Environmental Monitoring of Finfish Aquaculture Sites in Bay d'Espoir Newfoundland During the Winter of 1997

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ENVIRONMENTAL MONITORING OF FINFISH AQUACULTURE SITES IN BAY D'ESPOIR NEWFOUNDLAND DURING THE WINTER OF 1997

by

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Atlantic salmon and steelhead trout have been produced commercially in Bay d'Espoir Newfoundland for the past decade. However, while there has been some opportunistic sampling, little systematic monitoring of the environment has occurred during this time. Production is expected to increase approximately 350% by the year 2000 with a concomitant increase in loading of nutrients and organic matter to the Bay. At present it is unknown if the aquatic environment can assimilate this increased load without significant negative impacts. In particular, the bay has few suitable over-winter sites. The assimilative capacity of these sites may be the overall limiting factor for salmonid production in Bay d'Espoir.

Biological, oceanographic and aquaculture production data are needed to assess the assimilative capacity of an area. This report focuses on the wintertime levels of dissolved oxygen, biochemical oxygen demand, ortho-phosphate, nitrate-nitrogen, nitrite-nitrogen, and chlorophyll-a in the immediate vicinity of, and > 50m from net pen sites. In general, aquaculture imposed little to no effect on the quality of water in samples obtained during the winter of 1997. Levels of all parameters examined were within suitable bounds for the safe culture of salmonids. The minor increases in nutrients observed in some areas, such as the middle basin of Roti Bay, the most important overwinter site, could be explained by the geomorphology and hydrology of the area as opposed to the siting of aquaculture farms.

We calculated a preliminary assimilative capacity based on the allowable change in nutrients (ΔC), the rate of nutrient release by fish (R), the flushing time, and volume of the area. ΔC and R have been approximated for summer, but in winter they are likely to be different. It was assumed that ΔC could be greater when a fallow period is utilized. In winter, R should be lower than in summer since the fish are ingesting less food. Using these two assumptions, plus an estimated flushing time, the five-year industry expansion goal should be attainable. However, there is uncertainty about this estimate. The environment may not be able to assimilate the additional loading, because of some natural or aquaculture-related phenomenon (e.g. cages blocking water flow). In addition, it is possible that a different factor, such as benthic accumulation or increased pathogen transfer will set the upper limit to the amount of fish that can be over-wintered in Bay d'Espoir. We stress that the assimilative capacity value calculated here is just an approximation, and needs to be followed up with further monitoring and testing.

RESUME

Tlusty, Michael F., V. A. Pepper, and M. Robin Anderson. 1999. Environmental monitoring of finfish aquaculture sites in Bay d'Espoir Newfoundland during the winter of 1997. Can. Tech. Rep. Fish. Aquat. Sci. No. 2273: vi + 34 p.

Le saumon atlantique et le saumon arc-en ciel sont produit depuis dix ans à l'échelle commerciale dans la baie d'Espoir, Terre Neuve. Malheureusement, il y a eu peu d'échantillonage environmental systématique durant cette periode. L'industrie prévoit une augmentation de production de salmonidées de 350% d'ici l'an 2000 avec l'augmentation concomitante d'éléments nutritifs et de matière organique apportés à la baie. La capacité de l'environment aquatique à assimiler cet augmentation d'apport est présentement inconnue. En particulier, il y a peu de sites d'hivernage acceptables et la capacité d'assimilation de ces sites pourait être le facteur limitant la productivité totale de la baie.

L'évaluation de la capacité assimilative de cette région nécéssite l'évaluation des données biologiques, océanographiques et de la production aquicole. Les niveaux d'oxygène dissout, la demande biochimique d'oxygène, les phosphates, les nitrates, les nitrites et le chlorophyl *a* durant l'hiver sont reportès pour des sites près des cages à saumon, et a 50m de ces cages. En générale, l'aquiculture a eu peu ou pas d'influence sur la qualité de l'eau durant l'hiver, 1997. Tous les paramètres mesurés étaient celon les normes de limites acceptables pour la culture de salmonidées. Les augmentations mineurs d'éléments nutritives observées à certaines endroits tel le basin central de la baie Roti, (le site hivernal le plus important,) peuvent être expliquées par la géomorphologie et l'hydrologie du site.

Nous avons calculé la capacité assimilative préliminaire, basée sur un changement acceptable d'éléments nutritives (ΔC), le taux d'apport d'éléments nutritives par les poissons (R), le taux de renouvellement des eaux et le volume du site. Auparavant, ΔC et R furent approximés pour l'été, sans tenir compte des conditions hivernales et en suposant une plus grande capacité avec une periode en jachère. R devrait être plus petit en hiver car les poissons ingèrent moins de nouriture. Avec ces deux postulats, et avec l'estimation du taux de renouvellement des eaux, on postule que l'expansion de l'industrie devrait être achevable. Malheureusement, l'incertitude de cette estimation existe car il serait possible que le milieu ne soit pas capable d'assimiler l'excess d'éléments nutritifs et de matière organique soit pour des raisons naturelles ou reliés à l'aquaculture (par example des cages qui gênent la circulation de l'eau). Aussi, il serait possible qu'un autre facteur dont on n'a pas tenu compte, tel l'accumulation benthique ou la transfère de pathogènes, déterminera la limite superieur de la quantité de poissons pouvant êtres hivernées dans la baie d'Espoir. Par cette étude, nous concluons que les prédictions de capacité assimilative, ci-inclues, sont aproximatives et nécéssitent une étude de vérification plus élaboreé.

INTRODUCTION

Cage aquaculture of salmonids (Atlantic salmon *Salmo salar*, steelhead trout *Oncorhynchus mykiss*, and brook trout *Salvelinus fontinalis*) has occurred on the south coast of Newfoundland in the Bay d'Espoir estuarine fjord for the past decade. This region is the most important area within the province for aquaculture as over 90% of the product value originates from this area. The 1997 production level was approximately 1600 tonnes. The year 2000 production goal is 5000 tonnes.

Although Bay d'Espoir is a large estuarine fjord (250 km^2), further industry development may be limited by sufficient sites to over-winter fish. Being located at approximately 45° 50' N, and with significant fresh-water inflow, the bay freezes over during the winter making under-ice cage culture necessary. This is possible only in areas where stable ice forms (to protect cages from being ruined by ice pan movement, and fish from superchill associated with frazzle ice), and the temperatures remain above the lower lethal limit (-0.7° C, Saunders et al. 1975). In Bay d'Espoir, only four main sites (Table 1) are currently being used that meet these requirements. Since the entire effort of finfish aquaculture in Bay d'Espoir is concentrated in only four sites during the winter, it is critical to assess how the assimilative capacity of these areas compare to the maximum areal holding, and to assure that overstocking does not occur.

One of the simplest methods to determine production potential is to assess the total area available for production. Regions with more area available for aquaculture typically will accommodate greater annual production than regions with a smaller available area. However, setting potential production quotas based on a maximum available area runs the risk of overstocking. Overstocking is when the production potential determined by the maximum area capacity exceeds the biological capacity of that area. This can occur when the location has a low flushing rate, a high naturally occurring rate of organic deposition, other sources of nutrient input, or some other variable which indicates the area is highly sensitive to the increased nutrient loading associated with aquaculture. When overstocking occurs, nutrient buildup can lead to unacceptable environmental degradation (Wallin 1991) such as increased eutrophication, significant oxygen depletion, or lethal chemical buildup (Gowen and Bradbury 1987, Pillay 1992, Rosenthal et al. 1995, BC-EAO 1997, Ervik et al. 1997) which contribute to fish mortality. Over time, overstocking can lead to permanent environmental damage.

The challenge of interpreting if the physical capacity of an area exceeds the biological functioning of an area is to determine assimilative, holding, or carrying capacity of an area (Silvert 1992, 1994, Ward 1997). While there is nothing inherently superior about the term assimilative capacity, we utilize it in this report since it implies the environment's ability to adequately process or assimilate an increased nutrient load (Ward 1997). Holding capacity (Silvert 1992, 1994) can imply a limit set by the maximum areal capacity, while carrying capacity implies a biological process ("K") regarding the amount of food naturally available. Given that salmonids in net pen aquaculture are supplied with food, there may be some other feature of the environment than limits the total production level. Thus we feel that assimilative capacity is the most appropriate term in this context.

In any industry, it is critical to maintain the integrity of the environment surrounding production sites. This is especially true for aquaculture since salmonids are notoriously sensitive to decreased water quality (Smart 1981). Preventing environmental degradation of the region is one of the key factors to ensure long term success of the aquaculture industry (Tlusty et al. in press). For these reasons, the Newfoundland Salmonid Growers Association (NSGA), through a partnering arrangement with the Department of Fisheries and Oceans (DFO), and funding from the Aquaculture Component of the Canada – Newfoundland Economic Renewal Agreement (ACERA), initiated a study of the over-winter assimilative capacity of Bay d'Espoir in January, 1997.

Estimates of assimilative capacity rely on a combination of industry, biological and physical oceanographic data. Thus the initial phase of this project was to collect the pertinent background data. Biological data were obtained by considerable on-site monitoring and sample (water column and benthos) analyses. Oceanographic data collection focused on long term current array deployments and drifter-drogue studies while bathymetric mapping was conducted through an arrangement with the Geological Survey of Canada (Atlantic). Historical data were archived and made accessible by the Department of Fisheries and Oceans, St. John's, NF.

Here, we present results of monitoring the biological oceanography of aquaculture and appropriate control sites during a period in 1997 when ice covered the bay. Even though the Bay d'Espoir region is a unique ecosystem within Canada (Steele 1983, R. Hooper Pers. Comm.), these data are important, as ours is the most systematic and intensive examination of the biological oceanography of this area. It is also the first survey of its kind to be done subsequent to development of the Bay d'Espoir aquaculture industry in the mid-1980s. Our focus during this first winter was solely on water quality parameters. Although aquaculture affects both water column and benthic environments (Pillay 1992, Ervik et al 1997), we focused on the former as it is of more immediate concern to fish health than benthic processes. In addition, there was the prior concern that, in the Bay d'Espoir region, dissolved oxygen levels reach critically low levels during ice cover (Richard and Hay 1984). Finally, aquaculture activity has been present in Bay d'Espoir for over a decade. While there was preliminary assessment of the area for finfish aquaculture development (Sutterlin 1980) there has been no subsequent systematic environmental monitoring program, and no follow-up on the state of the environment concurrent with aquaculture loading.

The purpose of this report is to characterize the present water quality conditions within this estuarine fjord. We plan to use this research as a platform, from which additional biological data can be coupled to appropriate physical oceanographic and bathymetric data and information on production effort can be used to assess the assimilative capacity of over-wintering sites for salmonid aquaculture in Bay d'Espoir. At the end of this report, we undertake a preliminary assessment of assimilative capacity for Roti Bay, and Voyce Cove, two of the more important over-wintering areas.

METHODS

SAMPLE STATIONS AND LOCATIONS

Bay d'Espoir is a complex estuarine fjord located on the south coast of the island of Newfoundland. It is a northerly branch of Hermitage Bay, and extends inland approximately 70 km. It is a deep (>300m) estuarine fjord of 250 km^2 divided into 11 basins by 12 sills. It is subject to the largest freshwater inflow of any small Newfoundland Bay (2.0×10^6 m^3 d^{-1}, MSRL report 1980). This fresh water flows seaward in the top few meters of the water column. Finfish are over-wintered in three main stations, Voyce Cove (and the nearby Jersey Cove, 300,000 m^2), Roti Bay (2,660,000 m^2), and Northwest Cove (500,000 m^2; Figure 1). Voyce Cove and Roti Bay are heavily used winter sites. Voyce Cove has been used continuously in winter for the past fifteen years, while Roti Bay has been used for the previous decade. Jersey Cove and Northwest Cove are lesser-used sites. Jersey Cove was used one previous winter while Northwest Cove was used continuously for the past two years. Voyce and Jersey Coves are both semi-circular, with Voyce being larger. Roti Bay and Northwest Cove are both rectangular (approximately a 4:1 length: width ratio); Roti being larger with a smaller opening to the main channel of the Bay. Given the history of these stations, it is most likely that any measurable effects of aquaculture operations should be observed in Roti Bay and Voyce Cove, with little to no effect in Jersey Cove and Northwest Cove.

