PHYSICO-CHEMICAL ASPECTS OF SEDIMENT RECOVERY AT TWO ABANDONED SALMON FARM SITES IN BRITISH COLUMBIA

by

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B. Sc. Honours, Queen's University, 1999

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Department of Chemical and Biological Engineering

Bio-Resource Engineering Program

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

April 2003

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Abstract

The deposition and accumulation of fish farm waste discharges within marine sediments can induce geochemical and physical changes which may inhibit the survival of the natural benthic community. There is no primary literature published on the topic of benthic habitat recovery following fish farming activity in British Columbia. Furthermore, there is no standardized set of methods that has been recommended for determining rates and patterns of benthic habitat recovery at abandoned fish farm sites. Physical and chemical indicators of benthic impact have been determined to be cost and time-effective alternatives to biological indicators. Therefore, the primary focus of this research was to investigate physico-chemical aspects of sediment recovery in the proximity of two abandoned salmon farm sites in British Columbia. The results of this investigation were used to recommend a sampling design, data analysis methods, and sensitive indicators appropriate for determining spatio-temporal recovery rates that can be used to develop falling criteria for sites characterized by similar substrate, hydrography, and production levels.

The abandoned farm at one site operated as a low production farm for 11.5 years, and was located within an open, silty-sandy bay where the current speeds were slow, but the water column was considered to be well-mixed. The abandoned farm at another site had operated as a high production farm for 8.5 years, and was located in a sheltered, muddy bay with slow current speeds. Sediment grabs were collected at each site in order to measure physico-chemical parameters within the top two centimeters of sediment. Sediment cores were also collected at each site in order to measure profiles of sediment chemistry. Grabs and cores were collected at the low production site at 1, 3, 8, and 11 months following site abandonment. Grabs were collected at the high production site at 11, 24, and 35 months following site abandonment, and cores were collected at 36 and 40 months. Transects of stations were sampled with the objective of obtaining reasonable spatial coverage at each site. Physico-chemical parameters were compared with existing sediment quality guidelines, proposed impact and toxicity thresholds, and background values in order to determine if the sediments exhibited signs of impact or recovery. Statistical and mapping analyses were used to assess impact and recovery, as well as to establish three separate tiers of sensitive indicators (based on various time and budget allowances) that should be measured during recovery assessments at similar abandoned fish farm sites.
At the low production site the actual effects to the benthic environment due to deposits of organic fish farm wastes were not significant, despite organic matter accumulations detected immediately following site abandonment. Copper levels near the farms, however, were above Environment Canada's recommended sediment quality guidelines throughout the 11-month study period. Tier one recovery indicators (all valid recovery indicators) identified at the Chained Islands site were total carbon, organic content, organic carbon, nitrogen, chlorophyll, copper, zinc, porosity, bulk density, redox potential, and sulphides.

At the high production site, fish farming activity had significant effects on the benthic environment both within the vicinity of the farm, as well as up to several hundreds of meters away. Organic matter, copper, zinc, and anaerobic sediment conditions at the farm site had not yet fully recovered by the conclusion of the study, approximately three years after the site had been abandoned. Tier one recovery indicators identified at the Carrie Bay site were organic C:N, organic carbon, organic content, nitrogen, total carbon, inorganic carbon, copper, zinc, silicon, fine sand, very fine sand, coarse sand, silt, clay, medium sand, redox potential, and sulphides.

An effective method for assessing physico-chemical aspects of recovery at abandoned fish farm sites was determined to be a combination of traditional statistics (descriptive and inferential), contour mapping, and GIS analysis. It was recommended that in order to further understand recovery at fish farm sites in British Columbia for the purposes of developing adequate fallowing times and conditions, it also would be useful to define the spatial extents of the impacts and the rate of recovery at various sites. A systematic grid was proposed as a sampling design, and contour mapping and GIS analysis were recommended as effective data analysis methods for determining the zone of impact and monitoring its variation over time.

It was recommended that further research be performed into the mechanisms of sediment recovery at fish farm sites in British Columbia. Additionally, research on the toxicities of sediment sulphides and heavy metals within specific sediment environments needs to be further investigated. Confounding factors including grain size, organic matter, and sediment gases may significantly influence toxicity thresholds. If toxicity guidelines can be established for different sediment habitats, a more solid basis can be established for performing comparative analyses between recovering sites and background conditions. This study showed that the recovery rates of anoxic conditions and potentially toxic metals in sediments may be slow, and it is unclear whether or not certain sites may ever actually recover to a natural, pre-farming state.
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Acknowledgements

There are a number of people who have been a great source of help to me throughout the course of this project. I would like to take this opportunity to extend my sincere appreciation to them.

My participation in this project would not have been possible without the Department of Fisheries and Oceans, which provided the project idea and design, and contributed funding to support my research. I would like to especially thank my supervisors Dr. Terri Sutherland and Dr. Colin Levings, who provided me with recommendations and a wealth of knowledge and resources. I would also like to thank all of the DFO personnel who tirelessly contributed their time and energy on our numerous sampling trips, come rain, wind, or snow: Shane Petersen, Beth Piercey, Stacey Ong, Rod Davis, Jim Helfield, Mike McDermid, and Karen Barry. And three-cheers to the captains and crew of the Canadian Coast Guard vessels for keeping us on station!

I would also like to extend a warm thank you to my UBC supervisor, Dr. Royann Petrell, for her ability to rejuvenate and remotivate me in my moments of mental stagnancy and defeat. Her guidance and continual support have been a source of immense strength to me throughout my two and a half years in the program. Thank you also to Dr. Sheldon Duff, my fourth committee member, who was objective, reassuring, and provided constructive advice throughout the project.

I would like to also thank Dr. James Dalby (Ministry of W.L.A.P.) as well as the operators of both abandoned fish farms for kindly and cooperatively providing very valuable information on the details of farm production and hydrography at both abandoned fish farm sites. I am also grateful to the statisticians who provided me with invaluable statistical advice and guidance: Dr. Kozak (UBC), Dr. Lemay (UBC), Dr. Connor (SFSU), and Dr. Petkau (UBC).

I would like to take this opportunity to thank Jonathan Frantz for his unfailing love, companionship, and comforting shoulder. Despite the 'nerdy-scientist' cracks (not funny), he gets a big gold star for trying hard to restrain himself from continually asking the groan-inducing "So, how's the thesis going?" Also, a special thank you to my parents, Alan and Lola, for responding to every single one of my email rants with nothing but encouragement. I also owe many thanks to my two scrupulous editors, Lola Mehlenbacher and Mark Covvey. And, finally, my heartfelt appreciation to all the other friends and family who kept me bathed in love, support, and laughter!
1 Introduction

The focus of this research was to investigate physico-chemical aspects of sediment recovery at two abandoned salmon farm sites in British Columbia.

1.1 Background

The deposition and accumulation of fish farm waste discharges within the benthic environment can induce geochemical and physical changes to the sediments which may inhibit the survival of the natural benthic community (Brooks, 2002; Erickson et al., 2001; Pawar et al., 2001; Christensen et al., 2000; Karakassis et al., 1999; Mazzola et al., 1999; Findlay and Watling, 1997; Hargrave et al., 1997; Anderson, 1996; Findlay et al., 1995; Henderson and Ross, 1995; Tsutsumi, 1995; Hargrave et al. 1993; Ye et al., 1991; Cross, 1990; Weston, 1990). If fish farm wastes settle onto the sediments, organic enrichment conditions may follow, characterized by stimulated microbial activity, oxygen uptake and reduction, and in extreme cases anoxia and the eventual anaerobic release of sediment gases such as hydrogen sulphide (Wildish et al., 1999; Zobell, 1946). Simultaneously, the benthic community may begin to change, often becoming dominated by opportunistic species described by some as being pollution-tolerant (Pearson and Rosenberg, 1978), and in extreme cases becoming azoic (Brooks, 2002; Hargrave et al., 1997; Anderson, 1996; Brooks, 1996; Findlay et al., 1995; Henderson and Ross, 1995; Ye et al., 1991; Cross, 1990; Aure et al., 1988; Brown et al., 1987). Heavy metals associated with farm production, such as copper contained in antifouling paint and zinc included in the fish feed, can also accumulate within the sediments (Brooks, 2001a; 2001b; 2001c; Erickson et al., 2002; Uotila, 1991). After the cessation of fish cultivation, many of these habitats may undergo recovery toward some natural state according to a variety of biological, geochemical, and physical processes (Brooks, 2002; Karakassis et al. 1999; Lu and Wu, 1998; Anderson, 1996; Johannessen et al., 1994; Miller-Retzer, 1994; Ritz et al., 1989). Insight into recovery within these impacted environments is invaluable to the understanding of fallowing periods necessary to facilitate regeneration of natural benthic habitats.

Research conducted in various parts of the world, including British Columbia, substantiates the concerns over the ability of benthic habitats located near fish farms to assimilate organic inputs and simultaneously sustain natural levels of biological life. Within British Columbia, the most comprehensive studies on this topic have not been subjected to anonymous peer review for
publication in the primary literature (Brooks, 2002; Erickson et al., 2001; Brooks, 2000a; Anderson, 1996; Cross, 1990). Results of international research into this issue, particularly from Norway (Johannessen et al., 1994), Scotland (Henderson and Ross, 1995), and Washington State (Brooks, 1996), provide excellent background information but cannot be used as a basis for developing fish farm fallowing practices within British Columbia, largely for three reasons: (1) the submarine geography and hydrography of coastal British Columbia are both distinct and varied with complex networks of deep fjords, open channels, narrow inlets, and archipelagos; (2) indicators of benthic recovery specifically apply to the local physical and chemical sediment climate in which they were gathered; and (3) recovery of benthic habitats at fish farm sites is poorly understood.

A series of investigations needs to be undertaken in order to characterize common site types before further benthic recovery research is performed at abandoned or fallowing fish farm sites. For each site type, a set of methods should be developed which is appropriate for determining rates and patterns of benthic habitat recovery. In keeping with this rationale, the purpose of this thesis was to investigate physico-chemical aspects of sediment recovery in the proximity of two abandoned salmon farm sites characterized by soft sediments. This study makes unique contributions to environmental aquaculture research as follows:

(1) Recommendations have been made for sampling techniques that are conducive to the collection of sediment recovery data at abandoned fish farm sites that are hydrographically similar to those assessed during the project research.

(2) Recommendations have been made for a sediment sampling design and layout that are conducive to both statistical and Geographical Information Systems (GIS) analysis of physico-chemical aspects of sediment recovery at abandoned fish farm sites that are hydrographically similar to those assessed during the project research.

(3) Recommendations have been made for a suite of sensitive indicators of benthic recovery to be used for measuring geochemical and geophysical recovery at abandoned fish farm sites that are hydrographically similar to those assessed during the project research.
1.2 Objectives

The overall objective of this research was to investigate physico-chemical aspects of sediment recovery in the proximity of two abandoned salmon farm sites characterized by soft sediments. Specific subobjectives related to the main research problem were as follows:

(1) Apply multivariate statistics and GIS analysis to sediment data in order to isolate a suite of sensitive physical and chemical indicators of sediment recovery, and analyze physico-chemical aspects of sediment recovery.

(2) Use the results of the data analysis to recommend methods for assessing physico-chemical aspects of sediment recovery at similar sites.
2 Literature Review

2.1 Benthic Impact Associated with Fish Farming Activity

Effects on the benthic environment associated with fish farming activities have been identified at several sites in British Columbia (Brooks, 2002; Erickson et al., 2001; Brooks, 2000a; Levings and Sutherland, 1999; Anderson, 1996; Miller-Retzer, 1994; Cross, 1990). Effects on the benthic environment linked to fish farming activity have also been identified internationally in Norway (Johannessen et al., 1994; Johnsen et al., 1993; Aure et al., 1988), Denmark (Christensen et al., 2000), Finland (Uotila, 1991), Scotland (Brown et al., 1987; Henderson and Ross, 1995), New Brunswick (Hargrave et al., 1997; Hargrave et al. 1993), Maine (Findlay and Watling, 1997; Findlay et al., 1995), the North Western Mediterranean (Mazzola et al., 1999), Greece (Karakassis et al., 1999; Karakassis et al., 1998), New Zealand (Kaspar et al., 1988), Australia (Ye et al., 1991; Ritz et al., 1989), Japan (Pawar et al., 2001; Tsutsumi, 1995), and Washington (Brooks, 1996; Weston, 1990).

Locally there have been some reports about fish farm sites that did not appear to demonstrate impacts to the benthic environment, even after prolonged farming activity (Anderson, 1996). Similar results have also been reported internationally in England (Frid and Mercer, 1989), Washington (Erickson et al., 2001; Brooks, 1996), and Croatia (Katavic and Antolic, 1999). Most studies of this nature attribute a lack of negative impact to bottom topography and flushing mechanisms, typically citing average current speeds greater than 10cm s\(^{-1}\) (Anderson, 1996) or 100cm s\(^{-1}\) (Brooks, 1996). Moreover, most of the sites were characterized by larger sediment grain sizes (sand, cobble, boulder), evidencing the presence of relatively strong flushing activity.

In some cases, at farm sites where organic loadings are dispersed due to currents or distance from the source of organic enrichment, shifts in benthic activity concurrent with stimulated activity have been reported (Brooks, 1996; Frid and Mercer, 1989; Aure et al., 1988).

2.2 Benthic Recovery Associated with Cessation of Fish Farming Activity

Although impacts related to active fish farming have been studied in considerable detail both within and beyond British Columbia, the mechanisms and rates of recovery of benthic habitats
and communities after site abandonment are poorly understood. Studies looking at remediation of benthic sediments have been infrequent, making it difficult to generalize about the site characteristics that might be more likely or less likely to promote recovery.

In biological terms, recovery typically refers to the restoration of the benthic community to a state considered to be "natural," where "natural" refers to healthy sediment conditions. Healthy sediments may be characteristically different than those measured prior to disturbance, or they may be similar (Anderson, 1996; Pearson and Rosenberg, 1978).

In physico-chemical terms, recovery typically refers to the restoration of sediment geochemistry to conditions which no longer significantly inhibit the survival of "natural" biological communities (Pearson and Rosenberg, 1978). The organic load in the sediments is removed by a combination of bacterial degradation, diffusion, and resuspension (Christensen et al., 2000). If impacted sediments were significantly reducing, conditions ideally would return to an oxic, sulphide-free state (Wang and Chapman, 1999; Gowen and Bradbury, 1987; Berner, 1980; Pearson and Rosenberg, 1978; Jorgensen, 1977; Zobell, 1946). Toxic components of the sediments, such as heavy metals, eventually may decline to non-toxic levels as a result of burial within the sediments, biodegradation, or outward mobilization (Chapman et al., 1998; DeLaune and Gambrell, 1996; Orson et al., 1992). Recovery in this thesis was defined using the physico-chemical definition.

2.2.1 Review of Benthic Recovery Research in British Columbia

In British Columbia, recovery studies have provided some insight into benthic habitat remediation at abandoned fish farm sites.

Miller-Retzer (1994) looked quantitatively at bottom water oxygen levels, sediment organic carbon and nitrogen, grain size, benthic faunal community changes, currents, depth, and farm operational procedures associated with impact and recovery at an abandoned farm site in Village Bay, British Columbia. The depth at the site was approximately 28 meters, the average bottom current speed was ~2cm s⁻¹, and the sediments consisted predominantly of sand. Assessments were made at 1.5, 6, and 12 months fallow and Miller-Retzer found that according to certain indicators (organic carbon and nitrogen and benthic faunal assemblages), the site remediated from
severely disturbed at 1.5 months to highly disturbed at 6 months, and by 12 months was only moderately disturbed.

Anderson (1996) made quantitative measurements of sediment sulphides, organic content, grain size, benthic faunal community changes, currents, and depths, and also observed sediment oxygen and bacterial mats associated with impact and recovery at various fallowing fish farm sites along the coast of British Columbia. This research included a continued assessment of Miller-Retzer's (1994) study site at Village Bay. In Village Bay, Anderson found that after a full 2 years fallow, conditions at the abandoned farm site had improved such that the sediments were barely distinguishable from the reference site. Elsewhere, other sites had partially or completely remediated after 3 years fallow as typically indicated by an increase in faunal diversity and species numbers, a decrease in organic content, and a recovery of sulphides and associated sulphide bacteria. Silt/clay sediment and low bottom current velocities (<1 cm s\(^{-1}\)) were found to be associated with slower recovery rates (3 or more years), while rapid recovery sites (2 or less years) were characterized by higher proportions of coarser sand and low (~2 cm s\(^{-1}\)) to high bottom current velocities (~17 cm s\(^{-1}\)). Depths at all sites were not found to influence recovery, and ranged from 12-30m.

Brooks (2002) found that sediments began to chemically and biologically remediate during the harvest period at an active fish farm in British Columbia. The site was characterized by predominantly sand and silt-clay sediments, average bottom current speeds of 3.4 cm s\(^{-1}\), and depths within the range of 39-44m. Organic carbon, evidence of hydrogen sulphide, and total volatile solids all decreased significantly and were similar to reference levels by the end of the 5 month fallow period. Faunal diversity and associated abundance increased steadily during this time also.

### 2.2.2 Review of Benthic Recovery Research Outside of British Columbia

In an Australian bay, one cage within a fish farm was allowed to fallow for 14 weeks, and Ritz et al. (1989) found that after 7 weeks, the benthic community was reaching an undisturbed state, and by 14 weeks it had returned to fairly natural conditions. However, 7 weeks after restocking the cage, the benthic community had reached the moderately disturbed conditions observed prior to fallowing. No site characteristics were provided within this study. Also in Australia, McGhie et al. (2000) sampled sediments at two fish farm sites immediately after cessation of fish cultivation.
and found significantly organically enriched and reducing conditions beneath the cages compared to 30 meters away. The average bottom current speeds at both sites were ~0.7 cm s\(^{-1}\), the average depth was within the range of 15-30 m, and one site was dominated by coarser sand and the other was dominated by silt-clay. After 12 months, they found significant recovery at both sites had taken place. At an abandoned fish farm site situated within a shallow (~19 m), silty bay in Greece, Karakassis et al. (1999) detected benthic community and habitat disturbance directly beneath the old farm and mild disturbance 10 meters away at 3 months fallow. At 14 months fallow, slight improvements beneath the farm were detected and no disturbance was observed at 10 meters away. Lu and Wu (1998) transplanted azoic fish farm sediments to a similar, but reportedly clean, site in Hong Kong and found that by 1 month there was intensive benthic faunal recolonization, and by 4-5 months the community was fairly similar to that of its natural surroundings. The authors in this case concluded that recovery in sub-tropical climates might be quicker than in temperate climates. Johannessen et al. (1994) found only a slight indication of remediation after 11 months fallow at a negatively impacted farm situated in a deep (76-118 m), sheltered basin in Norway. The fallowing site was characterized by silt-clay sediments. This study reported that benthic recovery was slow, and the new faunal community observed after 11 months did not yet resemble the natural one observed prior to fish cultivation. Henderson and Ross (1995) detected severe impacts to the benthic community and habitat after 3 months fallow at a fish farm in Scotland.

2.3 Conditions Influencing Benthic Impact and Recovery

2.3.1 Farm Operational Conditions

Fish feed and faeces comprise the wastes that contribute to organic enrichment beneath fish farm sites (Gowen and Bradbury, 1987). Both factors depend on the characteristics of the fish and feed, and on the operational details of the farm. Waste outputs from a fish farm to the marine environment are dependent upon several operational factors including pen area, fish type, fish count, fish age, fish biomass, feed composition, feed rate, feed biomass, feed pellet sink rate, faecal pellet sink rate, and feed conversion ratio (Chen et al., 1999a and 1999b; Findlay and Watling, 1994; Gowen et al., 1994; Silvert, 1994). Waste inputs reaching the benthic environment are controlled by several oceanographic influences including current speeds, current direction, bottom topography, and depth (Findlay and Watling, 1994; Gowen et al., 1994; Silvert, 1994).
Several models have been developed for estimating the flux rates and areal extents of waste inputs to sediments. Findlay and Watling (1994) estimate the area of the sea bottom receiving feed pellets to be: 

$$A_{fp} = \pi \left( \left( \frac{D \times V}{SR_{fp}} \right) + \frac{P_d}{2} \right)^2$$

where $D$ is the mean depth of water below the net pen, $SR_{fp}$ is the settling rate of the feed pellets, $V$ is the average current velocity, and $P_d$ is the net pen diameter. The area of the sea bottom receiving faecal pellets can be estimated as:

$$A_{fc} = \pi \left( \left( \frac{D \times V}{SR_{fc}} \right) + \frac{P_d}{2} \right)^2$$

where $SR_{fc}$ is the settling rate of faecal pellets. They also estimate organic carbon deposition due to waste feed to be:

$$FLUX_{wf} = \frac{C_{wf}}{A_{fp}} / d$$

where $C_{wf} = C_{fd} \times \%WF$, $C_{fd} = (F \times (1-(\%water\ in\ feed/100)))(0.45)$, $F$ is the food fed in grams, $\%WF$ is the percentage of food wasted, and $d$ is the number of production days. Organic carbon deposition due to faeces is estimated as:

$$FLUX_{wf} = \frac{C_{fc}}{A_{fc}} / d$$

where $C_{fc} = (C_{fd} - C_{wf})(1-A)$, where $A$ is the assimilation rate.

Perez et al. (2002) estimate that 46% of feed input is carbon, 10% of which is deposited within the marine environment as waste feed and 32% of which is expelled within faeces. This model does not account for growth of the fish, and thus only provides a general estimation.

### 2.3.2 Oceanographic Conditions

Some of the most important distinguishing characteristics of the British Columbia coast are the fjords and inlets on the mainland and on the western side of Vancouver Island. These long, deep, and narrow channels are typically U-shaped due to glacial scouring, and they are therefore characteristically bordered by steep, rocky slopes and muddy bottoms (Thomson, 1981). River runoff into fjords and inlets creates estuarine circulation, while sills, remnants of glacial terminal moraines, form natural circulation barriers at the mouth.

The coastal oceanography in Norway is similar to that in British Columbia (Levings, 1994; Thomson, 1981), and fish farm impact studies conducted in Norway therefore provide scientists in British Columbia with valuable comparative research. There are notable differences between the two coasts, however, one of which is that Norwegian fjordal mouths can be much more shallow than those in British Columbia, resulting in differences in estuarine circulation (Pickard, 1961).

Fish farms in British Columbia tend to be sited within archipelagos or in deep fjordal basins, some having depths in excess of 100 meters (Levings, 1994). For the purpose of mooring, farms
are often situated close to the rocky walls of the channels (Levings, 1994). Therefore, farm sites in British Columbia can be characterized by a variety of substrates ranging from ultra-fine muds to rocky outcrops. Sills at the mouths of fjords act as barriers to deep water circulation in the basins, promoting stagnation near the bottom and often creating anoxic conditions (Thomson, 1981). Furthermore, due to the semi-enclosed nature of fjords, the residence time of the water within the basins is often quite long, resulting in a natural tendency for nutrient accumulation (Gowen, 1991; Pearson and Rosenberg, 1978). The additional deposition and accumulation of organic fish farm wastes may only enhance the natural tendency for some of the more secluded, silled, and thus poorly flushed fjordal basins to reach an anoxic state (Aure et al., 1988). Conversely, if fish farms are placed at a site which is characteristically dominated by erosion or transportation processes (typically not the case with silled fjords), wastes can disperse and settle in surrounding sediments (Holmer, 1991).

Strong currents discourage immediate deposition of organic particulates on the sea floor, and can encourage mainly the heavy particulates, typically low in organic content, to settle out (Pearson and Rosenberg, 1978). Currents reaching speeds of greater than 10cm s⁻¹ and up to 1m s⁻¹ have been identified at sites that did not exhibit significant benthic impact due to fish farming activity (Anderson, 1996; Brooks, 1996; Frid and Mercer, 1989). Conversely, weaker currents tend to encourage localized settling of organic particulates and finer sediments, typically of the silt-clay fraction (Pearson and Rosenberg, 1978). Current speeds of less than 10cm s⁻¹ have been observed at sites reported to be impacted by fish farming activity (Brooks, 2002; Anderson, 1996; Brooks, 1996; Findlay et al., 1995; Miller-Retzer, 1994; Johnsen et al., 1993; Cross, 1990; Weston, 1990; Aure et al., 1988; Brown et al., 1987).

Within British Columbia, fish farms tend to be sited in deeper waters and therefore impacted sediments are often associated with farms located over depths of greater than 20 meters (Brooks, 2002; Levings and Sutherland, 1999; Anderson, 1996; Miller-Retzer, 1994; Cross, 1990).

Fish farms outside of British Columbia are often sited in shallower waters reaching depths of less than 30 meters, and studies at impacted sites often cite depths of less than 20 meters (Pawar et al., 2001; Christensen et al., 2000; Karakassis et al. 1999; Mazzola et al., 1999; Karakassis et al. 1998; Hargrave et al., 1997; Brooks, 1996; Findlay et al., 1995; Tsutsumi, 1995; Johnsen et al., 1993; Uotila, 1991; Ye et al., 1991; Weston, 1990; Aure et al., 1988; Kaspar et al., 1988; Brown et al., 1987).
2.4 Sensitive Indicators of Impact and Recovery

2.4.1 Definition of a Sensitive Indicator

In the context of this research, an indicator acts as a gauge for assessing impact and recovery rates associated with benthic organic pollution. The sensitivity of an indicator lies within its ability to accurately detect trace alterations in the surrounding environment that are contributing to whatever effects it is decided constitute “impact” or “recovery.” Thus, a sensitive indicator is one that can be used to accurately assess benthic impact and recovery associated with organic enrichment effects of fish farm wastes. If, through rigorous scientific analyses, one or more indicators are found to be highly sensitive, they may be used in place of other less sensitive indicators to assess impact and recovery rates, thereby reducing investigative time and costs.

2.4.2 Sensitive Indicators of Benthic Impact and Recovery in the Literature

Analyzing the benthic faunal community can sometimes be more costly and time-consuming than measuring a suite of environmental variables that have been shown to be sensitive to changes within the community (Wildish et al., 2001). Typically, the scientific community supports the use of both geochemical and benthic community analyses in order to provide a more robust assessment of overall impact (Weston, 1990). In Atlantic Canada, Wildish et al. (1999) have identified methods for monitoring benthic sediments under fish farms in the Bay of Fundy using geochemistry as a cost-effective alternative to benthic faunal community analysis. In Scotland, however, Henderson and Ross (1995), reported that these same geochemical measurements did not provide enough evidence of impact to be used as sensitive indicators, and instead recommended that the benthic infaunal community be used to gauge impacts due to fish farming.

Impacts to the benthic environment resulting from anthropogenic sources other than fish farming have also been measured using sediment physical and chemical indicators. Sediment metals are often used as sensitive indicators of benthic impacts of pulp mill effluent (Sibley et al., 2000), mining wastes (Farag et al., 1998; Dave, 1992), sewage (Reish and Bellan, 1995; Ueda et al., 1994), industrial activities (Hart et al., 1986), and urbanization (Inglis and Kross, 2000). Sediment organics are commonly used as sensitive indicators of benthic impacts of pulp mill effluent (Sibley et al., 2000), sewage (DeBruyn and Rasmussen, 2002), industrial activities (Dell'Anno et al., 2002), and agricultural runoff (Riva-Murray et al., 2002; Bednarz and Starzecka, 1993). Sediment chlorophyll has also been used as an indicator of benthic impacts of
sewage (Gowen et al., 2000) and industrial activities (Dell'Anno et al., 2002). Sediment redox potential and sulphides have been used as indicators of impacts to the benthic environment resulting from sewage (Kumary et al., 2001; Bakri and Kittaneh, 1998) and pulp mill effluent (Vance, 1978).

2.4.3 Potential Sensitive Indicators of Benthic Impact and Recovery

2.4.3.1 Sediment Oxygen

In the northern portion of Georgia Strait, where the two farms sampled in this study were located, bottom water oxygen renewal is dependent upon mixing induced by cool winter conditions and, to a lesser degree, tidal mixing (Thomson, 1981). Fish farms in British Columbia are often sited within deep fjordal basins (Levings, 1994), and some fjords in this province have been found to be naturally anoxic (Pickard, 1961).

Pearson and Rosenberg (1978) identify oxygen reduction as perhaps one of the most serious impacts of organic pollution on marine life. Benthic microbes will decompose organic particulate matter as it accumulates on the sea floor, reducing oxygen in the process (Jorgensen, 1983; Zobell, 1946). As sedimentation of organics increases, microbial activity and thus oxygen reduction may also increase (Holmer, 1991). Microbial oxygen reduction, coupled with the tendency of certain hydrographic systems to inhibit bottom water oxygen renewal, can result in rapid depletion of the oxygen available to benthic macrofauna (Pearson and Rosenberg, 1978). In organically enriched areas where fish farm wastes have accumulated on the ocean floor, organisms can reduce sediment oxygen content to the point of near-anoxic or anoxic levels (Gowen and Bradbury, 1987). This situation can be exacerbated by the natural anoxia of an area.

All benthic invertebrates require oxygen for survival, and therefore many species may not colonize completely anoxic sediments unless they are specifically adapted to do so (Reish, 1972). The minimum oxygen concentration required to sustain marine aquatic life has been identified to be 5ppm (Reish, 1972). Lower values have been reported for the survival of certain species of benthic invertebrates, but many of these are also considered to be pollution tolerant (Reish, 1972). For example, Reish and Barnard (1960) and Reish (1966) found Capitella capitata to have a dissolved oxygen tolerances of 2.5ppm and 1.5ppm, respectively.
Low sediment and bottom water oxygen have been identified within impacted areas at several fish farm sites (Christensen et al., 2000; Mazzola et al., 1999; Lu and Wu, 1998; Hargrave et al., 1997; Anderson, 1996; Tsutsumi, 1995; Miller-Retzer, 1994; Aure et al., 1988; Brown et al., 1987).

2.4.3.2 Sediment Redox Potential

Particulate organic matter is prone to accumulate within the same depositional environments as fine grained sediments (Jickells and Rae, 1997). These finer sediments, particularly the silt-clay fraction, therefore tend to be characteristic of reducing conditions, while coarser sediments tend to be less reducing (Zobell, 1946). Oxic conditions are typically associated with the potential for aerobic microbial oxidization of organic particulates, while anoxic sediments are subject to anaerobic processes and can eventually become reducing. Redox potential measures the potential of a system to either oxidize or reduce constituents. Furthermore, it predicts whether newly accumulating materials are more likely to be oxidized or reduced (Zobell, 1946). Oxidizing conditions are typically associated with lower levels of organic input and have correspondingly high (positive millivolts) redox potential values. Reducing conditions are typically associated with elevated levels of organic input and have correspondingly low (negative millivolts) redox potential values (Pearson and Stanley, 1979). Negative and positive redox potential is measured against a zero standard for which oxidation potential equals reduction potential (Zobell, 1946).

Redox potential can be used to measure the reducing capacity of the sediments in organically enriched areas (Gowen and Bradbury, 1987; Pearson and Stanley, 1979; Zobell, 1946). According to Zobell (1946), aerobes can reduce a substance from +0.3V to <= -0.2V, while anaerobes (including sulfate-reducing bacteria) can further reduce the substance from ~0.0V to <= -0.4V. Thus, anaerobic conditions generally correspond to redox potential values of <=-0.1V (Zobell, 1946).

Pearson and Stanley (1979) found that in both the laboratory and the field, redox potential values in reducing marine sediments recovered simultaneously with decreases in organic loadings to the sediments. They further found that successional changes in benthic macrofauna and redox potential were highly correlative. Redox potential of > 0V corresponded with healthy and diverse faunal communities, and values much lower than -0.150V were associated with azoic conditions.
Lower-than-normal sediment redox potential has been found to be characteristic of impacted fish farm sites (Erickson et al., 2001; Pawar et al., 2001; Hargrave et al., 1997; Tsutsumi, 1995; Gowen et al., 1991; Brown et al., 1987). Redox potential at fallowing and abandoned sites has been found to increase and recover over time (McGhie et al., 2000; Karakassis, 1999).

### 2.4.3.3 Sediment Sulphides

In the marine environment the most common mode of hydrogen sulphide production is via the biological conversion of sulphate under anoxic conditions (Ruddy, 1997). As previously discussed in the literature review, fish farms in British Columbia tend to be sited in deeper inlets and fjords, some of which may be characterized by regions of naturally anoxic sediments. When organic material containing sulphur compounds is input into these anaerobic environments, putrefaction can occur, increasing the rate of hydrogen sulphide production.

As aerobic microbes in the sediments decompose organic particulates, they reduce oxygen (Jorgensen, 1983; Zobell, 1946). If particulates accumulate to a certain point of organic enrichment in the sediments, this decomposition process can continue until the available oxygen is fully reduced and conditions become anoxic (Holmer, 1991; Gowen and Bradbury, 1987). Eventually, after nitrate has been reduced out of the sediments, certain anaerobic microbes can reduce sulfates in order to decompose organic particulates (Berner, 1980). A byproduct of this process is hydrogen sulphide (H\textsubscript{2}S), which is released into the surrounding sediments (Wang and Chapman, 1999; Gowen and Bradbury, 1987; Berner, 1980; Jorgensen, 1977). Therefore, anoxic conditions present in areas of organic enrichment can be evaluated by observing total free sediment sulphides levels (Wildish et al., 2001). Total free sulphides consist of hydrogen sulphide (H\textsubscript{2}S), hydrosulphide anions (HS\textsuperscript{-}), and bisulphide anions (S\textsuperscript{2-}) (Wang and Chapman, 1999; Bagarinao, 1992). Hydrogen sulphide and the hydrosulphide anion are the most commonly found sulphide species in aqueous form, and hydrogen sulphide is the most apt to freely cross the membranes of aquatic organisms (Wang and Chapman, 1999; Bagarinao, 1992). Hydrogen sulphide, at a pH typical of seawater (8), forms approximately 9% of the total free sulphides (Erickson et al., 2001). Free sulphides are completely distinct from complexed or insoluble sulphides present within marine sediments (Rittmann and McCarty, 2001; Wang and Chapman, 1999). However, free sulphides can complex with heavy metals, such as cadmium, copper, lead, and zinc, rendering the sulphides out of free form into a non-toxic complexed form, and potentially reducing the availability of toxic free metal ions in sediment porewater (Rittmann and...
McCartt, 2001; Rozan et al., 2000; Wang and Chapman, 1999; Chapman et al., 1998). The term "sulphides" will be used in this paper to refer only to total free sulphides, present within the sediments in aqueous form.

In addition to serving as an indicator of organic enrichment, H$_2$S has also been proven to be toxic to fish (Bagarinao, 1992; Reynolds and Haines, 1980). Since H$_2$S freely crosses membranes, it can pass through the gills of the fish and inhibit circulation and ventilation (Bagarinao, 1992). In benthic invertebrates, H$_2$S toxicity results in an interruption of cellular respiration, thereby creating unfavourable conditions for survival (Theede, 1973). Many of the species-specific effects of H$_2$S have not yet been determined (Wang and Chapman, 1999). Some fish and macrofauna are capable of colonizing the borders of H$_2$S sediments where oxic conditions are still prevalent (Bagarinao, 1992). One of the more H$_2$S tolerant species is the polychaete $Capitella capitata$ (Pearson and Rosenberg, 1978; Reish, 1972).

An increase in sediment sulphides is characteristic within organically enriched, impacted areas at fish farm sites (Brooks, 2002; Erickson et al., 2001; Hargrave et al., 1997; Brooks, 1996; Tsutsumi, 1995; Johannessen et al., 1994; Johnsen et al., 1993; O’Connor et al., 1993; Gowen, 1991; Weston, 1990; Aure et al., 1988; Kaspar et al., 1988; Brown et al., 1987). Recovery at fallowing sites has been found to result in a decrease in sediment sulphides (Hargrave et al., 1997; Anderson, 1996).

2.4.3.4 Sediment Total Carbon, Nitrogen, and Organic Content

Fish farm wastes are comprised of food and faeces, both of which contain large amounts of organic carbon and nitrogen compounds (Gowen and Bradbury, 1987). Sedimentation of these wastes on the ocean floor can therefore be detected partially through total carbon and nitrogen levels, as well as total organic content.

Within the impacted areas at fish farm sites there is often evidence of elevated levels of organic carbon, nitrogen, and organic content (Pawar et al., 2001; McGhie et al., 2000; Mazzola et al., 1999; Hargrave et al., 1997; Brooks, 1996; Gowen, 1991; Uotila, 1991; Ye et al., 1991; Cross, 1990; Weston, 1990; Kaspar et al., 1988; Brown et al., 1987). At recovering sites, organic carbon, nitrogen, and organic content have been observed to significantly decrease over time (McGhie et al., 2000; Karakassis, 1999; Anderson, 1996; Brooks, 1996; Miller-Retzer, 1994).
Because of the elevated nitrogen content in the feed, organic C:N ratios are typically low for freshly accumulated fish farm wastes (Brooks, 2002; Findlay et al., 1995). Table 1 provides a list of typical organic carbon, nitrogen, and organic C:N for fish feed, salmon faeces, and marine organic matter. The organic C:N ratio for farm feed and marine organic matter are more similar (typically <10) while the organic C:N ratio for salmon faeces and terrestrial organic matter inputs are more similar (typically >10). The organic C:N ratio for feed is typically much lower than for faecal matter, largely due to a higher relative nitrogen content. Clearly, an absolute C:N ratio alone cannot identify the nature and origin of organic matter within marine sediments. However, relative changes or spatio-temporal discrepancies in C:N can offer some clue as to shifts in the nature of organic matter inputs being received by the benthic environment.

<table>
<thead>
<tr>
<th>Literature Source</th>
<th>Organic carbon</th>
<th>Nitrogen</th>
<th>Organic C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm Feed</td>
<td>Findlay &amp; Watling (1994)</td>
<td>0.463±0.061%</td>
<td>0.076±0.009%</td>
</tr>
<tr>
<td>Farm Feed</td>
<td>Sutherland et al. (2001)</td>
<td>0.571±0.012% (C\textsubscript{tot})</td>
<td>0.061±0.005%</td>
</tr>
<tr>
<td>Farm Feed</td>
<td>Hall et al. (1990 and 1992)</td>
<td>49.6 - 51.8% (w/w)</td>
<td>6.6 - 9.4%(w/w)</td>
</tr>
<tr>
<td>Salmon Faeces</td>
<td>Findlay &amp; Watling (1994)</td>
<td>0.217±0.041%</td>
<td>0.014±0.003%</td>
</tr>
<tr>
<td>Salmon Faeces</td>
<td>Chen et al. (1999b)</td>
<td>0.316-0.352% (C\textsubscript{tot})</td>
<td>0.032 - 0.034%</td>
</tr>
<tr>
<td>Marine SPOM</td>
<td>Andrews et al. (1998)</td>
<td>0.38% - 10.12%</td>
<td>0.04% - 1.32%</td>
</tr>
<tr>
<td>Marine Sediment</td>
<td>Andrews et al. (1998)</td>
<td>0.09% - 5.22%</td>
<td>0.02% - 0.4%</td>
</tr>
<tr>
<td>Marine Sediment</td>
<td>Macdonald &amp; Crecelius (1994)</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>Terrestrial Inputs</td>
<td>Macdonald &amp; Crecelius (1994)</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 1: Organic carbon, nitrogen, and organic C:N for fish farm feed, salmon faeces, and marine organic matter.

2.4.3.5 Sediment Grain Size

It has been hypothesized that finer particulate matter, including silt and clay-sized sediments, may be encouraged to settle beneath fish farms as a result of flow reduction induced by the presence of net-pens (Sutherland et al., 2001; Frid and Mercer, 1989). Sediments of the silt-clay fraction will also occur naturally in deep fjordal basins where the settling of fine particulates is encouraged by poor circulation and minimal tidal current speeds (Gowen, 1991; Aure et al., 1988; Thomson,
1981; Pearson and Rosenberg, 1978). Conversely, there tends to be an accumulation of larger grain sizes, mostly sand and cobble, in areas where currents are higher and transportation and erosion processes dominate (Holmer, 1991).

Typically, organic accumulations leading to enrichment tend to be associated with fine-grained sediments (Mayer and Rossi, 1982). High contents of finer-grained sediments, such as silt, clay, and fine sand, have been measured at fish farm sites reported to have some evidence of benthic impact (Brooks, 2002; McGhie et al., 2000; Karakassis et al. 1999; Mazzola et al., 1999; Hargrave et al., 1997; Anderson, 1996; Brooks, 1996; Tsutsumi, 1995; Johannessen et al., 1994; Miller-Retzer, 1994; Ye et al., 1991; Cross, 1990; Weston, 1990; Aure et al., 1988; Kaspar et al., 1988; Brown et al., 1987). Less commonly, benthic impacts have been observed at sites dominated by coarser sediments (McGhie et al., 2000; Brooks, 1996; Johnsen et al., 1993; Aure et al., 1988).

Rocky sites do not appear to exhibit much evidence of impact, but these areas cannot be sampled with the grab or coring methods used within softer sediments. Grab samplers typically bring up scrapings of samples if the mechanism happens to hit a pocket of organic material on the rock or within a crevice (Cross, 1990). This was found to be the case when sampling was attempted at the Eden Island site.

2.4.3.6 Sediment Porosity

Sediment water content provides an indication of the porosity of the sediments, and can be used as a partial indicator of the nature of accumulating sediments at a fish farm site. Water content and sediment porosity increase with decrease in sediment grain size (Caulfield and Filkins, 1999), and sediment porosity typically decreases with depth due to compaction, which effectively "squeezes" out the pore water (Jepsen et al., 1997; Xu et al., 1992). Porosity can be directly related to the organic matter content of sediments (UK Marine SAC, 2002; Avnimelech et al., 2001; Lu et al., 1998), and is also typically elevated in unconsolidated sediments, due to a lack of compaction and elevated presence of pore water (Jepsen et al., 1997; Maa et al., 1997). Sediment porosity has been found to be elevated within impacted areas at fish farm sites (La Rosa et al., 2001; Karakassis et al., 1998). La Rosa et al. (2001) also found that elevated sediment porosity declined as a result of fallowing at a fish farm site.
2.4.3.7 Sediment Bulk Density

Sediment bulk density is directly related to the grain densities and the relationships between particles (Herbert et al., 1997). Wet bulk density measures the density of the sediment grains and the interstitial waters, while dry bulk density only measures the density of the assortment of sediment grains. Wet bulk density typically tends to increase with sediment grain size (King and Galvin, 2002) and with sediment depth (Herbert et al., 1997; Jepsen et al., 1997; Xu et al., 1992). Fine-grained sediments, particularly silty clays, laden with organic matter also tend to have relatively low wet bulk densities (King and Galvin, 2002; Lu et al., 1998), and in general, wet bulk density of sediments is inversely related to organic matter content (Avnimelech et al., 2001; Lu et al., 1998) and water content (Lu et al., 1998; Jepsen et al., 1997; Lee and Chough, 1987). Wet bulk density is typically lower in unconsolidated sediments, because of the lack of compaction and the elevated presence of pore water (Jepsen et al., 1997; Maa et al., 1997).

2.4.3.8 Sediment Metals

Several metals, including copper and zinc, are considered to be essential minerals for fish and are incorporated into the feed used at farms (Jobling, 2001; Lorentzen and Maage, 1999; Lall, 1991; Watanabe, 1988; De Silva and Anderson, 1995). Many of the minerals in the feed often exceed the actual mineral requirements of the fish (Tacon and De Silva, 1983). This is largely due to the fact that the bioavailability of certain metals is partially dependent on the dietary source within the feed and adsorption rates (Lorentzen and Maage, 1999; Tacon and De Silva, 1983).

Metals associated with fish farm production can be deposited within the marine environment, and may accumulate within the sediments (Brooks, 2001a; 2001b; 2001c; Erickson et al., 2001; Uotila, 1991). Metals from both natural and anthropogenic sources are associated with particle surfaces, and therefore trace metals concentrations are largely dependent upon sediment grain size (Rae, 1997; Loring, 1991). Finer grained sediments, particularly within the clay and silt fractions, are comprised of metal-bearing minerals which may bind with, among others, aluminum, cadmium, copper, lead, silicon, and zinc (Loring, 1991). These metals also strongly bind with particulate organic matter (Chapman et al., 1998).

Bioavailable metals in sediments are found within the interstitial waters, where they exist in dissolved form as free metal ions which can penetrate membranes of organisms (Rozan et al.,
Therefore it is the metals in aqueous form that are toxic to organisms, and not the sediment-bound species (Chapman et al., 1998). Since metals are also found to be bound to particulate organic matter, to a certain extent faunal consumption of organic matter may also lead to the ingestion of toxic metals (Chapman et al., 1998). The mobilization of sediment and organic particulate-bound metals into dissolved phase is controlled by oxidation (Chapman et al., 1998). When there is even a slight increase in sediment redox potential, metals complexed with sulphides can be mobilized and released into the surrounding porewaters (Rozan et al., 2000; Chapman et al., 1998). Furthermore, when particulate organic matter is oxidized, organically-bound metals may be released in soluble form into the interstitial waters (Chapman et al., 1998).

