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A perspective on the use of Performance Based Standards to assist in fish habitat management on the seafloor near salmon net pen operations in British Columbia

Point de vue concernant l'utilisation de normes axées sur la performance pour faciliter la gestion de l'habitat du poisson situé sur le fond marin, près d'installations d'élevage de saumons dans des enclos de filets en Colombie-Britannique

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Abstract

In this paper we consider scientific techniques and parameters for measuring changes to the marine ecosystem related to finfish aquaculture in British Columbia, focusing on salmon net pen operations. Our review is limited to seafloor habitats and draws in information from the peer reviewed literature and unpublished data as appropriate. We found an almost complete absence of peer reviewed (journal) papers in the literature from B.C. As we do not support the idea of extrapolation of the extensive published data from other parts of the world to Pacific Region without local verification, our response to specific questions from habitat managers was conditioned by the lack of research publications.

The Performance Based Standards (PBS) approach is a management technique that is used by numerous engineering and education organizations and by a few environmental agencies. The approach is effective with the following conditions: 1) the problem has a narrow focus; 2) response to a system change is well understood by science; 3) when an effect is reversible; and 4) when there is a management response to a threshold or "trigger". Because the responses of seafloor ecosystems to organic waste from fish farms are poorly documented in B.C., we could not find scientific information on the use of PBS to conserve the productive capacity of their component fish habitats. One of the topical PBS methods recommended for evaluating habitat effects of salmon net pen rearing is based on sulfide-organism relationships in muddy sediments. Based on the field correlation data available in the scientific literature, there is a technical basis for these PBS in the particular ecosystems where they have been developed. There are limitations for applying them in B.C.; methods must be developed, which allows them to be used on a variety of habitat types and with an improved mapping scheme. Reversibility is also poorly documented. In our view, PBS are not effective for integrated coastal management, which is the long term direction that DFO scientists have recommended for the Department of Fisheries and Oceans' (DFO) Pacific Region – hereafter referred to as the Region. The choice of parameters and thresholds to indicate that an important ecological change has occurred from salmon net pens is dependent on the objectives that managers have selected, or the particular policies they are dealing with for a particular habitat or ecosystem. The objectives and policies will determine the scale at which effects are assessed - however for fish habitat management, we suggest the "lease scale". We suggest a number of biological and physico-chemical variables as threshold criteria or triggers that could be used if research information from B.C. were available on them. As a first principle, we would not recommend that a single number for any parameter be used as a threshold value. As data are provided from research and monitoring projects related to fish farming in B.C., we suggest that a scientific workshop be convened to discuss the results already available, variables used, and provide guidance for improvement where needed. The recommendations from this workshop should be subjected to the peer review process used by scientific journals.

Résumé

Nous examinons des techniques et des paramètres scientifiques pour mesurer les changements dans l'écosystème marin résultant des opérations de pisciculture en Colombie-Britannique, en ciblant en particulier les opérations d'élevage du saumon en enclos. Notre examen se limite aux habitats du plancher océanique et s'appuie sur des données présentées dans des études publiées jugées par les pairs et des données inédites, s'il y a lieu. Nous avons à peine trouver d'articles publiés jugés par les pairs dans les ouvrages portant sur la Colombie-Britannique. Comme nous ne souscrivons pas à l'idée de l'extrapolation à la Région du Pacifique de la vaste quantité de données publiées recueillies dans d'autres coins du monde sans qu'elles soient vérifiées au niveau local, notre réponse aux questions expresses des gestionnaires de l'habitat ont été modulées par l'absence de publications de recherche.

La méthode des normes axées sur la performance (NAP) est une technique de gestion utilisée par de nombreux groupements d'ingénieurs et organisations d'enseignants, ainsi que quelques organismes à vocation environnementale. Elle est efficace aux conditions suivantes : 1) le problème est de nature locale; 2) les scientifiques comprennent bien la réaction à un changement de système; 3) l'effet est réversible; et 4) les gestionnaires ont répondu à un seuil ou « déclencheur ». Étant donné que les réactions des écosystèmes du plancher océanique aux déchets organiques issus de piscicultures sont mal documentées en Colombie-Britannique, nous n'avons pas trouvé de données scientifiques sur l'utilisation des NAP pour préserver la capacité de production des habitats du poisson constitutifs de ces écosystèmes. L'une des méthodes spécialisées des NAP recommandées pour l'évaluation des effets sur l'habitat de l'élevage du saumon en enclos repose sur les relations entre les sulfures et les organismes dans les sédiments boueux. D'après les données de terrain à l'origine des corrélations présentées dans les ouvrages scientifiques, les NAP établies pour ces écosystèmes particuliers on un fondement technique. Mais des restrictions s'appliquent à leur application en Colombie-Britannique. Ainsi, des méthodes doivent être élaborées et le plan de cartographie doit être peaufiné pour pouvoir les appliquer à une variété de types d'habitats. La réversibilité des effets est aussi mal documentée. Selon nous, les NAP ne sont pas efficaces en ce qui concerne la gestion côtière intégrée, qui est l'orientation à long terme recommandée par les scientifiques du MPO pour la Région du Pacifique – ci-après appelée la Région. Le choix des paramètres et des seuils pour indiquer que les enclos à saumon ont causé un important changement écologique dépend des objectifs que les gestionnaires visent ou des politiques particulières qu'ils doivent mettre en oeuvre en regard d'un habitat ou d'un écosystème particulier. Les objectifs et politiques détermineront à quelle échelle les effets seront évalués et, dans le cas de la gestion de l'habitat du poisson, nous suggérons que cela se fasse à l'échelle du bail. Nous proposons diverses variables biologiques et physico-chimiques comme critères-seuils ou déclencheurs qui pourraient être utilisés si des données de recherche sur ces variables étaient disponibles pour la Colombie-Britannique. Comme premier principe, nous ne recommandons pas d'utiliser une valeur ponctuelle pour les paramètres établis. Lorsque des données issues de projets de recherche et de surveillance portant sur la pisciculture en Colombie-Britannique seront disponibles, nous

suggérons qu'un atelier de travail scientifique soit organisé en vue de discuter des résultats déjà disponibles et des variables utilisées, ainsi que d'orienter les recherches nécessaires, au besoin. Les recommandations formulées dans le cadre de cet atelier devraient être soumises au processus d'examen par les pairs, comme cela est le cas des études publiées dans des journaux scientifiques.

1. Introduction

Scientifically defensible methods to measure ecosystem change in the marine environment are the cornerstone of fish habitat management and coastal zone planning, and are especially important to habitat managers dealing with industries that are relatively new on particular coasts, such as finfish farming in British Columbia (B.C.). Because of the prevalence of the salmon farming industry in B.C., this Research Document (ResDoc) focuses on aquaculture of these particular finfish. Commercial salmon farms first became a DFO habitat management issue in the early 1980s (see Levings, 1994). Although some studies were then conducted on ecological topics that were considered research priorities, very little of this work was published in the peer reviewed literature. Even by the time of the B.C. Salmon Aquaculture Review (SAR, 1997) there were no journal papers that gave specific ecological data in relation to effects of marine finfish farms in B.C. This situation persists to this date. There are only two peer reviewed papers that deal directly with ecological effects of waste discharge from salmon net pens on the northeast Pacific. One is from Washington (Weston, 1990) and the other is from B.C. (Sutherland *et al*, 2001). All of the other work is in the report or contract literature, as seen in the citation list in SAR (1997) and verified in a recent literature search. Sutherland *et al*'s (2001) work was a short-term study, which focused on measurements of dispersion of fish farm wastes. The farm that Weston (1990) studied in Puget Sound was located in shallower water (minimum depth 13 m) compared to most B.C. farms. Almost all of the knowledge used to assist habitat managers and coastal planners in B.C. on environmental aspects of fish farming has been derived from scientific work published from temperate or subarctic oceans elsewhere (especially Norway, New Brunswick, New Zealand, Australia, Maine, Sweden, Washington, and Scotland). Reference to papers originating from these countries may be found in a Proceedings volume of a recent Symposium (Wildish and Heral, 2001).

Numerous monitoring and impact assessment data sets from fish farms in B.C. have been collected over the past two years, but the data have not been interpreted in scientific publications. Over the past year, because of our representation on a Technical Advisory Group, we have received large sets of chemical and biological data collected by Provincial government staff as well as reports from consultants working for the fish farming industry in B.C. All of these data are available on the Internet and we have referenced them as appropriate. More recently (December 2001), HEB staff gave us draft reports and interpretations of these data developed by scientists from a B.C. Provincial Scientific Advisory Group. To our knowledge, these reports have a limited distribution.

Our response to the overall question posed by habitat managers for this ResDoc, "what are the appropriate techniques/parameters for measuring changes to the marine ecosystem in the vicinity of finfish farms in Pacific Region" and related subquestions, is of necessity conditioned by the above-mentioned lack of published data in the refereed literature. Furthermore, given that marine scientists recognize regional and global differences between ecosystems (Sherman *et al*, 1998; Levings *et al*, 1998), we do not support the idea of extrapolation of data from other parts of the world to British Columbia without substantial local "groundtruthing". We initiated two DFO-Environmental Sciences Strategic Research Fund (ESSRF)-sponsored research projects in 2000 that will provide new data on environmental aspects of salmon farming in B.C., but the research is not complete. Preliminary results on some components of the studies are anticipated by December 2002. In addition to the lack of specific data on this particular industry in our Region, ecosystem change in the marine environment in general is poorly understood. Even change in well researched ecosystems that have been studied extensively for fisheries management cannot be predicted without uncertainty because the underlying processes (e.g. regime shifts, ecological succession, competition) are not understood (Rice, 2001).

Our ResDoc is therefore based on a focused review of what we consider the most relevant data from the peer-reviewed journal literature, unpublished reports, and preliminary data from our ongoing research, and draws in information from general ecological science where appropriate. We acknowledge the limitations in this approach, as described above. In addition, while we are aware of a need for advice on measuring changes at all components of the ecosystem, we are limiting the present review to benthic, or seafloor, habitats.

2. Ecological Functions of Seafloor Fish Habitat in the Pacific Region

Our current research projects are focused in the Broughton Archipelago (BA) (Central Coast of B.C.). We provide an overview of the fish and fish habitats of this area, with the caveat that other parts of the coast, such as the west coast of Vancouver Island, likely have different characteristics. The coastline in the BA is characterized by complexes of fjords, embayments, and seaways with seafloor sediments including mud, sand/gravel, and rock.

2.1 OCEANOGRAPHY

The oceanography of the area is poorly known except for a specific fjord namely Knight Inlet where there is a long history of physical oceanographic research (Farmer and Freeland, 1983; Thomson, 1981). Retreat Passage is a representative area of BA where we have made some preliminary oceanographic observations. We present some summary data below. The Passage is a short and narrow (about five km long and one km wide) channel that connects freely with the waters of Queen Charlotte Strait. Oriented in a northeast to southwest direction, Retreat Passage shallows from its 70 m depth at the southwest end to about 38 m at its northeast end. The water properties in Retreat Passage closely resemble those of Queen Charlotte Strait. Dissolved oxygen levels in the late summer and fall are at their seasonal low with values as low as 4.7 mg l^{-1} observed near the bottom at several stations along the Passage. During the winter, dissolved oxygen values are high (~ 9 mg l^{-1}) and the vertical gradient may be very weak. The temperature and salinity profiles are generally weakly stratified in the summer and may be well mixed in the winter. Changes of only 2 psu (practical salinity units) and 2 °C from top to bottom are typical in Retreat Passage during summer and fall. Currents measured at 15 m, 23 m, and 30 m depths in Retreat Passage were weak (5 to 10 cm s^{-1}) and showed no appreciable vertical gradients.

2.2 HABITATS

The shorelines of the BA are characterized by steep rock cliffs, with a few sand and gravel beaches. Bottom substrates are a mosaic of rock, gravel/sand, and mud. Mud is the dominant sediment in the deeper water with harder sediments found in the shallower water close to the shoreline. Each of these three general sediment habitats tends to have characteristic fish and invertebrate communities, although there are no site specific data from the BA. In the following, we give an overview of the ecology of the habitats, extrapolating from published studies conducted in the Region as required.