At each of these four stations, we sampled water quality at locations both 1m ("near") and >50m from cages ("off", Table 1). We also sampled water in areas where fish are not over-wintered, in the main channel of the Bay (the transect from St. Alban's to Roti Point, Figure 1). Our final station was near the fish processing plant in Ship Cove. At the time of sampling, untreated effluent from the processing plant was being dumped directly into the bay. Since then, a bloodwater treatment facility, the first of its kind in Atlantic Canada has been installed. All sampling occurred between 7 January and 14 April, except for the station near the processing plant which was sampled 1 March to 14 April. This period was when ice cover was safe enough to permit travel by snow machine. Each station was sampled a minimum of two and a maximum of seven times.

SAMPLE COLLECTION

Latitude and longitude were recorded for each location at the time of sampling by using a hand held Lowrance GPS. A 20.3 cm diameter hole was drilled through the ice with a gas powered ice auger. A 1.5 l Niskin bottle was then lowered through the hole to a predetermined depth, and a sample was collected. Samples were stored in collapsed 4 l cubitainers. Immediately after collecting a water sample, we lowered a secchi disk through the hole and took a reading while measuring the temperature of the water samples with a VWR Traceable Thermometer. After sampling was completed at five to eight stations, the samples were transported back to the laboratory at ambient air temperature (-25 to 2 °C). Water was sampled from each location at a depth of one, three, and five meters from the surface, plus one meter off the bottom (1m O.B.) to a maximum depth of 45 m. A total of 501 discrete water samples were collected during the period of safe ice in 1997.

In the laboratory, oxygen variables (dissolved, % saturation) and salinity were analyzed immediately while 300 ml was transferred to Wheaton BOD bottles for determination of biochemical oxygen demand. For each 1 meter sample (and select deeper samples), two lots of 300 ml of water were immediately filtered onto 47 mm diameter, 0.75 micron glass fiber filters and frozen for later analysis of chlorophyll a. Concurrently, two lots of 300 ml of water from every sample were filtered onto 25 mm diameter, 0.75 micron glass fiber filters and frozen for later analysis of particulate carbon and nitrogen. The filtrate from these samples was saved, and 100 ml was used for ortho-phosphate analysis, while two lots of 50 ml were used for the analysis of nitrite-nitrogen and nitrate-nitrogen. Initially, samples for ortho-phosphate, nitrite-nitrogen and nitrate-nitrogen were stored frozen, but beginning in March and henceforth, all samples were analyzed on the day of collection.

ANALYTICAL METHODS

Oxygen variables were measured with a YSI-58 meter equipped with a YSI-5905 BOD probe. The dissolved oxygen probe was calibrated daily against three titrations using the azide modification of the Winkler Method (Eaton et al. 1995). A salinity correction was made where salinity was measured with a Vista Refractometer. A 300ml sample was poured into a BOD bottle, measured for dissolved oxygen and % saturation, then placed in a low temperature incubator within 3°C of the field temperature. Another measure of dissolved oxygen was made 5 days later, and the biochemical oxygen demand calculated as the difference corrected for the sample size and number of days. Ortho-phosphate, nitrite-nitrogen, and nitrate-nitrogen were measured colorimetrically. End product color determination was measured with a Spectronic Genesys 5 spectrophotometer. Ortho-phosphate was determined by reacting a sample with a composite reagent (molybdic acid, ascorbic acid, and trivalent antimony), and reducing to a blue colored solution (Murphy and Riley 1962, in Parsons et al 1984); nitrite-nitrogen by forming a colored azo dye by diazotization of sulfanilamide followed by coupling with N-(1-naphthyl)-ethylenediamine dihydrochloride (Bendschneider and Robinson 1952, in Parsons et al 1984); and nitrate-nitrogen by the cadmium reduction method and formation of the colored azo dye as for nitrite nitrogen (Parsons et al. 1984, Eaton et al. 1995). A rough estimation of ammonia level was periodically determined using a Lamotte Aquaculture Test Kit with a resolution of 0.2 ppm.

Chlorophyll-a was determined by soaking the duplicate 47 mm glass fiber filters separately in 10ml acetone for 24 H. The samples were then centrifuged in a Triac Centrifuge (model # 0200) at 3500 rpm for 10 min. Eight ml of each sample was transferred to a 12.5mm x 100 mm cuvette, and absorbance was measured with a Turner Fluorometer (model 10-005 R). Sample absorbance was calculated as the average of the difference of the samples before and after being acidified with 0.25 ml 5% HCl. Total chlorophyll-a was then calculated by comparing the sample average absorbancy to that of a calibration curve created by serially diluting a 1mg sample of pure chlorophyll-a.

RESULTS AND DISCUSSION

WATER COLUMN

The hydrography of Bay d'Espoir was typical of an estuarine fjord in that there was a freshwater lens on the surface (Figure 2). This lens varied from being virtually absent to a maximum of five meters deep. Multiple random sampling showed that the three and five-meter samples were more comparable in salinity than the one and three meter samples (Figure 3). In addition to the halocline, there was also a thermocline generally within the top 3 meters. In winter, the thermocline and halocline were highly correlated to one another (Figure 2). These features combined with the bathymetric sills create a three layered current system, with the top freshwater layer, a middle tidal layer, and denser basin water that gets trapped below the sill (Richard and Hay 1984). Our sampling reflected an attempt to characterize each of these layers of water.

The oxygen environment of the water column at the winter sites did not appear to be a limiting factor for aquaculture production. In no sample did we observe a critically low level of dissolved oxygen. Averages for each water layer were > 8.0 mg/l, and the 1m sample had significantly greater levels than the basin water (Figure 3). Levels lower than 5 mg/l are lethal to fish (Smart 1981, Pillay 1992). One concern about Bay d'Espoir was that, as observed in lakes and ponds, dissolved oxygen levels might drop significantly with ice cover (Richard and Hay 1984). However, it appeared that the freshwater inputs at the head of the bay and the tidal flushing move enough water to avoid oxygen depletion. The biochemical oxygen demand followed a similar trend to that of dissolved oxygen, although higher BOD values indicate greater stress to the system. Levels greater than 3 mg/l/d indicated a significant oxygen demand (Weston et al. 1996). The greatest demand observed in Bay d'Espoir was in the 1m sample. However, this demand was not significant for fish production as all samples averaged < 1.5 mg/l/d, (Figure 3).

Bay d'Espoir as a whole has not suffered increased nutrification as a result of aquaculture. However, in contrast to the oxygen variables, both ortho-phosphate and nitrate-nitrogen were greatest in the 1m off bottom samples (Figure 4). This was likely a result of nutrient addition via leaching from the benthos as compared to a direct impact from the fish in the cages. Levels of nitrite-nitrogen were greatest in the mid-water samples. Nitrite is the intermediate product in the bacterial-driven oxidation of ammonia to nitrate (Russo and Thurston, 1991). The increased levels in the mid-water samples may potentially reflect a decreased number of bacteria in this layer. Even though we mention elevated levels of each of these nutrients, the levels of ortho-phosphate, nitrite-nitrogen or nitrate-nitrogen were not great enough (Russo and Thurston 1991, Lee et al 1995) to negatively impact the production of salmonids. Ammonia levels 1m off bottom were always in the 0 - 0.2 ppm range, while levels in the surface waters were undetectable. This, combined with the well-oxygenated waters, indicates that ammonia should not be a significant stress to salmonid production. However, we caution against generalization of the ammonia result until we can conduct more extensive sampling.

The high dissolved oxygen levels and low nutrient levels suggested no significant degree of eutrophication in Bay d'Espoir. This result was further corroborated by measurements of chlorophyll a, which averaged < 0.20 μg/l (Figure 5). However, in winter under the cover of ice, light rather than nutrients may limit phytoplankton production. Thus direct causation between low nutrient and chlorophyll a levels cannot be implied. When light is abundant in summer, the amount of nutrients, provided they remain at levels similar to those measured during this sample period, should not permit significant phytoplankton growth. Given that these over-winter areas are fallowed during the summer, the yearly total nutrient loading will be greatly reduced compared to areas used year round. Thus we anticipate that the potential consequences of low levels of nutrients in the winter should not correspond to summer-time eutrophication of the bay.

The chlorophyll a levels were greatest in the 1m samples, not surprising given the vertical stratification (Figure 2) in this estuarine fjord. However, the amount of chlorophyll a in the surface samples was not related to the amount of freshwater since there was no significant relationship between amount of chlorophyll a and salinity ($F_{1,62} = 0.30$, $p < 0.59$). An unusual result was the increased variability in chlorophyll a level in the 1m O.B. samples. This could not be a result of the increased error associated with detecting low amounts of chlorophyll a. The 5m samples had a similar average value, but a much lower error term (Figure 5). A more likely factor may have been the resuspension of benthic debris, which was then trapped in the Niskin bottle. The data set of 1m O.B. chlorophyll a samples was not large enough to determine if areas with different current and flow regimes differed in the variability of chlorophyll a. This suggests differing degrees of benthic resuspension. This work will have to be carried out into the summer months. While no eutrophication was observed during this sampling period, the true test will be to monitor summertime values of chlorophyll a, and determine if the values increase significantly in the fallowed over-winter sites compared to unused portions of the bay.

Station Differences

Although there was no significant nutrification observed in the bay as a whole, each sample station varied in the degree that aquaculture has affected water quality. In general, Roti Bay consistently demonstrated a greater impact than any other location sampled, although the Processing Plant occasionally exceeded the degree of impact demonstrated by Roti Bay (see Figures 6 through 10). A complete analysis of Roti Bay is conducted below. Only those stations that demonstrated an increased impact, exclusive of Roti Bay, are discussed in this section.

As mentioned above, the Processing Plant sample exhibited a relatively high impact. While the dissolved oxygen (Figure 6) did not differ significantly for this station, the biochemical oxygen demand at all depths (Figure 7), the amount of ortho-phosphate in the surface water (Figure 8), and the amount of nitrite-nitrogen in the 5m sample (Figure 9) was greater than for other stations. At the time of sampling, the Processing Plant was dumping untreated effluent directly into the bay. Thus the increased nutrient levels were not surprising. The water by the outflow pipe is relatively shallow (6m low tide), and it is likely that the current created by local boat traffic prevented much accumulation directly underneath the outflow pipe. This is likely to be why the 1m O.B. samples did not exhibit an increased effect similar to that of samples higher up in the water column. Northwest Cove also had relatively low dissolved oxygen levels in the 5m water sample (Figure 6), and relatively high levels of nitrate-nitrogen in the 1 and 3m samples (Figure 10). However, given the lack of fallowing at this site, the water parameters demonstrated little effect. Jersey Cove was another station that had elevated biochemical oxygen demand in the 1m O.B. sample (Figure 7). Although more detailed measurements are needed, Jersey Cove may be in the path of the current exiting Ship Cove (the part of the fjord that includes the town of St. Alban's sewage outfall, plus the Voyce Cove farm site and the Processing Plant), and may be subject to additional loading from these sources.

While Voyce Cove is stocked annually with the greatest density of fish of any of the stations, it has not demonstrated increased levels of nutrification with the exception of nitrite-nitrogen. Nitrite-nitrogen values were typically greater in Voyce Cove than any of the other stations (Figure 9). There are various factors which can interfere with the oxidation of nitrite-nitrogen to nitrate-nitrogen including pH, temperature, dissolved oxygen, number of nitrifying bacteria, and presence of inhibiting compounds (Russo and Thurston 1991). Since the pH, temperature, and dissolved oxygen were similar to other areas, there was either a reduced number of bacteria, or an inhibiting compound. Regardless, this result is one potential indication that the environment at this station was compromised.

There was no obvious trend in chlorophyll a levels at production sites. The lowest levels of chlorophyll a were observed in the main channel of the bay (the transect sites), and in Northwest Cove (Figure 11). Since Northwest Cove had the highest salinities, it may have had correspondingly low levels of chlorophyll a. As for the transect, this area is likely to be subject to a greater flow than any of the bays or coves. Thus phytoplankton may be less likely to accumulate in this area. While research in Norway has found a high correlation between chlorophyll a, as measured with a secchi disc, and nutrient loading (Håkanson and Wallin 1991, Wallin 1991), the present study did not find such a relationship. The vertical stratification of the water column appeared to be complicating this system beyond the point of finding one simple indicator of the impact of aquaculture on the environment of Bay d'Espoir.

