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Canadian Science Advisory Secretariat

Research Document 2005/038

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Secrétariat canadien de consultation scientifique

Document de recherche 2005/038

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A Preliminary Perspective on Dissolved Oxygen Standards and Models in the Marine Coastal Zone with Particular Consideration of Finfish Aquaculture in the southwest New Brunswick portion of the Bay of Fundy

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Perspective préliminaire sur les normes et les modèles applicables à l'oxygène dissous dans la zone marine côtière, en prêtant une attention particulière à la pisciculture dans les eaux de la baie de Fundy situées au sud-ouest du Nouveau-Brunswick

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ISSN 1499-3848 (Printed / Imprimé)

ABSTRACT

The trend toward setting standards pertaining to the concentration of dissolved oxygen in coastal marine and estuarine areas is increasing around the world. Most of the standards are aimed at protecting the production and ecosystem processes of the coastal zone and limiting the anthropogenic perturbation to natural levels of dissolved oxygen to only a few percent (5-10%). In Canada, the CCME has developed preliminary national dissolved oxygen standards for the coastal zone but these have not been fully adopted by the various coastal jurisdictions throughout the country.

Marine aquaculture requires oxygen for the respiration needs of the cultured organisms and the breakdown of its organic waste products or effluents. Historical experience with marine aquaculture around the world has shown that aquaculture has the potential to significantly reduce oxygen concentrations and in some cases the reductions can be severe. Although localized and moderate reductions can take place almost immediately upon the implementation of an aquaculture operation, severe reductions seem to take many years if not decades. In Canada, the Canadian Federal and Provincial governments also hope to enhance aquaculture development in the country and in the southwestern New Brunswick area the industry and governments, both provincial and federal, are working toward adopting a performance based approach to aquaculture environmental impacts. In some of Canadian areas aquaculture already is the major anthropogenic driving force influencing coastal zone concentrations of dissolved oxygen. A few Canadian marine aquaculture operations are already, periodically reducing dissolved oxygen concentrations on relatively small spatial and temporal scales to levels below accepted international guidelines and recommended national guidelines.

On a global basis models simulating and predicting the impact of fish farming on the concentration of dissolved oxygen are beginning to include consideration of both near-field and far-field processes. In some cases oxygen is being used as the model currency and oxygen standards are being used to estimate holding capacity limits for aquaculture. All of the modeling experience indicates that the major controlling factor for environmental impact and oxygen concentration in particular, is water circulation. In well flushed areas with sufficient minimum water velocities, oxygen supply rates can be balanced with farm production so that the demand of farming activities and the oxygen demands for degradation of organic waste products can be met and environmental standards achieved. In poorly flushed areas and areas with weak currents this balance is difficult to achieve and it is in such areas that water quality degradation has generally occurred.

The time has therefore arrived for Canada to proceed seriously and rapidly toward the development and implementation of adequate dissolved oxygen standards and management protocols for the marine coastal zone and aquaculture. Such an effort will enable us to avoid the serious eco-socio-economic consequences associated with poor water quality. From a risk analyses perspective the dissolved oxygen issue might be classified as manageable. Aquaculture takes place in a relatively small proportion of the Canadian coastline and it is only within some of these areas that aquaculture is intense enough to pose potential problems. Hence, the likelihood of a major aquaculture induced depletion of dissolved oxygen is probably low to moderate and the impact of reductions is also probably low to moderate.

It is suggested that the existing CCME guidelines and approaches for water quality guidelines can be used to guide the development of appropriate standards. It is also

suggested that aquaculture development may be potentially accommodated through the adoption of the use-protection approach and the Initial Dilution Zone concept. This accommodation will require the development and implementation of jurisdictionally specific monitoring and water quality modeling capabilities and the passing of jurisdictionally appropriate regulations. To be successful, and consistent with the principles underlying Canada’s desire for more holistic and integrated coastal zone planning and management, this process should engage all the appropriate stakeholders and levels of expertise. The process should begin with an intense oxygen monitoring program to determine natural variations in key aquaculture areas as well as variations within and around existing farms. The process should also include the development of high spatial and temporal resolution three dimensional water circulation models, relatively simple and empirically driven water quality models, the coupling or linking of these with each other and with GIS integrated management planning and management initiatives and calibration and validation with field data.

RÉSUMÉ

La tendance à l'établissement de normes relatives à la concentration d'oxygène dissous dans les estuaires et les zones côtières marines s'intensifie un peu partout dans le monde. La plupart des normes visent à protéger les processus de production et les processus écosystémiques de la zone côtière et à restreindre les perturbations anthropiques des taux naturels d'oxygène dissous à un pourcentage limité (5 – 10 %). Au Canada, le CCME a élaboré des normes nationales préliminaires concernant l'oxygène dissous pour la zone côtière, mais ces lignes directrices n'ont pas encore été entièrement adoptées par les divers secteurs de compétence du pays.

La mariculture nécessite de l'oxygène en raison des besoins respiratoires des organismes d'élevage, ainsi que de la décomposition des déchets organiques ou des effluents. L'expérience dans ce domaine dans le monde entier a montré que l'aquaculture pouvait réduire considérablement les concentrations d'oxygène et, dans certains cas, à un point grave. Même si des réductions limitées dans l'espace et modérées peuvent se produire presque immédiatement après la mise sur pied d'une exploitation aquacole, les réductions graves peuvent prendre de nombreuses années, voire des décennies. Au Canada, les gouvernements fédéral et provinciaux espèrent aussi améliorer le développement de l'aquaculture au pays et, dans le sud-ouest du Nouveau Brunswick, l'industrie et les gouvernements, provincial et fédéral, travaillent à l'adoption d'une démarche axée sur le rendement en vue de réduire les répercussions de l'aquaculture sur l'environnement. Dans certaines régions canadiennes, l'aquaculture est déjà le principal facteur anthropique à influer sur les concentrations d'oxygène dissous de la zone côtière. Quelques exploitations maricoles canadiennes réduisent déjà, périodiquement, les concentrations d'oxygène dissous, quoique à des échelles spatiale et temporelle relativement limitées, à des taux inférieurs aux lignes directrices acceptées à l'échelle internationale et recommandées à l'échelle nationale.

Sur le plan mondial, les modèles servant à simuler et à prévoir les effets de la pisciculture sur la concentration d'oxygène dissous commencent à tenir compte des effets rapprochés et éloignés. Dans certains cas, l'oxygène est utilisé comme facteur principal du modèle et les normes relatives à l'oxygène servent à estimer les limites de la capacité de charge pour l'aquaculture. Toute l'expérience de modélisation montre que le principal facteur de contrôle des répercussions environnementales et de la concentration d'oxygène en particulier est la circulation de l'eau. Dans les zones à grand renouvellement, où la vitesse minimale de l'eau est suffisante, le taux d'alimentation en oxygène peut être en équilibre avec la production aquacole, de sorte que la demande pour l'aquaculture et la demande en oxygène pour la décomposition des déchets organiques peuvent être satisfaites, tandis que les normes environnementales sont respectées. Dans les zones où le renouvellement d'eau est faible et où les courants sont limités, cet équilibre est difficile à atteindre et c'est dans ce genre de zones que la détérioration de la qualité de l'eau a généralement eu lieu.

Il est donc temps pour le Canada de s'attaquer sérieusement et rapidement à l'élaboration et à la mise en œuvre de normes appropriées relatives à l'oxygène dissous et de protocoles de gestion de la zone côtière marine et de l'aquaculture. Un tel effort nous aidera à éviter les conséquences éco-socio-économiques graves associées à une mauvaise qualité de l'eau. Du point de vue de l'analyse des risques, la question de l'oxygène dissous pourrait être classée comme impossible à gérer. L'aquaculture est pratiquée sur une proportion relativement limitée des côtes canadiennes et c'est seulement dans certaines de ces zones que sa pratique est suffisamment intense pour

causer des problèmes. Ainsi, la probabilité d'un appauvrissement important en oxygène dissous causé par l'aquaculture est faible à modérée et les effets des réductions sont aussi probablement faibles à modérés.

On propose d'utiliser les recommandations et les approches du CCME relatives à la qualité des eaux comme guide à l'élaboration de normes appropriées. Il est aussi indiqué que le développement de l'aquaculture pourrait profiter de l'adoption de l'approche de protection de l'utilisation et du concept de zone de dilution initiale. Ces mesures nécessiteront l'acquisition et l'utilisation de capacités de surveillance et de modélisation de la qualité de l'eau adaptées aux secteurs de compétence et l'adoption de règlements appropriés. Pour que ce processus soit efficace et conforme aux principes qui sous-tendent la volonté du Canada d'assurer une planification et une gestion mieux intégrées et holistiques de la zone côtière, il devrait assurer une participation de tous les intervenants et niveaux de compétence appropriés. Le processus devrait commencer par un programme de surveillance assidue de l'oxygène afin de déterminer les variations naturelles dans les principales zones d'aquaculture, ainsi que les variations dans les exploitations existantes et à proximité. Le processus devrait aussi inclure l'établissement de modèles de circulation d'eau tridimensionnels à haute résolution spatiale et temporelle et de modèles de qualité de l'eau relativement simples et empiriques, la combinaison de ces modèles entre eux et avec les initiatives de gestion et de planification de la gestion intégrée du SIG, ainsi que l'étalonnage et la validation avec les données recueillies sur le terrain.

INTRODUCTION

The concentration of dissolved oxygen is widely recognized as a useful and important variable for monitoring the health of a body of water (CCME 1999, EEA 2003, EPA). "Oxygen is required by all higher organisms for the production of energy; energy that is required not only to fuel the essential functions of the organism, such as digestion and assimilation of food, and maintenance of osmotic balance, but also for activity. Oxygen requirements vary with species, stage of development and size, and are also affected by environmental factors, such as temperature. If the supply of oxygen to an animal deviates from the ideal, then feeding, food conversion, growth, and health can be adversely affected, ..." (Beveridge 1997 p. 108-9). The concentration of dissolved oxygen also meets the criteria for a good indicator variable (Vandermeulen 1998). It is sensitive to change, supported by reliable and readily em available data, it is directly relevant to ecosystem health and aquaculture production issues and it is generally understood and accepted by stakeholders and users of environmental indicators.

Interest and concern in coastal nutrification and eutrophication is increasing around the world, particularly in the industrialized nations (Nixon 1990). Interest is also growing in Canada with the enactment of the Canada Oceans Act, development of the Oceans Action Plan, the growing desire for integrated coastal zone planning and management, the establishment of a wide range of water quality guidelines (CCME 1999) and the desire to promote the sustainable development of marine aquaculture (FOC 2005). “The Government of Canada states that development is essential to satisfy human needs and improve the quality of human life, but must be based on the efficient and environmentally responsible use of all of society’s scarce resources – natural, human and economic.” (FOC 2005).

One principal concern associated with nutrification and eutrophication is the elevated metabolic rate in the ecosystem and the associated demand for oxygen. Along the eastern seaboard of North America several high profile increases in anoxia have occurred in the coastal zones adjacent to industrialized areas (e.g. New York Bight – Falkowski et al. 1980; Chesapeake Bay – Officer et al. 1984; Long Island Sound – Parker and O’Reilly 1991). In the southwestern New Brunswick area of the Bay of Fundy, limited areas of anoxia have also been produced (e.g. Blacks Harbour – Wildish and Zitko 1991).

Aquaculture reguires good water quality in which to raise its organisms (Beveridge 1997 p. 108-9). Netpen finfish culture or shellfish culture takes place in the coastal marine waters and must operate with the quality of water that flows through its farms (Koops 1972, Caine et al. 1987). Hence aquaculture prefers to be, and tends to be, located in areas that have naturally high concentrations of dissolved oxygen and, at least in Canada, relatively low inputs of nutrients and organics from other anthropogenic sources.

The culture of finfish and shellfish is a source of nutrients and a sink for oxygen. It, therefore, has the potential to contribute, perhaps significantly in some cases, to localized nutrification and reductions in background oxygen concentrations (e.g. Hong Kong - Lee et al. 2003, Bay of Fundy - Strain and Hargrave in press, Page et al. in press). As a result of increases in the intensity of fish farming in various areas of the world, the interest in and the need for advice on the character, extent and environmental impact of marine cage culture has increased (e.g. Hall and Holby 1986). This is also the case in Canada.

There has not been a concerted effort in Canada to characterize the dissolved oxygen content of its coastal waters nor to develop guidelines, standards or regulations defining desired or acceptable concentrations of dissolved oxygen within Canada's coastal marine waters. Although the Canadian Council of Ministers of eh Environment has defined preliminary dissolved oxygen standards for the marine and estuarine environment, these have generally not been adopted into provincial regulatory statutes. Oxygen standards have however, been defined for aid in aquaculture site development in some of the Canadian jurisdictions. For example, British Columbia developed siting guidelines for marine finfish aquaculture that included oxygen (Anon. 1980). In eastern Canada oxygen levels have not been formally used as a siting criteria although advice on potentially adverse oxygen conditions or situations have been taken into siting considerations for salmon netpen culture. Recently considerations of the environmental impact of salmon aquaculture on the coastal marine environment and of caged salmon health issues in southwestern New Brunswick have suggested that issues associated with the concentration of dissolved oxygen should be examined more closely. The Aquaculture Environmental Coordinating Committee, a sub-committee of the steering committee implementing the Federal – New Brunswick Provincial Memorandum of Understanding on aquaculture, recently sponsored a workshop in the fall of 2004 that focused on exploring the merits of a performance based approach to aquaculture environmental management. The workshop was attended by university and government scientists, federal and provincial government regulators, aquaculture industry representatives and representatives of non-governmental organizations. The participants identified dissolved oxygen as worthy of further exploration as an environmental indicator and ecosystem management variable. The salmon aquaculture industry in SWNB has also expressed interest in the issue of dissolved oxygen, as part of integrated or multi-trophic aquaculture and fish health.

Outside of Canada there has been considerable effort directed towards developing and implementing dissolved oxygen standards for coastal marine areas, although these have often not made specific consideration of aquaculture (e.g. European Union – EEA 2003; United States - EPA , DEP 2004; Japan – Yokoyama 2003). In the scientific literature, there has also not been a concerted effort to characterize the impact of aquaculture on dissolved oxygen concentrations. Although, there have been several reviews of the impact of finfish cage culture on the marine environment, these have focused mainly on organic waste discharges and benthic impacts (e.g. Gowen and Bradbury 1987).

The intent of this manuscript is to provide an initial stepping stone for the development of a more extensive examination and discussion of the dissolved oxygen characteristics of Canadian coastal waters and to give some indication of potential considerations for working toward the development of suitable coastal zone water quality standards or guidelines for marine coastal areas supporting or hoping to support aquaculture. The purpose is to provide an overview of the marine dissolved oxygen issue, particularly from the perspective of marine cage culture, to promote discussion of the need for oxygen guidelines and standards and to suggest a starting point for the process for developing and implementing standards if they are desired. The document can be considered as a working document that can be updated as more information and perspectives become available.

1. Dissolved Oxygen as an Environmental Indicator

Oxygen is also a good candidate for an environmental indicator since it has good communication power in that it is easy to understand and it also has statistical power in that trends or deviations can be robustly detected if a proper monitoring program is established (EEA 2003).

However, like all indicators, a lot of work is needed to complete their development as useful and enforceable indicators (EEA 2003).

