmental Effects Monitoring Office
National Water Research Institute
Environment Canada

Executive Summary

Commercial, freshwater aquaculture is a relatively new industry in Canada, although early development of aquaculture practices including government hatcheries for fisheries enhancement date back to the 1800's. Freshwater aquaculture consists of government run hatcheries, open water commercial cage operations, land-based commercial operations, and small private ponds. These accounted for approximately 1.5% of total global aquaculture production in 1997.

Freshwater aquaculture involves growing a large number of fish in a small space, similar to livestock in feedlots. Land-based aquaculture uses recirculation and wastewater treatment technology. However, open net cage aquaculture generally disperse waste directly into publicly owned waters that have multiple uses. Even though the waste is less concentrated and less likely to be a direct health threat than other sources, such as municipal wastewater, public concerns are many.

Two types of waste are produced from feeding fish: (1) solid material includes feces, uneaten feed, and organic matter; and (2) soluble material includes dissolved phosphorus, ammonia, dissolved organic carbon, and lipids released from the diet. The amount of waste generated depends on feeding efficiency, feeding methodology, water currents, and net-pen configuration. As well, there are periodic inputs of drugs, disinfectants, and other chemicals as part of the ongoing operation and maintenance of aquaculture operations.

This report provides background information and identifies priorities in support of Environment Canada's (EC's) freshwater science initiatives under the federal Program for Sustainable Aquaculture (PSA), implemented in August 2000. Environmental impacts, environmental monitoring and environmental quality guidelines are reviewed. Information and research/science gaps are identified, and recommendations are made for future EC's science needs. The recommended science initiatives are intended to support one of the goals of the PSA, which is to increase knowledge for decision making through science, research, and development.

Environmental impacts of aquaculture operations are dependent upon the site conditions, the type and size of the aquaculture operation, and the nature of the wastes (and chemicals) released to the environment. The extent and nature of environmental impacts vary considerably on a site-specific basis. Fish farms that are well sited in areas with sufficient depth and water exchange generally noted few impacts, whereas farms that are poorly sited, such as in shallow water with insufficient mixing have noted severe impacts on water and sediment quality. Generally, environmental changes were typical of nutrient enrichment effects and were similar for both land-based operations that discharge to receiving waters and open net-cage operations.

Potential impacts of aquaculture on freshwater ecosystems include:

- increased loadings of nutrients potentially resulting in eutrophication and deterioration of water quality;
- increased input of organic matter resulting in impacts on sediment quality and changes in benthic communities;
- releases of therapeutant chemicals and increased incidence of resistant bacteria;
- increased abundance of pelagic and bottom dwelling organisms around net cages;
- escape of farmed fish resulting in increased competition for habitat and food with wild fish and potential cross breeding resulting in genetic impacts;
- transmission of diseases between wild and farmed populations;
- changes in the habitat and food supply for wild fish populations; and
- potential loss of habitat, injury, and persecution for wildlife and species at risk.

The review of monitoring programs indicate that there has been inconsistent monitoring and assessment of aquaculture sites across Canada. Monitoring is generally limited to a few water quality parameters and occasional sediment sampling. Biological monitoring is not routinely conducted at freshwater aquaculture sites in Canada but has been undertaken as part of research investigations. International monitoring programs also vary, but a number of them include both biological and physico-chemical components. Consistent, cost-effective monitoring targeted to site-specific conditions and specific operating practices would improve the scientific basis for environmental assessment and management, provide a level "playing field" for the industry, and enhance public confidence.

The review of environmental quality guidelines for the protection of aquatic life indicates that guidelines are only available or under development for core water quality parameters (e.g., dissolved oxygen, nutrients). Guidelines are lacking for most of the chemicals used in aquaculture including the chemotherapeutants, antibiotics, anesthetics, and disinfectants. In addition to developing generic guidelines for these chemicals for the protection of aquatic ecosystems, further efforts are required to develop site-specific guidelines to protect water quality from aquaculture operations.

Throughout this scoping assessment, many information gaps on the environmental effects of aquaculture were identified. The extent of impacts in Canada is largely unknown and in general, there is a paucity of Canadian studies on the environmental impacts of freshwater aquaculture in the literature. More data were available for Europe and the USA. As well, more information is available on the environmental impacts of mariculture than freshwater aquaculture. Although international studies have been incorporated into this report, their extrapolation to Canada is difficult and should be undertaken with caution because of differences in species cultured, aquaculture practices, and ecosystem characteristics. Some of the key science information gaps identified include:

- spatial extent and magnitude of nutrient and toxic effects to aquatic biota and wildlife;
- long-term effects of fish escapes on local biodiversity;
- the implications of expansion of the industry and methods for determining the carrying capacity of an area;

- current data on the type, frequency, and quantities of chemicals used and released to the environment by aquaculture operations and the associated environmental risks;
- the cause-effect relationships of changes in aquatic ecosystems resulting from aquaculture and the thresholds for these changes; and
- the cumulative impact from aquaculture (i.e., persecution) on wildlife populations in relation to other stressors.

To address these gaps and further enhance the science-policy linkages, the EC Freshwater Aquaculture Science Working Group recommends:

Research, Monitoring, and Knowledge Development

- A targeted science program to address the above information gaps to improve the understanding of the extent and significance of ecological changes from aquaculture operations and result in recommendations for policies to improve sustainable management practices for aquaculture.

Science-Based Tool Development

- Development of science-based tools and Best Management Practices to improve the sustainable management of aquaculture are required. This includes environmental quality guidelines, targeted environmental monitoring, and an environmental quality monitoring and assessment framework. This framework will assist in setting environmental quality benchmarks for receiving waters that could be used as the scientific basis for risk management in support of sustainable aquaculture.

Intergovernmental Science-Policy Coordination

- A mechanism is needed to better coordinate and integrate science activities among federal and provincial governments.

Sommaire

L'aquaculture en eau douce commerciale à grande échelle est une industrie relativement nouvelle au Canada, en dépit du fait que sa phase de développement initiale, comprenant les écloseries gouvernementales pour la mise en valeur des pêches, remonte au XIX^{e} siècle. Elle englobe l'exploitation d'écloseries gouvernementales, l'aquaculture commerciale en cages en eau libre, l'aquaculture commerciale à terre et les petits étangs privés. La production aquacole en eau douce au Canada représentait environ 1,5 % de la production aquacole mondiale en 1997.

L'aquaculture en eau douce consiste à élever un grand nombre de poissons dans un petit espace, un peu comme l'élevage de bétail dans des parcs d'engraissement. L'aquaculture à terre utilise des technologies de recyclage de l'eau et de traitement des eaux usées. Les déchets de l'aquaculture en cages sont habituellement rejetés directement dans des eaux publiques aux usages multiples. Certaines piscicultures emploient maintenant une technologie expérimentale de collecte des déchets. Même si ces déchets sont moins concentrés et constituent une menace sanitaire moins grande que d'autres types de déchets, telles que les eaux usées municipales, ils demeurent un sujet de préoccupations pour le public.

Deux types de déchets sont produits par les poissons en phase d'alimentation : (1) matières solides, comme les fèces, les aliments non consommés et la matière organique; (2) matières solubles, comme le phosphore et le carbone organique dissous, l'ammoniac et les lipides provenant de la nourriture. La quantité de déchets produits dépend de l'efficacité et de la méthode d'alimentation, des courants et de la configuration des cages. L'exploitation et l'entretien de piscicultures nécessitent également l'utilisation régulière de médicaments, de désinfectants et d'autres produits chimiques.

Dans ce rapport, nous fournissons des renseignements généraux sur les priorités et projets de recherche en eau douce réalisés par Environnement Canada (EC) dans le cadre du Programme fédéral d'aquaculture durable (PAD), lancé en août 2000. Nous abordons les répercussions environnementales, les recommandations pour la qualité de l'environnement et les programmes de surveillance liés à l'aquaculture en eau douce. Nous cernons les lacunes en matière d'information et de recherche et nous formulons des recommandations relativement aux besoins et activités scientifiques futurs d'EC. Les projets scientifiques recommandés visent à faciliter l'atteinte d'un des objectifs du PAD, soit l'approfondissement des connaissances pour améliorer le processus décisionnel par des travaux de recherche et de développement.

Les répercussions environnementales des activités aquacoles varient selon l'emplacement de la pisciculture, le type d'activités et leur ampleur ainsi que la nature des déchets produits (y compris les produits chimiques). L'étendue et la nature de ces répercussions varient considérablement d'un emplacement à l'autre. Les piscicultures bien situées, soit en des endroits où la profondeur et les échanges d'eau sont suffisants, ont habituellement des répercussions plus faibles sur la qualité de l'eau et des sédiments que les piscicultures mal situées. Généralement, les modifications du milieu consistent en son enrichissement en éléments nutritifs et elles sont semblables pour la pisciculture à terre qui rejette ses déchets dans les eaux réceptrices et la pisciculture en cages.

L'aquaculture peut avoir les répercussions suivantes sur les écosystèmes d'eau douce :

- l'accroissement de la charge en éléments nutritifs qui peut entraîner l'eutrophisation et la détérioration de la qualité de l'eau;
- l'augmentation de l'apport de matière organique qui peut modifier la qualité des sédiments ou les communautés benthiques;
- le rejet de produits chimiques thérapeutiques et une hausse de la fréquence de bactéries résistantes;
- l'accroissement de l'abondance d'organismes pélagiques ou benthiques autour des cages;
- l'évasion de poissons d'élevage qui peuvent concurrencer les poissons sauvages pour l'habitat et la nourriture et se reproduire avec eux et entraîner des modifications génétiques;
- la transmission de maladies entre les populations sauvages et d'élevage;
- la modification des habitats et de la nourriture disponibles pour les populations sauvages;
- la perte d'habitat et des atteintes directes aux espèces sauvages ou en péril.

L'examen des programmes de surveillance a révélé que les piscicultures existantes ont fait l'objet d'une surveillance. La capacité de prévision des répercussions des nouvelles piscicultures est très faible et qu'il existe un manque d'uniformité dans l'ensemble du pays. La surveillance se limite généralement à quelques paramètres de la qualité de l'eau et à l'échantillonnage occasionnel de sédiments. La surveillance biologique n'est pas effectuée régulièrement dans les piscicultures en eau douce au Canada, mais elle est menée dans le cadre d'études scientifiques. Les programmes de surveillance internationaux diffèrent, mais un certain nombre d'entre eux combinent des volets biologique et physico-chimique. Une surveillance méthodique et efficiente qui tient compte des conditions environnementales et des pratiques d'élevage propres à chaque pisciculture uniformiserait les règles du jeu pour l'industrie et améliorerait le degré de confiance du public.

L'examen des recommandations pour la qualité de l'environnement visant la protection de la faune aquatique a montré que des recommandations ne sont disponibles ou en élaboration que pour les paramètres de base de la qualité de l'eau (p. ex. oxygène dissous et éléments nutritifs). Aucune recommandation n'existe pour la majorité des produits chimiques utilisés en aquaculture, y compris les agents thérapeutiques, les antibiotiques, les agents anesthésiques et les désinfectants. En plus de formuler des recommandations générales pour les produits chimiques dans le but de protéger les écosystèmes aquatiques, il est nécessaire d'effectuer d'autres travaux pour élaborer des recommandations propres à chaque pisciculture et ainsi préserver la qualité de l'eau.

Tout au long de cette évaluation, nous avons cerné de nombreuses lacunes dans les données sur les répercussions environnementales de l'aquaculture. L'ampleur de ces répercussions au Canada est en grande partie inconnue, et il existe très peu d'études canadiennes sur celles-ci. Davantage de données sont disponibles pour l'Europe et les États-Unis. De plus, les répercussions environnementales de la mariculture sont mieux connues que celles de l'aquaculture en eau douce. Bien que nous ayons tenu compte d'études internationales dans ce rapport, leur extrapolation à la situation du Canada est difficile et doit être effectuée avec soin étant donné les différences au niveau des espèces élevées, des pratiques utilisées et des caractéristiques des écosystèmes concernés. Nous avons notamment cerné des lacunes importantes dans les données scientifiques sur les éléments suivants :

- l'étendue spatiale et l'ampleur des répercussions des substances nutritives ou toxiques sur le biote aquatique;
- les effets à long terme des évasions de poissons sur la biodiversité locale;
- les conséquences de l'expansion de l'industrie et les méthodes de détermination de la capacité de charge d'une région;
- les types, les fréquences d'utilisation et les quantités de produits chimiques employés, puis rejetés dans le milieu, de même que les risques environnementaux connexes;
- les relations de cause à effet qui entraînent les modifications des écosystèmes aquatiques attribuables à l'aquaculture et les seuils pour ces modifications;
- les effets cumulatifs de l'aquaculture sur les populations sauvages par rapport aux effets des autres sources de stress.

Afin de combler ces lacunes et de renforcer les liens entre la science et les politiques en matière d'aquaculture, le groupe de travail sur la science de l'aquaculture en eau douce d'EC recommande :

Recherche, surveillance et approfondissement des connaissances

- L'élaboration d'un programme scientifique ciblé pour combler les lacunes susmentionnées et ainsi approfondir les connaissances au sujet de l'ampleur et de l'importance des modifications écologiques entraînées par l'aquaculture. Ce programme permettra également de recommander des politiques visant à améliorer les pratiques de gestion durable pour l'aquaculture.

Mise au point d'outils scientifiques

- La mise au point d'outils scientifiques et de bonnes pratiques de gestion afin d'améliorer la gestion durable de l'aquaculture. Cela comprend des recommandations pour la qualité de l'environnement, une surveillance environnementale ciblée et un cadre de surveillance et d'évaluation de la qualité du milieu. Ce cadre facilitera l'établissement de points de référence en matière de qualité des eaux réceptrices, qui pourraient servir de base scientifique à la gestion des risques à l'appui d'une aquaculture durable.

Coordination intergouvernementale de la politique scientifique

- La création d'un mécanisme qui améliorera la coordination et l'intégration des activités scientifiques des gouvernements fédéral et provinciaux.

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1 Introduction

In August of 2000, the federal government implemented the Program for Sustainable Aquaculture (PSA) in Canada, led by Fisheries and Oceans Canada, to increase both the public's confidence that aquaculture is being developed in a sustainable manner and the industry's competitiveness in global markets. One of the goals of this program is improved knowledge for decision-making through additional environmental and biological research on the impacts of aquaculture on Canadian ecosystems and aquatic resources. In particular, Environment Canada was given responsibilities to develop science assessment tools (i.e., environmental effects monitoring and environmental quality guidelines), and conduct research to assess and track the effects of aquaculture operations on the quality of freshwater ecosystems.

The objective of this scoping science assessment is to provide background information and help identify future Environment Canada science needs to improve the sustainable management of freshwater aquaculture in Canada. This report is intended to support the goals of the PSA in Canada and, specifically, to increase knowledge for effective, science-based decision making relating to a sustainable freshwater aquaculture industry. The report:

- describes freshwater aquaculture and briefly reviews environmental legislation pertaining to the industry in Canada;
- reviews environmental monitoring programs;
- provides an overview of the environmental issues associated with both land-based and open cage freshwater aquaculture operations in Canada;
- reviews Canadian environmental quality guidelines applicable to aquaculture; and
- identifies information gaps, and the science and research needed to fulfill these gaps with an emphasis on areas within EC's mandate and responsibility.

This report is limited to freshwater aquaculture and focuses on areas of interest to EC (water and sediment quality, impacts on aquatic life, birds, wildlife and species at risk, environmental monitoring, and environmental quality guidelines). This report is not intended to be an exhaustive review and comprehensive assessment of all available literature as this type of review has been conducted elsewhere (e.g., BC Environmental Assessment Office 1996; Black 2001; US EPA 2002; Fisheries and Oceans Canada 2003a; Podemski et al. in prep.). Rather, the intent of this report is to identify and briefly review the environmental issues associated with both land-based and open net cage freshwater aquaculture so as to provide background information for future Environment Canada science initiatives including research, development of environmental quality guidelines, and design of an environmental quality monitoring and assessment framework. Where possible, the report has focused on North American studies. In the absence of North American studies, literature from Northern Europe was included. Marine studies were only included when freshwater studies on a specific topic were lacking. Studies conducted in tropical climates were excluded from the report since their ecological relevance to Canada was uncertain.

1.1 Background

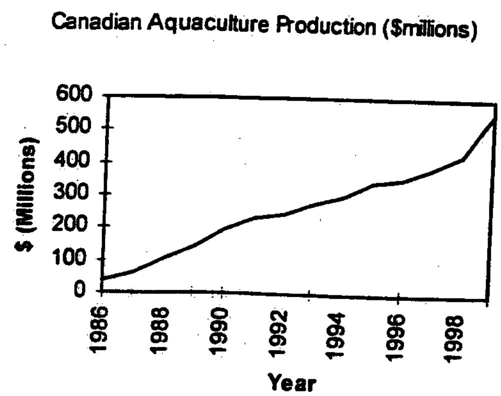
Aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans, and aquatic plants. Farming implies some form of intervention in the rearing process to enhance production, such as regular stocking, feeding, and protection from predators and disease. It also implies individual or corporate ownership of the stock being cultivated, which distinguishes aquaculture from the harvest fishery (FAO 1996). Aquaculture is achieved through the manipulation of an organism's life cycle and control of the environmental variables that influence it. Three main steps are involved: control of reproduction, control of growth, and elimination of mortality from predation (Beveridge 1996). Rearing systems, designed to hold organisms captive, are used in all types of aquaculture operations to allow the farmed organisms to increase in biomass while minimizing losses through predation and disease (Beveridge 1996). The techniques used in aquaculture vary from extensive systems, which are similar to natural ecosystems, to intensive systems requiring a high input of energy, food, and capital.

Aquaculture has ancient historical roots in Asia dating back 2000 years. In Canada, fish culture has been practiced by governments since the mid 1800's for the purpose of fisheries enhancement (Morin 2000a). A large network of government-run hatcheries was developed by the 1950's to stock rivers and lakes, as well as to maintain rare and endangered species (e.g., Copper redhorse, *Moxostoma hubbsi*) (www.fapaq.gouv.qc.ca/fr). Commercial aquaculture began in the 1940's in Québec (Boulanger and Hansen 1984) and in the 1950's in British Columbia. In 1962, changes to the *Ontario Game and Fish Act* permitted the private sector in Ontario to culture and sell certain fish species (Linington et al. 1999). Aquaculture remained in the developmental stages as an industry until the 1980's. Since that time, aquaculture development has greatly expanded from an industry of about $7 million in 1984 to an industry of $548 million in 1999 (Statistics Canada 2000).

With the expansion of the aquaculture industry in Canada, ENGOs and community groups (e.g., David Suzuki Foundation: Ellis 1996; Environmental Defense Fund: Goldburg and Triplett 1997; L'Order des agronomes du Québec 1997; Harvey and Buerkle 1997; Conservation Council of New Brunswick 1998; Georgian Bay North Channel Preservation Society: GBA Foundation 1999; Atlantic Salmon Federation: Taylor and Chase 2000) have raised a number of concerns regarding the environmental impacts of aquaculture practices. Marine aquaculture or mariculture has received more attention than freshwater aquaculture with regards to both studies and public concern. Some of the concerns expressed by these groups include: degradation of surface and ground water quality; the use of chemicals; habitat destruction; genetic mixing of escaped stocked fish with wild fish; disease transmission and habitat competition potentially resulting in depletion of wild fish stocks; nutrient enrichment; occurrence of harmful algal blooms; and aesthetic issues. These groups have also raised concerns about insufficient monitoring, inadequate enforcement of stipulated monitoring, and lack of enforcement with respect to discharge of pollutants into waters frequented by fish. In 1999, the International Joint Commission and the Great Lakes Fishery Commission held a roundtable on water quality impacts associated with Great Lakes aquaculture operations and made a number of recommendations to governments, the industry, and the commissions including research needs, policy and management measures (Great Lakes Fishery Commission and the International Joint Commission 1999).

2 Overview of Aquaculture Industry

Aquaculture is a growing industry in Canada. Canada's aquaculture industry generated estimated record revenues of $548 million in 1999, up 7 percent over 1998 with over 113 000 tonnes produced (Statistics Canada 2000). Although the industry is relatively young in Canada, production has steadily increased with a growth rate of approximately 15 percent per year (by volume) (Figure 2-1). Industry forecasts that aquaculture will continue to grow at about 20 percent per year in production volume over the next few years (OCAD 2001).



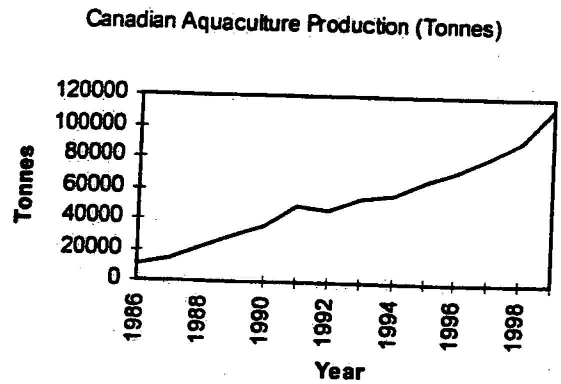


Figure 2-1: Canadian Aquaculture Production from 1986 to 2000. (Data from Statistics Canada 2000).

Currently, about 45 species of fish and seven invertebrates are licensed for farming at freshwater sites in Canada (Table 2-1). For comparison, the culture of trout (all species) is about one-tenth of the culture of salmon from marine farms (Figure 2-2). Rainbow trout (*Oncorhynchus mykiss*) is the main species farmed in Canadian freshwater. The production of trout in Canada serves three major markets (Manitoba Conservation 2001):

- food consumption;
- pond fishing; and
- lake/river stocking.

Table 2-1: Freshwater species eligible for licensing for aquaculture in Canada (Adapted from Chambers et al. 2001 with additional data from Lloyd 2000; Moccia and Bevan 2000; Morin 2000a,b; Alberta Agriculture, Food and Rural Development 2001; St. Jacques, Environment Canada, pers. comm.)