2.2.1 SAND/GRAVEL

Much of our understanding of the ecology of bottom fish habitats on sand/gravel in the Pacific region has been generated in studies from offshore trawlable habitat on the continental shelf where groundfish stocks are found (e.g. Hecate Strait, Queen Charlotte Sound; Fargo and Tyler, 1990). There is considerable overlap in the species composition in trawl surveys from the BA (Levings and Chilton, 1969; Ong *et al*, 2002) with similar habitats. There are also extensive Dungeness crab (*Cancer magister*) stocks found in all three areas. While adult groundfish (e.g. Pacific cod (*Gadus macrocephalus*), English sole (*Pleuronectes vetulus*), and rock sole (*Pleuronectes bilineata*)) spawn in deeper habitats (>50 m), their larvae drift inshore and rear in shallow waters. Several studies have documented the fact that smaller English sole are found in shallower water (e.g. Levings and Ong, 2001 and references therein) where they feed on bivalves, polychaetes, and crustaceans (Hulberg and Oliver, 1978; Toole *et al*, 1987). The food webs supporting groundfish on sand/gravel substrates in the Region have not been well described but some of the principal species found in adult Pacific cod and sole stomachs were sandlance (*Ammodytes hexapterus*), herring (*Clupea harengus pallasi*) and "shrimp" (assorted Crustacea) (Westrheim and Harling, 1983). The reliance on sandlance, which in turn live and spawn on clean sand habitats, emphasizes the importance of sandy areas for fish food webs. Black (1984) sampled juvenile Pacific cod (17-45 cm) from shallow subtidal areas in Queen Charlotte Strait near Port Hardy. Although the work focused on kelp beds, the findings showed that unvegetated habitats typical of embayments in the BA were important nursery habitats for Pacific cod. In a subsample of 20 fish from this data set, the five most common food items were polychaetes, gammarid amphipods (especially *Pontogeneia intermedia*), shrimp, bottom fish (e.g. cottids, blennies), and miscellaneous crustaceans. Bernard (1978) documented the stomach contents of Dungeness crabs in Hecate Strait and found polychaetes (especially *Sternapsis fossor*), bivalves (especially *Tellina carpenteri*), shrimps (especially *Crangon alaskensis*), and unidentified juvenile flatfish were the dominant prey. Burd and Brinkhurst (1987) sampled the infauna on sand/gravel areas of Hecate Strait and found communities were dominated by molluscs, polychaetes and crustaceans. All these invertebrates are important for fish food webs, as described above.

2.2.2 ROCKY HABITATS

Basic data on the commercially harvested fish found in these habitats have been obtained in support of the hook and line and trawl fisheries for rockfish (*Sebastes* spp.) (e.g. Kronlund *et al*, 1999). Fifteen species of rockfish (all in genus *Sebastes*) were reported from the hook and line fisheries from the Central Coast area (includes BA) by Kronlund *et al* (1999). There are no data on the feeding ecology of rockfish from this area but in Saanich Inlet, Murie (1995) found that copper rockfish (*S. caurinus*) and quillback rockfish (*S. maliger*) fed primarily on pelagic and demersal (near bottom) fishes and crustaceans. Bottom fishes (e.g. lingcod (*Ophiodon elongatus*) and rockfish (*Sebastes* spp.)) use rocky habitats and crevices for egg incubation and adult habitat (Low and Beamish, 1978; Pacunski and Palsson, 2001). Parra *et al* (2001) reported that juvenile wolfeel (*Anarrhichthys ocellatus*) used small crevices in rock habitat for rearing. Farrow *et al* (1983) used a submersible and documented the abundance and diversity of fishes and invertebrates near Tribune Channel in the BA. Some of the dominant epilithic species, or species attached to rock, observed in depths > 50 m included serpulid polychaete worms, brachiopods, cup corals, sponges and the stylasterine coral *Allopora verrilli*. All of these latter species are filter feeding organisms. Rocky habitats in the BA also support stocks of prawns (*Pandalus platyceros*) which are caught in a trap fishery conducted at numerous locations, including Kingcome and Knight Inlets (Boutillier and Bond, 1999).

2.2.3 MUD

Muddy sediments in the Broughton Archipelago are important rearing habitats for several species of pandalid shrimps, including spiny pink shrimp (*P. borealis eous*), humpback shrimp (*Pandalus hypsinotus*), pink shrimp (*P. borealis*), and sidestripe shrimp (*Pandalopsis dispar*) (Boutillier and Nguyen, 1999). The feeding habits of these shrimps have not been investigated in details in B.C. However, it is well known that pandalid shrimps eat invertebrates from both planktonic and benthic sources and Weinberg (1981) found that pink shrimp fed specifically on zoobenthos during daytime. Several species of bottom, or demersal, fish including flathead sole (*Hippoglossoides elassodon*), dwarf wrymouth (*Lyconectes aleutensis*), pollock (*Theragra chalcogramma*), and Pacific Tomcod (*Microgadus proximus*) have also been reported on mud sediments from the Broughton area (Farrow *et al*, 1983; Ong *et al*, 2002). All of these species are known to feed on invertebrates, including pandalid shrimp. Burd and Brinkhurst (1992) sampled the infauna of muddy fjord habitats in Kingcome Inlet but their stations were in very deep water (>200 m). In these habitats, the heart urchin (*Brisaster latifrons*) was one of the dominant species.

3. Use of performance-based standards in monitoring and managing benthic ecosystems near salmon net pen operations

3.1 QUESTION A: IS A PERFORMANCE BASED STANDARDS (PBS) APPROACH ECOLOGICALLY MEANINGFUL AND HAVE PBS BEEN SCIENTIFICALLY VALIDATED IN OTHER JURISDICTIONS OR FOR OTHER INDUSTRIES?

The PBS approach has been loosely defined as "the use of environmental standards/ demonstrated effects of waste discharges in the environment to regulate discharges as opposed to controls at source" (Wayne Knapp email November 28 2001). These two options for dealing with salmon net pen waste material are considered below.

3.1.1 SOURCE CONTROL

We would advocate source control over the use of PBS but realize there is a fundamental conflict between the operation of fish farms and control at source. Limiting or eliminating the amount of waste material deposited into a water body or particular habitat is a proven technique for removing stress from excess organic material deposited into marine ecosystems. There are several papers and reports which document the recovery, with widely varying time scales, of benthic habitats under salmon net pens when the farm has been moved (e.g. Johannessen *et al*, 1994; Anderson, 1996; Wildish *et al*, 2001a). The topic of reversibility is discussed in our response to Question C (below).

It is difficult to reconcile the idea of total source control ("zero emissions") by salmon net operations with the very rationale of having them in the sea in the first place. Pilot scale net pens have been built with chambers to collect waste (see http://www.futuresea.com/Waste%20Management.htm) but as far as is known, these systems are still experimental. The assimilative capacity of the ocean, and the seafloor in some circumstances, is being used to process the organic waste material (food, faeces) from the farm. In response to Question C (below), we provide a review of the possible application of oceanographic models to help determine thresholds or limits for assimilative capacity.

Organic waste produced by salmon net pen operations is difficult to quantify, and is a complex mixture consisting mainly of indigestible carbohydrate from the fish, excretions of nitrogen and phosphorus, and uneaten food. Waste food in itself is a mixture of carbohydrate and protein. It would be preferable to express these wastes as carbon units because several ecosystem models (see below, response to Question C, x) use carbon flows in their computations. However, this is not possible because of lack of understanding and simplistic parameterisation of the physical-chemical-biological processes, which affect the distribution, and turnover of carbon as well as lack of detailed information on the chemical composition of these various constituents.

Clearly any strategy, which limits the amount of organic wastes, especially food, entering the water body can reduce stress by minimizing reliance on the assimilative capacity of the receiving environment. This concept should be pursued wherever possible. As the food conversion ratio decreases below the current approximate value of 1.2 with better diet development and feeding practices, the amount of excess food being deposited should decrease (DFO, 1997). The developing oceanographic models discussed below may also help predict assimilative capacity limits.

3.1.2 PERFORMANCE BASED STANDARDS

The PBS approach is a management technique that is used by numerous engineering, medical, and educational organizations and some environmental agencies, but it is not explicitly a scientific process. Information on PBS was not found in the scientific literature. For example when the term was used in a commonly used scientific search engine ("Aquatic Sciences and Fisheries Abstracts"), no records were located. However, when the term was entered into a general Internet search engine ("Google"), several thousand references were found - twenty topics identified in the first 100 "hits" are shown in Table 1. PBS is a type of adaptive management, wherein an action is taken to remedy a situation when a criterion is met or exceeded (the "trigger"). The approach can be effective if the following conditions can be met: 1) the problem has a narrow focus; 2) response to a system change is well understood by science; 3) when an effect is reversible; and 4) when there is a management response to a trigger.

The first three conditions are often not met in marine ecological systems. Examples of the difficulty in using PBS in two DFO habitat problems might be the levels of dioxins in crabs and foreshore filling. In the case of dioxins, pulp mills in Howe Sound reduced loadings of organochlorines to coastal waters in the early 1990s with the expectation of reducing body burdens to below a trigger level and opening all fisheries for crabs (Nassichuk, 1992). However a decade later levels of dioxins in crab hepatopancreas are still above the trigger level and certain fisheries are still closed (Levings *et al*, 2002), but the reasons why the levels did not decrease are not known. In this case, conditions 2 and 3 for PBS were not met. Foreshore filling for port development is a situation where fish habitat loss is likely irreversible, violating condition 3. As an example, in 1972 several hundred hectares of intertidal fish habitat were covered with about 10 m of dredged sand at the Squamish estuary in preparation for a coal port (Levings, 1976). One of the "triggers" that led to the abandonment of plans to fill the entire estuary was the finding that the area served as fish habitat. Although the filling stopped, the affected habitats could not recover and to this date their functioning as fish habitat is impaired.

Because conditions 1, 2, and 3 are not established for PBS and salmon net pen operations in B.C., their use to conserve fish habitat is problematic. As mentioned above, we could not find mention of explicit use of PBS in the scientific literature. We did determine that the US Environmental Protection Agency (EPA) continues to use PBS to establish allowable pollutant loads, monitoring requirements and enforcement actions, using the concept of biocriteria. Recently, however, the EPA concluded PBS do not go far enough as they do not address the broad goal of biological integrity (US EPA, 2001), a concept which requires the development of ecosystem objectives. Biological integrity is commonly defined as "the ability to support and maintain a balanced, integrated, and adaptive community of organisms having a species composition, diversity, and functional organization comparable to those of natural habitats within a region" (Karr and Dudley, 1981). Ecosystem based management was also recommended as a long-term goal by DFO scientists in a recent national workshop (Jamieson *et al*, 2001).

A basic problem with the use of standards or fixed numerical criteria is that they do not allow for natural variability in space and time if this variability is not well documented in a specific water body. Another fundamental problem is that the scientific validation of PBS may in fact not be possible given that ecological science is an activity that strives to an understanding of natural phenomenon to assist in management, but the development of standards requires explicit value judgements. As noted by Cox and Offutt (1999) in a paper dealing with soil quality in the US, "The selection of performance standards depends, fundamentally, on the economic and non-economic values placed on the use and existence of the natural resource in question" (p. 99). However, as DFO applied scientists, we do recognize that if managers are able to give measurable objectives that can be evaluated, then it might be possible to validate PBS under certain circumstances.

To put the concept and its usage in context with DFO, we describe approaches to validation that are relevant to the Department's management needs. Because we could not find clear statements of objectives that were developed Regionally, we had to put our comments about scientific validation in the context of policy objectives such those found in the DFO habitat policy and Oceans Act. Therefore, for the purposes of this ResDoc, we have assumed that DFO habitat and ocean managers at this time have two main policy objectives:

1. Specific or short term objective: to ensure compliance to the habitat provisions of the Fisheries Act,
2. Broad or long term objective: to implement Integrated Management plans.