2. Natural Variations in Dissolved Oxygen

The concentration of dissolved oxygen varies naturally on a variety of time (e.g. D'Autilia et al. 2004) and space scales and in response to many factors and processes including the temperature and salinity of the water, winds, tides, freshwater runoff, the biological and chemical oxygen demands removing oxygen from the water and the photosynthetic processes adding oxygen to the water. In some areas upwelling can move low oxygen water into an area containing fish farms and depending on the concentration of oxygen in this upwelled water caged fish may die (e.g. Abo 2000, Koops 1972).

In general, in coastal areas and in areas supporting aquaculture operations, dissolved oxygen levels are positively correlated with water flushing, i.e. high (low) flushing rates correspond with high (low) concentrations of dissolved oxygen. For example, Yokoyama (2003) showed that the near-bottom concentration of dissolved oxygen in the vicinity of fish farms in the Kumano-nada coast of Japan varied in relation to an index of water exchange between farm sites such that the concentration of dissolved oxygen increased with water exchange and decreased with distance of a farm from the mouth of the bay in which it was located (related to reduced flushing). The experience from Hong Kong also indicates that the environmental impacts of fish farming and the consequences associated with poor water quality are generally reduced as the water flushing rate increases (Lee at al. 2003).

Scale and Magnitude of Temporal Variations

Inter-annual variation about the seasonal cycle is often of order 1-2 mg $O_2 \cdot L^{-1}$. In areas where severe hypoxia and/or anoxia have occurred there has been a historical time trend toward lower near bottom concentrations of dissolved oxygen. In retrospect, the trends in average and minimum concentrations have occurred over decadal time scales beginning in the mid-1900's and have declined at a rate of about 0.1-0.3 mg $O_2 \cdot L^{-1}$ yr^{-1}. (e.g. Long Island Sound - Parker and O'Reilly 1991).

Seasonal variations in the concentration of dissolved oxygen are typical of most coastal areas (e.g. Parker and O'Reilly 1991). The amplitude of this variation varies regionally but is often 3-5 mg $O_2 \cdot L^{-1}$. In New Brunswick dissolved oxygen ranges from a seasonal high of approximately 11 mg $O_2 \cdot L^{-1}$ to a seasonal low of about 7 mg $O_2 \cdot L^{-1}$, a range of about 4 mg $O_2 \cdot L^{-1}$. The seasonal variation in British Columbia is often greater than this.

Phytoplankton blooms can inject oxygen into the water during the day and remove it during the night causing supersaturation and hypoxia depending upon the magnitude and stage of the bloom and the time of day. During the growing bloom a daily minimum in the concentration DO may occur around dawn (Beveridge 1987 should have other references). During bloom senescence significant hypoxia and a times anoxia may occur (Beveridge 1987 should have other references).

Scale and Magnitude of Spatial Variations

Dissolved oxygen concentrations vary both horizontally and vertically. Typically the concentration is lower near the bottom than in the near surface waters (e.g. Parker and O'Reilly 1991). For example, in British Columbia low oxygen concentrations in deep water can be upwelled to the surface and cause occasional fish mortalities.

As part of an effort to revise water quality standards for the State of Maine in the northeastern United States exploratory surveys of the dissolved oxygen content of selected bays and inlets along the Maine coastline were conducted (DEPL 1996, 1997). The surveys were conducted in 1995 and 1996 during the summer (July through September), the time of year when the concentration of dissolved oxygen in the Gulf of Maine is near its seasonal low. Most of the locations were sampled at least once in each of the three months. The majority of the observations yielded dissolved oxygen concentrations of ~7-9 $mg{\cdot}L^{-1}$ and represented conditions that were ~90-105% of saturation values (DEPL 1996). In 1995 less than 1% of the observations yielded dissolved oxygen concentrations <5 $mg{\cdot}L^{-1}$ and in 1996 <1.3% of the observations were <5.5 $mg{\cdot}L^{-1}$. The minimum value recorded was 4.49 $mg{\cdot}L^{-1}$ and 53% saturation. The monthly mean concentrations of dissolved oxygen calculated from the values collected over the entire Maine coastline in 1995 were 8.97 (109% sat), 8.42 (103% sat) and 7.78 $mg{\cdot}L^{-1}$ (93% sat.) in July, August and September respectively. The phasing and amplitude of the seasonal trend varied between locations and within locations, both vertically and horizontally, within a specific bay or estuary. Near bottom oxygen concentrations tended to be lower than in near surface waters. There was also significant variation on tidal time scales with the amplitude and phase of the variation being somewhat location dependant.

3. How Dissolved Oxygen Influences Organisms

Dissolved oxygen is a fundamental variable in ecosystems. It is needed by all aerobic organisms. Its concentration is affected by human activities through various process including effluents from industrial activities such as fish processing, pulp and paper manufacturing, municipal sewage etc., effluent BOD and COD. Much has been written about how organisms utilize oxygen and how much oxygen they need to complete various processes. I have not attempted to completely review this here. However, I do introduce some of the general principles below.

Aerobic animals require oxygen to remain alive. The oxygen is used to oxidate food materials. The uptake of oxygen, and the release of carbon dioxide, by an animal as a whole and by its tissue cells is called respiration (Schmidt-Nielson 1975). The most important and sometimes the only process in moving oxygen from outside of an organism to the cells within an organism is diffusion, i.e. the oxygen moves as a dissolved substance down a concentration gradient (Schmidt-Nielson 1975). The oxygen diffuses into the blood of the organism which transports the oxygen to the various tissues within the organism and the oxygen diffuses from the blood into the cells.

The consequence of the environmental concentration of oxygen on living organisms can be thought of in the context of the above dissociation curves. At one extreme one may wish to maintain concentrations of oxygen in the environmental above that needed to saturate the blood of all of the organisms in the area of interest. At the other extreme one may wish to maintain the environmental concentration of oxygen above that needed to prevent mortality of the organisms in the area of interest.

The response of fish to the concentration of dissolved oxygen generally falls into two categories: a independent category and a dependent category. In the independent category the response of the fish is independent of the concentration of dissolved oxygen. In the dependent category the response of the fish depends upon the concentration of DO. The critical oxygen tension ($T_{c)}$ or concentration is the concentration of dissolved oxygen that marks the transition between an independent and dependent response in oxygen uptake (i.e. respiration rate). The incipient lethal level is the concentration of DO that marks the transition between active and standard metabolism. The critical oxygen tension varies between species and within species and organisms in relation to environmental factors such as temperature. The concept of a critical value for normal life (TL) indicates the minimum oxygen concentration that does not interfere with normal growth or reproduction of a particular population (p.128). Both TL and TC are difficult to determine and it has been suggested that a physiological correlate is the oxygen dissociation curve of the blood i.e. when the concentration of DO in the blood begins to drop in response to reduced ambient DO. However, this approach seems to underestimate both TL and TC although a good correspondence has apparently been found between the DO concentration in the blood of the dorsal aorta of some species (ell, carp and trout).

The oxygen tension at which the blood ceases to be fully oxygen saturated can be considered to be a threshold oxygen condition for fish since more circulatory and ventilatory work must be done by the fish for it to meet the oxygen demands of the tissues (Davis 1975).

Davis (1975) and EPA (2001) have reviewed the literature on the effects of oxygen on organisms and have suggested thresholds.

4. How Aquaculture Influences Dissolved Oxygen

The concentration of dissolved oxygen in the waters of the coastal marine environment can be influenced directly by processes using oxygen and indirectly by biological or chemical processes utilizing or producing oxygen. One of the processes that has received considerable attention is that of eutrophication. Eutrophication as defined by AErtebjerg et al. (2001 cited in EEA 2003) is the enhancement of primary production due to excess supply of nutrients from human activities, independent of the natural productivity level of an area. Eutrophication influences dissolved oxygen levels in several ways. The most commonly referred to process is the death and decay of plankton blooms that sometimes result from the enhanced primary production aspect of eutrophication and the reduction in the concentrations of dissolved oxygen that these may generate. These reductions in oxygen may result in the death of bottom dwelling organisms, the death or emigration of mobile organisms and the disruption of less severe ecological processes.

Aquaculture influences dissolved oxygen by directly extracting oxygen from the water in association with the respiration needs of the cultured organism and the bio-fouling community that exists on the farming structures. It also has the potential to influences oxygen levels through the process of nutrient release and eutrophication.

The potential for marine netpen or cage culture to reduce ambient dissolved oxygen concentrations within the netpens and on the scale of the fish farm has been recognized since the early years in the development of the marine cage culture industry. For example, in Japan, Hisaoka et al. (1966) measured the concentration of dissolved oxygen inside and outside a yellowfish farm in Daio Bay, Japan. Measurements were taken at hourly intervals for about 24 hours and the results indicated that the concentration of dissolved oxygen was sometimes lower inside the farm than outside and sometimes it was higher inside than outside the farm. The inside minus outside differences ranged from -1.93 $ml \cdot L^{-1}$ (2.7 $mg \cdot L^{-1}$) to +1.25 $ml \cdot L^{-1}$ (-1.8 $mg \cdot L^{-1}$). The time trend in the oxygen concentration inside the netpen closely tracked that outside the pen. Inoue (1972) also measured the concentration of dissolved oxygen over a 24 hour period inside and outside of netpens containing about 5 kg $fish \cdot m^{-3}$. In this study the concentration of dissolved oxygen inside netpens was consistently less than outside the netpen. The inside minus outside difference in oxygen concentration ranged from about 0.1 to 0.4 $ml \cdot L^{-1}$ (0.1 – 0.6 $mg \cdot L^{-1}$). As in the Hisaoka et al. (1966) study, the time trend in the oxygen concentration inside the netpen closely tracked that outside the pen.

In Sweden, Kils (1979) recognized that oxygen concentrations in marine net cage farms rearing trout could be reduced at night during periods of heavy plankton blooms to problematic levels for the caged fish, during the period of plankton bloom die off and decay and during certain hydrographic conditions that resulted in low oxygen water being advected into the cages. He also recognized that phytoplankton blooms may increase the concentration of dissolved oxygen in cages during the day to supersaturation levels that may be harmful to the caged fish. At the time these recognitions were considered in the context of problems for fish farmers rather than problems of environmental impact.

In the Puget Sound area of the United States, monitoring of fish farms over several decades showed that dissolved oxygen concentrations within netpens could be up to 2 $mg \cdot L^{-1}$ less than in the surrounding ambient water. In most cases the relative difference was ≤0.5 $mg \cdot L^{-1}$ (Weston 1986, Nash 2001 and references therein). The relative reductions in dissolved oxygen concentrations were related to farm site flushing with low flushing rates (currents < 3 to 5 $cm \cdot s^{-1}$) resulting in greater reductions in dissolved oxygen with netpens.

In some cases netpen finfish culture has also been associated with causing hypoxia over a larger area than just within the farm netpens. Abo (2000) reported that fish farming in Gokasho Bay, Japan, caused hypoxia in the bottom waters of the estuary and that wind driven intrusions of offshore water rich in oxygen caused the hypoxic layer to rise off the bottom and expose the fish farms to the hypoxic waters.

It was also recognized early on that the influence of a netpen or fish farm on the concentration of dissolved oxygen depended on the biomass of fish in the cage or farm and the intensity of water exchange through the cage or farm. Hisaoka et al. (1966) and Inoue (1972) both found that the temporal concentration of oxygen within netpens was highly correlated (no correlation coefficients given) with the water exchange through the netpens and that the inside to outside difference in oxygen concentration decreased with increased water exchange through the netpens.

The exchange of water within the cage depends upon several factors including the cage design, mesh type, degree of mesh fouling and the swimming behaviour of the fish within the cage. Hisaoka et al. (1966) found that water velocities within yellowtail netpens were about 60-70% less than the velocities measured outside the netpens. They also found that the direction of the current within the netpen was simialr to that outside the pen during periods of relatively strong currents, but that they became to differ from each other as the current speed decreased. They considered this to be due to the currents generated by the circular swimming of the fish within the pen.

Hisaoka et al. (1966) found that in netpens containing yellowtail, the caged fish influenced the exchange of water through the cage when the current velocities were weak but they did not influence the exchange at higher current speeds.

In general the impact varies with the biomass of fish in a farm and the near bottom water current (Yokoyama et al. 2004). For a given current speed the concentration of dissolved oxygen in the near bottom water decreased with increasing fish (yellowtail) biomass on the farm and for a given biomass of fish on a farm the dissolved oxygen content of the near bottom water increased with increasing current speed (Yokoyama et al. 2004). Hence, large farms need to be located in areas with relatively high water currents if reductions in near bottom concentrations of dissolved oxygen are to be avoided. Measurements of the near-sediment-surface water concentration of dissolved oxygen taken at stations located near a fish farm in Gokasho Bay, Japan, did not show any trend with distance away from the farm (Yokoyama 2003).

In Hong Kong, coastal marine fish farming is recognized as introducing excessive nutrients to the water and sediments and contributing to eutrophication in the farming region (Lee et al. 2003). The combination of aquaculture and other sources of organic enrichment and adverse hydro-meteorological conditions such as high water temperatures and reduced vertical mixing have resulted in severe depletion of dissolved oxygen and massive fish kills (Lee et al. 1991).

Fish farming also has the potential to impact the concentration of oxygen in the water column by influencing the oxygen utilization rate of the bottom. For example, Hall and Holby (1986) found that the oxygen uptake rate of sediments under a trout farm in the Gullmar Fjord in Sweden was 12-15 times higher than the rate measured at a reference station with comparable temperatures and bottom type.

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5. Guidelines for Siting Marine Aquaculture Operations

Marine cage culture takes place in the coastal marine environment and the dissolved oxygen concentration of the ambient water influences the production potential of the farming operation through the processes affecting the growth and health of the cultured organisms (e.g. Koops 1972). Farmers and developers are therefore interested in locating and operating farms in locations with adequate concentrations of dissolved oxygen for the species being considered for culture.

Siting guidelines have sometimes been developed for aquaculture operations in an effort to locate farming operations in environmental conditions that are generally suitable for the culturing of the organism of interest, rather than for purposes of environmental protection. The influence of the guidelines is usually through the site application and approval process. Once a site gains approval and becomes operational the guidelines have no enforceable influence. Also the guidelines are generally not developed from the perspective of environmental protection so they may or may not result in some degree of environmental protection and they be more or less stringent with respect to particular environmental standards.

Within Canada, siting guidelines that include consideration of dissolved oxygen levels have been developed in both eastern and western Canada. In British Columbia biophysical criteria for guiding the site evaluation of netpen salmon farms were developed in the 1980s (Caine et al. 1987). One of the priority factors they considered was the concentration of dissolved oxygen. They considered a “good” site to have a minimum dissolved oxygen concentration of 8.5 $mg \cdot L^{-1}$ and a minimum saturation of 100%. A “medium” site was considered to have a minimum dissolved oxygen concentration of 6.4 $mg \cdot L^{-1}$ and a minimum saturation of 79% whereas a “poor” site was considered to have a minimum dissolved oxygen concentration of 4.6 $mg \cdot L^{-1}$ and a minimum saturation of 57%. These oxygen levels were based on the work of Davis (1975) and incorporate the influence of temperature and salinity on oxygen solubility in water. In general they are meant to indicate levels at which sub-lethal effects of hypoxia will occur. These effects initially involve growth processes.