Fish	
Rainbow trout (*Oncorhynchus mykiss*)	Lake whitefish (*Coregonus clupeaformis*)
*Tiger trout (*Salmo trutta X Salvelinus fontinalis*)	Arctic char (*Salvelinus alpinus*)
Speckled trout (*Salvelinus fontinalis*)	*Tilapia (*Oreochromis, Sarotheradon, Tilapia*)
Brown trout (*Salmo trutta*)	Bluntnose minnow (*Pimephales notatus*)
Lake trout (*Salvelinus namaycush*)	Fathead minnow (*Pimephales promelas*)
Brook trout (*Salvelinus fontinalis*)	Redbelly dace (*Phoxinus eos*)
*American eel (*Anguilla rostrata*)	Finescale dace (*Phoxinus neogaeus*)
Lake sturgeon (*Acipenser fulvescens*)	Common shiner (*Luxilus cornutus*)
Lake herring (*Coregonus artedi*)	Golden shiner (*Notemigonus crysoleucas*)
Muskellunge (*Esox masquinongy*)	Emerald shiner (*Notropis atherinoides*)
Atlantic salmon (*Salmo salar*)	Carp (*Cyprinus carpio*)
Walleye (*Stizostedion vitreum*)	Grass carp (*Ctenopharyngodon idellus*)
*Coho salmon (*Oncorhynchus kisutch*)	Brown bullhead (*Ameiurus nebulosus*)
*Chinook salmon (*O. tshawytscha*)	Channel catfish (*Ictalurus punctatus*)
Pink salmon (*O. gorbuscha*)	Yellow perch (*Perca flavescens*)
*Sockeye salmon/Kokanee salmon (*O. nerka*)	Largemouth bass (*Micropterus salmoides*)
*Atlantic salmon (*Salmo salar*)	Smallmouth bass (*Micropterus dolomieu*)
*Goldfish (*Carassius auratus*)	Bluegill (*Lepomis macrochirus*)
Northern pike (*Esox lucius*)	Black crappie (*Pomoxis nigromaculatus*)
White sucker (*Catostomus commersoni*)	Creek chub (*Semotilus atromaculatus*)
*Bigmouth Buffalo fish (*Ictiobus cyprinellus*)	Sauger (*Stizostedion canadense*)
Pumkinseed (*Lepomis gibosus*)	Striped bass (*Morone saxatilis*)
Copper redhorse (*Moxostoma hubbsi*)	
Invertebrates	
Crayfish (*Cambarus robustus, C. bartonii, Orconectes immunus, O. virilis, O. propinquus*)	Snails (*Helix* sp.)
*Freshwater prawn (*Macrobrachium rosenbergii*)	

* License in Alberta allows fish to be kept and sold in contained waters only.

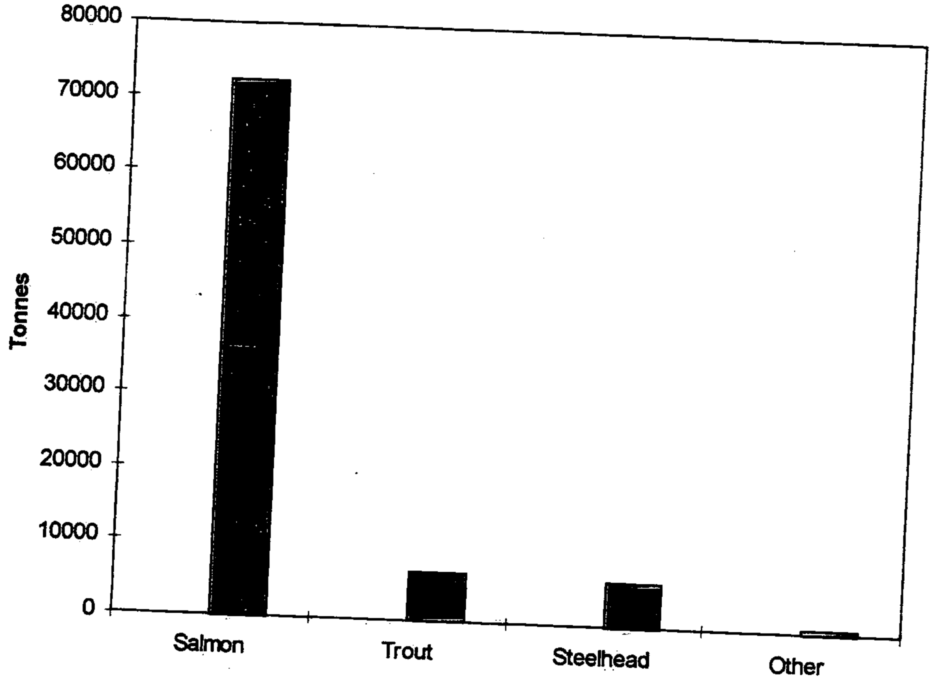


Figure 2-2: Canadian aquaculture finfish production for 1999 (Data from Statistics Canada 2000).

Rearing facilities for freshwater fish are either open water or land based. Open water systems are characterized by the installation of enclosures, such as cages or pens, under provisions of a lease. Land-based systems culture fish in a variety of semi-closed and closed structures including ponds, raceways, hatcheries, and holding tanks. Semi-closed systems use flow-through or recirculating technologies in specially designed facilities, which allows for controlled conditions to maximize production per unit area (Landau 1992; Muise & Associates 2000; Environment Canada 2001b). In closed or recirculating systems, organisms are raised in tanks or ponds in water that is extensively treated and recycled (Landau 1992; Beveridge 1996). Settling ponds, filtration systems, and constructed wetlands can be used to treat effluents from semi-closed systems before discharge to a receiving waterbody (Environment Canada 2001b). Fishing ponds, "U-fish", or fish-for-fee operations are also covered by provincial aquaculture legislation (Moccia and Bevan 2000; Alberta Agriculture, Food and Rural Development 2001; NS Department of Agriculture and Fisheries 2001). Accurate data on the numbers of different types of freshwater aquaculture operations in Canada were not found. It is estimated that there are about 15 open freshwater net cage operations and about 800 to 1000 land-based operations excluding private farms, hatcheries, and recreational fishing ponds (Table 2-2). It is anticipated that freshwater net cage aquaculture will grow in the near future, particularly around Lake Superior (S. Naylor, OMOE, pers. comm.).

Freshwater aquaculture systems are generally classified on the basis of feed inputs as extensive, intensive, or semi-intensive. In extensive culture, fish rely solely on natural available food sources. Intensive culture operations rely on an external supply of high protein food such as fish meal, whereas extensive methods are employed for the rearing of juvenile planktivorous stages of salmonids and pike. Intensive cage culture is commonly used for rearing high value carnivorous species such as rainbow trout. Semi-intensive aquaculture involves a combination of these techniques but with lower protein feed (Beveridge 1996).

Pond aquaculture can be classified based on the type of input made to supplement food, although multiple inputs are common (Boyd and Tucker 1998):

- ponds that are fertilized with chemical fertilizers;
- ponds that are fertilized with organic materials (manures); and
- ponds in which animals are fed a manufactured feed.

This results in three sources of food for animal growth in ponds (Boyd and Tucker 1998):

- food ultimately derived from plant growth within the pond (autotrophic food webs);
- food derived indirectly from organic matter added to the pond (heterotrophic food webs); and
- food derived directly from the consumption of organic matter, including manufactured feeds, added to the ponds.

Table 2-2: Distribution and description of land-based and open water freshwater aquaculture facilities in Canada.

Province/ Territory	Number of Freshwater Aquaculture Facilities	Description of facilities*	Species farmed	Comments	Reference
British Columbia	2 lake net pen sites Vancouver Island Hatcheries (15 commercial; 2 provincial; and 9 federal enhancement facilities)	187 commercial fish culture permits were issued between 1988 and 1989	- Atlantic, Chinook and Coho salmon - rainbow trout, cutthroat trout, Tilapia, and Arctic char,		Castledine (1999); Hopkinson (1991); L. Erickson (BC MWLAP, pers. comm.); Liboriron (2001)
Alberta	93 land-based farms (2700 private/ recreational farms)	All land-based facilities, open net cage not permitted in Alberta	- 6 species under 'A' license for commercial or sport: Arctic char, rainbow trout, brook trout, brown trout, tiger trout, and grass carp; - 10 species licensed ('B') in contained waters only: Atlantic salmon, Chinook salmon, Coho salmon, sockeye salmon/Kokanee salmon, freshwater prawn, goldfish, koi, Tilapia, bigmouth buffalo fish and American eel		Lloyd 2000
Saskatchewan	1 cage culture 50-70 land-based farms 2100 private farms	- land-based are prairie potholes, mainly raised for sport fishing	- rainbow trout	- 875 tonnes produced in 1998	Saskatchewan Agriculture and Food 2000; Hilton 1993
Manitoba	25-30 commercial operators 500-600 unlicensed hobby farms	-mainly use private waters but some licensed to use crown waters; also includes hatcheries, grow out facility, fee-for fishing operations	- rainbow trout	- 172,000 rainbow trout fingerlings sold in 2000; grow-out operators sold 6884 kgs of rainbow trout and 7273 kgs of Arctic char.	Manitoba Conservation 2001
Ontario	~10 cage culture ~ 190 land-based	Includes ponds, circular tanks and raceways, cages in open waters	- 40 species eligible for aquaculture - main species produced (over 95%) is rainbow trout	- 3580 tonnes produced in 1998 - 4500 tonnes projected for 2000	Moccia and Bevan 1999; N. Ali, Environment Canada – Ontario Region pers. comm.; Linington et al. 1999,

Province/ Territory	Number of Freshwater Aquaculture Facilities	Description of facilities*	Species farmed	Comments	Reference
			- other species include: Arctic char, brook trout, bass, yellow perch, brook trout , walleye, baitfish and sturgeon		www.aps.uoguelph.ca~aquacentre/faq/development.htm
Québec	170-190 land-based farms 3 cage culture farms - decommissioned 400-410 fishing ponds		- principal species farmed are rainbow trout, Arctic char, brook trout - other species include Atlantic salmon, walleye, brown trout, yellow perch, lake trout, bass and moulac		Morin 2000b
New Brunswick	1 cage culture 12-13 land-based hatcheries		- Atlantic salmon (fry and smolts), Japanese koi, American eel		S. Zwicker (Environment Canada - Atlantic Region pers. comm.)
Nova Scotia	26 land-based farms 21 hatcheries 17 U-fish operations >80 open water licensed for Lake Bras d'Or (brackish water) – no other freshwater netcage sites found		- rainbow trout, American eel, Atlantic salmon, Tilapia, striped bass, speckled trout, brown trout, halibut, flounder, European oyster, American oysters, sea urchins, clams		S. Zwicker (Environment Canada - Atlantic Region pers.. comm.) www.gov.ns.ca/nsaf/aquaculture/faq.htm;
PEI	2 land-based hatcheries no cage culture		- Arctic char, salmon, rainbow trout		S. Zwicker (Environment Canada - Atlantic Region, pers. comm.); Muise & Associates 2000
Newfoundland and Labrador	8 ponds		- Arctic char, rainbow trout, American eel	Freshwater aquaculture production insignificant	Doyon et al. 2002
Yukon	Yes	One firm owns broodstock, hatcheries, grow-out and fish processing facilities			Doyon et al. 2002
NWT	None				J. Tiemessen (Wildlife & Fisheries, GNWT, pers. comm.)

Province/ Territory	Number of Freshwater Aquaculture Facilities	Description of facilities*	Species farmed	Comments	Reference
Nunavut	None				

*Definitions:

Open (lake) cage culture - in cage culture operations, hatchery-produced stocks are grown in floating cages under provisions of a lease (OCAD 2001). (Not permitted in Alberta or Québec)

Land-based systems - in land-based operations, hatchery-produced stocks are grown in hatcheries, raceways, recirculation systems, tanks or ponds located on private property (OCAD 2001).

Private farms - farmers stock and raise fish for personal recreational fishing and consumption in ponds or dugouts (Alberta Agriculture, Food, and Rural Development, 2001). Private farms cannot sell fish or angling opportunities.

Recreational fishing ponds, U-fish farm, or Fish-For-Fee: producers stock ponds with ready-to-catch fish for the recreational consumer (Alberta Agriculture, Food and Rural Development 2001; Moccia and Bevan 2000; Morin 2000a,b)

3 Control and Regulation of Aquaculture

Under the *Constitution Act*, 1867, powers to make legislation are shared between the federal and provincial legislatures. Since little thought was given to environmental issues at the time this Act was created, there is not a clear division of powers for environmental management in Canada. The result is that both the federal and provincial governments have a variety of powers that may be used to address environmental issues. It is for this reason that governments endeavour to coordinate their environmental legislation (Environment Canada 1996). OCAD (2001), however, indicated that there is a need for improved coordination and integration of provincial and federal regulations for aquaculture.

Federal Powers: The Federal government has numerous powers that may be used to address environmental issues including: criminal law (including protection of human health), trade and commerce, sea coasts and inland fisheries, navigation and shipping, interprovincial and international transportation. An overview of selected federal legislation pertaining to environmental issues for aquaculture is provided in Table 3-1.

Provincial Powers: Provincial governments have broad powers to pass laws that are related to property and local matters in the province.

The provinces issue licenses to purchase, culture, sell, and transport species (Moccia and Bevan 2000). The cage culture of fish on public lands (i.e., lakes) in some provinces requires the monitoring and maintenance of water quality as specified on the particular license (Moccia and Bevan 2000). Some provinces require that effluent quality requirements be met under provincial regulations. Provincial licenses may also be required for diversion or use of water or to meet water quality limits (e.g., for nutrients) for effluent management. As well, licenses may be required for recreational (fee-for-fishing or U-fish operations) and operations intended for personal use by the applicant (Moccia and Bevan 2000; Morin 2000a,b; Alberta Agriculture, Food, and Rural Development 2001; www.gov.ns.ca/nsaf/aquaculture/faq.htm). Legislation varies among provinces but typically governs waste management, lands, water, environmental management, fisheries, and wildlife (Appendix A).

Table 3-1: Federal Environmental Legislation Applicable to Aquaculture (source: OCAD 2001 and Environment Canada 2001b,c).

Legislation	Purpose	Application to Aquaculture
Canadian Environmental Assessment Act	Environmental assessment to determine potential ecological impacts of proposed operations	▪ assessment required for new or expanded sites, if there is a federal trigger
Species at Risk Act	Provisions for the scientific assessment and listing of species, for species recovery, for protection of critical	▪ broad applicability to critical habitat protection and compensation

Legislation	Purpose	Application to Aquaculture
	habitat, for compensation, for permits and for enforcement	
Canada Wildlife Act	Permits EC to provide information on species at risk. Regulations under the Act allow for the designation and management of National Wildlife Areas	▪ permits are required for any activities that take place in National Wildlife Areas
Fisheries Act Section 36(3)	Prohibits the deposition of deleterious substances into waters frequented by fish	▪ spills, releases, or other deposits of hazardous materials ▪ chemical (fungicide, pesticide) application at open water cage facilities
Fisheries Act Section 35	Prohibits harmful alteration, disruption or destruction (HADD) of fish habitat	▪ erosion and sedimentation during construction ▪ accumulation of material under and near cage site
Fisheries Act – Management of Contaminated Fisheries Regulations	DFO uses these regulations to close areas based on recommendations by EC and CFIA. Prohibition orders are used which allow the area to be closed quickly	▪ ensures safety of fish and shellfish for human consumption
Canadian Environmental Protection Act	Permits control of such environmental issues as toxic substances, pollution prevention and control at federal facilities, nutrients, disposal at sea	▪ identification of chemical products to be used to determine applicability of new substances notification regulations ▪ newly developed, imported microbes used for wastewater treatment
Department of Environment Act	Permits EC to advocate the preservation and enhancement of the natural environment, including water, air, and soil; renewable resources; migratory birds; and other non-domestic flora and fauna	▪ broad applicability to the provision of advice and promotion of best environmental practices in all phases of aquaculture
International River Improvements Act	Permits issuance of a license for any projects involving construction work (temporary	▪ predicted hydraulic impacts on river at various proposed locations

Legislation	Purpose	Application to Aquaculture
	or permanent) that potentially impact water levels and flows in rivers that flow across an international border	▪ predicted short term hydraulic impacts of any temporary works to construct the project
Migratory Birds Convention Act	Allows for the conservation and protection of migratory birds and associated habitats. Provide for designation and management of migratory bird sanctuaries, establishment of hunting restrictions and placement of controls on impacting (e.g., killing, taking, injuring) birds, eggs or nests for purposes other than hunting.	▪ proximity of operation to areas where concentrations of breeding, staging, or overwintering migratory birds are known to occur ▪ disturbance during breeding, nesting and other sensitive periods ▪ control and deterrence of birds attracted to the site-Permits may be required
Fish Inspection Act – Fish Inspection Regulations	The Canadian Shellfish Sanitation Program (CSSP) ensures that all shellfish growing areas meet approved water quality criteria, that pollution sources to these areas are identified and that all shellfish sold commercially are harvested and handled in an approved manner (here shellfish refers to bivalve molluscs)	▪ CSSP is only implemented in marine waters as there are no standards for the freshwater environment ▪ without implementation of the CSSP, there can be no fresh-water shellfish aquaculture

The federal government is also responsible for navigable water approvals under the *Navigable Waters Protection Act.*

Some federal environmental policies that are also relevant with respect to aquaculture sites include (OCAD 2001; Environment Canada 2001b,c):

Environment Canada (EC):

- "Environmental Assessment of Freshwater Aquaculture Projects: Guidelines for Consideration of Environment Canada Expertise" for land based and open netcage operations (Environment Canada 2001b,c);
- The "Toxic Substances Management Policy", which outlines a framework for making science-based decisions to manage substances that could harm the environment or human health;
- "Pollution Prevention - A Federal Strategy for Action", "A Guide to Green Government" and "Code of Environmental Stewardship", which are among the policy

and program documents outlining the federal government's emphasis on prevention of pollution at the source, and sustainable development principles;

- the "Federal Policy on Wetland Conservation" which has the objective of promoting the conservation of Canada's wetlands to sustain their ecological and socio-economic functions now and in the future;

Department of Fisheries and Oceans (DFO):

- the "Aquaculture Policy Framework" has several objectives which include: orienting DFO around a common vision for aquaculture; clarifying, shaping, and guiding the development of policies and programs applicable to DFO regulations and responsibilities; and to clearly convey the framework to federal, provincial and territorial governments, the aquaculture industry, aboriginal groups, and stakeholders (Fisheries and Oceans Canada 2002);
- appropriate application of fisheries management policies to aquaculture activities;
- policy on introductions and transfers of aquatic organisms; and
- aquatic animal health management (eradication of diseased animals, access to therapeutants).

For a more comprehensive discussion on aquaculture-related legislation and regulations in Canada, see OCAD (2001).

4 Waste Loadings

Two types of waste are produced from feeding fish: (1) solid material includes feces, uneaten feed, and organic matter; and (2) soluble material includes dissolved phosphorus, ammonia, dissolved organic carbon, and lipids released from the diet (Kelly and Elberizon 2001). The amount of waste generated depends on feeding efficiency, which is principally influenced by feed composition, feeding methodology, water currents at the site, and net-pen configuration (Cho and Bureau 1997, 1998). As well, there can be periodic inputs of medications and other chemicals as part of the ongoing operation and maintenance of open water aquaculture operations (Environment Canada 2001c).

In open net cage aquaculture, wastes are difficult to collect (Cho et al. 1994) and are dispersed to the surrounding water and deposited on the sediment. In land-based fish farms, wastewater is commonly discharged to receiving waters (streams, ponds, lakes, rivers, etc.) after varying periods of retention (Lee et al. 1995). Provinces generally require that effluent requirements (e.g., TSS, TP) be met under provincial permits and regulations. The behaviour of waste released into the water column depends on the hydrographic conditions, bottom topography, and geography of the area (Fernandes et al. 2001).

Chambers et al. (2001) determined nutrient inputs in 1996 from Canadian fin fish aquaculture of 204 t•year^{-1} P and 956 t•year^{-1} N for inland waters. These figures were calculated by applying nitrogen (N) and phosphorus (P) loss coefficients developed by Fisheries and Oceans Canada (1997). In 1998, there was an estimated production of 3000 tonnes of rainbow trout in the Manitoulin Area of Lake Huron, which would have contributed an estimated 15 tonnes of phosphorous to Lake Huron that year. This loading would have represented about 0.3% of the total phosphorus loading target to Lake Huron (Great Lakes Fishery Commission and the International Joint Commission 1999).

Waste generation from land-based fish farms is highly variable. For example, at Scottish salmon farms, the ranges of annual waste loadings per tonne of fish were 9.1-11.1 kg total phosphorus•t fish^{-1}•year^{-1}, 1.2-2.1 kg dissolved reactive phosphorus•t fish^{-1}•year^{-1}, 71 kg total nitrogen•t fish^{-1}•year^{-1}, 410-485 kg biochemical oxygen demand (BOD)•t fish^{-1}•year^{-1}, 191-606 kg suspended solids (SS)•t fish^{-1}•year^{-1}, 20.3-39.3 total ammonia nitrogen•t fish^{-1}•year^{-1} (Hennessy et al. 1996; Kelly et al. 1996).

Canadian loadings data for freshwater aquaculture were found for Quebec and BC. Ouellet (1998) characterized contaminant loadings from aquaculture sites in Quebec and reported seasonal differences as both a function of nutrient distribution and fish inventory. These data are summarized in Tables 4-1 and 4-2. Effluent nutrient loadings data together with food supply rates and fish biomass were found for some BC hatcheries (Munro et al. 1985: Table 4-3), although the application of these data (~20 years old) is limited as farming practices and treatment technologies have changed substantially in recent years.