Roti Bay

Roti Bay demonstrated a greater overall environmental impact than any other monitored site. Nutrient levels and biochemical oxygen demand values were generally higher while dissolved oxygen values were lower than the other sample stations. It is necessary to distinguish if this increased nutrification is a result of the geomorphology of the Bay, or is a direct result of aquaculture. Again, the nutrient levels discussed in this section do not pose a serious threat to fish production or eutrophication. However, they are elevated with respect to other sites. Given this increased load, Roti Bay may be more subject to deleterious effects associated with additional nutrient loading compared to the other areas we surveyed. Since Roti Bay is one of the largest, and therefore most critical over-wintering sites in Bay d'Espoir, it is imperative that we can fully comprehend why nutrification was greater here than elsewhere.

Roti Bay has a triple basin configuration (Figure 12). The inner basin is too shallow for aquaculture use. However, of the 14 streams inputting fresh water to Roti Bay, five, including the two largest, enter this basin. The middle and outer basins are used for aquaculture purposes. The middle basin is larger than the outer (Table 2), and a 10m deep sill separates the two. This shallow sill makes the topographic openess factor (E, the ratio of the cross-sectional area of the mouth and the three-dimensional bottom area, Persson and Håkanson, 1996) 0.25 %. This value of E is approximately the median of 15 archipelago areas examined in the Baltic Sea (Persson and Håkanson, 1996). A 4m deep sill bounds the middle basin on the side toward the inner basin. There is a fairly large freshwater input into the middle basin as six of the 14 streams surrounding Roti Bay enter here (Figure 12). The outer basin is really a misnomer since there is no defined sill separating the bay from the main channel of Bay d'Espoir. Rather, the bottom gently slopes from 30 to 40m at the mouth, then quickly drops to more than 50m in the narrows, and over 160m in the main channel. Since the outer basin lacks a defined sill, it has a much larger cross-sectional area than that of the middle basin (Table 2). E is greater here than any of the 15 archipelagos examined in the Baltic Sea (Persson and Håkanson, 1996). The difference in cross-sectional area sets up the potential for the outer basin to have a higher rate of water exchange than the middle basin. Water exchange rates also will be greater in the outer basin since the deep, dense water is unlikely to become trapped for lack of a defined sill. In addition, any tidal water entering the middle basin first has to pass through the outer basin. Currently, four farms overwinter fish in Roti Bay. Two are located in the outer basin, and two in the middle basin (Figure 12). Thus water entering the middle basin has the potential to be impacted initially by the aquaculture sites in the outer basin. Given a low flushing rate in the middle basin and the location of aquaculture sites, it can be expected that the quality of water in the middle basin will be lower than that of the outer basin, particularly for the deeper samples.

Our data agree with the above intuitive hypothesis that the exchange of water between the middle and outer basins was influenced by the middle 10m sill. The salinity of the 5m and 1m O.B. samples in the middle basin was significantly less than their complimentary samples in the outer basin (Table 3). The entrainment of fresh water into the tidal layer, the large inputs of fresh water into the inner and middle basins, and an increased flushing time are most likely the cause behind the deep water in the middle basin being of lower salinity. However, this evidence of lowered water exchange did not fully carry over to the five main parameters we measured (dissolved oxygen, 5d BOD, ortho-phosphate, nitrite-nitrogen, and nitrate-nitrogen). Dissolved oxygen was the only parameter that was significantly lower 1m O.B. in the middle compared to the outer basin (Table 3). The other parameters did not exhibit any significant statistical trend at depths below the sill (Table 3).

The effect of the sill apparently carried over to the samples collected above it (the 1, 3 and 5m samples) with the middle basin demonstrating a greater degree of nutrient loading than the outer basin. The 5d BOD (1 and 5m samples), nitrite-nitrogen (3 and 5m samples) and nitrate-nitrogen (1m sample) were all higher in the middle compared to the outer basin (Table 3). As with the 1m O.B. samples, this result was not all encompassing. The level of dissolved oxygen in the middle basin was greater at these three depths, while the level of ortho-phosphate was greater in the outer basin (1 and 3m samples, Table 3). These results may be a function of the stream run-off and subsequent water flow in the upper layers. While variations in dissolved oxygen and ortho-phosphate are likely to be impacted by the freshwater runoff, we did not sample these inputs, and thus provide no further comment.

In Roti Bay, we examined an equal number of sites directly underneath the net pens and off the cage sites (> 50m, Table 1). This comparison yielded fewer significant contrasts than did comparisons between basins (Table 3). The 5d BOD was significantly greater near cages than off the cage sites for the 1m and 1m O.B. samples. This again indicates that aquaculture is influencing the environment, although not to a substantial degree that could harm the fish. The average BOD value from near cages was < 1.5 mg $O_2\ l^{-1}\ d^{-1}$ significantly lower than the critical value. The cage sites in Roti Bay were placed in coves, and thus the local currents were likely to be slow enough to prevent the dilution of bacteria responsible for high BOD values. The only other significant cage proximity treatment effect was in the 1m sample where the level of nitrate-nitrogen was relatively greater off cage sites compared to complimentary samples under the net pens. We are at a loss to explain this observation, and cannot speculate further without intensive bacteriological monitoring.

In general, Roti Bay typically showed a greater degree of nutrient loading than any other area that we examined. Much of this increase appears to be a result of the hydrology and geomorphology of the bay rather than a direct result of aquaculture. More significant treatment effects were associated with the basin from which the sample was collected than with the sample's proximity to a cage site. This will impact future management decisions given the need to overwinter a majority of farms here. The middle and outer basins cannot be treated equally. It is likely the outer basin, even though smaller, can assimilate a greater aquaculture load (per m^3) than can the middle basin.

ASSIMILATIVE CAPACITY BASED ON WATER QUALITY MONTORING

The production level in Roti Bay for the winter of 1997 was 594,583 kg, and for Voyce Cove was 850,243 kg (data for January). The industry's goal for the year 2000 is 5000 tonnes. However, the Roti Bay management plan calls for overwintering approximately 8,000 tonnes of fish, with an equal number of ' 000 t farms in the outer and middle basins (NFL-DFA 1998). What follows is an exercise to examine whether this projected level might be feasible.

Environmental monitoring during the winter of 1997 did not detect any significant nutrification in the Bay d'Espoir estuary. While Roti Bay had slightly elevated nutrient levels compared to other areas, this increase did not correlate to any measure of eutrophication. In addition, we never observed any nutrient level to be near an acute or chronic lethal level. Given this low level of nutrification, we are not completely sure at what point the ecosystem would stop assimilating additional nutrients. Therefore, until this capacity is established, extreme caution needs to be exercised when estimating the number of fish that can be held in any portion of the bay during any given period of time. Given this first caveat, we now elucidate some of the assumptions necessary to calculate an assimilative capacity for overwinter sites in Bay d'Espoir. This document focuses on Roti Bay and Voyce Cove. While Northwest Cove was used as an overwinter site in 1997, it is actually designated a summer site (P. James, DFA, St. Albans, pers. comm.). We are also lacking the essential data for flushing time for this and Jersey Coves, and hence cannot undertake a meaningful estimation of their assimilative capacities.

The assimilative (carrying / holding) capacity of an area (tonnes) can be estimated by:

$$H = \left(\frac{\Delta C}{R}\right) * \left(\frac{V}{T}\right) \qquad \text{(Silvert 1994)}$$

where ΔC is the allowable change in nutrient level, R is the rate of nutrient release by fish, V is the volume of water, and T is the flushing rate. Each of these four parameters is defined below.

ΔC (change in nutrient concentrations):

We use Silvert's (1994) allowable concentration increase of ammonia by a level of 1.0 μmol-N l^{-1}. However, this level is for year-round production at a site. Since Roti Bay is fallowed for six months (NFL-DFA 1998), we may be able to consider greater loading levels. The rationale here is that the ecosystem can assimilate a greater loading of nutrients over a short period if there is no further loading for some substantial amount of time. This makes the yearly output in μmol -N l^{-1} d^{-1} equivalent. Thus we will also consider concentrations of two and four times this level. There is little to no information on how fallow periods influence the assimilative capacity of the environment. A majority of the research on fallowing considers complete, longer-term removal of the cage units. Our seasonal fallowing is somewhat at odds with this connotation of longer-term fallowing (Gowen et al. 1991, Johannessen et al. 1994, Hargrave et al. 1997, Stewart 1998), although it has proven effective in parasite management (Grant and Treasurer 1993). Thus a two-fold increase at a six-month fallowed site is likely to be acceptable since the μmol -N l^{-1} d^{-1} of the fallowed and unfallowed sites would be the same. A four-fold increase may be acceptable assuming the benefits of fallowing allow an area a greater nutrient loading (a greater average μmol -N l^{-1} d^{-1}) and provided the nutrient level returns to the baseline value during the fallow period.

R (rate of release by fish):

The second parameter is the rate of release by fish. While fish digestion and elimination has been examined in detail in the literature, experiments usually do not consider temperatures lower than 5°C (Windell et al. 1978, Hudon and de la Noüe 1985, Mäkinen 1994). Since digestion in fish is solely enzymatic, there is the possibility that little to no digestion occurs at the winter time water temperatures found in Bay d'Espoir (0 to 2°C, Brett 1979) although this decreased efficiency has been questioned (Goddard et al 1989). Initial findings from the NSGA laboratory that analyzed the organic matter (% loss on ignition at 500°C) of fish in cold water support the assumption of low digestibility at winter temperatures (Tlusty et al, in press). The significance of this result is that the less a given amount of feed is digested, the fewer excretory products the fish will excrete into the water. Conversely, more organic matter (per kg waste) will reach the benthos. Fish excrete ammonia at a rate of 0.025 mol-N d^{-1} kg^{-1} (Silvert 1994), but this again is a summer time value. During winter fish are fed from 1/10 to 1/20 the summer amount, so in our calculations, we will look at the summertime value, plus values of 1/10 and 1/20. If the digestive efficiency of fish decreases at low temperatures, then they would excrete proportionately less, and ammonia excretion would be decreased further.

V (Volume):

The Canadian Hydrographic Service measured the volume of Roti Bay to be 51,636,794m^3. It is important to remember that there is a 10m sill in the middle dividing Roti in two useable basins. The middle basin is 28,461,269m^3, while the outer is 23,175,525m^3. Our initial data support the supposition that the middle basin exhibits a greater nutrient load because of its geomorphometry. However, as we have only a single value for the flushing time of Roti Bay (see below), we can only calculate an assimilative capacity for all of Roti Bay, not the separate basins. The volume of Voyce Cove is estimated at 2,500,000 m^3. The only aquaculture operation in this area occupies virtually the entire cove. Given the excess water around the edge of the lease, we estimated a total area of 500 x 500m at an average depth of 10m.

T (Flushing Time):

The DFO estimate of the flushing time of Roti Bay is 20 days, while Voyce Cove is 5 days (J. Helbig, DFO, St. John's, pers. comm.). Again, this number is subject to change with increased precision of measurement and estimation, particularly if Roti Bay is divided into its two useable basins.

We have one value for volume, one for flushing time, and a series for change in nutrient loading and the rate of release by fish. Entering these numbers and series into Silvert's (1994) equation, we get a range of assimilative capacities for Roti Bay. The low end is 103.27 tonnes (summertime values of $\Delta C = 1.0$ μmol -N l^{-1} and $R = 0.025$ mol-N d^{-1} kg^{-1}), and the high is 8261.89 tonnes ($\Delta C = 4.0$ μmol -N l^{-1} and $R = 0.00125$ mol-N d^{-1} kg^{-1}, Figure 13). The goal of 9,000 tonnes in Roti Bay is attainable if ΔC and R can be increased or decreased respectively from their summertime values. The difficulty with this goal is that it relies on utilizing each basin of Roti Bay equally, which may not be biologically possible. It also assumes that ΔC can be four times greater than the summer value. If only a two-fold increase is allowed, then the assimilative capacity would be 4130.94 tonnes. Using a realistic assumption of only a two-fold increase in nutrient concentration, the year 2000 goal of 5000 tonnes is feasible. The goal of establishing eight, 1,000 tonne farms may not be feasible on the basis of our present data and uncertainty regarding application of the Silvert model. Development beyond the 5,000 tonne limit should be delayed until each of the parameters of the model are thoroughly assessed, in particular those parameter estimates subject to statistical error. Voyce Cove, being smaller, has a range of assimilative capacities from 20 to 1600 tonnes (Figure 14).