In Atlantic Canada, Environment Canada includes dissolved oxygen as a variable to consider when generating advice on the suitability of a proposed aquaculture site. They suggest dissolved oxygen concentrations should be above 5 ppm (EC 2001). In the Maritimes Region of Fisheries and Oceans Canada, a decision support system used habitat assessors includes dissolved oxygen as a screening variable in evaluations of proposed aquaculture operations (Hargrave 2002). In this system the percent saturation for dissolved oxygen in surface waters during the summer/early fall (the annual minimum) is considered to be acceptable if the values are >90% and unacceptable if the values are <80%.

6. Standards or Thresholds

It is generally recognized that there are challenges in formulating dissolved oxygen standards or threshold criteria for aquatic environments. Concentrations of dissolved oxygen vary on multiple temporal and spatial scales and the sensitivities and responses of organisms and ecosystems varies in many ways, most of which are not understood. Some of the challenges are mentioned by Alabaster and Lloyd (1980) in their review of freshwater water quality criteria. They stated:

"Sensitivity of fish to low concentrations of dissolved oxygen (DO) differs between species, between the various life stages (eggs, larvae, and adults), and between the different life processes (feeding, growth, and reproduction, which in turn may depend on swimming ability, and specialized behaviour which may also be influenced by DO). Any DO standards set for fisheries must take all these into account, bearing in mind the type of fishery, the times and places the fish occur, and the likely impact on the fishery of impairment of each part of the life cycle.

Although there is a considerable volume of laboratory data on the effects of DO on fish life processes, much of it is incomplete in terms of the distribution of the responses within fish populations at given physiological and behavioural states, and difficult to interpret in terms of ecological significance. However, the general pattern which emerges is that, providing other environmental factors (including the absence of poisons) are favourable, a minimum constant value of 5 $mg \cdot L^{-1}$ would be satisfactory for most stages and activities in the life cycle in that some processes, such as juvenile growth, fecundity, hatch of eggs, larval morphology and survival, upstream movement of migratory salmon, and schooling behaviour of some species, including shad, are not particularly susceptible to levels of DO above 5 $mg \cdot L^{-1}$. However, this value may be unnecessarily high merely to ensure satisfactory survival of the fish and adequate growth of the juveniles.

Difficulties arise in formulating dissolved oxygen criteria for fisheries because of the widely different patterns of DO fluctuations which can exist in inland waters even when unpolluted and the uncertainty of predicting their effect even when adequatelydescribed, unless the levels are so low as to be directly lethal to fish or so high as to have no effect on them. There have been few experiments made which attempt to simulate natural conditions, most being made at constant DO levels; furthermore, field data are generally inadequate in that either the fish populations present or the DO regime are poorly described, and their interpretation is complicated by the presence of other poisons. In these circumstances, only tentative criteria can be put forward.

Because DO levels in a river normally fluctuate, it is inappropriate to put forward criteria based on a single minimum value never to be violated or even as several minima each not to be violated at a certain time of year, but they should be expressed as a minimum percentile distribution (e.g., a minimum 5- and 95-percentile value) over a year or part of a year, or, with estuarine fisheries, part of a tidal cycle.

From the limited data available it is suggested that for resident populations of moderately tolerant freshwater species, such as roach, the annual 50-percfentiole and 5-percentile DO values should be greater than 5 $mg \cdot L^{-1}$ and 2 $mg \cdot L^{-1}$ respectively and for salmonids the percentiles should be 9 $mg \cdot L^{-1}$ and 5 $mg \cdot L^{-1}$ respectively.

These values are to be regarded as being for general quidance only, because there are special circumstances where more consideration should be given to the seasonal distribution of DO, for example in estuaries through which migrant salmonids pass. Moreover, all these minimum values might need to be considerably increased in the presence of high temperature or poisons."

Despite these challenges, standards and guidelines have been developed, particularly for freshwater systems, and more recently for some coastal marine areas. In Canada, the Canadian Council of Ministers of the Environment (CCME) suggest that it is better to define interim guidelines than to have no guidelines (CCME 1999). Although it is beyond the scope of this manuscript to thoroughly review the regulatory frameworks and implications associated with water quality standards and dissolved oxygen, a brief overview of a few examples of regulatory regimes is instructive. It serves to give an indication that at least some jurisdictions feel it is worth while to monitor and regulate the concentration of dissolved oxygen and gives a flavor for the approaches and philosophies that have been adopted. A more thorough review of existing regulatory standards would be a worthwhile exercise.

In general there seem to have been one of two objectives motivating the development of the standards. In some jurisdictions the primary objective has been to developed standards and thresholds that protect the production potential and health status of the cultured organism. In other jurisdictions the primary objective is to protect the ecosystem to some degree.

Some of the standards that have been adopted for freshwater systems in North America are (DEP 2004):

United States

Washington: 6.5 ppm (lowest 1-day minimum) for coldwater and warm water species, higher criteria for certain species (charr and redband trout), and for salmonid spawing, rearing and migration.

Oregon: 8.0 ppm absolute minimum or 90% saturation (where attainable accounting for temperature and altitude); otherwise 8.0 ppm (30 day average), 6.5 ppm (7 day average), 6.0 pm absolute minimum. Higher criteria set for spawning areas.

Montana: 6.5 ppm (30 day average), 5.0 ppm (7 day average)

Wyoming: 6.5 ppm (30 day average), 5.0 ppm (7 day average), 4.0 ppm (instantaneous), higher criteria for spawning and early life stages

New York: 6.0 ppm (daily average), 7.0 ppm in spawning areas

Vermont: 7.0 ppm or 75% saturation daily minimum criteria for salmonid spawning and nursery areas; 6.0 ppm or 70% saturation daily minimum criteria in all other areas.

Canada

New Brunswick: 6.5 ppm minimum for coldwater species, 9.5 ppm for early life stages.

The Canadian National quidelines for the lowest acceptable dissolved oxygen concentrations are 6.0 and 5.5 $mg \cdot L^{-1}$ for the early life and other life stages, respectively, in warm-water ecosystems, and 9.5 and 6.5 $mg \cdot L^{-1}$ for the early life and other life stages, respectively, in cold-water ecosystems (CCME 1999).

In contrast to freshwater systems, standards for dissolved oxygen of coastal marine waters have not been as widely adopted. However, efforts to monitor and regulate water quality in the marine environment and in coastal zones are increasing in several areas of the world. The interest and effort is being driven by the general desire to prevent degradation of the marine environment that has and can be caused by human activities in general and to manage the water quality so that the coastal ecosystems and the socio-economic activities they support are sustainable.

One of the most extensive efforts that has been undertaken to define standards or thresholds concerning the dissolved oxygen content of coastal marine waters is that of the US Environmental Protection Agency. Over a ten period they reviewed the literature concerning the influence of oxygen on marine organisms and conducted directed studies to fill some knowledge gaps (EPA 2000). As a result of this effort they recommended for the Cape Cod, Massachusetts to Cape Hatteras, North Carolina coastal area, a chronic protective value for growth of 4.8 mg $O_2 \cdot L^{-1}$, i.e. if the dissolved oxygen concentration does not fall below 4.8 mg $O_2 \cdot L^{-1}$ the protection objectives are satisfied. They also indicated that the limit for juvenile and adult survival was 2.3 mg $O_2 \cdot L^{-1}$ and that if concentrations of dissolved oxygen fell below this value protection objectives would not be met. When the concentration of dissolved oxygen falls between these thresholds, they recommend that consideration of the duration and the intensity of the hypoxia is required to determine whether the desired environmental protection objectives are met.

In the State of Maine, coastal marine waters are classified on the basis of water quality objectives, or the degree of water quality protection desired, and there have been standards established for the dissolved oxygen in each of these classes for several decades (DEP 2004). For example, waters classified as SB waters require that the habitat for fish and other estuarine and marine life be unimpaired and that the growth of estuarine and marine life be unimpaired (DEP 2004). Class SC waters allow "… discharges to Class SC waters to cause some changes to estuarine and marine life provided that the receiving waters are of sufficient quality to support all species of fish indigenous to the receiving waters and the structure and function of the resident community is maintained. This standard allows some impacts on estuarine and marine life and could be compared to the "slight impairment" mentioned in the EPA freshwater dissolved oxygen document … as corresponding to a 10% reduction in growth of marine species. (DEP 2004)". Standards for SC waters allow some impact on the water quality. It requires that the habitat for fish and other estuarine and marine life be of sufficient quality to support all species of fish indigenous to the water body and to support the structure and functions of the resident community (DEPL 2001).

From 1965 to 1986 then classes SB had dissolved oxygen standards of 6.0 parts per million and class SC had a dissolved oxygen standard of 5.0 ppm. In 1986 the standards for SB and SC waters were changed to 85% and 70% of saturation, respectively. These changes were made in an effort to accommodate the spatial and temporal influence of temperature and salinity on the concentration of dissolved oxygen. The values of 85% and 70% were chosen somewhat arbitrarily (John Sowles, pers. comm..). However, in the middle to late 1990s it was recognized that these standards do not recognize that natural processes often cause the dissolved oxygen concentration of coastal waters to drop below these saturation values in the absence of anthropogenic influences and that these infrequent lower sub-saturation values are adequate for supporting a natural complement of organisms. Hence, socio-economic activities occurring in some areas can be in violation of the standards due to not fault of their own because some sequence of natural events results in the dissolved oxygen levels dropping below the standards. The percent saturation approach has also prevented socio-economic use of waters in ways that would likely have not made a serious impact on the environment because natural absolute concentrations of oxygen are high enough to support reductions below 85% (John Sowles, pers. Comm.).

In an effort to improve the 1986 standards, the Maine Department of the Environmental Protection initiated a review of its marine dissolved oxygen standards (DEP 2004). The review focused on the US EPA's approach for defining DO standards in the middle Atlantic region (EPA 2000) and adjusted the results so they were more applicable to the northern waters of the Gulf of Maine. The review included a literature search for information on the dissolved oxygen requirements of species found in the coastal waters of Maine and the application of the US EPA models using inputs appropriate for Maine's natural coastal environmental conditions and species life histories. It also included information on the chronic effects of dissolved oxygen on cod growth.

The review recommended that in class SB and SC waters the State adopt a dissolved oxygen standard that does not rely on a percent saturation value. It recommended that a concentration value be adopted that protects the growth of marine species (DEP 2004). In other words, the review adopted the philosophy that the impacts on the growth of marine organisms should drive the considerations for the defining the minimum acceptable dissolved oxygen concentrations for Maine coastal waters (DEP 2004). The review specifically recommended that in class SB waters the daily average dissolved oxygen concentration should not fall below 6.5 ppm and the instantaneous concentration should not fall below 6.0 ppm. In class SB waters the recommendation was that the daily average dissolved oxygen concentration should not fall below 5.5 ppm and the instantaneous concentration should not fall below 5.0 ppm. These recommendations were not adopted, in large part, because some stakeholders felt that adopting an absolute concentration threshold was a step backwards in that it provided less protection to the environment than the percent saturation approach (John Sowles, pers. comm.). In particular, these stakeholders felt that during the time of year when the oxygen concentration is naturally high, for example in winter when the saturation concentration of dissolved oxygen is about 12 $mg{\cdot}L^{-1}$, an absolute standard of 6 $mg{\cdot}L^{-1}$ would allow anthropogenic activity to reduce the oxygen concentration by about 50%. The regulators perspective is that the ecosystem can withstand this level of reduction because it only needs 6 $mg{\cdot}L^{-1}$ to function naturally.

As of 1996 the State of Massachusetts used a state standard of 6 $mg{\cdot}L^{-1}$ for coastal waters (DEPL 1997).

The Canadian National water quality quidelines for dissolved oxygen in marine and estuarine waters were developed with the knowledge gained by in ththe US EPA and other experiences. The guidelines are as follows (CCME 1999).

"The recommended minimum concentration of DO in marine and estuarine waters is 8.0 $mg{\cdot}L^{-1}$*. Depression of DO below the recommended value should only occur as a result of natural processes. When the natural DO level is less than the recommended interim quideline, the natural concentration should become the interim guideline at that site. When ambient DO concentrations are > 8.0* $mg{\cdot}L^{-1}$*, human activities should not cause DO levels to decrease by more than 10% of the natural concentration expected in the receiving environment at that time."*

The guidelines also state (CCME 1999)

"Because some species may be adapted to naturally lower DO levels, where they occur, such levels should be maintained. Marine and estuarine guidelines for Australia and for the United States jurisdictions of Alabama, Alaska, Delaware, Louisiana, Washington, Guam, American Samoa, Northern Mariana Islands, Puerto Rico, Trust Territory, and the Virgin Islands contain similar clauses."

The intent of the guidelines is to promote a high level of environmental quality and consistency across the country, i.e. a level that hopes to ensure there will be no observable long-term adverse effects on aquatic ecosystems. The guidelines (CCME 1999) "are set at such values as to protect all forms of aquatic life and all aspects of the aquatic life cycles" for existent and potential uses of the water body of concern. The guidelines 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." "Where water bodies are considered to be of exceptional value, or where they support valuable biological resources, it is the policy of the CCME that degradation of the existing water quality should always be avoided. Similarly, modifications of guidelines to site-specific objectives should not be made on the basis of aquatic ecosystem characteristics that have arisen as a direct result of previous human activities." The guidelines are derived, based on the availability of data, incorporating a 10% safety factor on top of the lowest observable effects level (i.e. effects observed above this level) or in the case of oxygen the highest observable effects level (i.e. effects observed below this level). If this information is not available "the most sensitive LC50 or EC50 from an acute exposure study is multiplied by an acute/chronic ration or appropriate application factor."

Although the guidelines are nationally endorsed, the CCME (Canadian Council of Ministers of the Environment) has no legislative and regulatory authority. Hence, the individual provincial and territorial jurisdictions, which have the necessary authority, determine the degree to which they will adopt the guidelines. To my knowledge there are presently no regulatory standards for dissolved oxygen in the coastal zones of Canada. Furthermore, before regulations concerning the dissolved oxygen content of coastal marine waters are defined and adopted, appropriate consultations and actions will need to be undertaken to determine what level of environmental protection is desired in each area being considered and what approach(es) can be taken to achieve these objectives.

Not all water quality standards are motivated by or aimed at limiting change to the environment. For example, the intensive culturing of fish in Japan has caused adverse environmental changes, including reductions in the concentration of dissolved oxygen in some fish farming areas (Yokoyama 2003). In response the Japanese established, in 1999, the "Law to Ensure Sustainable Aquaculture Production". This Law sets the lower limit for normal growth of yellowtail, 5.7 $mg \cdot L^{-1}$ (4 ml $O_2 \cdot L^{-1}$), as the minimum limit for a healthy fish farm environment (Yokoyama 2003). The Law also sets 3.6 $mg \cdot L^{-1}$ (2.5 ml $O_2 \cdot L^{-1}$) as the minimum limit for fish farm environments (Yokoyama 2003). These limits are based on the work of Harada (1978 cited in Yokoyama 2003) which indicates the extreme lower limit for the survival of cultured fish (mainly yellowtail) is 2 ml $O_2 \cdot L^{-1}$ and the limit at which the feeding activity of the cultured fish begins to decrease is 3 ml $O_2 \cdot L^{-1}$.

