Water circulation, dissolved oxygen, and ammonia concentrations in fish net-cages

By

STEPHEN JOSEPH GORMICAN

B.Sc., University of British Columbia, 1980

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTERS OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Department of Zoology)

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

April 1989

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Zoology

The University of British Columbia
Vancouver, Canada

Date 3 May 1989

DE-6 (2/88)

Abstract

Fish farming in the protected waters of British Columbia is relatively new, but has undergone a phenomenal growth in the last ten years. Little investigation has been reported with respect to conditions within the net-cages employed in growing salmon at fish farms. In particular, the role of water quality and water exchange has not been examined in relation to local mariculture husbandry practices and hydrography.

The first part of this study compared water quality and water flow in two locations, one in Jervis Inlet with a deep entrance sill and the other in Sechelt Inlet which has a shallow entrance sill. Marked variations in hydrography occurred between the two sites as a result of the differences in sill depth. An internal wave generated at the Sechelt Inlet sill caused daily fluctuations in stratification and hence water properties within the net-cages. No such variations were observed at the Jervis Inlet site.

In the second part of this study, water quality and water flow was measured in various locations in and near a raft of 24 net-cages. Generally, it was found that within the raft, water flow was diminished in those cages located downstream of the predominate flow direction. However, local topography was thought to have caused marked variation in

water quality and water exchange patterns in two of the cages.

Ammonia concentrations were not observed to exceed reported sublethal concentrations at any time, over a 25 h period, at any of the depths sampled, within the net-cages. Dissolved oxygen concentrations did, at some depths and times, approach values at which some stress may be felt due to low oxygen.

Linear regressions between water quality and water speed were not found to be significant in most cases. The coefficient of determinations were low, indicating that current speed accounted for less than 27% of the variation in water quality.

Table of Contents

List of Tables

List of Figures

Acknowledgements

I would like to thank all my committee members for their invaluable advice throughout this project. Special thanks goes to Dr. S. Pond for assistance in the field under less than ideal conditions. Mr. E. Black also played an invaluable role in obtaining equipment and funding. My supervisor, Dr. A.G. Lewis provided support throughout this project.

Field work would not have been possible without the extremely competent Mr. Jay McNee, and so to him goes a special word of gratitude. Anna Metaxas provided encouragement and words of wisdom - always.

The Skei family, at Sechelt Salmon Farms Ltd., were very kind in providing accommodation and access to their farm. I thank Dora Glover at the Sunshine Coast Aquaculture Association for everything she did to aid my research. Roderick Farquarson and his family helped to make the 1988 field season bearable. All the people at Hardy Sea Farms with whom I had contact were very helpful.

The National Research Council (NRC) provided me with two Industrial Research Assistantships (IRAP-H's) to help keep me sheltered and fed over the two summers of my program. The Department of Zoology provided teaching assistantships for which I am extremely grateful, not just for the financial benefits, but also for the opportunity to gain an appreciation of the teaching skills necessary for any academic pursuit, which are so lost in today's publish or perish attitude.

Last but not least, I thank Maureen Mann, for her patience and support during some very trying times.

General Introduction

Salmon farming in net-cages in the coastal waters of British Columbia is a young industry. Cage farming has been practiced in Asia and other parts of the world for decades (Beveridge, 1984) however, local proliferation has occurred within the last 10-15 years. Black and Carswell (1986) report that eight farms produced 107 tonnes of salmon in 1985. By 1988, 125 fish farms produced over 6,500 tonnes of salmon (Anonymous, 1989) and the B.C. Salmon Farmers Association projects an annual production of over 15,000 tonnes by 1995 (Black and Carswell, 1986). Rapid growth of the industry has allowed little time to assess the effect of this industry on the environment, nor has there been time to research husbandry practices for local conditions and cultured species.

Mariculture is known to have a negative impact on the waters in which it is located by lowering dissolved oxygen (DO) concentrations and increasing ambient nutrient concentrations. In Japan, DO concentrations were observed to have been lowered by as much as 0.5 mg/L by a single cage stocked at a density of 22 kg/m^3 (Rosenthal et al., 1988). In Usui Bay, Japan, stocking densities had to be reduced despite tidal currents of 3-4 knots (=154-206 cm/sec) because DO concentrations were falling below critical limits. Oxygen concentrations were reported to vary markedly, with lowest values reported to occur during slack

tides and feeding periods. Over time the situation became worse as waste feed and feces increased the biological oxygen demand.