SUGGESTIONS FOR FURTHER MONITORING

It is unlikely that winter (under ice) net pen culture of finfish will be constrained by impacts to the water column. We assume also that low nutrient levels in areas used solely in winter will remain low in the summer, and not experience significant eutrophication as water temperatures rise. Previous research has observed large effects on the water column in conditions of low volume, low flushing rate, or in eutrophic areas (Ervik et al 1997). While key over-winter areas in Bay d'Espoir have low flushing rates, no significant water column effects have been observed. This is most likely a result of a small biomass of fish being produced in large volumes of water. Impact to the water column will be further minimized in winter, under-ice aquaculture. The amount of feed utilized is much less in winter than in the summer. Thus based on a mass balance analysis, a proportional reduction in excretory wastes is expected, and fewer waste products enter the water column. Second, digestive efficiency is a direct function of water temperatures. At very low winter temperatures (0 to 3°C) digestive efficiency is likely to be low (Brett 1979). This reduces the proportion of soluble (ammonia, urea, and carbon dioxide) waste, but increases the proportion of solid (feces) waste. Finally, the length of time any winter site in Bay d'Espoir is utilized is limited to a maximum of six months. Fallowing is beneficial because it gives the ecosystem time to recover from a season's loading (Stewart 1998). It is likely that the total instantaneous rate of impact can be greater when fallowing is practiced compared to sites that are occupied year round, assuming no carryover between years. However, we do not yet know the extent to which site loading can be increased safely when fallowing is utilized. Much of the research on fallowing has focused on complete removal of an aquaculture operation from a site after year-round occupancy of the site for several consecutive years (Gowen et al. 1991, Johannessen et al. 1994, Hargrave et al. 1997, Stewart 1998). While fallowing is undoubtedly beneficial, the total benefits have yet to be quantified.

The increased proportion of food ultimately channeled into solid waste during winter may suggest that benthic impacts are likely to be relatively greater in winter compared to summer. Not only will the amount of solid waste be greater per unit food provided, but since digestive efficiency is lower, the amount of organic matter reaching the bottom per unit food provided will also be greater. Since it is the organic matter, particularly carbon, reaching the bottom that determines the nature of the impact (Hargrave 1994, Sowles et al 1994), benthic impacts from a winter site are likely to be different from a comparison summer site. However, this must be considered against the fact that the greater amount of feed provided in summer yields a greater total amount of solids reaching the bottom. The overall benthic effect depends on which factor is more important, the amount of organic mater or the total amount of settleable solids from aquaculture effluent that reach the bottom. Again, this is a topic that needs more investigation.

A second factor that may impact the total number of fish that can be produced in the Bay d'Espoir estuarine fjord is that of fish health (L. Hawkins, DFA, pers. comm.). Cold water vibriosis, furunculosis, and *Diphyllobothrium sp.* are all present in this environment, and impact the production efficiency of the farms. If rates of transfer of any of these conditions are density dependent, then they may dictate either the total biomass of fish per lease site, or the distance between lease sites. We use this as a cautionary note to raise the issue that biological limits on assimilative capacity do not rest solely on the determination of benthic or water quality parameters.

Continued work on the assimilative capacity of the Bay d'Espoir estuarine fjord is necessary. As the estimate of assimilative capacity for Bay d'Espoir becomes refined, it is important of monitor the environment to determine how environmental fluctuations influence the predictions (Ervik et al 1997). It is also essential to determine if the water quality model (Silvert 1994) is sufficient, or if a benthic model (Silvert 1994, Hargrave 1994) is more appropriate. While benthic and water column-based models often agree (Silvert 1994) it appears that this occurs only in well flushed areas (Cranston 1994). In low flushed areas (e.g. Roti Bay and Voyce Cove), the buildup of ammonia in the water column appears to limit production (Cranston 1994). However, this result is based on summertime production only, and does not account for the slowed biological processes and decreased feeding and feed utilization associated with low temperature fish digestion.

Water quality monitoring in Bay d'Espoir should be continued, but should be scaled down in favor of increased benthic monitoring. It is important to continue to trace the precepts set out here (plus additional critical nutrient variables such as ammonia). This will provide excellent information regarding the assimilative capacity of the bay as the industry grows. As the density of cages increases, the circulation of water, particularly in the upper freshwater layer, may be altered. Net-pens reduce water flow approximately 20 diameters in a down-current direction (Weston 1986). If the upper layer were responsible for a large proportion of the transport of nutrients away from sites, then any reduction in flow of this layer would limit the flushing dispersion of nutrients. This view is not solely advocating dilution of pollutants (i.e., "the solution to pollution is dilution"). It advocates biodegradation and maintaining loading at a low level so the ecosystem can adequately assimilate the load (e.g., the natural conversion of ammonium → nitrite → nitrate).

A full analysis of the benthic environment would include information on what loading occurs naturally, how aquaculture impacts ambient loading, and an estimate of how much settleable solids can be assimilated naturally. It is also critical to assess differences between winter and summer sites, and how each recovers during fallow events.

Finally, the prevalence and incidence of fish pathogens needs to be closely monitored. Appropriate husbandry techniques need to be utilized to minimize the transfer of pathogens, and management plans need to account for the probability of transfer based on stocking density and distance between sites. We intend to continue to explore the more traditional estimates of assimilative capacity as discussed above. In addition, alternate views such as pathogens as a limiting agent need to be considered.

Our monitoring to date has failed to identify significant environmental consequences at the present level of aquaculture industry development in Bay d'Espoir during winter. However, we also note that an expected industry expansion of >350% by the early 21st century carries with it the burden of industry responsibility for careful and rigorous monitoring as production is increased. In this context, we recommend a staged profile of production increases wherein the present model predictions may be refined, challenged and verified.

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TABLES

Table 1. The number of near and off cage sites at each of the sample stations. Area is the total available area in the station. Data regarding effort was obtained from month end farm reports for January 1997.

			Number of Locations	
Station	Area (m^2)	Effort (tonnes)	Near Cage	Off cage
Jersey Cove	200,000	15.0	1	2
Northwest Cove	600,000	86.4	2	4
Processing Plant	--	-	-	5
Roti Bay	2,661,977	594.5	4	4
Transect	--	-	-	7
Voyce Cove	250,000	850.2	2	6

Table 2. Physical hydrographic parameters of the outer and middle basins, Roti Bay, NF. Data were collected by the Canadian Hydrographic Service, October 1997.

Parameter	Middle Basin	Outer Basin
Surface area (m^2)	1,624,357	1,037,620
Volume (m^3)	28,461,269	23,175,525
Maximum Depth (m)	34	44
Mean Depth (m)	17.5	22.4
Median Depth (m)	17	23
25^{th} quartile depth (m)	8	14
75^{th} quartile depth (m)	27	31
Cross-sectional opening (m^2)	4045	10,536

Table 3. A non-parametric analysis of nutrients in Roti Bay. Numbers are the averages of ranked values[1] for nutrients measured under (near) and a minimum of 50m (off) from cage sites in the middle and outer basin of Roti Bay at each of four depths.

		Basin				
		Middle		Outer		
Parameter	Depth (m)	Off	Near	Off	Near	
Salinity	One	4.5	6.5	2	3.5	
	Three	3	5	7.5	2.5	c
	Five	2.5	2.5	5.5	7.5	a
	1m O.B.	2	3	6.5	6.5	a
Dissolved Oxygen	One	5.0	7.5	2.0	3.5	a
	Three	7.5	3.5	1.5	5.5	a,c
	Five	7.5	5.0	1.5	4.0	a,c
	1m O.B.	3.5	2.0	5.5	7.0	a
BOD (5d)	One	5.0	7.5	1.5	4.0	a,b
	Three	4.5	3.5	4.5	5.5	
	Five	6.5	6.5	2.0	3.0	a
	1m O.B.	4.0	6.5	1.5	6.0	b
Ortho-phosphate	One	1.0	2.5	6.0	7.0	a
	Three	1.0	3.0	4.0	6.5	a
	Five	1.0	4.0	4.5	5.0	
	1m O.B.	4.0	7.0	2.5	4.5	
Nitrite-nitrogen	One	5.5	6.5	1.5	4.5	
	Three	6.5	6.5	2.5	2.5	a
	Five	7	6	3	2	a
	1m O.B.	6	4	5	2.5	
Nitrate-nitrogen	One	6.5	3.5	5.0	1.5	a,b
	Three	4.0	5.0	7.0	1.5	c
	Five	4	4.5	7	2	
	1m O.B.	6	4	4	1.5	

[1]Data analyses: Two stations were sampled in each of the four treatment (basin / proximity to cages) combinations. For each depth, the values for each site were ranked each day (Low = 1, high = 8) and the ranks of replicate days were averaged (oxygen and salinity variables, 5 replicate days; nitrite-nitrogen, 2 days; nitrate-nitrogen and ortho-phosphate, 1 day). These data were then analyzed with a 2 way ANOVA with a significance level of $p < 0.05$. Superscripts denote a significant basin treatment effect ([a]), cage proximity treatment effects ([b]), or interaction ([c]).

FIGURES

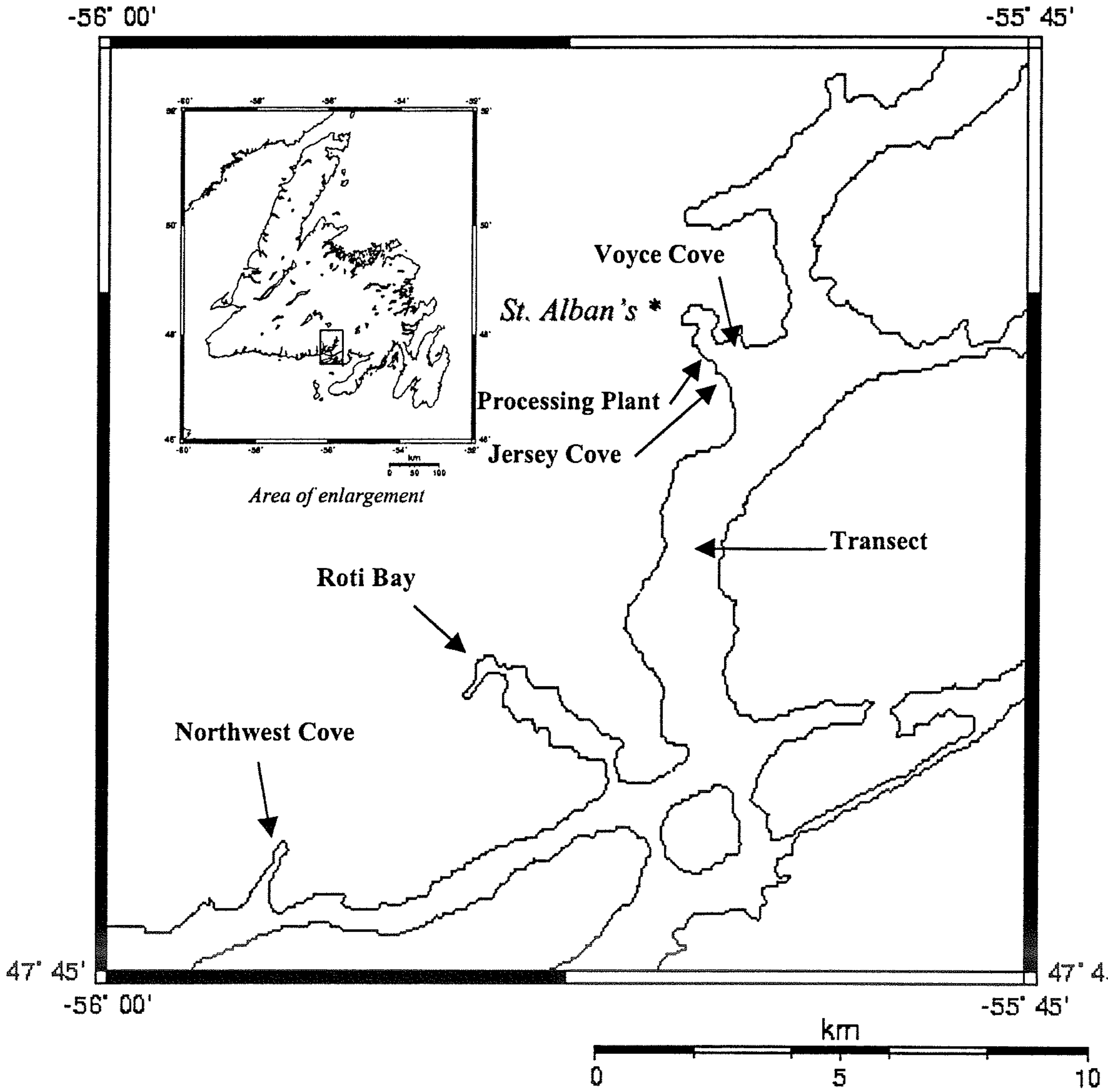

Figure 1. A map of Newfoundland with an enlargement of the Bay d'Espoir estuarine fjord. Station names are identified, as is the location of the town of St. Alban's.