1. SPECIFIC OBJECTIVE:

An example of a validation objective would be to verify the accuracy and precision of a particular apparent effect threshold (AET) or PBS for specific contaminants or toxic materials in sediments. For example, the Province of B.C. has established 270 mg kg^{-1} as the PBS (in this case Effects Range Median) for zinc in sediments, based on published data (Nagpal *et al*, 1995). Concentrations of zinc in sediments above that level are assumed to cause harm to organisms. If this PBS were to be validated, a series of experiments and field projects could be set up to independently verify the literature-derived value. This would be a relatively straightforward scientific task, but would require carefully designed experiments to sort out geochemical interactions (e.g. sulfides interacting with metals). PBS for metals have been verified in numerous reports (e.g.

Borgmann, 2000) but not for sediment affected by salmon farms. A somewhat similar procedure would be used for an element or compound for any particular PBS.

PBS for Fish Habitat Effects on Fish Farm Wastes

A specific and topical PBS recommended for fish habitat management on mud habitat near net pen operations is based on sulfide-organism relationships in this habitat. We discuss this in some detail below, and in response to Question C, we offer a variety of additional threshold parameters that could be used to augment sulfide measurement in mud.

i. PBS for mud habitat:

Based on the field correlation data available, as typified by Wildish *et al* (2001b) from studies in Southwest New Brunswick (swNB) and described below (see Table 1), there is a strong scientific basis for these PBS in the particular habitats where they have been verified with specific methods. In this sense, the sulfide PBS is ecologically meaningful for mud habitats in swNB. However, there are a number of important differences in the ecosystem and habitat "drivers" between B.C. and swNB - this makes a direct transfer of geochemical and biological data and methods between the two coastal areas difficult. In addition, sites are clustered in a few bays and it is easier to characterize or generalize from studies conducted at one farm site to another. For example, the bottom temperature regimes where all the farms are located in swNB are likely to follow the seasonal range (approximately 1 to 11 °C) shown by Trites and Garrett (1983). However, temperatures between 30 and 50 m in Knight Inlet, which may be typical of conditions in the BA, show a seasonal range of about 6-9 °C (Stucchi, unpublished). In B.C., farms are very dispersed and are located in coastal areas separated by several hundred kilometres (e.g. Broughton Archipelago, Clayquot Sound, Kyoquot Sound), many of which are poorly known oceanographically. Because the geographic locations of the seven B.C. farms are not given in Brooks' focus study (2001a), it is difficult to place them in any particular oceanographic regime. In general, the swNB sites are shallower than B.C. locations (range 7-20 m at 11 farms studied by Hargrave *et al* (1997)) enabling diver collection of samples. The mean depth of the seven farms sampled by Brooks (2001a) ranged from 39 to 44 m, requiring grab sampling. The integrity of the sediment surface in a grab sample compared to a diver-deployed core may be very different -in general a diver-deployed device is more effective at sampling the most recently deposited sediment (Bothner and Valentine, 1982). Finally, sediments at the farm sites in swNB are dominated by mud whereas there is a mosaic of habitat types on many fish farm leases in B.C.

Further experimental and mapping data are also required in B.C. to investigate cause-effect relationships. While PBS methods have been accepted in some jurisdictions as cost-effective for environmental monitoring of mud habitats near aquaculture operations, managers are generally advised to use them on a "point" or "distance from the farm" basis. Weston (1986) appears to have given the first recommendation for this sampling protocol in the northeast Pacific, specifically for salmon net pen operations in

Washington, USA. This sampling strategy is unlikely to cover the above-mentioned mosaic of sediment types.

ii. PBS for fish farm waste on sand/gravel, and rock:

Because the sulfide PBS can only be used on one sediment type, it needs to be validated on a variety of substrates before it can be defended as an ecologically meaningful measurement. As noted in Section II, sand/gravel and rock are key fish habitats in B.C. The PBS based on mud substrates cannot adequately assess sulfide levels in such habitats because currently available sampling methods are feasible only for unconsolidated sediments and verification data are only available for this particular substrate. This limitation of the sulfide PBS is recognized by its proponents - Wildish *et al* (2001b) state (p. 475) " Its value in other sediments….remains to be determined".

In addition, as far we know, there is no measurement of sulfides in the benthic boundary layer (BBL) under fish farms. The BBL is a specific aqueous habitat found within a few mm or cm of the sediment water interface. Low flow velocities in this near-bottom water are known to influence oxygen conditions which in turn affect secondary production in subtidal organisms (Nilsson, 2000). Sediment cores and grabs cannot be used to sample the BBL, especially in erosional areas, but methods using "benthic landers" or other automated devices are available to investigate physical and chemical parameters near the seafloor (e.g. Agrawal and Traykovksi, 2001). To our knowledge, these instruments have not been used near salmon net pens. The dynamics of particle-borne sulfides and resulting dissolved oxygen levels in the BBL are related to turbulence and eddy diffusion (see review in Diaz and Rosenberg, 1995). The exchange rates between deposited and suspended phases of organic matter particles likely control the level of sulfides in the BBL, and the rates are in turn controlled by bottom currents. Relationships between carbon sedimentation, benthic metabolism, and oxygen levels have been studied on muddy bottom near fish farms (Findlay and Watling, 1997, see below) in Maine, USA. Similar data are not available on relationships between sulfides and the former parameter or from coarse sediments.

2. BROAD OBJECTIVE:

We believe the PBS strategy proposed for environmental management of salmon net pen farming in British Columbia does not provide data for ecosystem management. As pointed out by Wildish *et al* (2001b), any contending method for monitoring and assessment must meet criteria of scientific defensibility, statistical validity, and provision of relevant decision points. In order to meet the latter criterion, PBS for salmon net pen operations should be assessed at a scale that corresponds to the ecosystem that is being managed. In the case of salmon net pens, we suggest the ecosystem scale is at the lease level, i.e. about 1: 5000 scale. As habitats are nested within ecosystems, if the broad objective is to conserve ecosystems then habitats will also be conserved. However, conserving habitats on a one by one basis will not necessarily conserve an ecosystem.

The use of narrowly based techniques, such as PBS, to manage ecological problems in the receiving water body is difficult to validate. As an example, in the Puget Sound Ambient Monitoring Program, PBS for sediment conditions in three areas of Puget Sound were assessed by determining the relationships between a number of variables. These variables were total organic carbon, grain size, chemical concentrations, etc and bioassay responses, including amphipod mortality, bivalve larvae mortality, juvenile polychaete mortality and biomass, etc (PTI, 1991). Sediment PBS for each pollutant or variable were used to help environmental managers decide which locations in Puget Sound were severely polluted, and hence qualified for funding to clean them up under the "Superfund" program. Restoration was attempted by capping, dredging, and other procedures, and was often successful in reducing the levels of the contaminants in sediments. However, ecosystems and habitats supporting fish in certain areas of Puget Sound are still impaired, judging from effects such as impaired immune systems on juvenile salmon and effects on English sole liver functions (e.g. Collier *et al*,1998). This implies that the PBS were not totally effective, since contaminants from unrecognized sources are still entering the ecosystem - in other words the approach was too narrow to resolve the problem.

The recent trend in coastal ecosystem management within DFO is towards measures of ecosystem performance (Jamieson *et al*, 2001), a strategy that requires broad and multiple objectives. This makes scientific validation on a "one by one" application of PBS toward specific sediment types (e.g. soft sediment, to the exclusion of other substrates such as rock, as discussed above) difficult. Situations where several industries share the use of an ecosystem, with possible overlapping and cumulative effects, are also problematic. The validation problem for broad management objectives can be resolved if an integrated, or ecosystem-based, approach is taken, preferably supplemented by "multimetric biological-community evaluation mechanisms" such as the index of biological integrity (Karr and Dudley, 1981; Yoder and Rankin, 1999). As described by Jamieson *et al* (2001), the key to a successful ecosystem based management plan for aquaculture is the articulation of ecosystem goals, which must be measured with scientifically defensible indicators or models. There is no reason why a variety of PBS could not be the measurable habitat indicators, but in order to provide guidance for seafloor use planning based on ecological data, they need to be placed in a proper spatial context. For example as discussed below, measuring PBS on a grid of stations, at the lease scale, might be more meaningful than regularly spaced stations on one or two transects arranged around the farm, as is the current practice. Measurements at this scale would require stations to be positioned about 50 m apart, which would be possible if a small grab were deployed between the net pens, using contemporary GPS devices for positioning.

The problems of applying PBS one industry at a time have been recognized in other situations where integrated management and assessment of cumulative effects is required. For example in the Rhode Island Salt Pond Region, the amount of nitrogen from individual sewage disposal systems as a PBS was recognized as an inadequate method that did not prevent unacceptable watershed loadings. A similar problem exists in coastal B.C. where standards for log storage and bottom trawling are not integrated with standards for the fish farming industry. All three industries have the potential for seafloor disruption and often use the same embayments. A management system based on impact standards rather than performance standards (Ernst, 1995) can be more effective for habitat management. Impact standards require that a certain result actually be achieved whereas performance standards only provide a trigger for trying to achieve the result.

An alternative that might be more scientifically defensible for ecosystem management at the lease scale is the concept of impact zoning (IZ) (Ernst, 1995), which allows for the use of multiple indicators and allows discretionary use of a variety of sampling scales to identify effects on fish habitat. Impact zoning would require mapping of fish farming effects on a grid rather than a transect basis, and would have to be done at a smaller scale (e.g. 1:5000, length scale 50 m). Another advantage to IZ is that this concept enables mapping of the capability of a landscape or seafloor to assimilate waste. Mapping at this scale would also allow identification of critical fish habitat such as nesting areas for lingcod (see above). As discussed in our response to Question C, a variety of threshold indicators could be mapped including cost-effective alternatives to chemical surrogates for surveying mud substrates such as digital images to measure the apparent Redox

Potential Discontinuity (SAIC, 1999; Rosenberg *et al*, 2001). Mapping of rocky fish habitat within the ecosystem found in the lease area could be done with RoVs or even simple drop cameras. Acoustic technology such as multibeam swath sounding and QTC View can also provide cost effective, high resolution mapping of sediment characteristics (benthic habitat or condition). This technique is being evaluated within our ESSRF project in collaboration with CHS (Sutherland *et al*, 2002). Researchers in Greece have used a similar technique to investigate sediments near fish farms (Dougall and Black, 1999).

3.2 QUESTION B:

1. What are the chemical surrogates and sampling methods currently being used?

3. Are the chemical surrogates and sampling methods currently being used in impact assessment and monitoring in B.C. providing meaningful information about the ecological condition of the environment near finfish farms?

3.2.1. WHAT ARE THE CHEMICAL SURROGATES AND SAMPLING METHODS CURRENTLY BEING USED?

In the Pacific Region, monitoring of benthic ecosystems in the vicinity of finfish aquaculture operations is carried out primarily by the British Columbia provincial government, environmental consultants hired by the provincial government and by finfish farm operators. Physicochemical parameters typically monitored include sediment grain size distribution (SGS), total organic carbon (TOC), total volatile solids (TVS), redox potential (ORP) and sulphide content (S). With the development of the PBS approach to aquaculture regulation by the provincial government, increased attention has been paid to sediment S as a surrogate for measuring changes to benthic marine ecosystems related to finfish aquaculture. As of January 2002, the province’s Draft Aquaculture Waste Control

Regulation and Compliance Strategy (BCMWLAP 2002) focuses on free sulphides ($S^{=}$) as the prime chemical indicator to be used for compliance monitoring. Specific levels of $S^{=}$ are advocated as thresholds or triggers for deciding if a farm should be relocated or other remediation undertaken.

Provincial monitoring guidelines (Erickson *et al*, 2001), call for benthic samples to be collected at distances of 0, 30 and 100 m along transects extending from the perimeter of the net pens. Samples are collected using a self-closing grab (e.g. van Veen) that penetrates to a depth of at least 4 – 5 cm below the sediment-water interface in mud and is capable of holding as much as 0.1 m^2 of sediment, including an undisturbed sediment surface layer. The top 2 cm of the sediment column is used for chemical analyses.

Provincial guidelines recommend that S be measured in homogenized sub samples of > 50 g, using a silver/sulphide electrode and a combination pH/reference electrode against a sodium sulphide standard as described in Hargrave *et al* (1995), although alternative procedures may also be accepted.