Ammonia concentrations in net-cages must also be considered due to potential toxicity. Ammonia in the marine environment may exist in two forms, un-ionized ammonia (NH_3) or ammonium ion (NH_4^+). Total ammonia, the sum of these two forms (NH_3 + NH_4^+), will be referred to as ammonia throughout this paper. The proportion of un-ionized ammonia existing in the environment is dependent upon pH, temperature, and salinity (Emerson et al., 1975). In the marine environment, excreted NH_3 is quickly converted to NH_4^+, and may account for 0.01 to 15 percent of total ammonia concentrations present (Bower and Bidwell, 1978).

Fish excrete ammonia as the major end-product of protein catabolism. Randall and Wright (1987) reviewed the mechanisms of ammonia formation and excretion in fish and concluded that ca. 80% of nitrogen excretion is in the form of ammonia. The gills are the major site of ammonia excretion, however the exact mechanism of this process is unclear. It is believed that un-ionized ammonia (NH_3) passes across the gills by simple diffusion processes, while ammonium ion (NH_4^+) excretion relies upon some sort of ion exchange process. The toxicity of un-ionized ammonia to fish is a result of a reversal of the internal/external gradient which allows NH_3 to re-enter the fish across the gills.

It is a well documented fact that ammonia, if allowed to build up in the rearing waters, may lead to reductions in stamina, growth rate, and resistance to disease (Burrows, 1964, Hillaby and Randall, 1979 and Alabaster and Lloyd, 1982). These authors also agree that sublethal effects of ammonia may be induced by long-term exposure to concentrations of >0.025 mg NH_3/L (=1.8 μmol/L). The majority of these studies have been conducted in freshwater systems in which water is at least partially recycled, thereby allowing a buildup of ammonia.

Information on ammonia levels resulting from marine fish farms is sparse (Gowen and Bradbury, 1987). Evrik et al. (1985) report that ammonia concentrations around net-cages may be 8-9 times higher than normal levels. Conversely, Black and Carswell (1986) report that ammonia levels were virtually identical at similar distances downstream from active and inactive fish farms. Weston (1986) modelled the impact that a theoretical 250 tonne fish farm, located in the Puget Sound area, would have on the environment. He predicted a rise in total ammonia concentration of 0.02 mg/L as well as a decrease in DO of 0.3 mg/L in the water passing through the site. Weston's (1986) model is applicable to the waters and culture techniques used in B.C. waters; however it could be improved with the addition of empirical data collected locally.

Successful net-cage fish farming relies upon the flow of water through the cage walls to maintain water quality.

(For the purposes of this study, water quality will be defined in terms of DO and ammonia concentrations.) Water flow through net-cages may be limited by a number of factors. Inoue (1972) indicated that the third cage downstream, in a series of three cages oriented parallel to the predominant current flow, may experience one-third less water exchange than the most upstream cage. Fouling of the netting by mussels and algae may reduce water exchange by as much as 80% (Wee, 1979 and Inoue, 1972). Wee (1979) also reported that increased time of submergence increases fouling, but that the rate varied with the seasons, and life history of the fouling organisms. Kennedy et al. (1977) found that fish deaths resulted when DO concentrations fell to 4.0 mg/L in a cage heavily fouled with "a mixture of sessile marine organisms, plus living and dead plankton and detritus". After net replacement, DO levels rose to 8.25 mg/L in the previously fouled cage.

Water quality may vary over a 24 hour period. Ammonia excretion exhibits a strong diurnal periodicity (McLean and Fraser, 1974 and Brett and Zala, 1975) with lowest values occurring before dawn and highest values about 4 h after the onset of feeding. Respiration rates are highest just prior to, and during feeding, with the lowest rates occurring at night (Brett and Zala, 1975). Local waters are subject to 4 slack tide occurrences in a 25 h period, which may further exacerbate ammonia buildup and DO depletion.