Sometimes the objectives motivating standards are attempted to be achieved by indirect regulations or standards. In Japan, regulations were based on the fact that it is difficult to monitor the impact of aquaculture on dissolved oxygen so regulations were developed that control the farming intensity in an area (regulation for far-field effects) and stocking densities within cages (regulation for near-field effects). In the Kagoshima Prefecture of Japan, the hamachi culture grounds were divided into several sub-areas that were determined by their minimum annual dissolved oxygen concentration. In one zone (designated as Zone A) oxygen concentrations outside fish cages could be as low as 5.5 $mg{\cdot}L^{-1}$, and stocking densities were could not exceed 11 $kg{\cdot}m^{-3}$ and culture intensity could not exceed 40 $tonnes{\cdot}hectare^{-1}$. In Zones where lower dissolved oxygen concentrations occur, stocking densities must be 7 $kg{\cdot}m^{-3}$ or less and culture intensity cannot exceed 20 $tonnes{\cdot}hectare^{-1}$ (K. Fukusho, National Aquaculture Research Institute, pers. comm.. cited in Rosenthal et al. 1988).

None of the above guidelines or standards address the issue of the spatial extent of the hypoxia. In other words if dissolved oxygen concentrations fall below a standard, hence suggesting that the aquatic life forms will be affected to some degree, the question arises as to how spatially extensive this effect needs to be before there is real concern is warranted.

Thresholds for Salmon Productivity and Health

Many sources accept that the minimum concentration of dissolved oxygen for the optimum health of cultured salmon is 6-7 $mg{\cdot}L^{-1}$ (e.g. Weston 1986, Nash 2001, Willoughby 1999).

7. Monitoring of Dissolved Oxygen at Aquaculture Sites

Although, dissolved oxygen standards are not yet in place in Canada, monitoring of dissolved oxygen in association with fish farms has sometimes been reguired. For example, in British Columbia, Ministry of Environment authorities implemented a mandatory environmental and data gathering program for marine finfish aquaculture in 1988 (Anon 1988). The monitoring activities varied with the amount of fish feed used such that larger users of feed, and hence presumably larger farms, were required to implement a more extensive monitoring program. The details of the monitoring requirements are given in (Anon 1988). Farms utilizing less than 120 tonnes dry weight of feed per year were not required to monitor dissolved oxygen. Farms utilizing between 120 tonnes and 630 tonnes inclusive of dry weight feed per year were required to take vertical depth profiles of dissolved oxygen on at least one day a month during the April to September period. During each sampling at least two locations around the farm were to be sampled. One location was to be on the “upstream” side of the netpen array and the other on the “downstream” side. The determination of “upstream” and “downstream” was to be based on site empirical observation of the nets and water movement rather than assumed or predicted currents. Profiles were to be taken in the early morning (within two hours of sunrise) in an effort to sample during the time period that was thought to encompass the daily minimum in dissolved oxygen. The profiles were to consist of samples taken at depths of at least 1, 5, 10, 20, 30 meters below the surface and 1 m above the bottom. Farms using in excess of 630 tonnes of dry weight feed per year were reguired to obtain the above profiles of dissolved oxygen during the early morning and again in the late afternoon. All data was to be submitted to the authorities not later than 30 days after each calendar quarter (Jan-Mar, Apr-Jun, etc.). These monitoring requirements were to be reassessed after three years. I do not know if these monitoring requirements still exist.

8. Models of Dissolved Oxygen

The impact of aquaculture on the concentration of dissolved oxygen can be thought of as consisting of the balance between the various sources and sinks of oxygen. The sink processes include (1) the respiration demand by the organism being cultured, (2) the chemical and biological oxygen demand (COD and BOD) associated with the breakdown of the organic effluent (the particulate and dissolved organic matter in the unused feed and in the feaces) released from the farming operation, (3) the respiration demand by the farm bio-fouling organisms, (4) the oxygen demand by the benthous and sediment. The source processes include the (5) the oxygen produced by phytoplankton and macroalgae, (6) the oxygen supplied by exchange through the air-sea interface and (7) the oxygen advected into the area of concern. The spatial and temporal variation in the concentration of dissolved oxygen can be estimated by coupling these sources and sinks with information on water circulation, particle sinking rates and rates of turbulent diffusion.

Models are tools for developing a quantitative assessment and understanding of the influence and importance of the processes influencing the oxygen content of the water. By necessity they are simplifications of the real world and it is generally recommended that they not be used as compliance or regulatory tools on their own (Sowles pers. Comm.). They should be used to help design empirical sampling and monitoring approaches and to help interpret empirical data. They can also be used to help estimate carrying or holding capacities by using the dissolved oxygen standards reviewed above as prescribed thresholds that are not to be breached.

Models estimating the impact of aquaculture on the concentration of dissolved oxygen consider various combinations of these processes. The relative importance of the various sources and sinks can be estimated by choosing typical values for the various rate processes and typical time and space scales to be considered.

The simplest models are sometimes referred to as “box models” or mass balance models. Some of the simplest and earliest of these were developed to estimate the concentration of oxygen within a netpen (e.g. Kils 1979, Silvert 1992, Page et al. 2005). Consideration of the various source and sink processes suggested that the concentration was controlled by the removal of oxygen from the water by the respiration demand of the caged fish and the addition of oxygen into the cage by the advection or flow of oxygenated water into or through the cage. The oxygen input to a cage through the air-sea interface is negligible. When the concentration of oxygen within the cage is set at a specific level, such as that established from fish health or water quality standard considerations, these models can be used to estimate the stocking density or holding capacity of a cage for a given flow velocity and ambient oxygen concentration (Page et al. in press).

The water velocity is often assumed to be the same as that in the local area since it is difficult to accurately model the water exchange through a cage or farm. The exchange of water within a cage depends upon several factors including the cage design, mesh type, degree of mesh fouling and the swimming behaviour of the fish within the cage. A simply way to attempt to account of these influences is to multiply the outside water velocity by a scaling factor that is consistent with observed reductions in water velocities. Estimates of the scaling factor are relatively few and have varied considerably. For example, Hisaoka et al. (1966) found that water velocities within yellowtail netpens were about 60-70% less than the velocities measured outside the netpens. They also found that the direction of the current within the netpen was simialr to that outside the pen during periods of relatively strong currents, but that they became to differ from each other as the current speed decreased. They considered this to be due to the currents generated by the circular swimming of the fish within the pen. Inoue (1972) measured the water velocities inside and outside of some netpens and found the inside current speeds to 81-35% of the outside speeds.

The oxygen sinks are usually assumed to be the respiration by the fish. This is calculated as the product of the respiration rate per unit weight of fish times the biomass of fish within the cage. Variations on this approach include greater or lesser sophistication in the estimation of the oxygen demand and in the velocity of water through the cage. Piercey et al. (2005) have estimated the oxygen demand of the bio-fouling community on fish cages and this demand can be incorporated into the above modeling structure.

The box model approach can be scaled up to give an index of the influence of fish farms on the oxygen dynamics in a farm or bay (Page et al. in press). When oxygen source or sink processes are expanded to include other sources of human induced demands the approach can be used to help identify the causes of oxygen depletion in larger spatial areas such as Chesapeake Bay (Officer et al. 1984) or southwestern New Brunswick (Wildish et al. 1990, 1992, Strain and Hargrave in press).

Another relatively simple model has been developed by Findlay and Watling (1997). They compare the oxygen utilization rate of the sediment with the rate of diffusive oxygen supply to the sediment. The ratio of the two rate processes gives an index of the capacity of the sediment to assimilate the organic flux generated by a fish farm. When the sediment demand for oxygen exceeds the supply the sediment assimilative capacity is exceeded and the sediment is likely to head toward anoxia. Conversely, when the sediment demand for oxygen is less than rate of oxygen supply the sediment can assimilate the farm induced organic flux. By setting the ratio to a value of one (demand = supply) an estimate of the holding capacity of the sediment or the farm size can be made.

The attractiveness of the box model approach rests in its relative simplicity. Its success depends upon the appropriate choice of spatial and temporal scales represented by the boxes and by the empirical information available to estimate the rate processes and total fluxes. Often these models are not rigorously calibrated and validated with empirical data concerning oxygen concentrations in fish cages. However, the models are generally accepted as giving reasonable order of magnitude indications of the oxygen dynamics. It would probably be worth developing some of these simple models and calibrating them with site specific data in areas of interest so they could be made more useful as husbandry and environmental management tools.

One of the more extensive modeling efforts that utilizes a series of relatively simple sub-model such as those above, is the MOM system (Stigebrandt et al. 2004). This modeling system includes a fish sub-model, a fish cage water quality sub-model, a dispersion sub-model, benthic sub-model and a regional water quality model. This modeling system estimates oxygen concentration as part of its water quality calculations. The fish cage water quality model is based on the simple box model approach discussed above and the benthic assimilation model is similar to that of Finlay and Watling (1997).

Fully Coupled Hydrodynamic and Water Quality Models

The most complex forms of oxygen impact models are those that combine the various source and sink processes with spatially and temporally varying hydro-meteorological models. Such models have been developed for estimating the impact of finfish farms on dissolved oxygen concentrations in coastal areas such as Japan (e.g., Kishi et al. 1994, Lee et al. 2003) and southwestern New Brunswick (e.g. de Margerie et al. 1990, Trites and Petrie 1995).

The combination of hydro-meteorological and water quality models holds a lot of promise. The best use of the approach is probably to keep the models relatively simple and focused on specific water quality processes that have indicator variables that can be measured and predicted. The models have the potential to generate information on spatial and temporal scales of interest and relevance to stakeholders. The results can also be displayed in a Geographical Information System (GIS) manner which facilitates good communication with the non-specialist stakeholder and regulatory community.

The present strength of the coupled hydro-meteorological models lies with the underlying water circulation and transport and dispersal models. This modeling capability is well advanced and continues to increase in its capability. It has the potential to accurately resolve processes and patterns on very small spatial (meters) and temporal scales (seconds) if necessary. This is due in part to increases in the availability of computing power, increases in the sophistication and efficiencies of numerical algorithms, increases in the fundamental understanding of the underlying physical processes and increases in the capability to generate high resolution datasets of the driving physical variables such as (bathymetry, sea level elevation, wind forcing and density structure). There is also a well developed capability to measure the physical characteristics (temperature, salinity, etc.), currents and drift trajectories so the models can be calibrated and validated.

Some of the circulation models are reasonably well established and suitable for application to applied issues in a particular area after it has been locally parameterized, calibrated and validated. A major output from the models, that is of fundamental importance to water quality issues, is an estimate of the water residence time or water flushing time (e.g. Lee et al. 2004, Koutitonsky et al. 2004). This output can be used as input to stand alone water quality models. Despite the value of hydrodynamic models it should be recognized that the models are generally not user friendly, and require access to modeling experts for model maintenance, upgrading and coupling with water quality modules. Never-the-less these modeling efforts should be encouraged. They offer one of the few approaches for estimating water quality characteristics on the small spatial and temporal scales needed.

At present, the most promising and most feasible use of the coupled hydro-meteorological water quality modeling approach is to use the high resolution capability of the physical models in conjunction with relatively simple models of the water quality processes and good quality monitoring programs (e.g. Kishi et al. 1994). However, even these models must be developed, customized, updated, calibrated and validated with good empirical data on inputs and outputs for the areas of interest.

A relatively early effort in this direction was made by de Margerie et al. (1990). They developed a coupled two dimensional tidal model with an oxygen water quality model for the Letang Inlet area of southwestern New Brunswick (SWNB). Despite several limitations of the model such as excessive numerical diffusion, no wetting and drying, and a grid resolution of 100m, the model successfully predicted the relative sensitivity of areas to oxygen reduction by salmon netpen farming. A more recent effort used a three dimensional hydrodynamic tidal circulation model with a very simple cage scale box model of oxygen dynamics in salmon cages to predict the areas in which salmon farms would likely experience reduced oxygen conditions within their farms (Page et al. pers. comm.).The circulation model included intertidal wetting and drying, 30m horizontal resolution in some areas and approximately 1m vertical resolution throughout the model domain (Greenberg et al. in press).

When the models are expanded to include ecosystem wide processes, they become very complex, have many poorly defined parameters and require large amounts of data for model calibration and validation (Fulton et al. 2004 and references therein). Although these models are beginning to do a reasonable job of simulating some of the major trophic and water quality features of some locations (e.g. Fulton et al. 2004), including areas that have aquaculture (e.g. Lee et al. 2003), they have many details and ecological processes that need to be better understood and parameterized before the ecosystem models will be robust enough to be useful as a readily available tool for routine applied application in the coastal zone (e.g. Fulton et al. 2004, Nixon 1990). At present and for the foreseeable future the models are most useful for learning purposes (Fulton et al. 2004).

The Lee et al. (2003) modeling effort estimated flushing rates from a three dimensional hydrodynamic circulation and particle tracking model for finfish culture areas in Hong Kong and used the flushing rates in a water quality box model that simulates sediment-water-pollutant interactions and predicts the seasonal average water quality in a fish culture zone. The water quality model is based on the United States Environmental Protection Agency's WASP (Water Quality Analysis Simulation Program) program. The authors claim the "predicted water quality as well as the relative carrying capacity are well-supported by field observations" (Lee at al. 2003 p.209, Lee and Arega 1999).

The Fulton et al (2004) modeling effort is an Australian based effort that was focused on the generic functioning a coastal bay. It utilizes a water circulation model coupled with the European Regional Seas Ecosystem Model (ERSEM) and the Integrated Generic Bay Ecosystem Model (IGBEM).

Statistical Models

In some cases there have been attempts to model the concentration of dissolved oxygen as a statistical function of multiple variables. To date these approaches have not been particularly successful, perhaps due to the spatial and temporal complexities of the factors influencing dissolved oxygen and the lack of understanding of the functional forms to be specified for each of the various variables. For example, in the State of Maine correlation and multiple regression analyses were used in an exploratory effort to identify the variables accounting for the major proportion of the variation in dissolved oxygen (DEPL 1996, 1997). The list of variables considered included bay and estuary morphometrics and hydrological characteristics as well as water characteristics such as nutrient concentration, temperature and salinity. The models explained a relatively low proportion of the variation in dissolved oxygen and had poor predictive power. However, they did provide some evidence of a link between the concentration of nutrients (NH_4, dissolved organic nitrogen, total nitrogen) in the coastal zone and the concentration of dissolved oxygen as might be expected if nitrification and eutrophication processes are beginning to be detectable in the

Maine coastal waters. The source of the nutrients was suggested to be dominated by freshwater inputs. Aquaculture was not a major activity in most of the locations surveyed in the studies. The authors also suggest that the models should be somewhat location specific because of the spatial variation in the importance of processes that influence dissolved oxygen levels.

9. Case Study: southwestern New Brunswick (SWNB)

The CCME provides guidance on how to approach the development of water quality standards. The overall approach is summarized in Figure 1, taken from the CCME (1999). The first step is to identify and assess a water quality issue using the CCME interium guidelines. The second step is to make a decision to develop water quality objective which is a numerical concentration or narrative statement that establishes the intent to support and protect the designated uses of water at a specified site. The third step is to begin development of these objectives and make them enforceable standards. The state of the process in SWNB can perhaps be pegged as being at the stage of deciding to develop objectives.

The Issue

The SWNB area has long been recognized as being an area of high marine bio-diversity, an area that supports the migratory pathways of dissolved oxygen sensitive species such as Atlantic salmon, a species that is listed as being at risk. The area also has a long history of socio-economically important fisheries (e.g. lobster and herring). More recently a vibrant eco-tourism industry has developed and a vibrant salmon netpen industry, which accounts for about 25% of the regional employment, developed throughout the 1980’s and 1990s. Hence, there is stakeholder interest in maintaining a high water quality standard while simultaneously enabling the activities of the aquaculture industry.