The bioavailability of heavy metal ions in dissolved form are thus directly controlled by sediment metal concentrations, as well as by oxidation potential and pH (Chapman et al., 1998). Concentrations of solid phase metals, normalized by sediment grain size, can therefore be good predictors of porewater concentrations (Chapman et al., 1998). The method used to assess metals for this project looked only at the solid phase metals complexed to the sediments (US EPA, 1994). The sediment toxicity guidelines (outlined in section 3.3.3 of the Methods) to which metals concentrations were compared also looked only at the solid phase metals (CCME, 1995; Environment Canada, 1995). The guidelines were developed by normalizing metals to background lithium concentrations and organic carbon (CCME, 1995).

2.4.3.8.1 Aluminum

Limited information is available on sedimentary aluminum background levels, inputs to the ocean, and tolerance thresholds, particularly for the northeastern Pacific region. Natural inputs of aluminum to ocean sediments can be from organic (diatoms uptake aluminum), lithogenic, and air-borne dust particle sources (Dixit et al., 2001). Anthropogenic inputs of aluminum to the ocean are typically from industrial sources (Weisberg et al., 2000). Aluminum is often naturally associated with clay sediments (Dean and Gardner, 2001). Aluminum has been reported to be detected in fish feed pellets ($57.567 ± 23.513 \mu g \, g^{-1}$) used at some British Columbia fish farms (Sutherland et al., 2001). Aluminum has not been reported to be a mineral requirement for fish (De Silva and Anderson, 1995; Lall, 1991), however, nor has it been reported as an element in feed (Lorentzen and Maage, 1999; Tacon and De Silva, 1983).
There are no sediment quality guidelines associated with aluminum. Background levels of aluminum were recorded at several locations along the British Columbia coast by Harding and Goyette (1989), who found ranges between 7190-34075 μg g⁻¹ in what they considered to be "natural" sediments.

2.4.3.8.2 Cadmium

Natural inputs of cadmium to the ocean are weathered terrestrial rock and air-borne particulate matter from volcanic, organic matter, or soil sources (McNee, 1997; Pedersen et al., 1989). Anthropogenic inputs of cadmium to the ocean can originate from smelters, waste product incineration, fossil fuel combustion, fertilizers, sewage, and certain industrial emissions (McNee, 1997; Odhiambo et al., 1996). Cadmium concentrations are typically higher in organic-rich sediments, and their presence is, in part, affected by organic matter remineralization (Morford and Emerson, 1999; McNee, 1997). Since phytoplankton can bioaccumulate cadmium, as they decompose within the sediments they can release cadmium into the surrounding environment (Cullen, 2002; Cullen et al., 1999; Radach and Heyer, 1997). Cadmium has also been found to be present in reducing or sulphidic sediments (Russell and Morford, 2001; McNee, 1997). Despite the fact that cadmium has not been reported to be a mineral requirement for fish (De Silva and Anderson, 1995; Lall, 1991), it has been reported to be present (0.25-0.29μg g⁻¹) in Atlantic salmon feeds (Tacon and De Silva, 1983), and has been detected (0.197±0.015μg g⁻¹) in fish feed pellets used at some British Columbia fish farms (Sutherland et al., 2001). Cadmium has not been found to be elevated within sediments receiving waste inputs from fish farms (Uotila, 1991).

The Interim Marine Sediment Quality Guideline (ISQG) threshold for cadmium is 0.7 μg g⁻¹ and reportedly corresponds to adverse biological effects in marine sediments (Environment Canada, 1995). The probable effects level (PEL) for cadmium is 4.2 μg g⁻¹. Cadmium background, baseline, and "natural" levels have been recorded for several regions along the lower British Columbia coastline. McNee (1997) found cadmium levels in several British Columbia fjords to be within the range of 0.09-8.0 μg g⁻¹. Detrital background levels were reported to be within the range of ~0.1-0.2 μg g⁻¹ (McNee, 1997). Odhiambo et al. (1996) compared cadmium levels measured in sediments collected from Alice Arm to marine background levels of 0.24±0.1 μg g⁻¹. Bloom and Crecelius (1987) found background levels of cadmium in Puget Sound to be 0.39 μg g⁻¹ in muddy sediments. MacDonald et al. (1991) reported natural cadmium levels within
Georgia Strait to be 0.22±0.05 µg g⁻¹. Natural levels of cadmium were recorded at several locations along the British Columbia coast by Harding and Goyette (1989), who found ranges between 0.38-1.3 µg g⁻¹.

2.4.3.8.3 Copper

Natural inputs of copper to the ocean are typically from dissolved riverine inputs, biogenic sources, and air-borne particulate matter or dusts (McNee, 1997; Francois, 1988). Anthropogenic inputs of copper to the marine environment are predominantly through domestic waste, industrial sources, and mining leachate (McNee, 1997; Odhiambo et al., 1996; Bloom and Crecelius, 1987). Copper has been found to be enriched in organic matter accumulations, partially due to elevated planktonic levels, and therefore it can be released into the sediments during organic matter oxidization (McNee, 1997; Francois, 1988). Moreover, organic matter has an ability to scavenge for copper from the overlying waters, also contributing to elevated sedimentary levels (McNee, 1997). Copper has also been found to be abundant in sediments beneath anoxic water, because of its propensity to precipitate and settle out as a particulate sulphide (McNee, 1997). Elevated levels of copper have been found in sediments at fish farm sites, presumably because of the copper contained in the antifouling paint used on the cages (Brooks, 2001a; Uotila, 1991). Cuprous antifoulants, such as Flexguard, are commonly used at fish farms in British Columbia and reportedly will protect a net for an entire growout cycle, lasting approximately 16-24 months (Brooks, 2001a). Copper is an essential mineral requirement for fish due to its importance in maintaining metabolic functions (Jobling, 2001; Lorentzen and Maage, 1999; Lall, 1991; Watanabe, 1988; De Silva and Anderson, 1995). Copper concentrations recommended for Atlantic salmon are between 5 and 6µg g⁻¹ (De Silva and Anderson, 1995; Lall, 1991), and 3ppm for carp and rainbow trout (Watanabe, 1988). Copper in Atlantic salmon feeds has been reported at concentrations of 11-20µg g⁻¹ (Tacon and De Silva, 1983), and 3.7-6.9µg g⁻¹ (Lorentzen and Maage, 1999). Copper has also been detected (10.7±0.265µg g⁻¹) in fish feed pellets used at some British Columbia fish farms (Sutherland et al., 2001).

The Interim Marine Sediment Quality Guideline (ISQG) threshold for copper is 18.7 µg g⁻¹ and reportedly corresponds to adverse biological effects in marine sediments (Environment Canada, 1995). The probable effects level (PEL) for copper is 108 µg g⁻¹. McNee (1997) found copper
levels in several British Columbia fjords to be within the range of 20-290 µg g\(^{-1}\). Detrital background levels were reported to be within the range of 60-120 µg g\(^{-1}\) (McNee, 1997). Odhiambo et al. (1996) compared copper levels measured in sediments collected from Alice Arm to marine background levels of 39±8 µg g\(^{-1}\). Bloom and Crecelius (1987) found background levels of copper in Puget Sound to be within the range of 17.1-30.6 µg g\(^{-1}\) in sandy and muddy sediments. MacDonald et al. (1991) reported natural copper levels within Georgia Strait to be within the range of 40-45 µg g\(^{-1}\). At several locations along the British Columbia coast, natural levels of copper were found to be within the range of 4.34-37.2 µg g\(^{-1}\) (Harding and Goyette, 1989).

2.4.3.8.4 Lead

Natural inputs of lead to the marine environment are typically of lithogenic origin, or from organic matter (Macdonald et al., 1991; Francois, 1988). Anthropogenic inputs of lead to the ocean are predominantly from pre-1980's leaded gasoline (Macdonald et al., 1991) and industrial or mining sources (Macdonald and O'Brien, 1996). Lead has been observed to be enriched in anoxic sediments (Francois, 1988). Lead was reported to be absent in fish feed pellets collected from a farm in British Columbia (Sutherland et al., 2001), and has been found to be absent from sediments receiving waste inputs from fish farms (Uotila, 1991). Lead has not been reported to be a mineral requirement for fish (De Silva and Anderson, 1995; Lall, 1991), but it has been detected (2-3.4 µg g\(^{-1}\)) as an element in feed (Tacon and De Silva, 1983).

The Interim Marine Sediment Quality Guideline (ISQG) threshold for lead is 30.2 µg g\(^{-1}\) and reportedly corresponds to adverse biological effects in marine sediments (Environment Canada, 1995). The probable effects level (PEL) for lead is 112 µg g\(^{-1}\). Odhiambo et al. (1996) compared lead levels measured in sediments collected from Alice Arm to marine background levels of 14.1±1.8 µg g\(^{-1}\). Bloom and Crecelius (1987) found background levels of lead in Puget Sound to be within the range of 4.9-7.2 µg g\(^{-1}\) in sandy and muddy sediments. MacDonald et al. (1991) reported natural lead levels within Georgia Strait to be within the range of 20-25 µg g\(^{-1}\). At several locations along the British Columbia coast, natural levels of lead were found to be within the range of 7.0-11.8 µg g\(^{-1}\) (Harding and Goyette, 1989).
2.4.3.8.5 Silicon

Natural inputs of silicon to the marine environment are typically from siliceous organisms, such as diatoms (Holby and Hall, 1994). Silicon availability is a primary factor limiting productivity of such organisms (Thurman, 1997). Other natural sources of silicon are lithogenic in origin (Thurman, 1997). Siliceous diatom production and sedimentary silicon are highly associated and fluctuate on a seasonal basis: during diatom blooms, productivity increases and silicon is taken up and removed from the surrounding sediments; once a bloom finishes the diatoms settle to the sediments and sedimentary silicon levels increase as a result of dissolution of the diatom shells (Sigmon et al., 2002; Woodruff et al., 1999). Silicon has not been reported to be a mineral requirement for fish (De Silva and Anderson, 1995; Lall, 1991), although it has been detected (110±37.510 μg g⁻¹) in fish feed pellets used at farms in British Columbia (Sutherland et al., 2001) and elsewhere (Holby and Hall, 1994). There are no sediment quality guidelines associated with silicon; its presence within the sediments is not indicative of toxic conditions, but rather is indicative of productivity.

2.4.3.8.6 Zinc

Natural inputs of zinc to marine sediments are predominantly from organic matter, with more minor inputs from weathered rock and from particulate matter originating from volcanic or soil sources (McNee, 1997). Anthropogenic inputs of zinc can originate from sewage and waste water, and from industrial sources (McNee, 1997; Macdonald and O'Brien, 1996). Zinc has been associated with organic matter, and sedimentary zinc is thought to be remobilized by the oxidation of organic matter (McNee, 1997; Macdonald et al., 1991; Francois, 1988). Furthermore, organic matter containing natural zinc may create reducing conditions during oxidation, which in turn encourage zinc to incorporate into sulphide minerals (McNee, 1997). Zinc has also been correlated with presence of silicon, possibly because of its incorporation into siliceous organisms (McNee, 1997).

Zinc is an essential mineral requirement for fish due to its importance in maintaining metabolic functions (Jobling, 2001; Lorentzen and Maage, 1999; Lall, 1991; Watanabe, 1988; De Silva and Anderson, 1995) and preventing cataracts in juveniles (Richardson et al., 1986). Zinc concentrations recommended for carp and rainbow trout are 15-30ppm (Watanabe, 1988). Zinc in Atlantic salmon feeds has been reported at concentrations of 80-92μg g⁻¹ (Tacon and De Silva, 1995).
1983), and 67-141µg g⁻¹ (Lorentzen and Maage, 1999). Zinc has also been detected (113.667±5.132µg g⁻¹) in fish feed pellets used at some British Columbia fish farms (Sutherland et al., 2001). In Finland, Uotila (1991) found zinc to be the most abundant metal within the sediments at an impacted fish farm site. Sutherland et al. (2001) also found zinc to be the most abundant of all metals detected in settling sediments within a fish farm net pen system in British Columbia, although they reported it to be well within background levels. Erickson et al. (2001) and Brooks (2001b; 2000c), however, found zinc levels to be well above Environment Canada’s sediment quality guideline of 124µg g⁻¹ (Environment Canada, 1995) at several farms along the British Columbia coast.

The Interim Marine Sediment Quality Guideline (ISQG) threshold for zinc is 124 µg g⁻¹ and reportedly corresponds to potentially adverse biological effects in marine sediments (Environment Canada, 1995). The probable effects level (PEL) for zinc is 271 µg g⁻¹. McNee (1997) found zinc levels in several British Columbia fjords to be within the range of 80-400 µg g⁻¹, reflecting a wide range of natural and anthropogenic inputs. Detrital background levels were reported to be within the range of 50-150 µg g⁻¹ (McNee, 1997). Odhiambo et al. (1996) compared zinc levels measured in sediments collected from Alice Arm to marine background levels of 138±12 µg g⁻¹. MacDonald et al. (1991) reported natural zinc levels within Georgia Strait to be within the range of 120-185 µg g⁻¹. At several locations along the British Columbia coast, natural levels of zinc were found to be within the range of 33.1-124 µg g⁻¹ (Harding and Goyette, 1989).

2.4.3.9 Sediment Chlorophyll

Chlorophyll is a pigment required for photosynthesis by certain microphytobenthos which adhere to the sediments, such as diatoms (Mitbavkar and Anil, 2002; Kelly et al., 2001; Cooksey and Wigglesworth-Cooksey, 1995). Sediments measured for chlorophyll content therefore might give some indication of the presence or absence of such organisms living on the sediments. Chlorophyll presence in sediments can not only be indicative of resident phytobenthos, but also of the sedimentation of phytoplankton from sources above the sediments (Karakassis et al., 1998). La Rosa et al., (2001) and Karakassis et al. (1998) found chlorophyll content to be elevated within impacted areas of sediments at fish farm sites.
3 Materials and Methods

There are several terms used throughout this paper that can be clarified with the following definitions: farm site: the entire area sampled near the farm site, reference site: the entire area of reference sediments sampled, study site: the entire sampled area including the farm and reference sites, farm: the entire area containing the farm operation, farm perimeter: the perimeter of the farm operation, farm center: the approximated center of the farm operation.

Sediment data was collected from two abandoned salmon farm sites along the British Columbia coastline. This data was analyzed using statistical and mapping techniques in order to isolate a suite of sensitive physical and chemical indicators of sediment recovery, and analyze physico-chemical aspects of sediment recovery.

The following is a list of the general tasks which were performed, with details to follow:

(1) Two abandoned farm sites characterized by soft sediments were available for sampling. Both sites were sampled as close to time-zero (final harvest) as possible, and both sites were resampled as many times as budget and time restrictions would allow.

(2) Reference sites were selected for each site based on proximity to the farm, as well as similarity to the farm sites in substrate, depth, and hydrography.

(3) The sampling plan at each site was designed with the objective of obtaining good spatial sampling coverage at each site, and was partially restricted by budget and time limitations.

(4) The following variables were measured from the top 2cm of sediment grab samples collected at the sites: total carbon, nitrogen, organic carbon, inorganic carbon, organic content, metals, porosity, and sediment grain size. Layers of chlorophyll, bulk density, and porosity were measured from the 2.5cm cores collected from grab samples at the sites. Sulphides, redox potential, and oxygen were measured within every 2cm of large core samples.

(5) Descriptive and inferential statistics were applied to the data in order to identify site characteristics, determine a suite of sensitive indicators of recovery, and assess physico-chemical aspects of sediment recovery at both sites.

(6) Mapping techniques were applied to the data in order to identify site characteristics and assess spatio-temporal patterns of sediment recovery at both sites.
Once the above tasks were used to analyze physico-chemical aspects of sediment recovery at both sites, the findings were then applied in order to develop and recommend a sampling and analysis plan suitable for assessing the patterns and rates of recovery at similar abandoned or fallowing fish farm sites in the future.

3.1 Data Collection

3.1.1 Site Selection

Two abandoned farm sites characterized by softer substratum were available for sampling along the British Columbia coastline (Figure 1). These sites were located in Kanish Bay (near the Chained Islands) and Carrie Bay.

Figure 1: The Carrie Bay and Chained Islands sites in relation to active fish farms tenures in British Columbia (Source: Ministry of Agriculture, Fisheries, and Food)
The Carrie Bay sediments were consistently soft enough to sample with grab and core samplers. Most of the Chained Islands site was also characterized by soft sediments. The nearshore regions of the site, however, were rocky and therefore difficult to sample. Although it was beyond the scope of the project, it was decided that photographic survey would be necessary to thoroughly sample the shallower, rockier regions of the site.

A third, rocky-bottomed site was located off the northern tip of Eden Island within the Broughton Archipelago roughly 9 kilometers, as the crow flies, northwest of Carrie Bay. The farm relocated in September, 2000 and was first sampled a few days after time-zero recovery. After an exhaustive survey of the area using a van Veen grab, only a few small scrapings of substance were obtained. It was decided that methods beyond the scope of the project (eg. photographic survey) would be better suited for sampling the rocky substrate, and the site was not revisited.

3.1.1.1 Chained Islands

One of the abandoned fish farm sites was located on the southernmost side of one of the Chained Islands in Kanish Bay (Figure 2 and Figure 3), on the northwestern side of Quadra Island. Two farms had operated within this site, and for the purposes of this project they will be referred to as the east farm and the west farm. Depths at the farm sites ranged between 9 and 40 meters, and sediments were predominantly silty/sandy in the deeper regions, and more rocky and shelly in the shallower, nearshore regions. Average current speeds in Kanish Bay were recorded by the farm operators to be 0.614 cm s\(^{-1}\). Cross (1990) reported that at a site very near the east farm site, the average surface current velocity was 2.15 cm s\(^{-1}\) and average bottom current velocity was 1.87 cm s\(^{-1}\). The site was reported to be relatively unstratified and well-mixed, based on observations of high dissolved oxygen and stable salinity throughout the water column. The general circulation pattern near the east farm site was recorded as ebb to the south-southwest and flood to the north-northeast. The net-pen systems at this site were removed in September 2000.

The farm at this site was first stocked with salmon in January 1989 and was last harvested in September 2000. Based on quarterly production information obtained for the final 11 years of production, the entire farm was using an average of approximately 64,000 kg (dry wt.) of feed and producing an average of approximately 86,000 kg of fish on a quarterly basis during production (Figure 6). During one full quarter in 1996, and again in 1998, the pens were empty of fish. The site was fallowed during the entire year of 1999, and in the following year (the final year of
operation) production was much lower, averaging approximately 18,700 kg of fish on a quarterly basis. There were twelve 15x15 m cages at the east farm site, and eight 15x15 m cages at the west farm site, and thus fish were produced within a total area of 4500 m². Using the waste carbon calculations proposed by Perez et al. (2002), it was estimated that a total of 12,000 kg of waste carbon was likely input to the marine environment on a quarterly basis. Over the 11.5 years of operation, an approximate total of 552,000 kg of waste carbon could be estimated to have been input to the marine environment.

![Figure 2: Map of Chained Islands site (designated by red circle).](image)

![Figure 3: Map of Chained Islands site and sampling stations.](image)
The reference site was located ~450 meters to the west of the west farm. Additional reference stations were added between the west farm and reference sites for all sampling trips subsequent to the first trip. These stations were located at approximately 160 and 300 meters to the west of the west farm. Sediments at this site were silty/sandy, and depths ranged between 30 and 40 meters.

### 3.1.1.2 Carrie Bay

One of the abandoned fish farm sites was located in Carrie Bay (Figure 4 and Figure 5), on the eastern side of Bonwick Island in the Broughton Archipelago, a small chain of islands located at the northern end of Johnstone Strait, just northeast of Port McNeill, off the northeastern tip of Vancouver Island.

![Figure 4: Map of Carrie Bay site (designated by red circle).](image)
Depths at the farm site located within this muddy, semi-sheltered bay ranged between 20 and 45 meters. Average current speeds in the bay were recorded by the farm operators to be \(7.6 \text{ cm s}^{-1}\), predominantly in the south-southwest direction. The general circulation pattern at the mouth of the bay was recorded as ebb to the south-southwest and flood to the north-northeast, while the waters within the bay ebbed inward to the west and outward to the east. The farm operators also reported an internal gyre within the bay, which they claimed created what they observed to be a depositional environment (name withheld, personal communication, 2003). The farm operators report that they abandoned the site in 1998 once they had determined that the wastes from the farm were accumulating at the site.

The farm at this site was first stocked with Atlantic Salmon (\textit{Salmo salar}) in March, 1990 and was last harvested in September, 1998. The pens annually contained approximately 300,000-450,000 fish which reached approximately 4.5-5kg at the end of each 24 month growing period. Stocking density was estimated at 15kg/m\(^3\). Based on quarterly production information obtained for the final 4 years of production, the farm was using an average of approximately 380,000kg (dry wt.) of feed and producing an average of approximately 800,000kg of fish on a quarterly basis (Figure 6). There were a total of eight 30x30m cages and four 15x15m cages at the site, and thus fish were produced within an area of 8100m\(^2\). Using the waste carbon calculations proposed
by Perez et al. (2002), it was estimated that a total of 74,000 kg of waste carbon was likely input to the marine environment on a quarterly basis. Over the 8.5 years of operation, an approximate total of 2,516,000 kg of waste carbon could be estimated to have been input to the marine environment. The cages were coated with Flexguard, a cuprous oxide based antifouling paint.

The reference site, also used by Levings and Sutherland (1999), was located at the mouth of a much smaller bay ~950 meters to the northeast of the farm site along the eastern side of Bonwick Island. Sediments at this site were also muddy, and depths ranged between 30 and 40 meters.

3.1.2 Sampling Design and Layout

Benthic impact and recovery assessment studies at fish farm sites in British Columbia have not typically analyzed impact or recovery at more than a few sampling points (Brooks, 2002; Erickson et al., 2001; Anderson, 1996; Cross, 1990). One of the major goals of this project was to gain a larger, more complete picture of sediment recovery at abandoned fish farm sites. Therefore, the objective was to sample as many stations as possible given time and budget allowances. For each site, the objective was to design a gridded sampling station layout with adequate spatial resolution and coverage that would allow for measurement of sediments directly beneath the removed pens as well as sediments extending outward from the middle of the farm. The sampling design used at the two sites was slightly different due to variations in farm orientation, site topography, and budgetary and time constraints.
3.1.2.1 Chained Islands

Using airphotos, hydrographic charts, and hand-sketched maps provided by the farm operators, the location of the net pens was determined at the Chained Islands site. Although a gridded sampling design was proposed for the Chained Islands site, it was decided that the layout of the stations would be determined in the field. On the May 2001 trip to the site, the geographic coordinates for the corners of the pens were noted down and inputted into Nobletec (navigational software) on the bridge's navigational computer system. Transects of stations were opted for over the grid system since the main goal was to perform initial reconnaissance at the site while at the same time keeping cost and time at a minimum (Figure 7).

Prior to the July 2001 trip to the site, a grid of potential sampling points spanning the entire site was designed in ArcView GIS (Figure 8).

An optimal distance of 50 meters was assumed between sampling stations, given the maneuverability limitations of the vessel, and the dimensions of the farms (60x30 meters and 90x30 meters). It was decided once again to maintain the transect system in favour of the grid system, although extra stations selected from the grid of points were added to the transects when and where possible (Figure 9). These stations were resampled on subsequent trips to the site.

![Figure 7: Location of successfully sampled stations at the Chained Islands site, May 2001.](image-url)
Figure 8: Grid of potential sampling stations designed for the July 2001 sampling trip to the Chained Islands site.

Figure 9: Location of successfully sampled stations at the Chained Islands site, July 2001.
3.1.2.2 Carrie Bay

The Carrie Bay site was originally sampled by Levings and Sutherland (1999) using a cross pattern of 13 stations on two sampling transects at the abandoned farm site (Figure 10), as well as a transect of three nearby reference stations (Figure 11). The intersection on the cross pattern was designed to be approximately within the center of the abandoned farm system, as interpreted from hydrographic charts.

A gridded sampling design was recommended for use at the Carrie Bay site. A complete grid, filling in the gaps on the cross pattern design, was originally thought to be the best design. However, sampling conditions, site characteristics, and time and budget constraints ultimately dictated the number of stations that could be sampled at each site. It was therefore decided that achieving a complete grid pattern of stations might be difficult. Several compromised grid patterns of sampling stations were designed based around the original cross pattern sampled in August 1999. However, the stations were selected once in the field on the September 2000 trip to the site. Where and when possible, stations were selected to fill in the spaces between the transects and create a more grid-like sample station layout at the abandoned farm site (Figure 12). The reference stations from the August 1999 trip were maintained (Figure 13). Distances between stations sampled in August 1999 varied, ranging between 30 and 50 meters. Since the 1999 cross pattern was used as a basis for selecting the extra stations in 2000, these distances were maintained and considered optimal given the size and maneuverability of the vessel, and the
dimensions of the cages (15x15 meters and 30x30 meters). The stations sampled on subsequent trips to the Carrie Bay site were selected from the September 2000 stations.

Figure 12: Layout of Carrie Bay farm site sampling stations (2000).

Figure 13: Layout of Carrie Bay reference site sampling stations (2000).

3.1.3 Pseudoreplicates

Although replication reduces the effects of random variation or error (Hurlbert, 1984), replication in space was not always feasible due to time and budgetary constrictions. Pseudoreplicates, although they are not truly independent replicates, can be used to statistically test the effects of a treatment (Hurlbert, 1994). Furthermore, pseudoreplicates can be used to minimize error within a site due to variation. For the purpose of statistical analysis, each of the stations that were sampled at either a farm or a reference site were considered to be pseudoreplicates for those sites. When possible, each of these pseudoreplicates was sampled twice in order reduce the effects of error due to variation at the pseudoreplicate level. The treatment at both the Carrie Bay and Chained Islands sites was farm effects at the abandoned farm site, and no farm effects at the reference site. Since the Chained Islands and Carrie Bay sites were not spatial replicates of each other, their results could not be statistically compared (Stewart-Oaten et al., 1986; Green, 1979). The two sites were therefore examined independently.

3.1.4 Repeated Measures Sampling

When performing analysis of variance with no spatial replicates, Green (1993) believes it is more appropriate to re-sample rather than re-randomize the same pseudoreplicates at each sampling time, a practice the author refers to as “repeated measures.” This means one is testing whether
changes occurring over time are different for the control versus the impacted areas. In this case, the error would be the within unit variation, over time. The error in a re-randomized sampling program would account for spatial variation among sampling stations from time to time, which only would serve to “cloud the comparison of differences” (Green, 1993). When possible, pseudoreplicates at both the Chained Islands and Carrie Bay sites were repeatedly measured.

3.1.4.1 Chained Islands

The Chained Islands farms relocated in May, 2001 and were first sampled within the first month of site abandonment. The entire sampling schedule is shown in Table 2. Cores were collected at a subset of the complete set of stations used for grab sampling. Cores extracted from the grab samples were used to analyze layers within the top 2.5cm for chlorophyll, porosity, and bulk density. The remaining data collected from the grab samples was used to analyze only the top 2cm of sediment, a common practice for this type of site assessment (Erickson et al., 2001). Sediment cores were used to evaluate sediment chemistry throughout the vertical core samples.

<table>
<thead>
<tr>
<th>Date</th>
<th>Months Since Site Abandoned</th>
<th># Stations Sampled</th>
<th>Sampling Method</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>May-01</td>
<td>1</td>
<td>15</td>
<td>Van Veen grabs</td>
<td>colour, odour, grain size, metals, C, N, porosity, org. content, chl a</td>
</tr>
<tr>
<td>Jul-01</td>
<td>3</td>
<td>19</td>
<td>Van Veen grabs</td>
<td>colour, odour, grain size, metals, C, N, porosity, org. content, chl a</td>
</tr>
<tr>
<td>Dec-01</td>
<td>8</td>
<td>18</td>
<td>Van Veen grabs</td>
<td>colour, odour, grain size, metals, C, N, porosity, org. content, chl a</td>
</tr>
<tr>
<td>Mar-02</td>
<td>11</td>
<td>18</td>
<td>Van Veen grabs</td>
<td>colour, odour, grain size, metals, C, N, porosity, org. content, chl a</td>
</tr>
<tr>
<td>May-01</td>
<td>1</td>
<td>4</td>
<td>Gravity cores</td>
<td>sulphides, redox potential, oxygen, porosity, bulk density</td>
</tr>
<tr>
<td>Jul-01</td>
<td>3</td>
<td>6</td>
<td>Gravity cores</td>
<td>sulphides, redox potential, oxygen, porosity, bulk density</td>
</tr>
<tr>
<td>Dec-01</td>
<td>8</td>
<td>9</td>
<td>Gravity cores</td>
<td>sulphides, redox potential, oxygen, porosity, bulk density</td>
</tr>
<tr>
<td>Mar-02</td>
<td>11</td>
<td>6</td>
<td>Gravity cores</td>
<td>sulphides, redox potential, oxygen, porosity, bulk density</td>
</tr>
</tbody>
</table>

Table 2: Chained Islands sampling schedule.

3.1.4.2 Carrie Bay

The Carrie Bay farm relocated in September 1998, and was first sampled by Levings and Sutherland (1999) 11 months after site abandonment. Subsequent trips began one year later in September, 2000. The entire sampling schedule is shown in Table 3. The analysis scheme used to collect data from cores and grabs at the Chained Islands site was also applied at the Carrie Bay site (see above).
<table>
<thead>
<tr>
<th>Date</th>
<th>Months Since Site Abandoned</th>
<th># Stations Sampled</th>
<th>Sampling Method</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug-99</td>
<td>11</td>
<td>16</td>
<td>Ponar grabs</td>
<td>colour, odour, metals, C, N</td>
</tr>
<tr>
<td>Sept-00</td>
<td>24</td>
<td>32</td>
<td>Van Veen grabs</td>
<td>colour, odour, grain size, metals, C, N, porosity, org. content, chl a</td>
</tr>
<tr>
<td>Aug-01</td>
<td>35</td>
<td>22</td>
<td>Van Veen grabs</td>
<td>colour, odour, grain size, metals, C, N, porosity, org. content, chl a</td>
</tr>
<tr>
<td>Sep-01</td>
<td>36</td>
<td>16</td>
<td>Gravity cores</td>
<td>sulphides, redox potential, oxygen, porosity, bulk density</td>
</tr>
<tr>
<td>Jan-02</td>
<td>40</td>
<td>3</td>
<td>Gravity cores</td>
<td>sulphides, redox potential, oxygen, porosity, bulk density</td>
</tr>
</tbody>
</table>

Table 3: Carrie Bay sampling schedule.

3.1.5 Sample Collection

In conjunction with Department of Fisheries and Oceans personnel, sediment samples were collected at both of the abandoned farm sites. Three different Canadian Coast Guard vessels were used for the field work.

The Otter Bay, a 13.4-meter inshore multi task patrol vessel, was used to access the Chained Islands site. A Van Veen grab sampler and gravity corer were deployed off the stern of the vessel using a cable and winch system. Global Positioning System (GPS) data was collected from the bridge.

A 0.04m$^2$ Ponar grab sampler was hand-deployed using soft lay nylon line from the Restless Bight, an inflatable 7-meter patrol craft, at the Carrie Bay site in August, 1999 (Levings and Sutherland, 1999). This trip took place prior to the onset of this thesis project. GPS data was collected from a hand-held unit that was positioned overtop of the entry point of the grab sampler into the water.

The Sooke Post, a 19.8-meter small multi task cutter vessel, was used in September, 2000 and August, 2001 to access the Carrie Bay site in order to collect grab samples. A Van Veen grab sampler was deployed off the side of the vessel using a cable and winch system. GPS data was collected from the bridge.

The Otter Bay was used in September, 2001 and January, 2002 to access the Carrie Bay site in order to collect core samples. A gravity corer was deployed off the stern of the vessel using a cable and winch system. GPS data was collected from a hand-held unit that was positioned overtop the line lowering the corer. This author was not present for either of these core sampling trips.
The gravity corer is not functional within coarse sediments (sand, gravel, or rock) or within those dominated by shell hash. The Van Veen grab sampler is more successful at sampling sand-dominated sediments, but cannot sample gravel or rock substrates. Coarser sediments dominated the nearshore areas at the Chained Islands site, and thus the gravity corer could only be used to sample the deeper, softer substrates at this site. The Van Veen grab sampler was more successful at sampling the sandy nearshore stations at the Chained Islands site, but rocky stations could not be sampled. The Carrie Bay site was more consistently dominated by softer sediments, and thus substrate was not a limiting factor for grab or core sampling.

3.1.5.1 Grab Samples

A Van Veen grab (Figure 14) was deployed at designated stations, and depth and geographic location coordinates obtained from a Global Positioning System (GPS) were recorded once the grab hit the bottom.

![Figure 14: A Van Veen grab.](image)

Once the sample was brought on board, the sediment was labelled with an index card, photographed, and visual observations were noted of grab fullness, sediment texture, colour, odour, presence of biofilm, and presence of bacterial mats. The temperature of the top 2cm of the sediment was recorded using a field thermometer. A 60cc syringe core was plunged into the top 4-6cm of sediment, with care being taken to not touch the plunger to the surface sediment and to keep the core vertical at all times. The syringe core was not extracted until the surface subsamples were collected, in order to minimize sample disturbance. Two plastic putty knives were then used to extract four subsamples of the top 2cm of sediment (10cm x 10cm x 2cm...
volume subsamples). These subsamples were used to entirely fill 4 plastic jars, which were sealed tightly and placed on ice in a cooler for transportation back to the lab. The 60cc syringe core was then extracted, sealed in a plastic bag using electrical tape, put into a Ziploc bag with the labelled index card, and placed upright on ice in a cooler for transportation back to the lab. The remaining portion of the sample was discarded. At the Chained Islands site, replicate grabs were deployed and the sediments were subsampled before moving on to the next station.

Once back at the lab, the top 2cm sediment samples were frozen prior to laboratory analysis of sediment grain size, metals, organic content, water content, organic carbon, inorganic carbon, and organic nitrogen. Syringe cores were also frozen prior to analysis of chlorophyll and bulk density.

3.1.5.2 Core Samples

Core barrels were prepared ahead of time by drilling 2cm diameter holes in a spiral pattern (every 2cm) down the length of a 8.15cm diameter tube constructed out of 3.5mm thick plexiglas (Figure 15). Several different lengths of cores were prepared to accommodate different substrate types. The holes were then sealed with duct tape to ensure the air tight seal necessary to enable proper suction.

A gravity corer (Figure 15) was deployed at designated stations, and depth and geographic location coordinates obtained from a GPS were recorded once the corer hit bottom. Collar weights were occasionally attached to the corer in order to assist penetration within more resistant (typically coarser) sediments. As soon as the corer emerged from the water, the winch was stopped so that the bottom of the core could be sealed with a plastic cap and electrical tape. The corer was then lifted on deck, and the core barrel was removed carefully, with care being taken not to disturb the sediment sample. The top of the core was then sealed with a plastic cap and electrical tape. The core was labelled with an index card, photographed, wrapped in a black garbage bag to prevent light reactions, and stored securely upright until analysis could be conducted. Given time constraints, replicate cores were not deployed.
3.1.6 Preparation for Collecting Redox Potential, Sulphides, and Oxygen from Cores Samples in the Field

3.1.6.1 Sulphides

Analysis of sulphides was performed according to methods developed in Atlantic Canada by Wildish et al (1999). Sulphides were measured using a Orion 9416BN Silver/Sulphide Half Cell Electrode with an Accumet AP63 pH/mV/ion Meter. The meter provided a measurement of total free sulphides (H$_2$S, HS$^-$, and S$^{2-}$), present within the aqueous portions of the sediment.

3.1.6.1.1 Laboratory Preparation

1) Buffer Solution (SAOB – Sulphide Anti-Oxidant Buffer)
a) Mix the following in a 250ml volumetric flask

- 20.0g NaOH
- 17.9g EDTA

b) Fill to volume with distilled water
c) Pour solution into a 500ml plastic bottle
d) Seal and place immediately in fridge

2) L-Ascorbic Acid (Vitamin C)

a) Weigh 8.75g L-Ascorbic Acid (some pre-weighed from last trip)

3) Na₂S₉H₂O

a) Weigh 0.2402g Na₂S₉H₂O under fumehood
b) Place in scintillation vial
c) Place scintillation vial in a white, plastic, sealed container to KEEP IN DARK
d) Seal and place immediately in fridge

3.1.6.1.2 24 Hours Prior to Sampling

a) Fill sulphide probe with Orion Optimum Results B AgCl filling solution
b) When filling the probe, push electrode down somewhat to allow solution to drip through and ensure the entire probe is wet throughout
c) After filling the probe, place a kimiwipe ball into the plastic cap in order to prevent soak up spillage and precipitation during transportation

3.1.6.1.3 Immediately Prior to Sampling

1) Buffer Solution

a) Add 8.75g L-Ascorbic Acid into 250ml buffer solution
b) LASTS 3 HRS

2) Na₂S₉H₂O

a) Place 0.2402g Na₂S₉H₂O into 100ml flask (may need to use a funnel and distilled water to ensure removal of all Na₂S₉H₂O from the vial)
b) Fill to volume with distilled water (0.01M Na₂S, 1000)
c) Pipette 5ml of 0.01M solution into a 50ml flask
d) Fill to volume with distilled water (0.001M Na₂S, 100)
e) Pipette 5ml of 0.001M solution into a 50ml flask
f) Fill to volume with distilled water (0.0001M Na₂S, 10)
g) LASTS 48 HRS
3.1.6.1.4 Calibration

a) Mix equal parts 0.01M Na₂S and buffer solution into a 50ml beaker (≥10ml)
b) Mix equal parts 0.001M Na₂S and buffer solution into a 50ml beaker (≥10ml)
c) Mix equal parts 0.0001M Na₂S and buffer solution into a 50ml beaker (≥10ml)
d) Calibrate sulphide meter for each

3.1.6.2 Redox Potential

Analysis of redox potential (Eh) was performed according to methods developed in Atlantic Canada by Wildish et al (1999). Redox potential was measured using an Accumet AP63 pH/mV/ion Meter with an Orion 9678BN Combination Platinum Redox Electrode. A constant correction value of 214mV had to be added to the redox potential measurements because of the type of filling solution used in the redox potential probe (Orion, 2003).

3.1.6.2.1 Laboratory Preparation

1) Zobells A (234 mV)
   a) Mix the following in a 50ml volumetric flask
      • 2.11g K₄Fe(CN)₆·3H₂O (yellow, potassium ferrocyanide (II) trihydrate)
      • 0.825g K₃Fe(CN)₆ (orange, potassium ferricyanide (III))
   b) Fill to volume with distilled water
c) Pour solution into a small nalgene plastic bottle
d) Seal and place immediately in fridge

2) Zobells B (300 mV)
   a) Mix the following in a 50ml volumetric flask
      • 0.21g K₄Fe(CN)₆·3H₂O (yellow, potassium ferrocyanide (II) trihydrate)
      • 0.825g K₃Fe(CN)₆ (orange, potassium ferricyanide (III))
      • 1.695g KF·2H₂O (potassium fluoride dihydrate)
   b) Fill to volume with distilled water
c) Pour solution into a small nalgene plastic bottle
d) Seal and place immediately in fridge

3.1.6.2.2 24 Hours Prior to Sampling

a) Fill sulphide probe with Orion Optimum Results A Ag/AgCl filling solution
b) When filling the probe, push electrode down somewhat to allow solution to drip through and ensure the entire probe is wet throughout
c) After filling the probe, place a kimwipe ball into the plastic cap in order to prevent soak up spillage and precipitation during transportation

3.1.6.2.3 Calibration

a) Calibrate redox meter using Zobells A solution (should read ~234mV±9mV)
b) Calibrate redox meter using Zobells B solution (should read ~300mV±9mV)
c) Record the readings and adjust sediment Eh values later based on any apparent error

3.1.6.3 Oxygen

Analysis of oxygen was performed according to laboratory methods suggested by the manufacturer of the oxygen meter (Orion, 2000). Oxygen was measured using an MI-730 Micro-Oxygen Electrode with an Orion OM-4 Oxygen Meter.

3.1.6.3.1 Laboratory Preparation

1) 0% Oxygen
   a) Weigh 2g of Na₂SO₃ (sodium sulfite)
   b) Place in scintillation vial

2) 20.9% Oxygen
   a) Distilled water

3.1.6.3.2 24 Hours Prior to Sampling

a) Fill oxygen probe with filling solution

3.1.6.3.3 Immediately Prior to Sampling

1) 0% Oxygen
   a) Add 10ml distilled water to 2g Na₂SO₃ in scintillation vial
   b) LASTS A FEW HOURS

2) 20.9% Oxygen
   a) Place 10ml distilled water into scintillation vial
3.1.6.3.4 **Calibration**

a) Calibrate oxygen meter for 0% oxygen  
b) Calibrate oxygen meter for 20.9% oxygen

3.1.7 **Sample Analysis**

The following suite of variables was measured from the sediment core samples collected at both sites: sulphides, redox potential, oxygen, porosity. Sulphides, redox potential, and oxygen were measured directly from the cores in the field, and porosity was subsampled for analysis in a laboratory environment.

The following suite of variables was measured from the sediment grab samples collected at both sites: bulk density, porosity, organic content, total carbon, organic carbon, inorganic carbon, nitrogen, chlorophyll, grain size, and metals. These variables were analyzed in a laboratory environment.

3.1.7.1 **Analyses of Redox Potential, Sulphides, and Oxygen from Core Samples in the Field**

Once a core was ready to be analyzed, the garbage bag and top cap were removed and an incision was made into the tape covering the top few holes to slowly allow the surface water to pour out. At least two centimeters of water was allowed to remain over the sediment surface, and an incision was made in the closest hole in order to take an oxygen reading of the surface water. The following analyses were repeated at each 2cm layer of sediment, starting with the top 2cm:

1. An incision was made in the tape covering the next hole.  
2. An oxygen probe was immersed in the sediment exposed by the hole and a reading was taken after 3 minutes of probe-to-sediment contact. The probe was rinsed with distilled water and wiped dry with a Kimiwipe.  
3. A redox potential probe was immersed in the sediment exposed by the hole and a reading was taken after 3 minutes of probe-to-sediment contact. The probe was rinsed with distilled water and wiped dry with a Kimiwipe.  
4. A 10mL sediment subsample was extracted using a 10cc syringe core.  
5. 5mL of the subsample was expelled into a scintillation vial and placed on ice in a cooler for post-trip porosity analysis.

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(6) The other 5mL of the subsample was mixed (homogenized) with 5mL sulphide anti-oxidant buffer in a plastic cup with a plastic pipette tip. A sulphide probe was immersed in the sediment/buffer mixture and a reading was taken after 3 minutes of probe-to-mixture contact. The probe was rinsed with distilled water and wiped dry with a Kimiwipe.

3.1.7.2 Laboratory Analyses

The top 2cm sediment subsamples stored in plastic jars had very watery consistencies, and thus underwent some mixing and re-stratification during sampling, transportation, and storage. Therefore, in order to obtain a representative subsample, these sediments had to be homogenized for laboratory analysis.

3.1.7.2.1 Porosity

For each station, two homogenized subsamples of the top 2cm of sediment were weighed using a Sartorius digital balance to obtain their wet weights. Both were dried for 48 hours at 55°C in a VWR scientific products 1370 GM gravity oven, desiccated in a sealed tub with Drierite for 2 hours, and weighed to obtain their dry weights. Water content was calculated as follows:

\[
\% \text{ Water Content} = \left(\frac{(\text{Wet Weight}) - (\text{Dry Weight})}{\text{Wet Weight}}\right) \times 100
\]

where: Wet Weight = Sample Wet Weight - Container Weight
      Dry Weight = Sample Dry Weight - Container Weight

Sediment porosity was set equal to % Water Content.