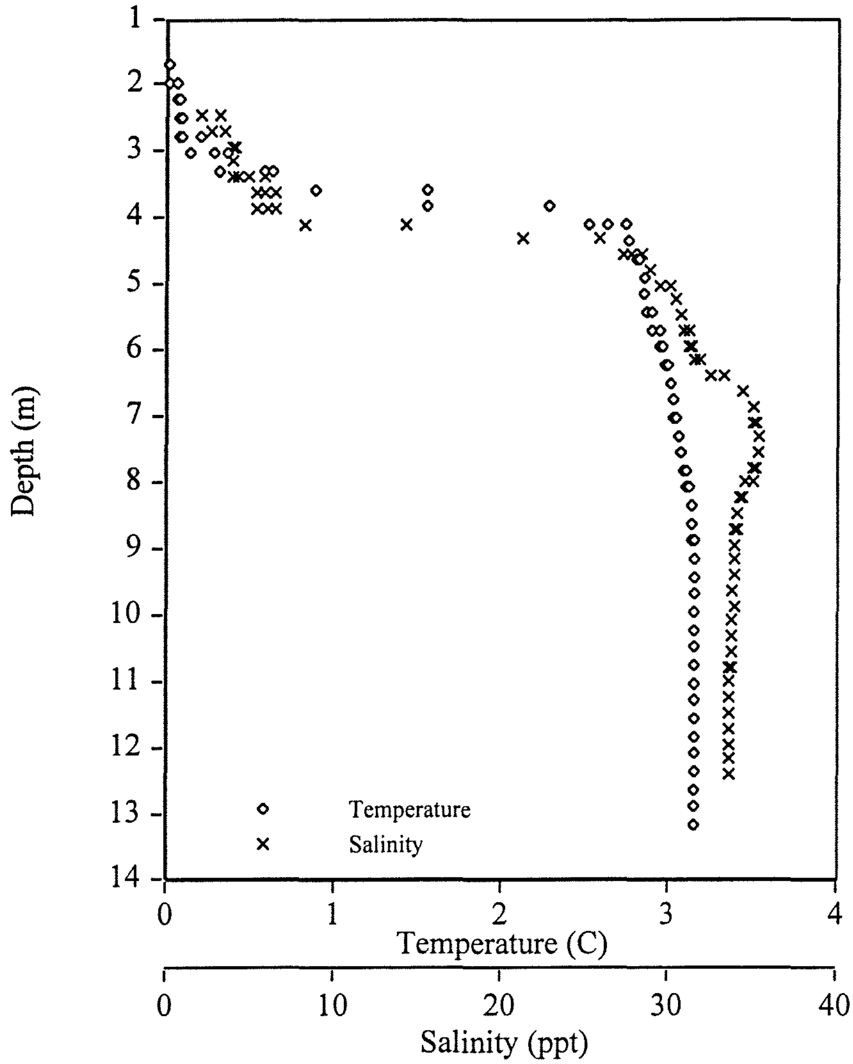

Figure 2. A CTD cast showing the halocline and thermocline in the water column of Bay d'Espoir, NF. Data are from Voyce Cove, 47 52.011N, 55 49.606W, 21 February, 1997.

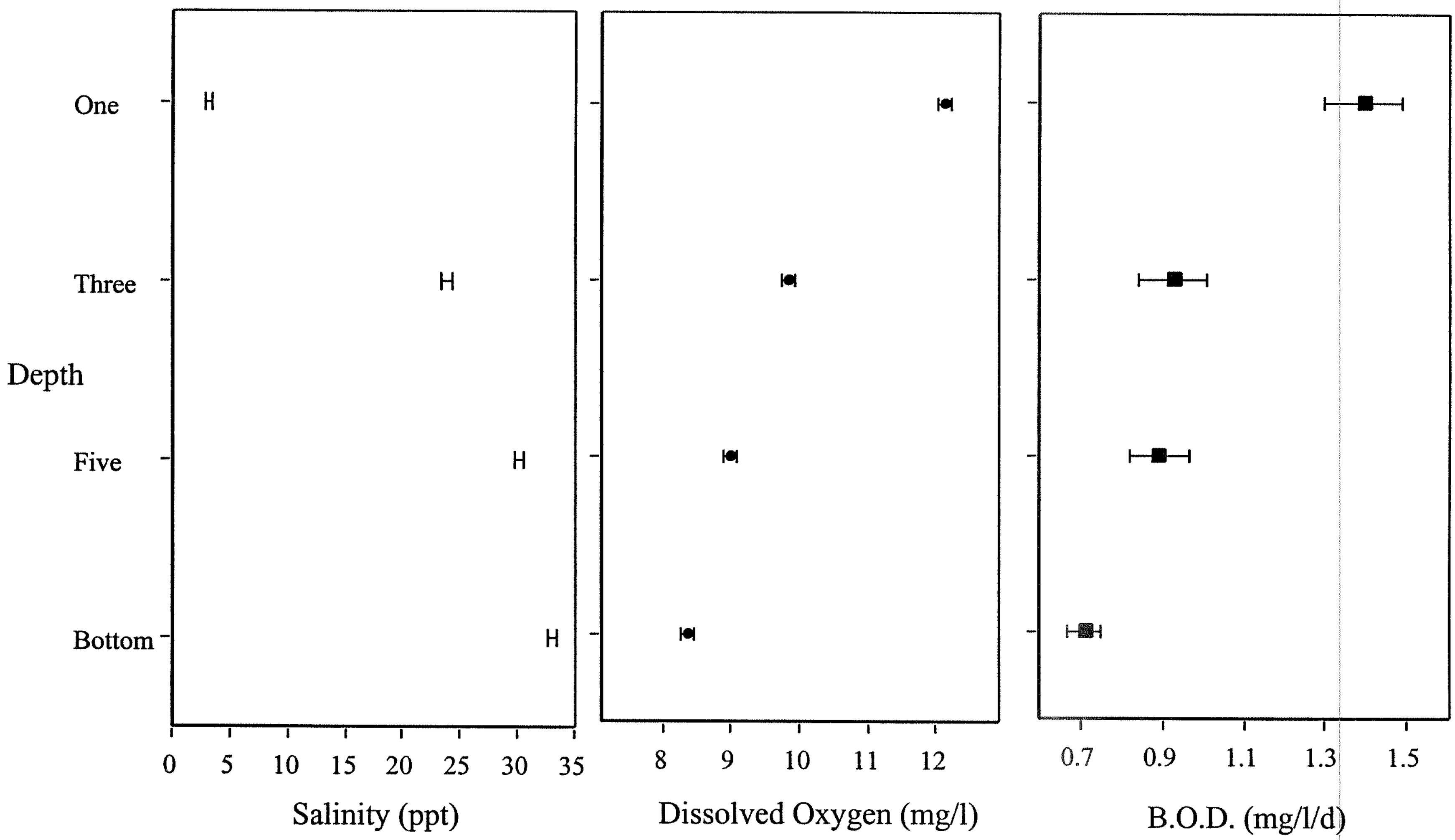

Figure 3. The average (+/- 1 S.E.) level of salinity (ppt), dissolved oxygen (mg/l), and biochemical oxygen demand (mg/l/d) at each of the four sample depths.

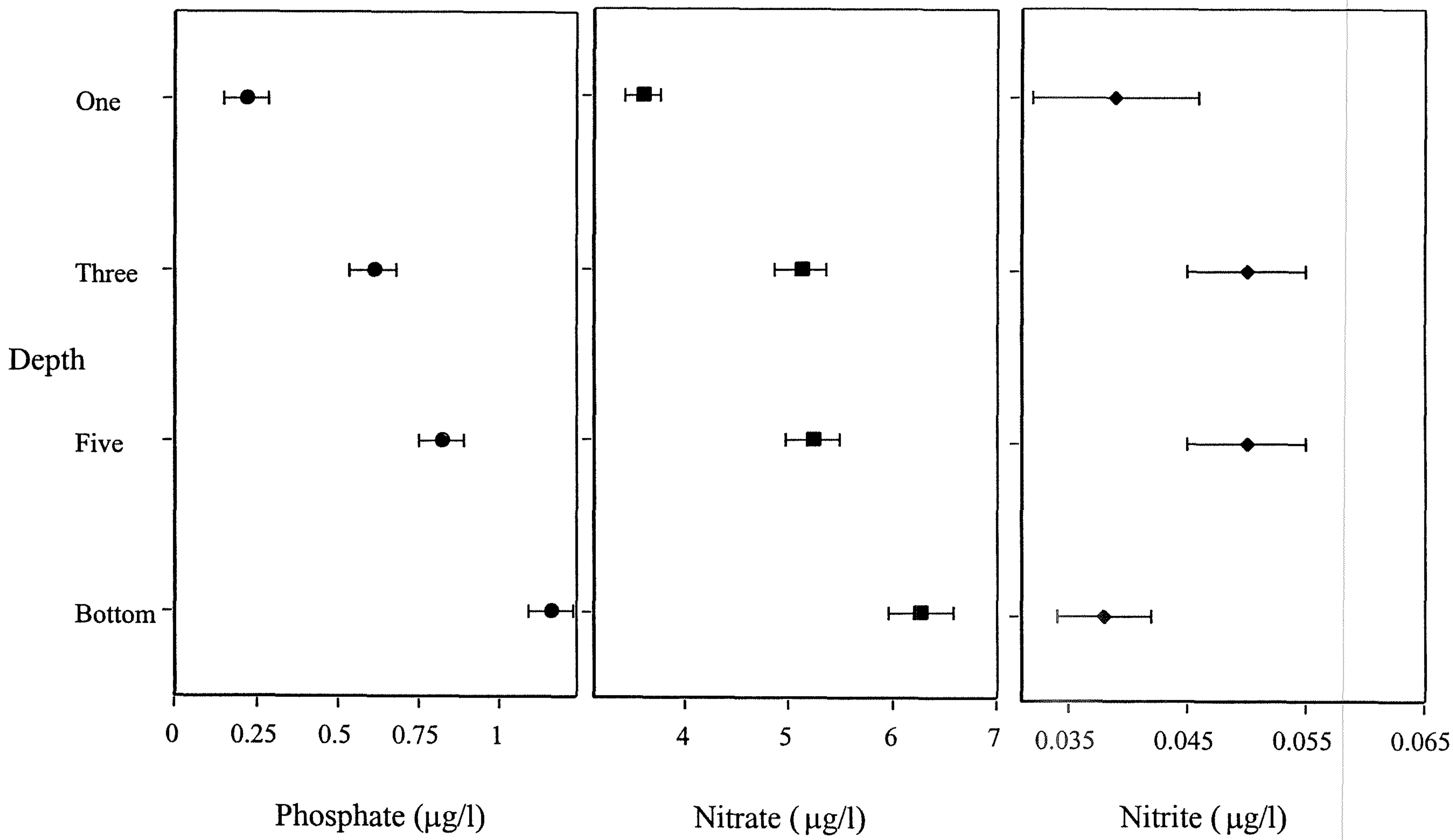

Figure 4. The average (+/- 1 S.E.) level of orthophosphate (µg/l), nitrate-nitrogen (µg/l), and nitrite-nitrogen (µg/l) at each of the four sample depths.