In recent years some members of the salmon aquaculture industry within SWNB have expressed concern that oxygen levels in some specific areas may be being impacted by aquaculture and hence may be degrading water quality that will effect salmon production through loss of growth and increases susceptibility to disease. Also in recent years budget calculations concerning the impact of the salmon aquaculture industry on regions within the SWNB area have indicated that there is the potential for the cultured salmon to reduce dissolved oxygen concentrations by perhaps as much as 10-20% in some areas (Strain and Hargrave in press).

These anecdotal concerns and calculations are supported by the limited time series data available from some fish farms in the SWNB area. These data indicate that it is not unreasonable to expect the time averaged concentration of dissolved oxygen within a salmon farm to be 1 $mg \cdot L^{-1}$ lower (i.e. ~6 $mg \cdot L^{-1}$) than the adjacent ambient concentration and that instantaneous concentrations can at times be 2 $mg \cdot L^{-1}$ or more lower (i.e. an absolute concentration of about 5 $mg \cdot L^{-1}$) than the adjacent ambient concentrations. In extreme cases, concentrations of dissolved oxygen within a farm may approach 4 $mg \cdot L^{-1}$. The temporal character of the variations is often tidally or diurnally dominated and the periods of relatively low oxygen concentrations can persist for several hours.

Finally a recent (fall 2004) workshop organized by the joint federal-provincial Aquaculture Environment Co-ordination Committee focused on discussing the merits of a performance based environmental monitoring approach to aquaculture management. The workshop was attended by industry, scientists, regulators and ENGOs. The workshop participants identified dissolved oxygen as a strong candidate for being adopted as an indicator variable for ecosystem health and environmental monitoring.

Natural Variation in Dissolved Oxygen

The first step in defining a dissolved oxygen standard is to characterize the natural variations in dissolved oxygen. Although data concerning dissolved oxygen levels in the SWNB area is relatively scarce, there is enough to help make a first order characterization of the natural variability in the area.

The existing data concerning the natural concentration of dissolved oxygen in the coastal marine area of the southwestern New Brunswick area of the Bay of Fundy consists for the most part of point measurements, taken during daylight hours, at established phytoplankton monitoring stations or along transects traversing a specific geographic area. In recent years some high frequency time series records of the dissolved oxygen concentration have been collected, primarily within fish farms.

The monitoring station data shows that the dissolved oxygen concentration undergoes a seasonal cycle (Fig. 2 and 3). At stations near or outside the coastal headlands (Fig. 2 seasonal cycle) the dissolved oxygen concentration varies from 7 mg·L^{-} to >12 mg·L^{-1} and from 80 to >120% saturation. This range in concentration also applies to the data collected from stations located well within the coastal headlands (Fig. 3 seasonal cycle). The annual minimum of 7 mg·L^{-1} corresponds to the lowest point value observed in the dataset considered as well as the lowest of the monthly means minus two times the corresponding monthly standard deviation. It would therefore seem reasonable to assume, as a first estimate, that these values are representative of most locations within the southwestern New Brunswick area that are not influenced by human activities. In other words, spatial gradients in the concentration of dissolved oxygen appear to be relatively small.

The above point data do not explicitly resolve higher frequency variations in dissolved oxygen that might be expected to be superimposed on the seasonal cycle. The SWNB area is tidally dominated and hence it might be expected that in some areas tidal advection of water masses past a monitoring point might generate a tidal frequency in the concentration of dissolved oxygen. However, this will only occur in areas where a spatial gradient in the concentration of dissolved oxygen exists. As stated above, it appears that strong spatial gradients do not naturally exist in the SWNB area. This is consistent with the very small amount of high frequency variation in the concentration of dissolved oxygen seen in time series records obtained from the mouth of one of the more exposed bays.

The SWNB area also experiences phytoplankton blooms. Time series recordings of dissolved oxygen taken during a bloom have shown that the dissolved oxygen concentration may vary from about 4 to 12 mg·L^{-1} over a 24 hour period (Fig. 4). This corresponds approximately to the appropriate seasonal mean ±3 mg·L^{-1}.

Like many coastal areas, there are also areas within SWNB that are known to be influenced by effluents from industrial activities such as fish processing and pulp mills. For example, effluents from a fish plant in Blacks Harbour reduced concentrations of dissolved oxygen within the entire harbour to near zero (Wildish and Zitko 1991). Presumably the dissolved oxygen concentrations in these areas would be similar to those in the relatively uninfluenced portions of the southwestern New Brunswick if these anthropogenic influences were not present.

Although a useful amount of data on dissolved oxygen concentrations exists for the SWNB area it is very site specific and indicative of the near surface and middle portions of the water column. Very little data exists for the near bottom, i.e. within 1m or so of the bottom. Hence, a data collection program should be initiated to help fill these spatial voids.

Dissolved Oxygen Standard

The challenge in the southwest New Brunswick area is to develop an oxygen standard that adequately protects the environment and allows sustainable development and use of the area. To my knowledge there are presently no regulatory standards for dissolved oxygen in the southwestern New Brunswick (SWNB) area of Canada. However, there is increasing interest in developing an appropriate position concerning dissolved oxygen. This is motivated, in part, because of a growing desire to adopt a performance based approach to management and regulation of the salmon netpen industry in the area. It is also motivated by some industry concerns over potentially reduced oxygen levels in specific areas and by a general recognition of the fundamental merits of dissolved oxygen as an indicator of water quality.

If dissolved oxygen standards are to be adopted for the SWNB area, a reasonably intense effort should initially be made to conduct a dissolved oxygen survey of the SWNB area. The survey should include transects through areas that might be expected to have spatial gradients in dissolved oxygen. It should also include high frequency recordings of dissolved oxygen and observations of dissolved oxygen within farms, within the vicinity of farms and at key locations throughout the area. These data could then be used to define the natural variation in the concentration of dissolved oxygen and then a suitable water quality standard.

The Canadian Council of Ministers of the Environment seems to provide one of the best approaches around the world for establishing water quality and hence dissolved oxygen standards. The CCME guidelines state that “Where water bodies are considered to be of exceptional value, or where they support valuable biological resources, it is the policy of the CCME that degradation of the existing water quality should always be avoided. Similarly, modifications of guidelines to site-specific objectives should not be made on the basis of aquatic ecosystem characteristics that have arisen as a direct result of previous human activities.” The guidelines are derived, based on the availability of data, incorporating a 10% safety factor on top of the lowest observable effects level (i.e. effects observed above this level) or in the case of oxygen the highest observable effects level (i.e. effects observed below this level).”

As stated earlier the CCME guideline for dissolved oxygen in marine and estuarine waters is stated as (CCME 1999):

“The recommended minimum concentration of DO in marine and estuarine waters is 8.0 $mg{\cdot}L^{-1}$*. Depression of DO below the recommended value should only occur as a result of natural processes. When the natural DO level is less than the recommended interim guideline, the natural concentration should become the interim guideline at that site. When ambient DO concentrations are >* $8.0\ mg{\cdot}L^{-1}$*, human activities should not cause DO levels*

to decrease by more than 10% of the natural concentration expected in the receiving environment at that time."

As noted above, the natural dissolved oxygen concentration in SWNB is greater than 8.0 $mg \cdot L^{-1}$ for much of the year. The relevant CCME guideline for these periods is that "*human activities should not cause DO levels to decrease by more than 10% of the natural concentration expected in the receiving environment at that time".*

As also noted above there are times of the year when the natural concentration of dissolved oxygen in SWNB is less than 8 $mg \cdot L^{-1}$. This seems to occur as part of the regular seasonal cycle and in association with plankton blooms. The CCME guideline indicates that for this period of the year the *natural concentration should become the interim guideline at that site.* In other words, human activities should not influence the concentration of dissolved oxygen at all.

The CCME guidelines also allow for the implementation of the "mixing zone concept". Under this concept the water quality standard must be met along the perimeter of the mixing zone. The mixing zone is usually of modest spatial extent (about 100m x 100m). This enables end of pipe effluents to be sufficiently diluted to standard conditions within a relatively small spatial area.

Although the CCME guidelines are nationally endorsed, the CCME has no legislative and regulatory authority. Hence, the individual provincial and territorial jurisdictions, which have the necessary authority, determine the degree to which they will adopt the guidelines.

It is worth noting that the CCME philosophies and objectives, at least with respect to dissolved oxygen appear to be consistent with those being developed and adopted elsewhere in the world but that their dissolved oxygen guidelines are perhaps more stringent. For example, in a decision support system consulted by the habitat assessors within the Maritimes Region of Fisheries and Oceans Canada, dissolved oxygen is used as a screening variable in evaluations of proposed aquaculture operations (Hargrave 2002). The system considers the percent saturation for dissolved oxygen in surface waters during the summer/early fall (the annual minimum) to be acceptable if the values are >90% saturation and unacceptable if the values are <80% saturation (~7.0 $mg \cdot L^{-1}$).

Since the southwestern New Brunswick area is adjacent to the State of Maine the regulatory standards proposed there are of direct interest to considerations for the SWNB area. The existing State of Maine standard for a water class SB is 85% saturation (i.e. >7 $mg \cdot L^{-1}$, DEP 2004). The water quality objective for this water class is that the habitat should support unimpaired growth of estuarine and marine life. This is interpreted to mean a growth impairment of less than 5%. A recent review committee recommendation was to adopt a standard for SB class waters that stated the daily average dissolved oxygen concentration should not fall below 6.5 $mg \cdot L^{-1}$ and the instantaneous concentration should not fall below 6.0 $mg \cdot L^{-1}$ (DEP 2004). The existing State of Maine standard for a water type (SC) with a less protective water quality objective, i.e. habitat into which discharges may cause "slight impairment" is 70% saturation (DEP 2004). In SC class waters some change to estuarine and marine life is allowed provided that the receiving waters are of sufficient quality to support all species of fish indigenous to the receiving waters and to maintain the structure and function of the resident community. The effluents should impair growth of estuarine and marine life by no more than 10%. A recent review committee recommendation was to adopt a standard for SC class waters that stated the daily average dissolved oxygen concentration should not fall below 5.5 mg·L^{-1} and the instantaneous concentration should not fall below 5.0 mg·L^{-1} (DEP 2004).

The Atlantic Canada component of Environment Canada includes dissolved oxygen as a variable to consider when generating advice on the suitability of a proposed aquaculture site. They suggest dissolved oxygen concentrations should be above 5 mg·L^{-1} (EC 2001).

Implementation of a DO Standard and Management Strategy

Although the purpose of this document is not to define an exact implementation strategy, it is useful to explore, at least to a preliminary extent, some existing possibilities. This exploration will help identify what observations and models of dissolved oxygen might be useful. For this exploration, I have followed the CCME (1999) guidelines in the context of the southwest New Brunswick (SWNB) area of Canada. I have chosen SWNB since this the area I am most familiar with. These preliminary thoughts should be followed up within each jurisdiction by a process that aims to develop its own definitions for water quality and its own implementation approach.

The CCME (1999) guideline documentation outlines the implementation process quite thoroughly and these guidelines have already been agreed upon by the various jurisdictions across the country. Although the guidelines were developed primarily for the introduction of toxic substances into the aquatic system, they do take situations like dissolved oxygen into consideration. They do not take a type of industry, like aquaculture, into consideration. I have therefore quoted some of the highlights below and provided comments concerning how aquaculture can be accommodated by these guidelines. These comments take into consideration the desire of the Canadian government, through DFO, to promote aquaculture development (DFO Science Strategic Plan 2005) and the CCME (1999) to allow uses of the aquatic environment.

The following quotations from the CCME (1999) are contained in quotation marks and appear in italics. Words or phrases within square brackets are comments inserted by the author. The wording outside of quotation marks are those of the author.

"Although the administrative tools available to support water resources management are similar across Canada, the approaches that have been used within the various jurisdictions differ depending on the management goals that have been established. For example, many jurisdictions have applied a technology-based approach to manage releases of liquid effluents. In the technology-based approach, limits on the releases of [substances] of potential concern … are frequently established for point source effluent discharges based on the ***best available technology - economically-achievable (BAT-EA).*** *…. receiving water quality primarily depends on the effectiveness of the existing treatment technology that is being used by a particular facility or industrial sector and the dilution capacity available in the receiving water system. The potential effects of wastewater discharges on designated water uses are generally not considered when discharge limits are established using the BAT-EA approach; however, environmental monitoring (such as that conducted under the Environmental Effects Monitoring Program) provides the information needed to assess the effects associated with point source discharges."*
"A second approach to the management of liquid effluents is commonly referred to as the ***use protection approach****. Application of this approach involves the establishment of*

discharge limits for substances of concern (i.e., from one or more point source effluent discharges) based on an understanding of the assimilative capacity of the water body under consideration. In this context, assimilative capacity is defined as quantity of a substance that can be released into a water body during a specific period of time without adversely affecting the designated water uses. This general approach allows environmental managers, in conjunction with stakeholders, to develop broad ecosystem management goals and to assess the benefits and costs of various management options in the context of these goals. Because the use-protection approach accommodates the multiple use of aquatic ecosystems and minimizes conflicts between competing interests, it has been incorporated as a central component of the approach to water management in several Canadian jurisdictions. In applying this approach, all reasonable and preventative measures should be taken to maintain conditions in waters with superior water quality characteristics (i.e., better than the Canadian WQGs; CCME 1999)"

"The third approach that can be used in water resources management is referred to as the ***non-degradation approach****. Using the non-degradation approach, discharge limits are established based on the natural background levels of substances of concern at the site. Implementation of this approach ensures that environmental receptors are not exposed to elevated levels of environmental contaminants and, hence, have no incremental risk of adverse effects due to discharges from point sources. However, technological limitations and costs are likely to preclude the implementation of this option under most circumstances (USEPA 1988a). For this reason, the non-degradation approach has generally been applied to waters of high regional, national, or international significance."*

"Two distinct strategies are commonly used to establish WQOs in Canada, including the anti-degradation strategy and the use protection strategy. For water bodies with aquatic resources of national or regional significance, the WQOs are established to avoid degradation of existing water quality. For other water bodies, the WQOs are established to protect the designated uses of the aquatic ecosystem. As long as the designated water uses are protected, some degradation of existing water quality may be acceptable in these water bodies, provided that all reasonable and preventative measures are taken to protect water quality conditions."

In considering the above approaches in the context of aquaculture, it seems that the BAT-EA approach is probably not ideally suited for aquaculture. The technology is constantly changing (e.g. feed types, cage designs, fish genetics, husbandry, stocking density, farm size, etc.), not particularly exact and hence it is difficult to get a handle on the expected releases of substances and to prescribe the technology to be used. The non-degradation approach is also probably not suitable for aquaculture since aquaculture has an impact, although generally relatively small if managed properly, on the environment and this impact must be allowed if suspended and bottom culture in the aquatic (freshwater and marine) environment is to be allowed. The approach that seems to have merit from the perspective of suspended aquaculture is the **use protection approach**. Within this context the concept of an initial dilution zone (IDZ) or zone of potential impact appears to be a useful and necessary concept since suspended aquaculture operations discharge effluents (e.g. organics) into, and remove oxygen from, the water flowing through the farms. The IDZ concept has been outlined by the CCME (1999) as follows:

"During the course of licensing or permitting wastewater discharges, responsible authorities may establish an IDZ, [an Initial Dilution Zone] (i.e., which is also referred to as

the mixing zone) in the vicinity of existing or proposed outfall. Although the definition of an IDZ differs among jurisdictions, the following definition is generally applicable:

An initial dilution zone is the area contiguous with a point source (effluent) where the effluent mixes with ambient water and where concentrations of some substances may not comply with water quality guidelines or objectives.