The draft provincial regulations (BCMWLAP 2002) identify a sediment $S^{=}$ concentration of 1300 μM as a "trigger" standard, which, if exceeded at any sampling station within the tenure boundary, necessitates repeat $S^{=}$ monitoring and initiation of biological sampling, reporting of monitoring results to a designated government officer, and, depending on the results of subsequent monitoring, a remediation plan, the details of which are as yet unspecified. In addition to the "trigger" standard, the provincial legislation seeks to identify an enforcement standard for $S^{=}$, which is not to be exceeded at any time within the tenure boundary. The precise value of this enforcement standard has not yet been determined, but will likely fall within a range of 4500 – 6000 μM (BCMWLAP 2002).

3.2.2 DO THE CHEMICAL SURROGATES PROVIDE MEANINGFUL ECOLOGICAL INFORMATION?

The $S^{=}$ standards proposed by the draft provincial legislation are intended to avoid ecological impairment of benthic ecosystems and are not focused on specific fish habitats. These standards have been developed based on data from studies in the Maritime Region (Hargrave *et al*, 1995; Wildish *et al*, 2001b), and from Brooks' (2001a) consultant report on seabed conditions near nine salmon aquaculture operations in B.C. As explained in Question A, few data are available in the peer-reviewed literature characterizing the relationships between sediment $S^{=}$ and benthic ecology in northeast Pacific coastal ecosystems and therefore there is need to groundtruth relationships developed elsewhere. We do provide a review of data from a number of published field and laboratory studies from elsewhere to give context to the currently used chemical surrogate (sulfide). As with all laboratory studies, we do recognize the limitations on applying the results to the field situation. As explained in Question A, because the chemical surrogates are currently only measurable on mud, they are only providing partial data on habitat effects, given that it is likely there is a mosaic of sediment types on most fish farm leases.

Naturally occurring (i.e. background) S concentrations of marine sediments are highly variable. For example, $S^{=}$ concentrations reported in pacific coastal habitats unaffected by aquaculture range in order of magnitude from 10^0 to 10^5 μM, depending on the structure and organic matter content of the sediment (Bagarinao, 1992). The habitats that show the high $S^{=}$ concentrations are in naturally anoxic basins such as Saanich Inlet, Minette Bay, and other silled fjords in the region. As a result, natural $S^{=}$ tolerance ranges of benthic organisms are highly variable among species.

Among marine polychaete worms, some species are strongly adapted to high $S^{=}$ environments. For example, the lugworm *Arenicola marina* can survive several days' exposure to $S^{=}$ concentrations in excess of 10 000 μM (Groendaal, 1980). Other taxa are more susceptible: survivorship of the spionid polychaete *Maranzelleria cf. wireni* is significantly reduced by exposure to $S^{=}$ concentrations in excess of 1 000 μM under anoxic conditions (LT_{50} = 4.5 days, Shiedek *et al*, 1997), while *Nereis (Neanthes) arenaceodentata* is adversely affected within 4 days exposure to concentrations as low as 170 μM (Dillon *et al*, 1993).

Among bivalves, $S^{=}$ tolerances are also variable, but generally lower. For example, bioassays with *Arctica islandica* show no significant metabolic effects following 10 days' exposure to $S^{=}$ concentrations of 200 μM (Oeschger and Storey, 1993). In contrast, embryonic development of bay mussels (*Mytilus edulis*) is adversely affected within 48 hours' exposure to total S concentrations of < 3 μM, with normal development completely inhibited at 8 μM (Knezovich *et al*, 1996).

Crustaceans are highly variable in their tolerance to $S^{=}$. Non-gravid females of the harpacticoid copepod *Cletocamptus confluens* can withstand 4 days' exposure to $S^{=}$ concentrations in excess of 2 000 μM with no significant effects on survival rates (Vopel *et al*, 1998). In contrast, the amphipod *Rhepoxynius abronius*, a food web species found in B.C. waters, showed significant mortality within 48 hours' exposure to 50 μM total $S^{=}$, with complete mortality occurring at <80 μM (Knezovich *et al*, 1996).

Marine fishes may also be adversely affected by high $S^{=}$ concentrations in coastal sediments. Whereas some deep-sea species are highly $S^{=}$ tolerant (e.g., Rosenblatt and Coehn, 1986; Cohen *et al*, 1990), groundfish species occurring in shallow, open coastal habitats often have relatively low tolerances. For example, speckled sanddab (*Citharichthys stigmaeus*), a species found in B.C., have been found to die within 2 hours' exposure to 200 μM hydrogen sulphide (Bagarinao and Vetter, 1989).

In natural environments, mobile organisms such as fish or crabs are unlikely to be exposed to adverse conditions for prolonged periods of time. In contrast, burrowing organisms such as polychaetes and bivalves are more likely to endure prolonged exposures, and may therefore be more susceptible to adverse effects, despite increased tolerance levels. Although there is generally a direct correlation between time of exposure and toxicological effects, relatively short exposures may have a significant effect during certain stages of development. For example, Knezovich *et al* (1996) report that bay mussel embryos exposed to $S^{=}$ concentrations of 2.5 μM for 48 hours do not exhibit any greater incidence of abnormal development than do embryos exposed to similar concentrations for only the first 10 hours of their development. These findings suggest that the early developmental stages are the most vulnerable, and that the initial period of exposure is critical in determining the magnitude of impacts that may be assessed later on.

In addition to direct toxicological effects, $S^{=}$ affects benthic organisms through interactions with other elements of the sedimentary environment. For example, Bagarinao (1992) shows that $S^{=}$ exacerbates hypoxia or anoxia. Similarly, sediment $S^{=}$ may influence bioavailability of metals such as cadmium, copper and nickel, confounding the effects of $S^{=}$ and metal toxicity (e.g., Ankley *et al*, 1996; DeWitt *et al*, 1996). Monitoring of sediment $S^{=}$ concentrations without concurrent investigations of other physicochemical parameters may therefore yield an incomplete picture of potential effects on benthic organisms.

The proposed standards appear to be insufficient to prevent loss of productive capacity on mud habitats within benthic ecosystems in the vicinity of finfish operations. Among the organisms included in toxicology studies, the majority show adverse effects within a few days' exposure to $S^{=}$ concentrations considerably lower than the 1 300 μM standard proposed by the B.C. draft aquaculture legislation. Data from Brooks' (2001a) report indicate that a sediment S concentrations of approximately 1 000 μM may result in a 50% reduction in benthic macroinvertebrate diversity at sites in coastal B.C. (Bright, 2001).

3.3 QUESTION C: WHAT ARE THE RECOMMENDED PARAMETERS AND APPROPRIATE THRESHOLDS TO INDICATE THAT AN IMPORTANT ECOLOGICAL CHANGE HAS OCCURRED? CONSIDERATION SHOULD BE GIVEN TO SPATIAL AND TEMPORAL FACTORS AS WELL AS CRITICAL VALUES OR RANGES OF VALUES FOR THESE PARAMETERS.

This is a focused review of some of the variables (unranked and likely incomplete) that could be used to answer the above question. Sulfide measurements on mud are discussed in detail in our response to Question B (above). Many of the potential variables such as sulfides, carbon, redox potential, Eh, and biofilm distribution covary. A rigorous review of potential methods and associated thresholds for detecting organic impacts near salmon farms in B.C. is difficult because the recent data sets collected by various agencies have not been thoroughly assessed, interpreted, and published in the open literature. It is also difficult to recommend specific variables for detecting threshold effects because of differences in the capacity of management staff to implement the various methods involved. Where comprehensive research has been done, for example in eastern Canada, the choice of methods and variables can be extensive - Hargrave *et al* (1997) evaluated 20 different variables before narrowing the list of what they considered the cost-effective key variables ($S^{=}$ and Eh) for mud habitats.

Threshold values for the objectives will determine the spatial and temporal extent of the change and the scale at which it is assessed. If the objective is to avoid a decrease of productive capacity ("Habitat Alteration Disruption or Destruction, HADD") as specified by the Fisheries Act, loss of over about 100 m^2 of fish habitat appears to be a threshold value for many habitat managers (Levings *et al*, 1999; also discussed below in ii). To detect such an areal loss under a net pen operation, sampling on a grid system at a scale of about 1: 5,000 (length scale 50 m) is required. This was the basic methodology used in an investigation of a HADD some of this reports co-author's were asked to conduct at an abandoned salmon net operation in the BA (Levings and Sutherland, 1999; see Appendix I in the present document). Other parameters are also scale dependent. The critical values for carbon loading, for example, are very different if considering 100 net pen operations spread over the coast of British Columbia, a particular system of inlets such as the BA, or a particular embayment. Assessment scales for these areas would be approximately 1: 1,000,000, 1:50,000, and 1:5,000 (10 km, 500 m and 50 m length scales; arbitrarily defined as macroscale, mesoscale, and microscale) respectively - each would require a radically different approach to measuring effects.

3.3.1 TOXICITY

Barrick *et al* (1991) recommended the use of multiple PBS based on acute toxicity in sediment bioassays using amphipods, bacteria and echinoderm larvae for sediment management in Puget Sound. The use of a single indicator PBS (e.g. toxic sulfide levels, see above) would not protect the ecosystem or its constituent habitats, according to these authors - a point we have also made earlier in this paper. However mapping toxicity effects to verify field observations of reduced faunal abundance would be worthwhile - this was the approach taken by Deniseger and Erickson (1998) in their synoptic survey of net pen operations in the BA. Experimental data on sulfide toxicity, such as those from our current DFO-sponsored research, are needed to compare with field information, as mentioned above in our response to Question B. In our view, if sulfide concentrations in sediment or in the BBL changed significantly above baseline underneath a net pen operation this would be cause for concern. As mentioned in our response to Question A, mapping sulfide levels on the seafloor at the microscale, which would account for the mosaic of sediment types, would yield more habitat oriented results.

3.3.2 AREA OF SEAFLOOR AFFECTED

There is evidence from general and specific scientific findings in a variety of ecosystems which argue strongly for maintenance of seafloor habitat integrity. There is general support for the idea that change from the baseline situation, i.e. reduction in productive capacity of individual habitats, will cause a shift in ecosystem structure and function. Ecological principles based on modelling of possible extinction in terrestrial systems, taking into account the amount of habitat needed to maintain a species, as well as patterns of habitat fragmentation, usually illustrate threshold effects (e.g. Fig. 1, from Fahrig, 2001). The question of how much habitat can be removed without significantly changing productive capacity is a topic central to DFO's habitat management mission and goals.

Even in relatively well understood ecosystems such as lakes and rivers, researchers and managers have had difficulties answering this question (Metikosh, 1997). Because these area threshold effects are poorly understood in marine habitats, in our view the risk of encountering them should be avoided by conservation of habitat in its original configuration. Studies of complex marine systems such as coral reefs (Knowlton, 2001) strongly suggest that habitat degradation and fragmentation can favour more rapidly growing competitors of sensitive species. Bottom fish communities and important species such as rock sole, flathead sole, and halibut use areas such as the Central Coast of B.C. as rearing habitat (Levings and Chilton, 1969). In Alaska, these three species, together with yellowfin sole, are known to partition the available habitat in ways that minimize resource competition (Norcross *et al*, 1997), and it is likely that similar processes occur in our area.

We could not find papers documenting specific thresholds for spatial effects of habitat alteration and species loss, at any scale, on the functional ecology of temperate region sediment ecosystems. We are aware of only a few situations in the Pacific Region where habitat loss owing to salmon net pens has been quantified and published in the open scientific literature. In an industry trade journal, Brooks (2001b) reported that the footprint for a farm producing 1 200 tonnes of salmon would likely be about 4 000 m^2 or up to 16 000 m^2 if effects extended 30 m from the edge of the farm. Weston and Gowan (1988, cited in Iwama, 1991) stated that a fish farm in Washington affected about 6 000 m^2 of benthic habitat. In Norway, perhaps because of environmental concerns, proposed new salmon net pen operations are not allowed to exceed a footprint of 2 860 m^2 (Maroni, 2000). A worse case situation in a shallow bay in Spain (Ruiz *et al*, 2001) reported the loss of about 21 ha of seagrass habitat (*Posidonia oceanica*) due to waste from mussel farms.