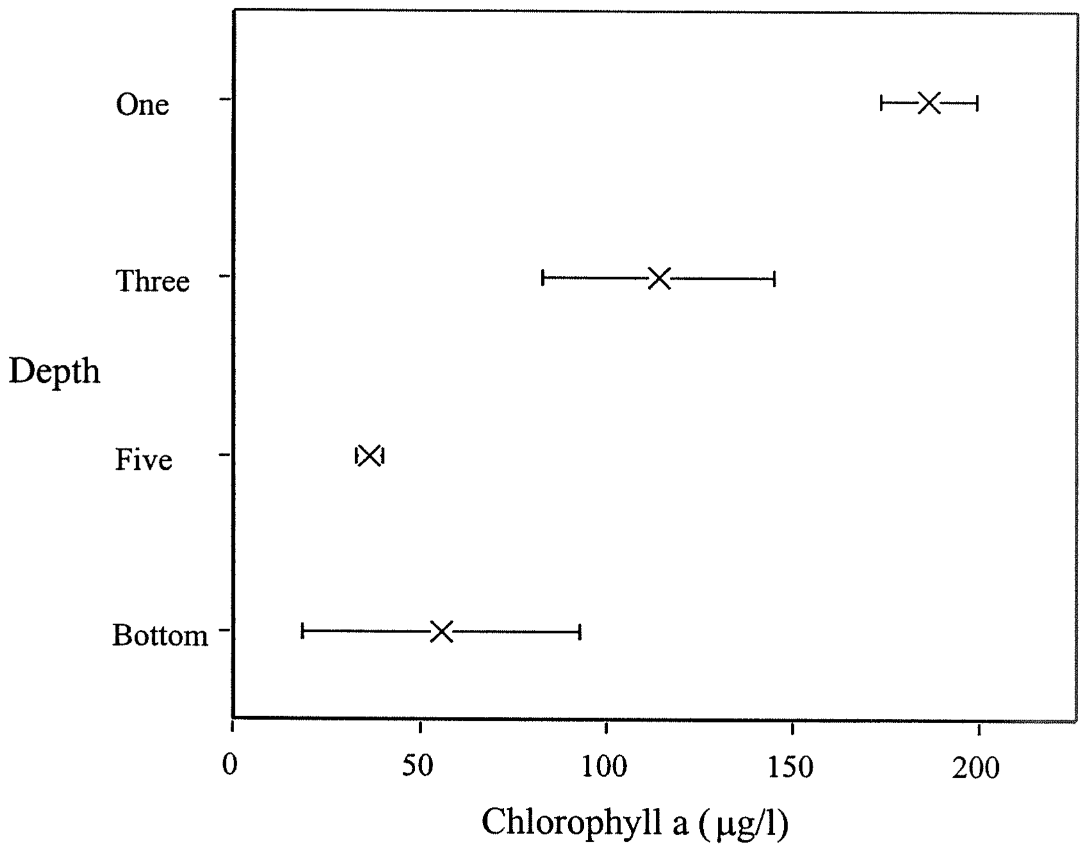

Figure 5. The average (+/- 1 S.E.) amount of chlorophyll-a (µg/l). Data are for 16 samples in which this parameter was determined at each of the four sample depths.

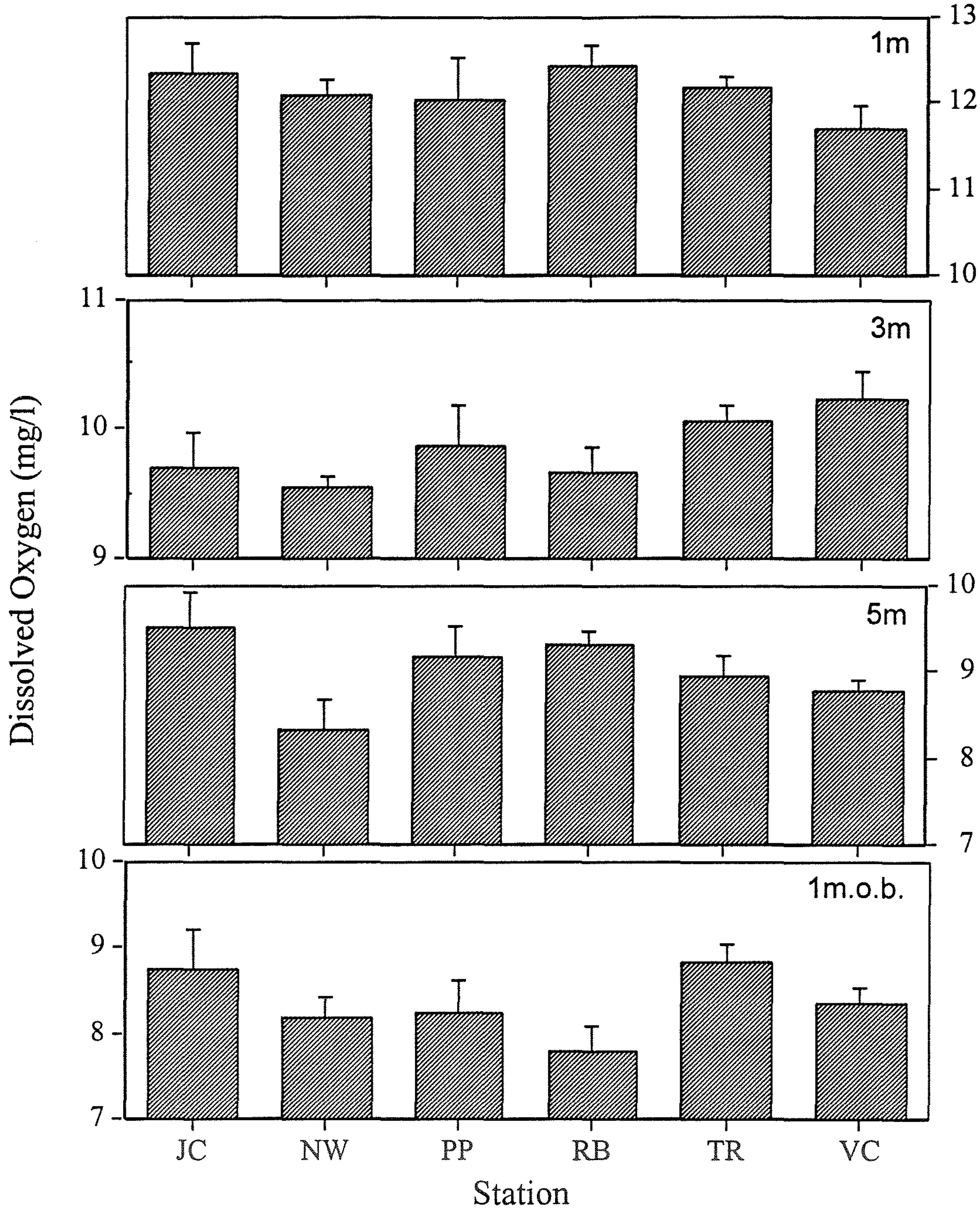

Figure 6. The average (+ 1 S.E.) amount of dissolved oxygen (mg/l) at each of the six sample stations. Samples from increasing depth are listed in order from top to bottom. The stations are Jersey Cove (JC), Northwest Cove (NW), Processing Plant (PP), Roti Bay (RB), Transect (TR), and Voyce Cove (VC).See Figure 1 for station locations.

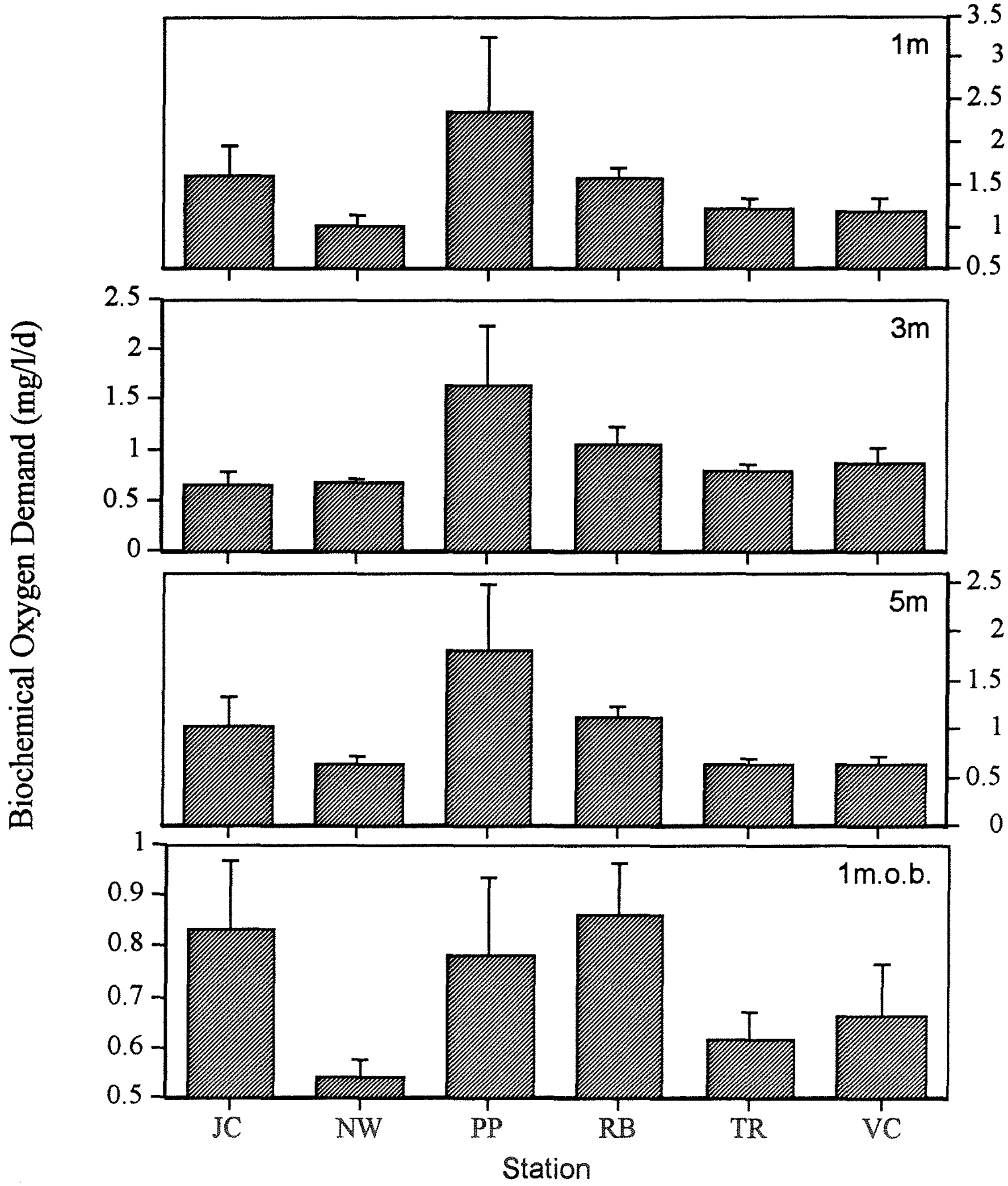

Figure 7. The average (+ 1 S.E.) biochemical oxygen demand (mg/l/d) at each of the six sample stations. Stations are as indicated in Figure 6.

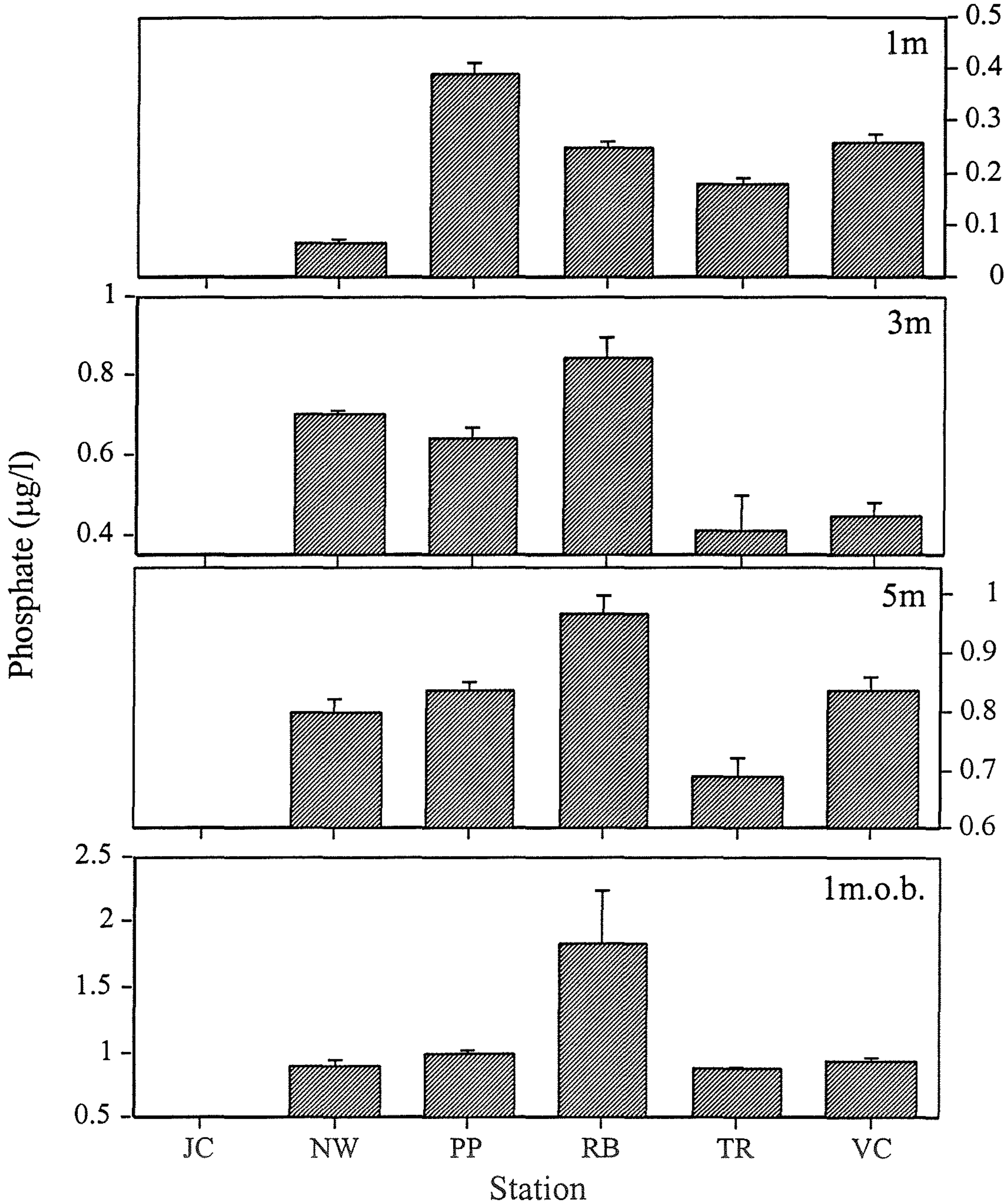

Figure 8. The average (+ 1 S.E.) amount of orthophosphate (μg/l) at each of the six sample stations. Stations are as indicated in Figure 6.