The concept of the IDZ is based on the understanding that it is often possible to allow somewhat elevated concentrations of [substances] to occur within relatively small areas of a receiving water body, without significantly affecting the integrity of the water body as a whole. Such IDZs are typically established when wastewater discharges are known or predicted to contain elevated levels of COPCs, the COPCs in the wastewater discharge have the potential to adversely affect the designated water uses in the receiving water system, and responsible authorities wish to limit the geographic area that could potentially be affected by the discharge."

"Importantly, establishment of an IDZ enables the regulated interest to utilize the dilution capacity of the receiving water system such that it is not necessary to achieve the water quality objectives at the end of pipe. Because authorization of IDZs has the potential to adversely affect existing and/or potential water uses, many jurisdictions have established a set of guiding principles to ensure that important water management interests are duly considered in the process. The following guiding principles, ….. , are intended to identify some of the factors that ought to be considered in the establishment of IDZs:

- *The dimensions of an IDZ should be restricted to avoid adverse effects on the designated uses of the receiving water system (i.e., the IDZ should be as small as possible);*
- *The IDZ should not impinge on critical fish or wildlife habitats (e.g., spawning or rearing areas for fish; overwintering habitats for migratory water fowl);*
- *Conditions outside the IDZ should be sufficient to support all of the designated uses of the receiving water system;*
- *Wastewaters that are discharged to the receiving water system must not be acutely toxic to aquatic organisms;*
- *Conditions within the IDZ should not cause acute or short-term chronic toxicity to aquatic organisms;*
- *Conditions within an IDZ should not result in bioconcentration of COPCs to levels that are harmful to the organism, aquatic-dependent wildlife or human health;*
- *A zone of passage for migrating aquatic organisms must be maintained;*
- *Placement of mixing zones must not block migration into tributaries;*
- *Mixing zones for adjacent wastewater discharges should not overlap with each other;*
- *Mixing zones should not unduly attract aquatic life or wildlife, thereby causing increased exposure to COPCs;*
- *Mixing zones should not be used as an alternative to reasonable and practical pollution prevention, including wastewater treatment (pollution prevention principle);*
- *Mixing zones must not be established such that drinking water intakes are contained therein;*
- *Accumulation of toxic substances in water or sediment to toxic levels should not occur in the mixing zone; and,*
- *Adverse effects on the aesthetic qualities of the receiving water system (e.g., odour, colour, scum, oil, floating debris,) should be avoided."*

"For substances that are readily degraded in aquatic ecosystems (e.g., nitrite, ammonia), regulation based on concentrations alone is likely to be sufficient to achieve the water management goals and objectives that have been established for the water body under consideration. In addition, this approach may be relevant to water bodies that receive wastewater discharges from only one facility. However, protection of existing and future water uses is more challenging when more persistent substances are discharged from a facility and/or when a water body receives discharges from multiple point and non-point sources. In these situations, it may be necessary to establish total maximum daily loadings (TMDLs) for each COPC that is released or is likely to be released into the receiving water system from all sources. In this way, effluent quality criteria and other measures to control or prevent contaminant releases can be established based on an understanding of the assimilative capacity of the water body. Guidance on the determination of TMDLs is currently being prepared by the USEPA."

In the case of suspended aquaculture and dissolved oxygen concentrations, an IDZ would need to encompass the farm plus a dilution zone around the farm. The IDZ, in the case of fish farms, would probably need to have dimensions of order 100-1000m, i.e. the farm site plus an advective-diffusive zone around the site. The IDZ approach would manage the near-field near surface and near-bottom concentrations of dissolved oxygen. The IDZ would probably be larger than the IDZs commonly associated with point source outfalls which often have dimensions of order 100m (CCME 1999).

In order to limit the size of the IDZ and the environmental impact within the IDZ, the concentration of dissolved oxygen could be reduced, relative to the ambient concentration, to a minimal concentration suitable for the local area. This approach recognizes that many free swimming pelagic organisms can avoid the IDZ and that the farmer has a vested interest in wanting the IDZ DO concentration relatively high because the production and health of the organisms being cultured is directly influenced by it. The concentration of dissolved oxygen within the IDZ will be influenced primarily by the biomass and stocking density of cultured organisms on the farm, the feeding efficiency, the local hydro-meteorological conditions and the layout of the farm. Hence, a limit to the biomass of fish on a particular farm will be implied in order for the DO standard to be met.

By definition the IDZ should also serve to manage the far-field effects on DO. This could be achieved if the flux of organics, and the associated BOD and COD, through the IDZ boundary into the far-field is such that the impact on the far-field oxygen demand is not sufficient to cause far-field dissolved oxygen concentrations to fall below established standards. Hydro-meteorological models of the water circulation will need to be coupled with fish farm production and water quality models to estimate the spatial and temporal patterns in the far-field oxygen field and the flux rates from the farm that are acceptable in terms of the water quality standard.

The realities of the coastal marine environment are that the water circulation and dispersal rates, and therefore the transport and dispersal or dilution of effluents is spatially and temporally complex. The effluent plumes from aquaculture sites are somewhat unique to each site. Hence, management approaches must adopt a relatively simple and conservative approach such as a circular zone IDZ around each farm or adopt a more sophisticated approach that delineates each plume. There are pros and cons to each of these. The simple approach is less costly and easier to implement. However, it probably hinders development and in some areas with intense aquaculture it may not be adequate for addressing existing management needs. The more sophisticated approach will be more expensive and time consuming to implement and maintain and will require a higher level of expertise. However, it will provide a framework and the necessary impetus for policy, science, regulatory and user advancement that will inevitably be needed to address the development and management pressures associated with the coastal zone. In either case the management regime will need to decide whether overlaps between IDZs are allowed. If they are not, as suggested by the CCME (1999) guidelines, management is somewhat simpler. If they are, as is likely the existing situation in parts of southwestern New Brunswick, the management task and decision making process is considerably more complex.

Strict adoption of the CCME guidelines to SWNB without the use of the "mixing zone concept" would protect the environment, the traditional fisheries and eco-tourism industries but it would prevent aquaculture from being practiced without the use of aeration. The dissolved oxygen concentrations within the fish farms routinely fall below ambient concentrations at times, particularly in the summer and fall when the natural levels fall below 8.0 $mg \cdot L^{-1}$ and the guidelines recommend that the natural DO levels should be maintained. Adoption of the State of Maine SB guidelines (the daily average dissolved oxygen concentration should not fall below 6.5 $mg \cdot L^{-1}$ and the instantaneous concentration should not fall below 6.0 $mg \cdot L^{-1}$) may also be difficult for farms to achieve, especially during plankton blooms. Adoption of the State of Maine SC class and Environment Canada's siting guidelines are probably not preferred if the desire is to achieve a high degree of protection for the growth and reproduction potential of the wild organisms and of the salmon being cultured.

Adoption of the CCME guidelines with the use of the "mixing zone" concept may protect the environment, the traditional fisheries and eco-tourism industries and enable the aquaculture industry to operate without the use of aeration. This approach would mean that the guidelines would apply to the far-field, i.e. outside the mixing zone. They would not apply within the "mixing zone", i.e. in the near-field. The "mixing zone" size would need to be at least the size of the farm and probably several times this to provide for dilution of the oxygen deficit to ambient concentrations. Typical polar circle netpens are 32m in diameter (100m in circumference) and typical farms are several hundred meters (~500m) long and a few hundred meters (~100m) wide. Therefore, the farm would cover about 50,000 m^2 and the complete mixing zone might cover an area of about 1 km^2.

Adoption of a guideline for the "mixing zone" such as a daily average concentration of dissolved oxygen not less than 6.0 $mg \cdot L^{-1}$ and an instantaneous value not less than 5.5 $mg \cdot L^{-1}$ may be a reasonable interim guideline approach. The exact values need to be defined through a thorough consideration of husbandry feasibility and dilution realities. The approach however, recognizes that in the reasonably well flushed areas of SWNB the aquaculture industry will have a buffer of 1^+ $mg \cdot L^{-1}$ to utilize for salmon culture. It also gives protection to the environment that is slightly higher than that recommended for class SC waters in the State of Maine. Such an approach also recognizes that natural schools of fish would reduce local concentrations of oxygen for short periods of time in any given area and that schools of herring trapped in fish weirs also reduce oxygen concentrations within weirs and their immediate vicinity for the relatively short periods of time the herring remain in the weir. Like weirs, the oxygen reductions associated with netpens are also stable in location. Free swimming organisms can probably avoid the areas of depressed oxygen. It should be noted, however, that there may be a potential for mixing zones in some areas to be of sufficient spatial scale that natural avoidance options are reduced, particularly given the location of some farms in narrow channels and the close proximity

(100s of meters) of some of the fish farms in some areas of SWNB. These cumulative effects should be also be taken into consideration.

Despite the challenges, if the IDZ approach is adopted, and suitable monitoring and modeling efforts are developed, calibrated, validated and implemented, the IDZ approach for aquaculture could mean the CCME (1999) guidelines for DO could be achieved. Aquaculture would fit into, and receive the benefits of being consistent with, an existing nationally coherent and consistent water quality framework that can be regionally customized.

At present the technology and expertise is available to design a dissolved oxygen monitoring program for areas identified to be of high priority. However, suitable models do not yet exist for the Canadian aquaculture and are just beginning to be developed for some other areas of the world. Existing models are only sufficient for highlighting situations of concern (E.g. Page et al. in press, Strain and Hargrave in press). They are not yet robust enough to accomplish all that is needed for the implementation of an acceptable DO water quality management program that resolves the issues on the spatial and temporal scales of importance, both to science and users. Hence, efforts will need to be made to have these models developed and tested. This development must be pursued in Canada so the models account for Canadian conditions and the expertise to use the models is readily available for users and managers. The development could be greatly helped by international collaborations.

In conclusion, it appears that aquaculture in SWNB has the potential to push and exceed the national and international dissolved oxygen standards that have been recommended or adopted. It also appears that there may be the potential to accommodate aquaculture in the SWNB area within dissolved oxygen guidelines that are consistent with existing national and international standards. This accommodation will require some monitoring and modeling research and stakeholder consultation. The monitoring should be aimed at better characterizing the natural magnitude and variability in dissolved oxygen throughout the SWNB region as well as the magnitude and variability of oxygen within and around fish farms. The effort should include point samples along transects as well as time series of observations taken at frequent time intervals (ca. <30 minutes apart). The modeling should be focused on developing predictive models of the impacts of farms on the temporal and spatial patterns in dissolved oxygen. The combination of information should be used to define a robust set of dissolved oxygen guidelines for the area.

10. Summary

- It is well recognized that dissolved oxygen is a fundamental and essential component of the aquatic habitats and ecosystems.

- It is well recognized that anthropogenic activities have resulted in the reduction of oxygen in some coastal marine areas and in some cases severe reductions.

- It is well recognized that the ecological, economic and social consequences associated with severely reduced dissolved oxygen, i.e. extreme hypoxic (<2-3 mg $O_2 \cdot L^{-1}$) and/or anoxic (~0 mg $O_2 \cdot L^{-1}$), are very serious. They usually include the death of most benthic organisms, large changes in the community structures of the ecosystem, the reduction in organism growth and changes in the distribution and migration patterns of mobile organisms. The ecological, social and economic magnitude of these consequences can be large with the exact impact depending upon the aerial extent, temporal duration and seasonal timing of the oxygen reductions and the social economic dependencies on these ecosystems.

- Experience to date indicates that the time scale needed to generate severe reductions in dissolved oxygen, and their associated consequences, is often relatively long (decades). Hence, there is time to gather and interpret data, make appropriate decisions and take appropriate actions to achieve desired environmental and development goals if appropriate actions are initiated now in areas of high risk.

- It is well recognized that once severe conditions (e.g. anoxia) that cover a large spatial area, are attained it takes many years (decades) to restore the oxygen regime and its associated ecosystem components to some acceptable degree. Severe conditions that occur on farm scales are somewhat ephemeral and recovery may be relatively quick (months to a few years).

- In addition to technical opportunity, there is also a stakeholder and government motivation to avoid the consequences of severely reduced oxygen. There is a growing public demand for responsible water quality management.

- It is well recognized that although much is known about the oxygen needs of some organisms, particularly fish (salmonids in particular) and some invertebrates (including lobster), and the various responses of these organisms to reductions in oxygen availability, much more is not known and needs to be known.

- Despite the limited knowledge, there is often sufficient information to establish initial water quality standards for dissolved oxygen and hence standards have been established in several coastal marine jurisdictions.

- Regulators have generally settled on a philosophy and dissolved oxygen standards that protect the growth potential of the more sensitive organisms in a body of water rather than the less stringent philosophy of preventing mortality. The desired degree of protection may vary depending upon local circumstances. The protection philosophy also seems to include the perspective that development is generally not allowed to occur in areas with naturally low dissolved oxygen since any additional reduction may result in significant mortalities and ecosystem impact. Therefore development is restricted to areas with naturally good water quality and the intent is the limit the impact on this water.

- It is also recognized that dissolved oxygen varies spatially and temporally in response to natural processes and that utilization of the coastal marine environment will often utilize some oxygen. Therefore standards have been regionally defined, following nationally accepted approaches.

- It is generally recognized that organisms react to absolute concentrations of dissolved oxygen, and hence most jurisdictions have adopted absolute concentrations as standards. Adoption of an absolute concentration standard recognizes that different environments have more or less capacity to accommodate anthropogenic activity that utilizes oxygen. Environments that have concentrations of dissolved oxygen that are naturally well above adopted standards have more tolerance for activities to use oxygen than environments in which the natural concentration of dissolved oxygen is only marginally above the standard.

- As information and knowledge increases these standards should, and generally have been, reviewed and modified as appropriate.

- Fish farming presents a challenge to the development of water quality standards since it explicitly needs to remove oxygen from the water and has the potential, under certain circumstances, to reduce oxygen levels. The degree to which aquaculture can reduce oxygen concentrations is largely dependent upon stocking density, farm configuration and local hydrography. Experience has shown that when fish farms are located in areas with adequate flushing they reduce local oxygen concentrations relatively little. However, in coastal marine areas with especially intense aquaculture activity and farms located in areas of weak flushing can be at risk of generating hypoxia. Hence, in some jurisdictions guidelines are developed to educate and encourage aquaculturists to locate in areas with naturally high water quality and usually reasonable water circulation and flushing. This approach helps protect the environments that naturally have lower dissolved oxygen and helps the aquaculturist avoid production inefficiencies and losses associated with low DO and low flushing areas.

- There is not a general environmental crisis concerning aquaculture induced hypoxia of coastal waters in Canada. However, there is an opportunity to establish dissolved oxygen water quality standards that are of mutual benefit to the aquaculture industry, the ecosystem and the other activities the ecosystem supports such as fisheries and ecotourism. It is in the vested interest of the aquaculture industry and coastal communities to maintain high water quality standards since the water quality and there are some areas that indicators suggest are on the verge of or are showing signs of potential hypoxia.