3.1.7.2.2 Bulk Density

The bulk density of sediment was calculated as follows:

\[
\text{Bulk Density} = \frac{\text{Sample Wet Weight}}{\text{Sample Wet Volume}}
\]
3.1.7.2.3 Organic Content

For each station, one homogenized subsample of the top 2cm of sediment was dried for 48 hours at 55°C in a VWR scientific products 1370 GM gravity oven, desiccated in a sealed tub with Drierite for 2 hours, and weighed using a Sartorius digital balance to obtain its dry weight. To remove organics, the sediment was then ashed in a ThermoLyne 1400 muffle furnace for 2 hours at 550°C, as specified in the total volatile solids ignition standards set by the U.S. EPA (1983). The ashed sediment was then desiccated for 2 hours with Drierite, and weighed to obtain its ashed weight. Organic content was calculated as follows:

\[
\text{% Organic Content} = \left( \frac{(\text{Dry Weight}) - (\text{Ashed Weight})}{\text{Dry Weight}} \right) \times 100
\]

where: Wet Weight = Sample Wet Weight - Container Weight
Ashed Weight = Sample Ashed Weight - Container Weight

3.1.7.2.4 Inorganic Carbon Content

For each station, one of the homogenized subsamples of the top 2cm of sediment was dried to obtain water content was pulverized, using a mortar and pestle, and placed into vials for carbon and nitrogen analysis. A UIC 5014 CO₂ coulometer was used to measure the inorganic carbon content for each of the subsamples. Sediment was weighed in small glass cups which were placed into larger glass test tubes using a pair of forceps. The tubes were then fitted onto the coulometer, ensuring a tight seal, and allowed to sit for 2 minutes to allow any CO₂ in the system to be flushed out. After 2 minutes, 5 mL of 20% HCl was used to evolve CO₂ from the calcium carbonate (CaCO₃) in the sediment samples, which in turn was interpreted by the coulometer to produce a reading 9 minutes later for μg carbon content. If sediment was visibly high in inorganic carbon content (e.g. shell matter) approximately 20-40 mg of the subsample was analyzed, whereas if sediment was not visibly high in inorganic carbon content (e.g. mostly sediment grains) approximately 70-90 mg of the subsample was analyzed. A blank value of μg inorganic carbon was measured first (i.e., no sample), followed by a test run to ensure consistent analysis of a 7-12 mg sample of 12% ±0.2 CaCO₃, and finally the sediment samples were analyzed. The corrected value of inorganic carbon for a sample was calculated as follows:
Sample Carbon* (µg) - Blank Carbon* (µg) x 100
Sample Weight (µg)

* coulometer reading

3.1.7.2.5 Organic Carbon and Nitrogen Content

Subsamples of dried sediment from the same vials used for inorganic carbon analysis were extracted for carbon and nitrogen analysis. A Carlo Erba NA-1500 Analyzer was used to measure organic carbon and nitrogen content for each of the subsamples. Sediment was weighed in small aluminum sample cups which were then crimped, sealed, and placed into a sample tray using a pair of forceps. If sediment was visibly high in inorganic carbon content, approximately 8-15mg of the subsample was analyzed, whereas if sediment was not visibly high in inorganic carbon content, approximately 20-30mg of the subsample was analyzed. Sample cups filled with blanks (i.e., no sample) and various weights of marine sediment standards (BESS and MESS) were also placed intermittently throughout each sample tray. Each sample tray was then run through the carbon nitrogen analyzer by Maureen Soon, UBC Earth and Ocean Sciences Lab.

3.1.7.2.6 Metals

For each station, one of the homogenized subsamples of the top 2cm of sediment was dried to obtain water content was pulverized, using a mortar and pestle, and placed into vials for metals analysis. The analysis was performed by Norwest Labs in Surrey, British Columbia. Norwest uses standard U.S. EPA method ICP-AES 200.15 for metals and trace elements analysis using ultrasonic nebulization (U.S. EPA, 1994). This method measures strong-acid leachable semi-trace metals in solids, and therefore provides concentrations of the solid phase metals complexed to the sediments (US EPA, 1994). The semi-trace detection limits were 1µg g⁻¹ for aluminum, 0.05µg g⁻¹ for cadmium, 0.1µg g⁻¹ for copper, 0.5µg g⁻¹ for lead, 5µg g⁻¹ for silicon, and 0.05µg g⁻¹ for zinc.
Each 60cc syringe core was allowed to thaw in a refrigerator overnight in order to be processed the following day for chlorophyll analysis. Each core was mounted to a laboratory counter with clamps, and the plunger was used to push the sediment up gradually from the bottom through the opening at the surface. A clean razor blade was used to slice and remove the following sediment layers from the surface downward: 0-1mm, 1-2mm, 2-5mm, 5-10mm, 10-15mm, 15-20mm, 20-25mm. A clear, plastic ruler was used to measure these increments. Each layer was placed into a scintillation vial and weighed to obtain a wet weight. EPA Method 445.0 (Arar and Collins, 1997) was used to analyze each subsample for chlorophyll content. 10mL of 90% acetone was pumped into the vials, and the mixture was homogenized, sealed, and placed in a fridge overnight (typically 18 hours) to allow time for the acetone to extract all the chlorophyll \(a\) out of the sediments. After 18 hours, the sediments settled out in the vials making it possible to pour approximately 8mL of the solvent into a glass cuvette. The cuvette was then placed in a Turner 10-AU Fluorometer, and a reading was taken for the fluorescence of the sample extract containing both pheophytin \(a\) and chlorophyll \(a\) pigments. Two drops of 10% HCl were added to the test tube to acidify the 8mL sample extract and remove the magnesium tail from each of the chlorophyll molecules, isolating the pheophytin \(a\) pigment and eliminating the chlorophyll \(a\) signal. A reading was then taken for the fluorescence of the sample extract containing only pheophytin \(a\).

A corrected chlorophyll \(a\) concentration for each sediment layer was obtained using the following equation:

\[
C_{Chla} = \frac{F_s (r/r-1) (R_b - R_a) (E_{vol}) \times DF}{S_{vol}}
\]

where:

- \(C_{Chla}\) = corrected chlorophyll \(a\) concentration (\(\mu g\) L\(^{-1}\)) in the sediment layer
- \(F_s\) = sensitivity coefficient
- \(r\) = before-to-after acidification ratio of a pure chlorophyll \(a\) solution
- \(R_b\) = fluorescence of sample extract before acidification
- \(R_a\) = fluorescence of sample extract after acidification
- \(E_{vol}\) = volume (L) of extract prepared before dilution
- \(S_{vol}\) = volume (L) of sediment layer
- \(DF\) = dilution factor
A pheophytin $a$ concentration was obtained using the following equation:

$$C_{Pa} = \frac{E_s (r/r-1) (rR_s - R_o) (E_{vol}) \times DF}{S_{vol}}$$

The remaining sediment slurry was dried under a fume hood for one week, and then weighed to obtain a dry weight. Water content, porosity, and bulk density were subsequently derived.

### 3.1.7.2.8 Sediment Grain Size

For each station, one full jar of subsample of the top 2cm of sediment was submitted for grain size analysis to Pacific Soils Analysis Labs, Richmond, British Columbia. Pacific Soils uses the pipette method to determine particle size, the Tanner and Jackson Nomograph I to determine sedimentation times, and wet sieving to determine sand content (McKeague, 1978). Grain sizes were determined for each of the fractions listed in Table 4.

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 2mm</td>
<td>gravel</td>
</tr>
<tr>
<td>&lt; 2mm</td>
<td>very coarse sand</td>
</tr>
<tr>
<td>&lt; 1mm</td>
<td>coarse sand</td>
</tr>
<tr>
<td>&lt; 500μm</td>
<td>medium sand</td>
</tr>
<tr>
<td>&lt; 250μm</td>
<td>fine sand</td>
</tr>
<tr>
<td>&lt; 100μm</td>
<td>very fine sand</td>
</tr>
<tr>
<td>&lt; 63μm</td>
<td>silt</td>
</tr>
<tr>
<td>&lt; 4μm</td>
<td>clay</td>
</tr>
<tr>
<td>&lt; 2μm</td>
<td>clay</td>
</tr>
</tbody>
</table>

Table 4: Grain sizes analysis fractions and descriptions.

### 3.2 Station Reassignments

Positional error in sampling can be caused by GPS error, navigational difficulties, and boat drift. In order to ensure accuracy for spatial data analysis, station positions were mapped and assessed for positional precision. Stations which were in a different location than had originally been intended were either (a) closer to another station and reassigned that station's number (b) assigned a new station number. Lists of station number reassignments are provided in Table 5 and Table 6.
Table 5: Changes made to station numbers as a result of positional errors at the Chained Islands site.

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Sample Type</th>
<th>Old Station #</th>
<th>New Station #</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>May, 2001</td>
<td>Reference</td>
<td>grab</td>
<td>CI 20</td>
<td>CI 21</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>grab</td>
<td>CI 20</td>
<td>CI 25</td>
<td>new</td>
</tr>
<tr>
<td></td>
<td>East Farm</td>
<td>core</td>
<td>CI 7</td>
<td>CI 26</td>
<td>new</td>
</tr>
<tr>
<td>July, 2001</td>
<td>West Farm</td>
<td>grab</td>
<td>CI 12</td>
<td>CI 11</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>West Farm</td>
<td>grab</td>
<td>CI 18</td>
<td>CI 27</td>
<td>new</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>core</td>
<td>CI 21</td>
<td>CI 28</td>
<td>new</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>core</td>
<td>CI 23</td>
<td>CI 29</td>
<td>new</td>
</tr>
<tr>
<td>March, 2002</td>
<td>East Farm</td>
<td>core</td>
<td>CI 8</td>
<td>CI 10</td>
<td>reassigned</td>
</tr>
</tbody>
</table>

Table 6: Changes made to station numbers as a result of positional errors at the Carrie Bay site.

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Sample Type</th>
<th>Old Station #</th>
<th>New Station #</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept, 2000</td>
<td>Farm</td>
<td>grab</td>
<td>C 1</td>
<td>C 2</td>
<td>reassigned</td>
</tr>
<tr>
<td>Aug, 2001</td>
<td>Farm</td>
<td>grab</td>
<td>C 2</td>
<td>C 1</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>Farm</td>
<td>grab</td>
<td>C 14</td>
<td>C 10</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>Farm</td>
<td>grab</td>
<td>C 21</td>
<td>C 24</td>
<td>reassigned</td>
</tr>
<tr>
<td>Sept, 2001</td>
<td>Farm</td>
<td>core</td>
<td>C 7</td>
<td>C 23</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>Farm</td>
<td>core</td>
<td>C 4</td>
<td>C 1</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>Farm</td>
<td>core</td>
<td>C 2</td>
<td>C 1</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
<td>core</td>
<td>R 2</td>
<td>R 1</td>
<td>reassigned</td>
</tr>
<tr>
<td>Jan, 2002</td>
<td>Farm</td>
<td>core</td>
<td>C 2</td>
<td>C 4</td>
<td>reassigned</td>
</tr>
<tr>
<td></td>
<td>Farm</td>
<td>core</td>
<td>C 10</td>
<td>C 1</td>
<td>reassigned</td>
</tr>
</tbody>
</table>

3.3 Data Analysis

The first stage of data analysis was the identification of habitat characteristics at each of the two sites. CHS charts, analysis of variance, contour mapping, descriptive statistics, and hydrographic information obtained from the Ministry of Water, Land and Air Protection were used to characterize each site according to bottom topography, hydrography, and sediment type, and to distinguish between these properties at farm and reference sites.
The second stage of data analysis was the analysis of physico-chemical aspects of sediment recovery at both sites. Analysis of variance, regression, contour mapping, GIS analysis, trend-plots, descriptive statistics, and various impact thresholds were used to assess differences between farm and reference sites, and the changes occurring at each site over time.

The third and final stage of data analysis was the isolation of a suite of sensitive physical and chemical indicators of sediment recovery at both sites. Analysis of variance, regression, contour mapping, GIS analysis, trend-plots, descriptive statistics, and various impact thresholds were used to isolate indicators of physico-chemical aspects of sediment recovery at each site. The results of the analysis of variance were used to determine the sensitivities of each of the indicators. Principal components analysis, correlation analysis, and regression analysis were used to determine redundancies amongst sediment variables in order to optimize the list of recommended indicators. Redundancies were said to exist amongst sediment variables which were highly correlated as well as meaningfully related.

### 3.3 Statistical Analysis

Excel and Systat 10.0 software were used to perform all statistical analyses.

#### 3.3.1 Descriptive Statistics

Descriptive statistics were used to summarize and show trends in the data. Bar graphs, means with standard deviations, time trend line plots, vertical core profile plots, and scatterplots were generated to describe trends in the sediment data collected at each abandoned farm site.

#### 3.3.2 Inferential Statistics

Inferential statistics were used to infer conclusions beyond those which were obvious by simply viewing the available data descriptively. Correlation, regression, principal components analysis, and analysis of variance were generated to infer trends in the sediment data collected at each abandoned farm site.
3.3.1.2.1 Correlation Analysis for Detecting Variable Redundancies

Correlation analysis is used to determine the strength of linear relationships between variables (Hicks and Turner, 1999; McGrew and Monroe, 1993). A highly correlative relationship implies there is a statistically significant correlation between two variables, but does not necessarily indicate a causal relationship (Sternstein, 1996). One particularly common method of correlation is Pearson’s Correlation Analysis (McGrew and Monroe, 1993). This analysis represents the strength of relationships between variables by using Pearson’s Correlation Coefficient, \( r \), to represent the degree to which data points cluster around a straight line (Walpole, 1982).

A correlation matrix can be generated to represent statistical correlations between variables (Manly, 2000). A Pearson Correlation Matrix was generated for each correlation analysis in order to represent the strength of linear relationships between measured variables. Each matrix contained correlation coefficients, \( r \), representing the degree to which the data points clustered around a straight line. When \( r \to 0 \), the variables exhibited a lack of linearity and thus a lack of correlation (Walpole, 1982). Conversely, when \( r \to 1 \) or \( r \to -1 \), the variables exhibited strong linearity, in the positive or negative direction, and thus were highly correlated. Collinearity, indicating possible dependence, exists between two variables when \( r \geq 0.9 \). (Tabachnick and Fidell, 2001; Wulder, 2001; Hicks and Turner, 1999). A scatterplot matrix containing one scatterplot per correlation (SPLOM plot) was also generated to visually assess relationships between each of the variables. A Bartlett Chi-Square test was used to test the significance of all correlations, and the results were displayed in a probability matrix of \( p \)-values.

For both sites, correlation analyses were run amongst variables measured within the top 2cm of sediment samples, and amongst variables measured throughout vertical core profiles. Variable pairs that were significantly linearly correlated \( (p \leq 0.05) \), meaningfully related, and were collinear \( (r \geq 0.9) \) were considered to be potentially redundant and were tested for dependence using regression analysis.

3.3.1.2.2 Regression Analysis for Detecting Variable Redundancies

Simple and multiple regression analyses can help to identify dependencies between variables (McGrew and Monroe, 1993). When examining the results of each regression analysis, three statistics were used to interpret the goodness of fit of a regression surface to the observations: an
F-test on the sum of squares regression versus the sum of squares residual error, the coefficient of determination \( (r^2) \), and the standard error of estimate (Hicks, 1999). A significant F-test indicated that the sum of squares regression was significantly larger than the sum of squares residuals, indicating a goodness of fit of the regression surface. The coefficient of determination, ranging between 0 and +1, indicated a stronger dependence of \( Y \) on \( X \) or some combination of \( X \)'s as \( r^2 \rightarrow 1 \). Finally, the standard error of estimate provided an explanation of the variation of the data points around the regression surface. The smaller the variation, the better the fit of the regression surface to the data points. The larger the variation, the more scattered the data points.

Goodness-of-fit for each regression curve was determined using the above three statistics and visual assessment of the curves themselves. The results were compiled and summarized within goodness-of-fit tables. Those results described as having "poor fit" were typical of data that were highly scattered, heteroscedastic, and non-normally distributed. Those results described as "mild fit" were typical of data that were heteroscedastic, quite scattered, and often slightly non-normal, non-linear, or with a low \( r^2 \) value. Typically such regression results were useful only to identify trends in the data, but could not be used to validate variable redundancies. Those results described as "fairly good fit" were typical of data that were slightly heteroscedastic or homoscedastic, slightly or quite scattered, and often with a higher \( r^2 \) value. Those results described as "good fit" were typical of data that were only slightly scattered or tightly fitting, slightly heteroscedastic or homoscedastic, and often with a high \( r^2 \) value.

For both sites, regression analysis was performed on variables measured within sediment cores and grabs that were determined to be significantly linearly correlated during correlation analysis, as well as those that appeared to be linearly or curvilinearly related on scatterplots. Variable pairs that were found to be meaningfully related, collinearly correlated \( (r \geq 0.9) \), and subsequently both demonstrated a significant regression relationship \( (p \leq 0.05) \) and were found to have a fairly good fit or a good fit, were defined as redundant.

3.3.1.2.3 Principal Components Analysis for Detecting Variable Redundancies

Principal components analysis attempts to reduce the total number of variables to a smaller number of principal components (Manly, 2000) by grouping variables in the most concise way in order to account for maximal variation in the data. The resulting groups are called principal components and can be thought of as new variables representing combinations of the original
variables. Each component or factor should exhibit a set of highly correlated variables that are independent from the other variables (Wulder, 2002).

For each site, the datasets collected from both the top 2cm sediment and from vertical core profiles were used to generate correlation matrices using Pearson Correlation Analysis. Rotation of a PCA solution is often necessary to make the results more meaningful and obvious for interpretation (Harris, 2001; Manly, 2000; Jackson, 1991; Jolliffe, 1986; Stevens, 1986; Srivastava and Carter, 1983). Kaiser's Varimax rotation (1958) is one of the most commonly used rotation methods because it repositions the results of a PCA such that, for a given component, the larger component loadings are accentuated and the smaller component loadings are depreciated (Fielding, 2001; Tabachnick and Fidell, 2001; Harris, 2001; Manly, 2000; Stevens, 1986; Srivastava and Carter, 1983). The correlation matrices were run through a Principal Components Analysis, and the component loadings were rotated using Varimax rotation with gamma = 1.0000. Only those principal components with eigenvalues > 1 were retained for analysis, according to Kaiser's (1960) commonly used rule of thumb (Fielding, 2001; Wulder, 2001; NIST/SEMATECH, 2000; Manly, 2000; Jolliffe, 1986; Stevens, 1986; Srivastava and Carter, 1983). According to this rule, the amount of variance explained by a significant component must be greater than that explained by a lone variable (Darlington, 2002).

There are several commonly used criteria for determining significant component loadings for inclusion in analysis. A typical rule of thumb is to include only component loadings > |0.3| or |0.4| (Schwab, 2002b; Harris, 2001; Hoffman, 2001; Tabachnick and Fidell, 2001; Stevens, 1986). However, after much consideration, it was determined that this criterion was not adequate for interpreting the results of the PCA analysis. When this rule of thumb was applied to the results of PCA, a large number of variables loaded significantly under more than one component, which goes against a fundamental principle of PCA (Harris, 2001; Tabachnick and Fidell, 2001). Stevens (1986) suggests a statistical method for determining significant component loadings, whereby the cutoff is equal to double the standard error (double the critical value for $r$ with N-2 degrees of freedom at $\alpha = 0.01$). Thus, a loading is significant if its absolute value is greater than the cutoff value. This method is recommended for sample sizes > 50. For sample sizes less than 50, the data were evaluated in order to select a cutoff that satisfied the general PCA principle that a variable ideally should not load highly under more than one component (Harris, 2001).
Since the first component explains the greatest proportion of variance in the data, the second component the next greatest proportion of variance, and so on (Garson, 2002), the results of the first principal component principal component are the most significant, the results of the second principal component are the second-most significant, and so on. A component is simply a linear combination of the original variables, and since the significant loadings for each component are highly correlated, each component provides useful information on how the total number of variables could be diminished to equal the number of components (Wulder, 2001; Manly, 2000; Jackson, 1991; Jolliffe, 1986; Stevens, 1986; Srivastava and Carter, 1983). For each site, principal components were used to categorize variables and identify redundancies amongst sediment variables measured within both the top 2cm of sediment and throughout vertical sediment cores.

3.3.1.2.4 Analysis of Variance

Analysis of Variance (ANOVA) was performed on the top 2cm sediment data collected at the Chained Islands and Carrie Bay sites with the intention of identifying differences between reference and farm sites, as well as changes over time.

Bonferroni- tests, Scheffe tests, and Tukey tests are among the most common post-hoc multiple means comparison tests for ANOVA (Simonoff, 2002; SPSS, 2000; Escobar, 1996; Winer et al., 1991). Scheffe tests are considered to be highly conservative (Tabachnick and Fidell, 2001; SPSS, 2000). Bonferroni- tests are more powerful than Tukey tests when the number of comparisons is small compared to the number of means (SPSS, 2000; Escobar, 1996). For each ANOVA run in this project, the number of means was never more than four, and thus the number of comparisons was never more than five. Bonferroni- tests were therefore chosen as the preferred method for determining significant differences among means.

3.3.1.2.4.1 Recovery Within the Entire Site

A two-way ANOVA was designed to test the effects of location, time, and location/time interaction on each of the geochemical and geophysical sediment variables measured within the top 2cm of sediment samples at both sites. The general sampling design is shown in Table 7.
Table 7: Sampling design for two-way ANOVA to test the effects of two factors (location, time) and their interaction (location x time) with unequal number of observations (x) in each experimental unit.

For the Chained Islands ANOVA, the locations used were the east farm, west farm, and reference sites. The times used were t1 = 1 month since abandonment, t2 = 3 months since abandonment, t3 = 8 months since abandonment, and t4 = 11 months since abandonment. Stations subjected to repeated measures acted as pseudoreplicates within each location.

For the Carrie Bay ANOVA, the locations used were the farm and reference sites. The times used were t1 = 11 months since abandonment, t2 = 24 months since abandonment, and t3 = 35 months since abandonment. Stations subjected to repeated measures acted as pseudoreplicates within each location.

Table 8: Summary for two-way ANOVA to test the effects of two factors (location, time) and their interaction (location x time) with unequal number of observations in each experimental unit [l = # locations, t = # times, nj = # pseudoreps (stations) in treatment j where j = 1...lt].

The summary for the two-factor ANOVA used to assess benthic habitat recovery at the two sites is shown in Table 8. The analysis was repeated for each of the geochemical and geophysical sediment variables collected during sampling. The measurements taken at each of the pseudoreplicates (stations) were averaged in the analysis in order to provide a mean for each
location (experimental unit). Thus, individual pseudoreplicates were not compared within this type of analysis, and patterns of spatial variation within location could not be identified.

If the result of the F-Test \( \frac{\text{MS}_{L \times T}}{\text{MS}_E} \) was significant, then there was a significant interaction between location and time — that is, location means were varying with respect to time. This could be an indicator of recovery, depending on the results. Significant interactions were assessed graphically. Next, the interactions were assessed statistically by looking at the results of two sets of Bonferroni t-tests. The first was used to compare location means within time. The results for this test indicated for each sampling time whether or not the measurements at the farm or reference sites were significantly different from one another. The second Bonferroni t-test was used to compare time means within location. The results for this test indicated for each sampling site whether or not the measurements at each of the sampling times varied significantly from one another. If a significant location x time interaction was identified, it was considered unnecessary to test the effects of time and location separately.

If the result of the F-Test \( \frac{\text{MS}_{L \times T}}{\text{MS}_E} \) was not significant, however, then the effects of time and location were tested individually. If the result of the F-Test \( \frac{\text{MS}_L}{\text{MS}_E} \) was significant, then location had a significant effect whereby the means for at least one pair of the farm or reference sites differed significantly from one another (for all times grouped together). If the result of the F-Test \( \frac{\text{MS}_T}{\text{MS}_E} \) was significant, then time had a significant effect whereby the means for at least one pair of sampling times differed significantly from one another (for all locations grouped together). If location and/or time effects were significant, the means were compared using a Bonferroni t-test in order to see which locations and/or times varied significantly.

### 3.3.1.2.4.2 Recovery At 0-50m, 50-100m, & >100m from Farm

A two-way ANOVA was designed to test the effects of location, time, and location/time interaction on each of the geochemical and geophysical sediment variables measured within the top 2cm of sediment samples at reference stations and farm stations located within the range of 0-50m, 50-100m, and >100m of the approximate farm centers. These distance increments were chosen in order to include sufficient degrees of freedom in each category. Therefore, three individual ANOVAs were conducted for each of the distance categories to ascertain recovery patterns at various distances from each of the farm centers. The sampling design, summary of
formulae, and statistical tests for each ANOVA are identical to those described for the ANOVA between all farm stations and all reference stations in Section 3.3.1.2.4.1.

3.3.1.2.4.3 Recovery Within Farm

A two-way ANOVA was designed to test the effects of distance, time, and distance/time interaction on each of the geochemical and geophysical sediment variables measured within the top 2cm of sediment samples at the farm sites. The distances used were 0-50 meters, 50-100 meters, and >100 meters from the approximate farm center. These increments were chosen to include sufficient degrees of freedom in each category. Stations subjected to repeated measures acted as pseudoreplicates within each location. The sampling design is shown in Table 9.

<table>
<thead>
<tr>
<th>DISTANCE</th>
<th>0-50m</th>
<th>50-100m</th>
<th>&gt;100m</th>
</tr>
</thead>
<tbody>
<tr>
<td>t1</td>
<td>x</td>
<td>x x</td>
<td>x x</td>
</tr>
<tr>
<td>t2</td>
<td>x x x</td>
<td>x x x</td>
<td>x x x</td>
</tr>
<tr>
<td>t3</td>
<td>x x x x</td>
<td>x x x x</td>
<td>x x x</td>
</tr>
<tr>
<td>:</td>
<td>x x x x x</td>
<td>x x x x x</td>
<td>x x x</td>
</tr>
</tbody>
</table>

Table 9: Sampling design for two-way ANOVA to test the effects of two factors (distance, time) and their interaction (distance x time) with unequal number of observations (x) in each experimental unit.

The summary of formulae and statistical tests for the ANOVA are identical to those described for the ANOVA between all farm stations and all reference stations in Section 3.3.1.2.4.1; however, in this case, distance effects are substituted for location effects.

3.3.1.2.4.4 Variation Within Reference

A one-way ANOVA was designed to test the effects of time on each of the geochemical and geophysical sediment variables measured within the top 2cm of sediment samples at the reference sites. The sampling design is shown in Table 10.

<table>
<thead>
<tr>
<th>Reference</th>
<th>t1</th>
<th>t2</th>
<th>t3</th>
</tr>
</thead>
<tbody>
<tr>
<td>t1</td>
<td>x x x x x</td>
<td>x x x x x</td>
<td>x x x x x</td>
</tr>
<tr>
<td>t2</td>
<td>x x x x x</td>
<td>x x x x x</td>
<td>x x x x x</td>
</tr>
<tr>
<td>t3</td>
<td>x x x x x</td>
<td>x x x x x</td>
<td>x x x x x</td>
</tr>
</tbody>
</table>

Table 10: Sampling design for one-way ANOVA to test the effects of one factor (time).
The summary for the one-factor ANOVA used to assess time effects at the reference sites is shown in Table 11. The analysis was repeated for each of the geochemical and geophysical sediment variables collected during sampling.

If the result of the F-Test ($\frac{MS^*_T}{MS^*_E}$) was significant, then time had a significant effect whereby the means for at least one pair of sampling times differed significantly one another. If time effects were significant, the means were compared using a Bonferroni $t$-test in order to see which times varied significantly.

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom</th>
<th>Adjusted Sums of Squares</th>
<th>Adjusted Mean Squares</th>
<th>F-Test Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>$t - 1$</td>
<td>$SS^*_T$</td>
<td>$MS^*_T$</td>
<td>$MS^<em>_T / MS^</em>_E$</td>
</tr>
<tr>
<td>Error</td>
<td>$\sum_{j=1}^{t} n_j - t$</td>
<td>$SS^*_E$</td>
<td>$MS^*_E$</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$\sum_{j=1}^{t} n_j - 1$</td>
<td>$SS^*_{TL}$</td>
<td>$MS^*_{TL}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 11: Summary for one-way ANOVA to test the effects of one factor (time) with unequal number of observations in each experimental unit [$t =$ # times, $n_j =$ # pseudoreps (stations) in treatment $j$ where $j = 1...t$].

### 3.3.1.2.4.5 Recovery Indicator Sensitivities

Recovery indicators were defined as any variables which demonstrated significant and logical changes indicative of physico-chemical aspects of sediment recovery. For those factors found to have a significant effect ($p \leq 0.05$) on a set of one or more indicator variables, the sensitivity of those indicators was determined by ranking the $p$ values. Lower $p$ values corresponded to more sensitive indicators, and higher $p$ values corresponded to less sensitive indicators.

### 3.3.2 GIS Modelling, Mapping, and Analysis

#### 3.3.2.1 Contour Maps of Spatio-Temporal Trends (Horizontal - Top 2cm Sediment)

The locational coordinates obtained from the GPS at each station during sample collection were entered into an Excel spreadsheet along with sediment variable values. The spreadsheet was converted to DBF format and imported into ArcView 3.1 GIS, where it was used to create
georeferenced station points. Digital nautical charts produced by Canadian Hydrographic Service (CHS) were imported into ArcView. The georeferenced sample station points were placed over the CHS base maps, and sample site maps were created. The location of the net pens at the Chained Islands site was estimated from airphotos and drawings provided by the farm operators. The location of the farm at the Carrie Bay site was estimated from a symbol marked on CHS Chart #3546 (Levings and Sutherland, 1999). The estimated location of the net pens at each site was digitized and added to the GIS maps. The GIS was then used to determine the geographical centroid of each fish farm, as well as the distance and bearing of each sampling station to the nearest fish farm.

The spreadsheet was imported into Surfer 7.0, a surface mapping program. Kriging interpolation was used to generate a grid of interpolated values from the sampled values at each site. Kriging is a flexible method of interpolation that has been found to be optimal, particularly in the event of sparse data (Burrough and McDonnell, 1998; Chang et al., 1998; Danielsson et al., 1998). The grids were then used to generate contour maps in order to identify visual patterns in the data. Contour maps were only generated when there were ample stations from which to accurately interpolate unknown points. The spatial distributions of core sample stations at the Chained Islands site were too sparse to justifiably create contour maps. Since interpolation relies on using values at adjacent known points to predict values at unknown points, contours for each sampling time were allowed to extend to a boundary that was half the distance between the two furthest, adjacent sampling points at a site. Contour maps were imported into ArcView GIS for spatial analysis.

A reference map showing the scale and orientation at the Chained Islands site was used as a spatial guide for interpreting the contour maps (Figure 16). Maps of sediment grain size and depth were also used for interpretation of maps of environmental variables.

Reference maps showing the station locations, interpolation boundary, approximate net-pen perimeter, scale, and orientation at the Carrie Bay site were used as spatial guides for interpreting the contour maps for each sampling time (Figure 17). Maps of sediment grain size and depth were also used for interpretation of maps of environmental variables.
Figure 16: Scale and orientation of contour maps at the Chained Island site.
Figure 17: Scale and orientation of contour maps at the Carrie Bay site.
3.3.2.2 GIS Maps of Spatio-Temporal Trends (Vertical - Sediment Core Profiles)

Vertical core profile plots were exported from Excel as individual image files, and imported into ArcView where they were arranged on a GIS map in order to determine spatial trends at each site.

3.3.3 Thresholds for Assessing Impact and Recovery

Of the six metals included in the data analysis (aluminum, cadmium, copper, lead, silicon, and zinc), the four listed in Table 12 have been identified to have marine Interim Sediment Quality Guidelines (ISQG) and Probable Effects Levels (PEL) according to Environment Canada's marine sediment quality guidelines (1995). Concentrations of solid phase metals, normalized by sediment grain size, are good predictors of porewater concentrations of bioavailable free metal ions (Chapman et al., 1998). The method used to assess metals for this project looked at the solid phase metals complexed to the sediments (US EPA, 1994). Metals concentrations were not normalized since spatial sediment homogeneity was assumed. The sediment toxicity guidelines to which metals concentrations were compared also looked only at the solid phase metals (CCME, 1995; Environment Canada, 1995). The Environment Canada guidelines suggest one blanket toxicity threshold for each of the metals, regardless of sediment grain size or other confounding factors. The non-normalized metals concentrations measured at both of the farm sites were compared to these singular toxicity thresholds in order to test for compliance with sediment quality guidelines. At the Chained Islands site, overall distributions of sediment grain size varied somewhat between the reference and farm sites, and thus some caution was exercised when comparing concentrations between the two regions of the site. At the Carrie Bay site, overall distributions of sediment grain size were similar between the reference and the farm sites.

<table>
<thead>
<tr>
<th>Metal</th>
<th>ISQG (µg g⁻¹)</th>
<th>PEL (µg g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium</td>
<td>0.7</td>
<td>4.2</td>
</tr>
<tr>
<td>Copper</td>
<td>18.7</td>
<td>108</td>
</tr>
<tr>
<td>Lead</td>
<td>30.2</td>
<td>112</td>
</tr>
<tr>
<td>Zinc</td>
<td>124</td>
<td>271</td>
</tr>
</tbody>
</table>

Table 12: Environment Canada's (1995) marine Interim Sediment Quality Guidelines (ISQG) and Probable Effects Levels (PEL) for Cd, Cu, Pb, and Zn.
In Eastern Canada, sediment sulphides levels > 6000μM have been reported to be associated with anoxic conditions, and 1300-6000μM with hypoxic conditions (Wildish et al., 1999). In Western Canada, Erickson et al. (2001) associate sulphide levels > 600μM with potential benthic impact, and levels > 1500μM with probable benthic impact.

Zobell (1946) and Wildish et al. (1999) found that anaerobic processes and anoxic conditions dominate when sediment redox potential is < -100mV. Wildish et al. (1999) and Erickson et al. (2001) also call attention to values < 0mV, associating them with hypoxic conditions.

The minimum oxygen concentration required to sustain marine aquatic life has been identified to be 5ppm (Reish, 1972).

Brooks (2000a) reported the mean organic content (total volatile solids) value for well-flushed reference sites in British Columbia to be 4.3%±0.9. Brooks (1996) also reports the total organic carbon triggers in Puget Sound, Washington to be 1.7% for 20-50% silt-clay sediments, 3.2% for 50-80% silt-clay sediments, and 2.5% for 80-100% silt-clay sediments. If organic carbon values exceed these triggers during an impact assessment, the sediments are to be evaluated for the health of the infaunal community.

An organic C:N ratio was generated for the purpose of impact detection in order to provide some evidence as to the origins of organic matter within sediments. C:N for marine sediments has been reported to be 5-6 in the Northern Strait of Georgia, British Columbia (Macdonald and Crecelius, 1994) and 6-10 elsewhere (Sutherland et al., 2001). Terrestrial inputs to marine sediments in British Columbia have been reported to have a C:N of 10->30 (Macdonald and Crecelius, 1994).

Contour maps were generated on the basis of the above thresholds, and results were reported for those sediment variables that exceeded the thresholds on any given sampling date. Maps of line graphs showing depth trends for redox potential, oxygen, and sulphides were also observed for threshold exceedances. The contour maps and GIS maps were also observed for recovery of any of the variables that were in exceedance of thresholds. Mean values of organic C:N, organic content, and organic carbon for each time/location combination were also compared to thresholds.
4 Results

Table 13 and Table 14 summarize the results of the recovery assessments for each site as measured within the top 2cm of sediment. Detailed results on analyses of the top 2cm of sediment and sediment cores are presented in subsequent sections.
<table>
<thead>
<tr>
<th>Site</th>
<th>Farm Production Level</th>
<th>Site Characteristics</th>
<th>Months Since Site Abandoned</th>
<th>Total # Grab Stations</th>
<th>Copper</th>
<th>Zinc</th>
<th>Cadmium</th>
<th>Total # Core Stations</th>
<th>Redox Potential</th>
<th>Sulphides</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI - East Farm Low</td>
<td>~27m depth; rocky outcrop and coarser, shelly sediments nearshore; organic-laden silt and finer sand in deeper areas</td>
<td>1</td>
<td>8</td>
<td>8 (of 8)</td>
<td>0 (of 8)</td>
<td>8 (of 8)</td>
<td>3 (of 8)</td>
<td>0 (of 3)</td>
<td>0 (of 3)</td>
<td></td>
</tr>
<tr>
<td>CI - West Farm Low</td>
<td>~31m depth; rocky outcrop and coarser, shelly sediments nearshore; organic-laden silt and finer sand in deeper areas</td>
<td>1</td>
<td>6</td>
<td>3 (of 6)</td>
<td>0 (of 6)</td>
<td>6 (of 6)</td>
<td>0 (of 6)</td>
<td>0 (of 3)</td>
<td>0 (of 3)</td>
<td></td>
</tr>
<tr>
<td>CI - Reference n/a</td>
<td>~30m depth; organic-laden silt and finer sand and some fine clay; absence of gravel and rock</td>
<td>1</td>
<td>2</td>
<td>2 (of 2)</td>
<td>0 (of 2)</td>
<td>0 (of 2)</td>
<td>1 (of 2)</td>
<td>0 (of 1)</td>
<td>0 (of 1)</td>
<td></td>
</tr>
</tbody>
</table>

Table 13: Summarized results of recovery within the top 2cm of sediment at the Chained Islands (CI) site.

<table>
<thead>
<tr>
<th>Site</th>
<th>Farm Production Level</th>
<th>Site Characteristics</th>
<th>Months Since Site Abandoned</th>
<th>Total # Grab Stations</th>
<th>Copper</th>
<th>Zinc</th>
<th>Cadmium</th>
<th>Total # Core Stations</th>
<th>Redox Potential</th>
<th>Sulphides</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB - Farm High</td>
<td>~35m depth; organic-laden silt and clay, with some finer sand and small amounts of coarser sand and gravel</td>
<td>11</td>
<td>13</td>
<td>13 (of 13)</td>
<td>7 (of 13)</td>
<td>0</td>
<td>0</td>
<td>0 (of 3)</td>
<td>0 (of 3)</td>
<td></td>
</tr>
<tr>
<td>CB - Reference n/a</td>
<td>~37m depth; organic-laden silt and clay, with some finer sand and small amounts of coarser sand and gravel</td>
<td>11</td>
<td>3</td>
<td>3 (of 3)</td>
<td>0 (of 3)</td>
<td>0</td>
<td>0</td>
<td>0 (of 3)</td>
<td>0 (of 3)</td>
<td></td>
</tr>
</tbody>
</table>

Table 14: Summarized results of recovery within the top 2cm of sediment at the Carrie Bay (CB) site.
4.1 Chained Islands

4.1.1 Habitat Characteristics

4.1.1.1 Descriptive Trends

Sediments at both the Chained Islands east and west farm sites consisted mostly of silt and finer sand with some finer clay and gravel, while sediments at the reference site consisted of a majority of silt and finer sand with some finer clay (Figure 18). The northernmost, nearshore edges of each farm were situated near shallow, rocky outcrops which precluded sampling.

Figure 18: Frequency distributions of sediment grain sizes averaged for all sampling trips at the Chained Islands east farm site (N=30), west farm site (N=25), and reference site (N=20).

The average depth was 27.0±6.3 meters at the east farm site, 31.0±9.7 meters at the west farm site, and 29.9±3.9 meters at the reference site.
4.1.1.2 **Analysis of Variance (Within the Entire Site)**

Medium sand and silt were significantly greater at the Chained Islands east farm site than at the reference site, while fine sand was significantly lower. Significantly lower values of fine sand were identified at the west farm site than at any other location within the Chained Islands site.

4.1.1.3 **Analysis of Variance (Within 50m of the Farms)**

Clay (<2μm) was found to be significantly greater within 50 meters of the Chained Islands east farm than within 50 meters of the west farm, and significantly lower within 50 meters of the west farm than at the reference site. Medium sand was greatest within 50 meters of the east and west farms, significantly so at many times during the study.

4.1.1.4 **Analysis of Variance (At 50-100m from the Farms)**

At both the Chained Islands east and west farm sites, medium sand was significantly higher and fine sand was significantly lower at 50-100 meters from the farms than at the reference site.

4.1.1.5 **Analysis of Variance (At >100m from the Farms)**

Medium sand was significantly greater at distances of >100 meters from the Chained Islands east farm than at distances of >100 meters from the west farm and at the reference site. Fine sand was significantly lower at distances of >100 meters from the east farm than at the reference site.

4.1.1.6 **Analysis of Variance (Within the Farm Sites)**

The only detectable variation in habitat characteristics within the Chained Islands east farm site was the significantly higher levels of medium sand at 50-100 meters from the farm than at distances of >100 meters. No variations in habitat characteristics were detected between distance categories at the west farm site.
4.1.1.7  Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for depth and each of the sediment grain size variables measured at the Chained Islands site (Appendix I). Very fine sand and fine sand were greatest to the south of the farms, in the deeper sediments. These grain size fractions were also dominant at the reference site, along with clay and silt. Gravel was absent or nearly absent throughout most of the Chained Islands site, with the greatest amounts being found in the nearshore area to the north of the east and west farm sites. Clay, medium sand, coarse sand, and very coarse sand appeared to reach their maximal values within these nearshore areas also. Silt was most pronounced at the east farm site, particularly within the southerly regions.

4.1.2  Recovery

4.1.2.1  Organic Matter

4.1.2.1.1  Time Trend Plots

Between 3 and 11 months following site abandonment, organic content decreased at all of the Chained Islands reference stations (Appendix A). Organic content did not change significantly over the study period at the east or west farm sites.

4.1.2.1.2  Analysis of Variance (Within the Entire Site)

Nitrogen, organic carbon, and organic content were significantly greater at the Chained Islands east farm site than at the west farm and reference sites. Total carbon and inorganic carbon were significantly greater at the east farm site than at the reference site.

4.1.2.1.3  Analysis of Variance (Within 50m of the Farms)

Nitrogen was found to be significantly higher within 50 meters of the east farm than within 50 meters of the west farm or at the reference site.
4.1.2.1.4 Analysis of Variance (At 50-100m from the Farms)

Levels of chlorophyll, total carbon, nitrogen, organic carbon, and organic content were determined to be significantly higher at 50-100 meters from the Chained Islands east farm than at the reference site.

4.1.2.1.5 Analysis of Variance (At >100m from the Farms)

Total carbon, nitrogen, organic carbon, and organic content were significantly greater at distances of >100 meters from the Chained Islands east farm than at distances of >100 meters from the west farm and at the reference site.

4.1.2.1.6 Analysis of Variance (Within the Farm Sites)

Chlorophyll was significantly greater at stations 50-100 meters from the Chained Islands east farm than at those at distances of >100 meters.

4.1.2.1.7 Analysis of Variance (Within the Reference Site)

No organic matter variables exhibited significant temporal variation within the Chained Islands reference site.

4.1.2.1.8 GIS Maps (Vertical Core Profiles)

Several spatial and temporal trends in sediment chlorophyll collected from grab samples at the Chained Islands site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix K). Typically, chlorophyll values fluctuated seasonally and corresponded to station depth. Chlorophyll at the surface was highest in the shallower sediments at stations nearest the farms in the north and westerly directions, and was typically higher in July 2001 than on subsequent dates. Typically, chlorophyll values rapidly declined to a minimum somewhere within the first 1.5 centimeters, and then remained at a relatively constant level with increasing depth beyond this point. The chlorophyll minimum at all stations in spring and summer was deeper (5-15mm) than in early and late winter (2-5mm), and gradients throughout the sediment
cores were significantly less pronounced in the winter months than in the summer months. Trend plots such as the one in Figure 19 depict natural seasonal chlorophyll variations typical of stations sampled within the Chained Islands site.

![Figure 19: Chlorophyll concentration sediment depth profiles (0-25mm) for each time sampled at station CI2 at the Chained Islands east farm site.](image)

4.1.2.1.9 Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for each of the organic matter variables measured at the Chained Islands site (Appendix I). In the nearshore areas, to the north of the east farm, nitrogen, organic carbon, total carbon, inorganic carbon, organic content, and chlorophyll appeared to reach some of their maximal values. Organic content, nitrogen, total carbon, and organic carbon appeared to be most pronounced at the east farm site, the latter three particularly in May 2001 (Figure 20, Figure 21, and Figure 22). Temporal fluctuations in sediment chlorophyll throughout the site were seasonal.
Figure 20: Contour maps showing spatio-temporal total carbon concentration distributions at the Chained Islands site.

Figure 21: Contour maps showing spatio-temporal nitrogen concentration distributions at the Chained Islands site.

Figure 22: Contour maps showing spatio-temporal organic carbon concentration distributions at the Chained Islands site.
4.1.2.1.10 Impact and Recovery Based on Thresholds (Within the Top 2cm of Sediment)

Contour maps of organic C:N ratios (Figure 23 and Appendix I) identified most of the organic content of the sediments at the Chained Islands site to have ranges bordering between those associated with marine and terrestrial origin. The maps showed evidence of slightly pronounced organic C:N ratios particularly at the east farm site, and to a lesser degree at the reference site, within the first month following site abandonment. Despite minor spatial fluctuations in organic C:N ratios over time, there was no obvious recovery as indicated by the nature of the organic matter in the sediments at the Chained Islands site, nor could any visible distinction be made between the nature of organic matter in sediments closer to the abandoned fish farm sites and those farther away.

Figure 23: Contour maps showing spatio-temporal organic C:N distributions at the Chained Islands site (areas shaded green have ratios characteristic of marine organic matter; areas shaded brown have ratios characteristic of terrestrial organic matter - Note: Colour map also available in Appendix I on CD).