DFO biologists have successfully argued on technical grounds in several court hearings that loss of small areas of marine foreshore habitat, much less than the surface area beneath a salmon net pen operation, is significant. We comment on the amount of habitat loss involved to put the information on salmon net pens in perspective. We are aware that the comparison of intertidal habitat with seafloor is strictly an "apples and oranges" situation and we provide the data below only as information on thresholds that the Department has invoked in other marine habitats. In the eight cases reviewed (Carl Yong, DFO, email dated Dec 21 2001), the average was 502 m^2 (range 15-1115 m^2).

The seafloor area removed from productive capacity by finfish net pens is site specific, but few quantitative data are available in the scientific literature, as noted above. In B.C., because of the steep topography and variable substrates, habitats under the pens could be heterogeneous. It is well known that impact on the seafloor depends on "between site" conditions such as depth, currents, and sediment type but these can also vary "within site". There are situations in B.C., all of them reported in the unreviewed literature, where seafloor has apparently not been affected severely, or at least recovered fairly quickly, because erosional conditions are prevalent (Anderson, 1996). Because conditions within the BBL (see above and Nilsson, 2000) and the role of larger long-lived species was not considered (see 4.3.4 and 4.3.6, below), these observations may be incomplete.

3.3.3 REDUCED RELIEF

Reduced relief of the rocky benthic habitat from excess sedimentation around fish farms is an example of a quantifiable "sublethal" physical effect. Crustaceans such as the spiny subtropical lobster (*Panulirus marginatus*) are dependent on a bottom type which has intermediate relief of a few centimetres (Parrish and Polovina, 1994) - more uniform substrates (e.g. homogenous algal turfs) supported fewer organisms. It is not known if there are crustacean species in B.C. with similar habitat requirements or if wastes from finfish aquaculture have changed the relief on the seafloor at any farm sites. Reduced relief might be assessed using the same techniques as depth of soft sediment over harder substrates (see xi, below).

3.3.4 BIODIVERSITY

The loss of sensitive species in a zone under certain net pen operations and species shift toward tolerant species in the moderately polluted zone on its perimeter often conforms to the well known response pattern from hypoxia, sulfides, and organic pollution described by Pearson and Rosenberg (1978). The tolerant species such as capitellid worms, found in sediments with high concentrations of organic material, are smaller than functionally important, larger invertebrates originally living in the non-disrupted habitat. This leads to a decreased ability of the benthic community as a whole to modify surface sediments for biogeochemical processes (e.g. nitrification and denitrification) through bioturbation (Rosenberg, 2001). Therefore the relationship between biodiversity and sulfide established in B.C. by Bright (2001) using data from Brooks (2001a) (Fig 2) does not necessarily represent a linear function.

The present rate of habitat degradation and species change in marine benthic ecosystems around the world is significant (Snelgrove *et al*, 1997), but experts in marine conservation and sediment ecology are not able to predict the exact implications of the loss of certain species of meiofauna and macrofauna. Conservation biologists in B.C. are also working with this uncertainty, with the added problem that seafloor invertebrate communities are poorly described in the Region, especially on the north and central coast. However changes in biodiversity from hypoxia is of international concern - Diaz and Rosenberg (1995) stated that there is no other environmental variable of such ecological importance that has changed so drastically in recent years.

3.3.5 SEDIMENTATION RATE

Sedimentation of organic material to the seafloor near fish farms is dependent on farm practices, bathymetry, and oceanographic variables. Exceedance of local and site specific sedimentation rate could be used as an indicator of possible excess organic loading to the seafloor. On the Atlantic coast, Hargrave (1994) concluded that when the sedimentation rate to benthic habitats exceeded one g C m^{-2} d^{-1}, enrichment effects were observed on organisms.

Three reliable estimates of natural sedimentation rates in B.C. waters ranged between 0.1 and 0.8 g C m^{-2} d^{-1} (Stephens *et al*, 1967 - Departure Bay near Nanaimo; Sancetta and Calvert, 1988 - Saanich Inlet; Timothy and Pond, 1997-Sechelt Inlet), but there are no comparable data near fish farms in B.C. Salmon net pens also result in local increases in sedimentation of natural material because they baffle or decrease local currents. Inoue (1972 cited in Iwama, 1991) documented a 65 % drop in current velocity in a 20 x 20 x 6 m net cage (5 cm mesh) relative to the outside current. This factor might be especially important in fjords such as Knight Inlet, characterized by glacial melt water with high suspended sediment load.

Spawning areas should be viewed as fish habitats that are sensitive to excessive sedimentation and avoided when siting salmon net pens. High sedimentation rates would be particularly important for species that incubate their eggs on rocky bottoms (e.g. lingcod, which require crevice spaces for spawning) (Low and Beamish, 1978). Levels of suspended sediment 0.5 mg l^{-1} affected the survival of lingcod eggs in laboratory experiments (Morgan and Levings, 1989). Effects on fish egg incubation would likely become evident through increased egg mortality before invertebrate filter feeders were impaired. Therefore general video surveys, as proposed by Crawford *et al* (2001) and others, of the seafloor and benthic communities would not necessarily provide data for conservation of key fish habitats. Effects on invertebrates would also be specific to the particular species involved. For example polychaetes with specialized feeding adaptations such as the maldanid *Praxillura maculata* (found in Pacific region; McDaniel and Banse, 1979) would likely be impaired because their filter apparatus would clog with sediment.

3.3.6 RECOVERY RATE

One of the criteria for determining if an important change in the vicinity of a fish farm has occurred or not could be an estimate of the reversibility of change in the seafloor habitat at a particular site. For example, if the sediment layer of waste organic material and sediment was impairing survival and recruitment of invertebrates and was too thick to be mobilized by bottom currents after fish production ceased at the site, it might be considered that a recovery rate threshold had been crossed. The time scale for approaching the point when recovery would take an unacceptably long time is dependent on local site conditions and operations. It is important to determine if effects are long-term, transient, or reversible. Anderson (1996) sampled benthic community structure at six fish farms in B.C. with depth range 18 to 27 m and current speeds 0.8 to 10.0 cm s^{-1} that were abandoned between 1.3 and 50.9 months before sampling. In his interpretation of the data, Anderson developed the concept of "practical recovery time (PRT)" - " the interval from cessation of aquaculture to the time when diversity cannot be distinguished reliably from the reference value". The PRT of the six farms ranged from five months at a current-swept location to 50 months at a poorly flushed site. The concept of PRT, coupled with an estimate of waste thickness, is a possible practical approach to determining if a particular site has passed a threshold for recovery. However, because of the great variation in community structure among locations, it is likely that PRT would require site specific data. For soft sediments such as mud, recovery rate is also likely to vary with initial waste thickness and depth within the sediment. For example, at a fallowed net pen location in swNB, sediments at six out of seven stations showed evidence of recovery of sulfide values at all depths in the sediment (0 - 6 cm) (Wildish *et al*, 2001a). At a seventh station, levels of sulfides at the 4-6 cm horizon in the sediment increased over the 200 d fallowing period. Data were not provided on the vertical distribution of fauna (e.g. burrowing invertebrates) but it is possible that the high levels of sulfide measured (1 2000 µ M) were limiting the burrowing depth and bioturbation capacity of the organisms.

3.3.7 CARBON

Environmental systems are dynamic recipients, processors, and producers of organic carbon. What varied compartments do depends on fluxes of carbon, but also depends on the setting - that is, sediments do different things than water (Iseki *et al*, 1984) and there is variation among sediment types that need to be accounted for as well. Although carbon fluxes in sediment and water have been examined at the basin-wide level (e.g. Beaufort Sea; Macdonald *et al*, 1998) there are no data from B.C. at the embayment scale. Information at this scale is needed to determine threshold criteria for carbon for identification of habitat loss at fish farms, as pointed out above.

Excess organic carbon in sediments has been hypothesized as a limiting factor for invertebrates in the vicinity of salmon net pens. According to Brooks' (2001b) data from a B.C. net pen operation, if total volatile solid concentrations do not exceed approximately 2.6 % (or about 1.3 % C) at 30 m from farm edge, the particular ecosystem and habitats he studied can assimilate wastes from 180 000 kg of salmon. No specific data were given on how reversible the habitat loss was. The results were likely site specific and could not be extrapolated to other farms with different sediment types, depths, and currents.

3.3.8 METALS

Zinc has been identified in previous studies as a contaminant introduced into the environment from fish food (e.g. Uotila, 1991). The distribution of stations with levels of Zn above AET at an abandoned fish farm was one of the variables used in mapping fish habitat effects (Levings and Sutherland, 1999; see appendix I of the present document). The toxicity of metals in sediments near fish farms is difficult to assess because their speciation, and hence toxicity, is dependent on interactions with sulfides, dissolved oxygen, pH, and other factors. Fish food pellets usually have zinc concentrations of between 125 and 134 $\mu g\ g^{-1}$ (Sutherland *et al*, 2001; Uotila, 1991).

3.3.9 DISSOLVED OXYGEN AND SEABED RESPIRATION

Dissolved oxygen (DO) in the water column and near the sediment under fish farms has been measured in several studies but levels were variable depending on site location and season and sometimes bracket natural levels. Usually data were obtained at least one metre off the bottom and therefore the BBL was not necessarily sampled. Cross (1990) reported DO levels of 3.1-3.5 mg/l near bottom at a B.C. fish farm, which would classify this location below the C class for protection of marine, non-anadromous species using the criteria described by Davis (1975). However, naturally occurring low (< 4 mg/l) DO waters are present on the west coast of Vancouver Island (Freeland and Denman, 1982) and in Queen Charlotte Strait during the late summer and early fall (Thomson, 1981).

Seabed respiration is an index of amount of oxygen demanding material, such as waste food and faecal material, being deposited on the seafloor. Hargrave *et al* (1993) measured benthic fluxes of dissolved oxygen adjacent to and under fish pens in L'Etang Inlet, New Brunswick and observed fluxes as high as 3.1 g O_2 m^{-2} d^{-1}. Although there are no data in reviewed publications on seabed respiration at or near aquaculture sites in B.C., information is available for several locations in the Pacific Northwest. At several sites in Puget Sound, Pamatmat and Banse (1969) measured *in situ* benthic oxygen demand rates in the range 0.6 to 1.2 g m^{-2} d^{-1}. Stucchi and Juahsz (1997) calculated maximum benthic uptake rates for DO in the range 0.1 to 1 g O_2 m^{-2} d^{-1} from an oxygen budget of a small bay (Minette Bay) on the northern B.C. coast.

3.3.10 ASSIMILATIVE CAPACITY

Models of varying complexities have been developed in many different jurisdictions to simulate and predict the dispersion, loading and impacts of wastes from finfish operations. They are potentially a useful management tool, but only if there is a reasonable assurance or confidence in the validity of their predictions and simulations. Often the field data required to initialize the models are unavailable or impractical to obtain. While most models have focused on specific net-pen wastes issues such as the sedimentation and dispersion of the waste solids (Gowen *et al*, 1994; Hevia *et al*, 1996; Dudley *et al*, 2000; Panchang *et al*, 1997), or enhancement of nutrient and theraputants levels in the water column (Gillibrand and Turrell, 1997), some investigators have attempted to model the assimilative capacity of the near field benthic environment or the benthic impact of salmon net-pen aquaculture.

Findlay and Watling (1997) attempt to predict the benthic impact of fish farms based on the presence of aerobic/anerobic conditions at the sediment-water interface. The fundamental premise of their model is that if the flux of oxygen to the sediments cannot satisfy the enhanced benthic oxygen demand created by the rain of organic wastes (carbon) from net-pen operations, the sediments become anoxic at the sediment-water interface and infauna are adversely affected and eventually azoic/*Beggiatoa*-mat conditions ensue. The model is multi-faceted and builds upon the parameterisation of physical, chemical and biological processes each with their own inherent assumptions. In its simplest form, the model yields an index of impact, which is the ratio of oxygen supply to oxygen demand of the sediments. If the ratio is < 1 then sediments exhibit severe impacts (azoic conditions often with *Beggiatoa*-mat end point) and if the ratio > 1 then impacts are minimal. Findlay and Watling (1997) tested their predictive model on several production sites in Maine and found qualitative agreement with the observed benthic impacts. Morrisey *et al* (2000) tested the Findlay and Watling (1997) model on salmon farm sites in New Zealand and found that model prediction of benthic impact compared reasonably well with the observed anoxic/*Beggiatoa* – mat conditions under the fish pens. Application of the Findlay and Watling model requires site specific near bottom current velocity measurements, ambient dissolved oxygen levels, and information on the production and configuration of the salmon net-pen operations. The model may be a useful tool for the prediction of impacts from salmon net-pens, but it has undergone limited testing and to our knowledge never been applied to B.C. salmon farms.