- The coastal marine aquaculture industry has a desire and motivation to maintain high water quality since the success of the aquaculture operations is related to some degree to water quality. The industry is directly influenced through production processes, and indirectly through product marketing strategies, consumer acceptability and the attention of environmental organizations and government environmental scrutiny.

- Although much research and stakeholder involvement needs to, and should, be done, there is sufficient information to make an informed start at developing a dissolved oxygen monitoring program and dissolved oxygen standards. Monitoring technology and approaches exist that can be implemented to maintain a watch on the state-of-the-dissolved oxygen component of the water quality. Simple modeling approaches exist that can help to interpret the monitoring information, help infer causal relations and help in a proactive manner to avoid significant reductions. As these monitoring and modeling capabilities improve the efforts to avoid significant reductions on dissolved oxygen should be modified appropriately.

- Simple process based models of the impact of fish farming on near surface concentrations of dissolved oxygen have been developed and appear to be qualitatively consistent with farming experience. These models should be further developed, calibrated and validated so they can become a more useful and respected tool for industry, policy makers and regulators in their various planning, implementation and enforcement considerations.

- Models of near-bottom oxygen concentrations are less well developed, although some promising work is being conducted. Efforts to further develop this modeling capability should be made and once the models are well calibrated and validated their use in industrial, policy and regulatory considerations should be encouraged and enhanced.

- Model systems that include coupling of near and far-field effects of aquaculture on dissolved oxygen are beginning to be developed and utilized.

11. Recommendations or Next Steps

1. **Regionally appropriate guidelines for interim dissolved oxygen standards should be adopted that are consistent with national philosophies and objectives.**

   a. Given the importance of international trade and the forces of the global economy, it is probably important that Canadian standards are comparable to, and accepted by, our major trading partners. If we accept this philosophy, the water quality criteria set by the United States and the European Union should be of particular interest to us in Canada. Since the level of consideration in these trade issues is often at the level of national standards, rather than at the local or provincial level, it would seem that it would be prudent to develop and adopt a national approach to the philosophy and objectives underlying specific water quality standards. The specific implementation of the national approach should be regionally specific to account for the realities of regional differences in the natural environment.

   b. Some general principles for the standards might include:

      1. The standards should have instantaneous limits as well as appropriate temporally and spatially integrated limits.
      2. The standards should take into consideration the location specific natural characteristics of dissolved oxygen.
      3. The standards should be more flexible as the oxygen levels move away from severe levels. The standards should become more rigid as the degree of hypoxia increases.
      4. The standards should adopt the philosophy that thresholds, standards or criteria that are aimed at protecting the growth potential of the ecologically and socio-economically most sensitive organism in a system (e.g. Atlantic salmon, American lobster).
      5. The oxygen thresholds are typically in the 5-7 $mg \cdot L^{-1}$ range with no instantaneous values below 5 mg/L and daily averages not below 6 mg/L. This means high frequency monitoring of DO is necessary. Determinations of DO concentrations once or twice a day are not sufficient to estimate a stable time averaged mean in

an environment that has significant tidal and wind driven fluctuations in DO.

c. in the SWNB area potential dissolved oxygen standards could be:

    1. Instantaneous concentrastions of oxygen should not fall below 3 mg $O_2 \cdot L^{-1}$. Mortality of many species of invertebrates and fish will likely occur in the SWNB area of the Bay of Fundy if they do.
    2. Instantaneous oxygen concentrations <5 mg $O_2 \cdot L^{-1}$ should be considered as the limit below which many species will change their distribution patterns and hence change the bio-diversity of the habitat in the Bay of Fundy. It is also the level that indicates the growth and health of the farmed salmonids will likely be influenced.
    3. Guidelines concerning nstantaneous oxygen concentrations that fluctuate between 5 and 7^+ mg $O_2 \cdot L^{-1}$ will need some further consideration. There are natural fluctuations within this range under certain circumstances such as phytoplankton blooms and human activities may enhance these fluctuations. The considerations should therefore take into consideration the duration and frequency of the fluctuations. Perhaps something along the lines of what has been suggested by Alabaster and Lloyd (1980), or the US EPA (EPA 2000) i.e. the dissolved oxygen concentration should not be below a specific threshold for more than 5 or 10% of the time over the period of the dominant frequency in temporal variability (e.g. tidal period in tidally dominated areas).
    4. Oxygen concentrations that are naturally and consistently >7 mg $O_2 \cdot L^{-1}$ should be considered as healthy waters in the Bay of Fundy and if CCME guidelines are adopted human activities should not reduce the ambient concentrations by more than 10% of the ambient. Salmon grown in these waters should have unimpaired growth.

2. **A intense effort should be made to survey and monitor concentrations of dissolved oxygen in Canada's coastal marine areas, particularly those with aquaculture operations, before guidelines and standards are implemented into regulatory and enforcement frameworks.**

    a. A survey approach should be designed and implemented for high priority areas to determine if there are immediate oxygen concerns. The program should involve industry, regulators and other relevant stakeholders and it should have appropriate checks and balances (e.g. audits).

        1. If concerns are not identified then further effort concerning oxygen may not be warranted although given the overall potential for oxygen impacts on the marine environment a survey should be conducted every few years to ensure the level of concern has not changed.

    2. If concerns are identified, efforts may need to be expended to design and implement a more rigorous cost-effective and regular oxygen monitoring program for the area of concern that will effectively monitor the state-of-the-oxygen environment and alert stakeholders, particularly the aquaculture industry and regulators to areas and times that have a increasing potential for degradation of the water quality in regards to dissolved oxygen.

b. Measurements should be taken in the surface waters and near the seabed, preferably within about 1m. The near surface concentrations directly influence netpen culture and suspended shellfish operations and the pelagic organisms. The near bottom oxygen concentrations, which are often lower than near surface concentrations, directly influence the benthic organisms, many of which are immobile, and near bottom cultured organisms.
c. Statistically rigorous data analyses procedures should be developed and adopted that are capable of distinguishing unnaturally induced change in dissolved oxygen concentration from the natural or ambient situation.
d. The results should be reported and reviewed every one or two years within regional or national forums. Perhaps every five years a national review should be held.

    1. This will give industry and regulators an indication as to the state of the environment in relation to the suggested interim guidelines and to the realities of potential influence and scale of impact of industrial effluents.
    2. It will give all stakeholders a solid database from which to review, revise and finalize the guidelines and standards.
    3. It will help identify areas with a high risk of hypoxia related water quality issues.
    4. Water quality models concerning dissolved oxygen should be developed, calibrated, validated and implemented.

e. The state-of-the-art models are not ready for enforcement use. They are generally in the development stage. However, they can be useful for guiding siting and policy development considerations and for guiding the needs for empirical monitoring.
f. Model development should initially focus on relatively simple models that are data driven and include empirical parameterizations of many ecological rate processes. The development of full ecosystem models is in its infancy and they are parameter and data intensive. Many years or decades of development and appropriate environmental monitoring are required before these models will become routinely available and generally useful.
g. The models must be predictive in nature and be calibrated and validated.
h. The models must also emphasize cause and effect relationships so if effects are predicted and observed in monitoring data some indication of the cause can be identified.
i. Models should predict the natural and human perturbations to the temporal and spatial characteristics of the pelagic and near bottom dissolved oxygen concentrations.

   j. The model outputs should be directly comparable to the monitoring data and guideline standards or thresholds and be useful for industry operating and management purposes as well as for policy, regulatory and understanding purposes.
   k. Progress on modeling efforts should be reported and reviewed every one or two years within regional or national forums. The reviews should be held in conjunction with the monitoring data reviews. Perhaps every five years a national review should be held.

3. **The suggested standards and the new data should be reviewed and modified as required with inputs from all relevant stakeholders.**

   a. A timeline target should be set for the development and adoption of dissolved oxygen standards in the high risk areas. Perhaps 2 years for gathering initial data and 5 years for adoption of best practice guidelines, standards and regulatory targets.
   b. Consideration should be given to adjusting the suggested thresholds to accommodate the local environmental situation, relevant legislation, stakeholder community input and relevant socio-economic factors in the context of the appropriate coastal management plan or integrated coastal zone management initiative.
   c. Thought should be given to the hosting of an international workshop/symposium concerning dissolved oxygen in coastal waters to bring the international experience to Canada. The objectives of the workshop could perhaps include a summary of the natural variation in dissolved oxygen within Canadian coasal waters, a recommended set of dissolved oxygen thresholds from a biological and environmental perspective and an examination of guidelines and regulations that have been adopted in various countries. This effort should be reported in the form of a peer reviewed book or special issue of a recognized scientific journal.

12. Acknowledgements

Many of the thoughts expressed in this manuscript have benefited from discussions with a wide range of industry, science, regulatory and policy related individuals over the past few years. In recent months, Victoria S. Chase assisted with information searches and retrievals associated with the preparation of this manuscript.

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Table 1: Summary of dissolved oxygen thresholds stated in regulatory statutes.

Location	**Threshold**		
Japan	>5.7 mg $O_2 \cdot L^{-1}$	Criteria identifying a healthy fish farm. Below 5.7 the fish, mainly yellowtail, do not grow normally.	Yokoyama 2003
	<3.6 mg $O_2 \cdot L^{-1}$	Criteria identifying a critical fish farm. Below 3.6 the fish, mainly yellowtail are in danger of dying.	Yokoyama 2003
State of Maine, USA	6.0 ppm	Standard for class SA, SB-1 and SB-2 coastal marine waters from 1965-1986	DEP 2004
	5.0 ppm	Standard for class SC coastal marine waters waters from 1965-1986.	DEP 2004
	85% saturation	Standard for class SB coastal marine waters waters from 1986 to present.	DEP 2004
	70% saturation	Standard for class SC coastal marine waters waters from 1986 to present.	DEP 2004
	Daily average of 6.5 mg $O_2 \cdot L^{-1}$ and instantaneous value not less than 6.0 pp.	Suggested revised standard for class SB coastal marine waters waters in 2004.	DEP 2004
	Daily average of 5.4 mg $O_2 \cdot L^{-1}$ and instantaneous value not less than 5.0 pp.	Suggested revised standard for class SB coastal marine waters waters in 2004.	DEP 2004

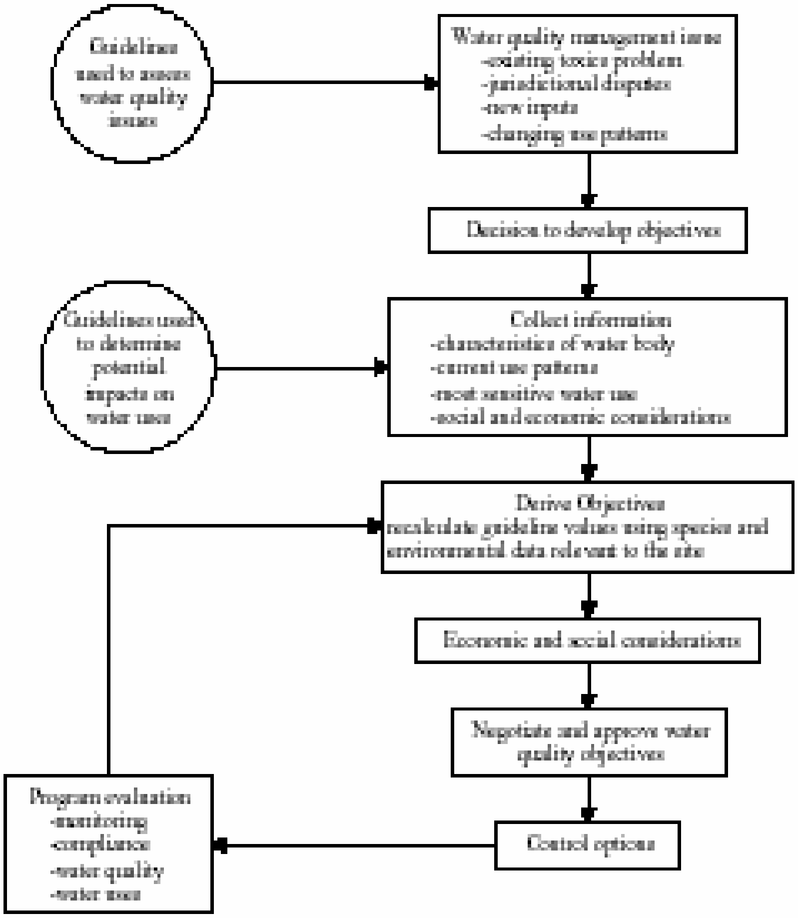

Figure 1: The role of water quality guidelines and objectives in water quality management. Copied from CCME (1999).

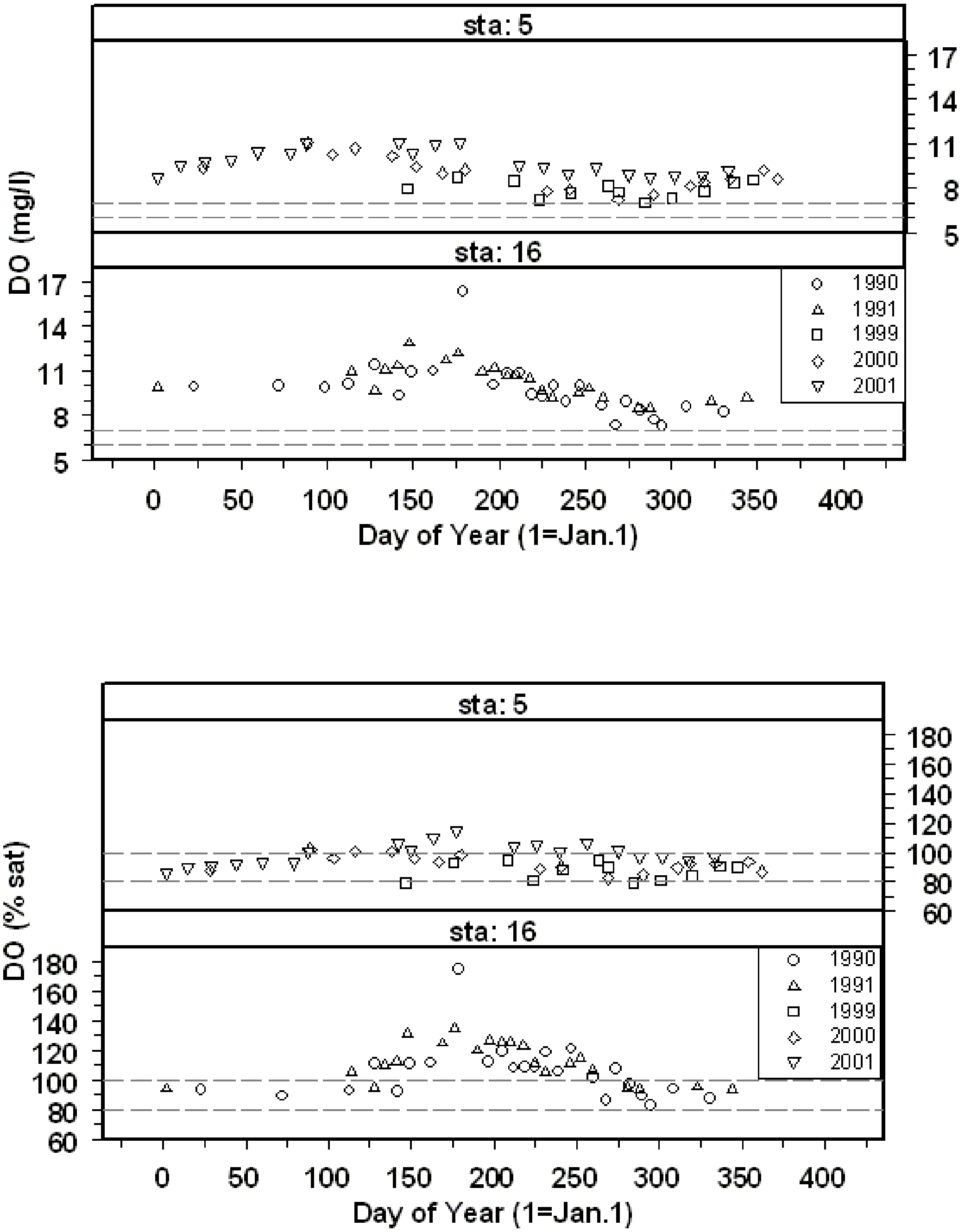

Figure 2: Point sample data showing the annual cycle in the dissolved oxygen at two offshore monitoring stations (Stations 5, also known as Prince 5 and Station 16) in the southwest New Brunswick area of the Bay of Fundy.