Table 4-1: Mean, minimum, and maximum loadings in the influent and effluent of sediment ponds (4 aquaculture sites), as a function of nutrient distribution (Source:Ouellet 1998).

Parameter	Mass Loading (g/kg nutrients/d)			
	Influent		Effluent	
	Summer	Winter	Summer	Winter
Biochemical Oxygen Demand (BOD_{total})	112.4 (76.4-158.7)	111.6 (43.6-204.8)	101.3 (64.0-146.0)	90.1 (43.6-157.6)
$BOD_{5\ dissolved}$	80.8 (53.3-113.4)	92.3 (29.0-141.8)	63.8 (23.5-92.8)	90.2 (29.0-126.1)
Total Suspended Solids (TSS)	155.0 (97.2-242.7)	162.2 (62.2-267.9)	90.6 (79.9-107.6)	114.7 (50.1-188.2)
Volatile Suspended Solids (VSS)	82.6 (59.3-120.0)	85.4 (55.9-144.8)	55.6 (38.7-71.8)	64.0 (10.9-149.6)
Total Ammonia	23.6 (20.0-30.0)	23.8 (8.3-33.3)	22.6 (15.2-27.4)	21.2 (7.1-33.8)
Total Kjeldahl Nitrogen (TKN)	34.1 (29.6-41.5)	38.3 (16.9-61.5)	32.6 (26.0-35.1)	36.8 (12.5-55.7)
Nitrites + nitrates	0.6 (0.2-1.9)	1.0 (0.2-2.0)	0.6 (0.2-1.8)	0.7 (0.2-1.2)
P total	4.9 (3.6-6.2)	4.7 (2.3-6.7)	4.0 (2.7-5.0)	3.9 (1.5-6.2)
P dissolved	2.9 (1.8-4.4)	2.9 (1.0-3.7)	2.6 (1.4-4.3)	2.6 (0.6-3.4)

Table 4-2: Mean, minimum and maximum loadings in the influent and effluent of sediment ponds (4 aquaculture sites), as a function of fish inventory (Source: Ouellet 1998).

Parameter	Mass Loading (g/kg fish/d)			
	Influent		Effluent	
	Summer	Winter	Summer	Winter
Biochemical Oxygen Demand (BOD_{total})	1.31 (0.93-2.20)	0.43 (0.26-0.68)	1.19 (0.66-2.02)	0.36 (0.16-0.52)
$BOD_{5\ dissolved}$	1.01 (0.55-2.02)	0.34 (0.23-0.47)	0.78 (0.29-1.65)	0.34 (0.23-0.43)
Total Suspended Solids (TSS)	1.92 (0.72-3.26)	0.64 (0.28-0.88)	1.07 (0.64-1.42)	0.42 (0.25-0.55)
Volatile Suspended Solids (VSS)	0.93 (0.62-1.24)	0.34 (0.26-0.44)	0.62 (0.47-0.81)	0.21 (0.09-0.38)
Total Ammonia	0.27 (0.17-0.36)	0.09 (0.07-0.12)	0.25 (0.18-0.28)	0.08 (0.06-0.10)
Total Kjeldahl Nitrogen (TKN)	0.40 (0.25-0.53)	0.15 (0.11-0.18)	0.38 (0.26-0.46)	0.14 (0.10-0.17)
Nitrites + nitrates	0.01 (0.001-0.02)	0.003 (0.002-0.01)	0.01 (0.001-0.02)	0.003 (0.002-0.01)
P total	0.06 (0.04-0.08)	0.02 (0.02-0.02)	0.04 (0.04-0.05)	0.01 (0.01-0.02)
P dissolved	0.03 (0.02-0.04)	0.01 (0.01-0.02)	0.03 (0.02-0.03)	0.01 (0.005-0.01)

Table 4-3: BC Hatchery food supply rates, effluent nutrient loadings and maximum fish biomass (adapted from Munro et al. 1985).

Hatchery	Mean daily rate of food supply[1] ($kg{\bullet}d^{-1}$)	Mean effluent ammonia load[2] ($kg{\bullet}d^{-1}$)	Mean effluent phosphate load[2] ($kg{\bullet}d^{-1}$)	Maximum fish biomass in hatchery[3] (kg)
Quinsam	226	4.17	1.42	29,700
Puntledge[4]	69.3	1.65	0.65	12,000
Big Qualicum	167.2	5.58	2.12	22,000
Capilano	78.0	1.02	0.37	10,6000

[1]Calculated from daily rates of food supplied between 1 Oct. 1978 and 10 Sept. 1979.
[2]Excludes phosphate or ammonia loads attributable to background levels.
[3]Prior to release of fish during spring.
[4]Data from 1980.

5 Environmental Monitoring at Aquaculture Operations

Science-based monitoring forms the basis of sound management and is essential for both public confidence and to ensure the sustainability of aquaculture (Fernandes et al. 2001). Monitoring of aquaculture sites has been defined as the regular collection of biological, chemical, or physical data from predetermined locations such that ecological changes attributable to aquaculture wastes can be quantified and evaluated (GESAMP 1996). Carmargo (1994) argued that both physicochemical and biological monitoring are needed at aquaculture sites for proper ecological risk assessment to provide adequate protection of freshwater aquatic ecosystems. Similarly, the Roundtable on Addressing Concerns for Water Quality Impacts from Large-Scale Great Lakes Aquaculture recommended that monitoring be conducted in partnership with government, industry, and academia to address water quality as well as structure, function and habitat requirements of biological communities (Great Lakes Fishery Commission and the International Joint Commission 1999).

The status of environmental monitoring in Canada is briefly reviewed below. Additional discussion of monitoring issues including considerations for study design, methods and techniques, monitoring parameters, interpretation, and analysis are presented in Appendix B.

5.1 Status

Monitoring of land-based and open net cage freshwater aquaculture operations varies across Canada by jurisdiction and is mainly limited to key water quality parameters such as total suspended solids (TSS), nutrients (i.e., phosphorus, nitrogen), BOD, dissolved oxygen (DO), and pH (Appendix B: Tables B-1 and B-2, Lee et al. 1995; Linquist 2001). Biological monitoring of freshwater operations is limited. Ontario recommends biological monitoring (e.g., periphyton and benthic invertebrate studies) if chemical triggers are exceeded. BC requires toxicity testing at land-based facilities using chemicals. There have been several Canadian research studies that have assessed impacts of aquaculture on water and sediment chemistry, planktonic and benthic communities, and occasionally fish populations (Cornel and Whoriskey 1993; MacIssac and Stockner 1995; Deniseger, BC MWLAP, pers. comm.; Charlton, NWRI pers. comm.).

In Ontario, land-based fin fish facilities are required to monitor effluent monthly (e.g., TSS, TP) as a condition of their permit. Monitoring at open net cage operations is currently performed by operators, both on a voluntary basis and as a requirement of their permits, as well as by the Ontario Ministry of Environment (OMOE). The OMOE (2001) have developed draft recommendations for water quality monitoring at cage culture operations including chemical, physical and biological components. These recommendations include:

- regional background water quality data for the area;
- location of water quality sampling stations;
- phosphorus sample collection and data analysis with trigger limits (Provincial Water Quality Objectives, PWQO) and actions (i.e., adjustment of feeding, frequency of phosphorus sampling, assessment of periphyton growth);
- water clarity (Secchi depth and colour);
- temperature/DO sample collection with trigger limits (PWQO) and actions (i.e., adjustment in feeding, may require benthic sampling program);
- sediment sample collection and data analysis (particle size, nutrients) with trigger limit [i.e., if statistical significant difference ($\alpha \leq 0.05$) at upstream and downstream sites] and actions (i.e., operational audit and abatement plan to reduce operational scale for next season, may require benthic sampling program to estimate extent of benthic habitat impairment).

The Ontario Sustainable Aquaculture Working Group is engaged with various stakeholders to further advance monitoring protocols for freshwater net cage sites in Ontario. The OMOE recently undertook extensive studies of the effects of cage aquaculture operations in the Manitoulin Island and Parry Sound areas. This included monitoring of both water (chlorophyll, nitrite/nitrate, total ammonia/ammonium, phosphate, pH, alkalinity, conductivity, suspended solids, total phosphorus, total Kjeldahl nitrogen, biochemical oxygen demand, chemical oxygen demand, dissolved inorganic carbon/dissolved organic carbon, pH, turbidity) and sediment quality (nutrient, particle size, TOC, LOI and metal analysis) as well as a qualitative field evaluation of benthic invertebrates (Boyd and Thorburn 2001; Thorburn and Boyd 2002). They noted for some locations application of the federal environmental effects monitoring (EEM) protocol for benthic invertebrate monitoring would be a benefical means of demonstrating significant biological impact in situations where the chemistry data and field observations provide an unclear indication of impairment (Thorburn and Boyd 2002).

In addition, several research projects are underway in Ontario to advance the monitoring efforts for the aquaculture industry. A study of the time and depth of excretion of fish in a farm is in progress as a partnership between University of Guelph, Environment Canada and the Ontario Ministry of the Environment. It is hoped this study will delineate the factors that would form a rational monitoring program (Charlton, NWRI, pers. comm.). Reid (University of Guelph, pers. comm.) is currently examining temporal and spatial variation in key water quality parameters on net cage farms in Georgian Bay with the goal of making recommendations to improve water quality monitoring programs for aquaculture. Podemski (DFO Freshwater Institute, pers. comm.) is leading an Experimental Lakes Area project in northern Ontario to assess the environmental and ecological impacts of cage aquaculture under current industry practices. This project will further contribute to the design of tools and methods to predict and assess the impacts of the aquaculture industry on freshwater ecosystems.

In BC, land-based aquaculture is subject to the 1994 *Land-Based Fin Fish Waste Control Regulation*. Under this regulation, land-based fin fish facilities must submit a receiving water quality report (e.g., nitrogen, phosphorus, DO and temperature) prior to construction, except for facilities with a dilution greater than 20 to 1. Effluent from these facilities must meet requirements for non-filterable residue concentration, TP and chlorine. Under the general requirements, detergents, disinfecting agents, cleaning agents or chemicals must not be discharged from fish farms to surface water or groundwater unless the effluent passes a 96-hour LC20 bioassay with rainbow trout. Liboiron (2001) noted in an audit of land-based facilities on Vancouver Island that although chemicals are used, no facilities on Vancouver Island have undertaken toxicity testing.

Both British Columbia and New Brunswick have monitoring programs for salmon mariculture that are more extensive than is typically found for freshwater operations. British Columbia recently promulgated the *Finfish Aquaculture Waste Control Regulation* under the *Waste Management Act* (September 2002). This regulation was developed to ensure that the aquaculture industry is environmentally sustainable. Aquaculture farm operators will be required to prepare and implement a best management practice and monitoring plan. The monitoring program must consist of physical, chemical, and biological analysis as well as seabed video surveys and analysis of contaminants. This regulation does not apply to freshwater open net cage operations. BC has, however, completed a monitoring study at one open net cage freshwater aquaculture operation (Deniseger, BC Ministry of Water, Land and Air Protection, pers. comm).

The New Brunswick Marine Environmental Monitoring Program of Salmon Aquaculture Operations is intended to describe organic enrichment in sediments (Anon. 1995). Details of the BC and NB monitoring programs are provided in Appendix B.

In Europe, routine monitoring varies by jurisdiction for land-based and open water fish farms but typically consists of water quality parameters (TSS, DO, various forms of N, and P) and some biological indices (biological surveys). Read et al. (2001) indicated that there is a need for harmonization of regulatory, control, and monitoring procedures into an overall system for marine aquaculture within the European Union. For example, Norway has developed a modeling and monitoring system to assist in the effort to prevent farms from overloading the environment with nutrients and organic matter. This system includes a classification tool with threshold values. A proposal has been put forward to make this system part of the regulatory framework for aquaculture in Norway (Norwegian Directorate for Nature Management 1999).

6 Potential Environmental Impacts of Aquaculture

Table 6-1 summarizes potential environmental impacts of freshwater aquaculture. The majority of research articles found on impacts were from Europe. There were only a few Canadian studies found in the literature on open net cage aquaculture and hatcheries. In this respect, it is difficult to draw substantive conclusions on the magnitude and extent of environmental impacts from aquaculture in Canada. However, general trends may be drawn from the European literature; although impacts may differ in Canada due to differences in species cultured, aquaculture practices, chemicals used, and environmental conditions.

The impacts of aquaculture operations are highly variable and are dependent on the aquaculture practices used, site characteristics, production scale, management approach, and the assimilative capacity of the surrounding environment (Fernandes et al. 2001). In general, cage aquaculture operations located in areas with sufficient flushing, water depth, and good management practices have few or minimal local impacts. Other operations that are poorly sited may function for a few seasons without impacts but when certain conditions are encountered (e.g., high temperature, low water flow, reduced circulation), these operations report severely lowered DO concentrations (and potentially anoxic conditions), high phosphorus concentrations, and higher incidence of toxic algae. The types of impacts caused by land-based farms tend to be similar to caged operations (i.e., nutrient enrichment, DO depletion, high levels of bacteria) and are dependent on chemical usage, management practices, and effluent treatment. Land-based systems, although typically higher in water usage, allow for the separation of farmed organisms and natural populations thus precluding possible impacts of escaped animals on natural stocks (Waller 2001). One advantage of land-based tank or raceway systems is that total loads of dissolved nutrients and particulate matter in effluent water can be reduced by wastewater treatment (Waller 2001). Recirculating systems also provide the opportunity for water reuse, however, these systems can also result in effluents that contain high concentrations of nutrients. As a result, one issue that has been raised for land-based systems using recirculation technology is that many existing regulations and environmental quality guidelines are concentration-based rather than loading-based (Ali, Environment Canada Ontario Region, pers. comm.).

Table 6-1: Summary of potential environmental impacts of freshwater aquaculture.

Environmental Concern	Causes	Potential Impacts	Supporting/ Conflicting Evidence
Deterioration of water and sediment quality	Organic enrichment	- low dissolved oxygen levels and increased incidence of anoxic conditions - elevated levels of ammonia, suspended solids, etc. - elevated levels of bacteria - accumulation of organic material on the sediments below or near cages	- some sites have operated for >20 years with minimal impairment, whereas at other sites isolated incidences have been reported of low dissolved oxygen and anoxic conditions at poorly sited locations near Manitoulin Island, Lake Huron (i.e., La Cloche Channel, Linquist 2001; Boyd et al. 1998b; Boyd and Thorburn 2001) - water quality impairment at Lac Heney, Forgeron and des Pins in Québec (Bird and Mesnage 1996; Soucy 2000) - high levels of bacteria reported at and downstream of trout farms in UK (Carr and Goulder 1993)
Elevated nutrient levels in receiving waters	Nutrient enrichment	- increased algal productivity potentially resulting in eutrophication which can cause loss of habitat and biodiversity - increased incidence of toxic algal blooms - decreased macroinvertebrate species diversity and abundance and shifts in species composition from pollution sensitive to pollution tolerant species	-localized nutrient enrichment and increased algal productivity – isolated incidences (3 sites in Ontario) of elevated phosphorus; other sites maintained background levels (Linquist 2001; Boyd et al. 1998a) - increased concentrations of pelagic plankton and fish surrounding net cage farms (Beveridge 1996); one incidence of decreased abundance of zooplankton (Cornel and Whoriskey 1993) - one incident reported of cyanobacteria in Québec associated with fish farm effluent (Carignan pers. comm.) - impacts on benthic communities up to 100 m from net cages and up to 1 km downstream of land-

Environmental Concern	Causes	Potential Impacts	Supporting/ Conflicting Evidence
			based aquaculture effluents in Europe and US (Camargo 1992; Selong and Helfrich 1998)
Chemical release into receiving waters	Use of chemicals for a variety of purposes [chemotherapeutants, antibiotics, anesthetics, disinfectants, detergents (surfactants) , pesticides, metals, minerals (e.g., zinc, copper, calcium as essential minerals in feed), etc.]	-uptake and toxicity to non-target organisms - persistence in environment - development of antimicrobial resistance - environmental risk assessment needed to assess toxicity	- A 1993 survey reported trout farmers in Ontario used chemicals rarely (Thornburn and Moccia 1993) - frequency, amount and types of chemicals used in Canada currently unknown - incidence of resistant bacteria in bottom sediments (Hansen et al. 1993; Samuelson et al. 1992; Samuelson 1994) – data lacking for Canadian freshwater aquaculture -Zn and Ca 2-6 fold greater in sediments below lake pens than surrounding sediment (MacIssac and Stockner 1995) - Copper, zinc and cadmium elevated at some marine salmon farm sites in Bay of Fundy, NB (Parker and Aubé 2002)
Transmission of disease - from wild to farmed fish - from farmed fish to wild populations	Collection/disposal of mortalities, release of blood water, introduction of fish to site	- increased incidence of disease in wild fish populations	- anecdotal evidence of increased incidence of disease in eels in eastern Canada (Barker and Cone 2000)
Introduction of exotic or non-native species/ decline of wild fish stocks	Escapes	genetic interactions with wild populations increased competition with wild stocks for food and habitat	- cultured stocks and hybrids have lower reproductive success when released into wild than natural populations in Norwegian study (Skaala 1994) -escaped cultured stocks of Altlantic salmon surviving and reproducing in rivers underutilized by wild fish on Vancouver Island (Volpe et al. 2001)
Risk to human health	water quality; toxic algae	- impacts on recreational waters	- incident in Québec of villagers unable to swim in Lacs Forgeron and des Pins for 3 years as a result

Environmental Concern	Causes	Potential Impacts	Supporting/ Conflicting Evidence
			of water quality impairment from fish cage farm (Soucy 2000). No other Canadian data found.
Deterioration of potable water supplies	Increased levels of bacteria and chemicals in receiving waters		- Issue identified for UK; one anecdotal incidence of well water contamination in Québec (Soucy 2000). No other Canadian data found.

6.1 Impacts on Water Quality

Impacts on water quality from fish farming are variable depending upon site-specific factors. They range from little or no impacts in areas that have good water flow with sufficient depths, and where good management practices are implemented to severe impacts where farms have been poorly sited (i.e., in areas of low water exchange rates). Typically, impacts are characterized as elevated levels of nutrients (phosphorus, nitrate, nitrite, total and ionized ammonia), suspended solids and bacteria, and low levels of DO (US EPA 2002).

US EPA (2002) indicated that solids represent the largest pollutant loading from aquaculture facilities in the US. Suspended solids (TSS) discharged in effluent can have a detrimental effect on ecosystems by reducing the depth to which sunlight can penetrate, which decreases photosynthetic activity and oxygen production by plants. Increased suspended solids can also increase the temperature to surface waters because the particles absorb heat from the sunlight, which, in turn, can result in lowered dissolved oxygen. TSS can abrade and damage fish gills (increasing the risk of infection), smother fish eggs and bottom-dwelling organisms, and destroy habitat for benthic organisms (US EPA 2002).

Aquaculture operations can be significant sources of nutrients (P and N) because the aquaculture wastes are often released directly into natural bodies of water, in the case of open netcage farms, or because effluents are directly discharged into them, in the case of some land-based operations. Excessive nutrients can accelerate plankton growth, resulting in die-offs and increased BOD in receiving waters (US EPA 2002). US EPA (2002) indicated that most nitrogen from US aquaculture facilities is in the form of ammonia, which is not usually found at toxic levels in these discharges. Phosphorus is discharged in both the solid and dissolved forms, the latter of which is available to plants. Although the solid form is generally unavailable, some phosphorus may be slowly released from the solid form, depending on environmental conditions (US EPA 2002).

The quantities of nutrients released are dependent on fecal and uneaten food composition, physical properties, temperature, depth of water, and turbulence (Beveridge 1996). Bureau (pers. comm., University of Guelph) indicates that approximately 50% gross energy (i.e., energy-yielding nutrients) is retained by the fish, but this figure is dependent on the species and size of the fish, type of feed, and the type of nutrient. He noted that phosphorus (~50%) is retained at a higher rate than nitrogen (~35-45%). The relationship between the magnitude of nutrient input and resulting effects is often not linear and can be affected by other environmental variables, other inputs, and conditions associated with the aquaculture operation. Site characteristics (morphometry, flushing rate, etc.) as well as farming practices (feed used, species raised, stocking density, etc.) can play a major role in the degree of impact of aquaculture activities.

Both open and semi-closed aquaculture operations have water exchange with natural water bodies and therefore, may shift oligotrophic (nutrient-poor), or mesotrophic (intermediate level of nutrients) water bodies into an eutrophic state where excessive algal growth and low levels of bottom oxygen prevail (Lee et al. 1995). Aquaculture induced eutrophication in receiving waters are similar to those derived from other point sources (Persson 1991) although the problem is most intense in areas with low currents and limited dilution. Nutrients are generally dissolved in the water or are accumulated on the bottom sediments and organic matter is dispersed or concentrated under the net cages.

In a recently published study on impacts of caged aquaculture in the Great Lakes, Hamblin and Gale (2002) indicated that in Lake Wolsey, Ontario (on Manitoulin Island in Georgian Bay) phosphorus concentrations at fall turnover have more than doubled over the 13 year history of a cage fish operation. No difference was found in spring total phosphorus (TP) concentrations in this study. They suggested that increased TP in fall could indicate increased loading and/or regeneration of TP from the sediments. They concluded that the long-term effects of caged aquaculture at its current level of production are probably minimal but in the short-term could result in algal blooms and increased oxygen demand.

Boyd et al. (1998b) reported that there was a general tendency for concentrations of nutrients within the LaCloche Channel (Manitoulin Area, Lake Huron, ON) to increase with depth. As well, the summer pattern of depressed surface concentrations of TP relative to mid-depth and near-bed is consistent with the effects of algal growth followed by settling and decomposition. Based on model predictions, they concluded that any TP loadings resulting in an average spring TP between 7 and 13 $\mu g \cdot L^{-1}$ have the potential to eliminate from 10 to 100% of hypolimnetic fish habitat through the increased oxygen demand associated with algal productivity and subsequent decomposition. Boyd and Thorburn (2001) indicated that a tendency for localized hypolimnetic oxygen depletion was observed at two net cage sites in Georgian Bay and suggested that the capacity for these sites to accommodate additional loads of oxygen consuming substances is limited.