Mean values of organic content measured at all times at the Chained Islands east farm site were slightly higher than the threshold value. Mean values of organic content measured at 1 and 3 months following abandonment of the west farm site were slightly elevated above threshold. From 8 months following site abandonment onward, mean organic content at the west farm site
remained well within natural limits. Mean values of organic content measured at all times at the reference site remained below the threshold.

Mean organic carbon values measured at all times within the entire Chained Islands site remained below thresholds.

There was no association between any of the organic matter variables and sediment oxygen variables measured within the top 2cm of sediment throughout the Chained Islands site (Appendix C). Thus, there was no evidence suggesting that organic matter accumulations were significantly affecting sediment oxygen conditions at the site.

4.1.2.2 Sediment Physical Properties

4.1.2.2.1 Time Trend Plots

Between 3 and 11 months following site abandonment, medium sand underwent an overall decrease at all of the Chained Islands reference stations (Appendix A). Medium sand did not change significantly over the study period at the east or west farm sites. At many of the stations throughout the study site, fine sand was lower within the sediments at 1 month following site abandonment than at all other times.

4.1.2.2.2 Analysis of Variance (Within the Entire Site)

Fine sand percentages over the entire Chained Islands site were significantly lower at 1 month following site abandonment than at all other times.

Porosity was significantly higher and bulk density was significantly lower at the east farm site than at the west farm and reference sites.

4.1.2.2.3 Analysis of Variance (Within 50m of the Farms)

When analyzing Chained Islands reference stations and farm stations within 50 meters of the farm centers, it was discovered that at the reference site only, medium sand underwent a significant gradual decrease over time.
Bulk density was found to be lower within 50 meters of the east farm than at the reference site. Porosity was found to be significantly higher within 50 meters of the east farm than within 50 meters of the west farm or at the reference site.

4.1.2.4 Analysis of Variance (At 50-100m from the Farms)

Porosity was significantly higher and bulk density was significantly lower at 50-100 meters from the east farm than at the reference site.

4.1.2.5 Analysis of Variance (At >100m from the Farms)

Porosity was significantly greater at distances of >100 meters from the east farm than at distances of >100 meters from the west farm and at the reference site. Bulk density was significantly lower at distances of >100 meters from the east farm than at the reference site.

4.1.2.6 Analysis of Variance (Within the Farm Sites)

No sediment physical property variables exhibited significant temporal, spatial, or spatio-temporal variation within either of the Chained Islands farm sites.

4.1.2.7 Analysis of Variance (Within the Reference Site)

No sediment physical property variables exhibited significant temporal variation within the Chained Islands reference site.

4.1.2.8 GIS Maps (Vertical Core Profiles)

Several spatial and temporal trends in sediment porosity collected from grab samples at the Chained Islands site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix K). Porosity at all times and at all locations tended to decrease with sediment depth to a minimum anywhere from 2-25mm below the surface, remaining relatively constant with increasing depth beyond that point. Occasionally, some stations at each location exhibited a
small pocket of slightly elevated porosity, typically within 5-15mm depth, decreasing again after 5-20mm. Porosity did not appear to vary much with distance from the farm or with time.

Figure 24: Porosity, bulk density, and chlorophyll sediment depth profiles (0-25mm) sampled at station CI14 in May 2001 at the Chained Islands west farm site.

Several spatial and temporal trends in sediment bulk density collected from grab samples at the Chained Islands site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix K). Bulk density at most stations at all locations and times tended to increase within the first 2mm of sediment, and then proceeded to decrease quickly to subsurface values. Regions of higher bulk density occurred in the deeper areas of the site. Otherwise, bulk density at all locations and times typically remained relatively constant from about 5-10mm downward through the sediment core. Occasionally, some stations at each location exhibited a small pocket of slightly elevated porosity, typically within 5-15mm depth, decreasing again after 5-20mm. No significant variation with time or distance from the farm was observed.

The trend plot shown in Figure 24 demonstrates a sediment property profile typical of stations sampled within the Chained Islands site.
4.1.2.9 Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for each of the sediment physical property variables measured at the Chained Islands site (Appendix I). Porosity appeared to be most pronounced at the east farm site, particularly in May 2001 (Figure 25). Bulk density was visibly at its lowest levels in May 2001 than at all other sampling times. Temporal fluctuations in sediment temperature throughout the site were seasonal.

Figure 25: Contour maps showing spatio-temporal porosity concentration distributions at the Chained Islands site.

4.1.3 Metals

4.1.3.1 Time Trend Plots

Cadmium and zinc at 1 month following site abandonment were slightly elevated above values observed at all other times at most stations within the Chained Islands east and west farm sites (Appendix A). Neither metal changed substantially over time at the reference site. Silicon at most of the reference stations increased between 3 and 11 months following site abandonment. Silicon did not change substantially with time at either of the farm sites.

4.1.3.2 Analysis of Variance (Within the Entire Site)

Cadmium and zinc concentrations within the Chained Islands site were significantly higher 1 month after site abandonment than at all other times during the study. Cadmium concentrations within the entire site were significantly lower 11 months following site abandonment.
Concentrations of copper and lead were significantly higher at the east farm site than at the west farm and reference sites.

4.1.2.3.3 Analysis of Variance (Within 50m of the Farms)

Copper was found to be significantly higher within 50 meters of the east farm than within 50 meters of the west farm or at the reference site. Zinc was found to be greater within 50 meters of the east farm than at the reference site.

4.1.2.3.4 Analysis of Variance (At 50-100m from the Farms)

Lead was the only indicator that was significantly greater at 50-100 meters from the east farm than at 50-100 meters from the west farm. Silicon levels were significantly lower at 50-100 meters from the east farm than at the reference site.

4.1.2.3.5 Analysis of Variance (At >100m from the Farms)

Copper and lead were significantly greater at distances of >100 meters from the east farm than at distances of >100 meters from the west farm and at the reference site. Levels of zinc were significantly greater at distances of >100 meters from the east farm than at the reference site.

4.1.2.3.6 Analysis of Variance (Within the Farm Sites)

At the Chained Islands east and west farm sites, cadmium concentrations were significantly higher at 1 month following site abandonment than at all other times during the study. Zinc concentrations at the east farm site were significantly higher at 1 month following site abandonment than at 3 and 11 months. Cadmium at the west farm site, and cadmium and zinc at the east farm site clearly decreased after farm removal. Copper was significantly less at stations 50-100 meters from the east farm than at those at distances of >100 meters.

4.1.2.3.7 Analysis of Variance (Within the Reference Site)

At the Chained Islands reference site, cadmium and zinc concentrations were significantly higher at 1 month following site abandonment, and significantly lower at 11 months than at all other
times during the study. Clearly both metals had significantly decreased throughout the study period at the reference site.

4.1.2.3.8 Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for each of the metals variables measured at the Chained Islands site (Appendix I). Copper, lead, and zinc appeared to be most pronounced at the east farm site, the latter particularly in May 2001 (Figure 26).

The greatest levels of lead were present within the southern portion of the east farm site. Zinc was greatest at the east farm and reference sites at all times, with the exception of one localized area of elevated zinc within the west farm site in May 2001. At the east farm site, zinc tended to be elevated at stations to the south of the farm, away from the shore.

![Contour Maps](image.png)

Figure 26: Contour maps showing spatio-temporal zinc concentration distributions at the Chained Islands site (not normalized to account for spatial variances in grain size present throughout the site).

Silicon was visibly at its lowest levels in May 2001 than at all other sampling times and, particularly at the reference site, showed a marked increase by March 2002 (Figure 27). Silicon was typically at its highest to the south of the farms, in the deeper sediments within the entire site.

Cadmium was at its maximum throughout the Chained Islands site in May 2001, and demonstrated a pronounced decrease throughout the entire site by March 2002. At all times, cadmium was higher at stations to the south of the farms, within the deeper sediments.
4.1.2.3.9 Impact and Recovery Based on Thresholds (Within the Top 2cm of Sediment)

Cadmium concentrations at many of the sampling stations in the Chained Islands site on all sampling dates exceeded the ISQG threshold. Contour maps (Figure 28 and Appendix I) demonstrate that cadmium throughout the entire sampling area in May and December 2001 exceeded the threshold.

The contour maps for July 2001 and March 2002 show only the southern portion of the sampling area, nearer to the farm sites, to contain concentrations higher than threshold.

Copper concentrations at many of the sampling stations in the Chained Islands site on all sampling dates exceeded the ISQG threshold. Contour maps (Figure 29 and Appendix I) and the results of the analysis of variance (Appendix G) show the highest concentrations falling at the stations in the vicinity of the eastern farm site.
Figure 28: Contour maps showing spatio-temporal cadmium concentration distributions at the Chained Islands site (areas shaded green fall below the ISQG threshold; areas shaded blue exceed the threshold) (not normalized to account for spatial variances in grain size present throughout the site - Note: Colour map also available in Appendix I on CD).

Figure 29: Contour maps showing spatio-temporal copper concentration distributions at the Chained Islands site (areas shaded green fall below the ISQG threshold; areas shaded blue exceed the threshold) (not normalized to account for spatial variances in grain size present throughout the site - Note: Colour map also available in Appendix I on CD).
At the east farm site, the percentage of repeatedly measured stations exceeding the ISQG thresholds for both copper and cadmium fluctuated over time, but had decreased overall by the conclusion of the study period (Table 15).

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>% Stations Exceeding Cd ISQG (0.7 μg/g)</th>
<th>% Stations Exceeding Cu ISQG (18.7 μg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entire Site</td>
<td>May, 2001</td>
<td>100</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>July, 2001</td>
<td>79</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>Dec, 2001</td>
<td>94</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Mar, 2002</td>
<td>72</td>
<td>67</td>
</tr>
</tbody>
</table>

Table 15: Percentage of Chained Islands stations exceeding cadmium and copper ISQG thresholds over time.

At the west farm site, the percentage of repeatedly measured stations exceeding the ISQG threshold for cadmium recovered somewhat between 8 and 11 months following site abandonment. Cadmium stayed above the ISQG threshold throughout the entire reference site at all times. The percentage of repeatedly measured stations exceeding the ISQG threshold for
copper actually increased over time at the west farm site. The percentage of stations exceeding the ISQG threshold for copper at the reference site decreased overall, but exhibited fluctuations over time.

By the conclusion of the study, at 11 months following site abandonment, cadmium at 43% of the east farm stations, 83% of the west farm stations, and 100% of the reference stations had yet to reach sub-ISQG concentrations. Copper at 71% of the east farm stations, 67% of the west farm stations, and 60% of the reference stations also had yet to reach sub-ISQG concentrations.

Lead and zinc concentrations at the Chained Islands site remained well below ISQG thresholds.

Cadmium and zinc, and copper and zinc showed strong, positive associations throughout the Chained Islands site (Figure 30 and Figure 31). None of the three metals, however, were well associated with organic matter variables or sediment oxygen condition variables measured at the Chained Islands site (Appendix C).

Figure 30: Relationship between zinc and cadmium at the Chained Islands site.
4.1.2.4 Sediment Oxygen Conditions

4.1.2.4.1 Analysis of Variance

None of the sediment oxygen condition variables measured at the Chained Islands site exhibited significant spatial, temporal, or spatio-temporal variance.

4.1.2.4.2 GIS Maps (Vertical Core Profiles)

Several spatial and temporal trends in sediment oxygen collected from core samples at the Chained Islands site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix K). Oxygen values at all stations were typically highest at the sediment surface, rapidly decreased with depth, and eventually became absent (0%) within the lower layers of sediment. Oxygen became absent in May 2001 at 12-14cm depth at the east farm site, and 6-8cm depth at the reference site. In July 2001 oxygen became absent at shallower sediment depths (2-8cm) at the east farm site, and slightly deeper sediment depths (14-16cm) at the reference site. Oxygen absence was observed at even shallower depths (0-4cm) throughout the entire site in December 2001. At many stations throughout the study period, a small pocket of
elevated oxygen was observed just below the surface at approximately 4-6cm depth. Many of the stations sampled in July 2001 also showed a second minor increase in oxygen values at 8-10cm depth. Surface levels of oxygen were much higher during the spring and summer months than during the winter. In May 2001, the highest surface value of oxygen was recorded at a reference station, in July 2001, it was recorded at an east farm station, and in December 2001 it was recorded at a west farm station.

Several spatial and temporal trends in sediment porosity collected from core samples at the Chained Islands site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix K). Porosity values at all stations were typically highest at the sediment surface, gradually decreasing with depth. Porosity values throughout the sediment cores were typically higher at the east farm stations and lower at the west farm and reference stations. Porosity was typically higher within the upper layers of sediment during May 2001 and July 2001, and typically lower during December 2001 and March 2002.

Several spatial and temporal trends in sediment redox potential collected from core samples at the Chained Islands site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix K). Redox potential values at stations sampled during May 2001 and July 2001 were typically highest at the sediment surface, rapidly decreased with depth until either remaining at a minimum or alternatively increasing and decreasing with each depth increment (oscillations). Redox potential values at stations sampled during December 2001 were typically highest at the sediment surface, and only slightly decreased with depth. Redox potential levels at east farm stations and reference stations showed no observable differences, but values at west farm stations in December 2001 were considerably lower than at the other locations. Redox potential was not significantly lower at any time at the reference site, despite the fact that some black patches were observed within otherwise healthy-looking sediments at most of the stations. The highest overall redox potential values were observed during December 2001, and the lowest values were observed during July 2001. Redox potential levels throughout the vertical core profiles never dropped below 0mV at any time throughout the entire Chained Islands site.

Several spatial and temporal trends in sediment sulphides collected from core samples at the Chained Islands site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix K). Sulphides did not vary substantially between the east farm, west farm, and reference sites, despite the fact that a very slight H₂S odour was detected consistently at most of the reference sites. Sulphides values at all stations throughout the study period were typically
lowest at the sediment surface, gradually increased from 2-6cm to a maximum typically at 4-8cm, and steadily declined throughout subsequent depths. Location and time of year did not appear to greatly affect depth of the maximum. Sulphides values throughout the sediments at the east farm site in May 2001 were within the range of 100-200 μMol and showed only minor changes with depth. At one reference station sampled in May 2001, sulphides increased to a value of 853 μMol at 8-10cm. Sulphides values at east farm and reference stations sampled during July 2001 and March 2002 showed substantial changes with depth, and were typically higher than other months, ranging between 100 and 500 μMol. Sulphides values at all stations sampled during December 2001 showed only minor changes with depth, and were typically lower than for other months, ranging between 0 and 100 μMol.

Figure 32 demonstrates a sediment geochemistry profile typical of the Chained Islands site.

![Figure 32](image)

**Figure 32**: Oxygen, redox potential, and sulphides sediment depth profiles (08cm) for each time sampled at station CI8 at the Chained Islands east farm site.

4.1.2.4.3 Impact and Recovery Based on Thresholds (Within the Top 416cm of Sediment)

At the Chained Islands site, oxygen values dropped below 5ppm, and reached 0% at 12-14cm within the sediments at an east farm station, and 6-8cm at a reference station in May 2001. In July, 2001 oxygen reached 0% between 2-4cm and 6-8cm at the east farm stations, and 14-16 cm
at a reference station. Oxygen also reached 0% typically between 0-2cm and 2-4cm at all stations in all locations during December 2001.

With the exception of one sample taken at 10-12cm within a reference core in July 2001, redox potential levels throughout the vertical core profiles never reached subzero levels associated with hypoxic conditions at any time throughout the entire Chained Islands site.

Sulphides values throughout the vertical core profiles were consistently low throughout the entire study period at the Chained Islands site, never exceeding the potential impact threshold of 600μMol. The one exception was at a reference station within the first month following site abandonment. At this station, sulphides reached 853 μMol at 8-10cm sediment depth.

Redox potential and sulphides measured throughout the vertical cores typically showed a negative association throughout the Chained Islands site (Figure 33).

![Figure 33: Relationship between sulphides and redox potential at the Chained Islands site.](image)

The two variables did not, however, exhibit an association within the top 2cm of sediment alone (Appendix C). No relationships were identified between redox potential and oxygen, or sulphides
and oxygen within the vertical cores or the top 2cm of sediment. There was also no association between any of the organic matter variables and sediment oxygen variables measured within the top 2cm of sediment throughout the site. Thus, there was no indication that fish farming activity had affected the sediment oxygen conditions at the Chained Islands site.

### 4.1.3 Sensitive Indicators of Recovery

#### 4.1.3.1 ANOVA Sensitivity Analysis (Within the Entire Site)

Cadmium and zinc were the only significant indicators of temporal change within the entire Chained Islands site. The $p$-values show that cadmium had a slightly higher sensitivity than zinc (Table 16).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cadmium</td>
<td>0.000</td>
</tr>
<tr>
<td>zinc</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 16: ANOVA $p$-values for significant indicators of temporal change within the entire Chained Islands site.

Copper, lead, total carbon, porosity, bulk density, nitrogen, organic content, and organic carbon were the only significant indicators of differences in organic matter accumulations between locations. The $p$-values show that copper, lead, total carbon, porosity, and bulk density had the highest sensitivities, with slightly decreasing sensitivities being observed with nitrogen, organic content, and organic carbon (Table 17).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA $p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>copper</td>
<td>0.000</td>
</tr>
<tr>
<td>lead</td>
<td>0.000</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.000</td>
</tr>
<tr>
<td>porosity</td>
<td>0.000</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.000</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.001</td>
</tr>
<tr>
<td>organic content</td>
<td>0.002</td>
</tr>
<tr>
<td>organic carbon</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Table 17: ANOVA $p$-values for significant indicators of differences in organic matter accumulations between locations within the Chained Islands site.
4.1.3.2 **ANOVA Sensitivity Analysis (Within 50m of the Farms)**

Porosity, zinc, copper, nitrogen, bulk density, total carbon, and organic carbon were the only significant indicators of differences in organic matter accumulations between reference stations and farm stations located within 50 meters of the farms. The \( p \)-values showed porosity to have the highest sensitivity, with slightly decreasing sensitivities being observed with zinc, copper, nitrogen, bulk density, total carbon, and organic carbon (Table 18).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA ( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>porosity</td>
<td>0.002</td>
</tr>
<tr>
<td>zinc</td>
<td>0.003</td>
</tr>
<tr>
<td>copper</td>
<td>0.006</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.006</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.007</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.011</td>
</tr>
<tr>
<td>organic carbon</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Table 18: ANOVA \( p \)-values for significant indicators of differences in organic matter accumulations between reference stations and farm stations located within 50m of the farms in the Chained Islands site.

ANOVA did not identify any significant indicators of spatio-temporal change at the Chained Islands site.

4.1.3.3 **ANOVA Sensitivity Analysis (At 50-100m from the Farms)**

Porosity, nitrogen, silicon, organic content, total carbon, organic carbon, bulk density, and lead were the only significant indicators of differences in organic matter accumulations between reference stations and farm stations located at 50-100 meters from the farms. \( P \)-values show that porosity had the highest sensitivity, with slightly decreasing sensitivities being observed with nitrogen, silicon, organic content, total carbon, organic carbon, bulk density, chlorophyll, and lead (Table 19).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA ( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>porosity</td>
<td>0.000</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.002</td>
</tr>
<tr>
<td>silicon</td>
<td>0.003</td>
</tr>
<tr>
<td>organic content</td>
<td>0.004</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.005</td>
</tr>
<tr>
<td>organic carbon</td>
<td>0.007</td>
</tr>
</tbody>
</table>

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All of the variables listed in (Table 20) were significant indicators of differences in organic matter accumulations between reference stations and farm stations located at >100 meters from the farms. The \( p \)-values show that copper, total carbon, nitrogen, and porosity had the highest sensitivities, with slightly decreasing sensitivities being observed with organic carbon, organic content, bulk density, lead, zinc, and aluminum.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA ( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>copper</td>
<td>0.000</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.000</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.000</td>
</tr>
<tr>
<td>porosity</td>
<td>0.000</td>
</tr>
<tr>
<td>organic carbon</td>
<td>0.001</td>
</tr>
<tr>
<td>organic content</td>
<td>0.001</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.002</td>
</tr>
<tr>
<td>lead</td>
<td>0.009</td>
</tr>
<tr>
<td>zinc</td>
<td>0.012</td>
</tr>
<tr>
<td>aluminum</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Table 20: ANOVA \( p \)-values for significant indicators of differences in organic matter accumulations between reference stations and farm stations located at >100m from the farms in the Chained Islands site.

4.1.3.5 ANOVA Sensitivity Analysis (Within the Farm Sites)

Cadmium and zinc were the only significant indicators of temporal change within the Chained Islands east farm site. The \( p \)-values showed that cadmium had a higher sensitivity than zinc (Table 21).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA ( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cadmium</td>
<td>0.000</td>
</tr>
<tr>
<td>zinc</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 21: ANOVA \( p \)-values for significant indicators of temporal change at the Chained Islands east farm site.
Cadmium was the only significant indicator of temporal change within the west farm site. It had a \( p \)-value of 0.000.

Copper and chlorophyll were the only significant indicators of differences in organic matter accumulations between sediments located at 0-50m, 50-100m, and >100m from the Chained Islands east farm. The \( p \)-values showed that copper had a higher sensitivity than chlorophyll (Table 22).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA ( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>copper</td>
<td>0.003</td>
</tr>
<tr>
<td>chlorophyll</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Table 22: ANOVA \( p \)-values for significant indicators of differences in organic matter accumulations between sediments located at 0-50m, 50-100m, and >100m from the Chained Islands east farm.

There were no significant spatio-temporal change indicators identified at the Chained Islands farm sites, nor were there any significant sensitive indicators of differences in organic matter accumulations with distance from the farm at the Chained Islands west farm site.

4.1.3.6 ANOVA Sensitivity Analysis (Within the Reference Site)

Cadmium and zinc were the only significant indicators of temporal change within the Chained Islands reference site. The \( p \)-values showed that cadmium and zinc sensitivities were equal (Table 23).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA ( p )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cadmium</td>
<td>0.000</td>
</tr>
<tr>
<td>zinc</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 23: ANOVA \( p \)-values for significant indicators of temporal change at the Chained Islands reference site.

4.1.4 Redundancies Amongst Variables

4.1.4.1 Principal Components Analysis

The results of the Principal Components Analyses performed on each of the geochemical and geophysical parameters measured at the Chained Islands site demonstrated some significant
relationships, trends, and redundancies amongst variables. Four categories of variables were isolated from the principal components shown in Table 25, Table 27, Table 26, and Table 24: sediment physical properties, metals, organic matter, and sediment oxygen conditions.

Coarse sediment grain sizes (gravel, very coarse sand, coarse sand, and medium sand) were significantly highly positively correlated with each other, and significantly highly negatively correlated with fine sediment grain sizes (silt and very fine sand) under the same components. Both clay fractions, silt, and porosity were significantly highly positively correlated with each other, and significantly highly negatively correlated with fine sand. These variables collectively comprised a category that was defined as sediment physical property variables.

Aluminum, copper, lead, and zinc were significantly highly positively correlated with each other. These variables formed a second category that were defined as metals variables.

Organic carbon, inorganic carbon, nitrogen, organic content, and porosity were significantly highly positively correlated with each other. These variables collectively made up a third category that were defined as organic matter variables.

Within the vertical sediment cores, redox potential was significantly highly negatively correlated with sulphides, and oxygen was significantly positively correlated with porosity. These variables collectively made up a fourth category that were defined as sediment oxygen conditions.

\[ N = 19; \text{ Sample size too small (N<50) to use 2(std. error) significance test} \]

Significant Loading Estimated At \(> |0.4| \)

\[
\begin{array}{c|cc}
\text{Principal Components} & 1 & 2 \\
\hline
\text{OXYGEN} & 0.870 & 0.168 \\
\text{POROSITY} & 0.123 & -0.897 \\
\text{REDOX} & 0.098 & 0.443 \\
\text{SULPHIDES} & 0.895 & -0.102 \\
\end{array}
\]

% Total Variance Explained by Component

\[
\begin{array}{cc}
% \text{Cumulative Variance} & 39.557 & 25.964 \\
\end{array}
\]

Table 24: Results of Principal Components Analysis performed on sediment variables measured within the top 2cm of core samples at the Chained Islands site.
Rotated Loading Matrix (Varimax, Gamma = 1.0000)
N = 84; df = N - 2 = 82; $R_{critical}(y) = 0.28$; $2(\text{std. Error}) = 2(0.28) = 0.56$
Significant Loading > |0.56|

<table>
<thead>
<tr>
<th>Principal Components</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>OXYGEN</td>
<td>0.081</td>
<td>0.779</td>
</tr>
<tr>
<td>POROSITY</td>
<td>0.030</td>
<td>0.709</td>
</tr>
<tr>
<td>REDOX</td>
<td>-0.888</td>
<td>0.167</td>
</tr>
<tr>
<td>SULPHIDES</td>
<td>0.896</td>
<td>0.105</td>
</tr>
</tbody>
</table>

% Total Variance Explained by Component

| % Total Variance Explained by Component | 40.461 | 28.249 |

% Cumulative Variance

| % Cumulative Variance | 40.461 | 68.710 |

Table 25: Results of Principal Components Analysis performed on sediment variables collected throughout vertical core samples at the Chained Islands site.
Rotated Loading Matrix (Varimax, Gamma = 1.0000)

N = 65; df = N - 2 = 63; $R_{\text{critical}}(y) = 0.318$; 2(Std. Error) = 2(0.318) = 0.636

Significant Loading $>|0.636|$  

<table>
<thead>
<tr>
<th>Principal Components</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUMINUM</td>
<td>-0.342</td>
<td>-0.518</td>
<td>-0.132</td>
<td>0.674</td>
<td>-0.199</td>
<td>-0.094</td>
</tr>
<tr>
<td>BULK DENSITY</td>
<td>-0.602</td>
<td>-0.056</td>
<td>-0.040</td>
<td>-0.515</td>
<td>-0.188</td>
<td>0.110</td>
</tr>
<tr>
<td>CADMIUM</td>
<td>-0.047</td>
<td>-0.157</td>
<td>0.152</td>
<td>0.097</td>
<td>-0.017</td>
<td>0.903</td>
</tr>
<tr>
<td>CHLOROPHYLL</td>
<td>0.499</td>
<td>0.480</td>
<td>0.548</td>
<td>-0.255</td>
<td>-0.067</td>
<td>0.030</td>
</tr>
<tr>
<td>ug/g CARBON</td>
<td>0.905</td>
<td>0.371</td>
<td>0.024</td>
<td>-0.165</td>
<td>0.074</td>
<td>0.015</td>
</tr>
<tr>
<td>ug/g INORG. CARBON</td>
<td>0.723</td>
<td>0.571</td>
<td>0.029</td>
<td>-0.318</td>
<td>0.056</td>
<td>0.002</td>
</tr>
<tr>
<td>ug/g NITROGEN</td>
<td>0.936</td>
<td>0.277</td>
<td>0.068</td>
<td>0.085</td>
<td>0.086</td>
<td>-0.012</td>
</tr>
<tr>
<td>ug/g ORG. CARBON</td>
<td>0.923</td>
<td>0.142</td>
<td>-0.018</td>
<td>0.195</td>
<td>0.052</td>
<td>0.048</td>
</tr>
<tr>
<td>COPPER</td>
<td>0.055</td>
<td>-0.127</td>
<td>-0.103</td>
<td>0.946</td>
<td>-0.098</td>
<td>0.029</td>
</tr>
<tr>
<td>&gt;2mm</td>
<td>0.532</td>
<td>0.792</td>
<td>0.034</td>
<td>-0.075</td>
<td>0.124</td>
<td>0.036</td>
</tr>
<tr>
<td>LEAD</td>
<td>0.528</td>
<td>-0.174</td>
<td>-0.174</td>
<td>0.574</td>
<td>-0.231</td>
<td>0.056</td>
</tr>
<tr>
<td>&lt;100um</td>
<td>-0.153</td>
<td>-0.717</td>
<td>-0.150</td>
<td>0.068</td>
<td>0.176</td>
<td>0.280</td>
</tr>
<tr>
<td>&lt;1mm</td>
<td>0.470</td>
<td>0.789</td>
<td>0.086</td>
<td>-0.128</td>
<td>0.275</td>
<td>-0.093</td>
</tr>
<tr>
<td>&lt;250um</td>
<td>-0.811</td>
<td>-0.112</td>
<td>0.010</td>
<td>-0.072</td>
<td>-0.318</td>
<td>-0.167</td>
</tr>
<tr>
<td>&lt;2mm</td>
<td>0.517</td>
<td>0.792</td>
<td>0.061</td>
<td>-0.187</td>
<td>0.169</td>
<td>0.004</td>
</tr>
<tr>
<td>&lt;2um</td>
<td>0.916</td>
<td>0.002</td>
<td>0.122</td>
<td>-0.045</td>
<td>0.046</td>
<td>-0.119</td>
</tr>
<tr>
<td>&lt;4um</td>
<td>0.769</td>
<td>0.158</td>
<td>0.006</td>
<td>-0.072</td>
<td>-0.170</td>
<td>-0.219</td>
</tr>
<tr>
<td>&lt;500um</td>
<td>0.427</td>
<td>0.718</td>
<td>0.088</td>
<td>0.005</td>
<td>0.358</td>
<td>-0.160</td>
</tr>
<tr>
<td>&lt;63um</td>
<td>0.252</td>
<td>-0.799</td>
<td>0.034</td>
<td>0.366</td>
<td>0.136</td>
<td>-0.019</td>
</tr>
<tr>
<td>ORG. CONTENT</td>
<td>0.893</td>
<td>0.016</td>
<td>0.102</td>
<td>0.182</td>
<td>0.129</td>
<td>-0.007</td>
</tr>
<tr>
<td>PHEOPHYTIN</td>
<td>-0.012</td>
<td>0.161</td>
<td>0.868</td>
<td>-0.146</td>
<td>-0.146</td>
<td>0.132</td>
</tr>
<tr>
<td>POROSITY</td>
<td>0.772</td>
<td>0.276</td>
<td>0.022</td>
<td>0.302</td>
<td>0.207</td>
<td>-0.105</td>
</tr>
<tr>
<td>% CARBON</td>
<td>0.883</td>
<td>0.399</td>
<td>0.019</td>
<td>-0.213</td>
<td>0.061</td>
<td>0.019</td>
</tr>
<tr>
<td>% INORG. CARBON</td>
<td>0.702</td>
<td>0.542</td>
<td>0.035</td>
<td>-0.429</td>
<td>0.036</td>
<td>0.009</td>
</tr>
<tr>
<td>% NITROGEN</td>
<td>0.930</td>
<td>0.309</td>
<td>0.073</td>
<td>0.047</td>
<td>0.064</td>
<td>-0.004</td>
</tr>
<tr>
<td>% ORG. CARBON</td>
<td>0.915</td>
<td>0.171</td>
<td>-0.034</td>
<td>0.157</td>
<td>0.036</td>
<td>0.048</td>
</tr>
<tr>
<td>SILICON</td>
<td>-0.192</td>
<td>-0.111</td>
<td>-0.086</td>
<td>0.188</td>
<td>-0.841</td>
<td>0.007</td>
</tr>
<tr>
<td>ZINC</td>
<td>0.147</td>
<td>-0.341</td>
<td>-0.220</td>
<td>0.714</td>
<td>-0.041</td>
<td>0.300</td>
</tr>
<tr>
<td>SED. TEMPERATURE</td>
<td>0.043</td>
<td>-0.057</td>
<td>0.789</td>
<td>-0.094</td>
<td>0.332</td>
<td>0.013</td>
</tr>
</tbody>
</table>

| % Total Variance Explained by Component | 40.151 | 19.088 | 6.548 | 11.565 | 5.176 | 4.026 |
| % Cumulative Variance               | 40.151 | 59.239 | 65.787 | 77.352 | 82.528 | 86.554 |

Table 26: Results of Principal Components Analysis performed on sediment variables measured within the top 2cm of grab samples at the Chained Islands site.
Rotated Loading Matrix (Varimax, Gamma = 1.0000)

N = 14; Sample size too small (N<50) to use 2(std. error) significance test

Significant Loading Estimated At > |0.6|

<table>
<thead>
<tr>
<th>Principal Components</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUMINUM</td>
<td>0.605</td>
<td>-0.263</td>
<td>-0.203</td>
<td>0.125</td>
<td>-0.390</td>
<td>-0.321</td>
<td>-0.244</td>
</tr>
<tr>
<td>BULK DENSITY</td>
<td>-0.303</td>
<td>0.008</td>
<td>-0.467</td>
<td>-0.418</td>
<td>-0.643</td>
<td>-0.002</td>
<td>0.047</td>
</tr>
<tr>
<td>CADMIUM</td>
<td>0.388</td>
<td>-0.394</td>
<td>0.106</td>
<td><strong>-0.649</strong></td>
<td>0.257</td>
<td>-0.179</td>
<td>0.128</td>
</tr>
<tr>
<td>CHLOROPHYLL</td>
<td>0.078</td>
<td>0.393</td>
<td>0.119</td>
<td>0.356</td>
<td>-0.008</td>
<td><strong>0.807</strong></td>
<td>0.012</td>
</tr>
<tr>
<td>ug/g CARBON</td>
<td><strong>0.574</strong></td>
<td>-0.085</td>
<td>0.062</td>
<td>0.005</td>
<td>0.047</td>
<td>-0.058</td>
<td>0.141</td>
</tr>
<tr>
<td>ug/g INORG. CARBON</td>
<td>0.148</td>
<td>0.225</td>
<td><strong>0.929</strong></td>
<td>-0.098</td>
<td>-0.019</td>
<td>0.028</td>
<td>0.156</td>
</tr>
<tr>
<td>ug/g NITROGEN</td>
<td>0.975</td>
<td>-0.007</td>
<td>0.043</td>
<td>0.029</td>
<td>0.010</td>
<td>-0.063</td>
<td>0.136</td>
</tr>
<tr>
<td>ug/g ORG. CARBON</td>
<td>0.974</td>
<td>-0.089</td>
<td>0.012</td>
<td>0.010</td>
<td>0.050</td>
<td>-0.058</td>
<td>0.141</td>
</tr>
<tr>
<td>COPPER</td>
<td>0.764</td>
<td>0.366</td>
<td>0.246</td>
<td>0.190</td>
<td>-0.075</td>
<td>0.189</td>
<td>-0.037</td>
</tr>
<tr>
<td>&gt; 2mm</td>
<td>-0.024</td>
<td><strong>0.932</strong></td>
<td>0.085</td>
<td>0.077</td>
<td>-0.023</td>
<td>0.280</td>
<td>-0.089</td>
</tr>
<tr>
<td>LEAD</td>
<td>0.696</td>
<td>-0.400</td>
<td>0.068</td>
<td>-0.029</td>
<td>-0.335</td>
<td>0.114</td>
<td>0.114</td>
</tr>
<tr>
<td>&lt; 100um</td>
<td>0.272</td>
<td>-0.370</td>
<td>0.171</td>
<td>0.218</td>
<td>0.094</td>
<td><strong>-0.730</strong></td>
<td>0.115</td>
</tr>
<tr>
<td>&lt; 1mm</td>
<td>-0.225</td>
<td><strong>0.867</strong></td>
<td>0.148</td>
<td>0.254</td>
<td>0.147</td>
<td>0.279</td>
<td>0.015</td>
</tr>
<tr>
<td>&lt; 250um</td>
<td><strong>-0.827</strong></td>
<td>-0.010</td>
<td>-0.109</td>
<td>-0.353</td>
<td>-0.070</td>
<td>0.397</td>
<td>0.070</td>
</tr>
<tr>
<td>&lt; 2mm</td>
<td>-0.211</td>
<td><strong>0.891</strong></td>
<td>0.125</td>
<td>0.220</td>
<td>0.134</td>
<td>0.265</td>
<td>-0.012</td>
</tr>
<tr>
<td>&lt; 2um</td>
<td>0.861</td>
<td>-0.334</td>
<td>0.128</td>
<td>0.048</td>
<td>0.043</td>
<td>0.153</td>
<td>0.108</td>
</tr>
<tr>
<td>&lt; 4um</td>
<td>0.245</td>
<td>-0.277</td>
<td>0.428</td>
<td>0.144</td>
<td><strong>-0.716</strong></td>
<td>0.063</td>
<td>-0.039</td>
</tr>
<tr>
<td>&lt; 500um</td>
<td>-0.207</td>
<td><strong>0.849</strong></td>
<td>0.129</td>
<td>0.330</td>
<td>0.165</td>
<td>0.266</td>
<td>0.005</td>
</tr>
<tr>
<td>&lt; 63um</td>
<td>0.835</td>
<td>-0.390</td>
<td>-0.107</td>
<td>0.079</td>
<td>-0.045</td>
<td>-0.275</td>
<td>-0.166</td>
</tr>
<tr>
<td>ORG. CONTENT</td>
<td>0.957</td>
<td>-0.156</td>
<td>-0.136</td>
<td>0.052</td>
<td>-0.083</td>
<td>-0.078</td>
<td>-0.124</td>
</tr>
<tr>
<td>OXYGEN</td>
<td>0.010</td>
<td>0.187</td>
<td>0.076</td>
<td><strong>0.818</strong></td>
<td>0.087</td>
<td>0.006</td>
<td>0.185</td>
</tr>
<tr>
<td>% CARBON</td>
<td>0.573</td>
<td>-0.085</td>
<td>0.051</td>
<td>0.008</td>
<td>0.045</td>
<td>-0.062</td>
<td>0.142</td>
</tr>
<tr>
<td>% INORG. CARBON</td>
<td>-0.005</td>
<td>0.022</td>
<td><strong>0.947</strong></td>
<td>0.009</td>
<td>-0.106</td>
<td>0.033</td>
<td>-0.069</td>
</tr>
<tr>
<td>% NITROGEN</td>
<td>0.973</td>
<td>0.003</td>
<td>0.067</td>
<td>-0.026</td>
<td>0.007</td>
<td>-0.090</td>
<td>0.115</td>
</tr>
<tr>
<td>% ORG. CARBON</td>
<td>0.973</td>
<td>-0.088</td>
<td>0.012</td>
<td>0.011</td>
<td>0.054</td>
<td>-0.060</td>
<td>0.143</td>
</tr>
<tr>
<td>PHEOPHYTIN</td>
<td>-0.154</td>
<td>0.282</td>
<td>0.116</td>
<td>0.286</td>
<td>0.097</td>
<td><strong>0.848</strong></td>
<td>0.088</td>
</tr>
<tr>
<td>POROSITY</td>
<td>0.946</td>
<td>0.182</td>
<td>0.075</td>
<td>-0.043</td>
<td>0.062</td>
<td>-0.035</td>
<td>-0.063</td>
</tr>
<tr>
<td>REDOX</td>
<td>-0.158</td>
<td>0.074</td>
<td>-0.062</td>
<td>-0.130</td>
<td>-0.065</td>
<td>-0.041</td>
<td><strong>-0.896</strong></td>
</tr>
<tr>
<td>SED. TEMPERATURE</td>
<td>0.231</td>
<td>0.214</td>
<td>-0.095</td>
<td><strong>0.855</strong></td>
<td>0.129</td>
<td>0.205</td>
<td>0.012</td>
</tr>
<tr>
<td>SILICON</td>
<td>-0.419</td>
<td><strong>-0.643</strong></td>
<td>0.117</td>
<td>-0.045</td>
<td>-0.015</td>
<td>0.168</td>
<td>-0.527</td>
</tr>
<tr>
<td>SULPHIDES</td>
<td>0.338</td>
<td>0.179</td>
<td>-0.217</td>
<td>0.437</td>
<td><strong>0.620</strong></td>
<td>0.113</td>
<td>0.178</td>
</tr>
<tr>
<td>ZINC</td>
<td>0.755</td>
<td>-0.364</td>
<td>0.067</td>
<td>-0.351</td>
<td>0.244</td>
<td>-0.113</td>
<td>0.025</td>
</tr>
</tbody>
</table>

| % Cumulative Variance               | 39.252 | 55.706 | 63.694 | 73.184 | 78.994 | 87.670 | 92.274 |

Table 27: Results of Principal Components Analysis performed on sediment variables measured within the top 2cm of core and grab samples at the Chained Islands site.
4.1.4.2 Correlation and Regression Analysis

Several variable redundancies were identified through regression analysis amongst sediment variables measured within the top 2cm of sediment at the Chained Islands site (Appendix E).

Redundant sediment variables measured at the Chained Islands east farm site (Table 28) were used, along with the results of PCA, for grouping sediment variables and determining redundancies between them. These variable pairs demonstrated meaningful relationships, collinearity, and goodness-of-fit according to regression analysis.

<table>
<thead>
<tr>
<th>Related Sediment Variables</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>chlorophyll and pheophytin</td>
<td>positive</td>
</tr>
<tr>
<td>cadmium and zinc</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and nitrogen</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>organic carbon and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>organic carbon and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>medium sand and coarse sand</td>
<td>positive</td>
</tr>
<tr>
<td>silt and coarse sand</td>
<td>negative</td>
</tr>
<tr>
<td>silt and medium sand</td>
<td>negative</td>
</tr>
</tbody>
</table>

Table 28: Sediment variables measured at the Chained Islands east farm site that demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.

The regression curves fit between total carbon and nitrogen (Figure 34a) and total carbon and organic carbon (Figure 34b) visually demonstrate the strength of relationships between redundant variables collected at the east farm site.

Redundant sediment variables measured at the Chained Islands west farm site (Table 29) were used as well as the results of PCA for grouping sediment variables and determining redundancies between them. These variable pairs demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis. The regression curve fit between nitrogen and organic content (Figure 35) demonstrates the strength of relationships between redundant variables collected at the west farm site.
Inverse Transformed Carbon vs. Nitrogen

Inverse Transformed Carbon vs. Log Transformed Organic Carbon

(a) Regression between total carbon and nitrogen (N=29, p=0.00, S.E.E. = 0.000(INV), 'fairly good fit')

(b) Regression between total carbon and organic carbon (N=29, p=0.00, S.E.E. = 0.000(INV), 'good fit')

Figure 34: Regression curves between (a) total carbon and nitrogen and (b) total carbon and organic carbon measured at the Chained Islands east farm site.

<table>
<thead>
<tr>
<th>Redundant Variable Pairs</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>total carbon and inorganic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and nitrogen</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>organic carbon and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>organic carbon and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>organic carbon and inorganic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and inorganic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>organic content and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>porosity and medium sand</td>
<td>positive</td>
</tr>
<tr>
<td>clay (&lt;2μm) and clay (&lt;4μm)</td>
<td>positive</td>
</tr>
<tr>
<td>clay (&lt;4μm) and medium sand</td>
<td>positive</td>
</tr>
<tr>
<td>clay (&lt;4μm) and gravel</td>
<td>positive</td>
</tr>
<tr>
<td>medium sand and gravel</td>
<td>positive</td>
</tr>
<tr>
<td>medium sand and very coarse sand</td>
<td>positive</td>
</tr>
<tr>
<td>medium sand and coarse sand</td>
<td>positive</td>
</tr>
<tr>
<td>coarse sand and gravel</td>
<td>positive</td>
</tr>
<tr>
<td>coarse sand and very coarse sand</td>
<td>positive</td>
</tr>
<tr>
<td>very coarse sand and gravel</td>
<td>positive</td>
</tr>
</tbody>
</table>

Table 29: Sediment variables measured at the Chained Islands west farm site that demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.
Figure 35: Regression curve between nitrogen and organic content measured at the Chained Islands west farm site (N=25, $p=0.00$, S.E.E.=163.9,'fairly good fit').

Redundant sediment variables (Table 30) collected from the Chained Islands reference site were used as well as the results of PCA, for grouping sediment variables and determining redundancies between them. These variable pairs demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.

<table>
<thead>
<tr>
<th>Redundant Variable Pairs</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>cadmium and zinc</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>organic content and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>chlorophyll and pheophytin</td>
<td>positive</td>
</tr>
<tr>
<td>copper and zinc</td>
<td>positive</td>
</tr>
<tr>
<td>clay ($&lt;2\mu m$) and fine sand</td>
<td>negative</td>
</tr>
<tr>
<td>silt and fine sand</td>
<td>positive</td>
</tr>
<tr>
<td>very fine sand and fine sand</td>
<td>positive</td>
</tr>
</tbody>
</table>

Table 30: Sediment variables measured at the Chained Islands reference site that demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.

The regression curves fit between cadmium and zinc (Figure 36a) and total carbon and organic carbon (Figure 36b) visually demonstrate the strength of relationships between redundant variables collected at the reference site.
Redundant sediment variables (Table 31) collected throughout the entire Chained Islands site were used as well as the results of PCA, for grouping sediment variables and determining redundancies between them. These variable pairs demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.