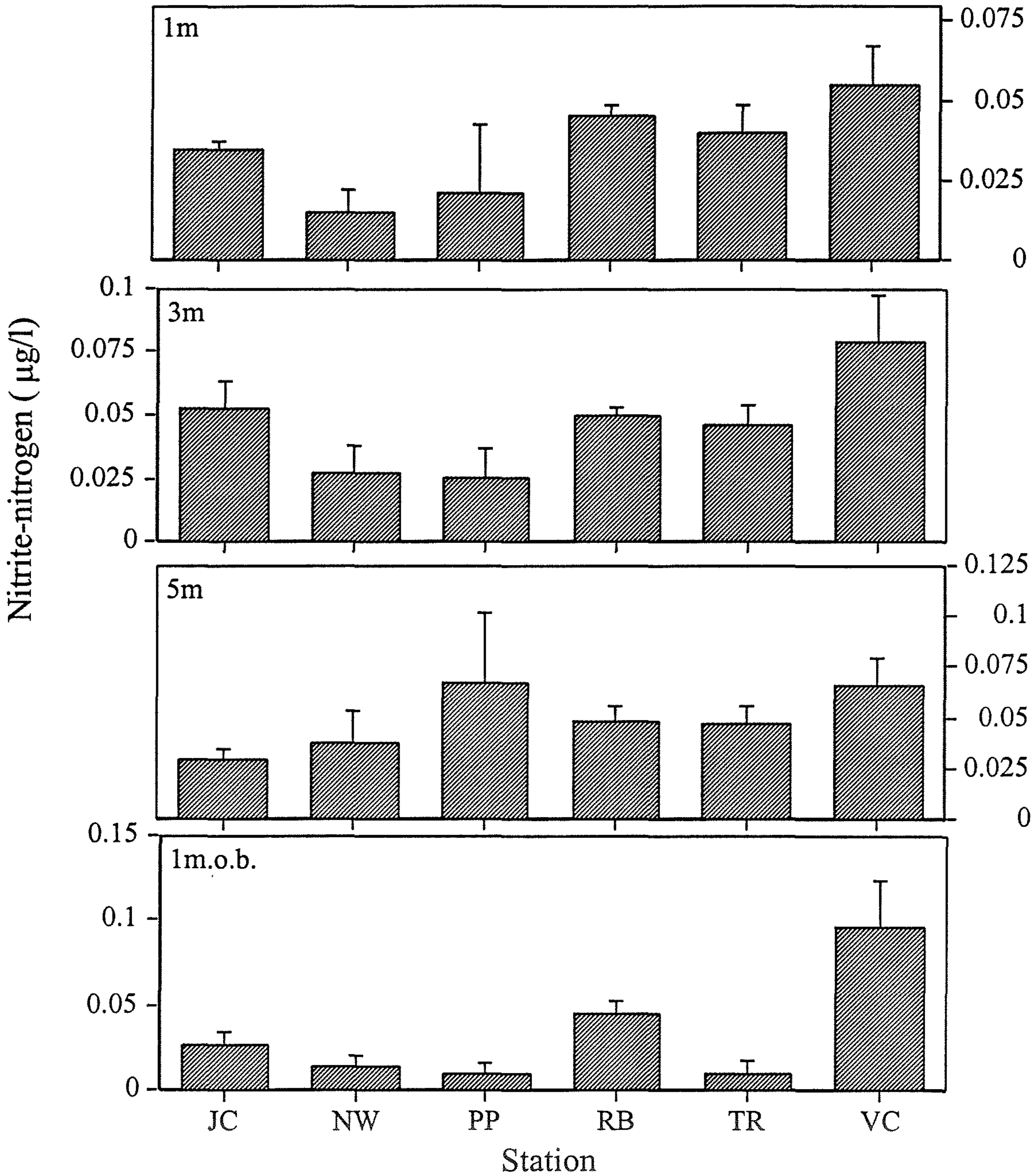

Figure 9. The average (+ 1 S.E.) amount of nitrite-nitrogen (μg-N/l) at each of the six sample stations. Stations are as indicated in Figure 6.

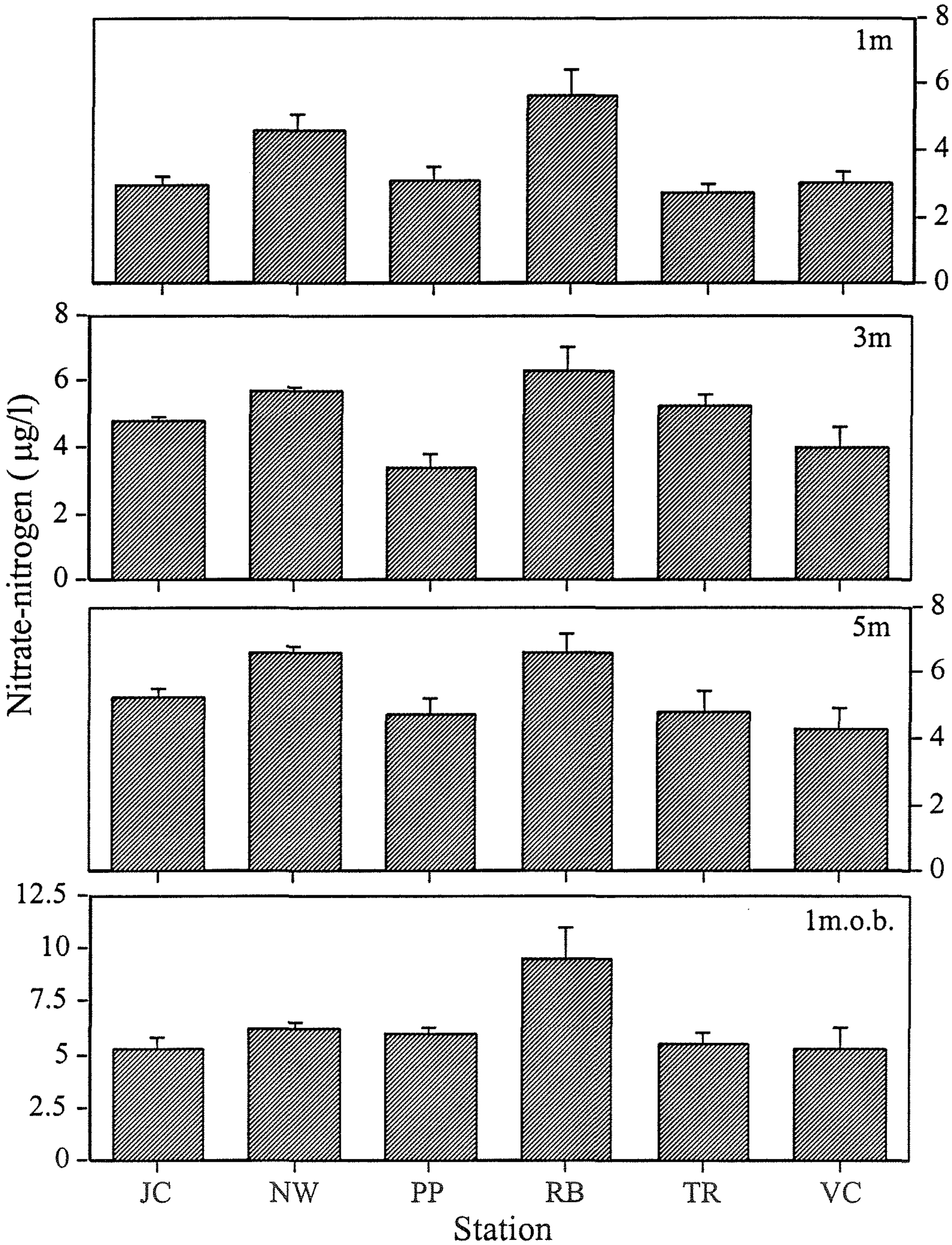

Figure 10. The average (+ 1 S.E.) amount of nitrate nitrogen (µg-N/l) at each of the six sample stations. Stations are as indicated in Figure 6.

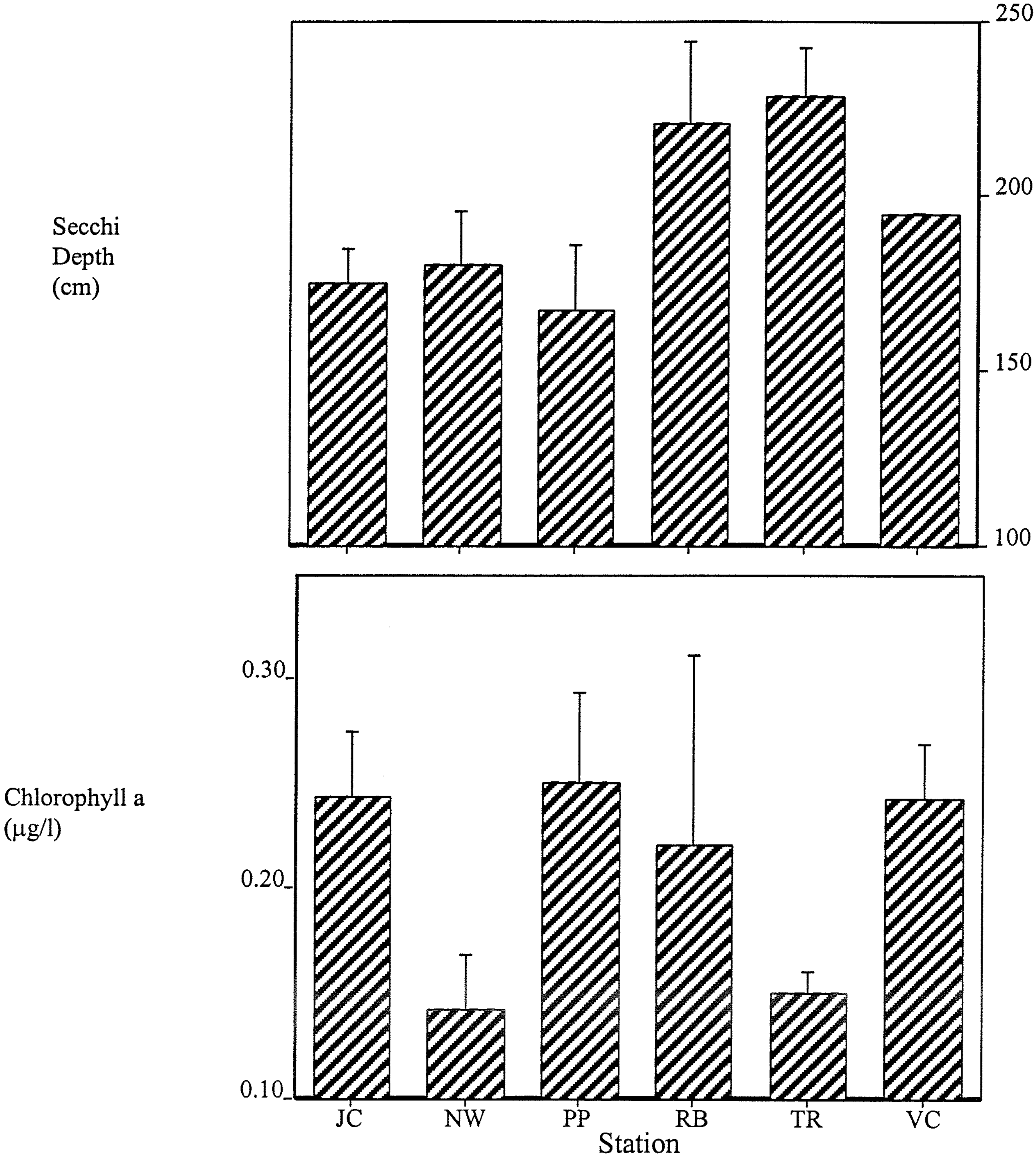

Figure 11. The amount of chlorophyll-a (µg/l) and the secchi depth at each of the six sample stations. Station are indicated in figure 6.