In intensive systems, fish are routinely fed fishmeal. Nutrient release (dissolved and particulate) is heavily dependent on the phosphorus (P) and nitrogen (N) contents in the feed. In common feeds, nutrients range from 1.4 to 13.6% N and 0.3 to 5.9% P, depending upon the ingredients used in the product (Cho et al. 1994). The magnitude of P and N losses from aquaculture operations are related to food composition, feeding practice, and fish production (Persson 1988). The distribution of dissolved and particulate forms of nutrients can vary between different areas, mainly dependent on differences in local environmental conditions.

Nitrogen losses from aquaculture operations are predominately in the form of dissolved nitrogen, primarily ammonia and urea. Both these nitrogen forms are immediately available to algae.

However, a minor fraction of dissolved organic nitrogen compounds may not be immediately bioavailable. Nitrate is produced from the nitrification of ammonia excreted by fish and from ammonium mineralization from wasted food and fish feces. Ammonia, which can be toxic to aquatic life, exists in both un-ionized (toxic) and ionized (non-toxic) forms, the proportions of which depend on the pH and temperature of the water (Durborow et al. 1997).

Particulate P released from fish pens sinks and enriches the sediment immediately below the cages (Kelly 1992). Release of this accumulated P from the sediment over time can result in enhanced primary production. The relationship between the P release from the bottom sediment and the increase of primary production is influenced by many factors such as:

- availability of N (Foy and Russell 1991);
- the presence of humic substances (Kelly 1993; Erickson BC MWLAP pers. comm.);
- water clarity (Massik and Costello 1995);
- alkalinity (Shrestha and Lin 1996);
- physical events leading to sediment resuspension (Foy and Russell 1991); and
- temperature (Massik and Costello 1995).

A review of water quality monitoring data for caged aquaculture facilities in Ontario can be found in Linquist (2001) and is summarized in Table 6-2. Linquist noted that impacts on receiving water quality surrounding fish farms are a function of the carrying or assimilative capacity at an individual location. In this review, an overall increase in total phosphorus over time (>4 years) was found at 3 locations in Ontario (LaCloche Channel, Swift Current, Lake Wolsey) while other facilities maintained background or pre-operative water quality. Linquist (2001) reported that nutrient levels (nitrate, nitrite, total ammonia, and un-ionized ammonia) and other characterization parameters (BOD, chemical oxygen demand (COD), conductivity, TSS, turbidity, DOC) were generally low with the exception of one site at LaCloche in the North Channel of Georgian Bay. This site was decommissioned in May of 1998 and is currently being monitored to assess recovery.

Impacts on lowered dissolved oxygen (DO) levels can vary on a site-specific and seasonal basis, with waste loading, morphometry, and flushing rate being the determining factors. Little or no DO was present below a depth of 13 m throughout the LaCloche Channel (Manitoulin Area, Lake Huron, ON), in a 1998 study to assess recovery of the channel following decommisioning of an aquaculture operation following anoxia problems (Boyd et al. 1998b). In a subsequent study at this site in 1999, Boyd and Thorburn (2001) noted that the residual effects of historic operations in this area were still evident, however, their results did provide some evidence of recovery at the site. In other studies from Ontario, Linquist (2001) reported DO levels were above water quality criteria (6 mg•L^{-1}) throughout the year at some cage farms whereas DO was depleted during lake stratification at two stations 15 m from cages and 16 m from the bottom. However, in Lake Wolsey (Manitoulin Area, Lake Huron, ON) DO levels less than 6 mg•L^{-1} were measured in the bottom waters in July at all stations, although it is uncertain as to whether the low DO can be solely attributed to the fish farm (Charlton, NWRI, pers. comm.). At all locations, DO levels were restored following fall turnover. In another study, at a rainbow trout cage culture site at Lac du Passage, Québec, Cornel and Whoriskey (1993) reported localized hypolimnetic oxygen depletion in the waters surrounding the cages. Both of these sites have since been decommissioned.

Table 6-2: Comparison of Ontario water quality monitoring data near open net cage operations with Water Quality Guidelines.

Parameter	Water Column Concentration*	Canadian Water Quality Guidelines (CWQG) and/or ON Provincial Water Quality Objective (PWQO)	Comments*
Total Phosphorus (TP)	≤0.010 mg•L^{-1} at 10 of 12 sites	0.10 mg•L^{-1} (PWQO) Guidance Framework[1] (CWQG)	Elevated levels found at 2 sites in LaCloche Channel in 1997; these sites were phased out and TP levels were less than PWQO in 1999
Total ammonia	0.1-0.25 mg•L^{-1} maximum of 0.786 mg•L^{-1} (0.011 mg•L^{-1} un-ionized ammonia)	0.043-153 mg•L^{-1} [2] (CWQG)	Highest levels found at LaCloche Channel in 1996-97measured in bottom waters at LaCloche Channel in 1997
un-ionized ammonia (NH_3)	<0.02 mg•L^{-1} [3]	0.019 mg•L^{-1}(CWQG) 0.02 mg•L^{-1}(PWQO)	Concentration calculated from total ammonia as a function of temperature and pH
Total Kjeldahl nitrogen (TKN)	<0.3 mg•L^{-1}	NA	Levels range from 0.1-0.5 mg•L^{-1}in unimpacted surface waters; control locations reported at ~0.05 mg•L^{-1}
Nitrate (NO_3) Nitrite (NO_2)	<0.250 mg•L^{-1}(NO_2 + NO_3)	13 mg•L^{-1} (CWQG) 0.06 mg•L^{-1}(CWQG)	Draft value
Biochemical Oxygen Demand (BOD)	≤1.0 mg•L^{-1}	NA	At all sites with exception of Depot Harbour (2.2 mg•L^{-1}at depth in 1999)
Chemical Oxygen Demand (COD)	1.0-15.0 mg•L^{-1} average ~6.0 mg•L^{-1}	NA	No spatial or temporal trends found
Conductivity	160 µS•cm^{-1}	NA	"
PH	8.0	6.5-9 (CWQG)	"
Total Suspended Solids (TSS)	1-2 mg•L^{-1}	Maximum increase of 25 mg•L^{-1}(short-term- 24 h) and maximum average increase of 5 mg/L (long-term- 30 day) -(CWQG)	"
Turbidity	≤1 mg•L^{-1}	Maximum increase of 8 NTU (short-term –24 h) and maximum average	"

Parameter	Water Column Concentration*	Canadian Water Quality Guidelines (CWQG) and/or ON Provincial Water Quality Objective (PWQO)	Comments*
		increase of 2 NTU (long-term - 30 day) (CWQG)	
Chlorophyll a	0-2 $\mu g \cdot L^{-1}$ at most samples 2-5 $\mu g \cdot L^{-1}$ at East Rous Island and Depot Harbour	30 $\mu g \cdot L^{-1}$ (PWQO)	"
Dissolved Organic Carbon (DOC)	average ~1.9 $mg \cdot L^{-1}$, range 1.4-3.5 $mg \cdot L^{-1}$ average 2.4 $mg \cdot L^{-1}$ at Lake Wolsey and Depot Harbour	NA	"
Metals		CWQGs[4] (as $\mu g \cdot L^{-1}$): Al: 5-100; As: 5; Cd: 0.017; Cu: 2-4; Fe: 300; Hg: 0.1; Pb: 1-7; Ni: 25-150; Zn: 30.	1987 data low or below detection and all below PWQO
Dissolved Oxygen (DO)	<1.0 $mg \cdot L^{-1}$ 1997 at LaCloche 1999: >6.0 $mg \cdot L^{-1}$ throughout year at most sites <6.0 $mg \cdot L^{-1}$ 15 m from cages at 16 m from bottom at 2 sites <6 $mg \cdot L^{-1}$ in bottom waters in July at one site at Lake Wolsey	6.0 $mg \cdot L^{-1}$(PWQO) 5.5-9.5 $mg \cdot L^{-1}$ [5] (CWQG)	DO levels restored at all locations following fall turnover Note LaCloche operations phased out in 1998

* Data from Linquist (2001)
[1]For the CCME Water Quality Guidelines for phosphorus a Guidance Framework for phosphorus has been developed for Canadian freshwater systems.
[2]Dependent on pH and temperature (for details see CCME 1999).
[3]Reported as no exceedences of PWQO as a function of the total ammonia concentration.
[4]See Appendix C for details.
[5]This range is for cold and warm water ecosystems covering different life stages of aquatic life (for details see CCME 1999).

For land-based fish farms, receiving water quality is affected by effluent discharges and is dependent upon the volume and composition of the effluent as well as the characteristics of the receiving water. Some studies have reported minimal impacts on waters receiving fish farm effluent. The volume and composition of effluents discharged from ponds is highly variable and depends on rainfall, type of pond, and management procedures (Boyd and Tucker 1998). Boyd and Tucker (1998) reported that in the United States, concentrations of total ammonia-nitrogen, total phosphorus, and suspended solids are potentially the most problematic in pond effluents. Munro et al. (1985) found elevated concentrations of total phosphate and ammonia downstream of salmon hatchery effluent discharges in BC. In addition, higher periphyton, chlorophyll a, and organic weight accumulations on artificial and natural substrates as well as greater abundance of benthic invertebrates were found 60-700m downstream of effluent discharges than in upstream areas. They noted that these changes were characteristic of a nutrient enrichment effect. In a study of Virginia trout farm effluents, Selong and Helfrich (1998) reported some changes in water quality variables including significant increases in total ammonia-nitrogen, un-ionized ammonia-nitrogen, and nitrite-nitrogen concentrations downstream of the effluent discharges but these levels were below recommended thresholds for lethality to aquatic organisms. Dissolved oxygen levels were also reduced but were generally greater than 7 $mg \cdot L^{-1}$. Effluent water temperatures, pH, nitrate-nitrogen and total phosphorus did not differ significantly from upstream levels.

Lac Heney, located in the Outaouais region of Québec, provides a clear example of the impact of aquaculture on receiving water quality. The lake supports a valuable trout fishery. It is a deep lake (maximum depth 33 m) with a surface area of 12.4 km^2. Total lake water P concentrations ranged from 10 to 30 $\mu g \cdot L^{-1}$ during the summer of 1995. During the period of spring overturn in 1996, P concentrations of 21 $\mu g \cdot L^{-1}$ remained uniform in the water column. The concentration of P in Lac Heney classifies it as mesotrophic. A fish farm opened in 1993 on a tributary of Lac Heney, Québec (Bird and Mesnage 1996). During the five years of operation, the effluent from the fish farm was implicated in an almost doubling of the P load to the lake, which led to a dramatic decrease in water transparency and oxygen concentrations and an increase in algal concentrations. The high nutrient concentration in the farm wastewater was attributed to the presence of waste food pellets in the effluent. The fish farm caused elevated P concentrations and low oxygen (anoxia) near the water-sediment interface resulting in an increased abundance of filamentous algae and macrophytes in the lake (Bird and Mesnage 1996). Planktonic algal abundance was (chlorophyll *a)* 1 to 3 $\mu g \cdot L^{-1}$ with concentrations peaking at 14 $\mu g \cdot L^{-1}$ in August of 1996, accompanied by an increase in biomass and production. Low oxygen levels may have caused long-term effect by reducing the growth and reproductive rates of sensitive species (e.g., trout) (Prairie 1994). Excessive growth of macrophytes had also destroyed the spawning sites of lake trout.

The Québec government closed the Lac Heney fish farm in November 1998. In order to devise a site-specific remediation plan for the lake, it was necessary to determine the contribution of P from the fish farm relative to other sources (e.g., atmosphere, cottages, cultivated land in the basin, wastewater inputs, and lake sediment). Sampling undertaken during 1995 and 1996 indicated that the total P entering the lake from all tributaries was 762 kg and the aquaculture farm alone contributed 450 kg to this total. The amount of P lost from the lake was 231 kg, giving a coefficient of retention of 0.81. These data clearly identified that the fish farm was the most significant contributor of P to the lake and was responsible for the rapid deterioration in water quality. The Québec government and the Association for the Protection of Lac Heney predicted that the closure of the fish farm would avoid further deterioration in the water quality of Lac Heney. However, in a subsequent study, Prairie (2001) reported that further monitoring did not suggest an improvement in the water quality of Lac Heney suggesting that the recovery of the lake is much slower than anticipated. A more detailed study is required to quantify the changes associated with the sources of phosphorus in the lake.

In another incident in Québec, Sousy (2000) reported water quality contamination of Lacs Forgeron and des Pins from fish farm effluent. The impairment was characterized by high nutrient loads and concentrations (100 $\mu g\ P \cdot L^{-1}$), hypolimnetic anoxia, and the presence of cyanobacteria (Carignan, University of Montreal, pers. comm.). Following decommissioning of the farm, the lakes have recovered fully due to their short water residence time and to the short duration of the impact (Carignan, University of Montreal, pers. comm.).

One study from Minnesota was found on the restoration of a mine pit lake following the decommissioning of an intensive net-pen salmonid aquaculture operation. Axler et al. (1998) reported that the lake rapidly recovered to near baseline water quality and returned to an oligo-mesotrophic status.

6.2 Impacts on Bottom Sediment

Environmental impacts on the sediment below caged aquaculture operations are dependent upon the conditions at the site and range from little or no impacts to various physical and chemical changes which, in turn, can result in changes in the benthic communities. The deposition of waste material from uneaten food and fecal material from the fish farm results in increased concentrations of carbon, phosphorus, and nitrogen under aquaculture cages (Axler et al. 1996; Beveridge 1996). For example, Enell and Löf (1983) reported sedimentation rates of 17-26 g $DM{\bullet}m^{-2}{\bullet}d^{-1}$ (where DM = Dry Matter) compared with rates of 2.3-3.6 $DM{\bullet}m^{-2}{\bullet}d^{-1}$ at undisturbed sites in Norway. Similarly, Cornel and Whoriskey (1993) reported increased sedimentation rates and significantly higher organic matter in sediments below a caged rainbow trout farm compared with control sites in Lac du Passage, Québec. Changes in sediment can include increased oxygen demand, increasingly anaerobic and reduced sediments, increased nutrient concentrations, and an increase in the flux of nutrients (i.e., N and P compounds) to the overlying water (Beveridge 1996). Boyd and Thorburn (2001) note that low oxygen regime near the sediment bed at some sites near Manitoulin Island, Georgian Bay, in combination with localized nutrient enrichment of sediment, could be expected to manifest itself in alteration of the local benthic macroinvertebrate community. However, they noted that the extent of this potential effect is hard to quantify in the absence of direct sediment quality and benthic community assessment data. Impacts on sediment tend to be very localized (i.e., within 15-25 m of the net cage) (Enell and Löf 1983). Recovery of sediments can be slow following decommissioning of net cage sites. For example, Doughty and McPhail (1995) reported that severe impacts on sediments were still evident three years after removal of a cage operation in Scotland.

Rates of waste deposition depend upon the amount of feed applied as well as the energy conversion efficiency of this food. Cornel and Whoriskey (1993) found that most excreted phosphorus is in the form of particulates and sinks to the sediment. In contrast, nitrogenous waste is largely in a dissolved form and is retained in the water column. Cornel and Whoriskey (1993) reported no measurable effects on sediment available NO_3 and available NH_4 from an aquaculture operation at Lac du Passage in Québec. Boyd and Thorburn (2001) found a pattern of increased TP and phosphate concentrations compared with reference in near-bed samples at net pen sites in Georgian Bay. They noted that this pattern was consistent with the effects of increased algal productivity followed by settling and decomposition. As well, they noted that all sediment samples at net pens in Georgian Bay had TP levels greater than 0.6 $mg{\bullet}g^{-1}$, the provincial lowest effect level and in some cases exceeded the severe effect level of 2.0 $mg{\bullet}g^{-1}$.

Thorburn and Boyd (2002) conducted a sediment survey of active and historical cage culture sites in Georgian Bay. They reported that median concentrations of TP, TOC, and TKN were significantly greater than for reference stations in sediments at aquaculture site tenure boundaries at Eastern Island (Georgian Bay, ON) but for TP only at Fisher Harbour. They noted that this finding is indicative of nutrient enrichment associated with the aquaculture operation. In particular, at one station at Eastern Island, levels of TP and TKN exceeded provincial sediment quality guidelines and that there was evidence of benthic habitat impairment. They concluded that the operation is significantly exceeding the carrying capacity of its defined operational zone. They suggested that there may be a need to apply the federal Environmental Effects Monitoring (EEM) protocol for benthic invertebrate monitoring to assess the incidence of biological impacts in situations where the chemistry data and field observations are ambiguous.

MacIssac and Stockner (1995), in a study of salmon net-pens on BC lakes, reported higher phosphorus and nitrogen concentrations in net-pen sediment compared with natural lake sediments. Rates of release of nutrients to the water column (49 mg P $\cdot m^{-2} \cdot h^{-1}$ and 154 mg N$\cdot m^{-2} \cdot h^{-1}$) were also higher for net-pen sediments than control sediments (0.60 mg P$\cdot m^{-2} \cdot h^{-1}$ and 5 mg N $\cdot m^{-2} \cdot h^{-1}$) and had higher dissolved P relative to N ratios than controls. They reported that urea-N is released from the sediments at low rates and noted that urea is carried to the sediment in sedimenting feces.

Increased oxygen consumption as a result of increased COD and microbial activity can decrease oxygen concentrations in sediments and change the balance between oxidation and reduction processes (reflected in the redox potential) at sites with insufficient water exchange (Gowen et al. 1991). For example, Enell and Lõf (1983) reported increased oxygen consumption in sediments (45-55 mg $O_2 \cdot m^{-2}$) below a caged fish culture farm in a Swedish Lake in comparison to reference sites (16 mg $O_2 \cdot m^{-2}$). MacIssac and Stockner (1995), however, found no evidence of oxygen depletion at or near the sediment-water interface under net-pens in BC lakes and noted that oxygen levels were never lower than 60% saturation. Further, they found that oxygen consumption rates in net-pen sediments were 2-4 fold higher than the natural lake sediments, indicative of highly labile organic matter. They suggested that either the net-pen sediments at their study sites had very low oxygen consumption rates or there was sufficient deep-water movement to maintain high oxygen levels at the sediment-water interface under the net-pens. Thus, site-specific factors such as size of the farm in relation to the hypolimnion, timescale of isolation of the hypolimnion from the atmosphere, and water depth, will influence the potential for changes in sediment oxygen supply.

As a result of changes in the oxygen supply in the sediments below fish pens, decomposition may switch from aerobic to anaerobic processes. As well, anoxia in bottom sediments can cause re-release of P (Gowen et al. 1991). In freshwater sediments, the main anaerobic processes are likely to be denitrification and methanogenesis (Gowen et al. 1991). Anaerobic conditions have also been noted to change the color of sediment from the background matrix to black as a result of iron reduction (FeS_2) (Brooks 2001).

Fish food contains various supplements such as vitamins and provides a route for the administration of antibiotics. The deposition of uneaten food and fecal matter can result in increased concentrations of these substances in the sediments. Increased concentrations of antibiotics and other chemicals in bottom sediments have been observed to affect microbial communities (Samuelson et al. 1992; Samuelson 1994; Brooks 2001) and increase the potential for the presence of resistant bacteria (Hansen et al. 1993). Likewise, calcium and zinc (both common feed supplements) were 2-6 fold higher below net-pens in a BC lake than in natural lake sediments (MacIssac and Stockner 1995). Concentrations of copper, nickel, aluminum, and magnesium, however, were 26-33% lower in the net-pen sediments, possibly due to dilution by loadings of organic material from the fish pens. MacIssac and Stockner (1995) suggested that organic enrichment of the surface sediments under the net-pens might be mobilizing and affecting the distribution of metals sensitive to changes in reduction-oxidation conditions in the sediments. Parker and Aubé (2002) found elevated copper and zinc in marine sediments collected under salmon net pen sites in the Bay of Fundy, NB. Although the sources of these elevated metal concentrations are not understood, they indicated that there is some evidence of copper-based antifouling coatings on net pens. In addition, some salmon food formulations can contain zinc and/or copper, which are essential minerals in the fish diet. The applicability of these results to freshwater requires further evaluation.

6.3 Impacts on Microbes

High levels of bacteria have been reported in fish ponds and tanks (Bedwell and Goulder 1996; US EPA 2002) and downstream of trout farm effluents in the UK (Carr and Goulder 1993 and references therein). These researchers reported that the mean abundance of total bacteria and percentage of particle-bound bacteria increased through the land-based farm and were noted in the effluent. As well, they indicated that bacteria in the effluent could increase bacterioplankton populations in receiving waters and oxygen demand and deoxygenation of rivers. US EPA (2002) reported elevated levels of indicator pathogens such as *Aeromonas*, fecal coliform bacteria, fecal *streptococcus* in treated effluents and solids storage effluents at two facilities sampled. In a study of a net-pen aquaculture site at Georgie Lake, BC, which is used for enhancement of wild salmon and trout, Castledine (1999) also reported enhanced microbial activity. Carr and Goulder (1993) suggested that increased bacterial populations could result in the need for improved treatment of potable water supplies from rivers currently used as drinking water sources in the UK.

Erickson (BC MWLAP, pers. comm.) indicated there are two key issues with development of bacterial resistance in sediment. First, there is the potential for resistance to therapeutants, which leads to a cycle of increasing dosage and increasing resistance. Second, there is a potential that the use of chemicals combined with the amplification of population growth, due to elevated nutrients, could lead to an increased mutation rate, which subsequently leads to new variants to which the fish have no or decreased immunity. The incidence and mechanism for bacterial resistance in freshwater requires further investigation.