<table>
<thead>
<tr>
<th>Related Sediment Variables</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>total carbon and nitrogen</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>total carbon and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and organic carbon</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>nitrogen and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>organic carbon and organic content</td>
<td>positive</td>
</tr>
<tr>
<td>organic carbon and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>organic content and porosity</td>
<td>positive</td>
</tr>
<tr>
<td>clay and total carbon</td>
<td>positive</td>
</tr>
<tr>
<td>clay and organic content</td>
<td>positive</td>
</tr>
</tbody>
</table>

Table 31: Sediment variables measured throughout the entire Chained Islands site that demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.

Several variable redundancies were identified through regression analysis amongst sediment variables measured throughout vertical core profiles collected at the Chained Islands site (Appendix E). The positive relationship between redox potential and porosity throughout core samples collected in December 2001 at the reference site demonstrated a meaningful relationship,
collinearity according to correlation analysis, and goodness-of-fit according to regression analysis (Figure 37). These results implied a redundancy between the two variables.

Figure 37: Regression curve between redox and porosity measured in December 2001 at the Chained Islands reference site (N=10, p=0.00, S.E.E.=12.5, 'fairly good fit').

4.2 Carrie Bay

4.2.1 Habitat Characteristics

4.2.1.1 Descriptive Trends

Sediments at the Carrie Bay farm site were dominated by silt and clay, and consisted also of some finer sand and small amounts of coarser sand and gravel (Figure 38). Sediments at the reference site consisted predominantly of silt, clay, and finer sand and some small amounts of coarser sand and gravel (Figure 38). The average depth was 34.4±4.6 meters at the farm site and 36.9±4.7 meters at the reference site.

Figure 38: Frequency distributions of sediment grain sizes averaged for all sampling trips at the Carrie Bay farm site (N=47) and reference site (N=6).
4.2.1.2 Analysis of Variance (Within the Entire Site)

Fine and very fine sand were significantly greater at the Carrie Bay reference site than at the farm site.

4.2.1.3 Analysis of Variance (Within 50m of the Farm)

Clay was found to be significantly greater within 50 meters of the Carrie Bay farm than at the reference site, while levels of fine sand were significantly greater at the reference site.

4.2.1.4 Analysis of Variance (At 50-100m from the Farm)

Clay was found to be significantly greater within the range of 50-100 meters from the Carrie Bay farm than at the reference site, while levels of fine sand were significantly greater at the reference site.

4.2.1.5 Analysis of Variance (At >100m from the Farm)

No significant difference between habitat characteristics was detected between stations at >100 meters from the Carrie Bay farm and the reference site.

4.2.1.6 Analysis of Variance (Within the Farm Site)

At the farm site, clay was significantly greater at stations 0-50 meters from the Carrie Bay farm than at those >100 meters from the farm. Very fine sand was significantly lower at stations 50-100 meters from the farm than at those >100 meters from the farm.

4.2.1.7 Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for each of the sediment grain size variables measured at the Carrie Bay site (Appendix J). Clay was always higher at the farm site than at the reference site, particularly at stations nearest to the farm. The coarser grain
sizes were observed predominantly within the northern half of the farm site. Silt was highest at stations to the southeast and southwest of the farm, and clay was most commonly found at stations to the north or south.

Clay at the farm site was visibly higher in September 2000 than in August 2001, particularly at stations nearest to the farm. Very fine and fine sand were contrarily lower nearest the farm. By August 2001, very fine sand was visibly more abundant at both the reference and farm sites, particularly at stations close to the farm. Patches of fine and medium sand were evident near the farm, predominantly in September 2000. Very fine sand, fine sand, medium sand, and coarse sand had actually decreased at the reference site by August 2001. Very coarse sand appeared to be absent near the farm, especially in September 2000. Gravel, however, was highest nearest to the farm in September 2000.

4.2.2 Recovery

4.2.2.1 Organic Matter

4.2.2.1.1 Time Trend Plots

Between 24 and 35 months following site abandonment, organic carbon and pheophytin increased while inorganic carbon simultaneously decreased at most of the Carrie Bay farm stations and at all of the reference stations (Appendix B). Organic C:N increased during this time period at all stations within both the farm and reference sites. Organic content at the reference site decreased substantially between 11 and 24 months following site abandonment, and further declined somewhat between 24 and 35 months (Appendix B). Organic content at the farm site did not change substantially over the study period. Total carbon underwent an overall decrease at most of the farm stations between 11 and 35 months following site abandonment, although total carbon concentrations did increase somewhat at about half of the stations between 24 and 35 months. Total carbon at the reference site did not change substantially over the study period. Nitrogen at four stations surrounding the approximate farm center decreased substantially between 11 and 35 months following site abandonment, while nitrogen actually underwent an overall decrease at the remainder of the stations and at the reference stations.
4.2.2.1.2 Analysis of Variance (Within the Entire Site)

Levels of total carbon, nitrogen, organic carbon, and organic content were significantly greater at the Carrie Bay farm site than at the reference site.

4.2.2.1.3 Analysis of Variance (Within 50m of the Farm)

Nitrogen, organic carbon, organic content, and total carbon were found to be significantly greater within 50 meters of the Carrie Bay farm than at the reference site.

Total carbon was significantly greater within 50 meters of the farm than at the reference site at 11 months following site abandonment only.

4.2.2.1.4 Analysis of Variance (At 50-100m from the Farm)

Levels of total carbon, nitrogen, organic carbon, and organic content were significantly greater within the range of 50-100 meters from the Carrie Bay farm than at the reference site.

4.2.2.1.5 Analysis of Variance (At >100m from the Farm)

Levels of total carbon, nitrogen, and organic content were found to be significantly greater at distances of >100 meters from the Carrie Bay farm than at the reference site.

4.2.2.1.6 Analysis of Variance (Within the Farm Site)

At the Carrie Bay farm site, total carbon was significantly higher at the onset of the study, 11 months after the site had been abandoned, than at all other times. Organic C:N and organic carbon were significantly lower when they were first measured 24 months after site abandonment than at the conclusion of the study at 35 months.

At the farm site, nitrogen and organic content were significantly greater at stations 0-50 meters from the farm than at >100 meters from the farm.
4.2.2.1.7 Analysis of Variance (Within the Reference Site)

At the Carrie Bay reference site, levels of nitrogen and organic content were significantly lower at 11 months following site abandonment than at all other times. Inorganic carbon was significantly higher when it were first measured at 24 months than at 35 months.

4.2.2.1.8 GIS Maps (Vertical Core Profiles)

Several spatial and temporal trends in sediment chlorophyll collected from grab samples at the Carrie Bay site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix L). In September 2000, surficial chlorophyll values were highest at stations close to the farm, and lower at those further away. Thus, chlorophyll gradients near the farm were much greater than those on the perimeter. The highest values at the farm site exceeded those found at the reference site. In September 2000 chlorophyll values typically rapidly declined to a minimum at 2-5mm depth, and then remained at a relatively constant, low level with increasing depth beyond this point. At some stations, chlorophyll values increased somewhat between the surface and 1-2mm depth. In August 2001, surficial chlorophyll values had declined at a few stations very close to the farm center, but at all other stations had typically increased. The values within the farm site were typically similar to those found at the reference site, with the exception of a few stations which were in exceedance. In August 2001 chlorophyll values typically increased until 1-2mm depth, then rapidly declined to a minimum at 5-10mm or deeper, and remained at a relatively constant, low level throughout the remaining depths. Trend plots such as the one in Figure 39 depict the overall tendency chlorophyll surficial values, gradients, and depth of minimums had to increase between September 2000 and August 2001.
Figure 39: Chlorophyll concentration sediment depth profiles (0-25mm) for each time sampled at station C27 (~139m from the farm center) and station C4 (~19m from the farm center) at the farm site in Carrie Bay.

4.2.2.1.9 Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for each of the organic matter variables measured at the Carrie Bay site (Appendix J). As shown in Figure 40, total carbon concentrations were at their highest near the farm at all times, particularly at stations east of the farm, and particularly in August 1999. The organic C:N ratio was lower throughout the farm and reference sites in September 2000 than in August 2001. Organic C:N ratios were particularly depressed at stations nearest to the farm in September 2000, but seemed to decrease with depth at both sites by August 2001. Inorganic carbon content was visibly higher at both sites in September 2000 than in August 2001. At all times, nitrogen and organic content were higher near the farm than elsewhere, particularly at stations east of the farm. Organic content at the reference site actually increased after August 1999. Organic carbon was also higher near the farm at both times, and had actually increased somewhat by August 2001, particularly at a small area east of the farm.
Both chlorophyll and pheophytin were visibly less at both the reference and farm sites in September 2000 than they were in August 2001. Concentrations of both pigments were obviously elevated at stations nearest to and east of the farm at both sampling times.

Figure 40: Contour maps showing spatio-temporal total carbon concentration distributions at the Carrie Bay site.

4.2.2.1.10 Impact and Recovery Based on Thresholds (Within the Top 2cm of Sediment)

Contour maps of organic C:N ratios (Figure 41 and Appendix J) demonstrate that organic content in September 2000 at both the Carrie Bay farm and reference sites was characterized by organic C:N ratios that were entirely within or below the levels expected for marine organic matter. The lowest ratios, typically falling below levels observed for marine organic matter in the northern Strait of Georgia, were observed within small patches of sediment to the near east of the farm center. Contour maps also show that in August 2001 organic C:N ratios had increased throughout both the farm and reference sites. By August 2001, in the shallower, nearshore regions at both sites, organic C:N ratios had reached those characteristic of terrestrial organic matter. In the remaining, deeper regions, organic C:N ratios had increased to be well within levels expected for marine organic matter.
Mean values of organic content at the Carrie Bay farm and reference sites were consistently higher than the threshold. Mean values of organic content at the reference site were, however, consistently lower than values measured at the farm site. Organic content did not appear to change much over time at either site.

Mean organic carbon levels at the reference site were always within the threshold. However, mean organic carbon levels at the farm site were always slightly elevated above the threshold. Organic carbon at both sites actually increased somewhat between 24 and 35 months following site abandonment.

4.2.2.2 Sediment Physical Properties

4.2.2.1 Time Trend Plots

Between 24 and 35 months following site abandonment, silt and porosity substantially increased and very fine sand and fine sand decreased at most of the Carrie Bay farm stations and at all of the reference stations (Appendix B). Clay also increased at some of the farm stations, fairly close to the approximate farm center, and at all of the reference stations. At all other farm stations, clay
decreased between 24 and 25 months following site abandonment. Medium and coarse sand
decreased at all of the reference stations.

Between 24 and 35 months following site abandonment, sediment temperature at three of the
stations near the farm center decreased substantially while temperature either stayed the same or
increased at the remaining farm stations and at all of the reference stations.

4.2.2.2.2 Analysis of Variance (Within the Entire Site)

Porosity was significantly higher at the Carrie Bay farm site than at the reference site, while bulk
density was significantly higher at the reference site.

4.2.2.2.3 Analysis of Variance (Within 50m of the Farm)

Bulk density was significantly higher at the Carrie Bay reference site than within 50 meters of the
farm.

4.2.2.2.4 Analysis of Variance (At 50-100m from the Farm)

Porosity was found to be significantly higher within the range of 50-100 meters from the Carrie
Bay farm than at the reference site.

4.2.2.2.5 Analysis of Variance (At >100m from the Farm)

Porosity was found to be significantly higher at distances of >100 meters from the Carrie Bay
farm than at the reference site.

When they were first measured 24 months after site abandonment, clay was significantly higher
and very fine and fine sand were significantly lower at distances of >100 meters from the farm
than at the reference site.
4.2.2.6 Analysis of Variance (Within the Farm Site)

At the Carrie Bay farm site, porosity was significantly greater at stations 0-50 meters from the farm than at >100 meters from the farm. Bulk density, conversely, was significantly lower. Porosity was also significantly greater at stations 50-100 meters from the farm than at >100 meters.

4.2.2.7 Analysis of Variance (Within the Reference Site)

At the Carrie Bay reference site, clay and silt were significantly lower when they were first measured 24 months after site abandonment than at 35 months. Very fine sand, fine sand, medium sand, and coarse sand were significantly higher when they were first measured at 24 months than at 35 months.

4.2.2.8 GIS Maps (Vertical Core Profiles)

Several spatial and temporal trends in sediment porosity collected from grab samples at the Carrie Bay site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix L). At the reference stations during both sampling trips, porosity tended to decrease rapidly to a depth of 1-2 or 2-5mm, and then decrease slightly and gradually with depth beyond that point. At stations nearest to the farm center, porosity at both sampling times tended to decrease slightly and gradually from the surface to the bottom of the core. At stations further from the farm in September 2000 porosity tended to follow a gradient pattern similar to that of the stations nearest the farm. In August 2001 these perimeter stations porosity tended to have a gradient pattern similar to that of the reference stations. At some stations, particularly those at the reference site and further from the farm, there was a small pocket of increased porosity values typically at 5-10mm or deeper within the sediment cores. In September 2000 porosity within the top few millimeters at stations near the farm center were clearly elevated by approximately 10% above those measured at further distances from the farm. Porosity within the top few millimeters at the perimeter stations was more similar to the porosity of the surficial sediments at the reference stations. By August 2001 porosity had not changed much and still remained elevated at the stations near the farm. However, porosity had slightly increased at many of the stations further away, and thus porosity values over the farm site were slightly more consistent.
Reference porosity values had also increased somewhat by this time, and tended to be similar to values measured at the perimeter stations.

![Graph showing porosity and bulk density profiles](image)

**Figure 42:** Porosity (left) and bulk density (right) sediment depth profiles (0-25mm) measured in September 2000 at stations C4 (~19m from the farm center) and station C11 (~92m from the farm center) at the farm site in Carrie Bay.

Several spatial and temporal trends in sediment bulk density collected from grab samples at the Carrie Bay site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix L). At stations near to the farm, during both sampling times, bulk density decreased fairly steadily until approximately 5-10mm, and then remained relatively constant throughout the remaining depths in the core. In September 2000 at the stations further from the farm, bulk density at most stations tended to increased slightly between 0-1mm and 1-2mm, then decreased sharply until 2-5 or 5-10mm depth, and then remained relatively constant throughout the remaining depths. In August 2001 bulk density at these same stations increased much more dramatically between 0-1mm and 1-2mm depth, indicating a burial of some of the higher surficial values measured in September 2000. Bulk density at the reference stations during both sampling times tended to increase somewhat within the top 2mm and then sharply decline until 5-10mm depth or gradually decline with depth. During both sampling times, bulk density at the surface was much lower at stations near the farm than at those on the perimeter or at the reference site. Bulk density at the perimeter stations resembled values found at the reference site. Bulk density in the top millimeter at most of the stations in the farm site had actually decreased between September 2000 and August 2001. Bulk density at all stations, both farm and reference, was similar past approximately 10mm depth. Figure 42 demonstrates the tendency for porosity in
surficial sediments to be greater and bulk density to be lower nearer to the farm than further away, particularly when the stations were first measured in September 2000.

4.2.2.2.9 Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for each of the sediment physical property variables measured at the Carrie Bay site (Appendix J). Bulk density was considerably lower and porosity considerably higher near the farm center than anywhere else, particularly in September 2000 (Figure 43)

Sediment temperatures were typically at their most spatially variable within the farm site in September 2000. Overall, sediment temperature was slightly lower in early fall (September 2000) than in late summer (August 2001). There was, however, a seemingly anomalous patch of
elevated sediment temperature close to the farm in September 2000. Temperatures were elevated 3-4 degrees above those measured in sediment further from the farm and at the reference site.

4.2.2.3 **Metals**

4.2.2.3.1 **Time Trend Plots**

Zinc and copper concentrations substantially decreased at most of the farm stations and all of the reference stations between 11 and 35 months following site abandonment (Appendix B). Zinc increased over the study period at three stations, all of which were located 70 or more meters to the east of the farm. Copper also increased at three different stations which were located within 80 meters of the approximate farm center. Between 24 and 35 months following site abandonment, silicon and cadmium substantially increased at all of the farm and reference stations. Lead decreased during this timeframe at most of the farm stations and at all of the reference stations. Lead increased at a few stations, most of which were located 40 or more meters in an easterly direction from the farm.

4.2.2.3.2 **Analysis of Variance (Within the Entire Site)**

Concentrations of aluminum, copper, lead, and zinc were significantly higher at the Carrie Bay farm site than at the reference site, while cadmium was significantly higher at the reference site.

4.2.2.3.3 **Analysis of Variance (Within 50m of the Farm)**

Copper, lead, and zinc, were found to be significantly higher within 50 meters of the Carrie Bay farm than at the reference site, while levels of cadmium were significantly higher at the reference site.

4.2.2.3.4 **Analysis of Variance (At 50-100m from the Farm)**

Levels of aluminum, copper, lead and zinc were found to be significantly higher within the range of 50-100 meters from the Carrie Bay farm than at the reference site.
4.2.2.3.5 Analysis of Variance (At >100m from the Farm)

Levels of aluminum, lead, and zinc were found to be significantly higher at distances of >100 meters from the Carrie Bay farm than at the reference site.

4.2.2.3.6 Analysis of Variance (Within the Farm Site)

At the Carrie Bay farm site, zinc concentrations were significantly higher at the onset of the study 11 months after site abandonment. Cadmium and silicon were significantly lower when they were first measured 24 months after site abandonment than at the conclusion of the study at 35 months.

At the farm site, copper was significantly greater at stations 0-50 meters from the farm than at >100 meters from the farm.

4.2.2.3.7 Analysis of Variance (Within the Reference Site)

At the Carrie Bay reference site, zinc and copper concentrations were significantly higher at the onset of the study, 11 months after the site had been abandoned, than at all other times.

4.2.2.3.8 Contour Maps (Top 2cm Sediment)

Aluminum levels in September 2000 and August 2001 were visibly elevated at the farm site, particularly at stations nearest to the Carrie Bay farm (Appendix J).

Lead was also visibly elevated at stations nearest to the farm, particularly in September 2000 (Appendix J). Lead concentrations were also elevated at the reference site in September 2000 and had decreased by August 2001.

Copper levels were visibly elevated near the farm and the shore in August 1999, September 2000, and August 2001 (Figure 44). Copper had somewhat decreased over the entire farm site by September 2000 with the exception of an area of elevated copper levels near the farm site in both September 2000 and August 2001. Copper concentrations were also elevated at the reference site in August 1999 and had diminished by September 2000.
Figure 44: Contour maps showing spatio-temporal copper concentration distributions at the Carrie Bay site.

Zinc concentrations were visibly greater nearest the farm at all times, and were particularly elevated in August 1999 (Figure 45). By September 2000 and August 2001 there were still some patches of elevated zinc concentrations near the farm, but concentrations throughout the rest of the site had diminished considerably.

Cadmium levels in September 2000 were lowest at stations nearest the farm site, and gradually increased with distance from the approximate farm center (Figure 46). By August 2001, cadmium had increased to be similar to reference levels at all areas except a small area near the farm center. The reference site for both dates shows cadmium concentrations decreasing in an easterly direction, away from the shoreline.

Silicon was lower at the farm site in September 2000 and had increased substantially by August 2001 beyond reference levels (Appendix J).
Figure 45: Contour maps showing spatio-temporal zinc concentration distributions at the Carrie Bay site.

Figure 46: Contour maps showing spatio-temporal cadmium concentration distributions at the Carrie Bay site.

4.2.2.3.9 Impact and Recovery Based on Thresholds (Within the Top 2cm of Sediment)

Cadmium concentrations at all of the Carrie Bay farm and reference stations sampled in September 2000 and August 2001 exceeded the ISQG threshold (Figure 47 and Appendix J).
Since cadmium concentrations actually increased between 24 and 35 months following abandonment of the farm site, and did not appear to change substantially at the reference site, there is no indication of cadmium recovery at the Carrie Bay site.

Copper concentrations at all of the Carrie Bay farm stations sampled in August 1999 exceeded the ISQG threshold, and the copper concentration at one station ~75 meters to the north-northeast of the farm exceeded the PEL threshold. Copper concentrations at all of the Carrie Bay reference stations sampled in August 1999 also exceeded the ISQG, and at the eastern-most reference station exceeded the PEL. Contour maps (Figure 48 and Appendix J) show lower copper concentrations falling in the region approximately 50 meters east of the approximated farm center. All sediments within 100 meters of the sampling stations exceeded the ISQG. A small area of sediments exceeded the PEL and was located approximately 60 meters north of the approximated farm center, extending up toward the shoreline. A contour map of the reference site shows copper concentrations incrementing gradually in an easterly direction, away from the shoreline.

Copper concentrations at all of the Carrie Bay farm stations sampled in September 2000 exceeded the ISQG threshold, and the copper concentrations at three stations at ~36, ~58, and ~92 meters to the west of the farm exceeded the PEL threshold. Copper concentrations at all of the Carrie Bay
reference stations sampled in September 2000 were below the ISQG. Contour maps (Figure 48 and Appendix J) show lower copper concentrations to the southeast of the approximate farm center. Most of copper concentrations in the sediments within 100 meters of the sampling stations exceeded the ISQG, with the exception of the area within the southeastern quadrant. A smaller area of sediments exceeded the PEL, and was located approximately 20 meters west of the approximated farm center, extending westward as well as to the southwest and northwest of the farm up toward the shoreline. A contour map of the reference site shows evenly distributed, low copper concentrations over the entire area.

Figure 48: Contour maps showing spatio-temporal copper concentration distributions at the Carrie Bay site (areas shaded white fall below the ISQG threshold; areas shaded blue exceed the ISQG; areas shaded red exceed the PEL threshold - Note: Colour map also available in Appendix J on CD).

Copper concentrations at all but two of the Carrie Bay farm stations sampled in August 2001 exceeded the ISQG threshold, and the copper concentrations at two stations to the north-northeast and the west of the farm exceeded the PEL threshold. Copper concentrations at all of the Carrie Bay reference stations sampled in August 2001 were below the ISQG. Two recovered stations were observed at ~14 and ~29 meters from the farm center. Contour maps (Figure 48 and Appendix J) show that copper concentrations in many areas of sediment within 100 meters of the
sampling stations exceeded the ISQG, particularly within the area extending from the immediate southeast of the approximate farm center. Two smaller areas contained copper concentrations that exceeded the PEL, and located approximately 50 meters west of the farm center and 40 meters northeast extending up toward the shoreline. The contour map of the reference site showed evenly distributed, low copper concentrations over the entire area.

Lead concentrations at the Carrie Bay site were well below the ISQG threshold.

![Figure 49: Contour maps showing spatio-temporal zinc concentration distributions at the Carrie Bay site (areas shaded grey fall below the ISQG threshold; areas shaded blue exceed the ISQG threshold; areas shaded red exceed the PEL threshold - Note: Colour map also available in Appendix J on CD).](image)

Zinc concentrations at all of the Carrie Bay reference stations sampled in August 1999, September 2000, and August 2001 fell below the ISQG threshold.

Zinc concentrations in August 1999 at most of the Carrie Bay farm stations to the east of the approximate farm center exceeded the ISQG. Concentrations at two farm stations to the immediate east-southeast and northwest of the approximate farm center exceeded the PEL. Contour maps (Figure 49 and Appendix J) show that the entire eastern area of the farm site had
zinc concentrations exceeding the ISQG. Zinc concentrations within a smaller area of sediments to the immediate east of the farm exceeded the PEL.

Zinc concentrations in September 2000 at six of the stations immediately east and west-northwest of the approximate farm center exceeded the ISQG, and no stations in the sampling area exceeded the PEL. Contour maps (Figure 49 and Appendix J) show the areas immediately southeast and northwest of the farm site to have zinc concentrations exceeding the ISQG, as well as an area approximately 40 meters northeast of the approximate farm center extending to the east.

Zinc concentrations in August 2001 at three of the Carrie Bay farm stations at 60 and 130 meters east from the approximate farm center exceeded the ISQG, and the station at 60 meters to the east exceeded the PEL. Contour maps (Figure 49 and Appendix J) show an area located approximately 50 meters to the east of the approximate farm center to have zinc concentrations exceeding the PEL. Zinc concentrations exceeding the ISQG surrounded and included this more affected area, and extended outward to the east and northeast.

At the Carrie Bay farm site, the percentage of repeatedly measured stations exceeding the ISQG thresholds for both copper and zinc had decreased overall by the conclusion of the study period (Table 32). These results would indicate a partial recovery of both metals at the farm site. The percentage of repeatedly measured stations exceeding the ISQG thresholds for cadmium did not decrease, and thus cadmium did not exhibit recovery at the farm site. The percentage of repeatedly measured stations exceeding the PEL thresholds for both copper and zinc had decreased overall by the conclusion of the study period, but exhibited fluctuations over time. At the reference site, the percentage of repeatedly measured stations exceeding the ISQG threshold for copper had decreased overall by the conclusion of the study period. The percentage of repeatedly measured stations exceeding the ISQG thresholds for cadmium did not decrease, and thus cadmium did not exhibit recovery at the reference site.

By the conclusion of the study, at 35 months following site abandonment, zinc at 18% of the farm stations had yet to recover to sub-ISQG concentrations. Cadmium at 100% of the farm and reference stations had not recovered, and copper at 88% of the farm stations had yet to recover. Copper had recovered fully by 35 months at the reference site.
Copper and zinc showed a mild, positive association throughout the Carrie Bay farm and reference sites (Figure 50). Cadmium did not exhibit an association with either copper or zinc (Appendix D), but did show a mild positive association with silicon (Figure 51). Neither copper nor cadmium exhibited any strong associations with any of the organic matter variables measured at the Carrie Bay site (Appendix D), although cadmium showed a mild positive association with organic C:N ratios (Figure 52). Zinc showed a mild, positive association with organic carbon, total carbon, and nitrogen (Figure 53), and a mild negative association with organic C:N ratios.
Figure 50: Relationship between zinc and copper at the Carrie Bay site.

Figure 51: Relationship between cadmium and silicon at the Carrie Bay site.

Figure 52: Relationship between zinc, cadmium, and organic C:N at the Carrie Bay site.
Figure 53: Relationships between zinc and total carbon, nitrogen, and organic carbon at the Carrie Bay site.

4.2.2.4 Sediment Oxygen Conditions

4.2.2.4.1 Contour Maps (Top 2cm Sediment)

Several trends were evident upon observation of contour maps generated for each of the sediment oxygen condition variables measured at the Carrie Bay site (Appendix J). Oxygen, redox potential, and sulphides appeared to have increased within the small area of revisited sediments between September 2001 and January 2002. In September 2001, oxygen and redox potential were visibly lower nearest the farm than elsewhere, while sulphides were higher (Figure 54).

Since only one station was repeatedly measured at 36 and 40 months following site abandonment, temporal trends in sediment oxygen conditions were difficult to assess.

During grab sample trips in August 1999, September 2000, and August 2001 sediments nearest the farm were characterized by black, anoxic, nearly-azoic or azoic mud, while sediments at 80
meters or more from the approximate farm center were observably healthier, taking on a green-brown appearance and observable fauna. In August, 1999 the black muds near the farm were also coated with white or orange bacterial mats. These mats had disappeared by the August 2001 sampling trip.

Figure 54: Contour maps showing spatio-temporal sulphides distributions at the Carrie Bay site.

4.2.2.4.2 GIS Maps (Vertical Core Profiles)

Several spatial and temporal trends in sediment oxygen collected from core samples at the Carrie Bay site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix L). Overall, oxygen values seemed relatively patchy and inconsistent over core depth, location, and distance from the approximate farm center. Oxygen values at all stations were typically lower at the sediment surface, gradually increased with depth toward a maximum value, and in some cases gradually decreased again. The maximum oxygen value was not consistent between stations, and neither was it observed at any consistent core depth. Overall, oxygen values throughout the core depth were much lower at stations sampled in January 2002 than at those sampled in September 2001. Of the stations sampled in September 2001, the highest surface value of oxygen was recorded at both a reference station and a station roughly 90 meters to the west-northwest of the approximate center of the farm. The overall lowest oxygen values throughout the sediment cores were observed at stations within 100 meters of the farm on both
sampling dates. Although oxygen approached anoxic levels in most of the sediments near the farm at both sampling times, oxygen values actually only reached 0% twice, both times at 36 months following site abandonment, and at sediment depths greater than 8cm.

Several spatial and temporal trends in sediment porosity collected from core samples at the Carrie Bay site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix L). Porosity values at all stations were typically highest at the sediment surface, and gradually decreased with depth. Porosity values throughout the sediment cores were typically higher at the farm stations, by roughly 10-20%, than at the reference stations. Occasional higher porosity pockets appeared within the sediment cores, eventually decreasing again with depth.

Several spatial and temporal trends in sediment redox potential collected from core samples at the Carrie Bay site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix L). Redox potential at all times, at all stations was typically highest at the sediment surface, rapidly decreased with depth to a point at approximately 4-8cm depth, and then gradually decreased to a minimum at approximately 6-12cm depth. Occasionally, higher redox potential pockets appeared within the sediment cores, typically between 6-12cm depth, and eventually decreased again with depth. Redox potential values at farm stations sampled during both September 2001 and January 2002 were typically between 100 and -300 mV at the surface, reaching minimums between -200 and -400 mV at depth. Redox potential gradients were much larger at stations to the southeast of the farm during both sampling times, due to elevated and typically oxic values within the top few centimeters of sediment. Redox potential values at reference stations in September 2001 were >0mV at the surface, reaching ~100mV at 8-10cm depth. The redox potential gradients at the reference stations were much smaller than those observed at the farm stations, particularly those east of the farm center. The lowest redox potential values were observed at farm stations sampled in January 2002, reaching minimums approaching -400 mV. The highest redox potential values were observed at reference stations in September, 2001.

Several spatial and temporal trends in sediment sulphides collected from core samples at the Carrie Bay site were identified through visual analysis of the GIS maps of graphed vertical profiles (Appendix L). Sulphides values at all stations were typically lowest at the sediment surface, sharply increasing with depth to a maximum thousands of μMol greater at approximately 6-18cm depth, or gradually increasing with depth to a maximum a few hundred μMol greater at approximately 12-16cm depth. Most increases to a maximum were often followed by a steady
decline in values again, although sulphides did not reach the low levels measured at the surface. The highest sulphides values were observed at the farm stations that fell closest or close to the approximate farm center. The lowest sulphides values were observed at the reference stations. Sulphides values observed at reference stations increased very minimally with core depth. Sediments sampled at the farm site in September 2001 appeared to have overall lower sulphides values throughout the cores than those sampled in January 2002.

C1 was the only station core sampled more than once at the Carrie Bay site, and Figure 55 demonstrates the sediment geochemistry profiles for both September 2001 and January 2002 at this station. Oxygen, redox potential, and sulphides within the top few centimeters of sediment were higher in September 2001 than in January 2002.

![Figure 55: Oxygen, redox potential, and sulphides sediment depth profiles (0-30cm) for each time sampled at station C1 at the farm site in Carrie Bay.](image)

**4.2.2.4.3 Impact and Recovery Based on Thresholds (Within the Top 2cm of Sediment)**

Oxygen values within the top 2cm of sediment at Carrie Bay consistently remained above 5ppm. Contour maps (Figure 56 and Appendix J) show that redox potential within the sediments surrounding the farm and to the northwest of the farm in September 2001 fell below the 0mV
oxic/hypoxic threshold. A smaller pocket of sediments within this area, between the farm and the shore, had redox potential values which fell below the -100mV hypoxic/anoxic threshold. Redox potential values exceeding 0mV fell within the area extending southeast from the approximate farm center. At the reference site in September 2001, redox potential values in the westernmost area exceeded 0mV, with values decreasing to the east with distance from the shoreline and eventually dropping below 0mV. None of the reference stations measured redox potential below -100mV. A contour map for the farm site in January 2002 shows redox potential surrounding the approximate farm center to be less than -100mV. The station nearest the farm measured -347mV. Redox potential gradually increased to the east and with distance from the farm center.

![Carrie Bay REDOX POTENTIAL (mV) Measurements, September, 2001](image1)

![Carrie Bay REDOX POTENTIAL (mV) Measurements, January, 2002](image2)

**Figure 56:** Contour maps showing spatio-temporal redox potential distributions at the Carrie Bay site (areas shaded green exceed the threshold associated with oxic/hypoxic conditions; areas shaded blue fall below the oxic/hypoxic threshold; areas shaded red fall below the hypoxic/anoxic threshold - Note: Colour map also available in Appendix J on CD).

Sulphides within the top 2cm of sediment at the Carrie Bay farm and reference sites always remained below 600μM, the sulphide threshold associated with potential benthic impact in British Columbia. The one exception was at a station measured in September 2001 at 11 meters east-northeast of the approximate farm center. The value measured within the top 2cm of sediment at this station was 1160μM. As a result of this value, the contour map for September
2001 shows a small area about 5 meters to the northeast of the farm center to have sulphides values exceeding 600μM (Figure 57 and Appendix J).

None of the sediment oxygen variables showed associations within the top 2cm of sediment alone (Appendix D). No metals or organic variables were measured at the time the sediment cores were collected, and thus no associations could be made with sediment oxygen conditions.

Figure 57: Contour maps showing spatio-temporal sulphides distributions at the Carrie Bay site (areas shaded blue exceed the threshold associated with potential benthic impact - Note: Colour map also available in Appendix J on CD).

4.2.2.4.4 Impact and Recovery Based on Thresholds (Within the Top 8-30cm of Sediment)

Oxygen values at Carrie Bay farm stations only twice dropped below 5ppm, reaching 0% at 14-16cm depth at a station 30 meters to the west of the farm, and at 8-10cm depth at another station 100 meters south-southwest of the farm. Both values were recorded in September 2001. Oxygen values observed at Carrie Bay reference stations did not drop below 5ppm.

Redox potential observed throughout cores during both sampling trips to the farm site typically remained below the anaerobic threshold of -100mV. Surface values at some stations were slightly more oxic, exceeding the 0mV anoxic/oxic threshold. At the reference site in September
2001, redox potential was more oxic at the surface, and dipped slightly below 0mV at greater sediment depths. Redox potential throughout cores measured at the reference site did not dip below -100mV.

Sulphides values at many of the Carrie Bay farm stations observed in September 2001 increased to and exceeded the potential impact threshold of 600μMol at somewhere between 0 and 18cm core depth. Of these stations, those closest to the farm reached the threshold at much shallower depths than those furthest from the farm. Three of the four stations at which sulphides remained above the threshold were actually the stations closest to the approximate farm center, situated 10-30 meters away to the west, south, and east-northeast. The fourth station was situated further away, approximately 130 meters to the east.

Sulphides values at a few of the Carrie Bay farm stations observed in September 2001 increased to and both exceeded the probable impact threshold of 1500μMol and fell within the hypoxic range of 1300-6000μMol at somewhere between 2 and 12cm core depth. These values were recorded at stations in all directions from the approximate farm center with the exception of the southerly direction.

Sulphides values at one farm station observed in September 2001 increased to and exceeded the anoxic threshold of 6000μMol at 12-14 cm depth. This station was located approximately 70 meters east of the approximate farm center. No values measured at any core depths at any stations measured in January 2002 exceeded this threshold.

Sulphides values at all of the farm stations observed in January 2002 increased to and exceeded 600μMol at 2-4cm core depth and fell within the hypoxic range of 1300-6000μMol between 2 and 6cm core depth.

Sulphides values at all core depths at all reference stations remained below 600μMol.

Redox potential and sulphides measured throughout the vertical cores did not show a strong association throughout the Carrie Bay site (Figure 58 and Figure 59). Redox potential values greater than approximately -200mV did, however, appear to be associated with much lower sulphides, typically less than 1000μMol.
Figure 58: Relationship between sulphides and redox potential for all sampling dates at the Carrie Bay site.

Figure 59: Relationship between sulphides and redox potential for each individual sampling date at the Carrie Bay site.

When the data for the Carrie Bay site were plotted with the data for the Chained Islands site, the Chained Islands data clearly fell toward the more oxic end of the relationship, and the Carrie Bay data fell toward the more anoxic end (Figure 60).
Figure 60: Relationship between sulphides and redox potential for all sampling dates at both the Chained Islands (CI) and Carrie Bay (CB) sites.

Figure 61: Relationship between sulphides <1000 µMol and redox potential >200 mV for all sampling dates at both the Chained Islands (CI) and Carrie Bay (CB) sites.
However, it remained difficult to observe any strong association between the two variables. When only the relationships between sulphides less than 1000μMol and redox potential greater than -200mV were plotted for both sites, a slightly stronger association between the two variables was evident (Figure 61).

Oxygen did not exhibit associations with either sulphides or redox potential throughout the vertical cores (Appendix D). No metals or organic variables were measured at the time the sediment cores were collected, and thus no associations could be made with sediment oxygen conditions.

4.2.3 Sensitive Indicators of Recovery

4.2.3.1 ANOVA Sensitivity Analysis (Within the Entire Site)

All of the variables listed in Table 33 were significant indicators of differences in organic matter accumulations between locations at the Carrie Bay site. The p-values showed that zinc, total carbon, nitrogen, porosity, and organic content had the highest sensitivities, with slightly decreasing sensitivities being observed with organic carbon, copper, lead, aluminum, cadmium, and bulk density.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>zinc</td>
<td>0.000</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.000</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.000</td>
</tr>
<tr>
<td>porosity</td>
<td>0.000</td>
</tr>
<tr>
<td>organic content</td>
<td>0.000</td>
</tr>
<tr>
<td>organic carbon</td>
<td>0.001</td>
</tr>
<tr>
<td>copper</td>
<td>0.004</td>
</tr>
<tr>
<td>lead</td>
<td>0.012</td>
</tr>
<tr>
<td>aluminum</td>
<td>0.030</td>
</tr>
<tr>
<td>cadmium</td>
<td>0.034</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.040</td>
</tr>
</tbody>
</table>

Table 33: ANOVA p-values for significant indicators of differences in organic matter accumulations between locations within the Carrie Bay site.

There were no sensitive indicators of spatio-temporal change at the Carrie Bay site.
4.2.3.2 ANOVA Sensitivity Analysis (Within 50m of the Farm)

All of the variables listed in Table 34 were significant indicators of differences in organic matter accumulations between Carrie Bay reference stations and farm stations located within 50 meters of the farm. The $p$-values showed that nitrogen, total carbon, and organic content had the highest sensitivities, with slightly decreasing sensitivities being observed with zinc, organic carbon, bulk density, cadmium, lead, and copper.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nitrogen</td>
<td>0.000</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.000</td>
</tr>
<tr>
<td>organic content</td>
<td>0.000</td>
</tr>
<tr>
<td>zinc</td>
<td>0.001</td>
</tr>
<tr>
<td>organic carbon</td>
<td>0.001</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.001</td>
</tr>
<tr>
<td>cadmium</td>
<td>0.002</td>
</tr>
<tr>
<td>lead</td>
<td>0.019</td>
</tr>
<tr>
<td>copper</td>
<td>0.028</td>
</tr>
</tbody>
</table>

Table 34: ANOVA $p$-values for significant indicators of differences in organic matter accumulations between reference stations and farm stations located within 50m of the farm in the Carrie Bay site.

Total carbon was the only significant indicator of spatio-temporal change within 0-50 meters of the Carrie Bay farm. It had a $p$-value of 0.010.

4.2.3.3 ANOVA Sensitivity Analysis (At 50-100m from the Farm)

All of the variables listed in Table 35 were significant indicators of differences in organic matter accumulations between Carrie Bay reference stations and farm stations located at 50-100 meters from the farm. The $p$-values showed that total carbon, nitrogen, organic content, and porosity had the highest sensitivities, with slightly decreasing sensitivities being observed with copper, zinc, organic carbon, aluminum, and lead.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>total carbon</td>
<td>0.000</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.000</td>
</tr>
<tr>
<td>organic content</td>
<td>0.000</td>
</tr>
<tr>
<td>porosity</td>
<td>0.000</td>
</tr>
</tbody>
</table>
There were no significant indicators of spatio-temporal change at 50-100 meters from the farm.

4.2.3.4 ANOVA Sensitivity Analysis (At >100m from the Farm)

All of the variables listed in Table 36 were significant indicators of differences in organic matter accumulations between Carrie Bay reference stations and farm stations located at >100 meters from the farm. The p-values showed that nitrogen had the highest sensitivity with slightly decreasing sensitivities being observed with total carbon, organic content, aluminum, lead, and porosity.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>nitrogen</td>
<td>0.000</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.002</td>
</tr>
<tr>
<td>organic content</td>
<td>0.002</td>
</tr>
<tr>
<td>aluminum</td>
<td>0.012</td>
</tr>
<tr>
<td>lead</td>
<td>0.015</td>
</tr>
<tr>
<td>porosity</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Table 36: ANOVA p-values for significant indicators of differences in organic matter accumulations between reference stations and farm stations located at >100m from the farm in the Carrie Bay site.

All of the variables listed in Table 37 were significant indicators of spatio-temporal change at distances of >100 meters from the farm. The p-values showed that clay had the highest sensitivity with slightly decreasing sensitivities being observed with very fine and fine sand.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>clay (&lt;2μm)</td>
<td>0.008</td>
</tr>
<tr>
<td>very fine sand</td>
<td>0.023</td>
</tr>
<tr>
<td>fine sand</td>
<td>0.032</td>
</tr>
</tbody>
</table>

Table 37: ANOVA p-values for significant indicators of spatio-temporal change at farm stations located >100m from the farm in the Carrie Bay site.
4.2.3.5 **ANOVA Sensitivity Analysis (Within the Farm Site)**

All of the variables listed in Table 38 were significant indicators of temporal change within the Carrie Bay farm site. The *p*-values showed that organic C:N, cadmium, and silicon had the highest sensitivities with slightly decreasing sensitivities being observed with total carbon, zinc, and organic carbon.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA <em>p</em>-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>organic C:N</td>
<td>0.000</td>
</tr>
<tr>
<td>cadmium</td>
<td>0.000</td>
</tr>
<tr>
<td>silicon</td>
<td>0.000</td>
</tr>
<tr>
<td>total carbon</td>
<td>0.001</td>
</tr>
<tr>
<td>zinc</td>
<td>0.003</td>
</tr>
<tr>
<td>organic carbon</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 38: **ANOVA *p*-values for significant indicators of temporal change at the Carrie Bay farm site.**

Porosity, copper, nitrogen, bulk density, and organic content were significant indicators of differences in organic matter accumulations between sediments located at 0-50m, 50-100m, and >100m from the Carrie Bay farm. The *p*-values showed porosity to have the highest sensitivity with slightly decreasing sensitivities being observed with copper, nitrogen, bulk density, and organic content (Table 39).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA <em>p</em>-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>porosity</td>
<td>0.005</td>
</tr>
<tr>
<td>copper</td>
<td>0.013</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.019</td>
</tr>
<tr>
<td>bulk density</td>
<td>0.028</td>
</tr>
<tr>
<td>organic content</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Table 39: **ANOVA *p*-values for significant indicators of differences in organic matter accumulations between sediments located at 0-50m, 50-100m, and >100m from the Carrie Bay farm.**

There were no significant indicators of spatio-temporal change within the Carrie Bay farm site.

4.2.3.6 **ANOVA Sensitivity Analysis (Within the Reference Site)**

Copper and zinc were significant indicators of temporal change within the Carrie Bay reference site. The *p*-values showed that zinc had a higher sensitivity than copper.
### Table 40: ANOVA p-values for significant indicators of temporal change at the Carrie Bay reference site.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>zinc</td>
<td>0.002</td>
</tr>
<tr>
<td>copper</td>
<td>0.011</td>
</tr>
</tbody>
</table>

All of the variables listed in Table 41 changed over time at the reference site, but were hypothesized to actually be significant indicators of temporal change within the Carrie Bay farm site. The p-values showed silt to have the highest sensitivity with slightly decreasing sensitivities being observed with fine sand, organic content, very fine sand, coarse sand, inorganic carbon, nitrogen, clay, and medium sand.

### Table 41: ANOVA p-values for significant indicators of temporal change at the Carrie Bay farm site variables (measured at the reference site).

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>silt</td>
<td>0.000</td>
</tr>
<tr>
<td>fine sand</td>
<td>0.001</td>
</tr>
<tr>
<td>organic content</td>
<td>0.003</td>
</tr>
<tr>
<td>very fine sand</td>
<td>0.009</td>
</tr>
<tr>
<td>coarse sand</td>
<td>0.018</td>
</tr>
<tr>
<td>inorganic carbon</td>
<td>0.022</td>
</tr>
<tr>
<td>nitrogen</td>
<td>0.024</td>
</tr>
<tr>
<td>clay (&lt;4μm)</td>
<td>0.030</td>
</tr>
<tr>
<td>medium sand</td>
<td>0.032</td>
</tr>
</tbody>
</table>

### 4.2.4 Redundancies Amongst Variables

#### 4.2.4.1 Principal Components Analysis

The results of the Principal Components Analyses performed on each of the geochemical and geophysical parameters measured at the Carrie Bay site demonstrated some significant relationships, trends, and redundancies amongst sediment variables. Four categories of variables were isolated from the principal components shown in Table 43, Table 42, and Table 44: sediment physical properties, metals, organic matter, and sediment oxygen conditions.