Clearly there is a need for a better understanding of the interaction between the environment and mariculture as practiced in British Columbia. The biology of the species reared, husbandry practices employed, and hydrography are unique to local waters. The problems seen in Japan may not arise locally as our inlets are much deeper than the Inland Sea of Japan. Conversely, shallow entrance sills to many of our inlets (Pickard, 1975) may restrict water exchange or mixing processes to the point where near surface waters are rendered unsuitable for the practice of mariculture.

The experiments discussed in this thesis were designed to investigate the condition of water quality in fish net-cages located in the waters of British Columbia. In Chapter 1, a comparison is made of water quality in two farm sites, one located in Jervis Inlet which possesses a deep sill, and the other in Sechelt Inlet which has a shallow sill. It was hypothesized that the presence of the shallower entrance sill would result in marked variation in temperature and DO profiles, relative to the Jervis site. As the flood tide progresses across the sill, a turbulent jet is formed which entrains waters below the sill depth (Lazier, 1963). These below surface waters may reach anoxic concentrations, and hence conditions in the resulting mixed waters may be deleterious to fish health. Based on the reviewed literature, it was also hypothesized that, over a 25 h period (one tidal cycle), ammonia concentrations and/or dissolved oxygen concentrations would reach sublethal

thresholds. Also examined was the relationship between current speed and water quality. It was believed that increased current speed would flush the net-cages of ammonia and would also replenish DO concentrations. Formally stated, this hypothesis postulated that water quality ([NH_3] & [O_2]) is directly related to water exchange.

In Chapter 2 the Jervis Inlet site was examined in detail with respect to within site water flow properties. This farm is a large raft of 24 cages and it was desired to gain confirmation of Inoue's (1972) observations and to determine if they applied to local conditions. The biomass at this site was 260 tonnes, which compares closely to Weston's (1986) hypothetical farm biomass of 250 tonnes. Thus, verification of his hypotheses regarding the impact of salmon farming on the environment could be made. It was hypothesized that water flow would be diminished in cages located downstream of the predominant flow direction relative to those cages upstream. Water quality was also hypothesized to be lower in cages located downstream of the predominant flow direction. Water exchange as a function of depth across one net-cage was examined. It was hypothesized that any reductions of current speed inside the net-cage would be equal over the depth of the cage.

Chapter 1:

Water quality and water exchange at two fish farms located in Jervis and Sechelt Inlets, B.C.

Introduction

The primary source of DO to a net-cage is through water exchange with the surrounding environment (atmospheric input is too slow and the necessary phytoplankton biomass contained within a net-cage insufficient). Any decrease in water exchange is of utmost concern to the fish farmer. Kils (1979) estimated that oxygen input through the surface (by wind and wave action) and phytoplankton photosynthetic activity, can supply only 0.5% of total oxygen demand. Kils (1979) however, assumed stocking densities of 20-25 kg/m^3 and, although not explicitly stated, based oxygen production values on a much lower phytoplankton standing stock than is typically observed for local Pacific waters. Assuming spring concentrations of nitrate in local waters to be 20 μmol/L, a nitrogen to carbon ratio of 10, and a photosynthetic quotient of 1.5 (Williams, 1979), yields a potential increase of 4.2 mg O_2/L under ideal conditions. If even one-quarter of this theoretical standing stock existed, phytoplankton would contribute a significant amount of oxygen to the waters. Conversely, such a bloom, upon death of the phytoplankton and subsequent bacterial respiration, would cause a much greater lowering of oxygen concentration due to the rapid growth kinetics of bacteria. Doubling times

for bacteria are in the order of hours whereas phytoplankton typically double once per day (Parsons et al., 1984a) and so, oxygen increases would occur much less rapidly than decreases. Consequently, fish kills may result from anoxia caused by bacterial respiration of after a bloom.

Davis (1975) reviewed the literature on DO requirements for marine salmonids and concluded that >9.0 mg O_2/L assures a high level of safety for most of the fish population with few members exhibiting symptoms of low oxygen. At the next lower criterion of 6.43 mg O_2/L, Davis (1975) suggests that the average member of a fish population will exhibit symptoms of oxygen distress and that some risk is involved if exposure to this level of DO is allowed to continue for more than a few hours.