Silvert and Sowles (1996) reviewed models of environmental impact of finfish aquaculture and illustrated how these models may be useful management tools. With regards to benthic impact, Silvert and Sowles (1996) formulate the problem in terms of carbon loading and not oxygen fluxes as with Findlay and Watling (1997). They recognise that carbon by itself is not directly harmful but its degradation may have either beneficial or detrimental effects. Instead of modelling the complex physical, chemical and biological processes involved in the degradation of organic carbon and the effects of the by-products on the benthic community, Silvert and Sowles (1996) propose a simplistic uptake-clearance models for benthic carbon accumulation and for an index of benthic condition. The balance between accumulation and recovery determines the index of benthic condition. Silvert and Sowles (1996) tested their benthic index model against the scores of benthic impacts determined by the State of Maine's aquaculture monitoring program and found reasonable agreement. The models are overly simplified, but they may be readily applied, as their data requirements are minimal. Silvert and Sowles (1996) illustrate how their model might be used to evaluate proposed guidelines for finfish operations in New Brunswick, and suggest that their model could be used to draft regulations in other regions. To our knowledge this model has not been tested or used in B.C.

The province of B.C. has embarked on a model development exercise, which extends an earlier initiative of theirs, the "Modular Aquaculture Modelling System" (Chandler and Carswell 1995). Seaconsult Marine Research Ltd., under contract to the province, has developed the "Rapid Assessment Salmon Farm Model". The model incorporates a fish production model, tidal hydrodynamics and settling characteristics of organic matter and uses a geo-referenced map-based graphical user interface from which input data files are set up. The model outputs maps of the footprint of accumulated organic matter, carbon or sedimentation rate based on particular finfish farm configurations and production levels and stages. An important next step for the model is the validation of the simulated sedimentation rates with field data collected at various finfish sites. To our knowledge, the model is not in use on an operational basis.

Most models discussed above deal with the wastes and impacts from individual salmon farms, and work on scales of a few metres to several hundred metres. Few models deal with the cumulative effects of many finfish operations in a larger ecosystem to determine if the assimilative capacity of a water body is exceeded. Gillibrand and Turrell (1997) model the nutrient and chemical levels for individual Scottish sea lochs. Kishi *et al* (1994) model Mikame Bay, Japan for the cumulative effects of several yellowtail aquaculture operations on the dissolved oxygen conditions and accumulation of solid wastes in the Bay. Modelling larger ecosystems build upon the modelling of the processes at individual farms, but is based on hydrodynamic models of the larger system. Once again, validation and field measurements are essential for the testing and initialization of these models. In B.C., we have in place the backbone of tidal circulation models for large parts of the coast. From these large-scale tidal models, we can focus on smaller scale models of key aquaculture production regions as is presently being done in the Broughton region of B.C. These regional circulation models can provide managers and farm operators with information on individual sites for input into farm specific models or assist in site screening exercises. The regional models are the foundation of any further models that attempt to address the cumulative ecosystem wide impacts of aquaculture. Unfortunately, we are one or two years away from having these modelling tools and information available on this coast.

3.3.11 SEDIMENT GRAIN SIZE AND DEPTH OF ORGANIC SEDIMENT

As mentioned above (4.3.5), the baffling effect of net pens can lead to changes in the local sedimentation field. If the changes are substantial and prolonged, this could lead to change in dominant sediment type, for example from sand to mud. In this case, sediment grain size would be the appropriate indicator for loss of productive capacity from sand habitats. As mentioned, seafloor relief can also be changed by excess sedimentation and a measure of the depth of fine-grained sediment atop coarser material could be useful data. If the underlying sediment was sand/gravel then a core might be able to assess the depth of fine material. Rock would require different technology and data might be obtained by a combination of Remote Operated Vehicle (RoV) and video observations if the RoV was equipped with a depth probe on a manipulator arm. Another possible instrument for measuring depth of organic sediment would be the sediment profiling camera system (Rosenberg *et al*, 2001).

3.3.12 APPEARANCE OF BACTERIAL MATS AND BIOFILMS

The replacement of brown and green algal biofilms for whitish microbial biofilms dominated by the sulfur oxidizing bacteria (*Beggiatoa* spp) could be a useful indicator to map effects on fish habitats. The bacterial mats are visible signs of the rapid exhaustion of oxygen caused by the mineralization of excessive organic material (Meyer-Reil and Koster, 2001). Because the mats can be mapped and quantified (e.g. percent cover of seafloor) by observations from RoVs and remote cameras, they do hold promise for this purpose. However further work is needed to correlate of bacterial mats distribution with organisms.

4. Conclusions and Recommendations

4.1 QUESTION A: IS A PERFORMANCE BASED STANDARDS (PBS) APPROACH ECOLOGICALLY MEANINGFUL AND HAS PBS BEEN SCIENTIFICALLY VALIDATED IN OTHER JURISDICTIONS OR FOR OTHER INDUSTRIES?

The Performance Based Standards (PBS) approach is a management technique that is used widely to deal with numerous engineering and education organizations and by a few environmental agencies. The approach is effective with the following conditions: 1. the problem has a narrow focus; 2. response to a system change is well understood by science; 3. when an effect is reversible; and 4. when there is a management response to a "trigger". We could not find scientific information that validated the use of PBS to conserve the productive capacity of bottom fish habitat in B.C. Methods need to be developed which allow PBS to be used on a variety of sediment types with an improved mapping scheme, appropriate for mapping fish habitat. In our view, PBS are not effective for integrated coastal management, which is the direction that DFO scientists have recommended for the Department. A system that allows for the use of multiple indicators and allows discretionary use of a variety of sampling scales should be developed for B.C. coastal habitats and ecosystems supporting finfish farms and other industries.

4.2 QUESTION B: ARE THE CHEMICAL SURROGATES AND SAMPLING METHODS CURRENTLY BEING USED IN IMPACT ASSESSMENT AND MONITORING IN B.C. PROVIDING MEANINGFUL INFORMATION ABOUT THE ECOLOGICAL CONDITION OF THE ENVIRONMENT NEAR FINFISH FARMS? WHAT ARE THE CHEMICAL SURROGATES AND SAMPLING METHODS CURRENTLY BEING USED?

According to the 2002 Draft Aquaculture Waste Control Regulation and Compliance Strategy (BCMWLAP 2002), $S^{=}$ is one of the key chemical surrogates to be used in impact assessment and monitoring of wastes from finfish aquaculture operations in British Columbia. Taken alone, $S^{=}$ measurements do not necessarily provide meaningful information about the loss of productive capacity on the seafloor, as the effects of $S^{=}$ on aquatic organisms are influenced by interactions with other physicochemical parameters (e.g., anoxia, metals). Moreover, benthic organisms in coastal B.C. ecosystems may be adversely affected by sediment $S^{=}$ concentrations lower than the proposed 1 300 µM threshold, so that $S^{=}$ standards are likely inadequate to prevent loss of productive capacity near finfish aquaculture operations. We recommend that monitoring guidelines include other physicochemical and ecological parameters.

4.3 QUESTION C: WHAT ARE THE RECOMMENDED PARAMETERS AND APPROPRIATE THRESHOLDS TO INDICATE THAT AN IMPORTANT ECOLOGICAL CHANGE HAS OCCURRED? CONSIDERATION SHOULD BE GIVEN TO SPATIAL AND TEMPORAL FACTORS AS WELL AS CRITICAL VALUES OR RANGES OF VALUES FOR THESE PARAMETERS.

The choice of parameters and thresholds to indicate that an important ecological change has occurred from salmon net pens is dependent on the policy objectives that managers are implementing for a particular habitat or ecosystem. The objectives will determine the spatial and temporal extent of the change and the scale at which it is assessed. For example if the objective is to avoid loss of productive capacity, parameters and thresholds need to be mapped using methods that can detect fish habitat loss at 1: 5000 scale (50 m length scale). As a first principle, we would not recommend that a single number for any parameter be used as a threshold value. The following is a list of some potential indicators that could be used in a multiple indicator scheme; toxicity, area of seafloor affected, reduced sediment relief, biodiversity, sedimentation rates, recovery rates, sediment carbon, metals, dissolved oxygen and seabed respiration, assimilative capacity, sediment grain size and depth of organic sediment, and bacterial and algal biofilms. Research recommendations to provide data on these topics are given in Appendix II. As data are provided from research and monitoring projects related to fish farming in B.C., we suggest that a scientific workshop be convened to discuss the results and variables used in the work. The recommendations for variables and methods from this workshop should be subjected to the peer review process used by scientific journals.

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7. List of Tables

8. List of Figures

9. Tables

Table 1. Areas of society and technology that use Performance Based Standards as a management procedure. The list shows 20 topics identified from the first 100 "hits" in a general internet search.

Juvenile correction and detention facilities
Teaching (all grades and post secondary)
Reading
Emergency response
Judicial performance
Truck size and weight regulations
Bus performance
Aquaculture in British Columbia (B.C. Govt website)
B.C. Salmon Farmers Association
General work performance
Animal care
Aviation safety
Respiratory devices
Public health agencies
Electronic equipment
Decontamination devices
Fibre production by a forestry company
Turbine Engines
Process Safety Requirements
Technology Specialists for Council for Exceptional Children

Table 2. Characterization of the two sites sampled on 9 June 1999 in Passamaquoddy Bay, Bay of Fundy. For the dominant species (present in >8 replicates per site), the median and range of density per replicate core are indicated (from Wildish *et al*, 2001).

Variable	Farm	Reference
Eh_{NHE}, mV		
Median	-141.5	-21.5
Range	-95.0 to –174.0	+9.0 to –54.0
Sulphide, μM		
Median	12 200	1625
Range	4200 – 21 600	319 – 5710
Macrofauna		
Total species	10	43
Dominant species		
Capitella capitata	128, 28 – 177	0, 0 – 52
Mediomastus ambiseta	0	19, 0 – 51
Aricidea sp.	0	10, 2 – 28
A. quadrilobata	0	3, 0 – 12
Ninoe nigripes	0	4, 0 – 13
Tharyx sp.	0	4, 0 – 15
Micrura sp.	0	3, 0 – 6
Paraonis fulgens	0	2, 0 – 9
Lumbrineris impatiens	0	2, 0 – 6
Anobothrus gracilis	0	2, 0 – 7
Cylichna alba	0	9, 0 – 17
Yoldia sapotilla	0	2, 0 – 7

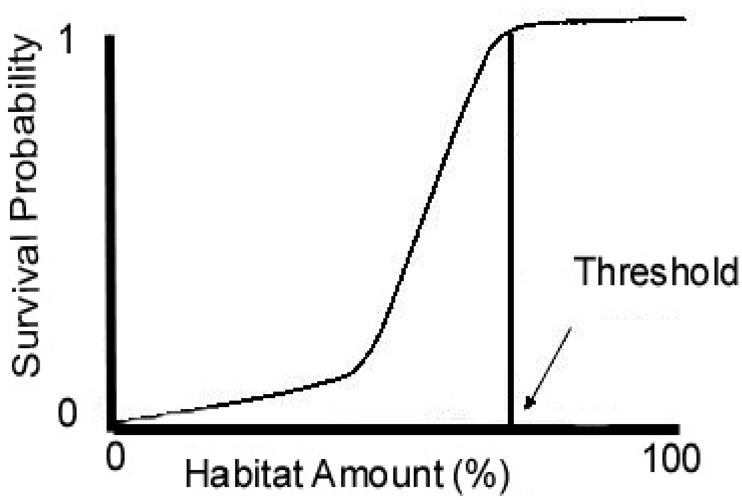

Fig 1. Illustration of an extinction threshold for a single species using a specific habitat (from Fahrig, 2001).