Fine to coarser sediment grain sizes (very coarse sand, coarse sand, medium sand, and fine sand) were significantly highly positively correlated with each other, and significantly highly negatively correlated with ultra-fine sediment grain sizes (silt and clay <4μm) under the same components.
Bulk density and gravel were also significantly highly positively correlated with each other. These variables collectively comprised a category defined as sediment physical property variables.

Aluminum, copper, and zinc were significantly highly positively correlated with each other, as were cadmium and silicon. These variables formed a second category that was defined as metals variables.

Organic carbon, nitrogen, total carbon, organic content, and porosity were significantly highly positively correlated with each other. Chlorophyll and pheophytin were also highly positively correlated with one another. These variables collectively made up a third category that was defined as organic matter variables.

Within the vertical sediment cores, redox potential and oxygen were significantly highly positively correlated with each other, and were significantly highly negatively correlated with sulphides and porosity. These variables collectively made up a fourth category that was defined as sediment oxygen conditions.

---

**Rotated Loading Matrix (Varimax, Gamma = 1.0000)**

<table>
<thead>
<tr>
<th>Principal Component</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>OXYGEN</td>
<td>-0.614</td>
</tr>
<tr>
<td>POROSITY</td>
<td>0.648</td>
</tr>
<tr>
<td>REDOX</td>
<td>-0.743</td>
</tr>
<tr>
<td>SULPHIDES</td>
<td>0.501</td>
</tr>
</tbody>
</table>

**% Total Variance Explained by Component**

40.010

**% Cumulative Variance**

40.010

Table 42: Results of the Principal Components Analysis performed on all variables measured within the top 2cm of core samples collected in Carrie Bay during September 2001 and January 2002.
Rotated Loading Matrix (Varimax, Gamma = 1.0000)
N = 47; Sample size too small (N<50) to use 2(std. error) significance test
Significant Loading Estimated At > |0.575|

<table>
<thead>
<tr>
<th>Principal Component</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUMINUM</td>
<td>0.529</td>
<td>0.124</td>
<td>0.284</td>
<td>-0.574</td>
<td>0.088</td>
<td>0.270</td>
<td>0.276</td>
</tr>
<tr>
<td>BULKDENSITY</td>
<td>-0.281</td>
<td>0.276</td>
<td>0.028</td>
<td>0.004</td>
<td>-0.255</td>
<td>-0.649</td>
<td>0.259</td>
</tr>
<tr>
<td>CADMIUM</td>
<td>-0.121</td>
<td>-0.034</td>
<td>0.842</td>
<td>0.051</td>
<td>-0.299</td>
<td>-0.273</td>
<td>0.042</td>
</tr>
<tr>
<td>CHL</td>
<td>0.345</td>
<td>-0.229</td>
<td>0.071</td>
<td>-0.001</td>
<td>0.029</td>
<td>0.228</td>
<td>-0.813</td>
</tr>
<tr>
<td>ug/g CARBON</td>
<td>-0.117</td>
<td>-0.954</td>
<td>-0.196</td>
<td>-0.082</td>
<td>-0.034</td>
<td>0.094</td>
<td>-0.021</td>
</tr>
<tr>
<td>ug/g INORG. CARBON</td>
<td>-0.259</td>
<td>-0.121</td>
<td>-0.832</td>
<td>-0.062</td>
<td>-0.332</td>
<td>-0.074</td>
<td>0.210</td>
</tr>
<tr>
<td>ug/g NITROGEN</td>
<td>-0.033</td>
<td>-0.672</td>
<td>-0.101</td>
<td>-0.193</td>
<td>-0.069</td>
<td>0.636</td>
<td>-0.072</td>
</tr>
<tr>
<td>ug/g ORG. CARBON</td>
<td>0.099</td>
<td>-0.894</td>
<td>0.284</td>
<td>-0.067</td>
<td>0.142</td>
<td>0.097</td>
<td>-0.187</td>
</tr>
<tr>
<td>COPPER</td>
<td>-0.069</td>
<td>-0.401</td>
<td>-0.050</td>
<td>0.805</td>
<td>-0.021</td>
<td>0.001</td>
<td>-0.123</td>
</tr>
<tr>
<td>LT_2MM</td>
<td>-0.478</td>
<td>-0.039</td>
<td>-0.223</td>
<td>-0.045</td>
<td>0.128</td>
<td>-0.527</td>
<td>0.161</td>
</tr>
<tr>
<td>LEAD</td>
<td>0.437</td>
<td>0.079</td>
<td>-0.115</td>
<td>0.464</td>
<td>0.252</td>
<td>0.493</td>
<td>0.175</td>
</tr>
<tr>
<td>LT_100UM</td>
<td>-0.449</td>
<td>0.501</td>
<td>-0.146</td>
<td>0.248</td>
<td>-0.489</td>
<td>-0.180</td>
<td>0.148</td>
</tr>
<tr>
<td>LT_1MM</td>
<td>-0.937</td>
<td>-0.067</td>
<td>-0.159</td>
<td>-0.051</td>
<td>-0.064</td>
<td>-0.129</td>
<td>0.138</td>
</tr>
<tr>
<td>LT_250UM</td>
<td>-0.807</td>
<td>0.135</td>
<td>-0.160</td>
<td>0.223</td>
<td>-0.390</td>
<td>0.082</td>
<td>0.152</td>
</tr>
<tr>
<td>LT_2MM</td>
<td>-0.748</td>
<td>0.045</td>
<td>-0.174</td>
<td>-0.118</td>
<td>0.042</td>
<td>-0.462</td>
<td>0.209</td>
</tr>
<tr>
<td>LT_2UM</td>
<td>0.719</td>
<td>-0.182</td>
<td>-0.240</td>
<td>-0.111</td>
<td>0.072</td>
<td>0.437</td>
<td>-0.207</td>
</tr>
<tr>
<td>LT_4UM</td>
<td>0.318</td>
<td>-0.116</td>
<td>0.131</td>
<td>0.005</td>
<td>0.708</td>
<td>0.300</td>
<td>0.017</td>
</tr>
<tr>
<td>LT_500UM</td>
<td>-0.885</td>
<td>-0.218</td>
<td>-0.142</td>
<td>-0.137</td>
<td>-0.078</td>
<td>0.181</td>
<td>0.132</td>
</tr>
<tr>
<td>LT_63UM</td>
<td>0.609</td>
<td>0.079</td>
<td>0.657</td>
<td>-0.091</td>
<td>-0.101</td>
<td>0.118</td>
<td>-0.121</td>
</tr>
<tr>
<td>ORG. CONTENT</td>
<td>-0.061</td>
<td>-0.510</td>
<td>-0.059</td>
<td>-0.179</td>
<td>0.207</td>
<td>0.572</td>
<td>0.043</td>
</tr>
<tr>
<td>PHEO</td>
<td>0.195</td>
<td>-0.094</td>
<td>0.164</td>
<td>-0.014</td>
<td>0.079</td>
<td>0.030</td>
<td>-0.912</td>
</tr>
<tr>
<td>POROSITY</td>
<td>0.471</td>
<td>-0.376</td>
<td>0.126</td>
<td>-0.265</td>
<td>0.308</td>
<td>0.505</td>
<td>-0.283</td>
</tr>
<tr>
<td>% CARBON</td>
<td>-0.117</td>
<td>-0.954</td>
<td>-0.196</td>
<td>-0.082</td>
<td>-0.034</td>
<td>0.084</td>
<td>-0.021</td>
</tr>
<tr>
<td>% INORG. CARBON</td>
<td>-0.253</td>
<td>-0.167</td>
<td>-0.834</td>
<td>-0.039</td>
<td>-0.313</td>
<td>-0.086</td>
<td>0.198</td>
</tr>
<tr>
<td>% NITROGEN</td>
<td>0.036</td>
<td>-0.837</td>
<td>-0.119</td>
<td>-0.263</td>
<td>-0.004</td>
<td>0.685</td>
<td>-0.018</td>
</tr>
<tr>
<td>% ORG. CARBON</td>
<td>0.099</td>
<td>-0.894</td>
<td>0.284</td>
<td>-0.067</td>
<td>0.142</td>
<td>0.096</td>
<td>-0.188</td>
</tr>
<tr>
<td>SED. TEMPERATURE</td>
<td>-0.220</td>
<td>0.016</td>
<td>0.382</td>
<td>0.120</td>
<td>0.485</td>
<td>-0.171</td>
<td>-0.150</td>
</tr>
<tr>
<td>SILICON</td>
<td>0.186</td>
<td>-0.406</td>
<td>0.756</td>
<td>-0.072</td>
<td>0.248</td>
<td>0.032</td>
<td>0.073</td>
</tr>
<tr>
<td>ZINC</td>
<td>-0.216</td>
<td>-0.497</td>
<td>-0.144</td>
<td>-0.626</td>
<td>-0.181</td>
<td>0.420</td>
<td>0.006</td>
</tr>
</tbody>
</table>

| % Cumulative Variance                  | 19.144| 39.247| 52.784| 59.727| 66.249| 78.069| 85.518|

Table 43: Results of the Principal Components Analysis performed on all variables measured within the top 2cm of grab samples collected at the Carrie Bay site.
Table 44: Results of the Principal Components Analysis performed on all variables measured throughout vertical core samples collected in Carrie Bay during September 2001 and January 2002.

4.2.4.2 Correlation and Regression Analysis

Several variable redundancies were identified through regression analysis amongst sediment variables measured within the top 2cm of sediment at the Carrie Bay site (Appendix F).

Redundant sediment variables (Table 45) collected from the Carrie Bay farm site were used, along with the results of PCA, for grouping sediment variables and determining redundancies between them. These variable pairs demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.

<table>
<thead>
<tr>
<th>Redundant Variable Pairs</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>chlorophyll and pheophytin</td>
<td>positive</td>
</tr>
<tr>
<td>fine sand and coarse sand</td>
<td>positive</td>
</tr>
<tr>
<td>coarse sand and very coarse sand</td>
<td>positive</td>
</tr>
<tr>
<td>medium sand and coarse sand</td>
<td>positive</td>
</tr>
<tr>
<td>medium sand and fine sand</td>
<td>positive</td>
</tr>
<tr>
<td>porosity and fine sand</td>
<td>negative</td>
</tr>
</tbody>
</table>

Table 45: Sediment variables measured at the Carrie Bay farm site that demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.
The regression curves fit between sulphides and porosity (Figure 62a) and chlorophyll and pheophytin (Figure 62b) visually demonstrate the strength of relationships between redundant variables collected at the Carrie Bay farm site.

Redundant sediment variables (Table 46) collected from the Carrie Bay reference site were used, along with the results of PCA, for grouping sediment variables and determining redundancies between them. These variable pairs demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis. A lack of degrees of freedom resulting from the small number of sampling stations prevented regression analyses of many variable pairs collected at the reference site. Thus, the results of the PCA weighed more heavily when analyzing variable redundancies.

<table>
<thead>
<tr>
<th>Redundant Variable Pairs</th>
<th>Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>copper and zinc</td>
<td>positive</td>
</tr>
<tr>
<td>lead and zinc</td>
<td>positive</td>
</tr>
<tr>
<td>clay (&lt;4μm) and very fine sand</td>
<td>negative</td>
</tr>
</tbody>
</table>

Table 46: Sediment variables measured at the Carrie Bay reference site that demonstrated meaningful relationships, collinearity according to correlation analysis, and goodness-of-fit according to regression analysis.

The regression curve fit between copper and zinc (Figure 63) visually demonstrates the strength of relationships between redundant variables collected at the Carrie Bay reference site.
Figure 63: Regression curve between copper and zinc measured at the Carrie Bay reference site.

The negative relationship between sulphides and porosity throughout core samples collected at the farm site demonstrated collinearity according to correlation analysis, and goodness-of-fit according to regression analysis. This indicated a possible redundancy between the two sediment variables.

No variable redundancies were identified through regression analysis amongst sediment variables measured throughout vertical core profiles collected from the Carrie Bay site (Appendix F).
5 Discussion and Recommendations

5.1 Chained Islands Recovery

5.1.1 Variable Redundancies

Significant redundancies were identified amongst sediment variables at the Chained Islands site. These redundancies were used to reduce the set of variables to a smaller subset for assessing recovery at similar sites in the future. Four categories of variables were isolated: sediment physical properties, metals, organic matter, and sediment oxygen conditions.

There was a consistent contrast between the presence of coarse substrate and the absence of finer, more porous substrate, and vice versa. However, there was also evidence of the coexistence of coarser and finer sediments at the site. Sites dominated by fine substrate are typically representative of areas where currents are lower and rapid settlement of fine particulates is encouraged (Holmer, 1991). Sites dominated by coarse substrate are usually representative of areas where faster currents preclude the settlement of the finer sediment fractions (Holmer, 1991). Anderson (1996) also found a significant contrast between the presence of silt-clay and sand at fish farm sites in British Columbia. Sediment porosity is typically higher in clay sediments than in coarser grained sediments (McConnell, 2002; Caulfield and Filkins, 1999; Ward and Robinson, 1990). High porosity can also be indicative of rapidly depositing sediments which have not had sufficient time to undergo compaction (UK Marine SAC, 2002). Based on the redundancies found amongst certain sediment physical property variables, the nine grain size categories could feasibly be reduced to the following five categories when analyzing sediments at sites similar to those found at the Chained Islands site: clay (< 4μm), silt (< 63μm), finer sand (< 250μm), coarser sand (< 2mm), and gravel (>2mm). These and similar categories have been used at farm site assessments in British Columbia by Anderson (1996), Brooks (2000a), and are currently recommended for use within the Aquaculture Information Request and Interim Monitoring Program (Erickson et al., 2001). Porosity was directly related to grain size at this site, and thus may be considered to be a redundant variable at other similar sites.

Copper, zinc, aluminum, and lead concentrations tended to vary concurrently within the sediments at the Chained Islands site. Cadmium and zinc were also found to vary concurrently.
Copper and zinc concentrations have been found to be high in sediments underlying fish farm sites due to the copper contained in the antifouling paint used on the cages and the zinc provided in the feed (Brooks, 2001a and 2001b; Erickson et al., 2001; Morrisey et al., 2000; Uotila, 1991). Lead has not been identified as a toxic constituent in sediments receiving fish farm waste inputs (Sutherland et al., 2001; Uotila, 1991). Aluminum and cadmium have not been identified as indicators of farm waste inputs to sediments, but are have been detected in fish farm feed pellets in trace amounts (Sutherland et al., 2001; Tacon and De Silva, 1983). Natural organic matter contains varying concentrations of all five metals (Dixit et al., 2001; McNee, 1997; Macdonald et al., 1991; Francois, 1988). Based on the redundancies identified amongst certain metals variables, the number of metals could feasibly be grouped within a smaller number of categories: those commonly associated with fish farming activity (copper and zinc), and those commonly associated with natural organic matter (aluminum, cadmium, copper, lead, zinc).

Organic carbon, inorganic carbon, nitrogen, organic content, and porosity tended to vary concurrently within the sediments at the Chained Islands site. Brooks (2002) also found organic carbon and organic content to be highly correlated in sediments at fish farm sites in British Columbia. Total carbon and nitrogen are significant elements present in organic matter compounds (Thurman, 1997), and have been found to be present in elevated concentrations in sediments receiving fish farm waste inputs (Brook, 2002; Levings and Sutherland, 1999; Gowen and Bradbury, 1987). Porosity has been found to directly relate to the organic matter content of sediments (UK Marine SAC, 2002; Avnimelech et al., 2001; Lu et al., 1998). Based on the redundancies found amongst certain organic matter variables measured at this site, the number of variables could feasibly be reduced to a smaller number.

Chlorophyll and pheophytin, phytoplanktonic pigments which are also organic matter variables, were found to vary concurrently at the Chained Islands site. Based on the redundancy observed between the two variables, chlorophyll or pheophytin alone would serve as an adequate measurement of productivity at sites similar to the one at the Chained Islands site.

Throughout the upper sediment column at the Chained Islands site, there was a consistent inverse relationship between redox potential and sulphides. Low redox potential is known to be associated with reducing sediment conditions which also exhibit elevated levels of hydrogen sulphide (Zobell, 1946). Hargrave et al. (1995) also found a negative correlation between sediment sulphides and redox potential at both reference and farm sites on the East Coast of Canada. Based on the observed redundancy, these two indicators of sediment oxygen conditions
could feasibly be reduced to one when analyzing sediments at sites similar to those found at the Chained Islands site.

Oxygen and porosity tended to vary concurrently throughout the upper sediment column at the Chained Islands site. Porosity also varied concurrently with redox potential. Typically, finer sediments, particularly the silt-clay fraction, tend to be characteristic of reducing conditions while coarser sediments tend to be less reducing (Zobell, 1946). Porosity tends to increase with decreasing sediment grain size (Caulfield and Filkins, 1999), and thus finer sediments tend to have a higher porosity. It was expected that high porosity would occur simultaneously with low oxygen. However, this was not the case at the Chained Islands site. Due to the unpredictable nature of oxygen and porosity at this site, it is not recommended that these sediment oxygen condition variables be reduced to just one.

5.1.2 Recovery Indicators

5.1.2.1 Sensitive Indicators of Temporal Recovery

Cadmium and zinc were the most sensitive indicators of temporal recovery within the sediments at the Chained Islands site. Overall, cadmium was a slightly more sensitive indicator than zinc, although the two were very similar. Zinc, which is included in fish feed, has been identified as an indicator of benthic impact within sediments at fish farm sites in British Columbia (Brooks, 2001a and 2001b; Erickson et al., 2001). Cadmium has not been identified as an indicator of benthic habitat recovery at fish farm sites, but it has been detected in fish farm feed in trace amounts (Sutherland et al., 2001; Tacon and De Silva, 1983).

Porosity, nitrogen, total carbon, and organic carbon were not significant indicators, but were nonetheless minor indicators of recovery, at the east farm site only. These indicators have been used to assess benthic impact at fish farm sites (Brooks, 2002; Anderson, 1996; Miller-Retzer, 1994; Cross, 1990), but are rarely cited as recovery indicators. Brooks (2002) found organic carbon to be a sensitive indicator of biological recovery at a fish farm site in British Columbia.

Despite the fact that redox potential and sulphides were not identified as significant indicators, they were used to conclude that sediment conditions at the Chained Islands site were oxic and likely dominated by aerobic processes. Thus, the variables were likely indicative of one of two
situations: (1) sediment oxygen conditions had already recovered, assuming they had been impacted, prior to the first sampling trip, or (2) sediment oxygen conditions had not been affected by waste inputs. Sulphides and redox potential were therefore considered to be recovery indicators at the Chained Islands site.

5.1.2.2 Sensitive Indicators of Spatial Variation

Copper, lead, zinc, chlorophyll, porosity, bulk density, total carbon, nitrogen, organic content, and organic carbon were the most sensitive indicators of spatial variations in organic matter accumulations throughout the Chained Islands site. Of these, copper, lead, total carbon, nitrogen, porosity, and bulk density were the most sensitive indicators.

5.1.2.3 Sensitive Indicators of Spatio-Temporal Recovery

There were no significant indicators of spatio-temporal recovery at the Chained Islands site.

5.1.2.4 Summary of Sensitive Indicators

Cadmium, zinc, copper, lead, chlorophyll, porosity, bulk density, total carbon, nitrogen, organic content, organic carbon, redox potential, and sulphides were identified as indicators of temporal recovery and spatial variations in organic matter accumulations at the Chained Islands site. At the Chained Islands site, cadmium was identified as a recovery indicator due to its association with fish farm wastes. That is, a decrease in cadmium was indicative of recovery. However, at the Carrie Bay site, cadmium was identified as a recovery indicator due to its association with natural organic matter, and not fish farm wastes. That is, an increase in cadmium was indicative of recovery. This inconsistency led to the recommendation that cadmium, although it was identified as one of the most sensitive indicators, not be used as an indicator in future recovery assessments at similar sites. Lead was also identified as an indicator of recovery at both sites, but its origins could not be traced and thus it is not recommended that lead be used as an indicator in future recovery assessments at similar sites.

Given the exclusion of cadmium and lead from the list of valid recovery indicators, three tiers of recovery indicators were developed for future assessments at sites characterized by similar
production levels, substrate, and hydrography (Figure 43). Tier 1 contained all valid recovery indicators, tier 2 contained a condensed version of the tier 1 list based on variable redundancies, and tier 3 contained the most sensitive of these indicators. The most appropriate tier of indicator variables to be measured in a future recovery assessment would be selected based on budget, equipment, and time allowances.

<table>
<thead>
<tr>
<th>TIER 1</th>
<th>TIER 2</th>
<th>TIER 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Valid Recovery Indicators</td>
<td>Autonomous Recovery Indicators</td>
<td>Most Sensitive Recovery Indicators</td>
</tr>
<tr>
<td>zinc</td>
<td>zinc or copper</td>
<td>zinc</td>
</tr>
<tr>
<td>copper</td>
<td>total carbon, nitrogen, org. content, org. carbon</td>
<td>copper</td>
</tr>
<tr>
<td>total carbon</td>
<td>porosity</td>
<td>total carbon</td>
</tr>
<tr>
<td>nitrogen</td>
<td>bulk density</td>
<td>nitrogen</td>
</tr>
<tr>
<td>porosity</td>
<td>chlorophyll</td>
<td>porosity</td>
</tr>
<tr>
<td>bulk density</td>
<td>redox potential or sulphides</td>
<td>bulk density</td>
</tr>
<tr>
<td>chlorophyll</td>
<td></td>
<td></td>
</tr>
<tr>
<td>organic content</td>
<td></td>
<td></td>
</tr>
<tr>
<td>organic carbon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>redox potential</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sulphides</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 47: Three tiers of indicators to be used for assessing recovery at fish farm sites similar to the one near the Chained Islands.

5.1.3 Habitat characteristics

At the Chained Islands site, the average depth was 27.0±6.3 meters at the east farm site, 31.0±9.7 meters at the west farm site, and 29.9±3.9 meters at the reference site. At the east farm site, the shallowest areas were near the islands to the north and northwest of the farm. Depths increased in a south-southeasterly direction away from the farm reaching in excess of 40 meters in the deepest sections sampled. Depths in the immediate vicinity of the farm were ranged between approximately 25 and 30 meters. At the west farm site, the shallowest areas were near the islands north of the farm. Depths increased in south and south-southeasterly directions away from the farm, reaching in excess of 40 meters in the deepest sections sampled. Depth in the immediate vicinity of the farm was approximately 20 meters. At the reference site, the shallowest areas were nearest the islands to the north, and depths increased in south and southeasterly directions away from the shore.
Typically, organic accumulations leading to enrichment are associated with fine-grained sediments (Mayer and Rossi, 1982). Clay, silt, and fine sand have all been found to dominate substrates found at various impacted fish farm sites in British Columbia (Brooks, 2002; Levings and Sutherland, 1999; Anderson, 1996; Miller-Retzer, 1994; Cross, 1990) and elsewhere (McGhie et al., 2000; Karakassis et al. 1999; Mazzola et al., 1999; Hargrave et al., 1997; Brooks, 1996; Tsutsumi, 1995; Johannessen et al., 1994; Ye et al., 1991; Weston, 1990; Aure et al., 1988; Kaspar et al., 1988; Brown et al., 1987). Sediments at the Chained Islands site were dominated by silt and finer sands.

Sediments at the east farm site consisted primarily of silt and finer sand, and some finer clay and gravel. At the west farm site, sediments also consisted predominantly of silt and finer sand, with some finer clay and gravel. Sediment collected at the east and west farm sites consistently contained olive-green mud with some sand and shell hash at nearshore, shallower stations, and olive-green mud at deeper stations. The northernmost, nearshore edges of each farm were situated near shallow, rocky outcrops which precluded sampling. Sediments at the reference site consisted of a majority of silt and finer sand, with some finer clay. Sediment collected at the reference site consistently contained dark olive-green mud with observable black streaks and a very slight \( \text{H}_2\text{S} \) smell.

Throughout the entire Chained Islands site, the silt-clay sediments were also the most organic-rich. Sediments at the east farm site were more silty than those at the west farm site, and contained more medium sand than those at the reference site. Coarse grain sizes larger than fine sand were either negligible or absent in the sediments sampled at the reference site. The reference site contained more fine sand than at either of the farm sites. The coarser sands and gravel were observed predominately at stations to the north and northeast of the farms within the shallower nearshore areas. Finer sands and organic laden silt appeared more often at stations to the south and southwest of the farms, within the deeper areas. Organic laden clay was highest at stations to the north, northeast, and southwest of the farms. There was some indication of a decrease in inputs of finer sediments into the entire site over the study period, which may be partially indicative of a decrease in waste material inputs reaching the site. The presence of fish farm cage structures can act to decrease flow rates thereby inducing an increase in siltation and particulate matter settling to the sea floor (Sutherland et al., 2001; Frid and Mercer, 1989).
5.1.4 Recovery Assessment

5.1.4.1 Organic Matter

Nitrogen, organic carbon, organic content, and total carbon were significantly greater throughout the sediments at the Chained Islands east farm site than at the west farm and reference sites. Nitrogen, total carbon, and organic carbon were found to be most pronounced within the first month of site abandonment. Carbon and nitrogen are significant components of organic matter, and elevated concentrations have been detected in sediments receiving inputs from fish farms (Brooks, 2002; Levings and Sutherland, 1999; Brooks, 1996; Hargrave et al., 1997; Gowen, 1991; Weston, 1990).

Organic matter accumulations were similar at the west farm and reference sites. The only distinguishing characteristics between the two sites were minor differences in grain sizes. No temporal variations in any of the organic matter variables could be detected at the west farm site.

Chlorophyll in the surface sediments appeared to be slightly elevated at stations nearest to both farms. Since chlorophyll also varied with station depth, which is known to influence presence of phytoplankton (Thurman, 1997), these minor spatial variations are likely natural. The overall decrease in sediment chlorophyll and increase in sediment silicon over the sampling year, particularly at the reference site, was likely indicative of a gradual decline in the presence of sedimentary siliceous phytoplankton and thus a gradual return of silicon to the surrounding sediments (Sigmon et al., 2002; Woodruff et al., 1999). Phytoplankton pigment concentrations were found to be lower in the winter months than in the summer months, which can be typical of natural, seasonal trends occurring in this general region of the oceans (Thurman, 1997). Thus, temporal variations detected in phytoplanktonic indicators were likely reflective of natural, seasonal phytoplankton productivity.

Organic content at the reference site decreased gradually over time, but average values at each sampling time remained just below the mean value (4.3%±0.9) reported at well-flushed reference sites in British Columbia (Brooks, 2000a). Organic content at the east farm site at all sampling times remained just above the mean value for well-flushed sites. At the west farm site, organic content remained just above the well-flushed mean until it dropped below at 8 months following site abandonment. At a biologically impacted site close to the east farm site in Kanish Bay, Cross
(1990) found organic content to be elevated to 10.95%±6.32 relative to 6.60%±0.56 at a reference site. Anderson (1996) also found organic content at the same site to be elevated to 10.7% relative to 4.7% at two healthier sites nearby. Organic carbon levels at all locations, at all times, did not exceed triggers reported by Brooks (1996) and thus were not indicative of unhealthy sediments.

A decrease in organic matter content over time, as indicated by a reduction in organic content, organic carbon, and nitrogen, has been associated with recovery at falling fish farm sites in British Columbia (Brooks, 2002; Miller-Retzer, 1994) and elsewhere (Karakassis et al., 1999). At the Chained Islands site, organic matter content was elevated slightly above natural levels within the first month of site abandonment at the east farm, and to a lesser degree at the reference site, with values decreasing significantly over time. Concentrations of organic matter were greater at the east farm site than at the west farm and reference sites. However, the results of an investigation into organic C:N ratios did not show any significant difference in the origins of the organic matter either between sites or over time. There was evidence of slightly pronounced C:N ratios particularly at the east farm site, and to a lesser degree at the reference site, within the first month following site abandonment. This result was not expected, since C:N ratios within fresh fish farm wastes are typically lower due to their characteristically high nitrogen content (Brooks, 2002; Findlay and Watling, 1995). C:N ratios within the entire Chained Islands site were consistently similar to the C:N ratios of sediment trap material measured at a British Columbia farm site and a control site by Sutherland et al. (2001).

5.1.4.2 Sediment Physical Properties

Porosity was significantly greater throughout the sediments at the Chained Islands east farm site than at the west farm and reference sites, and was found to be most pronounced within the first month of site abandonment. Sediments at the east farm site also had a lower bulk density than at the other two sites. Water content and sediment porosity increase with decrease in sediment grain size (Caulfield and Filkins, 1999). Sediment water content, or porosity, has been found to be significantly elevated in sediments underlying fish farms as compared to more "natural" sediments (La Rosa, 2001; Karakassis et al., 1998). Bulk density typically tends to increase with sediment grain size (King and Galvin, 2002). Fine-grained sediments, particularly silts and clays, laden with organic matter also tend to have relatively low bulk densities (King and Galvin, 2002). Sediments throughout the entire Chained Islands site were dominated by silt and finer sand.
Fine sand was significantly less throughout the entire Chained Islands site within the first month following site abandonment, and after this point, concentrations throughout the site increased.

The surface millimeter of sediment at most stations throughout the Chained Islands site was consistently characterized by unconsolidated, low bulk density, high porosity, organic-laden matter. The sediment within the 1-2 millimeter range appeared to be more consolidated, having a higher bulk density, lower porosity, and less presence of photosynthetic pigments. Sediment properties below 5 millimeters remained relatively constant to the maximum depth of 25 millimeters. Despite slightly elevated organic matter accumulations at the east farm site immediately following removal of the fish farm, the physical properties of layers formed by settling sediments indicated that the accumulations were not substantial.

5.1.4.3 Metals

Cadmium is found naturally in organic matter (Morford and Emerson, 1999; McNee, 1997; Holby and Hall, 1994), and has also been detected in fish farm feed pellets (Sutherland et al., 2001; Tacon and De Silva, 1983). Cadmium levels exceeded Environment Canada's (1995) ISQG of 0.7μg g⁻¹ throughout the entire Chained Islands site at both 1 and 8 months following site abandonment. Concentrations were slightly greater at the farm sites than at the reference site. Throughout the entire site, cadmium was found to be most pronounced within the first month following site abandonment, and it exhibited a decrease over time. By the end of the study at 11 months following site abandonment, cadmium at 43% of the east farm stations, 83% of the west farm stations, and 100% of the reference stations had not yet recovered to sub-ISQG levels. By this time, cadmium had dropped below ISQG thresholds throughout most of the northern, nearshore areas of the Chained Islands site.

Copper has also been found to be enriched in organic matter accumulations (McNee, 1997; Francois, 1988). It has been associated with fish farming inputs to the sediments, both due to its incorporation into the feed (Jobling, 2001; Sutherland et al., 2001; Lorentzen and Maage, 1999; De Silva and Anderson, 1995; Lall, 1991; Watanabe, 1988; Tacon and De Silva, 1983) and as a component of the antifouling paint used on the net pen cages at many farms (Brooks, 2001a). Copper was greatest within the sediments at the east farm site. Concentrations at many of the sampling stations for all sampling dates exceeded Environment Canada's (1995) ISQG threshold,
but remained well within natural and background ranges (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989; Bloom and Crecelius, 1987). Copper concentrations had declined somewhat within the sediments by the end of the study period at 11 months following site abandonment. By this time, copper at 71% of the east farm stations, 67% of the west farm stations, and 60% of the reference stations had not yet recovered to sub-ISQG levels.

Despite the overall decrease at the site in potentially harmful cadmium and copper concentrations, there were temporal fluctuations for both metals at the east farm site that would indicate that one or more of the following might be occurring in these particular regions: (1) shifts in metals between solid and dissolved phase in the sediments, (2) intermittent dispersion and relocation of sediments over time due to erosion and resuspension, (3) arrival of metals inputs from sources other than the fish farm, or (4) positional error in sampling.

Zinc is found naturally in organic matter (Morford and Emerson, 1999; McNee, 1997; Holby and Hall, 1994). Substantial concentrations of zinc are typically added to fish feed in order to ensure proper metabolic function (Jobling, 2001; Lorentzen and Maage, 1999; De Silva and Anderson, 1995; Lall, 1991; Watanabe, 1988) and to prevent cataracts in juveniles (Richardson et al., 1986). Zinc was found to be most pronounced throughout the Chained Islands site within the first month following site abandonment. Concentrations were slightly greater at the farm sites than at the reference site. Zinc concentrations at the site did not exceed Environment Canada's (1995) ISQG thresholds, and were well below the natural and background ranges observed in marine sediments along or near the British Columbia coastline (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989; Bloom and Crecelius, 1987).

Cadmium, copper, and zinc showed strong, positive associations throughout the Chained Islands site. Each of the three metals are all associated strongly with organic matter in sediments (Morford and Emerson, 1999; McNee, 1997; Macdonald et al., 1991; Francois, 1988). None of the metals, however, showed much association with any of the organic matter variables or sediment oxygen condition variables measured at the Chained Islands site. All of the metals were typically observed to be more elevated at deeper stations to the south of the farms than in any other direction, while organic matter was typically observed to be most elevated at stations to the north, northeast, south, and southwest of the farms. Since cadmium, copper, and zinc are all included to varying degrees in feed, and copper is typically a major constituent of antifouling
paint, it is likely that the fish farm contributed to accumulations of the three metals at the Chained Islands site. Potentially harmful concentrations of cadmium and copper at the site indicated that these accumulations resulted in some minor environmental effects within the sediments. These effects appeared to be recovering within the first year following site abandonment.

Finer grained sediments, particularly within the silt and clay fractions, are comprised of metal-bearing minerals which may bind with heavy metals such as copper, zinc, and cadmium (Loring, 1991). These metals also strongly bind with particulate organic matter (Chapman et al., 1998). Metals bound within the sediments are not bioavailable unless they are oxidized into a free ionic form and mobilized into the interstitial waters (Chapman et al., 1998). Such oxidization can occur as a result of only a minor increase in redox potential (Rozan et al., 2000; Chapman et al., 1998). Alternatively, dissolved metal ions in the porewaters can complex with sulphides, when they are available, and be rendered non-toxic (Rozan et al., 2000; Chapman et al., 1998). At the silty/sandy Chained Islands east farm site, zinc was slightly negatively associated with coarser grain sizes. Otherwise, copper, cadmium, and zinc did not show strong associations with sulphides, sediment grain size, or organic matter variables at the Chained Islands site. Due to the absence of high levels of sulphides throughout the site, it is unlikely that the metals were being entirely complexed out of dissolved form within the sediments. Furthermore, due to the oxic conditions observed at the site, it is likely that the metals bound to organic matter were being released through oxidation processes. Therefore, it may be reasonable to conclude that the concentrations of copper and cadmium observed to be in exceedance of guidelines may have been reflective of the presence of toxic levels of bioavailable metals within the sediments. Under these conditions, most of the potential for restoration of the metals to non-toxic levels lies within the ability of the sediments to accumulate new particulate matter and subsequently bury the toxic metals (Chapman et al., 1998; DeLaune and Gambrell, 1996; Orson et al., 1992).

Lead was observably greater at the east farm site than at the west farm and reference sites. Lead is a component of organic matter accumulations (Macdonald et al., 1991; Francois, 1988). It has been detected in trace amounts in feed (Tacon and De Silva, 1983) but has not been reported to be a mineral requirement for fish (De Silva and Anderson, 1995; Lall, 1991). Lead was not detected by Sutherland et al. (2001) in fish feed pellets used at some farms in British Columbia. Thus, it may be reasonable to assume that although the elevated lead concentrations at the site could have resulted from either natural organic matter accumulations or materials used at the fish farm, they likely were not indicative of feed or faecal waste inputs to the environment. Moreover, lead
concentrations at the site did not exceed Environment Canada's (1995) ISQG thresholds, and were well below the natural and background ranges observed in marine sediments along or near the British Columbia coastline (Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989; Bloom and Crecelius, 1987).

### 5.1.4.4 Sediment Oxygen Conditions

Sediment redox potential measured throughout cored sediments collected at the Chained Islands site was consistently high, remaining above zero at all times throughout the site, indicating oxic conditions (Erickson et al., 2001; Wildish et al., 1999; Zobell, 1946). Sediment sulphides were correspondingly low throughout the entire site, and they did not come close to exceeding the thresholds reported to have detrimental biological consequences to benthic organisms (Erickson et al., 2001; Wildish et al., 1999). Oxygen within the top few centimeters of sediment throughout most of the site remained above zero during the summer and spring sampling trips, but during the winter trip values dropped to 0% near or at the surface of the sediments. The lowest redox potential and oxygen values at all times were typically observed at stations southwest of the farms in the deeper, organic-laden, silt-clay sediments, and the highest values were typically observed at stations to the east. Finer grained sediments, such as those found at the Chained Islands site, tend to be characteristic of more naturally reducing conditions (Zobell, 1946). Sediments appeared healthy throughout the site at during all sampling trips, and did not exhibit the visual characteristics typical of impacted, sub-oxic sediments. There was no evidence to suggest that fish farming activity had affected sediment oxygen conditions at the Chained Islands site.

### 5.1.4.5 Summary

Immediately following the removal of the Chained Islands fish farms, there was evidence of minor organic matter accumulations at the east farm site, and to a lesser degree at the reference site. These minor accumulations were found to be at a maximum within the first month following site abandonment. The significant presence of elevated levels of cadmium and zinc in the vicinity of the farms indicated that the accumulations may indeed have been a consequence of fish farming activity in the area. Furthermore, the presence of potentially harmful concentrations of copper in the sediments indicated the use of toxic chemicals, such as cuprous antifoulant paint, at the farm site. Concentrations of organic matter at the east farm and reference sites decreased with
time over the 11 month study period. The nature of the origin of the organic matter at the east farm and reference sites within the first month following site abandonment may have been slightly different than at other times during the study period, as indicated by minutely elevated C:N ratios. The east farm site both demonstrated the greatest relative organic matter inputs within the first month following site abandonment and experienced the most recovery over time. The reference site demonstrated only minor organic matter inputs relative to the east farm site, and also experienced minor recovery over time. The sediments within the entire Chained Islands site were naturally oxic, and sediment oxygen conditions did not ever appear to be influenced by fish farming activity. Phytoplankton productivity within the benthic environment did not stray significantly from natural seasonal patterns expected for the entire site, evidenced by natural variations in both sediment chlorophyll and silicon. Sediments at the site appeared to be healthy throughout the study period, as indicated by natural sediment colour and observations of fauna. Cadmium and copper were the only two detected sediment constituents which indicated that there were some minor, yet potentially toxic, effects due to fish farming activity at the Chained Islands site. These effects indicated that the sediments were not affected as much by waste accumulations as they were by chemicals used at the site. These metals had partially recovered according to sediment quality guidelines throughout the site by the end of the study at 11 months following site abandonment. Due to the oxic conditions observed at the site, it was hypothesized that the metals were not likely being entirely complexed out of dissolved form within the sediments, but that the metals bound to organic matter were likely being released into the porewaters via oxidation processes. Therefore, it is likely that, to a certain extent, copper and cadmium at the site was bioavailable. Under these oxic conditions, burial within the sediments would likely be the best candidate for restoration of metals to non-toxic levels.

The Chained Islands farm site was a low production site compared to the higher production Carrie Bay site. Perez et al. (2002) estimate that approximately 10% of the 46% carbon content of feed input to a fish farm is lost as waste feed, and another 32% is wasted in the faeces. At the Chained Islands site, where estimated average quarterly feed usage over the final 11 years of operation was 64,000 kg, an estimated total of 12,000 kg of waste carbon was likely input to the marine environment on a quarterly basis. Over the 11.5 years of operation, an approximate total of 552,000 kg of waste carbon could be estimated to have been input to the marine environment. The site underwent fallowing for a full quarter during the seventh year of operation, and again for another quarter during the ninth year of operation. The pens were also empty of fish for the entire tenth year, and during the eleventh and final year of operation, production was considerably
lower, averaging approximately 18,700 kg of fish on a quarterly basis. Current speeds in Kanish Bay are reportedly quite low, reaching an average of only 0.614 cm s\(^{-1}\) at nearby Orchard Bay, and 2.15 cm s\(^{-1}\) (surface) and 1.87 cm s\(^{-1}\) (bottom) at the east farm site. Despite slow current speeds, waste inputs were clearly not substantial enough to cause any major impact in the vicinity of the Chained Islands farms.

There are no currently or recently operating mines, refineries, smelting operations, quarries, or processing plants in the vicinity of the Chained Islands site (Ministry of Energy and Mines, 2003). The nearest pulp and paper mills as of February, 2001 were located in Powell River and Campbell River, several kilometers away (Ministry of Water, Land, and Air Protection, 2001). The closest municipality to the site is located approximately 2.25 kilometers to the southeast in Granite Bay, and has a population of under 1000 (ITMB, 2001). There are no major roads or rivers near the site, and the only major creek runs into the bay from Quadra Island, approximately 1.5 km to the southeast. No major logging or agricultural operations were observed during field trips to the site. Maps obtained from the Campbell River Forest Service District (Ministry of Forests) office documenting logging activity back to the 19\(^{th}\) century show that no logging operations have taken place on the land surrounding Kanish Bay within the past 25 years (TimberWest, 2001). Most of the terrestrial area surrounding bay was logged and successfully reforested prior to the mid-seventies. After speaking with Ministry of Forests staff and observing logging maps, it was concluded that the land surrounding the Chained Islands site is sufficiently reforested and the effects of logging would not be observable within the Kanish Bay sediments.

According to the TimberWest scaling supervisor within the Kanish Bay region, a log dump site located approximately 450 meters to the southwest of the westernmost reference station at the Chained Islands site was last active in 1995 (Figure 64). Little is known about the relationship between metals and log dump activity. Possible sources of metals at such a site could be from the woodwaste, chemicals, machinery, and metal cables. A water quality biologist reported to have data from several woodwaste leachate discharges and had not found metals to be a problem (M. Wright, personal communication, 2003). Specifically, cadmium was found to be below detection limits in all samples. This, coupled with the fact that elevated organic matter and metals accumulations were largely centered around the farm sites, away from the reference site, which would indicate that there were no detectable effects of the log dump at the Chained Islands site.
As of November 2002, two shellfish farms and one finfish farm (Figure 64) were officially operating in the vicinity of the site (Ministry of Agriculture, Food, and Fisheries and DFO, 2002). All three operations were observed to be in place during sampling trips to the site. The closest shellfish farm was approximately 800 meters to the east-southeast of the site, and another was located approximately 1.7 kilometers in the same direction. The finfish farm was located in Orchard Bay, approximately 850 meters to the north-northeast of the site.

![Map of current and recently abandoned industry in Kanish Bay](image)

**Figure 64: Map of current and recently abandoned industry in Kanish Bay**

Shellfish farm wastes have been reported to have significant impacts on benthic habitats, although the effects are considerably more minor in comparison to those observed at finfish farms (Scottish Executive Central Research Unit, 2002; Crawford et al., 2001; Holmer, 1991). Typically, shellfish are cultivated without the use of extra feed, since they are filter feeders and can extract their own food naturally from the water column (Scottish Executive Central Research Unit, 2002; Holmer, 1991). It is possible that wastes at the Chained Islands site may have also have been transported from the finfish farm located 850 meters away. However, given that the effects
observed at the Chained Islands site began to recover immediately following site abandonment, it is more likely that impacts observed within the sediments were resulting from localized inputs.

It seems reasonable to conclude that despite the organic matter accumulations linked to fish farming activity that were detectable within the first month following site abandonment, the actual effects to the benthic environment due to waste inputs were not significant. In support of this conclusion, it has been found that sites that exhibit negligible benthic impact or are in the final stages of recovery can be characterized by slightly elevated levels of aging organic matter accumulations and otherwise relatively healthy conditions (Anderson, 1996; Brooks, 2002; Katavic and Antolic, 1999; Brooks, 1996; Frid and Mercer, 1989). Cross (1990) also found evidence of some localized benthic impact due to fish farming activity at a vacated farm site located near the east farm site in Kanish Bay. Currents at the site were reported to be relatively slow, but water column at the site was reported to be relatively well-mixed. Shelter provided by the neighbouring islands and the slower current speeds were purported to have contributed to organic waste accumulations at the site. Anderson (1996) further found evidence of some recovery of biological impacts due to fish farming activity at the same site. The biological recovery time at the site was estimated as moderate, and conditions had reportedly recovered to near normal conditions after 3.5 years fallow.

5.2 Carrie Bay Recovery

5.2.1 Variable Redundancies

Significant redundancies were identified amongst sediment variables at the Carrie Bay site. These redundancies were used to reduce the set of variables to a smaller subset for assessing recovery at similar sites in the future. Four categories of variables were isolated: sediment physical properties, metals, organic matter, and sediment oxygen conditions.