6.4 Impacts on Algal Communities

Due to their high response to nutrients, algal assemblages are sensitive to aquaculture activities. Studies suggest that phytoplankton respond similarly to aquaculture as to other nutrient sources (e.g., sewage, agriculture) (Stirling and Day 1990). Localized increased algal productivity has been reported to occur in response to nutrient (TP) enrichment (e.g., Munro et al. 1985; Boyd et al. 1998a). Munro et al. (1985) reported that species composition of periphyton differed upstream and downstream of effluent discharges from BC salmon hatcheries. Green algae (*Ulothrix zonata* and *U. tenuissima*) and diatoms (*Nitzschia palea, N. fonticola,* and *Navicula pelliculusa*) were more abundant downstream of hatchery effluents reflective of nutrient enrichment (Munro et al. 1985). Overall, aquaculture activities have been shown to favour eutrophic algal species (Stirling and Day 1990). The ratio of several nutrients, rather than the quantity, may be a factor influencing the phytoplankton species composition. For example, in fish ponds, diatom production is favoured at a high N:P ratio of available nutrients (Boyd 1997), whereas low N:P ratios in lakes produce blooms of cyanobacteria (also referred to as blue-green algae) (Foy and Russell 1991). Fish farm discharges often have low N:P ratios and this impacts phytoplankton communities by producing a condition of N limitation and by encouraging the growth of nitrogen-fixing species (Foy and Russell 1991). The solid wastes from fish farms, which are high in P, can cause a persistent ecosystem-level shift to a dominance of cyanophytes if released over long time periods. The cyanophytes, which have adaptations to light limitations (e.g., *Microcystis aeruginosa*), modify abundance of all other primary producers by reducing available light.

There are many deleterious effects of excessive algal growth. Initial nutrient enrichment can result in increased water turbidity, reduced aesthetic appeal, and even decreased recreational use. Excessive nutrient enrichment can cause severe algal blooms that not only negatively impact water quality but can also cause fish kills (Hansen et al. 1994; Hallegraeff et al. 1995). Highly eutrophic systems are dominated by blue-green algae (cyanophytes) that form dense, foul-smelling, and noxious blooms on the surface of water as many of these algae are buoyant. Many species of blue-green algae produce potent toxins, which can poison zooplankton, fish, avian waterfowl, terrestrial wildlife, livestock, and even humans (Carmichael 1986, 1994; Pybus et al. 1986; Codd et al. 1988; Kotak et al. 1993a, 1994; Onodera et al.1997; Matsunaga et al.1999; Jacoby et al. 2000). Lopez and Costas (1999) suggest that animals have a preference for consuming toxic cyanobacteria over clean water increasing their mortality risk. Blue-green algal toxins are either neurotoxic (i.e., affect the nervous system) or hepatoxic (i.e., affect the liver) (Kotak et al. 1993b). There are numerous factors that influence toxin production including: elevated water temperature, high nutrient levels, high pH waters that have elevated concentrations of bicarbonate and carbonate, relative populations of other algae species (and resulting relative degree of grazing by zooplankton), and low light levels (Federal-Provincial Subcommittee of Drinking Water 1998). Of particular concern to fish farmers is that Health Canada recommends that fish caught in water containing cyanobacterial blooms should not be eaten as the toxins can be concentrated in the fish flesh (Federal-Provincial Subcommittee on Drinking Water 1998).

6.5 Impacts on Zooplankton

Addition of nutrients from aquaculture waste can cause changes in the abundance and composition of zooplankton. Beveridge (1996) indicated that the addition of nutrients can cause domination of the zooplankton community by *Daphnia*. Similarly, Johnston et al. (1992) reported shifts to large bodied plankters and colonization by *Daphnia pulex* following fertilization of earthen ponds used to culture walleye (*Stizostedion vitreum*) in Manitoba. In contrast, in a study of a rainbow trout caged culture site in Lac du Passage, Quebec, Cornel and Whoriskey (1993) found zooplankton, mainly *Daphnia*, were less abundant in the vicinity of the farm during the summer months than at the control sites. They suggested that available nutrients are assimilated quickly by the algae, eventually increasing their productivity and, in turn, cause changes in zooplankton populations. They also suggested that yellow perch (*Perca flavescens*) and escaped trout, which reside around the cages because of the easy availability of waste feed, graze upon the *Daphnia* in the area. They further suggested that *Daphnia* might avoid the farm because of predators or changes in water currents, oxygen depletion or a scarcity of food in the area arising from the shading effect. As well, the increase in solid wastes in the water column might also deter zooplankton. These bottom-up trophic interactions can result in communities vastly different from those occurring prior to nutrient input and that long-term impacts are of concern to lakes that support sport fishing or food sources for other predators (Cornel and Whoriskey 1993).

6.6 Impacts on Benthos

The effects of aquaculture on benthos are similar to those on bottom sediments, in that they are highly localized, usually within 10-100 m of cage aquaculture operations, and decrease in intensity with increasing distance from the site (Brown et al. 1987; NCC 1990; Gowen et al. 1991; Doughty and McPhail 1995; Brooks 2001). The response of benthic communities in freshwater lakes to organic inputs from freshwater cage farming is typical of the response of benthic communities to any point source of organic enrichment (NCC 1990). Responses vary by site location and the amount of organic enrichment. Benthic communities near aquaculture sites are generally dominated by enrichment-tolerant taxonomic groups (i.e., Oligochaeta and Chironomidae) and have lowered species diversity beneath cages while less tolerant taxa (Ephemeroptera, Hydracina, Hirudina) are absent beneath cages, although present in surrounding sediment (NCC 1990; Doughty and McPhail 1995).

Both structural and functional responses to fish farm effluents have been reported for land-based fish farms discharging effluent, and can include changes in species diversity, abundance and biomass as well as shifts from pollution sensitive to pollution tolerant species (Brown et al. 1987; Gowen et al. 1991; Camargo 1994; Selong and Helfrich 1998; GBA Foundation 1999). For example, effluent discharges from five trout farms in Virginia, USA caused decline in macroinvertebrate richness and abundance of sensitive taxa [Ephemeroptera spp.(mayflies), Plecoptera spp. (stoneflies), and Trichoptera spp. (caddisflies)] and increase in pollution tolerant taxa (isopods and gastropods) within 400 m but was similar to reference at 1 km downstream (Selong and Helfrich 1998). Munro et al. (1985) reported changes in benthic communities 60 to 700 m downstream of effluent discharges from BC salmon hatcheries indicating that these changes reflected nutrient enrichment rather than degradation of habitats. They noted that the benthic community response to the discharges was affected by the size of the hatchery and the quantity of phosphate and ammonia in the effluent. Loch et al. (1996) reported decreases in species richness that were greatest in months when flows were low and temperatures high. Carmargo (1994) indicated that the changes were mainly due to siltation of organic matter on the stream bottom and included decrease in diversity and the disappearance/reduction of sensitive macroinvertebrate groups (plecopterans, planarians, coleopterans, trichopterans) while tolerant species dominated (tubificid worms and chironomids).

Carmargo (1992) studied the suitability of using dominance, diversity, and biotic indices to assess benthic macroinvertebrate response in streams receiving trout farm effluent in Spain using four stations (reference, 10, 150, and 1000 m downstream). He reported changes in macroinvertebrate responses (species richness, diversity indices, and biotic indices) up to 1000 m downstream of this land-based farm but differences in dominance indices were found at only one station (150 m downstream). He concluded that species composition and richness were the most sensitive indices whereas dominance indices were the least sensitive macroinvertebrate response. Low levels of organic enrichment from aquaculture activities could provide an enhanced food supply to benthos and result in biostimulation (i.e., increase in species richness and macrofaunal biomass) (Gowen et al. 1991). The rate of recovery after temporary or permanent decommissioning of the facility may depend on factors such as the level of enrichment, rate of sediment transport, mixing between the sediment-water interface, re-establishment of the bacterial activity typical of unenriched conditions, life history of the resident species, and timing of their reproductive cycles relative to availability of suitable habitat (Gowen et al. 1991). For example, Doughty and McPhail (1995) reported recovery of benthic fauna in a stream receiving wastes from a land-based farm in Scotland within 19 months of the discharge ceasing.

6.7 Impacts on Fish

Fish farming can potentially affect wild fish populations by altering fish habitat and food supply as a result of deposition of organic matter (food and feces) and nutrient (and potentially chemical) loading. Escaped fish from farms can compete with wild fish for food and habitat, potentially introduce new genotypes through genetic interactions (via reproduction) with wild fish populations, and potentially introduce exotic species into ecosystems. They may also introduce disease and pathogens to wild organisms. As well, it has been argued that fish farming contributes to depletion of wild marine fish stocks that are used to manufacture fish food. Little is known about the potential impact of discharges from land based fish farms on the physiological and reproductive health of fish in receiving waterbodies.

6.7.1 Effects of Nutrients on Wild Fish Populations

Increased loadings of nutrients from aquaculture operations can cause increased growth and abundance in indigenous fish populations. In a review of the literature, Phillips et al. (1985b) noted that the introduction of wastes from aquaculture operations stimulates growth in indigenous fish populations as a result of consumption of nutrient-enhanced zooplankton populations. Phillips et al. (1985a) described several studies that have demonstrated that wild fish populations can increase and become reliant on waste feed from netpen cages.

In a study of the effect of cage aquaculture on wild fish in an oligotrophic Norwegian lake, Gabrielsen (1999) reported an increase in size and changes in feeding habit of Arctic char (*Salvelinus alpinus*) but not brown trout (*Salmo trutta*). He suggested that this difference was the result of differences in diet choices for the two species. Oberdorff and Porcher (1994) evaluated the impact of salmonid farm effluents on fish assemblages in Brittany (France) streams using the Index of Biotic Integrity (IBI). They concluded that fish farming causes both structural and functional changes in wild fish assemblages. They characterized these changes as an increase in total abundance and biomass together with shift in species composition towards a greater number of pollution tolerant species in the immediate vicinity of the farm. No Canadian studies were found that examined the impact of fish farm effluent on wild fish.

6.7.2 Potential Effects of Escaped Fish

Fish escapes periodically occur from open net cage operations as a result of damage to nets from storm events and predators, vandalism or poaching, and losses during fish grading and harvesting (Phillips et al. 1985b). The impacts of escaped fish from aquaculture operations on freshwater ecosystems have not been widely studied. In general, escaped non-native fish species can cause ecological impacts such as increased competition and predation as well as potential impacts on genetic integrity of native stocks. Native species introduced into novel wetlands can also affect size structure and species composition of plankton and fish communities (Almond et al. 1996; MacRae and Jackson 2001). One of the largest freshwater escapes in Canada occurred in the spring of 2000 when 490 000 rainbow trout escaped from a fish farm in Lake Diefenbaker, SK (Anonymous 2000b). The damage to the lake ecosystem was predicted to be minimal (Anonymous 2000b), although no studies were undertaken to substantiate this prediction.

6.7.2.1 Ecological Impacts

Escaped cultured species can alter ecosystem balances by competing for food and habitat niches as well as predating on native fish and other food sources such as invertebrates. The viability of escaped farm populations and their potential effects on wild fish populations has been the subject of considerable research and debate (i.e., Kapuscinski and Hallerman 1991; Johnsson et al. 1996; Unwin and Glova 1997; Clifford et al. 1998; Youngson and Verspoor 1998; Stevens et al. 1998; Gross 1998; Volpe et al. 2001). In a study of intra- and inter-specific competition between introduced juvenile Atlantic salmon (*Salmo salar*) and resident steelhead (*Oncorhynchus mykiss)* populations in Vancouver Island rivers, resident populations were always found to outperform introduced individuals (Volpe et al. 2001). Volpe et al. (2001) suggested that, although the resident steelhead will likely continue to predominate in Vancouver Island rivers, escaped Atlantic salmon are capable of colonizing and persisting in coastal British Columbia river systems that are underutilized by native species such as steelhead. This hypothesis is consistent with the observation that Atlantic salmon are now naturally reproducing in Vancouver Island rivers (Volpe et al. 2000). In contrast, Clifford et al. (1998) reported only a small proportion of farmed Atlantic salmon bred successfully in a study of Atlantic salmon in Northwest Irish rivers.

In a review of the literature, Phillips et al. (1985b) noted that escaped rainbow trout widely disperse in UK lochs providing ample opportunity for interactions with indigenous brown trout. However, in a preliminary analysis they found no significant adverse effect on brown trout. They suggested that although there is a broad basis for competition between the two species, there are differences in diet and a divergence in the feeding niches of brown trout and rainbow trout such that predominance of the latter is unlikely to occur. The applicability of these results to Canadian waters requires further research since the species composition and interactions differ in Canadian lakes (i.e., Lake Diefenbaker, Lake Huron) with net cage operations.

6.7.2.2 Impacts on Genetic Integrity

Cultured fish are commonly crossed populations that represent distinctive gene pools. They have often experienced a certain amount of inbreeding, selective breeding, domestication, or have been genetically modified through transgenic techniques such as gene insertion of desirable traits such as increased growth rates. The result is fish with a less diverse genetic background or novel gene assemblages. Escape can lead to contamination of natural stock, and have eventual potential adverse impact on local populations such as phenotypic changes or extinction.

In a recent review of the literature, Kapuscinski and Brister (2001) indicate that aquaculture has the potential to alter the genetic make-up and diversity among wild populations of aquatic organisms. They argue that the maintenance of adequate levels of genetic variation, both between and within populations, is essential for their long-term sustainability and evolutionary potential. Kapuscinski and Brister (2001) indicate that the potential for genetically-distinct fish to escape from cage aquaculture operations to survive, reproduce, and interbreed with indigenous or naturalized descendants of an introduced species that has become socio-economically important. Escapes from aquaculture operations can cross with closely-related species in the accessible ecosystem and result in interspecific hybridization among aquatic species which can yield fertile hybrids that can back-cross to wild populations. As such, genetic makeup of wild stock can be modified through interbreeding with escaped farm fish. A taxonomically distinct population of a native species is then at risk of being lost from this ecosystem. Kapuscinski and Brister (2001) argue that this, in turn, could result in the loss of coadapted gene and chromosomal complexes of rare alleles (i.e., specific adaptations and variation in wild populations important for natural selection) and threaten the long-term sustainability of capture fisheries. Local fish populations exhibit local adaptations critical to survival in the distinct conditions of local ecosystems. Although ecological impacts are not fully understood they will depend on the scale and frequency of introductions of cultured fish into the natural population.

Kapuscinski and Brister (2001) also indicate that aquatic genetically-engineered organisms (GEOs) (interspecific hybrids and chromosomal-manipulated finfish, shellfish or plants) are derived from parental populations and so are similar in genetic makeup to wild-types; thus, offspring of cultured fish are ecologically competent if they escape into the wild. However, they also note that the scientific community has barely begun to study the ecological risks of aquatic GEOs. Currently, GEO fish are not permitted in Canada.

In an *in situ* experiment on a Norwegian river containing freshwater resident trout as the only fish species, Skaala (1994) released cultured brown trout, which had been genetically marked, to examine effects on the characteristics of the populations. The study found that the non-indigenous spawners had little influence on the reproductive success of the wild rainbow trout and the reproductive success of the hatchery fish was 25-30% of the native population. Further, although genetic changes were recorded in the wild trout populations, these declined in frequency and number over the observation period. Skaala (1994) concluded that a single introduction of hatchery fish is not likely to critically affect wild populations as the reproductive success of the farmed fish is low and the survival rates of their offspring may be reduced. However, the study cautioned that frequent input of farmed fish could potentially affect the genetic characteristics of wild stocks. In a subsequent paper, Skaala et al. (1996) reported that survival was nearly three times higher in wild trout than in hybrids of wild and introduced trout. They indicated that this difference could be due to difference in the size of eggs and alevins between introduced and wild stocks.

The Ontario Ministry of Natural Resources (OMNR 1997) have considered concerns regarding the potential of escaped farmed rainbow trout to harm unique, self-sustaining populations through loss of genetic diversity by inter-breeding with escaped aquaculture fish. Both Wilson (pers. comm. Ontario Ministry of Natural Resources) and Danzmann (1996) advised the OMNR that the issue of genetic contamination of naturalized rainbow trout populations by escapement from commercial rainbow trout hatcheries or cage culture facilities is not a major concern in the Great Lakes drainages. They emphasize that this is only because rainbow trout are not native to the Great Lakes region, but have been introduced, and that high levels of genetic variation within Great Lakes metapopulations would provide a diverse array of genotypes, which would greatly speed up adaptive responses to selection pressures. However, these researchers also indicate that for species that are native to the region, escapes could have more serious consequences. Wilson (citing Allendorf and Leary 1988) indicates that native populations are much more vulnerable to hybridization and introgression from introduced or escaped fish, with the resultant loss of adaptive genotypes and/ or populations. They indicate that caution should be used with possible species introductions in headwater sections of drainages where sensitive species, such as brook charr, exist. Although all aquaculture operations must go through a risk analysis process, which includes assessing genetic impacts associated with fish escapes before a Certificate of Approval is issued, the OMNR do not consider genetic impacts as a significant risk in areas (e.g., Great Lakes) where rainbow trout have been previously introduced. Both Wilson (pers. comm.) and Danzmann (1996) note that the information necessary to evaluate the impacts of aquaculture escapes on native or naturalized populations is lacking. Further research is required in this area to determine the potential consequences of escapes from aquaculture on naturalized and natural species.

6.7.2.3 Introduction of Non-Native Species

Aquaculture can potentially result in the introduction of non-native species into water bodies. Aquatic species that are not naturally present in a particular geographic region can be considered non-native. Non-native species released into the environment can harm ecosystems by altering species composition and trophic structure, altering and degrading habitat, increasing competition for space, deterioration of gene pool, and introduction of diseases (US EPA 2002). These factors can contribute to reduced biodiversity and altered species composition. For example, in 1990, tench (*Tinca tinca*) escaped from a private farm in Québec and has since been detected in Richelieu River. This species has been recently identified as a concern for native fish (www.fapaq.gouv.qc.ca).

Non-native species released into natural systems, act as predators on native species and their eggs, compete for spawning sites, food and space, destroy habitat, and introduce disease and parasites. The introduction of non-native fish species in Canada can potentially lead to fish extinctions or place fish species at risk of extinction. For example, Gasaway and Drda (1997) found that lakes stocked with carp pose a definite threat to diving ducks. Carp introduced into natural lakes and ponds tend to eliminate submerged vegetation, a dietary requirement of ducks.

Provinces in Canada generally require that exotic species be raised and sold in contained systems only, thereby reducing the risk of release to natural waters.

6.7.3 Transmission of Fish Diseases

When fish are farmed intensively, infectious diseases that are normally present in wild populations, can become much more prevalent in the farm environment as a result of stresses associated with dense stocking (Lee et al. 1995). Fish diseases are caused by a wide variety of viruses, bacteria, fungi, protozoan, and metazoan parasites. For salmonids reared in freshwater, the most common diseases in Canada include bacterial gill disease, columnaris disease, protozoal infections, and saprophytic fungi (Speare and Arsenault 1997). US EPA (2002) review a number of studies that document disease transmission from aquaculture facilities to wild populations [e.g., Asian tapeworm (*Bothriocephaus acheilognathi)* from facilities raising golden shiners, fathead minnow and grass carp; whirling disease (*Myxobolus cerebralis)* associated with trout facilities]. Barker and Cone (2000) noted anecdotal evidence that two species of metazoan gill parasites have been identified among wild populations of American eels (*Anguilla rostrata)* in Atlantic Canada for the past three years associated with the operation of four facilities farming eels. Further investigation is needed to determine the incidence and risk of disease transfer between wild and farmed fish in Canadian fresh water.

In response to the occurrence of fish diseases, a number of therapeutants, antibiotics (disease treatment), and vaccines (disease prevention) have been developed for the aquaculture industry. These are further discussed in section 6.9. Barker and Cone (2000) have also examined and recommended the use of environmental factors (i.e., pH, stream velocity, and water temperature) as alternative measures to chemicals to control infectious diseases. Please note that this section is only briefly reviewed as this topic will be covered in DFO State of Knowledge report (McVicar in prep.).

6.7.4 Depletion of World Fisheries Resources

It is a common belief that the aquaculture industry is a food producer; however, current practices for the culture of carnivorous fish result in a net consumption of fish by the industry. Naylor et al. (2000) expressed concern that farming of carnivorous species requires large inputs of wild fish for feed, which in turn may deplete world wild fish stocks. Naylor et al. (2000) found that 8 of the top 20 commercially-fished species are used in feed production for the aquaculture and livestock industry. They estimated that intensive and semi-intensive aquaculture systems use 2-5 times more fish protein, in the form of fishmeal, to feed farmed fish than is supplied by the farmed product. Bottom feeders and traditionally planktivorous fish species are also fed fishmeal to increase weight and size class in a shorter time in preparation for market. As a result, oceans are being fished at a lower trophic level to supply aquaculture farms. As well, removal of small fish from the food chain means there is less food available for marine carnivores such as seals, whales, and seabirds (Goldburg and Triplett 1997). Rees (1999) also argues that domestic fish consumption in poorer nations is declining because their catch is being diverted to produce fish feed to supply wealthy nations.

Tydemyers (2000) indicated that fish food companies are now incorporating livestock-derived and plant protein into fish diets, which may relieve some of this pressure on wild fisheries. It should be noted that the wild marine fish are also used in feed manufacture for the agriculture and pet food industries.

6.8 Impacts on Wildlife

As a user of aquatic resources, the aquaculture industry has the potential for conflict with wildlife, particularly piscivorous birds. Much attention has focused on the impacts of wildlife and birds on the aquaculture industry with effort devoted to alleviate depredation by piscivorous birds and wildlife (see Mott and Boyd 1995). Less obvious and less studied, however, is the impact that aquaculture has on wildlife.