Inner Basin Middle Basin Outer Basin

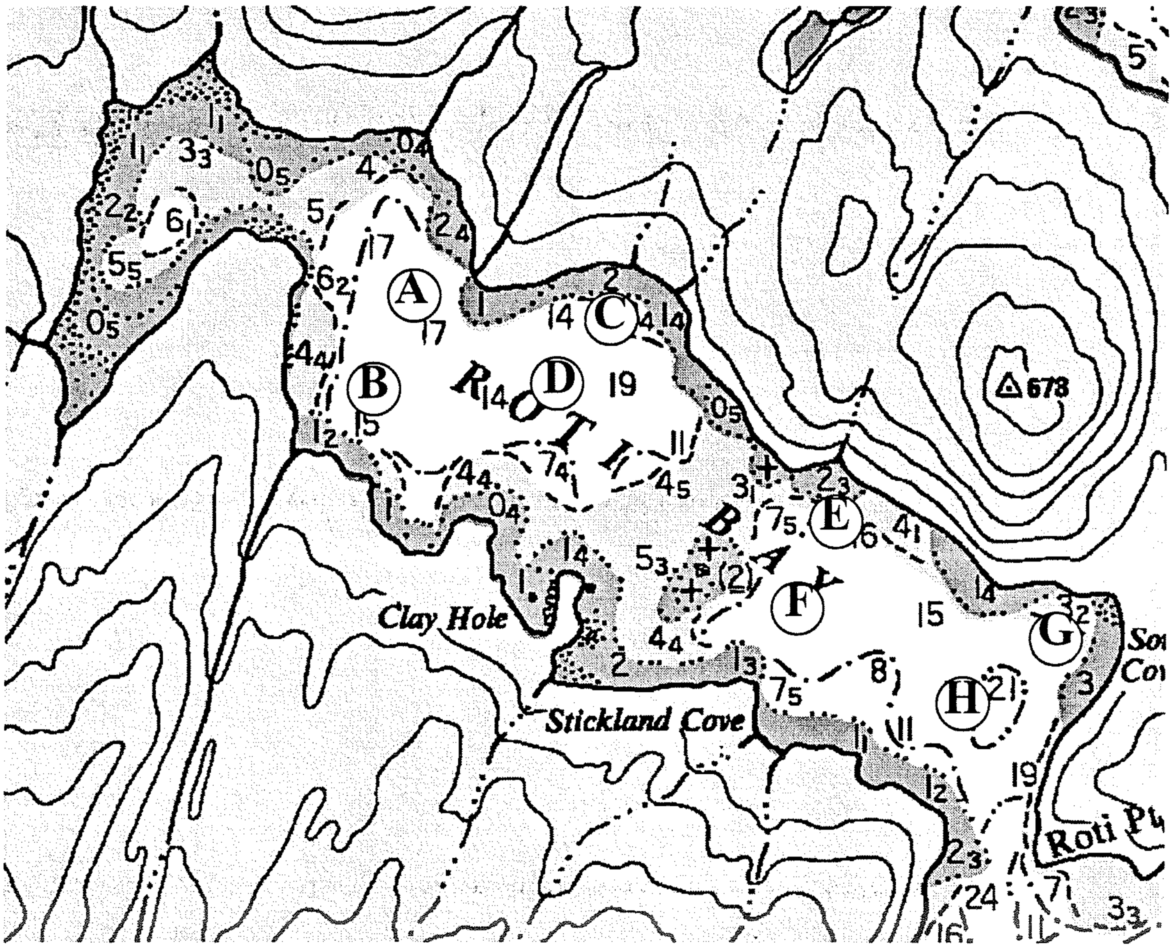

Figure 12. The chart of Roti Bay. The inner, middle and outer basins are identified at the top of the chart. Letters refer to sample locations. B, C, E, and G are farm locations, while A, D, F, and H are "off" farm (> 50 m) locations. Depth is in fathoms. The chart is reprinted with permission of Nautical Data International.

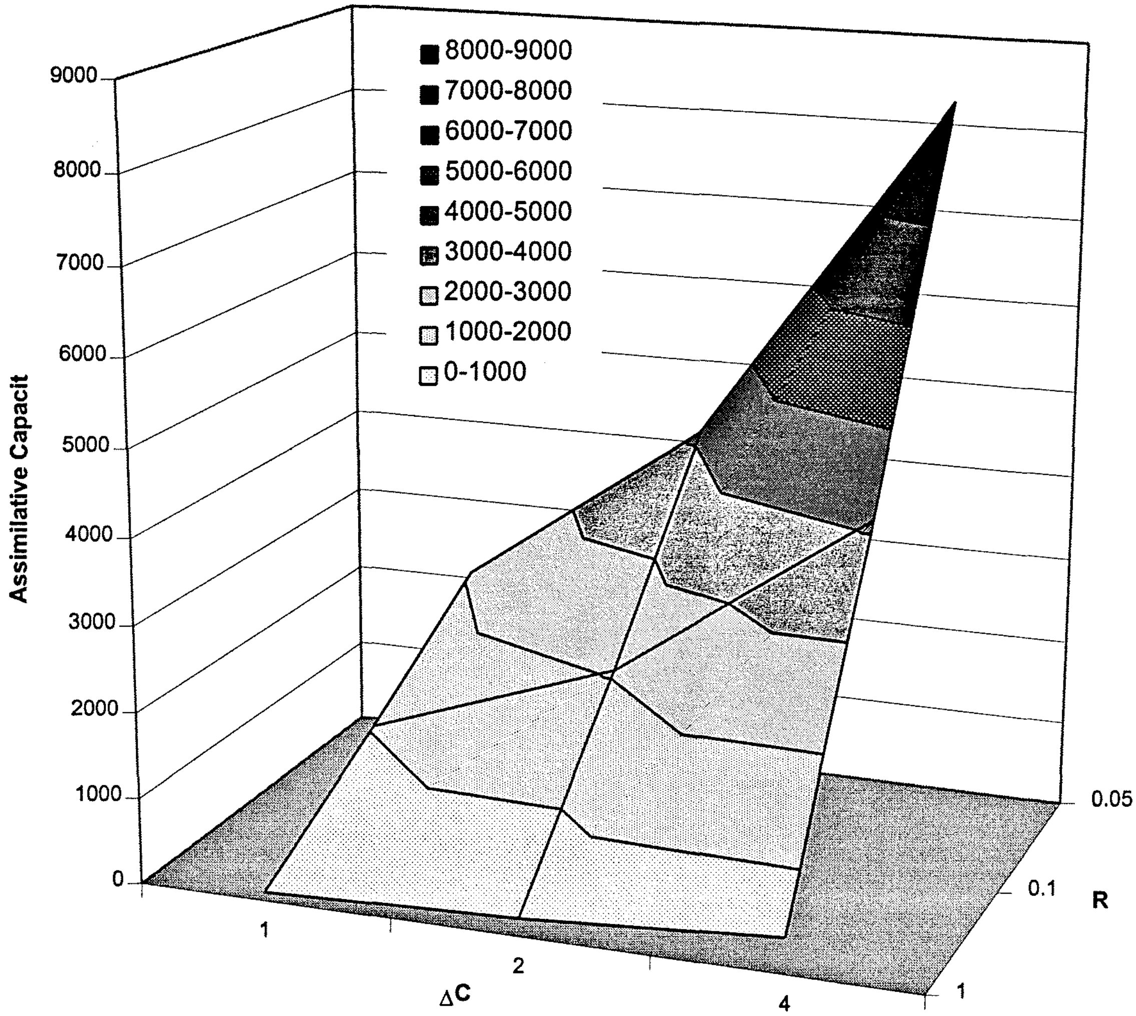

Figure 13. The assimilative capacity of Roti Bay based on a volume of 51,636,794m^3, and a flushing time of 20 days. The rate of nutrient release (R) and allowable concentration increase (ΔC) range from summer to estimated winter values. This analysis assumes Roti Bay functions as a single basin.

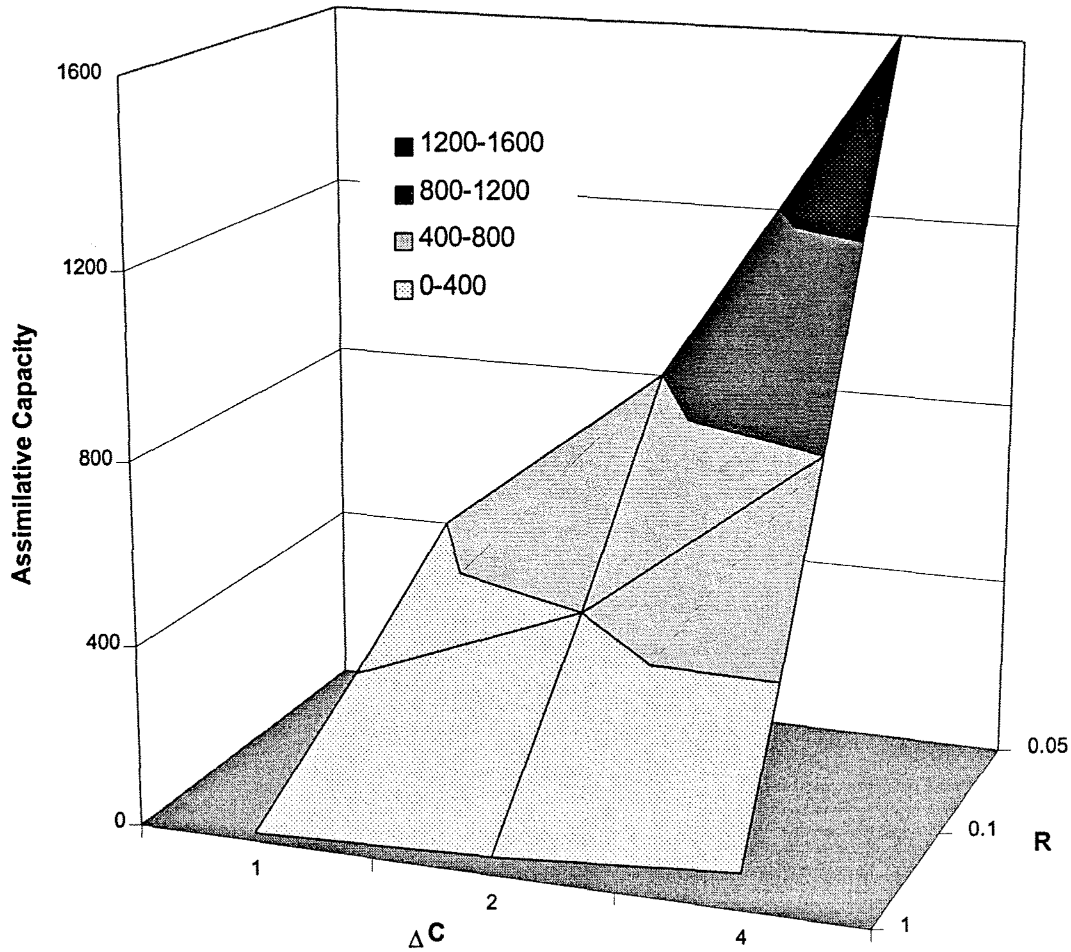

Figure 14. The assimilative capacity (tonnes) of Voyce Cove based on a volume of 2,500,000m^3, and a flushing time of 5 days. The rate of nutrient release (R) and allowable concentration increase (ΔC) range from summer to estimated winter values.