Occasional phytoplankton blooms may raise oxygen concentrations to the point of supersaturation (Holeton, 1979). However, Weitkamp and Katz (1980) reviewed gas bubble disease (GBD) in fish, and found that no natural occurrences of GBD due to oxygen alone had been reported. GBD usually results from an increase in total dissolved gas pressure (TGP) most often caused by supersaturation of water with nitrogen. While concurrent high oxygen levels may serve to mitigate the effects of GBD, oceanic waters rarely become supersaturated in nitrogen due to its rapid incorporation into the nitrogen cycle (Parsons et al., 1984a).

Water exchange is the only bulk method of ammonia dissipation. Ammonia uptake by phytoplankton and

transformation by bacteria to nitrite and then nitrate, accounts for only a small portion due to the large differences in biomass within a net-cage.

This study was designed to monitor DO and ammonia levels inside and outside net-cages while simultaneously measuring current speed over a 25 h period. (The outside-cage sampling was performed as a control). This was to determine first, if DO and ammonia levels became deleterious to fish health. Secondly, it was to see if these water quality parameters correlate linearly to water exchange rate. This would provide an indication of the role of hydrographic conditions in determining water quality relationships in two locations - Jervis Inlet with a deep sill and Sechelt Inlet with a shallow sill.

Materials and Methods

The locations of the study sites are illustrated in Figure 1. The Jervis Inlet site (referred to as JER) is located near a deep sill (385 m). The Sechelt inlet site (designated as SEC) is located approximately 8 km south of a shallow sill. The SEC entrance sill has a depth of 14 m at high water (Pickard, 1975). Figure 2 shows a plan view of the sites and cages used in this study. Cage size varied between the sites, the JER location employed cages of 15X15X15 m (length X width X depth), whereas 12X12X5 m net-cages were used at the SEC site. Walkways at both sites, surrounded each net-cage, with the central walkway (oriented on the long axis of the raft) ca. 2 m in width, and the remaining three walkways, ca. 1 m wide. Therefore, except under conditions of high current flow, adjacent net-cages did not make contact.

Estimated total biomass at the JER site was 260,000 kg of primarily *Oncorhynchus tshawytscha* (chinook salmon) contained in 24 cages. Stocking density in the study cage was 4.3 kg/m^3 (9843 chinook, average weight 1.4 kg). Total biomass at the SEC farm was ca. 156,000 kg, primarily *O. kisutch* (coho salmon) and *O. tshawytscha* contained in 28 cages. The net-cage used in this study was stocked with 4737, 1.1 kg coho at a density of 7.2 kg/m^3.

Figure 1. Locations of study sites. The Jervis Inlet site is designated by a (1) and the Sechelt Inlet site by a (2).