6.8.1 Habitat loss

Aquaculture facilities are commonly located in relatively undeveloped sites with an abundance of freshwater such as streams, rivers, lakes, or wetlands. The area surrounding such facilities is often typical of the natural habitat required by piscivorous birds and other wildlife. The amount of space aquaculture facilities require along with increased levels of human activity (similar to a large house or cottage), have the potential to displace birds from their habitat (Booth and Rueggeberg 1989).

Establishing aquaculture sites in important bird breeding and molting areas can have deleterious effects on populations in the long term. Species most likely to be affected have few large colonies and a lack of alternative breeding sites. This may be more common in marine situations such as for auklets (*Ptychoramphus* spp.) and puffins (*Fratercula arctica*), however, colony nesting birds such as great blue herons (*Ardea herodias*) and double-crested cormorants (*Phalacrocorax auritus*) are vulnerable to disturbance and population impacts as a result of their colonialism. Gulls (*Larus argentatus*), loons (*Gavia* spp.), goldeneyes (*Bucephata* spp), and raptors are also vulnerable to displacement from fin fish aquaculture sites because they use similar habitat. Areas where bird habitat and aquaculture development are likely to conflict, should be the focus of planning and management to limit disturbance and displacement as well as minimize economic losses.

In some areas in North America, conversion to aquaculture is the primary reason for natural wetland habitat loss (Lannoo 1998). Permitting aquaculture in seasonal, semi-permanent wetlands is contributing to amphibian decline as it displaces important breeding sites for native amphibians. Fish artificially stocked and maintained in wetlands can destroy a wetland ecosystem. Introduced fish often reduce or eliminate macroinvertebrates such as insects, the invertebrate prey base that amphibians and other animals depend on (Northcote 1988; Evans 1989). The feeding of fish can lead to the swift decimation of zooplankton collapsing the food web (Lannoo 1998). Bradford (1989) documents that fish and viable frog populations do not coexist in lakes of the Sierra Nevada, USA. Salmonids introduced over the past four decades may have predated to exclusion, tadpoles and frogs.

Aquaculture can stabilize water levels on natural water bodies reducing natural water fluctuations possibly limiting access to food and nest sites. Aquaculture facilities may also divert high quality water needed for wild populations, negatively impacting certain piscivorous birds and migratory waterfowl (Robinette et al. 1990).

While aquaculture facilities may contribute to habitat loss and birds can be actively displaced by aquaculturists, winter exploitation of aquaculture facilities may enhance the survival of piscivorous birds over winter. It has been suggested that the population increase in cormorants observed in recent decades is due to increased feeding opportunities presented by aquaculture in their wintering grounds (Erwin 1995). Others say the cormorant resurgence in the Great Lakes is due to the decrease in contaminants and the occurrence of enormous quantities of forage fish such as alewife (Charlton, NWRI, pers. comm.).

Ecological effects of nutrient enrichment (and potential eutrophication) from metabolic wastes and uneaten food from fish farms can disrupt wildlife communities. Effluent from fish farms can smother bottom flora and fauna reducing the food source for bottom feeders. However, in some situations enhanced food sources provide additional resources to local fish species, positively benefiting local wildlife populations.

6.8.2 Persecution

Wild animals are attracted to aquaculture facilities as a source of food as they contain high densities of fish and are often in close proximity to natural habitat. Many aquaculturists consider wildlife and particularly piscivorous birds to cause extensive economic losses to aquaculture operations by injuring and consuming fish. The double-crested cormorant, great blue heron, and great egret (*Casmerodius albus*) are the principal species reprobated for cultured freshwater fish losses in North America. Much available information concentrates on how birds negatively impact aquaculture and assesses the effectiveness of various control strategies including buffer prey populations, physical barriers, mechanical and chemical repellents, and auditory scare techniques such as pyrotechnics (e.g., Pennsylvania State University 1998). Wildlife and particularly piscivorous birds, are often injured or killed by entanglement from attempting to overcome the barriers to the fish. Further studies are required to determine the frequency and extent of injury and loss of wildlife due to these aquaculture activities and the resulting impact on wildlife populations.

In Canada and some states in the USA, aquaculturists are permitted to supplement non-lethal harassment programs with lethal control methods. The need to evaluate the impact of issuing bird permits on local and regional bird populations was discussed by Trapp et al. (1995). Belant et al. (2000) showed that increasing numbers of depredation permits are being issued in turn resulting in increasing numbers of birds being killed or injured each year. They suggested that the increase in issued permits is likely due to increased awareness of permit availability rather than an increase in depredating birds. They concluded that birds taken by permit represent a small percentage of the breeding population and do not impact on the population as a whole. ~~Others suggest reported kills represent only a fraction of those killed illegally (Williams 1992).~~

There is less information available on mammalian predators at aquaculture facilities, but muskrats (*Ondatra zibethicus*), mink (*Mustela vison*), river otters (*Lutra canadensis*), bears (*Ursus* spp.), and raccoons (*Procyon lotor*) are known to be attracted to freshwater aquaculture facilities for food.

6.8.3 Disease and Parasites

New diseases and parasites can be spread to wild species with the introduction of infected non-native or non-local species. Without natural defenses to introduced disease, native fish populations are extremely vulnerable (Stewart 1991; Clugston 1990). Within an aquaculture facility or stocked pond, bird hosts are attracted to the area by introduced fish, which in turn consume parasite predators. The combined increase in densities of fish and bird hosts can concentrate parasitic loads, compromising the health of birds and the economic value of fish.

6.9 Chemicals Used in Aquaculture

Data on the types, quantities, and frequency of chemicals used in Canadian freshwater aquaculture are currently lacking in the literature. The types and quantities of chemicals used by aquaculturalists vary from site to site as well as from year to year (Thornburn and Moccia 1993). Although chemical usage is common in mariculture, Thornburn and Moccia (1993) reported Ontario freshwater trout farmers used chemotherapeutants only rarely if at all, in a survey conducted over 10 years ago. Chemical use varies with farm location, water temperature, stock health histories, farm management practices, and therapeutant availability (Muise and Associates 2000). A thorough risk assessment of chemicals used in aquaculture is beyond the scope of this report. Chemicals potentially used in aquaculture are briefly reviewed below. For a more comprehensive discussion, the readers are referred to relevant literature (Thornburn and Moccia 1993; Boyd and Massaut 1999; Muise and Associates 2000; Costello et al. 2001; US EPA 2002; Fisheries and Oceans Canada 2003a). As a component of Fisheries and Oceans Canada State of Knowlede initiative on aquaculture, a literature review is under preparation on the environmental fate and effects of chemotherapeutants used in Canadian freshwater aquaculture (Scott in prep.).

Cantox Environmental Inc. (2001) recently scored and ranked the ecological risk potential of many of the chemicals used in aquaculture in Atlantic Canada. In general, environmental concerns related to aquaculture chemicals include (Redshaw 1995; Midlen and Redding 1998):

1) uptake of contaminants by wild organisms;
2) direct toxicity to non-target organisms;
3) persistence of chemicals in the environment;
4) development of resistance to compounds by pathogenic organisms; and
5) contamination of receiving waters used for drinking, recreation, and agriculture.

6.9.1 Therapeutants

The most common therapeutants used for freshwater-farmed salmonids are formalin and chloramine-T, which are used to treat various infections (Thornburn and Moccia 1993). Chloramine-T is used to treat bacterial gill diseases and as a prophylactic and disinfectant. Its degradation products include hypochlorite and paratoluenessulphonamide (Thornburn and Moccia 1993; Lee et al. 1995; Powell and Perry 1996; Muise & Associates 2000; Manitoba Conservation 2001). Hydrogen peroxide has been proposed as a safe and effective alternative treatment to chloramine-T to treat gill and skin diseases (Speare and Arsenault 1997). Anecdotal information suggests that some hatcheries use malachite green (Erickson, BC MWLAP pers. comm.).

6.9.2 Antibiotics

A variety of antibiotics are used by the aquaculture industry such as oxytetracycline, terramycin-aqua, and tribrissen. Muise & Associates (2000) indicated that increased availability of vaccines for the major diseases infecting aquaculture stocks has reduced the use of antibiotics over the past eight years in Atlantic Canada. Antibiotics are used to treat diseases in farmed fish and are typically applied orally or by immersion (US EPA 2002). US EPA (2002) indicate that these routes can allow significant amounts of antibacterial agents (through uneaten medicated feed or leached, unabsorbed, or excreted drugs) to escape into the environment. For example, NCC (1990) estimated that 70-90% of oxytetracycline (OTC), a broad spectrum antibiotic administered in fish feed, is lost to the environment. The persistence of antibiotics in marine sediments is variable depending on site conditions (e.g., half-lives for oxytetracycline are 9 to 419 days) (Jacobsen and Berglind 1988; Samuelson et al. 1992; Samuelson 1994). No studies were found on the environmental fate, persistence and accumulation of antibiotics in freshwater ecosystems.

Potential adverse impacts from the release of antibiotics into the environment include increased incidence of antimicrobial resistance, changes in benthic communities, and toxic effects on natural bacterial populations. These, in turn, can affect nutrient cycling, selection for antibiotic resistant strains of fish pathogens, and elevated concentrations of antibiotic in wild aquatic biota (Spanggaard et al. 1993; Samuelson 1994; Axler et al. 1996). For example, Guardabassi et al. (2000) reported that the use of oxolinic acid-medicated feed at a freshwater rainbow trout farm in Denmark significantly affected the level of antimicrobial resistance of *Acinetobacter* spp. in the stream receiving farm effluent. Further work is required to determine the incidence of antibiotic use in Canada, the presence of antibiotic resistance organisms in Canadian freshwater sediment, and the resulting biological effects.

6.9.3 Anesthetics

Anesthetics, applied via a bath solution, are used to minimize stress on fish during routine weighing, tagging and vaccinating, grading fish, and performing sea lice counts. These are disposed on land or in the wastewater stream (Muise and Associates 2000). Some types of anesthetics used include Aqualife TMS, MS 222 (active ingredient is tricainemethanesulphonate), Benzocaine, and Marinil (for non-salmonids only) (Lee et al. 1995; Muise and Associates 2000; Manitoba Conservation 2001).

6.9.4 Detergents, Cleaning and Disinfecting Agents

Various detergents, cleaning and disinfecting agents are used in aquaculture, particularly land-based operations to prevent the establishment of disease. Some of the common chemicals used include iodothor, iovidine, chloramine T, sodium hydroxide and formalin, chlorine, hydrogen peroxide, hypochlorites formaldehyde) are used to sterilize equipment for disease management on fish farms and hatcheries (Zitko 1994; Potts and Jolly 1998; Muise & Associates 2000;

Costello et al. 2001; Liboiron 2001). Iodine and chlorine can escape to the environment via dissipation to the air, dilution to surrounding water from net cage sites or in wastewater streams from land-based facilities (Muise & Associates 2000). Liboiron (2001) indicate that most facilities flush the chemically-treated water from BC land-based facilities out with the effluent. Although the BC *Land-Based Fin Fish Waste Control Regulation* prohibits the discharge of chemicals to receiving waters unless the effluent passes a 96-hour LC_{20} on rainbow trout, none of the land-based facilities on Vancouver Island have conducted toxicity tests even though detergents, cleaning disinfecting agents and other chemicals are routinely used by these facilities (Liboiron 2001).

6.9.5 Antifoulants

Antifoulants, used periodically to treat nets, are mainly copper based (Costello et al. 2001). Based on the limited literature found, antifoulants appear to be used on a small scale in Canada and primarily on marine sea cages (Zitko 1994; Muise & Associates 2000).

6.9.6 Metals

Elevated concentrations of metals in sediments above background have been found below both freshwater (e.g., zinc at net pen in Georgian Bay: Thorburn and Boyd 2002) and marine salmon net pen operations (e.g., copper and zinc: Parker and Aubé 2002). Although the sources of these metal concentrations are not fully understood, some food formulations can contain zinc and/or copper, which are essential minerals in the fish's diet or metals can occur in sanitation products or result from deterioration of machinery and equipment (Parker and Aubé 2002; US EPA 2002).

6.9.7 Pesticides

The incidence of pesticide use at freshwater aquaculture sites in Canada was not found in the literature. Pesticides are mainly used in marine aquaculture to control parasites such as sea lice in salmonids. Salmosan® (azamethiphos) is currently the only pesticide registered for use in Canada, although ivermectin and Slice® (emamectin benzoate) are authorized for use at some marine sites as off-label drug treatment under veterinary prescription and emergency drug release, respectively (Fisheries and Oceans Canada 2003a). These pesticides have been shown to be highly toxic to shrimp and lobster, particularly the juvenile life stages (Abgrall et al. 2000; Burridge and Haya 1993, 1995, 1997; Burridge et al. 1999, 2000a,b).

Algaecides and herbicides (i.e., copper sulfate, chelated copper compounds, simazine, and potassium ricinoeate) are used extensively in pond aquaculture to reduce the abundance of nuisance aquatic plants (Boyd and Massaut 1999). Copper sulfate is acutely toxic to fish at high concentrations. Simazine is very toxic to phytoplankton but has low toxicity to fish at application rates used for algal control (Boyd and Massaut 1999).

Limited use of piscicides (i.e., teaseed cake, rotenone, lime, potassium permanganate, and ammonium fertilizer) occurs in pond aquaculture to treat water that remains after harvest. The compounds are then degraded by natural processes before fish are stocked for the next crop (Boyd and Massaut 1999).

Bactericides (i.e., BKC, providone iodine, glutaraldehyde, and formalin) are added to pond water to prevent excessive development of pathogenic bacteria (Boyd and Massaut 1999). Little information is known about the bioaccumulation potential and degradation products of these compounds.

6.9.8 Fertilizers

Fertilizers are applied to pond aquaculture to increase nutrient concentrations, stimulate phytoplankton growth, and ultimately enhance production of fish or crustaceans (Fox et al. 1992; Boyd and Massaut 1999). Boyd and Massaut (1999) indicate that most fertilizers will have been absorbed by the pond organisms, sediments or lost to the atmosphere through denitrification or ammonia volatilization before pond water is discharged. Examples of fertilizers include urea, ammonium sulfate, ammonium nitrate, potassium nitrate, triple superphosphate, manure, and trace and secondary element mixes (Boyd and Massaut 1999).

6.9.9 Water Treatment

Liming materials are applied to ponds and soils to neutralize acidity and increase total alkalinity. Burnt lime and hydrated lime, if used excessively, can temporarily increase water pH and cause toxicity to aquatic plants and animals (Boyd and Massaut 1999). Coagulants are applied to aquaculture ponds to flocculate suspended clay particles and cause them to precipitate in order to clear the water of turbidity (Boyd and Massaut 1999). Salt (sodium chloride) and calcium sulfate or gypsum are used to increase salinity or water hardness, respectively, to improve conditions for osmoregulation by certain culture species (Boyd and Tucker 1998).

6.10 Contaminants in Fish Feed, Fish Oil and Farmed Fish

Recently, there has been some controversy concerning potentially elevated contaminants in farmed fish. Although these concerns have been expressed, they remain unsubstantiated. Easton et al. (2002) examined contaminant loadings in farmed salmon, wild salmon, and commercial salmon feed and found that with one exception, farmed salmon showed consistently higher levels of polychlorinated biphenyls (PCBs), polybrominated diphenylethers, and organochlorine pesticides. They hypothesized that the elevated levels in farmed salmon arise from contaminated feed and may pose a risk to frequent human consumers of farmed fish. Easton (pers. comm.) cautioned against extrapolating these results to freshwater aquaculture without further monitoring and analyses. Santerre (2002) criticized this study arguing that the presentation of results (which were given in an unconventional manner) as well as the small sample size and lack of statistical analyses may mislead the reader to inaccurate conclusions. In a freshwater aquaculture study in the southern USA, farm-raised channel catfish, rainbow trout, and red swamp crayfish were examined for metal, organochlorines, organophosphates, and pyrethroids residue (Santerre et al. 2000, 2001). They concluded that metal residues were much lower than recommended safety limits and that most residues of organochlorines, organophosphates, and pyrethroids were well below action limits. Overall, Santerre et al. concluded that the risk of obtaining contaminated fish from aquaculture is lower than for wild fish.

The Canadian Food Inspection Agency (CFIA 2002) recently published a preliminary survey on contaminants (dioxins, furans, PCBs, DDT, and mercury) in fish feed, fish- meal, and fish oil. They found levels of dioxins, furans, and PCBs in fish feed and fish- meal would not be expected to result in fish containing contaminant levels exceeding Canadian Guidelines for Chemical Contaminants and Toxins for Fish and Fish Products (maximum limit of 20 ppt TEQ for Dioxin and Furan and 2.0 ppm for PCBs). Higher levels of dioxins, furans, and PCBs were observed in fish oil (mean 130.73 ppb). Mercury and DDT levels in fish feed, fish meal, and fish oil did not exceed Canadian Guidelines for chemical contaminants and toxins in fish and fish products (maximum limit of 0.5 ppm for mercury and 5.0 ppm for DDT). The CFIA is currently utilizing the results from this survey to develop a continued monitoring plan with the goal to minimize dioxins, furans, and PCBs in the food chain.

6.11 Impacts on Drinking Water Supplies

Freshwater aquaculture likely has minimal impact on drinking water supplies in Canada. Redshaw (1995) indicated that aquaculture wastes and chemicals released into receiving waters in the UK could potentially impact potable water supplies and increase the level of water treatment required. There were no incidences of impacts found in drinking water supplies associated with aquaculture in Canada (Green, Health Protection Branch, Health Canada, pers. comm.) with the exception of one anecdotal incidence of well water contamination apparently resulting from the discharge of aquaculture effluent into Lacs Forgeron and des Pins at Notre-Dame-du-Laus in Québec (Sousy 2000).

6.12 Recreational Impacts of Aquaculture in Canada

Documented incidences of recreational impacts caused by fish farms are rare in Canada. In one incident in Québec, villagers of Notre-Dame-du-Laus were unable to swim in the lakes for three years as a result of water quality impairment of Lacs Forgeron and des Pins from fish farm effluent. This fish farm has since been decommissioned (Soucy 2000) and the lake has fully recovered (Carignan, University of Montreal, pers. comm.).

Green (Health Protection Branch, Health Canada, pers. comm.) noted that swimming adjacent to fish farms could potentially increase the risk of infections in swimmers caused by *aeromonas* bacteria. However, there have been no reported incidences of *aeromonas* infections in Canada associated with aquaculture operations.

Aquaculture also has a positive impact on recreational activities. Aquaculture supplies some fisheries sites with fish for anglers where in some areas these fish would not exist (St. Jacques, Environment Canada, Quebec Region, pers. comm.).

7 Canadian Environmental Quality Guidelines (EQGs) Relevant for Aquaculture Operations

Canadian Environmental Quality Guidelines (EQGs) are nationally endorsed, science-based goals for the quality of aquatic and terrestrial ecosystems. EQGs are defined as numerical concentrations or narrative statements that are recommended as levels that should result in negligible risk to biota, their functions, or any interactions that are integral to sustaining the health of ecosystems and the designated resource uses they support (CCME 1999). The guidelines are used by federal, provincial, and territorial governments to achieve the highest levels of environmental quality. In many cases, EQGs form the scientific basis upon which further site-specific criteria, guidelines, objectives, or standards can be developed for various jurisdictions.

Canadian Water Quality Guidelines (CWQGs) have been developed to provide basic scientific information about water quality parameters and to protect Canadian species and water uses. The water quality guideline development protocol for Canada is intended to deal specifically with toxic substances and provide numerical limits or narrative statements based on the most current, scientifically defensible toxicological data available.

Environmental quality guidelines applicable to the aquaculture sector are available or under development for core water quality parameters (e.g., nutrients, pH, dissolved oxygen). However, guidelines are lacking for most chemicals used in aquaculture such as therapeutants (e.g., chloramine-T, sulfamerazine), antibiotics (e.g., oxytetracycline, terramycin-aqua, romet, tribissen), anesthetics (e.g., aqualife TMS, defome FG-10), and disinfectants (e.g., formaldehyde).

Even for the available water quality guidelines, it may become necessary to develop site-specific guidelines that can accommodate both environmental quality and sustainable aquaculture. For example, the effects of nutrient enrichment and associated eutrophication processes in Canadian surface waters are site-specific and vary widely among ecosystems (Chambers et al. 2001). These conditions emphasize that any national approach developed for addressing nutrient related concerns should incorporate flexibility in management-driven goals among jurisdictions.

Site-specific water quality guidelines are typically based on generic guidelines and criteria and can be modified to account for local conditions. The identification of contaminants and their loadings, physical and chemical characteristics of the water body, resident biotic species and aquatic community, local water uses, and other factors have to be carefully considered in developing site-specific water quality guidelines. The National Guidelines and Standards Office in conjunction with the Canadian Council of Ministers of the Environment (CCME) has developed a guidance document (Guidance on the Site-specific Application of Water Quality Guidelines in Canada: Procedures for Deriving Numerical Water Quality Objectives) on site-specific Water Quality Guidelines (CCME 2002). This document has been nationally endorsed.

Canadian Water Quality Guidelines for parameters that have been identified of relevance to the aquaculture sector are presented in Appendix C.

8 Environmental Management for Aquaculture

The use of good management practices can greatly reduce environmental impacts related to feeding such as (see Environment Canada 2001b,c; Anon. 2002 for further information):

- using optimized feed formulations with low phosphorus content;
- using optimal feed types such as dry, floating, and appropriate size pellets;
- using efficient feeding regimes; and
- monitoring feeding behavior and adjusting feeding accordingly.