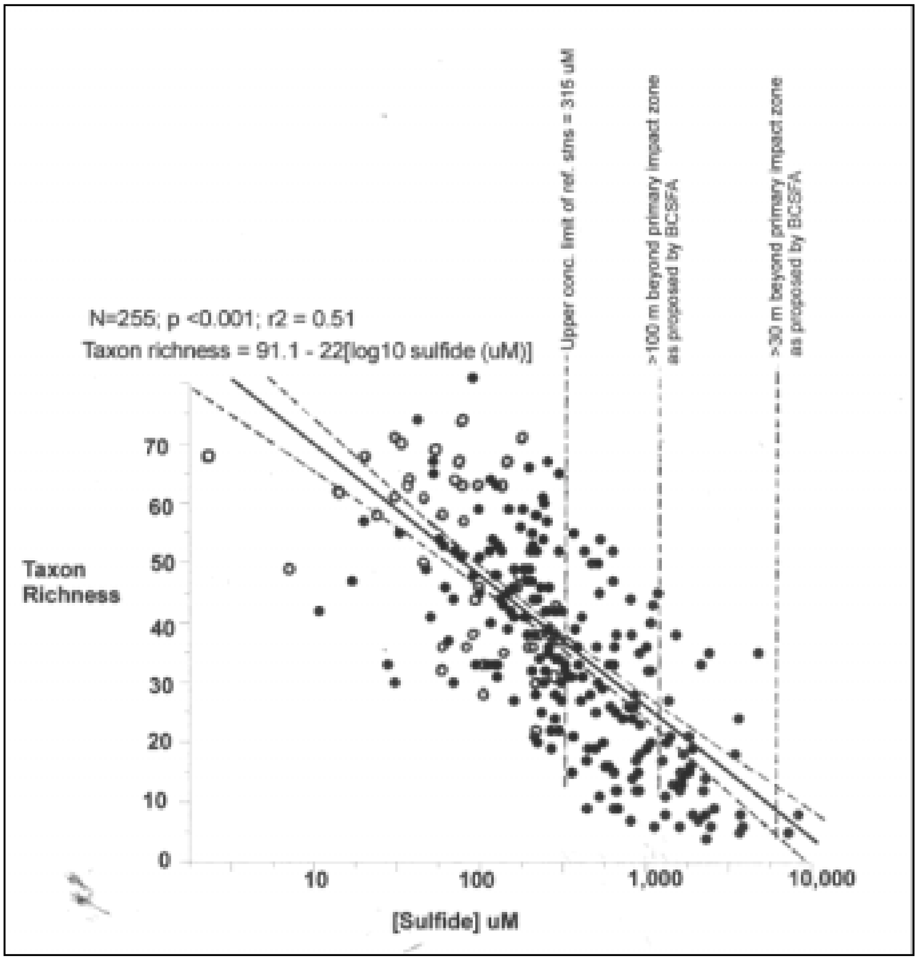

Figure 2. Relationship between benthic community impairment (loss of biodiversity) and sediment sulfide levels. Open symbols are data for reference sites (at or greater than 300m). From Bright (2001) with minor modification; the cited author in turn adapted this plot from Brooks (2001).

APPENDIX I

Effects of aquaculture operations on fish habitat at an abandoned salmon net pen operation in the Broughton Archipelago, British Columbia

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Objectives and Background

As requested by staff in the Habitat and Enhancement Branch (HEB), on August 11 and 12 1999 the authors conducted an ecological survey of an abandoned net pen operation in an embayment in the Broughton Archipelago, British Columbia. The location was used for rearing salmon between May 1990 and September 1998. The purpose of the survey was to determine if the productive capacity of the seafloor fish habitat had been changed and to obtain evidence on habitat alternation, disruption, or destruction (HADD). Aerial photos obtained in 1993, 1994, 1995, and 1996 showed the number of pens changed between years, resulting in variation in the farm's surface area (1993 - 6150m^2; 1994 - 33750 m^2; 1995 -8750 m^2; 1996 -9375 m^2).

This document is an abridged and updated version of our "expert report" which was given to HEB staff (November 1999) and subsequently used by them in internal discussions of fish habitat management policies.

Survey methods

POSITIONING

Stations were chosen based on the known position of the fish farm in the embayment. The marked position of the farm in 1998 as shown on a hydrographic chart was used to initially plot the stations within an electronic chart aboard the sampling vessel. The station positions were then modified based on the location of the farm in an aerial photo taken in 1996, which showed the pens had been moved seaward. Figure 1 outlines stations aligned along two intersecting transect lines, 8 on an approximate east-west transect and another 5 on an approximate north-south transect. The east-west transect was aligned to avoid abrupt changes in seafloor depth due to a narrow channel running along the axis of the embayment. Originally each transect was to contain 7 stations, however, one transect was shortened due to a steeply sided rock bottom. A total of 16 stations were sampled. Because the seafloor sloped from the bay to the edge of an adjacent channel, sample depths ranged from 29 m to 38 m. One station, common to both transects, was located at the centre of the former net pen complex. Three additional stations, also aligned east-west over a similar depth gradient, were sampled at a reference location about 800 m north of the abandoned fish farm location. This location was chosen because it was also on the south side of a point of land extending into the adjacent channel where any tidal current eddies might be similar to those in the embayment where the fish farm had been located. Stations from the fish farm area were designated as "C" and those from the reference location "R". Stations were about 30 m apart at the farm site and about 20 m apart at the reference location. Samples were obtained with a 0.04 m^2 Ponar grab, deployed by hand. Depth was measured at the same time that the grab struck the bottom, using a Lowrance sounder (Model X-85), taking care the nylon sampling line was vertical.

SAMPLE TREATMENT

After the Ponar grab was retrieved, contents were emptied carefully into a plastic tray to minimize disturbance of the intact samples. Only intact samples were retained. The Ponar grab was washed thoroughly with surface seawater between collections. Observations of intact samples consisted of sediment colour, smell, appearance of biofilms[1] and/or bacterial mats. When condition of the sample permitted, a vertical profile through the sediment was made and the colour and texture of the sediment was recorded. A plastic scoop was used to obtain three separate subsamples from the intact surface of the sediment that were analyzed for total sediment carbon and nitrogen content, sediment grain size, and sediment metal content. About 200 ml of each sediment subsample was placed in a previously unused sample jar or bag, which was then sealed and labeled with a waterproof felt pen. The samples were sealed with tape before placing in a cooler containing an ice pack. The remainder of each grab sample was placed in individual plastic buckets. Each grab sample was then sieved with seawater through a 1 mm size screen mesh and living organisms were picked from the screen using forceps and preserved in 10% formalin. The presence or absence of live macroscopic organisms was noted for each sample. The organisms and unsorted material retained on the sieve from each sample were then placed in a plastic jar with 10% formalin and rose bengal. In the laboratory, using a Wild M5 Stereomicroscope, these samples were sorted to major taxonomic groups.

After completion of the survey and return to Port McNeil on August 12, the sediment samples were transported to the West Vancouver Laboratory and placed in a cool, dark room at 4 °C. On August 13, they were taken to Environment Canada's (EC) Pacific Environmental Science Centre in North Vancouver. Samples were then analyzed for total

[1] Biofilms consist of high densities of photosynthetic benthic diatoms or bacteria that form a mucous matrix skin at the seabed surface.

carbon, total nitrogen, and metal content, as well as grain size. Standard methods used by EC were used in the analyses.

MAPPING METHODS

Initially, an Arcview GIS presentation was used to compute the area of a polygon of affected area on the seafloor. The boundary of the polygon was determined by the apparent absence of invertebrates in particular stations during the field sorting.

Further comparative analyses of six variables measured in the study (percent silt/clay, sediment nitrogen, quantitative invertebrate (fish food), bacterial biofilm presence or absence, algal biofilm presence or absence, zinc concentrations) were conducted using a contour software package (SURFER). The location of the farm as it was shown by CHS in 1998 was used with a base map and an arbitrary boundary.

Results and discussion

A. ENRICHMENT BY ORGANIC WASTE

Observations in the field (Table 1) as well as chemical analyses of the sediment (Table 2) showed that benthic habitats were disrupted by excess organic material and chemicals generated during the period of salmon farming operations. The food pellets found on the bottom at this site in 1997 by Deniseger and Erickson (1998), as well as faecal material from the fish, were the sources of these materials**.** The study area is characterized by weak tidal currents and is not known as an area of strong water movements. During our survey a tide change of about 2.7 m occurred, but surface currents of less than 25 cm s^{-1} were observed based on the drift of floating objects. The dispersion of waste material surrounding the farm system was likely reduced due to the baffling of the net-pen system by surface current and wave activity. This dampening of current and wave action will enhance the deposition of farm-derived material within a localized region associated with the net-pens.

The spatial distribution of the eight samples characterized by heavy H_2S odour (C1, C2, C4, C4+, C5, C6, C7, C10), coincided closely with the stations where live organisms were not observed in the field sorting. These were the same stations where laboratory sorting subsequently showed invertebrate abundance was reduced relative to reference stations present in low abundance (Table 3) and with the location of the farm when it was operating. As an example, the abundance of polychaetes ranged from 4-19 per sample at these 8 stations compared to 31-75 per sample at reference stations or those on the peripheral ends of the transects.

The polygon enclosing the affected stations represented an area of approximately 8200 m^2 (0.82 ha). In addition, bacterial mats, typically found on organically enriched sediments, were observed at stations C4, C5, C6, C7 and gel-mud characterized the sediments at stations C4, C4+, and C5. Conversely, at many of the less affected stations (C8, C9+, C10, C11) and all of the reference stations, a green brown biofilm of diatoms was observed on the sediment, indicating normal or healthy conditions at the sediment-water interface. However, the biofilm did not penetrate the underlying black, anoxic sediment column at the least affected stations. Total sediment nitrogen values > 0.50 % were observed at all stations except C3+, C11, and C12. These stations, as well as those from the reference locations, were characterized by lower sediment nitrogen values (0.31-38 %). Total carbon values at the affected stations were > 5.50 %; all other stations in the survey showed lower values for total carbon, especially the reference stations (range 3.68 to 3.80 %). The silt and clay content of most stations at the farm site was higher than the average value at the reference stations (62.3%), indicating the fish farm nets had had a baffling effect on the local sedimentation field. Stations C3+ and C11 were the exception, characterized by coarser sediments as they were at shallower depths influenced by nearshore processes.

The capacity of sediments to biodegrade organic waste from fish farms can be exceeded in poorly flushed areas, as shown by studies in British Columbia (e.g. Cross, 1990), Puget Sound (Weston, 1990), and elsewhere in the world (Levings, 1994). A number of factors prevent the normal colonization of invertebrates in organically enriched sediment; particularly 1) the absence of oxygen within the sediment 2) presence of toxic H_2S 3) bacterial mats that provide poor feeding conditions relative to algal biofilms, and 4) textural aspects of gel-mud may prevent colonization. Sediment bioassays were conducted by Deniseger and Erickson (1998), using the amphipod *Eohaustorious washingtonianus* and sediment from the same location. Out of the 9 sediment samples that were toxic, 8 exhibited moderate to extreme H_2S levels, confirming the pattern of habitat effects that we observed in our field observations.

B. ZINC IN SEDIMENTS

Zinc has been identified in previous studies as a contaminant introduced into the environment from fish food (e.g. Uotila, 1991). At this location near Gilford Island, zinc levels were well above those found at the reference site ($\leq 65\ \mu g\ g^{-1}$), and were highest ($>200\ \mu g\ g^{-1}$) at stations C1, C4, and C4+, located directly below the previously-operated farm. The probable source of zinc was fish food used at the farm. Fish food pellets usually have zinc concentrations of between 125 and 134 $\mu g\ g^{-1}$ (Sutherland *et al*, 2001; Uotila, 1991). The threshold effect limits for biological effects of zinc in sediment used by Environment Canada (Environment Canada, 1995) is 123 $\mu g\ g^{-1}$; most of the sediment samples collected from the study area exceeded this value.