There was a consistent contrast between the presence of ultra-fine, low bulk density, high porosity substrate and the absence of coarser, high bulk density, lower porosity substrate, and vice versa. Sites dominated by fine substrate are representative of areas where currents are lower and rapid settlement of fine particulates is encouraged (Holmer, 1991). Sites dominated by coarse substrate are representative of areas where faster currents preclude the settlement of the finer sediment fractions (Holmer, 1991). Wet bulk density typically tends to increase with
sediment grain size (King and Galvin, 2002). Fine-grained sediments, particularly silty clays laden with organic matter, tend to have relatively low wet bulk densities (King and Galvin, 2002; Lu et al., 1998). Wet bulk density is also typically lower in unconsolidated sediments, due to lack of compaction and elevated presence of pore water (Jepsen et al., 1997; Maa et al., 1997). Sediment porosity is typically higher in clay sediments than in coarser grained sediments (McConnell, 2002; Caulfield and Filkins, 1999; Ward and Robinson, 1990). High porosity can also be indicative of rapidly depositing sediments which have not had sufficient time to undergo compaction (UK Marine SAC, 2002). Anderson (1996) also found a significant contrast between the presence of silt-clay and sand at fish farm sites in British Columbia. Based on the redundancies found amongst certain sediment physical property variables, the nine grain size categories could feasibly be reduced to the following four categories at sites similar to the one at Carrie Bay: clay (< 4μm), silt (< 63μm), finer sand (< 250μm), coarser sand (< 2mm), and gravel (>2mm). These and similar categories have been used during farm site assessments in British Columbia by Anderson (1996), Brooks (2000a), and are currently recommended for use within the Aquaculture Information Request and Interim Monitoring Program (Erickson et al., 2001). Bulk density and porosity were directly related to grain size at this site, and also served as useful indicators of sediment layering and organic matter accumulations. They were not, however, related strongly enough to be labelled redundant. Thus, it is recommended that bulk density and porosity be maintained as autonomous variables at sites similar to the one at Carrie Bay.

Copper, zinc, and aluminum concentrations tended to vary concurrently within the sediments at the Carrie Bay site. The same was true for cadmium and silicon. Copper and zinc concentrations have been found to be high in sediments underlying fish farm sites, presumably due to the copper contained in the antifouling paint used on the cages and the zinc provided in the feed (Brooks, 2001a and 2001b; Erickson et al., 2001; Morrisey et al., 2000; Uotila, 1991). Aluminum has not been identified as an indicator of farm waste inputs to sediments, nor is it considered to be a mineral requirement for fish (De Silva and Anderson, 1995; Lall, 1991). Aluminum has, however, been detected in fish feed pellets in British Columbia (Sutherland et al., 2001). Organic matter can also naturally contain aluminum, since certain diatoms can uptake the element (Dixit et al., 2001). Aluminum is also often naturally associated with clay sediments (Dean and Gardner, 2001). Cadmium concentrations are typically higher in natural, organic-rich sediments (Morford and Emerson, 1999; McNee, 1997). Phytoplankton bioaccumulate cadmium, and thus as they decompose within the sediments, they release cadmium into the surrounding environment (Cullen, 2002; Cullen et al., 1999; Radach and Heyer, 1997). Siliceous phytoplankton, once they
decompose, also release silicon into the surrounding sediments (Sigmon et al., 2002; Woodruff et al., 1999). Based on the redundancies identified amongst certain metals variables, the number of metals variables used at this site could feasibly be grouped and reduced to a smaller number of categories: those commonly associated with fish farming activity (copper and zinc), and those commonly associated with natural organic matter (aluminum, cadmium, and silicon). Due to the redundancy amongst the variables within these categories, one of the metals within each might together suffice as indicators of the nature of organic matter accumulations at sites similar to the one at Carrie Bay. In order ensure sediment metals toxicity is appropriately assessed, however, it would be wise to analyze concentrations of both copper and zinc.

Organic carbon, nitrogen, total carbon, organic content, and porosity tended to vary concurrently within the sediments at the Carrie Bay site. Brooks (2002) also found organic carbon and organic content to be highly correlated in sediments at fish farm sites in British Columbia. Carbon and nitrogen are significant elements present in organic matter compounds (Thurman, 1997), and have been found to be present in elevated concentrations in sediments receiving fish farm waste inputs (Brook, 2002; Levings and Sutherland, 1999; Gowen and Bradbury, 1987). Porosity has been found to directly relate to the organic matter content of sediments (UK Marine SAC, 2002; Avnimelech et al., 2001; Lu et al., 1998). Based on the redundancies identified between certain organic matter variables at this site, the number of variables measured could feasibly be reduced.

Chlorophyll and pheophytin, phytoplanktonic pigments which are also organic matter variables, were found to vary concurrently at the Carrie Bay site. Based on the redundancy observed between the two variables, chlorophyll or pheophytin alone would serve as an adequate indicator of productivity at sites similar to the one at Carrie Bay.

Throughout the upper sediment column at the Carrie Bay site, there was a positive relationship between redox potential and oxygen, and between porosity and sulphides. Inverse relationships were observed between redox potential and porosity, oxygen and porosity, redox potential and sulphides, and redox potential and porosity. Porosity tends to increase with decreasing sediment grain size (Caulfield and Filkins, 1999), and thus finer sediments generally have higher porosities. Finer sediments, particularly the silt-clay fraction, also tend to be characteristic of reducing conditions while coarser sediments tend to be less reducing (Zobell, 1946). Low redox potential is known to be associated with reducing sediment conditions which also exhibit elevated levels of hydrogen sulphide (Zobell, 1946). Hargrave et al. (1995) also found a negative correlation between sediment sulphides and redox potential at both reference and farm sites on the East Coast.
of Canada. Redox potential and oxygen are naturally positively associated since low oxygen conditions result in reducing sediments which have a lower redox potential, and higher oxygen conditions result in oxic sediments which have a higher redox potential (Zobell, 1946). Sulphide production is merely one of the later phases that can occur within suboxic or anoxic sediments (Berner, 1980; Froflich et al., 1979; Jorgensen, 1977), and thus is not necessarily a guaranteed consequence of low oxygen or redox potential. It is recommended that sulphides as well as either redox potential or oxygen be used as indicators of sediment oxygen conditions at sites similar to the one at Carrie Bay.

5.2.2 Recovery Indicators

5.2.2.1 Sensitive Indicators of Temporal Recovery

Organic C:N, cadmium, silicon, total carbon, zinc, and organic carbon were significant indicators of temporal recovery at the Carrie Bay farm site. Of these, organic C:N, cadmium, and silicon were equivalently the most sensitive indicators. Organic C:N ratios are typically low for freshly accumulated fish farm wastes and have been used as indicators of impacts to and recovery within benthic sediments at fish farm sites in British Columbia (Brooks, 2002) and elsewhere (Findlay et al., 1995). Cadmium and silicon have not been identified as indicators of benthic habitat recovery at fish farm sites, though concentrations are typically higher in natural organic matter containing phytoplankton (Cullen, 2002; Cullen et al., 1999; Morford and Emerson, 1999; Radach and Heyer, 1997; McNee, 1997). Carbon and organic carbon are present in fish farm wastes (Brooks, 2002; Findlay et al., 1995; Gowen and Bradbury, 1987) and have been identified as indicators of recovery at fish farm sites in British Columbia (Brooks, 1996; Miller-Retzer, 1994). Zinc, which is included in fish feed, has been identified as an indicator of impact within benthic sediments at fish farm sites in British Columbia (Brooks, 2001a; 2001b; Erickson et al., 2001).

Copper, lead, chlorophyll, and pheophytin were not identified as significant indicators, but were nonetheless indicators of temporal recovery at the farm site in Carrie Bay. Copper, which has been found to be a component of the antifouling paint used on net pen cages, has been identified as an indicator of varying degrees of impact within benthic sediments at fish farm sites in British Columbia (Brooks, 2001a) and elsewhere (Uotila, 1991). Chlorophyll has been found to be a significant indicator of varying degrees of impact in sediments at fish farm sites in the Mediterranean (La Rosa et al., 2001; Karakassis et al., 1998), but is not typically used to
investigate recovery. Lead has also not been reported to be a recovery indicator at fish farm sites, and it is typically not reported to be a constituent of farm feeds (Sutherland et al., 2001; De Silva and Anderson, 1995; Lall, 1991).

Despite the fact that redox potential and sulphides could not be identified as statistically significant indicators of spatial or temporal variation, they were used to conclude that sediment conditions at the Carrie Bay site at 36 months following abandonment were anoxic and likely dominated by anaerobic processes. According to organic matter and metals variables analyzed between 11 and 35 months following site abandonment, the sediments at the farm site were found to be significantly impacted as a result of fish farming activity. Therefore, it appeared that the anoxic conditions observed at 36 months were likely a continuum of what were hypothesized to be anoxic conditions induced 3 years earlier by fish farming activity. Sulphides and redox potential were thus considered to be recovery indicators at the Carrie Bay site.

Silt, fine sand, zinc, organic content, very fine sand, copper, coarse sand, inorganic carbon, nitrogen, clay, and medium sand were significant indicators of temporal recovery measured at the Carrie Bay reference site. Copper and zinc were indicative of recovery at the Carrie Bay reference site. Of these two, zinc was the most sensitive indicator. The remaining indicators were actually hypothesized to be indicative of effects on the reference site due to net-pen removal at the farm site. Of these, silt was the most sensitive indicator. The presence of fish farm cage structures can act to decrease flow rates thereby inducing an increase in siltation and particulate matter settling to the sea floor (Sutherland et al., 2001; Frid and Mercer, 1989). Thus, shifts in sediment grain size have been used to demonstrate effects of fish farming activity, but typically sediment grain size is not used as a recovery indicator at fish farm sites. Brooks (2002) and Anderson (1996) found organic content to be a sensitive indicator of biological impact and recovery at fish farm sites in British Columbia. Cadmium, silicon, organic C:N, porosity, chlorophyll, and pheophytin were not identified as significant indicators, but were nonetheless partial indicators of temporal recovery at the reference site in Carrie Bay. Carbon, nitrogen, and porosity have been used as indicators of impact and recovery within sediments at fish farm sites in British Columbia (Brooks, 2002; Anderson, 1996; Miller-Retzer, 1994; Cross, 1990).
5.2.2.2 Sensitive Indicators of Spatial Variation

Zinc, total carbon, nitrogen, porosity, organic carbon, organic content, copper, lead, aluminum, cadmium, and bulk density were significant indicators of spatial variations in organic matter accumulations throughout the Carrie Bay site. Of these, zinc, total carbon, nitrogen, porosity, and organic content were the most sensitive indicators. Aluminum and bulk density are not commonly used as indicators of spatial variations in impact at fish farm sites. Redox potential, sulphides, oxygen, chlorophyll, pheophytin, and silicon were not identified as significant indicators, but were nonetheless also indicators of spatial variations in organic matter accumulations throughout the site. Redox potential and sulphides have both been identified as indicators of varying degrees of impact and recovery at fish farm sites (Erickson et al., 2001; Anderson, 1996) and elsewhere (McGhie et al., 2000; Karakassis et al., 1999; Hargrave et al., 1997; Gowen et al., 1991; Weston, 1990).

5.2.2.3 Sensitive Indicators of Spatio-Temporal Recovery

Total carbon, clay, very fine sand, and fine sand were significant indicators of spatio-temporal recovery at the Carrie Bay site. Of these, clay and total carbon were the most sensitive indicators.

5.2.2.4 Summary of Sensitive Indicators

Cadmium, silicon, copper, zinc, organic C:N, organic content, total carbon, organic carbon, nitrogen, inorganic carbon, silt, fine sand, very fine sand, coarse sand, clay, medium sand, redox potential, and sulphides were identified as indicators of temporal recovery and spatial variations in organic matter accumulations at the Carrie Bay site. At the Carrie Bay site, cadmium was identified as a recovery indicator due to its association with natural organic matter, and not fish farm wastes. That is, an increase in cadmium was indicative of recovery. However, at the Chained Islands site, cadmium was identified as a recovery indicator due to its association with fish farm wastes. That is, a decrease in cadmium was indicative of recovery. This inconsistency led to the recommendation that cadmium, although it was identified as one of the most sensitive indicators, not be used as an indicator in future recovery assessments at similar sites.

Given the exclusion of cadmium from the list of valid recovery indicators, three tiers of recovery indicators were developed for future assessments at sites characterized by similar production
levels, substrate, and hydrography (Figure 44). Tier 1 contained all valid recovery indicators, tier 2 contained a condensed version of the tier 1 list based on variable redundancies, and tier 3 contained the most sensitive of these indicators. The most appropriate tier of indicator variables to be measured in a future recovery assessment would be selected based on budget, equipment, and time allowances.

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<th>TIER 1</th>
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<th>TIER 3</th>
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<tr>
<td>All Valid Recovery Indicators</td>
<td>Autonomous Recovery Indicators</td>
<td>Most Sensitive Recovery Indicators</td>
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<td>zinc</td>
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<td>silicon</td>
<td>silicon</td>
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<td>silt (&lt;63μm)</td>
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<tr>
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<td>clay (&lt;4μm)</td>
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Table 48: Three tiers of indicators to be used for assessing recovery at fish farm sites similar to the one in Carrie Bay.

5.2.3 Habitat Characteristics

At the Carrie Bay site, the average depth was 34.4±4.6 meters at the farm site and 36.9±4.7 meters at the reference site. At the farm site, the shallowest areas were near the shores of the bay to the north, west, and southwest of the farm. Depths increased in the east-southeasterly direction toward the mouth of the bay, at which point depths were in excess of 30 meters. Depths continued to decrease in the east-southeasterly direction out into Retreat Passage. Depth in the immediate vicinity of the was approximately 35 meters. The shallowest areas at the reference site were near the western shores of Bonwick Island, increasing in the east-southeasterly direction.
Organic accumulations leading to benthic enrichment are typically associated with fine-grained sediments (Mayer and Rossi, 1982). Clay, silt, and fine sand have all been found to dominate substrates found at various impacted fish farm sites in British Columbia (Brooks, 2002; Levings and Sutherland, 1999; Anderson, 1996; Miller-Retzer, 1994; Cross, 1990) and elsewhere (McGhie et al., 2000; Karakassis et al. 1999; Mazzola et al., 1999; Hargrave et al., 1997; Brooks, 1996; Tsutsumi, 1995; Johannessen et al., 1994; Ye et al., 1991; Weston, 1990; Aure et al., 1988; Kaspar et al., 1988; Brown et al., 1987). Sediments at the Carrie Bay farm site were dominated by silt and clay, and consisted also of some finer sand and small amounts of coarser sand and gravel. Sediments nearest to the farm were consistently characterized by black, anoxic, azoic gel mud and a strong H\textsubscript{2}S smell, while many of sediments 80 or more meters beyond the approximate center of the farm had a healthier, green-brown appearance and observable fauna. Sediments nearest the farm at 11 months following site abandonment had clearly observable surface coatings of white or orange bacterial mats, but by 35 months these mats were no longer visually detectable, despite the continued presence of black, anoxic, and nearly-azoic to azoic conditions. Sediments at the reference site consisted predominantly of silt, clay, and finer sand and some minute amounts of coarser sand and gravel. Sediments at the reference stations were consistently green-brown in colour and contained observable fauna.

The reference site was found to contain more fine and very fine sand than the farm site, while the farm site was found to contain slightly more coarser grained sands than the reference site. Clay was always more present at the farm site than at the reference site, particularly at stations nearest to the farm. The coarser grain sizes were observed predominantly within the shallower northern half of the farm site. Silt was highest at deeper stations to the southeast and southwest of the farm, and clay was highest at stations to the north or south. Organic matter concentrations did not appear to strongly associate with sediment grain size at either site in Carrie Bay. There was a strong indication of an increase in inputs of finer sediments into the reference site over the study period matched by a corresponding decrease of coarser grain sizes at the site. Very fine sand diminished throughout the farm site over the study period, while silt content within 50 meters of the farm increased and clay content more than 100 meters from the farm decreased.
5.2.4 Recovery Assessment

5.2.4.1 Organic Matter

Carbon and nitrogen are significant components of organic matter, and elevated concentrations have been detected in sediments receiving inputs from fish farms (Brooks, 2002; Levings and Sutherland, 1999; Brooks, 1996; Hargrave et al., 1997; Gowen, 1991; Weston, 1990). Total carbon, nitrogen, organic carbon, and organic content were substantially greater at the farm site than at the reference site at all times during the study period. Mean levels of organic content at all times both the farm and reference sites were substantially greater than the mean value (4.3%±0.9) reported for well-flushed reference sites in British Columbia (Brooks, 2000a). Mean levels of organic carbon at the reference site were within thresholds reported for similar substrates by Brooks (1996). However, levels of organic carbon at the farm site were consistently elevated slightly above thresholds (Brooks, 1996).

Within the farm site, nitrogen, organic content, organic carbon, and total carbon were consistently higher near the farm than elsewhere, particularly within a localized area east of the farm. Organic content and total carbon were particularly elevated above reference values at stations within 50 meters of the farm. Brooks (2001b) also found organic content and organic carbon to be greatest near the farm at an active, and eventually fallow, site. McGhie et al. (2000) found that organic content, total carbon, and nitrogen declined with distance from the center of fish cages at two fallowing sites. Chlorophyll and pheophytin concentrations within the sediments at the farm site were highest at stations nearest to, and particularly east of the farm. This suggests the elevated presence of phytoplankton within the areas of the greatest organic matter accumulations. In Greece, Karakassis et al. (1998) found chlorophyll content to be elevated beneath fish farm cages compared to a control area, and concluded that the source was primarily sedimentation. La Rosa et al. (2001) also found chlorophyll content to be greater at a fish farm site than at a control site, and after 4 months following site abandonment, found the values to be more similar.

Total carbon concentrations declined over the course of the two year study period within the entire farm site. None of the other organic matter variables decreased significantly over time at the farm site, indicating that significant degradation of the organic matter accumulations had not yet occurred. Typically organic carbon and organic content have been found to eventually diminish at fallowing sites in British Columbia (Brooks, 2001b; Anderson, 1996; Miller-Retzer,
However, significant amounts of accumulated and aging organic matter have been found to degrade at a much slower rate under anoxic versus oxic conditions (Hulthe et al., 1998; Kristensen et al., 1995). Initially, fresh organic matter is more easily hydrolyzable, and the presence or absence of oxygen does not significantly affect the rate of degradation. However, after prolonged accumulation and burial within anoxic sediments, aging organic matter becomes structurally more complex and exceedingly difficult for anaerobic microbes to degrade. Furthermore, the absence of bioturbation within azoic sediments will also limit the potential for the organic matter to eventually be exposed to oxic conditions. Hulthe et al. (1998) found that aged organic material degraded up to 3.6 times faster under oxic versus anoxic conditions.

24 months following site abandonment, organic C:N ratios within the sediments at both the farm and reference sites were entirely within or below the levels expected for marine organic matter (Sutherland et al., 2001; Macdonald and Crecelius, 1994). Due to the elevated nitrogen content in the feed, organic C:N ratios are typically low for freshly accumulated fish farm wastes (Brooks, 2002; Findlay et al., 1995). The lowest ratios observed at the Carrie Bay site, typically falling below levels observed for marine organic matter in the northern Strait of Georgia, were observed within small patches of sediment to the near east of the farm center. Spatial distributions of organic C:N ratios indicate that the organic matter deposits observed at the onset of the study nearest to the farm were characterized by fish farm waste inputs. By 35 months following site abandonment, organic C:N ratios had increased throughout both sites and in the shallower, nearshore regions the ratios had reached those characteristic of terrestrial organic matter (Macdonald and Crecelius, 1994). In the remaining, deeper regions, organic C:N ratios had increased to be well within levels expected for marine organic matter (Sutherland et al., 2001; Macdonald and Crecelius, 1994). Mean organic C:N ratios within the farm site by the conclusion of the study were similar to organic C:N ratios of sediment trap material measured at a British Columbia farm site and a control site (Sutherland et al., 2001). Organic carbon at the farm site had substantially increased between 24 months and 35 months following site abandonment, likely indicating an inverse shift in carbon and nitrogen contents and thus a change in the origins of organic matter settling on the sediments.

There was a substantial increase in silicon, chlorophyll, and pheophytin between 24 and 35 months following site abandonment within sediments at the farm site. Both measurements were taken at the same time of year in the early autumn, a season during which phytoplankton numbers are characteristically low (Thurman, 1997). Elevated concentrations of dissolved silicon in the

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sediments originate mainly from the decomposition of siliceous phytoplankton, and thus can be expected after blooms of high productivity have finished (Sigmon et al., 2002; Woodruff et al., 1999). It seems likely that phytoplankton productivity at the farm site in the year 2001 was significantly greater than in the year 2000, as indicated by the increase in the numbers of siliceous phytoplankton settling to the sediments.

Levels of chlorophyll, pheophytin, nitrogen, organic content, and organic carbon actually substantially increased over time at the reference site. Inorganic carbon also had substantially decreased at the reference site by the end of the study period. These results would indicate an increase in the amount of organic matter and phytoplankton settling onto the sediments at the reference site after farm removal. The presence of fish cage structures can act to decrease flow rates, thereby inducing an increase in siltation and particulate matter settling to the sea floor (Sutherland et al., 2001; Frid and Mercer, 1989). Removal of the net pens from the site may explain the subsequent increase over time in particulate organic matter settling within the neighbouring reference site.

Depreciated levels of organic C:N observed at the reference site at the onset of the study could have been indicative of far-field depositions of wastes originating from the Carrie Bay fish farm. The organic C:N ratio at the reference site increased substantially between 24 and 35 months following site abandonment, indicating that the increase in organic carbon over time outweighed the corresponding increase in nitrogen. In fact, the mean organic C:N ratio measured at the reference site by 35 months was similar to ratios observed in sediments at other sites in British Columbia (Sutherland et al., 2001).

5.2.4.2 Sediment Physical Properties

Porosity was substantially greater at the farm site than at the reference site at all times during the study period. Correspondingly, bulk density and finer sands were substantially less at the farm site than at the reference site. Sediment water content and porosity tend to increase with a decrease in sediment grain size (Caulfield and Filkins, 1999). Sediment water content has been found to be significantly elevated in sediments underlying fish farms as compared to more "natural" sediments (La Rosa, 2001; Karakassis et al., 1998). Areas dominated by silt and clay tend to be characterized by lower relative amounts of coarser grain sizes, like sands (Holmer, 1991). Bulk density typically tends to increase with sediment grain size (King and Galvin, 2002).
Fine-grained sediments, particularly silts and clays, laden with organic matter also tend to have relatively low bulk densities (King and Galvin, 2002). Elevated levels of porosity and depreciated levels of bulk density and sand can thus be characteristic of organic matter accumulations in sediments.

The layers formed by settling sediments at the farm site, as indicated by bulk density and porosity, indicated that there were substantial spatial variations in sediment physical properties throughout the study site. At both 24 and 35 months following site abandonment, both chlorophyll and porosity within the top few millimeters of sediment at stations near the farm center in Carrie Bay were elevated substantially above those measured at further distances from the farm. Porosity values at all core depths near the farm site were clearly greater than those measured at stations further from the farm. Bulk density at both sampling times was conversely much lower within the top few millimeters of sediment at stations nearest the farm. Bulk density values at all core depths within the farm site were clearly less than those measured at stations further from the farm. In general, these results support the conclusion that the Carrie Bay site received organic waste inputs from the fish farm when it was active, particularly within the immediate vicinity of the farm.

At stations near the farm center, the top millimeter of sediment was characterized by unconsolidated, low bulk density, high porosity, organic-laden matter. The sediment within the 1-2 millimeter range appeared to be slightly more consolidated, having a slightly higher bulk density, lower porosity, and slightly lower amounts of photosynthetic pigments. Sediment properties below 5 millimeters remained relatively constant to the maximum depth of 25 millimeters, progressively becoming slightly more compacted, as indicated by a gradual, but minor decrease in porosity with depth. At both sampling times, both the porosity and bulk density of sediments at the perimeter stations resembled values measured at the reference site.

At stations further from the farm and at the reference site, the top millimeter of sediment was characterized by unconsolidated, low bulk density, high porosity, organic-laden matter. The sediment within the 1-2 millimeter range appeared to be more consolidated, having a substantially higher bulk density, lower porosity, and minor amounts of photosynthetic pigments. Sediment properties below 5 millimeters remained relatively constant to the maximum depth of 25 millimeters, progressively becoming slightly more compacted, as indicated by a gradual, but
minor decrease in porosity with depth. Bulk density at both the farm and reference stations was similar past approximately 10 millimeters depth.

The majority of differences in sediment layering between the farm and reference sites were evident within the top 10 millimeters of sediment. The most noticeable differences in depositional layers were observed within the top 1-2mm of sediment. Subsurface layers at the farm site were less consolidated and more characteristic of abundant organic matter accumulations, while at the reference site these layers were characterized by more consolidated, natural accumulations.

In September 2000, there was a patch of higher sediment temperature very close to the approximate farm center. Temperatures within these sediments were elevated 3-4 degrees above those measured in sediments further from the farm and at the reference site. Microbial activity within organic-rich sediments can lead to increased metabolic heat production (Toernblom, 1996; Pammatmat, 1982). It is possible that elevated sediment temperatures observed in this area were due, in part, to elevated rates of organic matter degradation near the farm center. This zone of elevated temperature, however, was not actually found to be correlated with the zone of accumulated organic matter near the farm.

Levels of clay, silt, and porosity actually substantially increased over time at the reference site. Fine and coarse sand had substantially decreased at the reference site by the end of the study period. These results would indicate an increase in the amount of finer particulate matter settling onto the sediments at the reference site after farm removal. The presence of fish cage structures can act to decrease flow rates, thereby inducing an increase in siltation and particulate matter settling to the sea floor (Sutherland et al., 2001; Frid and Mercer, 1989). Removal of the net pens from the site may explain the subsequent increase over time in ultra-fine sediment grain sizes settling within the neighbouring reference site.

5.2.4.3 Metals

Copper has been found to be associated with fish farming inputs to sediments, both due to its incorporation as a required mineral into the feed (Jobling, 2001; Sutherland et al., 2001; Lorentzen and Maage, 1999; Lall, 1991; Watanabe, 1988; De Silva and Anderson, 1995; Tacon and De Silva, 1983) and as a component of the antifouling paint used on the net pen cages at many farms (Brooks, 2001a). At all times during the study period, concentrations of copper were
substantially higher at the Carrie Bay farm site than at the reference site, particularly within the sediments located nearest to the farm and the shore.

At the Carrie Bay farm site, levels of copper decreased over the course of the study period between 11 months and 35 months following site abandonment. Copper concentrations throughout the farm site in Carrie Bay exceeded Environment Canada's (1995) ISQG threshold of $18.7 \mu g \, g^{-1}$ at the onset of the study at 11 months following site abandonment as well as at 24 months. By 35 months, copper at the farm site had diminished but remained in exceedance of the ISQG threshold at all but two stations, which were both located within 30 meters of the farm. At all sampling times, a few stations within approximately 92 meters of the farm exceeded the PEL threshold of $108 \mu g \, g^{-1}$. Copper concentrations at the onset of the study exceeded natural and background ranges of copper found in British Columbia sediments throughout the entire Carrie Bay site (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989; Bloom and Crecelius, 1987). At 24 and 35 months following site abandonment, copper tended to exceed these ranges in the region lying between the shore and the farm. By the time metals were last measured at 35 months following site abandonment, copper at 88% of the farm stations had not yet recovered to sub-ISQG levels. Copper at 6% of the farm stations had also not yet recovered to sub-PEL levels.

Sediments at the reference site also exhibited an overall decrease over time in concentrations of copper, suggesting that waste inputs from the fish farm in Carrie Bay had extended to far-field distances of greater than 950 meters from the farm. At the onset of the study, in August 1999, copper concentrations at the reference site exceeded the ISQG threshold and at the eastern-most reference station exceeded the PEL threshold. At this time, copper at the reference site also exceeded natural and background ranges of copper found in British Columbia sediments (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989; Bloom and Crecelius, 1987). By 24 months following site abandonment, copper concentrations at the reference site had dropped below the ISQG.

Substantial concentrations of zinc are typically added to fish feed in order to ensure proper metabolic function (Jobling, 2001; Lorentzen and Maage, 1999; De Silva and Anderson, 1995; Lall, 1991; Watanabe, 1988) and to prevent cataracts in juveniles (Richardson et al., 1986). Zinc has been found to be elevated within sediments receiving waste inputs from fish farms (Erickson et al., 2001; Brooks, 2001b; Brooks, 2000c; Uotila, 1991). At all times during the study period,
concentrations of zinc were substantially higher at the farm site than at the reference site, particularly within the sediments nearest to the farm. Brooks (2001b) also found zinc to be significantly elevated nearer to the farm at an active, and eventually fallow, site.

At the Carrie Bay farm site, levels of zinc decreased over the course of the study period, between 11 and 35 months after site abandonment. Brooks (2001b) also reported significant recovery of zinc in sediments at a fallowing fish farm site in British Columbia. Zinc concentrations throughout the eastern region of the farm site in Carrie Bay exceeded Environment Canada's (1995) ISQG threshold of 124μg g⁻¹ at the onset of the study at 11 months following site abandonment. At two stations within 40 meters of the farm, zinc also exceeded the PEL threshold of 271μg g⁻¹ (Environment Canada, 1995). Zinc concentrations within much of the eastern and southeastern regions of Carrie Bay at this time were also in exceedance of natural and background ranges observed in marine sediments along the British Columbia coastline (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989). By 24 months following site abandonment, zinc within the sediments at the Carrie Bay farm site had clearly diminished, and concentrations only exceeded the ISQG within a small area to the southeast and northwest of the farm and a patch of sediment approximately 40 meters to the northeast of the farm. Zinc at all areas except those exceeding the ISQG nearest the farm had diminished to be well within natural and background ranges observed in marine sediments along the British Columbia coastline (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989). By 35 months following site abandonment, zinc concentrations were similar throughout the farm site to those observed at 24 months, but values which exceeded the ISQG appeared to be confined to a patch of sediment to the far east and northeast of the farm. Zinc at one station within this patch of sediment exceeded the PEL. Zinc concentrations to the far east of the farm still exceeded natural and background ranges observed in marine sediments along the British Columbia coastline (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989). By the time metals were last measured at 35 months following site abandonment, zinc at 18% of the farm stations had not yet recovered to sub-ISQG levels. Zinc at 6% of the farm stations had also not yet recovered to sub-PEL levels.

The reference site also exhibited an overall decrease with time in zinc, supporting the conclusion that waste inputs from the fish farm in Carrie Bay had extended to far-field distances of greater than 950 meters away. At all times, zinc concentrations at the reference site remained below Environment Canada's (1995) ISQG threshold of 124μg g⁻¹ and were well within the natural and
background ranges observed in marine sediments along the British Columbia coastline (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989).

Despite the overall decrease throughout the Carrie Bay farm site in harmful zinc and copper concentrations, there were minor temporal fluctuations for both metals that would indicate that one or more of the following were occurring: (1) shifts in metals between solid and dissolved phase in the sediments, (2) intermittent dispersion and relocation of sediments over time due to erosion and resuspension, or (3) positional error in sampling. Copper and zinc showed a mild, positive association throughout the Carrie Bay farm and reference sites. Copper and zinc are both associated strongly with organic matter in sediments (Morford and Emerson, 1999; McNee, 1997; Macdonald et al., 1991; Francois, 1988). Copper did not exhibit any strong associations with any of the organic matter variables measured at the Carrie Bay farm or reference sites. Therefore, it is unlikely that the elevated copper concentrations observed at the fish farm site were associated with the organic waste accumulations detected at the site. Since copper was a major constituent of the Flexguard antifouling paint that was reportedly used on the pens, its elevated presence at the Carrie Bay farm site was very likely associated with fish farming activity. Zinc did exhibit a mild, positive association with several of the organic matter variables. Zinc also showed a mild negative association with C:N ratios. Since zinc is included in fish feed, and low C:N, organic matter containing high zinc concentrations was present at the farm site, it seems likely that the fish farm was a contributing source of zinc to the sediments at the Carrie Bay site.

Finer grained sediments, particularly within the silt and clay fractions, are comprised of metal-bearing minerals which may bind with heavy metals such as copper, zinc, and cadmium (Loring, 1991). These metals also strongly bind with particulate organic matter (Chapman et al., 1998). Metals bound within the sediments are not bioavailable unless they are oxidized into a free ionic form and mobilized into the interstitial waters (Chapman et al., 1998). Such oxidation can occur as a result of only a minor increase in redox potential (Rozan et al., 2000; Chapman et al., 1998). Alternatively, dissolved metal ions in the porewaters can complex with sulphides, when they are available, and be rendered non-toxic (Rozan et al., 2000; Chapman et al., 1998). At the muddy Carrie Bay farm site, zinc was slightly positively associated with organic matter. Neither copper nor zinc showed strong associations with sediment grain size, and copper was not associated to organic matter. Correlations with sulphides could not be assessed since metals and sediment oxygen variables were assessed at different sampling times. However, high levels of
sulphides were detected throughout the farm site, particularly in sediments nearest to the farm, and therefore it is likely that some of the metals were being actively complexed out of dissolved form and bound within the sediments. The presence of sulphides also indicated that the oxidation of sulphates was occurring (Berner, 1980). If oxidation processes are taking place within the sediments, it is likely that the metals bound to organic matter are being released into dissolved form (Chapman et al., 1998). If reduction exceeds the capacity for oxidation, however, the metals will remain bound to the organic particulates until redox potential increases somewhat and oxidation processes can start again (Rozan et al., 2000; Chapman et al., 1998). Therefore, it may be reasonable to conclude that several temporal shifts in the bioavailability of potentially toxic concentrations of copper and zinc might have been occurring within the sediments at the farm site. This conclusion is supported by the observed spatial and temporal fluctuations observed in the concentrations of both metals in sediment-bound phase. Overall increases observed in silt and porosity, and decreases observed in very fine and fine sand indicated an increase in the concentrations of metal-rich sediment grain sizes at the site. This may also have been a contributing factor to fluctuating metals concentrations. Under the anoxic conditions observed at Carrie Bay farm site, most of the potential for restoration of the metals to non-toxic levels likely lies within the ability of sulphides to complex the metals out of bioavailable form, and of the sediments to accumulate new particulate matter and subsequently bury the potentially toxic metals (Chapman et al., 1998; DeLaune and Gambrell, 1996; Orson et al., 1992).

Clay, silt, porosity, chlorophyll, pheophytin, nitrogen, organic content, and organic carbon all increased at the reference site over the study period, indicating an increase in the amount of particulate matter accumulating within the sediments. This substantial increase in sedimentation may have resulted in adequate burial of metals over time within the sediments, explaining the overall decline in zinc and potentially toxic copper concentrations at the reference site.

At all times during the study period, concentrations of aluminum and lead were also substantially higher at the farm site than at the reference site. Concentrations of both metals at the farm site fell within natural and background ranges observed in marine sediments along or near the British Columbia coastline (Odhambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989; Bloom and Crecelius, 1987). Lead can be introduced to the marine environment through natural inputs which are of lithogenic origin, or are derived from organic matter inputs (Macdonald et al., 1991; Francois, 1988). It is rarely reported as a constituent in fish feed (Sutherland et al., 2001; De Silva and Anderson, 1995; Lall, 1991), nor has it been identified in sediments receiving waste
inputs from fish farms (Uotila, 1999). Thus, it may be reasonable to assume that the elevated lead concentrations at the site could have resulted from materials used at the fish farm, but likely were not indicative of feed or faecal waste inputs to the environment. Aluminum and clay at the farm site were found to be positively associated. Aluminum is often naturally associated with clay sediments (Dean and Gardner, 2001). It is not typically reported to be a mineral requirement or constituent in fish feeds (Lorentzen and Maage, 1999; De Silva and Anderson, 1995; Lall, 1991; Tacon and De Silva, 1983), but has been detected in feed pellets collected at some fish farms in British Columbia (Sutherland et al., 2001). Thus, it is possible that the elevated aluminum concentrations observed at the Carrie Bay farm site were partially indicative of the effects of fish farming activity, due both to elevated amounts of waste inputs and clay within the sediments.

Cadmium concentrations are typically higher in natural organic matter (Morford and Emerson, 1999; McNee, 1997) and the element has been reported to not be elevated within sediments receiving waste inputs from fish farms (Uotila, 1991). Phytoplankton bioaccumulate cadmium, and as they decompose within the sediments, they release cadmium into the surrounding environment (Cullen, 2002; Cullen et al., 1999; Radach and Heyer, 1997). Thus, cadmium can be an element characteristic of organic matter accumulations in sediments. Cadmium concentrations when they were first measured at 24 months following site abandonment were significantly depressed near the farm as compared to the perimeter of the entire site and reference site. By 35 months, values had rebounded to be similar to those at the reference site, although a small pocket of depressed values was still present within a patch of sediment immediately to the east of the farm center. Thus, the marked depression in cadmium concentration measured at 24 months at the farm site may have been indicative of an absence of natural organic matter offset by a presence of fish farm waste accumulations. At all sampling times, cadmium throughout the entire farm and reference sites exceeded both Environment Canada's (1995) ISQG threshold of 0.7μg g\(^{-1}\) and natural and background ranges observed in marine sediments along or near the British Columbia coastline (McNee, 1997; Odhiambo et al., 1996; Macdonald et al., 1991; Harding and Goyette, 1989; Bloom and Crecelius, 1987).

Cadmium and silicon concentrations actually substantially increased over time while lead had decreased at the reference site. These results, along with the observed increase in organic content, would indicate an increase in the amount of natural organic matter and phytoplankton settling onto the sediments at the reference site after farm removal. The presence of fish cage structures can act to decrease flow rates, thereby inducing an increase in siltation and particulate
matter settling to the sea floor (Sutherland et al., 2001; Frid and Mercer, 1989). Removal of the net pens from the site may explain the subsequent increase over time in particulate organic matter settling within the neighbouring reference site.

Cadmium did not exhibit an association with copper or zinc at either the farm or reference site. It did, however, exhibit a positive association with silicon. Cadmium also was positively associated with organic C:N ratio. Therefore, it is likely that the cadmium concentrations observed at both the farm and the reference sites were linked, in part, to the nature of the origin of the organic matter settling to the sediments.

5.2.4.4 Sediment Oxygen Conditions

Sediment oxygen conditions were measured at both the reference and farm sites only once, at 36 months following site abandonment. At 40 months, conditions were measured at the farm site only. Station C1 was the only station that was actually measured at both sampling times.

At 36 months following site abandonment, oxygen was overall slightly lower at the farm site than at the reference site. Oxygen throughout much of the farm site approached, but rarely reached (except at two stations, at greater than 8cm core depth), 0% oxygen at 36 months. Within the small area of sediments that was revisited at 40 months, oxygen was slightly lower than it was 4 months earlier, but still did not reach 0%. At station C1, located approximately 11 meters from the farm in Carrie Bay, oxygen throughout core depths decreased between 36 and 40 months following site abandonment.

At 36 months following site abandonment, redox potential was overall slightly lower at the farm site than at the reference site. Sediment redox potential throughout most of the cores collected at the farm site at both 36 and 40 months typically ranged between <0mV, the oxic/anoxic threshold (Erickson et al., 2001; Wildish et al., 1999), and <-100mV, the anaerobic threshold (Wildish et al., 1999; Zobell, 1946). Sediment redox potential measured throughout sediment cores at the reference site ranged between >0mV and -100mV. Within the small area of sediments that was revisited at the farm site at 40 months, redox potential was lower than it was 4 months earlier. At station C1, approximately 11 meters from the farm in Carrie Bay, redox potential throughout core depths decreased between 36 and 40 months following site abandonment.
At 36 months following site abandonment, sulphides were overall higher at the farm site than at the reference site. Sulphides observed throughout cores collected at the farm site at 36 months following site abandonment consistently increased with depth, eventually exceeding the 600μMol threshold associated with potential benthic impact in British Columbia (Erickson et al., 2001). At some of the farm stations, sulphides increased with depth to exceed the probable impact threshold of 1500μMol (Erickson et al., 2001), also falling within the hypoxic range of 1300-1600μMol (Wildish et al., 1999). Sediment closest to the farm reached this threshold at much shallower core depths than at those further away. At one station in the farm site at 36 months following abandonment, sulphides increased with depth to exceed the anoxic threshold of 6000μMol (Wildish et al., 1999). Sulphides at the reference site at 36 months were below all impact thresholds throughout the core depths. By 40 months, sulphides at all farm stations increased with depth to exceed 1300μMol. Within the small area of sediments that was revisited at the farm site at 40 months, sulphides appeared to be higher than they were 4 months earlier. At station C1, located approximately 11 meters from the farm in Carrie Bay, sulphides throughout the top 10cm of the core depths decreased between 36 and 40 months following site abandonment, but below this point, sulphides had actually increased.

The lack of repeated measures, reference data, and absence of organics and metals data meant that the cause of temporal shifts in oxygen conditions between 36 and 40 months following site abandonment could not be identified. There was, however, an identifiable difference in sediment oxygen conditions between the farm and reference site at 36 months following site abandonment. Oxygen and redox potential measured throughout sediment cores were lower at the farm site than at the reference site, and sulphides were higher. At 11 months following site abandonment, sediments nearest the farm were observed to be black, anoxic, smelling of H₂S, nearly-azoic to azoic, and coated with white or orange bacterial mats. By 35 months, the bacterial mats had disappeared, but the sediments remained black, anoxic, smelling of H₂S, and nearly-azoic to azoic in appearance. Also at 35 months, concentrations of organic matter and toxic metals measured within sediments at the farm site were still elevated well above those measured at the reference site. Thus, there was reasonable evidence to suggest that one month later, when the first set of core samples was collected and analyzed for sediment chemistry, that sediment oxygen conditions would be much worse at the farm site than at the reference site.
5.2.4.5 Summary

Eleven months after fish farm removal, there was evidence of substantial organic matter accumulations at the Carrie Bay farm site as compared to both the reference site and natural conditions reported along other areas of the British Columbia coastline. The significant presence of potentially toxic levels of copper and zinc within these accumulations at the onset of the study, as well as the characteristically low C:N ratio, indicated that the accumulations at the farm site were a consequence of fish farming activity in Carrie Bay. The effects resulting from fish farm waste accumulations were more apparent within sediments nearest to the farm. Copper and zinc within the accumulations decreased significantly over time, but by 35 months following site abandonment had not yet recovered to innocuous levels throughout the entire farm site. Overall concentrations of organic matter at the farm site did not show an overwhelming decline. Over the course of the study, however, the nature of the origin of the organic matter settling at the farm site did appear to shift from being characteristic of fish farm wastes to being characteristic of more natural marine inputs. There was also evidence by 35 months of a possible increase in phytoplankton productivity at the site. Since gravity cores were not collected at the Carrie Bay site until after the grab sampling program was complete, the sediment chemistry measurements could not be compared to organic or metals data. Thus, it was not possible to quantify the sediment oxygen conditions present during the first 35 months following site abandonment at the Carrie Bay site. However, field observations indicated that the sediments at the farm site by 35 months fallow had not yet regained a healthy, oxic appearance or odour. Sediment chemistry measured at 36 months indicated that the sediments at the farm site were characterized by far more reducing conditions than at the reference site. Therefore, it seems reasonable to conclude that reducing conditions were also present throughout the grab sampling period between 11 and 35 months following site abandonment, that these reducing conditions were associated with depositions of fish farm wastes, and that the reducing conditions had not recovered by 36 months.

The results indicated that the degradation rate of the labile organic matter components did not exceed the accumulation rate of wastes at the site. During the 11 years of farm production, the aging wastes became structurally more complex and slow to degrade under what were observed to be significantly anoxic sediment conditions. Three years after the site had been abandoned, the accumulated and buried organic matter still had not undergone significant decomposition.
Due to the high levels of sulphides detected throughout the farm site, it is likely that some of the metals were being actively complexed out of dissolved form and bound within the sediments. Spatial and temporal fluctuations were observed in the concentrations of copper and zinc in sediment-bound phase at the farm site. This may have been occurring due to low, fluctuating oxidation/reduction potentials resulting in several temporal shifts in the bioavailability of potentially toxic concentrations of the two metals. Under the anoxic conditions observed at the Carrie Bay farm site, these metals will likely only be restored to non-toxic levels when they can be completely complexed out of bioavailable form, and buried within the sediments.