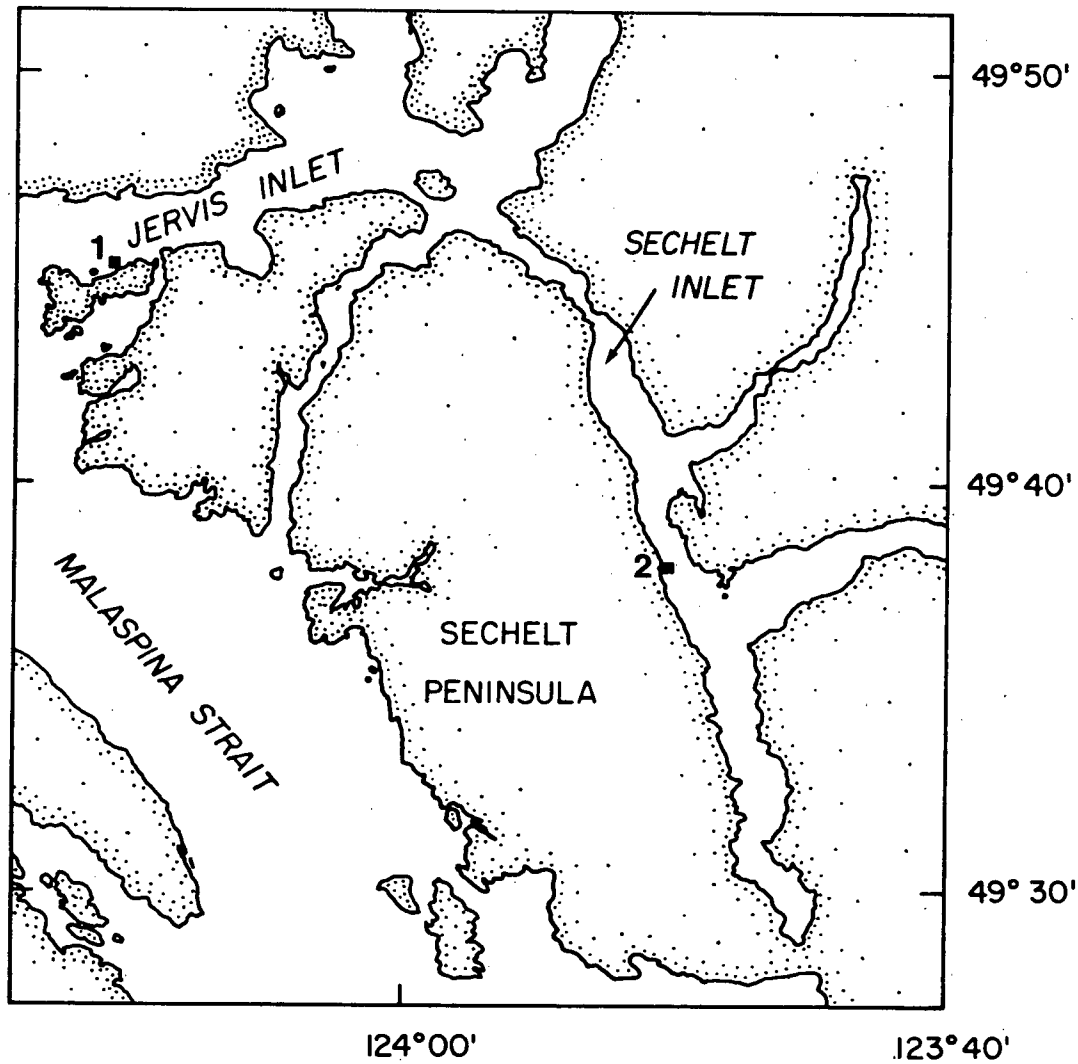
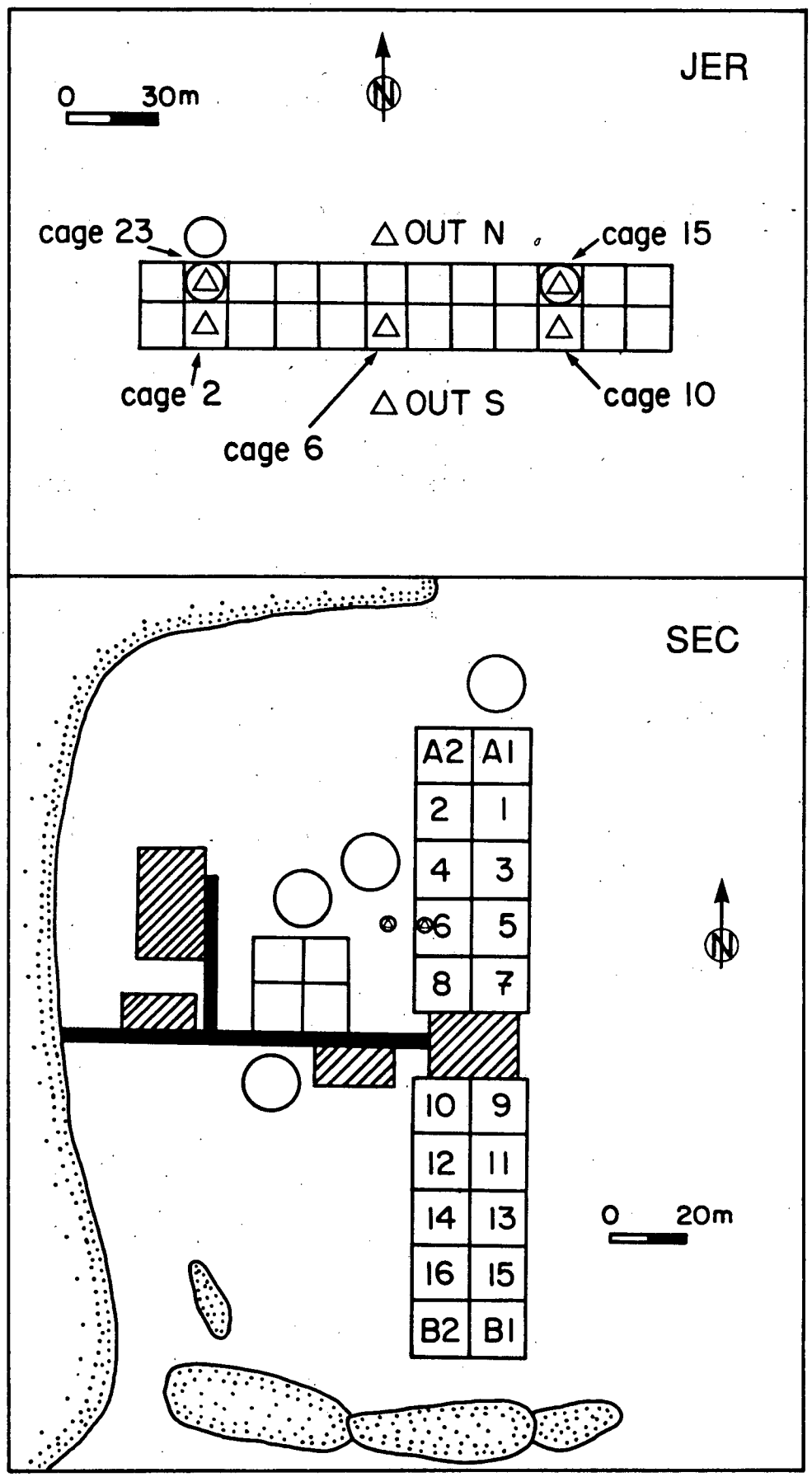