A Best Management Practices Guide for freshwater aquaculture report is under development by Fisheries and Oceans Canada, which discusses recommended guidelines for waste management, quality control measures, and other management practices (Anon. 2002). One key challenge for aquaculturalists is to efficiently convert feed into fish growth in order to minimize feed waste. Considerable effort has been undertaken in recent years to improve biological conversion of food into animal production and reduce the production of waste (e.g., Cho et al. 1994; Cho and Bureau 1997). One approach is to increase the bioavailability of dietary phosphorus in animal feeds in order to produce low polluting feeds (Skonberg 1997). Aquaculture operations with good management practices strive to minimize the feed conversion ratio, which is the weight of feed used to produce a given weight of fish. To help aquaculturalists minimize the generation of waste, high nutrient dense (HND), low-pollution diets have been developed (i.e., Cho et al. 1994). These HND diets optimize protein:energy ratios to minimize levels of dissolved nitrogenous compounds in effluent (Cho et al. 1994). Rennert (1994) demonstrated that waste output from a land-based rainbow trout farm in Germany was reduced by about 53% for nitrogen and 42% for phosphorus from past performance by improving feed conversion ratio by about 40%. In a study of freshwater lakes in Scotland, Gavine et al. (1995) also demonstrated that there was significant improvement in the phosphorus content in diets and reduction in phosphorus waste loadings from cage rainbow trout farms through the use of better-quality diets and improved feed management. Cole (AquaCage, Parry Sound, ON, pers. comm.) indicated that most open water net cage fish farms in Ontario are currently using HND diets with low phosphorus (~1%). Information on the extent to which these HND diets are used at land-based fish farms in Canada was not found.

8.1 Waste Treatment

A comprehensive discussion of waste treatment is beyond the scope of this report. Briefly, waste discharge and treatment vary from site to site and differ greatly between open net cage and land-based aquaculture operations. In open net cage operations, wastes are generally released directly into the environment where they disperse by water currents and, ultimately, are deposited on the lake bottom, diluted in surface waters, ingested by other organisms or, in the case of certain substances, volatilized to the atmosphere. Some technologies to retain, collect, and minimize waste generation beneath cage sites include (see OMOE 1988, 1990; Environment Canada 2001c for further discussion):

- bag system;
- fallowing;

- vacuuming; and
- harrowing.

Wastewater treatment/conservation methodologies for land-based operations include (OMOE 1988, 1990; Cripps and Kelly 1995; Lee et al. 1995; Schwartz and Boyd 1995; Kristiansen and Cripps 1996; Summerfelt et al. 1997):

- gravitational separation (settling ponds/stabilization ponds);
- filtration;
- groundwater recharge;
- ultraviolet radiation;
- ozone;
- polyculture (e.g., Corriveau 2002);
- screening;
- aeration and settling;
- land application;
- ion exchange; and
- oxygen injection.

8.2 Mitigation Techniques

A comprehensive review and discussion of mitigation measures to reduce the environmental impacts of aquaculture is beyond the scope of this report. Briefly, some mitigation techniques include:

- Appropriate site selection to reduce effects on local habitat and wildlife;
- Development of vaccines to reduce the use of antimicrobials;
- Development of scare techniques to reduce kills of "nuisance" wildlife attracted to aquaculture operations as a food source;
- Increased planning and management to limit disturbance and displacement of wildlife;
- Predictive modeling to determine the appropriate carrying capacity of the operation;
- Improved husbandry techniques to reduce risk of disease and parasites;
- Effluent treatment and water reuse to reduce or eliminate impacts on receiving water systems (Robinette et al. 1990; Boyd and Tucker 1998);
- Use of a polyculture system to utilize plants to enhance the removal of phosphorus and nitrogen from fish farm effluent (e.g., Corriveau, 2002)
- Use of low phosphorus feeds and feeding strategies to minimize excretion losses (Boyd and Tucker 1998); and
- Improved management of water body to enhance water quality (Boyd and Tucker 1998).

9 Information Gaps

In the preparation of this scoping assessment report, numerous information gaps were identified. There is a paucity of information on the impacts of freshwater aquaculture on the Canadian environment, however, information was largely available for aquaculture in Europe and the United States. In general, the environmental impacts of mariculture have been more widely studied than freshwater aquaculture in Canada. The following information gaps were identified:

Research, Monitoring, and Knowledge Development

- What is the spatial extent and magnitude of nutrient and toxic effects to aquatic biota and wildlife that may occur? This includes the relationship between nutrient loadings and food chain (i.e., abundance and richness of phytoplankton, zooplankton, and fish) and cumulative effects of aquaculture effluents on aquatic ecosystems?

- What are the implications of aquaculture to the overall nutrient budget in a water body (i.e., what is the relative magnitude and importance of nutrients from fish farms)?

- What is the relationship between the time of fish excretion relative to feeding and overall effects of fish feeding on water quality?

- What are the impacts and what is the importance of waste/organic deposits on natural benthic community (e.g., invertebrates, attached algae) and sediment quality?

- Up-to-date data are needed on the types, amount and frequency of chemical usage in both land-based and open net cage freshwater aquaculture and the associated fate, toxicity, and environmental quality guidelines of these substances.

- What are the impacts of introduced or escaped species over the long term on ecosystem health in Canada (e.g., species composition and diversity, effects of escaped fish on wild fish and potential crossbreeding resulting in genetic impacts and loss of biodiversity)?

- What are the potential implications of possible expansion of the industry in ecologically sensitive regions of Canada (e.g., North Channel of Lake Huron) and what tools can be developed, evaluated and used to determine the ultimate carrying capacity of these areas?

- What is the status of land-based operations, including their monitoring and effects on receiving waters in Canada?

- What is the prevalence of wetland conversion and habitat loss from aquaculture in Canada and its potential implications on wildlife habitat (e.g., feeding, nesting)?

- Reliable data are needed on persecution of wildlife (e.g., numbers of birds killed or injured), which are a nuisance for aquaculturalists, and the resulting cumulative impacts on wildlife populations in relation to other stressors.

- What are,the global implications of energy transfer from the oceans to freshwater by way of the use of ocean fish to make fish-meal?

- What is the mechanism for the development of resistance to therapeutants, which leads to a cycle of increasing dosage and increasing resistance. Does the use of chemicals, combined with the amplification of population growth due to elevated nutrients, lead to an increased mutation rate, which subsequently leads to new variants to which the fish have no immunity?

- Standard analytical methods for measuring most therapeutants and other chemicals used in aquaculture in receiving waters need to be developed.

- Information is needed on the relationship between current flow and flushing and accumulation of total Phosphorus.

- What are the physiological and reproductive effects of fish farm practices on wild fish?

Science-based Tool Development and Best Management Practices

- What best practices could still be developed such as fallowing, seasonal moves, and manure collection to minimize the impacts of aquaculture?

- What makes a good cage aquaculture site in fresh water?

- What kinds of impacts are acceptable and would any of these be beneficial in some way?

- A national monitoring and assessment framework that is scientifically defensible and cost-effective needs to be developed to support sustainable management decisions.

- Chemical and biological indicators need to be developed and evaluated to assess ecological integrity implications of aquaculture over the long term.

- There is a need to improve the understanding of cause-effect relationships for ecosystem changes and determine thresholds for aquaculture. Scientific uncertainty associated with predictions needs to be incorporated and accepted into the assessment and management process.

- Along with the site-specific applications of available environmental quality guidelines in aquaculture sector, there is a pressing need to develop guidelines for chemicals that have no guidelines.

Science-Policy

- What are the socioeconomic effects of the industry in fresh water? What are the tradeoffs?

- Are there any mitigating circumstances that distinguish fish farming from other feedlot activities? Is there an environmental subsidy that is unfair?

- Trigger limits (in terms of acceptability) for size of area (foot print) under cage impacted by aquaculture operations.

10 Recommendations for Science and Research

Throughout this scoping assessment, many information gaps were identified for the environmental effects of aquaculture and the extent of impacts in Canada is largely unknown. To address these gaps and further enhance the science-policy linkages, the EC Freshwater Aquaculture Science Working Group recommends:

Research, Monitoring, and Knowledge Development

- A targeted science program that will address the information gaps to improve the understanding of the significance of ecological changes from aquaculture operations and result in recommendations for policies to improve sustainable management practices for aquaculture. Improving the scientific understanding of ecological changes associated with aquaculture will indicate limitations and/or how and where the industry may grow in a sustainable fashion.

Science-Based Tool Development

- Development of Science-Based Tools and Best Management Practices for Decision Making towards sustainable aquaculture practices are required. Development of science-based tools and Best Management Practices to improve the sustainable management of aquaculture are required. This includes environmental quality guidelines, targeted environmental monitoring, and an environmental quality monitoring and assessment framework. This framework will assist in setting environmental quality benchmarks for receiving waters that could be used as the scientific basis for risk management in support of sustainable aquaculture.

Intergovernmental Science-Policy Coordination

- A framework/mechanism is needed to better coordinate and integrate science activities among federal and provincial governments.

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Appendix A. Provincial and Territorial Legislation and Regulations Pertaining to Aquaculture (Source: OCAD 2001 with modifications)

British Columbia
- *Aquaculture Regulation*
- *Aquaculture Waste Control Regulations*
- *Land-Based Fin Fish Waste Control Regulation*
- *Corporation Capital Tax Act*
- *Environmental Assessment Act*
- *Farm Practices Protection Act*
- *Fisheries Act*
- *Freedom of Information and Protection of Privacy Act*
- *Industrial Development Incentive Act*
- *Lands Act*
- *Municipal Act*
- *Small Business Venture Capital Act*
- *Social Service Tax Act*
- *Waste Management Act*
- *Wildlife Act*
- *Fish Inspection Act*
- *Water Act*

Alberta
- *Alberta Fisheries Act - Alberta Fisheries Regulations*
- *Alberta Water Act*
- *Land Act*
- *Environmental Protection and Enhancement Act*
- *Water Act*
- *Public Health Act*

Saskatchewan
- *Fisheries Act - Fisheries Regulations*
- *Animal Protection Act*
- *Provincial Land Act*
- *Environmental Management Protection Act*
- *Wildlife Act*

Manitoba
- *Water Rights Act*
- *Environment Act*
- *Crown Lands Act*
- *Manitoba Fisheries Act*

- *Health Act*

Ontario
- *Fish and Wildlife Conservation Act*
- *Ontario Water Resources Act*
- *Public Lands Act*
- *Fish Licensing Regulations*
- *Environmental Protection Act*
- *Pesticide Control Act*
- *Environmental Assessment Act*
- *Lakes and Rivers Improvement Act*
- *Nutrients Management Act*

Québec
- *Loi sur les pêcheries et l'aquaculture commerciales*
- (An Act Respecting Commercial Fisheries and Aquaculture)
- *Loi sur la conservation et la mise en valeur de la faune*
- *Loi sur la qualité de l 'environnement*
- *Loi sur les produits alimentaires*
- *Loi sur le régime des eaux*
- *Loi sur la transformation des produits marins*

New Brunswick
- *Aquaculture Act -Aquaculture Regulations*
- *Fish and Wildlife Act*
- *Fish Inspection Act*
- *Fish Processing Act*
- *Fisheries Development Act*
- *Inshore Fisheries Representation Act*
- *Clean Environment Act*
- *Pesticide Control Act*

PEI
- *Environmental Protection Act*
- *Fish and Game Protection Act*
- *Fisheries Act*
- *Institute of Man and Resources Act*
- *Pesticides Control Act*
- *Fish Inspection Act*

Nova Scotia
- *Environment Act*
- *Executive Council Act*
- *Fisheries and Coastal Resources Act - Aquaculture License and Lease Regulations*

- *Public Service Act*
- *Remembrance Day Act*
- *Pesticide Control Act*
- *Crown Lands Act*
- *Wildlife Act*

Newfoundland

- *Aquaculture Act -Aquaculture Regulations*
- *Environment Act*
- *Lands Act*
- *Pesticides Control Act*
- *Historic Resources Act*

Yukon

- *Fish Processing Act*
- *Indian Act*
- *Yukon Territory Fishery Regulations*

Appendix B: Environmental Monitoring for Aquaculture

Status and Background

Monitoring of land-based and open net cage freshwater aquaculture operations varies among jurisdictions across Canada and is mainly limited to key water quality parameters such as suspended solids, nutrients (i.e., phosphorus, nitrogen compounds), TSS, dissolved oxygen, and pH (Tables B-1 and B-2, Lee et al. 1995; Linquist 2001). In general, biological monitoring of freshwater operations is limited to research studies which have assessed impacts of aquaculture on pelagic plankton, benthic communities, and occasionally fish populations (Cornel and Whoriskey 1993; Charlton, NWRI, pers. comm.; MacIssac and Stockner 1995). Few of the chemicals used in aquaculture are routinely monitored.

In Ontario, land-based fin fish facilities are required to monitor effluent monthly (e.g., TSS, TP) as a condition of their permit (S. Naylor, OMOE, pers. comm.). Monitoring at open net cage operations is currently performed by operators, both on a voluntary basis and as a requirement of their permits, as well as by the Ontario Ministry of Environment (OMOE). The OMOE (2001) have developed draft recommendations for water quality monitoring at cage culture operations including chemical, physical and biological components. These recommendations include:

- regional background water quality data for the area;
- location of water quality sampling stations;
- phosphorus sample collection and data analysis with trigger limits (PWQO) and actions (e.g., adjustment of feeding, frequency of phosphorus sampling, assessment of periphyton growth);
- water clarity (Secchi depth and colour);
- temperature/DO sample collection with trigger limits (PWQO) and actions (adjustment in feeding, may require benthic sampling program);
- sediment sample collection and data analysis (particle size, nutrients) with trigger limit [if statistical significant difference ($\alpha \leq 0.05$) at upstream and downstream sites] and actions (operational audit and abatement plan to reduce operational scale for next season, may require benthic sampling program to estimate extent of benthic habitat impairment).

In Ontario, monitoring is currently performed by operators, both on a voluntary basis and as a requirement of their permits, as well as by various provincial ministries and is even duplicated at some locations (i.e., Georgian Bay: Linquist 2001). The Ontario Sustainable Aquaculture Working Group is currently assisting multistakeholder projects to advance or develop better monitoring protocols for freshwater netcage sites.

Several research studies that have been undertaken or are underway in Ontario should provide a more solid scientific basis for environmental monitoring at aquaculture sites. For example, in a study of cage aquaculture sites at Manitoulin Island and Parry Sound, Boyd and Thorburn (2001) analyzed sediment samples for nutrient, particle size, TOC, LOI, and metals. As well, they undertook a qualitative field evaluation of benthic invertebrates. A study of the time and depth of excretion of fish in a farm is in progress as a partnership between University of Guelph, Environment Canada, and the Ontario Ministry of the Environment. It is hoped this study will delineate the factors that would form a rational monitoring program (Charlton, NWRI, pers. comm.). Reid (University of Guelph, pers. comm.) is currently examining temporal and spatial variation in key water quality parameters on net cage farms in Georgian Bay with the goal of making recommendations to improve water quality monitoring programs for aquaculture. Podemski (Fisheries and Oceans Canada, pers. comm.) is leading an Experimental Lakes Area project in northern Ontario to assess the environmental and ecological impacts of cage aquaculture under current industry practices. As well, this project will contribute to the design of tools and methods to predict and assess the impacts of the aquaculture industry on freshwater ecosystems.

In BC, land-based aquaculture is subject to the 1994 Land-Based Fin Fish Waste Control Regulation. Under this regulation, land-based fin fish facilities must:

- submit a receiving water quality report (e.g., hydralic effects, effects of nitrogen and phosphorus on potential for eutrophication, effect on receiving water DO and temperature) prior to construction, except for facilities with a dilution greater than 20 to 1;
- meet effluent standards for non-filterable residue concentration, total phosphorus, and chlorine;
- not discharge to surface or groundwater (under general requirements):
  - sand, silt, mud solids filter debris or other pollutants
  - untreated cleaning wastes
  - accumulated solids from raceways or ponds
  - detergents, disinfecting agents, cleaning agents or chemicals, if the effluent does not pass a 96-hour LC_{20} bioassay with rainbow trout; or
  - dead fish, blood, or processing wastes.

BC recently promulgated the *Finfish Aquaculture Waste Control Regulation* (September 2002) under the *Waste Management Act*. This regulation was developed to ensure that the aquaculture industry is environmentally sustainable. Aquaculture operators are required to prepare and implement best management practices and a monitoring plan. The monitoring program must consist of physical and chemical analyses and triggers for biological sampling. As well, the operator is required to provide a seabed video survey and analysis of contaminants. This regulation does not apply to freshwater open net cage operations. However, BC has recently conducted a monitoring program on Georgie Lake, where there are two small, seasonal smolt net cage operations (Deniseger, BC MWLAP, pers. comm.). This study focused on trophic status, metals, phytoplankton and zooplankton communities, and water quality parameters on the lake. As well, depth profiles were taken for temperature, pH, DO, condition, and redox. Sampling was undertaken at three sites: a control and 30 m from each smolt site. They also emphasized the use of a good baseline inventory prior to any cage installation.

The NB marine environmental monitoring program of salmon aquaculture operations is intended to describe organic enrichment in sediments and includes (Anon. 1995):

- physico-chemical measurements (Eh/sulfides);

- sediment chemical testing for therapeutants (once protocols are established);
- observations of percentage of bacterial matting, presence and relative abundance of macroinvertebrates, presence of gas bubbles, depth of organic build-up, estimated current speed and direction, depth, etc.;
- video survey of the sediment; and
- regional monitoring (once monitoring protocols are established) to assess far field impacts.

Fisheries and Oceans Canada (2003b) has recently developed an interim guide for the application of S. 35 of the *Fisheries Act* to salmonid cage aquaculture developments at marine sites. The strategy incorporates performance-based standards (physical or chemical indicators), risk assessment and an adaptive management approach. Indicators include parameters such as percent volatile organic solids in sediment, production of sulfides, and sediment redox potential. The guide proposes the use of three instruments to provide a practical and nationally consistent approach for the application of S. 35 to assess and manage the harmful alteration, disruption or destruction (HADD) of fish habitat. The three instruments include:

- a Letter of Advice if a HADD is not anticipated;
- an Avoidance, Mitigation and Monitoring Agreement if there is uncertainty with respect to the effectiveness of measures to prevent a HADD; or
- a Subsection 35(2) Authorization (or rejection of project) if a HADD will result.

In Europe, routine monitoring varies by jurisdiction for land-based and open water fish farms but typically consists of water quality parameters (TSS, DO, various forms of nitrogen and phosphorus) and some biological indices (general biological survey, benthic survey, macroinvertebrate survey). Read et al. (2001) indicated that there is a need for harmonization of regulatory, control, and monitoring procedures into an overall system for marine aquaculture within the European Union. For example, Norway has developed a modeling and monitoring system to assist in the effort to prevent farms from overloading the environment with nutrients and organic matter. This system includes a classification tool with threshold values. A proposal has been put forward to make this system part of the regulatory framework for aquaculture in Norway (Norwegian Directorate for Nature Management 1999).

Considerations for Designing Monitoring Programs

A joint group of international experts that examined the monitoring of ecological effects of coastal aquaculture wastes established an environmental management framework for regulating development and evaluating impacts (GESAMP 1996). They suggest that the level of monitoring (number of variables and frequency of monitoring) should be related to size of the operation and sensitivity of the receiving water body. They indicate that successful monitoring will depend on:

- a baseline survey to obtain data which can assist in designing an appropriate monitoring program and provide reference data against which changes caused by farm waste can be measured;
- selection of reference stations;
- standardization of sampling and analytical procedures; and
- analysis and interpretation of data.

GESAMP (1996) proposed the following considerations as reference for the development of aquaculture-specific monitoring guidelines:

- programs or requirements should consider the diversity of aquaculture practices (e.g., species, culture methods, etc.) and their environmental settings;
- environmental assessment and monitoring effort should be related to the scale of the perceived impact of a given aquaculture operation;
- simplicity, flexibility and affordability of environmental assessment and monitoring to facilitate the acceptance and enforcement of such measures;
- consultation with stakeholders;
- the ecological component of an environmental impact assessment should be designed such that all significant impacts are identified and an appropriate monitoring program constructed;
- monitoring should be preferably undertaken within a framework of established Environmental Quality Objectives and Standards (EQS); and
- monitoring for ecological protection should be regarded as an integral part of managing aquaculture operations - the results derived from monitoring should be used to evaluate the ecological effects of the operation, the suitability of relevant EQSs, and the utility of the monitoring program itself.

Fernandes et al. (2001) recommend a tiered approach to monitoring in which more comprehensive and frequent sampling is applied to larger operations, operations in sensitive areas, or operations which are likely to have a significant impact. Further, they recommend that the following factors be taken into consideration when designing a monitoring approach for aquaculture:

- species cultured;
- proposed or cultured biomass;
- methodology;
- technology;
- location;
- type of feed; and
- chemicals used.

In a European research study on the effect of organic pollution from trout farm effluent on downstream ecosystems, Camargo (1994) found that with the exception of phosphorus, physicochemical surveys did not yield any evidence of pollution. Total hardness, water temperature, dissolved oxygen, nitrate, organic matter, sulfate, sodium, pH and chloride were similar along the study area whereas phosphorus increased significantly downstream of the discharge. In contrast, biological monitoring, based on macroinvertebrates, showed clear evidence of pollution, with diversity, similarity and trophic structure changing markedly downstream from the trout farm.

To minimize genetic risks to wild populations and conserve biological integrity associated with escapees from fish farms, Kapuscinski and Brister (2001) recommend an adaptive approach with a systematic, technically, and financially feasible monitoring plan for the aquaculture sector. They recommend that this plan should include baseline preoperational biological measurements and threshold limits, although these researchers do not elaborate on the specifics of such a monitoring plan.

Study Design

Any good monitoring study should be designed to have sufficient statistical power to detect significant change in environmental parameters above background variability and provide information required to adequately assess the impact of aquaculture on the environment. As such, determining appropriate numbers of samples, location, and replicates are imperative in any monitoring program. Reference or control sites should be selected that are as similar as possible to the aquaculture site to minimize variability among samples. For further discussion of study design see Metal Mining EEM Guidance (Environment Canada 2002), Pulp and Paper Technical Guidance Document (Environment Canada 1998), and Fernandes et al. (2001).