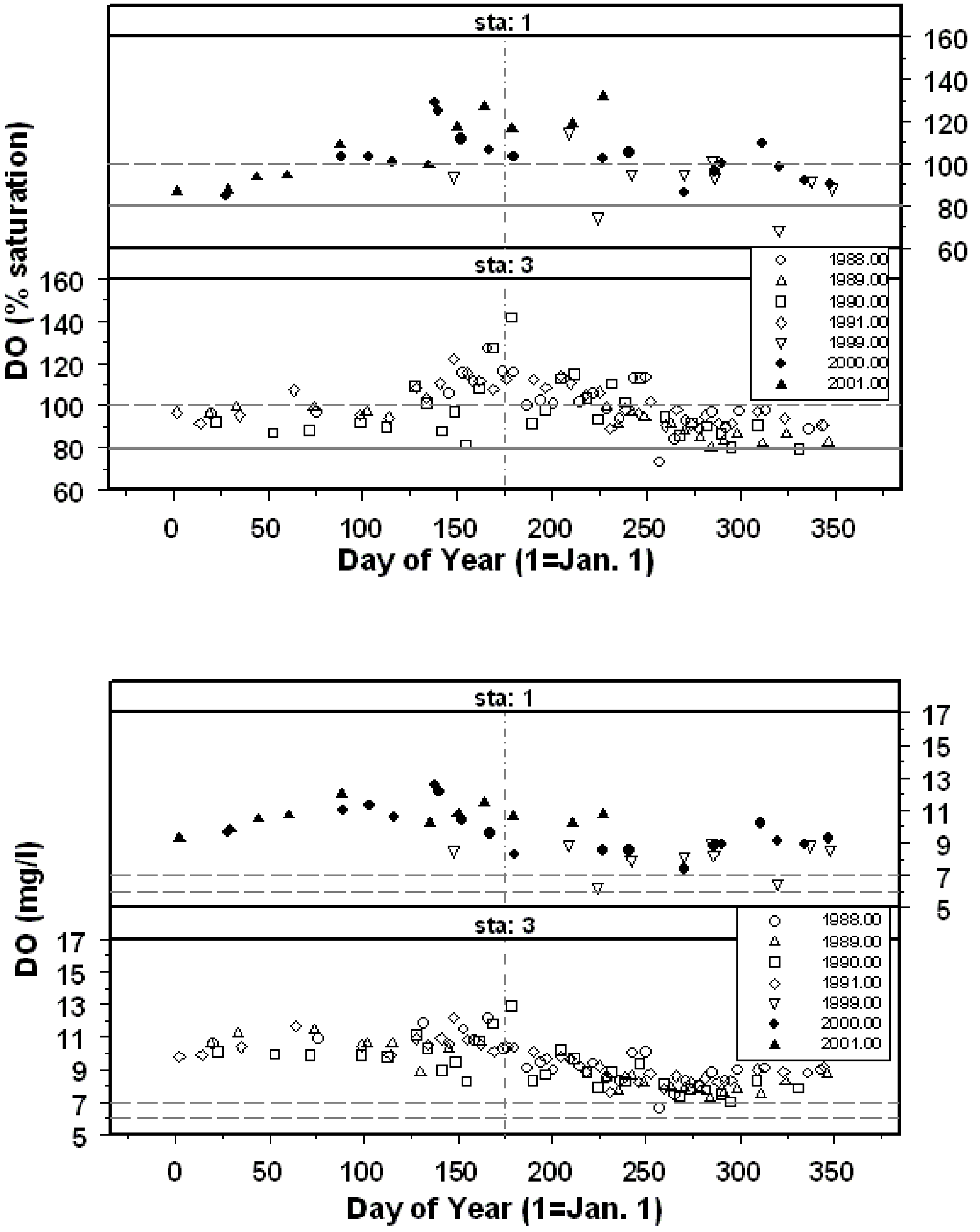

Figure 3: Point sample data showing the annual cycle in the dissolved oxygen at two inshore monitoring stations (stations 1 and 5) in the southwest New Brunswick area of the Bay of Fundy.

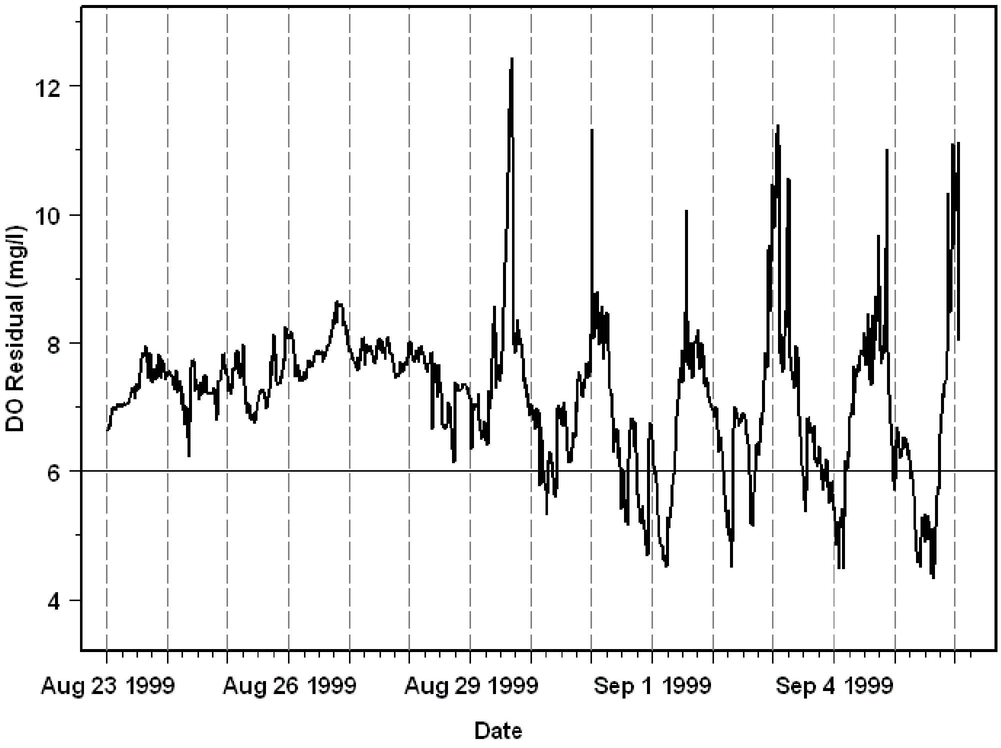

Figure 4: A time series of the concentration of dissolved oxygen near a fish farm that includes the movement of a phytoplankton bloom into the farm area

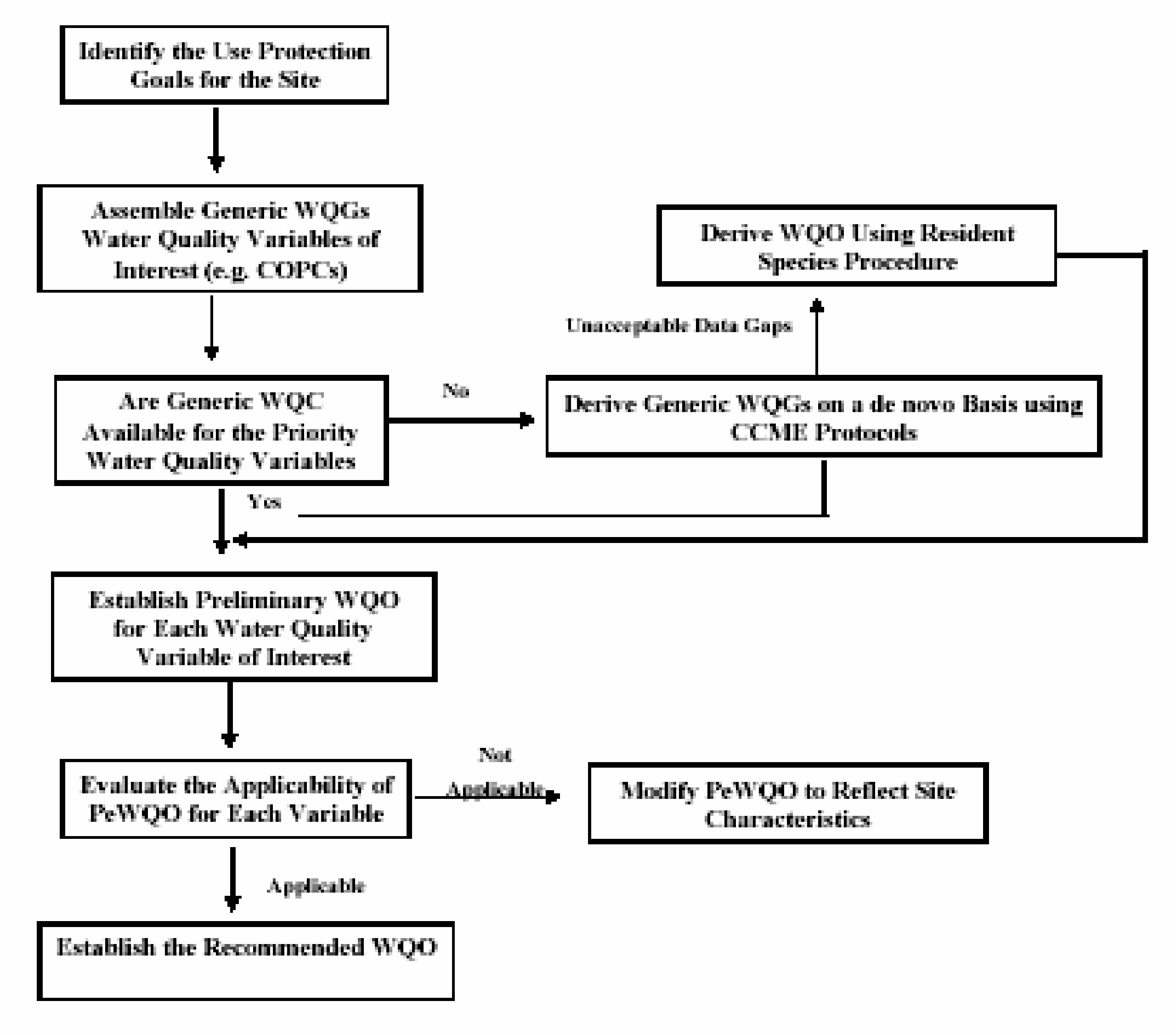

Figure 5: The CCME (1999) overview of the recommended process for deriving numerical water quality objectives.

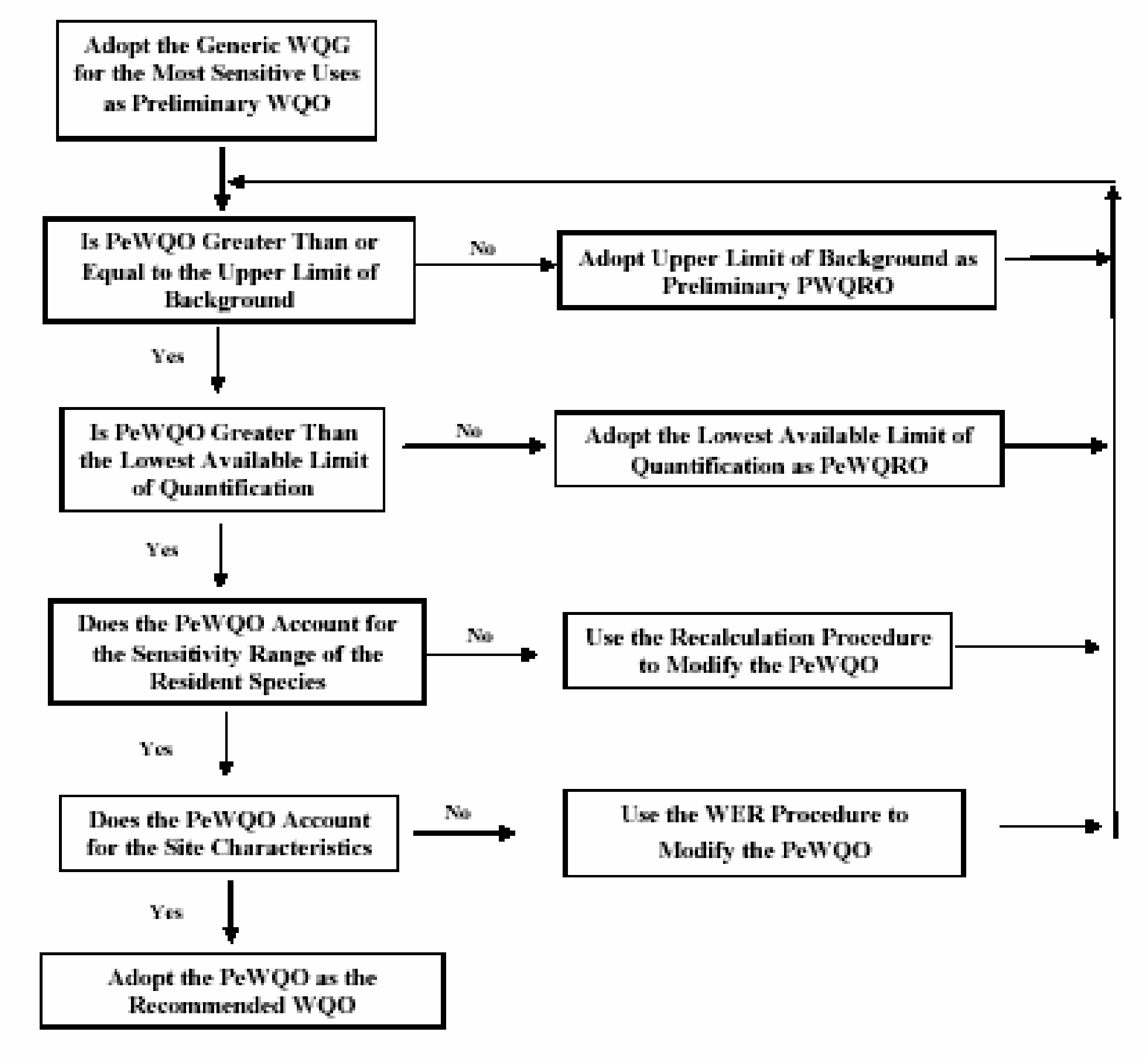

Figure 6: The CCME (1999) recommended process for evaluating and modifying preliminary water quality objectives.