Figure 2. Plan views of the, A) Jervis Inlet (JER) and B) Sechelt Inlet sites. Stations at which water quality samples were collected and profiling performed, are designated by (◯). Current meters were deployed at locations indicated by (△). See text for details of depths of deployments and sampling protocol.


JER
0 30m
N
cage 23
OUT N
cage 15
cage 2
OUT S
cage 10
cage 6
SEC
A2
A1
2
1
4
3
6
5
8
7
10
9
12
11
14
13
16
15
B2
B1
N
0 20m

Sampling was carried out in July-August in 1987 (SEC) and 1988 (JER). During these months temperatures reached their annual peak and the fish were expected to reach their highest metabolic rate.

A Hydrolabs® Surveyor® II probe was used to profile the water column for temperature, salinity, pH, and dissolved oxygen. Hydrolabs® claims a calibrated accuracy of ±0.05 °C, 0.2 ppt, and 0.2 mg/L for T, S, and DO, respectively. Calibration of the instrument before and after each field use indicted that temperature and pH remained within ±2% of their initial values, and conductivity within ±3%. However, the dissolved oxygen sensor drifted by a maximum of -10%. *In situ* DO measurements were always performed within a 25 h period and therefore the instrument drift would presumably account for less than 1% error during the sampling interval. Moreover, differences, not absolute values were important in this study, and so, DO readings were considered acceptable.

Samples for ammonia determination were collected *in situ* using either a diaphragm pump or a 2 L Niskin bottle. Collected samples were either processed on site (1987-SEC) or filtered through precombusted Whatman GF/F glass fiber filters and frozen for subsequent laboratory analysis (1988-JER). Ammonia determinations in either case followed methods outlined in Parsons et al. (1984b) which converts all ammonia to the ammonium ion. Values reported will be expressed as total ammonia measured - the sum of NH_4^+ and

NH_3. Tables in Bower and Bidwell (1978) were consulted to determine the proportion of un-ionized ammonia present in the water column given the *in situ* T, S, and pH. No more than 5% of total ammonia existed in the un-ionized ammonia (NH_3) form in any part of this study.