C. ESTIMATION OF HADD AREA

The area of seafloor affected by the fish farm waste varied according to the variable used and the computational method. When we simply drew a boundary around the affected stations, as estimated by observations in the field, the area computed with a GIS program was 0.82 ha, as mentioned above. However, later computations using a contouring program (SURFER) and six variables (percent silt/clay, sediment nitrogen, invertebrate abundance, bacterial mats, algal biofilms, and zinc) varied by as much as a factor of 50 (Table 4). Invertebrate abundance (50% decrease relative to reference stations, bacterial mats, and algal biofilms) were within the same order of magnitude as the simple polygon. These results are only relative to one another and do reflect the real spatial distribution because of the arbitrary nature of basic map data (farm location, 30 m boundary). However, they do show how estimates of the area of a HADD will vary depending on the variable chosen to evaluate it.

D. DISRUPTION OF FISH HABITAT AND POTENTIAL FOR RECOVERY

The absence of invertebrate fish food organisms and significant degradation of the sediments at this location represents an alteration or disruption of fish habitat caused by the aforementioned factors. The types of invertebrates found in the reference stations, as well as stations in the vicinity of the abandoned net pen site outside of the azoic area, were typical of those used as food by fish living on the bottom in these waters. These invertebrates were absent from about 0.82 ha of the sea floor and this is a minimum estimate because our survey was limited in spatial coverage. The shallow waters of the channels in the Broughton Archipelago are recognized as habitat for demersal fish (species which live on or near the seabed) which feed on invertebrates living in the sediment. For example, Pacific cod (*Gadus macrocephalus*), lemon sole (*Pleuronectes vetulus*), and rock sole (*Pleuronectes bilineata*) were recorded from Broughton Channel, a body of water contiguous with Retreat Passage, by Levings and Chilton (1969). These three fish species are known to feed on amphipods, polychaetes, and bivalve molluscs, all invertebrates that were excluded from the area of organic enrichment. Dungeness crabs also use invertebrates as food, especially bivalve molluscs.

It is likely that the fish habitat effects we observed at the abandoned net pen site will persist for at least another few years, and possibly longer. Even though the farm ceased operations in September 1998, 11 months before our survey, all of the environmental factors mentioned above slowed recolonization of sediment by inhibiting the survival of invertebrate larvae settling on the bottom and discouraging the movement of adult animals from adjacent areas. It was clear that impacts on fish habitat were still evident in August 1999. Sediment conditions were similar to those observed by Deniseger and Erickson (1998) during their last survey of the area, in August 1997. The oceanographic conditions at this location, especially slow currents and shallow depth, mitigate against rapid recovery at this particular site. Anderson (1996) found that between 1.3 and 50 months were required for reversal of organic enrichment effects from fish farms in coastal BC, with the maximum time needed for sites characterized by reduced current action. Some sites were not fully recovered after 50 months.

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Tables

TABLE 1.: SAMPLING DEPTH, SEDIMENT COLOUR AND SMELL, AND OBSERVATIONS ON BIOFILMS, BACTERIAL MATS, TIME OF SAMPLING (PST) AND SEDIMENT CHARACTERISTICS.

Station number	Water Depth (m)	Sediment Colour	Sediment Smell	Biofilm presence	Time (PST), Observations on sediment profile characteristics	Observations on fauna
C1	36.6	Orange-white	Heavy H_2S	Bacterial mat	1750.	No living macrofauna observed
C2	31.7	Green-brown	Heavy H_2S	diatoms	1830. Black mud under biofilm. Twig in sample.	No living macrofauna observed
C3+	31.1	Whitish shell hash and sand	No H_2S	No	1845. Shell hash and sand/mud.	Polychaetes and amphipods observed during sieving
C4	32.9	Orange-white	Heavy H_2S	Bacterial mat	1915. Patches of orange-white mat, black gel-mud underneath. Small twig in sample.	No living macrofauna observed
C4+	33.2	Green brown	Heavy H_2S	diatoms	1900. Grey black gel-mud under biofilm.	No living macrofauna observed
C5	36.0	Orange-white	Heavy H_2S	Bacterial mat	1945. Continuous orange-white mat. Unconsolidated mud.	No living macrofauna observed
C6[1]	38.4	Orange white	Heavy H_2S	Bacterial mat	1958. Continous orange-white mat, est 1 mm thick. Moderately consolidated mud.	No living macrofauna observed

C7[2]	31.1	Green, traces of orange-white	Heavy H_2S	Diatoms with trace of bacterial mat	0800. Traces of orange-white mat. Biofilm almost continuous. Olive-grey mud, consolidated underneath black gel-mud.	No living macrofauna observed
C8	32.6	Green-brown	Light H_2S	diatoms	0811. Biofilm continuous. Grey-black mud underneath	Numerous bivalves and polychaetes observed
C9+	34.1	Green brown	Light to heavy H_2S	diatoms	0828. Biofilm continuous. Grey-black-olive underneath. Moderately consolidated mud.	Several bivalves and polychaetes observed
C10	30.8	Green brown	Heavy H_2S	diatoms	0838. Biofilm continuous. Black mud underneath. Moderately consolidated mud.	One polychaete observed
C11	29.0	Brown	Low to moderate H_2S	no	0849. Gravel/shell debris, some bark.	Several amphipods and polychaetes observed.
C12	30.5	Green brown	Light to moderate H_2S	Diatoms	0901. Olive-grey green mud beneath biofilm. Moderately to well consolidated mud.	Several polychaetes observed

R1	35.1	Green brown	No data	diatoms	0950. Olive coloured mud beneath. Moderately to well consolidated mud.	Maldanid polychaetes in tubes observed as well as bivalves
R2	37.8	Green brown	No H_2S	diatoms	0940. Olive-grey sediment beneath biofilm. Moderately to well consolidated mud.	Several polychaetes, bivalves, and a crab observed.
R3	30.8	Green brown	No H_2S	diatoms	1005. Olive green sediment beneath biofilm	Numerous bivalves, gastropods, brittle star, one crab and a polychaete observed

Footnotes
[1] Last sample on August 11 1999
[2] First sample on August 12 1999

TABLE 2. TOTAL ORGANIC CARBON AND NITROGEN, ZINC, AND GRAIN SIZE

Station number	Total nitrogen (%)	Total Carbon (%)	Zinc ($\mu g\ g^{-1}$)	Percent silt and clay
C1	0.74	8.09	308	72.62
C2	0.69	7.33	150	73.63
C3+	0.37	9.52	150	49.71
C4	1.20	15.19	256	75.45
C4+	0.94	9.39	316	63.49
C5	1.10	11.04	98	68.20
C6	0.58	7.30	192	74.43
C7	0.59	6.87	100	82.26
C8	0.50	4.91	94	83.47
C9+	0.51	4.83	160	87.21
C10	0.52	6.20	100	83.94
C11	0.40	7.55	88	48.61
C12	0.45	4.85	88	81.72
R1	0.35	3.78	53	60.48
R2	0.38	3.68	65	66.39
R3	0.31	3.80	54	59.93

TABLE 3. COUNTS OF INVERTEBRATES FROM STATIONS AT AN ABANDONED NET PEN REARING SITE AND A REFERENCE LOCATION IN THE BROUGHTON ARCHIPELAGO. DATA ARE NUMBER OF ORGANISMS PER PONAR GRAB (0.04 M^2).

Station	Class Polychaeta	Class Oligochaeta	Class Bivalvia	Class Gastropoda	Class Scaphopoda	Phylum Crustacea	Class Ophiuroidea	Phylum Nematoda	Phylum Bryozoa	Class Hydroza
C-1	4	19	5	1	0	1	0	0	0	0
C-2	18	0	3	0	0	2	0	23	0	0
C-3+	14	0	2	1	0	1	0	33	0	0
C-4	9	10	2	0	0	2	0	6	0	0
C-4+	9	0	8	0	0	0	0	4	0	1
C-5	15	0	2	1	0	1	0	0	1	0
C-6	25	0	1	1	0	4	0	0	1	0
C-7	22	0	5	0	0	3	1	5	0	0
C-8	54	0	17	1	0	25	0	3	0	0
C-9+	75	0	43	2	0	19	0	2	1	1
C-10	19	0	6	1	0	2	0	38	1	0
C-11	33	0	17	0	0	32	0	92	0	0
C-12	31	0	24	2	0	8	0	4	1	0
Station	**Class Polychaeta**	**Class Oligochaeta**	**Class Bivalvia**	**Class Gastropoda**	**Class Scaphopoda**	**Phylum Crustacea**	**Class Ophiuroidea**	**Phylum Nematoda**	**Phylum Bryozoa**	**Class Hydro**
R-1	53	0	199	5	17	7	3	29	0	0
R-2	75	0	149	0	7	23	2	21	0	0
R-3	72	0	161	2	22	23	4	13	0	0

TABLE 4. A COMPARATIVE ANALYSES OF POSSIBLE HADD AREAS (M^2) USING SURFER WITH VARIOUS VARIABLES WITH DATA FROM A SURVEY OF AN ABANDONED SALMON NET PEN OPERATION IN BA, AUGUST 1999 (TABLES 1-3).

Parameter	**Area (m^2)**
Percent silt/clay[1]	20718
Sediment nitrogen[2]	10858
Fish food relative to outer boundary stations: 50% reduction[3]	5071
Fish food relative to reference stations: 20% reduction	21868
Fish food relative to reference stations: 90% reduction	4040
Bacterial mat present	4316
Algal biofilm absent	3766
Zinc[4]	459

Footnotes

[1]percent silt/clay>mean of reference stations (62%)
[2]percent sediment nitrogen > by at least 50% of reference station values (0.52)
[3] outer boundary stations used were those at the ends of the C transects
[4] >123 $\mu g g^{-1}$.

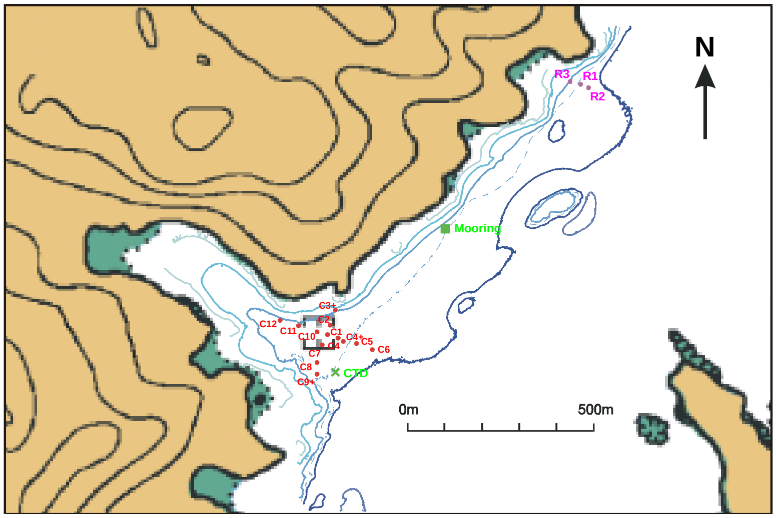

FIGURE 1. TRANSECT PATTERN FOR STATIONS SAMPLED AT AN ABANDONED FISH FARM AND A REFERENCE LOCATION, BROUGHTON ARCHIPELAGO. THE POSITION OF THE FARM AS MAPPED BY CHS IN 1998 (BLACK SQUARE) AND TWO LOCATIONS FOR OCEANOGRAPHIC SAMPLING (GREEN SYMBOLS) ARE ALSO SHOWN.

Appendix II

RESEARCH RECOMMENDATIONS

1. Investigate geochemical conditions (hypoxia, sulfides, redox, etc) and organisms in the benthic boundary layer under and near fish farms. This will require development of specific instruments or modification of existing equipment.

2. Determine effects of fish farm waste and sediment on incubating eggs of demersal and benthic fish.

3. Document reversibility of loss of productive capacity owing to net pen operations.

4. Develop methods for assessing cumulative effects of salmon net operations together with other seafloor disruptions such as wood waste and trawling.

5. Develop tracers for far field effects.

6. Continue development of assimilative capacity models.

7. Synoptic investigation investigation of sedimentation rates in representative coastal Areas.

8. Contribution of algal biofilms to productive capacity and effects of bacterial biofilms on invertebrate production.

9. Test the practicality of using a grid system to map sediments in a farm lease including habitats under pens.

10. Investigate how changes in key invertebrate species can affect productive capacity.