Monitoring Parameters

Fernandes et al. (2001) indicated that monitoring parameters and the design and frequency of sampling should be carefully selected to ensure the program provides an adequate indication of environmental status above background variability. They proposed that appropriate monitoring parameters will depend on the nature of the aquaculture operation and receiving environment but, although for mariculture, may include:

<u>Physical</u>
Bathymetry;
Currents, waves, tides;
Wind;
Precipitation;
Substrate type;
Sediment movement;
Erosion/accretion;

<u>Chemical</u>
pH, alkalinity;
Redox;
Temperature;
Salinity;
Dissolved Oxygen;
Nutrients;
Particulate/dissolved organic matter;
Suspended solids;
Specific chemicals;

Biological
Species abundance and diversity: plankton, benthos, nekton, birds;
Biomass;
Productivity;
Population structure;
Trophic interactions;
Habitat mapping; and
Rare and endangered species/habitats.

For pond aquaculture, Boyd and Tucker (1998) recommended that water sampling programs be based on experience and good judgment, and indicated that there are not firm rules for sampling frequency or location. They suggested the following parameters are useful to consider in the design of a sampling program:

- water temperature;
- salinity (for brackish water aquaculture);
- pH;
- total alkalinity, total hardness, and calcium concentration;
- dissolved oxygen;
- carbon dioxide;
- ammonia;
- nitrite;
- phytoplankton biomass (using Secchi disk to estimate relative plankton abundance, or chlorophyll *a* as a measure of algal biomass); and
- organic matter (BOD, COD, TOC or DOC).

Methods and Techniques

In general, biological monitoring protocols are well established for benthos, fish, and plankton. Similarly, protocols for many of the physical-chemical measurements (redox, sulfides, nutrients, DO, BOD, etc.) are well established. Standard methods, however, are lacking for chemical analysis of many of the therapeutants and prophylactic treatment chemicals used in aquaculture (Anon. 1995).

For sediment sampling, some considerations include station positioning, type and proper operation of sampler, penetration depth, sample sorting and evaluation, taxonomic identification, and all related quality assurance/quality control procedures.

There has been some discussion in the literature over appropriate monitoring of nutrients. Massik and Costello (1995) studied the bioavailability of different forms of phosphorus (total, total reactive, total soluble and soluble reactive) and noted that no single phosphorus fraction was consistently related with bioavailable phosphorus but they indicated that total phosphorus, at least, should be determined. Further, Doughty and McPhail (1995) noted that trends in phosphorus concentrations, which can vary on a daily basis, are difficult to detect without frequent monitoring. They noted that indirect methods such as noting the frequency of occurrence of algal blooms might give warning of excessive nutrient enrichment. For the Pulp and Paper EEM programs, Glozier and Culp (National Water Research Institute, pers. comm.) recently recommended the following changes for nutrient sampling for pulp mills conducting standard surveys at freshwater sites:

Phosphorus: TP and either 1) SRP or 2) TDP (*all three if possible*)
Nitrogen: TN and either 1) NO_2-NO_3 and NH_4 or 2) TKN (*all four if possible*)
Carbon : DOC and TOC
where:
TP = Total Phosphorus
SRP = Soluble Reactive Phosphorus
TDP = Total Dissolved Phosphorus
TN = Total Nitrogen
NO_2-NO_3 = Nitrite-Nitrate
NH_4 = Ionized Ammonia
TKN = Total Kjeldahl Nitrogen
DOC = Dissolved Organic Carbon
TOC = Total Organic Carbon

Number 1) options for P and N are the prefered combination. The difficulty with some nutrients like SRP is that the analyses must be performed within 24-48 hours. Thus the number 2) option is recommended for sites where timely analyses are unavailable. The applicability of these relationships to monitoring nutrients at aquaculture sites needs to be further assessed.

Data Analysis and Interpretation

A variety of numerical techniques such as traditional univariate and multivariate statistics (ANOVA, regressions, ordination etc.) are used in environmental monitoring to analyze data. Summary indices (i.e., species diversity index, Bray-Curtis Index) are used for classifying impacts on macroinvertebrates. These are fully discussed elsewhere (Metal Mining EEM Guidance: Environment Canada 2002, Fernandes et al. 2001). The significance of physical and chemical measurements can be interpreted by comparing against reference levels or environmental quality guidelines or objectives.

Table B-1. Summary of routine monitoring conducted by various jurisdictions for open cage aquaculture.

Jurisdiction	Parameters Monitored	Frequency (per year)	Comments	Source
Canada				
British Columbia	**Finfish Aquaculture Waste Control Regulation–** - physical parameters (currents), -biological and chemical analysis of sediment samples, -seabed video (photographic) surveys, - analysis of contaminants (pesticides, metals)	Within 30 days of peak finfish biomass for each production cycle	This program is applicable to mariculture only; freshwater monitoring requirements are not yet available for BC	BC Finfish Aquaculture Waste Control Regulation 2002
	Interim Aquaculture Sediment Sampling Program (marine) (1996-2002) - physical and chemical characteristics (sediment colour, texture, TC, TN, total volatile residue, Zn, acid volatile sulfides, and extractable metals) sediment toxicity bioassays			Anon. 2000a
	Georgie Lake Monitoring Program - trophic status, metals, phytoplankton and zooplankton communities - depth profile for Temp, pH, DO, cond., redox		Control and 30 m from each cage	Deniseger and Erickson 1998; Deniseger, BC MWLAP pers. comm.
Alberta	No data found			
Saskatchewan	No data found			
Manitoba	No data found			
Ontario	SS, TP (1988-1994)	12x	Composite at cage, 30 m distant and control	Linquist 2001
	variable - TP, TSS, TKN (by operator 1994-present)	variable		
	- variable – TP, PO4, TKN,NH3+NH4, NO3+NO2, DOC, DIC, chl a, Cond, TSS, Turb, Secchi, COD, BOD, TDS, TSS, pH, hardness (by MOE 1996-present)	variable		
Québec	No open water sites currently permitted			

Jurisdiction	Parameters Monitored	Frequency (per year)	Comments	Source
New Brunswick	-Eh/sulfide, video transects of sediment, diver observations of: % bacterial matting; presence and relative abundance of macroinvertebrates; presence of gas bubbles; depth of organic build up; estimated current speed and direction; depth	1X	Marine salmon sites during period of peak growth and feeding along transects	Anon. (1995)
Nova Scotia	No data found			
PEI	No data found			
Newfoundland	SS, pH, BOD, PO4 , TN, NH3, NO2, NO3, colour, Tur, T, DS, TKN	12x	Open water - at cage site, control site, inlet, outlet, sensitive areas	Lee et al. 1995
Yukon	No data found			
NWT	No facilities			
Nunuvut	No facilities			
US	TSS, real time monitoring of rate of feed consumption	Daily	Proposed effluent regulations applicable to net pen facilities producing 100 000 lb/year. Facilities are also required to develop BMP plan, and report drug and chemical usage	US EPA 2002
Ireland	PH, DO, NH3, SS, BOD, PO4	12X	Near cage and at control site	Lee et al. 1995
Scotland	Varies by county but can include: DO,T, NO3, PO4, NH3, pH, alk, cond., TP, TDP, TN, Cl, Tur. Benthic biological survey	Varies by county (1-12X)	Depends upon farm size and lake sensitivity	Lee et al. 1995

Cl - Chlorine
TP - Total phosphorus
P - Phosphorus
PO4 - Dissolved Reactive Phosphorus
NH3 - Ammonia
TDP - Total Dissolved Phosphorus
DIC - Dissolved Inorganic Carbon
NO2 - Nitrite
NO3 - Nitrate
TN - Total Nitrogen
TKN - Kjeldahl Nitrogen
SS - Suspended Solids
alk. - alkalinity
BMP – Best Management Practices
Tur - Turbidity
DO - Dissolved Oxygen
T - temperature
DS - dissolved solids
BOD - Biological Oxygen Demand
DOC - Dissolved Organic Carbon

Table B-2. Summary of routine monitoring conducted by various jurisdictions for land-based aquaculture.

Jurisdiction	Parameters Monitored	Frequency (per year)	Comments	Source
Canada				
British Columbia	Cl, TP, non-filterable residue	Variable	Toxicity test required if detergents, disinfecting agents, cleaning agents, or other chemicals discharged (96-h LC20 rainbow trout)	Liboiron 2001
Alberta	No data found			
Saskatchewan	No data found			
Manitoba	No data found			
Ontario	TSS, TP	12X	Land based in flow and outflow	Naylor (OMOE pers. comm.)
Québec	BOD, SS, TP	2x	Certificats d'autorisation provided by Ministère de l'Environnement du Québec with specific OER (objectifs environnementaux de rejet)	Perron, Environment Canada – Québec Region, pers comm.
New Brunswick	NH3, BOD, SS, DO, PO4, pH	52x (large site > 100000 fish) 12x (for small sites)	Land-based inflow, outflow, and 100m downstream (if discharged into river) Inflow, outflow and 100 m downstream (if discharged into river) Open water sites?	Lee et al. 1995
Nova Scotia	No data found			Lee et al. 1995
PEI	No data found			
Newfoundland	SS, pH, BOD, P04, TN, NH3, NO2, NO3, disinfectants	12x	Land based - outflow	Lee et al. 1995
Yukon	No data found			
NWT	No facilities			
Nunuvut	No facilities			
US	TSS	Daily	Proposed effluent regulations also require development of BMP, and reporting of drug and chemical usage depending on size and type of facility	US EPA 2002
Denmark	SS,TN,TP, BOD	2-4X		Lee et al. 1995
Ireland	PH, DO, NH3, SS, BOD,PO4	12X	Inflow and outflow, upstream and	Lee et al. 1995

Jurisdiction	Parameters Monitored	Frequency (per year)	Comments	Source
			downstream	
Scotland	Varies by county but can include: NH3, BOD, SS, DO, Tur, TP, TN, PO4, NO3, TSS, pH, and alk. Biological or macroinvertebrate survey	Varies by county (1-12X)	Upstream, downstream and outfall Upstream and downstream of discharge	Lee et al. 1995

Cl - Chlorine
TP - Total phosphorus
P - Phosphorus
PO4 - dissolved reactive phosphorus
NH3 - Ammonia
BMP – Best Management Practices
NO2 - Nitrite
NO3 - Nitrate
TN - Total Nitrogen
DS - dissolved solids
BOD - Biological Oxygen Demand
Tur - Turbidity
DO - Dissolved Oxygen
T - temperature
SS - Suspended Solids

Biological survey - survey of the flora and fauna or a marked (consistent) location over time to determine if changes due to effluent contamination have occurred.

Macroinvertebrate survey - survey of the macroinvertebrate community structure of a marked (consistent) location over time to determine if changes due to effluent contamination have occurred.

Appendix C: Canadian Environmental Quality Guidelines Applicable to Aquaculture

Canadian Water Quality Guidelines for parameters that have been identified of relevance to the aquaculture sector are presented below.

Phosphorus

Because some of the effects of phosphorus are aesthetic, its management requires consideration of societal values. As such, no federal or national guidelines for phosphorus have been derived, but a guidance framework that is consistent with CCME philosophy is currently being developed. The proposed framework for phosphorus provides a tiered approach in which water bodies are marked for further assessment by comparing their trophic status to these predefined 'trigger values'. Trigger values are concentrations that, if exceeded, would indicate a potential environmental concern, and so "trigger" further examination. The trigger values are then categorized according to the trophic classification scheme of OECD (1982) that provides a trigger range (Table C-1) which is relevant to the ecosystem type and locality. For example, if the baseline P concentration for the site in question is 12 $\mu g \cdot L^{-1}$, than the trigger range for this site would be mesotrophic (10-20 $\mu g \cdot L^{-1}$).

Table C-1: Draft trigger ranges for total phosphorus based on OECD (1982) trophic classification of lakes.

Trophic level	Total Phosphorus ($\mu g \cdot L^{-1}$)
Ultra-oligotrophic	<4
Oligotrophic	4-10
Mesotrophic	10-20
Meso-eutrophic	20-35
Eutrophic	35-100
Hypereutrophic	>100

Nitrogen (Nitrite, Nitrate, and Ammonia)

The form of nitrogen occurring in surface waters largely depends on the levels of oxygen present. Nitrate is considerably less toxic than nitrite or ammonia (Colt and Armstrong 1981). The existing Canadian Water Quality Guideline for nitrate is a draft value of 13 mg $NO_3^- \cdot L^{-1}$ with advise that concentrations stimulating excess aquatic plant growth and resultant eutrophication should be avoided (Table C-2) (Environment Canada 2001a). The guideline values for nitrogen are only intended to protect against direct toxic effects; indirect toxic effects resulting from eutrophication may still occur at concentrations below the guideline value, depending on the total amount of bioavailable nitrogen and other site-specific factors (e.g., phosphorus, oxygen, temperature).

Table C-2. Canadian Water Quality Guidelines for various forms of inorganic nitrogen in fresh water.

Nitrogen Parameter	Guideline
Nitrate	13 mg $NO_3^- \cdot L^{-1}$
Nitrite	0.06 mg $NO_2^- \cdot L^{-1}$
Ammonia (total NH_3 + NH_4^+)	0.043 to 153 mg $NH_3 \cdot L^{-1}$ Note: pH and temperature dependent – see Table C-3)
Ammonia (un-ionized)	0.019 mg $NH_3 \cdot L^{-1}$

In water, ammonia exists in two forms simultaneously, namely NH_3 (un-ionized ammonia) and NH_4^+ (ionized ammonia or ammonium ion). Together, they are referred to as total ammonia. There are several factors that influence the toxicity of total ammonia in freshwater including pH, temperature, dissolved oxygen, ionic strength, salinity, previous acclimation to ammonia, fluctuating or intermittent exposure, and the presence of other toxic substances. Of these, pH and temperature are the most important factors influencing ammonia toxicity. Canadian Water Quality Guidelines for un-ionized ammonia for the protection of freshwater aquatic life is 0.019 mg $NH_3 \cdot L^{-1}$. Because of the influence of temperature and pH on ammonia speciation, the guideline is presented as a matrix of CWQGs for total ammonia, which vary according to pH and temperature (Table C-3).

Table C-3: Canadian Water Quality Guidelines for total ammonia ($mg{\cdot}L^{-1}$) at different combinations of pH and temperature (source: CCME 2000).

Temp °C	PH							
	6	6.5	7	7.5	8	8.5	9	9.5
0	231	73	23.1	7.32	2.33	0.749	0.25	0.042
5	153	48.3	15.3	4.84	1.54	0.502	0.172	0.034
10	102	32.4	10.3	3.26	1.04	0.343	0.121	0.029
15	69.7	22	6.98	2.22	0.715	0.239	0.089	0.026
20	48	15.2	4.82	1.54	0.499	0.171	0.067	0.024
25	33.5	10.6	3.37	1.08	0.354	0.125	0.053	0.022
30	23.7	7.5	2.39	0.767	0.256	0.094	0.043	0.021

Dissolved Oxygen

The Canadian Council of Ministers of the Environment recommends that dissolved oxygen should not be less than those concentrations developed by the U.S. EPA, shown in Table C-4. When applying these guidelines, natural variations in dissolved oxygen concentrations must be taken into account. As well, the CCME recommends that the interstitial water of the gravel should be considered to be at least 3 $mg{\cdot}L^{-1}$ lower than the oxygen concentration in the overlying water (U.S. EPA 1986 as cited in CCME 1999). In salmonid spawning habitats, the water column concentration of dissolved oxygen should, therefore, be 9.5 $mg{\cdot}L^{-1}$, so that the interstitial concentration (Table C-4 in parentheses) is 6.5 $mg{\cdot}L^{-1}$. The guideline for the early life stages applies from spawning through to 30 d after hatching. In eutrophic waters, minimum concentrations may occur at night (or dawn). This is because aquatic plants produce oxygen during photosynthesis and can consume considerable quantities of oxygen in the absence of light.

Table C-4. Numerical limits for ambient dissolved oxygen (U.S. EPA 1986).

Description	Ambient dissolved oxygen limits ($mg{\cdot}L^{-1}$) Cold Water Early life stages	Other life stages	Warm Water Early life stages	Other life stages
30-d mean	NA	6.5	NA	5.5
7-d mean	9.5 (6.5)	NA	6.0	NA
Minimum	NA	5.0	NA	4.0
1-d minimum	8.0 (5.0)	4.0	5.0	3.0

pH

The Canadian Council of Ministers of the Environment recommends that for the protection of freshwater aquatic life, the pH of water should not vary beyond the range of pH 6.5-9.0.

Chlorine

The CCME Water Quality Guideline for the Protection of Freshwater Aquatic Life for reactive chlorine species (hypochlorous acid and monochloramine) is 0.5 $\mu g \cdot L^{-1}$.

Simazine

Simazine is a triazine herbicide used for the control of weeds on both land and water. In aquatic environments, it is applied for weed control in ditches, farm ponds, fish hatcheries, and aquaria (CCME 1999). The CCME Water Quality Guideline for the Protection of Freshwater Aquatic Life for simazine is 10 $\mu g \cdot L^{-1}$.

Total Suspended Sediments and Turbidity

The CCME Water Quality Guidelines for the Protection of Aquatic Life are available for total suspended sediments and turbidity (Table C-5). Because of the changes in water flow and site-specific conditions, separate values are recommended for clear and high flow periods.

Table C-5. Canadian Water Quality Guidelines for total particulate matter for the protection of aquatic life (source: CCME 1999).

	Guideline value
Suspended sediments	
Clear flow	Maximum increase of 25 $mg \cdot L^{-1}$ from background levels for any short-term exposure (e.g., 24-h period). Maximum average increase of 5 $mg \cdot L^{-1}$ from background levels for long-term exposures (e.g., inputs lasting between 24 h and 30 d).
High flow	Maximum increase of 25 $mg \cdot L^{-1}$ from background levels at any time when background levels are between 25 and 250 $mg \cdot L^{-1}$. Should not increase more than 10% of background levels when background is >250 $mg \cdot L^{-1}$.
Turbidity	
Clear flow	Maximum increase of 8 NTUs from background levels for a short-term exposure (e.g., 24-h period). Maximum average increase of 2 NTUs from background levels for a long-term exposure (e.g., 30-d period).
High flow or Turbid waters	Maximum increase of 8 NTUs from background levels at any one time when background levels are between 8 and 80 NTUs. Should not increase more than 10% of background levels when background is >80 NTUs.

Trichloromethane (Chloroform)

The interim CCME Water Quality Guideline for the protection of freshwater aquatic life for trichloromethane or chloroform is 1.8 $\mu g \cdot L^{-1}$.

Metals

Increased metal inputs into aquatic environment can be both directly and indirectly influenced by the aquaculture operations. High metal inputs may come from the feed and application of various chemicals. For example, zinc and copper are trace nutrients and are added to fish feed. Copper oxide is a widely used antifouling agent for impregnating fish pens. Changes in organic matter, pH, dissolved oxygen, and redox potential can also influence metal concentrations. The CCME Water Quality Guidelines for selected metals are given in Table C-6.

Table C-6. Canadian Water Quality Guidelines for the Protection of Freshwater Aquatic Life for selected metals (source: CCREM 1987; CCME 1999).

Parameter	Guideline
Aluminum	5 $\mu g \cdot L^{-1}$ at pH <6.5; $[Ca^{2+}]$ <4 $mg \cdot L^{-1}$; DOC <2 $mg \cdot L^{-1}$ 100 $\mu g \cdot L^{-1}$ at pH ≥6.5; $[Ca^{2+}]$ ≥4 $mg \cdot L^{-1}$; DOC ≥2 $mg \cdot L^{-1}$
Arsenic	5 $\mu g \cdot L^{-1}$
Cadmium	0.017 $\mu g \cdot L^{-1}$ (interim value) – normalizing this value for the water hardness of 48.5 $mg \cdot L^{-1}$ provided an equation for deriving the site-specific guideline for Cd as a function of hardness: $WQG = 10^{\{0.86[\log(hardness)] - 3.2\}}$
Copper	2 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 0-120 $mg \cdot L^{-1}$ 3 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 120-180 $mg \cdot L^{-1}$ 4 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ > 180 $mg \cdot L^{-1}$ Guideline values were derived for waters of different hardness using the US EPA (1985a) equation (for details see CCREM 1987)
Lead	1 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 0–60 $mg \cdot L^{-1}$ 2 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 60–120 $mg \cdot L^{-1}$ 4 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 120–180 $mg \cdot L^{-1}$ 7 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = >180 $mg \cdot L^{-1}$ Guideline values were derived for waters of different hardness using the US EPA (1985b) equation (for details see CCREM 1987)
Mercury	0.1 $\mu g \cdot L^{-1}$
Nickel	25 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 0–60 $mg \cdot L^{-1}$ 65 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 60–120 $mg \cdot L^{-1}$ 110 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = 120–180 $mg \cdot L^{-1}$ 150 $\mu g \cdot L^{-1}$ at $[CaCO_3]$ = >180 $mg \cdot L^{-1}$ Guideline values were derived for waters of different hardness using the US EPA (1980) equation (for details see CCREM 1987)
Zinc	30 $\mu g \cdot L^{-1}$

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National Water Research Institute
Environment Canada

Canada Centre for Inland Waters
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

National Hydrology Research Centre
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

Water Quality Monitoring Branch
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3

NATIONAL WATER RESEARCH INSTITUTE
INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX

Institut national de recherche sur les eaux
Environnement Canada

Centre canadien des eaux intérieures
Case postale 5050
867, chemin Lakeshore
Burlington, Ontario
L7R 4A6 Canada

Centre national de recherche en hydrologie
11, boul. Innovation
Saskatoon, Saskatchewan
S7N 3H5 Canada

Direction de la surveillance de la qualité de l'eau
351 boul. St-Joseph
Gatineau, Québec
K1A 0H3

Environment Canada Environnement Canada

Canada