There was a strong indication that over the course of the 3 years following site abandonment, a slight spatial shift had occurred in the waste accumulations eastward toward the deeper, more open water areas toward the mouth of the bay. Likely this shift was primarily a result of erosion and resuspension of materials over the 2 year study period. Eleven months following removal of the fish farm, minor organic accumulations were also present at the reference site, situated more than 950 meters to the northeast and east-northeast of the farm site. The significant presence of zinc and potentially toxic levels of copper within these accumulations at the onset of the study, as well as the characteristically lower C:N ratio, indicated that the accumulations at the reference site were a consequence of fish farming waste inputs being transported away from the Carrie Bay farm. Copper had recovered to biologically harmless levels throughout the entire reference site by 24 months following site abandonment. While the sediments at the reference site became characteristically healthier throughout the study period, the absence of net pen baffling within the neighbouring Carrie Bay also appeared to allow the area to receive more natural particulate inputs than it did prior to the period following site abandonment. These natural particulates were likely responsible for burying and thus diminishing the potentially toxic effects of metals at the site.

The Carrie Bay farm site was a high production site compared to the lower production Chained Islands site. At the Carrie Bay site, estimated average quarterly feed usage over the final 4 years of operation was 380,000 kg. Using the waste carbon calculations proposed by Perez et al. (2002), it was estimated that a total of 74,000 kg of waste carbon was likely input to the marine environment on a quarterly basis. Over the 8.5 years of operation, an approximate total of 2,516,000kg of waste carbon could be estimated to have been input to the marine environment. Fallowing information was not available, and thus these estimates are very rough. Despite reported current speeds at the mouth of the bay averaging 7.6 cm s⁻¹, there was clear evidence of deposition and accumulation of waste deposits in the vicinity of the farm, as well as several
hundred meters away. This was likely due to the high amounts of waste inputs coupled with the internal circulation patterns within the bay leading to inadequate flushing.

There are no currently or recently operating mines, refineries, smelting operations, quarries, or processing plants in the vicinity of the Carrie Bay farm or reference sites (Ministry of Energy and Mines, 2003). The nearest pulp and paper mill as of February, 2001 was located in Campbell River, several kilometers away (Ministry of Water, Land, and Air Protection, 2001). There are no major roads or rivers near the farm or reference sites, and the only water bodies emptying into the ocean near the sites are very small creeks. The closest municipality to the site is located approximately 4.25 kilometers to the east-southeast in Health Bay, and has a population of under 1000 (ITMB, 2001). No major logging or agricultural operations were observed during field trips to the site. Maps obtained from the Port McNeill Forest Service District (Ministry of Forests) office documenting logging activity back to the 19th century show that no logging operations have taken place on the land surrounding Carrie Bay within the past 60 years (Small Business Forest Enterprise Program, 1998). The most recent logging operations in the vicinity of the reference site took place over 20 years ago. Inland approximately 500 meters from the reference site, the most recent harvest took place over 10 years ago, but the surrounding shores are populated by 20-250 year-old forests. After speaking with Ministry of Forests staff and observing logging maps, it was concluded that the land surrounding the Carrie Bay farm and reference sites is thus sufficiently reforested and the effects of logging on Bonwick Island would not be observable within the sediment data. As of November 2002, no aquaculture operations were officially operating in the vicinity of the site (Ministry of Agriculture, Food, and Fisheries and DFO, 2002). The closest three finfish farms were located approximately five kilometers to the northeast, southeast, and southwest of the Carrie Bay farm site.

Benthic recovery has been assessed at a few abandoned or fallowing fish farm sites in British Columbia. Anderson (1996) found that fallowing farm sites in British Columbia had partially or completely remediated by 3 years fallow, and sediments at one farm had recovered to match reference sediments by 2 years fallow. Brooks (2001b) found that after 5 months fallow benthic sediments below another farm in British Columbia had recovered to reference conditions. These varying recovery times are influenced by a number of varying factors that are not consistently reported between studies, and therefore it is only possible to roughly compare recovery times at different sites. Clearly, the site at Carrie Bay which remained impacted after 3 years had not
recovered within the same timeframe observed for remediation at other abandoned sites assessed in British Columbia by Anderson (1996) and Brooks (2001b).

5.3 Siting and Fallowing Recommendations

Although actual recovery rates could not be determined at either of the abandoned farm sites, the trends observed were useful for making site-specific siting and falling recommendations.

The abandoned Chained Islands site did not exhibit signs of significant impacts to the sediments due to deposits of organic fish farm wastes. The site did, however, demonstrate significant effects thought to be linked to the use of a cuprous antifoulant paint. This farm, when in operation, was a low production farm. The site was predominantly characterized by silt and finer sands, and was located within a large bay. Current speeds at the site were slow (1-2 cm s\(^{-1}\)), but healthy sediment conditions nonetheless indicated that there were good mixing and flushing conditions near the farm. The minor impacts that were detected at the site had not fully recovered 11 months after the site had been abandoned. 11 years (with intermittent falling) of low production at this site did not appear to promote harmful accumulations of organic waste matter, but did lead to accumulations of some of the more potentially toxic metals contained within chemicals used at the site. 11 months was insufficient falling time, following 11 years of production, to allow the metals detected at the site to become buried or complexed within the sediments, or to diffuse out of the sediments. Thus, it is recommended that if these chemicals cannot be discontinued or replaced with more innocuous compounds, such a site should be fallowed more regularly in order to ensure the sustainability of the sediments.

The abandoned farm site at Carrie Bay, however, did exhibit signs of significant impacts to the sediments. This high production farm produced ten times the amount of fish on a quarterly basis as the Chained Islands farm and was situated in a relatively sheltered, muddy bay with slow to moderate current speeds at the mouth, but a slower, internal gyre induced deposition within the bay. The anoxic, contaminated sediments at the Carrie Bay farm site had not recovered, nor had they nearly recovered, 3 years after the site had been abandoned. It is recommended that high production farms such as the Carrie Bay farm (800 tonnes quarterly) not be sited at sheltered, muddy sites with low current speeds (<10 cm s\(^{-1}\)). 8.5 years of high production at such a site leads to unsustainable conditions, and 3 years is insufficient falling time to allow the sediments at
such a site to remediate. If it were known prior to siting the Carrie Bay farm that the bay had poor circulation and the sediments were naturally prone to be low in oxygen, it is possible that the operation would not have been approved. Performing surveys at potential farm sites in order to determine their ability to assimilate waste inputs is a necessary component of siting fish farms.

5.4 Methods Assessment and Recommendations

5.4.1 Farm Site Selection

Site selection was contingent upon the availability of abandoned sites at the onset of the study. In order to gain an understanding of the effects of fallowing under a variety of conditions, it is recommended that future recovery assessments be conducted at sites characterized by a variety of different substrates, hydrographic regimes, and farm production levels. Furthermore, selected sites should ideally be available for sampling immediately following the final harvest or fish relocation, in order to obtain time-zero analysis. Sediments near fallowing farms have been recorded to recover in as little as 14 weeks (Ritz et al., 1989), and thus time-zero analysis is important if the research goal is to ascertain a recovery rate. Sediments near one of the abandoned sites assessed in this project had not recovered 3 years following site abandonment, and therefore it is recommended that an ideal study site should be available for investigation until full recovery can be detected.

5.4.2 Reference Site Selection

The Aquaculture Interim Monitoring Program guidelines require reference sites to have similar substrate and depth to the farm site, and to be clearly away from the influence of the farm (Erickson et al., 2001). It is also ideal to have other hydrographic conditions, such as current speeds, vertical mixing, and surrounding topography, be similar at both sites.

At the Chained Islands site, the average depth was 27.0±6.3 meters at the east farm site, 31.0±9.7 meters at the west farm site, and 29.9±3.9 meters at the reference site. Depths were thus fairly similar between all three sites. However, the overall ranges of depths sampled at the farm sites were significantly more widespread than those within the reference site. Sediments at the east and west farm sites consisted mostly of silt and finer sand, with some finer clay and gravel. Sediments at the reference site consisted of a majority of silt and finer sand, with some finer clay.
Sediments larger than fine sand were present at the east and west farm sites, but were absent at the reference site. At the reference stations, sediments appeared to consist of finer, consolidated muds, devoid of shell hash, and exhibiting occasional patches of black below the surface. Thus, substrates at the reference site were slightly different than those found at the farm sites, likely due to the lack of shallower, nearshore reference stations. Despite the fact that these conclusions were made in the absence of baseline data at the sites, it is likely that even prior to farm production the sediments were different given that the amount of influence from the fish farm was found to be minimal.

Some minor effects suggestive of fish farming impacts were detected at the Chained Islands reference site. Sediments at the west farm site appeared to be relatively free of impact altogether. Thus, the sediments at the reference site could not be used to generate baseline data to which the farm site sediments could be compared. The reference stations were located within the range of approximately 160-640 meters of the approximate west farm center. A more suitable reference site at the Chained Islands site would ideally have been located much further from the farm sites in order to avoid far-field effects, and would have consisted of a wider range of depths and substrates similar to those found at the farm sites.

The average depth at the Carrie Bay farm site was 34.4±4.6 meters, and 36.9±4.7 meters at the reference site. Depths were thus fairly similar between the sites. Sediments at the Carrie Bay farm site were dominated by silt and clay, and consisted also of some finer sand and small amounts of coarser sand and gravel. Sediments at the reference site were similar, consisting predominantly of silt, clay, and finer sand and some minute amounts of coarser sand and gravel.

The sediments at the reference site were used to generate baseline data to which the farm site sediments could be compared. However, some minor effects that were clearly a result of fish farming activity were detected at the Carrie Bay reference site. The toxic metals within the sediments at the reference site recovered 24 months after the Carrie Bay farm was removed. The reference stations were located within the range of approximately 940-980 meters from the approximate center of the farm in Carrie Bay. A more appropriate reference site would have been located at a much further distance from the farm site, in order to avoid far-field effects.

Both the Carrie Bay and Chained Islands reference sites exhibited effects due to fish farming activity. Research into the magnitude and extent of far-reaching effects of aquaculture waste inputs would be highly useful for determining the minimum distance for reference stations.
5.4.3 Sampling Design

A single sampling design will not provide satisfactory input for all forms of statistical and spatial data analysis. Therefore, it is crucial to the success of a sampling program that research objectives and data analysis procedures be identified and used as the basis for formulating a sampling design.

The major objective of this project was to analyze physico-chemical aspects of sediment recovery at abandoned fish farm sites. The recovery at each site was analyzed in so far as it was ascertained if each site had (a) recovered or not recovered, and (b) according to what indicators. In order to better understand recovery at fish farm sites in British Columbia for the purposes of developing adequate fallowing times and conditions, it also would be useful to define (c) the spatial extents of the impacts, and (d) the rate of recovery. The methods used for this project were successful for determining (a) and (b). Fundamental changes to the sampling design would be necessary in order to determine (c) and (d).

Contour mapping involves estimating values at unsampled points from measurements gathered at nearby sampled points in order to obtain a continuous spatial pattern within an experimental unit. Contour maps can thus be designed to provide quite accurate, illustrated snapshots of spatial extents of benthic impact according to environmental variables. If a set of maps is designed for each sampling time, then an invaluable visual time-series can be constructed, and spatio-temporal recovery rates can be determined. The current sampling design was not conducive for generating the spatial coverage needed to determine the spatial extents of impact or spatio-temporal recovery rates. The chief limitations of the design were the spatial layout of the sampling stations, the minimal number of sampling times, irregularity of sampling times, the lack of replication, and temporal inconsistencies in the pseudoreplicate motif.

When sampling with the objective of mapping in mind, it is recommended that sample locations be spaced evenly over the area of study (Burrough and McDonnell, 1998). It has been suggested that the most logical pattern fitting this objective is a grid system (Lohr, 1999; Cochran, 1977; Dixon and Leach, 1976). Matern (1960 as cited in Cochran, 1977) assessed the best way to estimate the area covered by forest or water on a map, and found the square grid to be a superior method over the random sampling method. Green (1979) encourages randomization of sampling locations, but agrees with Cochran (1977) that if variation of a parameter is fairly continuous, and
if spatial pattern analysis is necessary, a systematic grid is optimal. He furthermore stresses that if randomly placed replicate samples are taken within grid squares, a happy statistical medium can be achieved (Green, 1979). Unfortunately, with boat drift this would be difficult and time-consuming. Typically, systematic samples on natural populations have similar precision to stratified random samples (Cochran, 1977). Randomization can actually result in spatial unevenness and the risk for under or over representation of certain areas (McGrew and Monroe, 1993). Unlike a stratified random sample, a systematic sample ensures equal coverage over a study area, and is much easier to carry out (Lohr, 1999; Cochran, 1977; Dixon and Leach, 1976). For these reasons, systematic sampling is more appropriate for the purposes of contour mapping.

Many studies similar to this one support the use of systematic grid sampling. Kuenitzer et al. (1992) mapped benthic infaunal assemblages and distributions in the North Sea using a regular grid system of sampling points, and Adami et al. (2000) mapped sediment pollutants in a harbour in the Adriatic Sea using systematic sampling. Wang and Qi (1998) compared the effects of systematic sampling, random sampling, and systematic random sampling on spatial structure analysis of contaminated soil. They found that the systematic sampling design offered a better estimation than the other two, given a certain sampling density.

If time-series maps of recovering impacts at a fish farm site are the sought deliverables of a project, it follows that the optimal design for experimental units for such a project would be a simple systematic, aligned grid. If impact is detectable through initial reconnaissance, the center of the grid should be placed strategically over the center of the zone of impact. Otherwise, if the location of the abandoned net-pens is either known or can be estimated from airphotos, maps, accurate sketches, or other sources, then the center of the grid should be placed over top of the farm center.

The length of the vessel used for sampling coupled with boat drift creates some positional error, and if stations are too close, any resemblance to a grid will be lost. Furthermore, cost and time restrictions make high-resolution sampling unfeasible. A distance of 30 meters between stations can be considered optimal. This corresponds well with the spacing of net pens, which are often 30x30 meters or 15x15 meters. Experimentation would be necessary to statistically verify optimal sampling interval distance.
The *Waste Management Act* (1996) identifies 100 meters as the initial dilution zone for point source discharges. Since fish farms are diffuse sources of wastes, the Aquaculture Interim Monitoring Report (2000) requires that sampling take place out to at least 100 meters away from the perimeter of the net cages. Thus, an absolute minimum of 100 meters on either side of the edges of the abandoned fish farm should be sampled for recovery analysis. Given the varying size and sway of net pens, and the evidence of far-ranging effects detected in this study, the grid would benefit from being as large as possible. Figure 65 shows six examples of sampling designs centered around a farm containing eight 30x30m net pens, much like the Carrie Bay farm.

Depending on the grid chosen, all stations could be sampled within 3-5 days without replicates, and 6-10 days with replicates. These calculations are based on an average sampling rate during this project of 34 grab samples per day, processed by a scientific crew of 3 or 4, off a small but robust multi-task vessel (13-20m length). How the grid is applied at a site will be situation-specific and should be left to the discretion of the researcher. However, one recommendation would be to obtain duplicate grab samples at each station in order to assess physico-chemical indicators. Another recommendation would be to grab sample each station once for physico-chemical indicators, and to obtain a second grab sample at each station in order to collect biological indicators. Alternatively, the second sample could be obtained using a corer in order to collect indicators of sediment chemistry. Core samples can be processed at a rate of 6 to 8 stations per day. Since core sampling will only be successful within soft silt/clay sediments, they will usually be collected at fewer sites than can be assessed using a grab sampler. If all three sets of indicators are desired, the sampling trips may have to be extended and/or the grid designs amended. Costs could be reduced by sampling only the most sensitive recovery indicators, and funds could be reallocated into subsidizing longer sampling trips.

The purpose of the first trip to an abandoned farm site would be to survey the full grid of sampling points in order to provide a snapshot of the zone of impact, should it exist. If a zone of impact could be identified and isolated after the first trip, then only the portion of the grid contained within this area need be re-sampled on subsequent trips. It is suggested that a couple of extra days be added to the first sampling trip in order to allow for compensation of sampling difficulties that may occur during initial site reconnaissance.
Once a grid of measurements is obtained from field-sampled data, in order to generate continuous spatial patterns from point sampled data, it is necessary to convert the data using interpolation (Jones, 1997; Burrough and McDonnell, 1998). Spatial interpolation provides an estimate of the
values for variables at unknown locations given values measured via point sampling at nearby, known locations. Kriging, the method used for this research project, is a flexible method of interpolation that has been found to be optimal, particularly in the event of sparse data (Burrough and McDonnell, 1998; Chang et al., 1998; Danielsson et al., 1998). Kriging has recently evolved into a more popular method for generating spatial patterns of marine sediment pollution. Poon et al. (2000) found kriging to be a useful technique for identifying sewage pollution patterns in coastal sediments, and Buettner et al. (1998) used kriging to assess spatial distributions of elements in sediments in an acidic mining lake. Once the data has been interpolated, contour maps based on individual variables can be created using a surface mapping program. Surfer, the software used for this project, proved to be an adequate modelling program for the purpose of spatial interpolation and contour mapping.

To the best of this author's knowledge, contour mapping techniques have not been used within any published studies for analyzing recovery of sediments at fish farm sites in British Columbia.

Repeated measures, or repeated sampling of the same stations over time, are required in order to generate a time-series analysis. In order to both obtain an adequate recovery time-series and to account for seasonal effects on environmental variables, stations at each site should be sampled at least once per season, for a duration of two or more years. It is furthermore recommended that the frequency of sampling be as consistent as possible in order to determine a relatively continuous rate of recovery. In order to maintain the integrity of the time-series analysis, virtually identical sampling layouts should be applied at each sampling time. Otherwise, attempts at spatio-temporal pattern recognition may be rendered ineffective.

For example, if a gridded sampling design was repeatedly applied to the same exact area of sediments at a consistent frequency, then it would be feasible to construct a continuous series of maps spanning the same geographical area for each sampling time. This done, the area of sediments exceeding a particular threshold or set of thresholds could be calculated for each sampling time. These area calculations could be compared to one another for the purpose of determining spatio-temporal recovery rates at the site. Following these methods would allow for an accurate calculation of the number of hectares of sediments within a site that are recovering, per time unit, according to one or more environmental variables.
5.4.4 Sample Collection

5.4.4.1 Grab Samples

It is common practice to use a grab sampler to obtain the top few centimeters of sediment from the ocean floor for the purpose of sediment characterization (Shin and Fong, 1999; Nilsson and Rosenberg, 1997; Somerfield and Clarke, 1997; Service, 1993;). This method has been used by a number of researchers, both locally and internationally, for sampling sediments beneath fish farm sites (Brooks, 2002; Erickson et al., 2001; Brooks, 2000a; Levings and Sutherland, 1999; Anderson, 1996; Henderson and Ross, 1995; Tsutsumi, 1995; Miller-Retzer, 1994; Johannessen et al., 1994; Johnsen et al., 1993; Cross, 1990; Aure et al., 1988; Brown et al., 1987).

In a relatively recent review of soft sediment samplers, Blomqvist (1991) reports that bucket grabs will provide the most representative samples, and furthermore that of all reviewed grabs, the Van Veen grab will obtain the most undisturbed sample with the most uniform depth. The author cautions, however, that the Van Veen grab is not without its limitations and sources of sampling error, particularly due to oblique or asymmetrical closing and variance in sampling due to grab design or substrate type (Blomqvist, 1991).

The Van Veen grab used for this project was useful in sediments that did not impede grab penetration or block and prevent the mechanical jaws from opening or closing. Thus, it was not particularly useful for sampling cobble and gravel dominated substrates, and could not be used on bedrock substrate.

5.4.4.2 Core Samples

Core sampling is an ideal method for sampling softer sediments when vertical integrity and resolution during analysis are necessary (Danielsson et al., 1998). Blomqvist (1991) suggests that if the researcher’s intention is to quantitatively sample sediments vertically, a corer that encloses and retains the sediment with minimal disturbance will provide the most accurate analyses. Typically, cores are used when the researcher intends to perform analyses that both require minimization of sediment exposure to oxygen, and rely on an intact vertical profile to some preferred depth below the surficial sediments (Parker and Dumaresq, 2002; Somerfield and Clarke, 1997; Blomqvist, 1991). Corers have been used by a number of researchers, both locally
and internationally, for sampling softer sediments beneath fish farm sites (Karakassis et al., 1999; Mazzola et al., 1999; Wildish et al., 1999; Hargrave et al., 1997; Anderson, 1996; Miller-Retzer, 1995; Findlay et al., 1995; Weston, 1990; Brown et al., 1987).

The gravity corer used for this project was only useful within sediments dominated by silt or clay grain sizes. It was not possible to obtain intact cores within sandy or rocky sediments. Redox potential, oxygen, and sulphides were measured from the cored sediments. At the Carrie Bay site, it was difficult to detect a pre-farm sediment chemistry signature throughout the cores, even at 36 months following site abandonment. Maximum core depths at the site ranged between 8 and 30cm, and therefore it is suggested that, if possible, deeper cores be obtained during future recovery assessments. This may be achieved using longer core barrels and heavier weights.

Core lengths varied between 4cm and 16cm at the silt/sand dominated Chained Islands site, and between 8cm and 30cm at the silt/clay dominated Carrie Bay site. Core depths were dependent on substrate type, weight of the corer, winch speed, wire angle (boat drift), and current speeds. Deeper cores were able to be extracted from softer sediments, and therefore less weight needed to be affixed to the corer. On one sampling trip, too much weight was added to the core sampler, and the mechanism actually returned cores that had plunged too deep within the sediments. These cores were not used within the data analysis because they did not provide surface measurements. Winch speed is important when controlling the corer. If the core approaches the sediments at too low of a speed, it may not penetrate adequately, and in some cases may actually tip over. If the winch is operated at too high of a speed, the wire may become too slack and the corer may semi-free fall in any number of positions down toward the sediments. Achieving the straightest possible wire angle is important in order to ensure that the corer penetrates perpendicular to the sediments. Boat drift can be responsible for shifts in wire angle.

Other forms of analyses that can be used to characterize sediments or assess the effects of organic enrichment on sediments include multibeam sonar (Hughes et al., 1996), sediment profile imaging (Nilsson and Rosenberg, 1997; Grizzle and Penniman, 1991), and near-infrared spectroscopy (Malley, 1998). These imaging techniques may pose a viable alternative to the sediment sampling techniques used for this project, and thus may merit further investigation at falling fish farm sites.
5.4.4.3 *Sampling Rocky Substrate*

Benthic impacts have also been observed, although not commonly, at sites dominated by coarser sediments (McGhie et al., 2000; Brooks, 1996; Johnsen et al., 1993; Aure et al., 1988). Due to the difficulty in sampling these areas, it is difficult to conclude whether or not these substrates exhibit impacts due to fish farming inputs. It has been recommended that video or photographic reconnaissance be used to sample rocky environments (Erickson et al., 2001; Mallik, 2001; Gordon et al., 2000; Lybolt and Eaken, 2000). Photographic surveys of substrates underlying fish farm sites have been performed in British Columbia with varying success (Brooks, 2002; Erickson et al., 2001; Cross, 1990).

5.4.5 *Sample Analysis*

5.4.5.1 *Bulk Density*

The bulk density measurements used were based on sediment volume calculations also applied within chlorophyll analyses. These volumes were calculated using a ruler and the equation for calculating the volume of a cylinder. The dry weight of the sediments was measured after the acetone in the sediments had completely evaporated. Exposure to acetone, and minor sediment losses incurred during chlorophyll analysis may have resulted in a slight errors in the dry weight readings. Thus, porosity and bulk density of the sediment reported for the chlorophyll cores were rough measurements. However, the results were consistent within and between the sites, and therefore both variables were still considered to be useful during the recovery assessments.

5.4.5.2 *Metals*

Finer grained sediments, particularly within the clay and silt fractions, are considered to be metal-rich minerals (Loring, 1991). Metals may also strongly bind with particulate organic matter (Chapman et al., 1998). It has been proposed that the most accurate method of comparing sediment metals concentrations is to normalize the metals to sediment grain size, naturally occurring elements associated with grain size, and sometimes to organic matter (Loring, 1991). Normalization techniques were not applied to metals concentrations within this project, although the guidelines used to analyze the potential toxicities of the metals were developed by normalizing metals to background lithium concentrations and organic carbon (CCME, 1995).
None of the metals at either of the abandoned farm sites were found to be consistently well correlated with concentrations of natural sediment metals (Li, Al) or with any fractions of sediment grain size. Therefore, the application of these normalization techniques to the metals data was deemed not feasible. One normalization technique that would have been applicable, under these circumstances, would have involved fractionating out certain sediment grain sizes, and analyzing them individually for metals concentrations (Loring, 1991). This is recommended as a more favourable approach for analyzing sediment metals during future recovery assessments at fish farm sites.

5.4.6 Data Analysis

5.4.6.1 The Best Approach

Two approaches to data analysis were adopted in order to achieve the objectives of this project. The first approach was characterized by a strict adhesion to statistical rules and assumptions, and included correlation analysis, regression analysis, and ANOVA. Violation of assumptions for these statistical tests leads to erroneous results, and thus data was tailored, when necessary, to meet these assumptions. Tailoring was applied to data which was not normally distributed, and involved first an attempt to transform the values followed by a last resort removal of outliers. ANOVA provided a quantitative analysis of spatio-temporal recovery at the sites, as well as determining the sensitivities of recovery indicators. Inferential statistics were useful for identifying trends in the data that might not otherwise have been apparent using descriptive statistics. Correlation and regression analysis were used to identify redundancies amongst sediment variables. Since two variables can only be considered redundant if there is a strong linear relationship between them, a strict statistical analysis approach was appropriate.

The second approach to data analysis was characterized by a more liberal style of data analysis which included descriptive statistics, investigative principal components analysis, contour mapping, and GIS analysis. Since there was no risk of rule violation, these methods of analysis used all of the data, untailed. This approach provided a clearer picture of the magnitude and gravity of the zones of benthic impact and spatio-temporal recovery at the sites. It was useful for extracting results from the portions of the data that were characterized by abnormal distributions, anomalies, extreme values, uncertainties, and patchiness. The combined application of the two
data analysis approaches provided the fullest picture of spatio-temporal recovery that could possibly be ascertained from the available dataset.

5.4.6.2 Distance Analysis

The distance categories used for the analyses of variance (0-50m, 50-100m, and >100m) were selected based on the number of stations available in order to ensure adequate degrees of freedom. Unfortunately, depth and substrate were two confounding factors that could not be factored into the analysis. In particular, the stations >100 meters from the Chained Islands farm site were quite varied in terms of sediment grain size, depth, and hydrography. The results of these analyses of variance did not provide useful information, and it was rare that differences observed between the distance categories could be used to determine recovery patterns at either of the abandoned farm sites. However, if in the future such an analysis were opted for, more stations would need to be sampled than were available during this research. A more scientifically sound method for categorizing the stations would be to select distance categories based on spatial gradients of impact observed at other fish farm sites. Furthermore, depth, substrate, and current direction should be included as nested factors, if possible.

5.4.6.3 Chained Islands East and West Farm Analysis

The Chained Islands site was divided into two regions, the west farm and the east farm sites, for the purposes of statistical analyses. Since a depositional pattern radiating outward from the farms was not detected, and since the farms may have migrated within the lease boundaries somewhat, it would have been an option to group the data for the two sites and analyze them together as one site. At the Chained Islands west farm site, there was no evidence to indicate any impacts due to fish farming activity, and therefore this grouping was not deemed necessary. However, in the future, it is recommended that adjacent farms be analyzed both individually and together, in order to assess any impact overlap that may be taking place.

5.4.7 Recovery Indicators

At the Chained Islands site, the following recovery indicators were recommended for use within future recovery assessments at similar sites: organic carbon, organic content, nitrogen, total carbon, chlorophyll, copper, zinc, porosity, and bulk density. At the Carrie Bay site, the
following recovery indicators were recommended: organic C:N, organic carbon, organic content, nitrogen, total carbon, inorganic carbon, copper, zinc, silicon, fine sand, very fine sand, coarse sand, silt, clay, and medium sand.

Redox potential and sulphides were identified as potential indicators of recovery at both sites. At the Chained Islands site, the two variables were used to conclude that sediment conditions were oxic and likely dominated by aerobic processes. Thus, the variables were likely indicative of one of two situations: (1) sediment oxygen conditions had already recovered prior to the first sampling trip, or (2) sediment oxygen conditions had not been affected by waste inputs. Neither of the variables changed significantly over time, nor were they sensitive to changes in organic matter accumulations, and therefore their sensitivities could not be assessed.

At the Carrie Bay site, sediment oxygen variables were not assessed until 3 years after the site had been abandoned, after the grab sampling program was already complete. The variables at this time were measured at both the farm and reference sites. 4 months later, the variables were again assessed at the farm site, but not at the reference site. Thus, there were only two times available from which a time series could be formed at the farm site, and no reference data with which to compare the farm site the second time. There was therefore no basis for a recovery analysis, and sediment oxygen variables could not be assessed for their sensitivities as recovery indicators. At 36 months, however, the two variables indicated that sediment conditions at the site were anoxic and likely dominated by anaerobic processes. According to the results of other analyses performed prior to this time, it appeared that the anoxic conditions observed at 36 months were likely a continuation of what were hypothesized to be anoxic conditions induced 3 years earlier by fish farming activity.

It is recommended that future efforts be made to assess sediment redox potential and sulphides at impacted and recovering sites in order to determine their effectiveness as recovery indicators.

There was an observable but weak inverse relationship observed between redox potential >-200mV and sulphides <1000μMol at both abandoned farm sites. Sulphides measuring >1000μMol and redox potential <-200mV were not correlated. In the later stages of anoxia, sulphates can be totally oxidized out of the sediments, slowing the production of sulphides, and instigating the production of methane (Froflich et al., 1979). There is a transition period during which sulphides begin to diminish and, simultaneously, methane begins to appear in the sediments (Holmer and Kristensen, 1994). This may explain the scattered relationship between
such high levels of sulphides and such low levels of redox potential observed at the Carrie Bay site. It is recommended that caution be exercised when investigating the indicators of extremely anoxic conditions. Sulphides may not be the best indicator of the state of anaerobic conditions past a certain point of anoxia, and if possible, methane production should be investigated.

### 5.4.8 Impact Detection Thresholds

Research on the toxicities of sediment sulphides and heavy metals within specific sediment environments needs to be further investigated. Confounding factors including grain size, organic matter, and sediment gases may significantly influence toxicity thresholds. If toxicity guidelines can be established for different sediment habitats, a more solid basis can be established for performing comparative analyses between recovering sites and background conditions.

The results at both sites for sediment redox potential, sulphides, and oxygen provided some interesting contradictions to existing thresholds. Table 49 gives a list of the mean values of each geochemical variable measured from the gravity cores categorized according to thresholds.

<table>
<thead>
<tr>
<th>CARRIE BAY</th>
<th>CHAINED ISLANDS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sulphides</strong></td>
<td><strong>Sulphides</strong></td>
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<tr>
<td>(μMol)</td>
<td>(μMol)</td>
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<tr>
<td>&lt;600</td>
<td>&lt;600</td>
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<td>600-1300</td>
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<td>1300-6000</td>
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<tr>
<td>&gt;6000</td>
<td>&gt;6000</td>
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<tr>
<td><strong>Redox</strong> (mV)</td>
<td><strong>Redox</strong> (mV)</td>
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<tr>
<td>&lt;0 and &gt;-100</td>
<td>&gt;0</td>
</tr>
<tr>
<td>0</td>
<td>&lt;0 and &gt;-100</td>
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<tr>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Oxygen</strong> (%)</td>
<td><strong>Oxygen</strong> (%)</td>
</tr>
<tr>
<td>&gt;0.0</td>
<td>&gt;0.0</td>
</tr>
<tr>
<td>0</td>
<td>&lt;0 and &gt;-100</td>
</tr>
<tr>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 49: Mean values of each geochemical variable measured from gravity cores categorized according to thresholds (highlighted) of sulphides, redox potential, and oxygen.

There was a clear difference between redox potential as it corresponded to sulphides thresholds, and sulphides as they corresponded to redox potential thresholds. Table 50 gives a list of the combined thresholds of redox potential and sulphides as reported by Erickson et al. (2001) and
Wildish et al. (1999). By comparing the two tables, it is clear that there was a significant discrepancy between actual sediment oxygen conditions at both the Carrie Bay and Chained Islands sites and the conditions expected according to the thresholds.

<table>
<thead>
<tr>
<th>Sulphides ((\mu\text{Mol}))</th>
<th>Redox (mV)</th>
<th>Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;600</td>
<td>&gt; 0</td>
<td>oxic</td>
</tr>
<tr>
<td>600-1300</td>
<td>&lt; 0 to 100</td>
<td>oxic</td>
</tr>
<tr>
<td>1300-6000</td>
<td>-100 to 0</td>
<td>hypoxic</td>
</tr>
<tr>
<td>&gt;6000</td>
<td>&lt; -100</td>
<td>anoxic</td>
</tr>
</tbody>
</table>

Table 50: Redox potential and sulphides thresholds according to different sediment oxygen conditions associated with fish farming (Erickson et al., 2001; Wildish et al., 1999).

At the Carrie Bay site, redox potential values were actually lower (less oxic) than expected for all categories of sulphides thresholds. Sulphides values were also lower (more oxic) than expected for all categories of redox potential thresholds. According to these observations, redox potential indicated that sediments at the Carrie Bay site were much more anoxic than the sulphides readings would suggest. On the flip side of the coin, sulphides indicated that the conditions were much less anoxic than the redox potential readings would suggest. Either a decision must be made as to which variable should be considered the stronger indicator of sediment oxygen conditions, or the thresholds must be modified for sites similar to the Carrie Bay site.

At the Chained Islands site, redox potential values were slightly lower (less oxic) than expected for the lowest category of sulphides thresholds (<600\(\mu\text{Mol}\)). However, redox potential values were within the threshold values expected for sulphides ranging from 600-1300\(\mu\text{Mol}\). Sulphides were within the values expected for redox potential readings above zero, but were lower (more oxic) than expected for sub-oxic levels of redox potential. According to these observations, redox potential indicated that some of the sediments at the Chained Islands site were slightly less oxic than some of the lower sulphides readings would suggest. Sulphides, on the other hand, would indicate that some of the sediments were more oxic than some of the redox potential readings would suggest. The dilemma with the Chained Islands data is similar to that observed with the Carrie Bay data, only to a much less drastic extent, since conditions were clearly less reducing. A decision needs to be made as to whether to use redox potential or sulphides as the dominant indicator oxygen of sediment oxygen conditions. Otherwise, the thresholds will need to be slightly modified for sites similar to the Chained Islands site.
At the Chained Islands site, no relationship was observed between sediment oxygen condition variables and organic matter variables. Thus, organic carbon and organic content thresholds could not be evaluated. At the Carrie Bay site, sediment oxygen conditions were not assessed within the same timeframe as the organic matter content, and thus the indicator thresholds at this site could also not be evaluated.

5.4.9 Physico-Chemical Recovery

This study showed that the recovery rates of anoxic conditions and potentially toxic metals in sediments may be slow, and it is unclear whether or not certain sites may ever actually recover to a natural, pre-farming state.

Potentially toxic concentrations of heavy metals were detected at both abandoned farm sites. Educated evaluations were made of the possible modes of recovery for the metals at both sites. However, since heavy metals are consistently found to be one of the more toxic constituents arriving to the benthic environment from fish farms (Brooks, 2001a; 2001b; 2001c; Erickson et al., 2001; Uotila, 1991), it is important that mechanisms of their recovery are better understood. The remediation of heavy metals within sediments relies on a combination of processes, including burial, formation of solid-phase complexes, and outward diffusion (Chapman et al., 1998; DeLaune and Gambrell, 1996; Orson et al., 1992). Therefore, metals deposited within the benthic environment do not actually disappear. They can only be diluted, rendered non-toxic, or mobilized into the water column. Alternatives to cuprous antifouling paints have been investigated at length by Brooks (2001a) in British Columbia. The two safest, most viable alternatives suggested were the incorporation of innocuous chili pepper extracts into the antifoulant paint, and regular washing of the net pens at a land-based site. Special attention should therefore be devoted to the development of these and other significantly less harmful chemical alternatives to be used at fish farm sites.

5.4.10 Biological Recovery

A wide range of environmental variables was sampled at both of the abandoned fish farm sites. Macrofauna and meiofauna data were collected but not analyzed due to budget restrictions. This biological data would help to corroborate the results of any environmental investigation into impact and recovery at a fish farm site, since ultimately the scientific question being asked is: what are the impacts upon and recovery rates within the benthic communities dwelling in the
sediments underneath fish farms? However, analysis of the benthic community can be both a costly and time-consuming process, arguably to a much greater degree than collection of a small suite of environmental variables (Wildish et al., 2001). A substantial amount of scientific literature has sought to draw correlations between the effects of fish farm wastes, and other forms of organic pollution, on both biological and environmental elements of marine sediments (e.g. Brooks, 2002; La Rosa et al., 2001; Wildish et al., 2001; Nilsson and Rosenberg, 2000; Christensen et al., 2000; Karakassis et al., 1999; Wang and Chapman, 1999; Hargrave et al., 1997; Anderson et al., 1996; Hargrave, 1994; Ye et al., 1991; Cross, 1990; Weston, 1990; Aure et al., 1988; Brown et al., 1987; Pearson and Stanley, 1979; Pearson and Rosenberg, 1978; Reish et al., 1972). On the one hand, such research provides a justification for using sediment chemistry to represent the health of benthic communities. On the other hand, the use of sediment geochemistry sampling techniques is still relatively new at fish farm sites within British Columbia. Insufficient local evidence exists to create definite thresholds based on specific biological tolerances to sediment redox potential and sulphides. Until such local thresholds can be established, it is difficult to gauge the effects of changes in sediment geochemistry due to fish farming. The unusual combinations of values observed for redox potential, oxygen, and sulphides at both the Carrie Bay and Chained Islands site support this conclusion (Section 5.4.8).
6 Conclusions

Physico-chemical aspects of sediment recovery were investigated at two abandoned salmon farm sites in British Columbia. The purpose of these investigations was to perform an initial reconnaissance-type evaluation of falling and abandoned farm sites. Many of the methods for performing such research are still in the development process. Therefore, the results of this project will be a useful part of the iterative process that is necessary in order to determine the most effective methods for performing recovery assessments at future sites. In turn, these recovery assessments will provide invaluable information for the establishment of falling criteria at fish farm sites in British Columbia.

The Chained Islands farm was a low production operation that had been sited within a relatively large, silty/sandy bay characterized by slow current speeds (1-2 cm s\(^{-1}\)) and a well-mixed water column. The farm had operated for 11.5 years with intermittent falling periods. The pens were empty of fish for one full quarter during the seventh year of operation, and again for another quarter during the ninth year of operation. The pens were also empty for the entire tenth year, and during the eleventh and final year of operation, production was considerably lower. The investigation at the Chained Islands site led to the conclusion that, despite organic matter accumulations detected immediately following site abandonment, the effects to the benthic environment due to deposits of organic fish farm wastes were not significant. However, copper concentrations, thought to be linked to the use of cuprous antifoulant paint at the site, still exceeded sediment quality guidelines 11 months after the site had been abandoned. It was therefore recommended that if the toxic chemicals used at a farm, such as cuprous antifoulant paint, cannot be discontinued or replaced with more innocuous compounds, such a site should be fallowed more regularly in order to ensure adequate time for potentially toxic metals to be sufficiently buried or complexed within the sediments.

The sensitive indicators of temporal recovery and spatial variations identified at the Chained Islands site were predominantly indicative of healthy sediments. Based on the results of the investigation performed at the site, it was recommended that the following three tiers of sensitive indicators be monitored during future recovery assessments at abandoned fish farm sites characterized by similar production levels, substrate, and hydrography:
(1) When time and budget allow: total carbon, organic content, organic carbon, nitrogen, chlorophyll, copper, zinc, porosity, bulk density, redox potential, and sulphides.

(2) When time and budget are slightly restrictive: one of total carbon, organic content, organic carbon, or nitrogen; chlorophyll; copper or zinc; porosity; bulk density; and redox potential or sulphides.

(3) When time and budget are more restrictive: total carbon, nitrogen, copper, zinc, porosity, bulk density.

The Carrie Bay farm was a high production operation that had been sited within a sheltered, muddy bay characterized by slow current speeds (<10cm s\(^{-1}\) at the mouth of the bay). The farm had operated for 8.5 years prior to its removal. There was significant evidence to support the conclusion that fish farming activity at the Carrie Bay site had detrimental effects on the benthic environment both near to the farm, as well as up to several hundreds of meters away. The sediments at the farm site had not yet fully recovered by the conclusion of the study, approximately 3 years after the site had been abandoned. Based on these results, it was recommended that high production farms not be sited within sheltered, muddy bays characterized by slow current speeds. Existing farm sites of this nature may require quite lengthy fallowing times after several years of production. At the Carrie Bay site, 3 years was determined to be substantially deficient fallowing time after only 8.5 years of operation.

The sensitive indicators of temporal recovery and spatial variations identified at the Chained Islands site were predominantly indicative of impacted and recovering sediments. Based on the results of the investigation performed at the Carrie Bay site, it was recommended that the following three tiers of sensitive indicators be monitored during future recovery assessments at abandoned fish farm sites characterized by similar production levels, substrate, and hydrography:

(1) When time and budget allow: organic C:N, organic carbon, organic content, nitrogen, total carbon, inorganic carbon, copper, zinc, silicon, fine sand, very fine sand, coarse sand, silt, clay, medium sand, redox potential, and sulphides.

(2) When time and budget are slightly restrictive: one of organic C:N, organic carbon, organic content, nitrogen, total carbon, or inorganic carbon; copper or zinc; silicon;
coarser sand (<2mm); finer sand (<250μm); silt (<63μm); clay (<4μm); redox potential; and sulphides.

(3) When time and budget are more restrictive: organic C:N (organic carbon and nitrogen), zinc, silicon, and silt.

It was recommended that future recovery assessments be performed at sites characterized by a variety of different substrates, hydrographic regimes, and farm production levels. It was also recommended that the effects of sediment grain size on sediment metals be controlled at each site through the use of the size-fractionation normalization technique. Sites ideally should be sampled immediately following final harvest or fish relocation in order to obtain an impact analysis at time-zero. At both the Carrie Bay and Chained Islands sites, possible far-field effects from the farms were detected. At the Carrie Bay site, there was significant evidence to suggest that fish farm waste inputs had reached the reference site at more than 900 meters away. It was therefore recommended that future research into the magnitude and extent of far-reaching effects of aquaculture waste inputs would be highly useful for determining the minimum distance for reference stations.

A combination of traditional statistics (descriptive and inferential), contour mapping, and GIS analysis were recommended as effective methods for assessing physico-chemical aspects of recovery at abandoned fish farm sites. It was further recommended that in order to better understand recovery at fish farm sites in British Columbia for the purposes of developing adequate falling times and conditions, it also would be useful to define the spatial extents of the impacts and the rate of recovery at various sites. Contour mapping and GIS analysis were recommended as effective methods for completing this task, although fundamental changes to the current sampling design would be required in order to do so.

A more appropriate sampling design for assessing the spatial extents and rates of physico-chemical aspects of sediment recovery at abandoned fish farm sites was recommended. Six examples of sampling designs were proposed for trips ranging from 6-10 days in length. Each trip would involve taking replicate samples at points within a systematic grid pattern. The grid of stations would ideally be sampled at least once per season, for a duration of two or more years. The gridded points would be used to generate contour maps for each sampling time based on each sampled environmental variable. The complete set of contour maps would effectively provide a
visual and quantitative time series of spatial variation within the sediments at an abandoned farm site. The area(s) of sediments within a site which exceeded some predetermined threshold or set of thresholds could be calculated for each sampling time, and compared to one another in order to determine a spatio-temporal recovery rate.

The key factor influencing the effectiveness of the approach recommended for mapping spatio-temporal recovery is the determination of accurate thresholds. No one set of local guidelines exists defining specific biological tolerances to changes in sediment geochemistry resulting from fish farming waste input accumulations. The results at both abandoned farm sites for sediment redox potential, sulphides, and oxygen provided some contradictions to existing thresholds established for the interim in British Columbia (Erickson et al., 2001) and on the coast of Atlantic Canada (Wildish et al., 1999). Until a local set of thresholds can be established, it will be difficult to accurately gauge impact and spatio-temporal recovery at fish farm sites in British Columbia. It was therefore recommended that the efforts of future environmental aquaculture investigations be focused primarily on this area of research.

It was recommended that future efforts be made to assess sediment oxygen, redox potential, and sulphides at impacted and recovering sites in order to determine their effectiveness as recovery indicators. It was furthermore recommended that, if possible, cores deeper than 30cm be obtained during future recovery assessments in order to attempt to detect a pre-farm sediment chemistry signature.

It was also recommended that the mechanisms of recovery for potentially toxic metals be given greater consideration. The remediation of heavy metals within sediments relies on burial, formation of solid-phase complexes, and outward diffusion. Therefore, metals deposited within the benthic environment do not actually disappear, they can only be diluted, rendered non-toxic, or mobilized into the water column. Special attention should be devoted to the development of safe chemical alternatives to be used at fish farm sites.
References


Fisheries Act. 1985. r.s.c, c. F-14, s. 35(1).


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