Interocean S4® current meters (7) were employed at the JER site whereas Aanderaa RCM-4® current meters (4) were used at the SEC site. Both instruments are internally self-recording for T, S, pressure and current speed/direction, with programmable sampling duration and frequency. The S4 is a true vector-averaging instrument with an accuracy of ±2% of the reading for current speed and ±2.0 degrees direction. Without corrections accuracy is ±0.5-0.6 ppt for salinity and ±0.2 °C for temperature, for a total error of ±0.6 in sigma-t. (Sigma-t is a shorthand notation for expressing water density and is defined as density [kg/m^3] minus 1000.00, it is usual to omit the units (Pond and Pickard, 1986)). Corrections were not made as absolute values were not required and differences between depths were much larger than the error. Claimed accuracy for the RCM-4 instruments is ±1 cm/sec (speed), ±5 degrees (direction), ±0.05 °C (temperature), and ±0.025 mS/cm (conductivity). The S4 current meters were programmed to sample for 2 min every 10 min. The RCM-4 instruments were set to sample once every 10 minutes.

Current meters were suspended simultaneously inside and outside net-cages via a series of aluminum poles, Viny®

floats, and polypropylene rope. In all deployments, the instruments were positioned 3-3.6 m from adjacent nets to ensure that they did not become entangled in the nets during periods of high current flow. Depths of deployment varied with each experiment conducted at the JER site. Experiments concerned with detecting flow patterns across the site used instruments deployed at 6 m. Determination of flow as a function of depth required instruments to be deployed at 2, 5, and 8 m inside the net-cage and at 2, 5, 8, and 11 m outside the cage. Current meters were deployed at 2 and 4 m only at the SEC site. The locations of deployments is illustrated in Figure 2.

Sampling of the water column was performed over a 25 h period in order to include the full tidal cycle. Vertical profiles inside and outside the net-cages were taken once every hour, while discrete samples for ammonia determination were collected every 1.5 h at the JER site and every 1.0 h at the SEC site. At both locations, samples were collected over a continuous 25 h sampling program.

Ten replicate ammonia samples were collected and analyzed to determine the error of the sampling protocol. Near surface samples with a mean of 0.35 μmol/L total ammonia showed a standard deviation of 0.19. During the freezing process, ammonium concentrations of 2, 4 and 8 μmol/L were altered by 2% of their original values whereas standards of 1 μmol/L varied by 65%. The high variability at low concentrations, resulting from the freezing process,

perhaps accounts for the substantial variation of the replicate samples.

Data for each depth and location were pooled for each 25 h sampling period in order to allow comparisons of ammonia levels, DO and current speed inside and outside of the net-cages. A Student's *t* statistic was computed using |STAT (Perlman, 1986) data analysis programs. Regression analysis was also performed (using |STAT software) to determine if a relationship existed between water quality parameters and water flow rates. Differences and regression relationships were judged to be significant at the 95% level ($p \leq 0.05$).

Results and Discussion

The water column at the JER site is strongly stratified as indicated by both the temperature and density structure (Figure 3). At the SEC site, stratification varies over the 25 h sampling period (Figure 4). The periodicity in stratification is due to internal waves generated at the shallow sill, passing through the net-cages, and modifying the density structure by causing convergences and divergences in the upper layers of water. As these internal waves are generated tidally, a semi-diurnal periodicity is evident in the density and temperature profiles.

The expected daily pattern of ammonia production is a peak late in the afternoon and an ebb near dawn as reported by McLean and Fraser (1974). This pattern is apparent only at 6 m at the JER site (Figure 5) with peaks at 17:30 and an ebb at dawn. There was no clear pattern observed between current speed and ammonia concentrations, i.e. an increase in ammonia was not always preceded by, or found to occur during periods of slower water speed (Figure 5). On this particular morning, the automatic feeders were empty and thus, while feeding usually commenced at 05:30 (sunrise), no feed was supplied until 08:00, upon the arrival of the farm staff. The fish may have been conditioned to receive feed at 05:30, and so, were induced into ammonia production by

Figure 3. Plots of A) temperature and B) Sigma-t (density - see text for explanation) versus time for the indicated depths sampled at the Jervis Inlet farm site. Temperature data was collected hourly using the Hydrolabs instrument at the station outside of cage 23. Sigma-t data was collected using Interocean S4 current meters suspended simultaneously outside cage 19 (Figure 2).

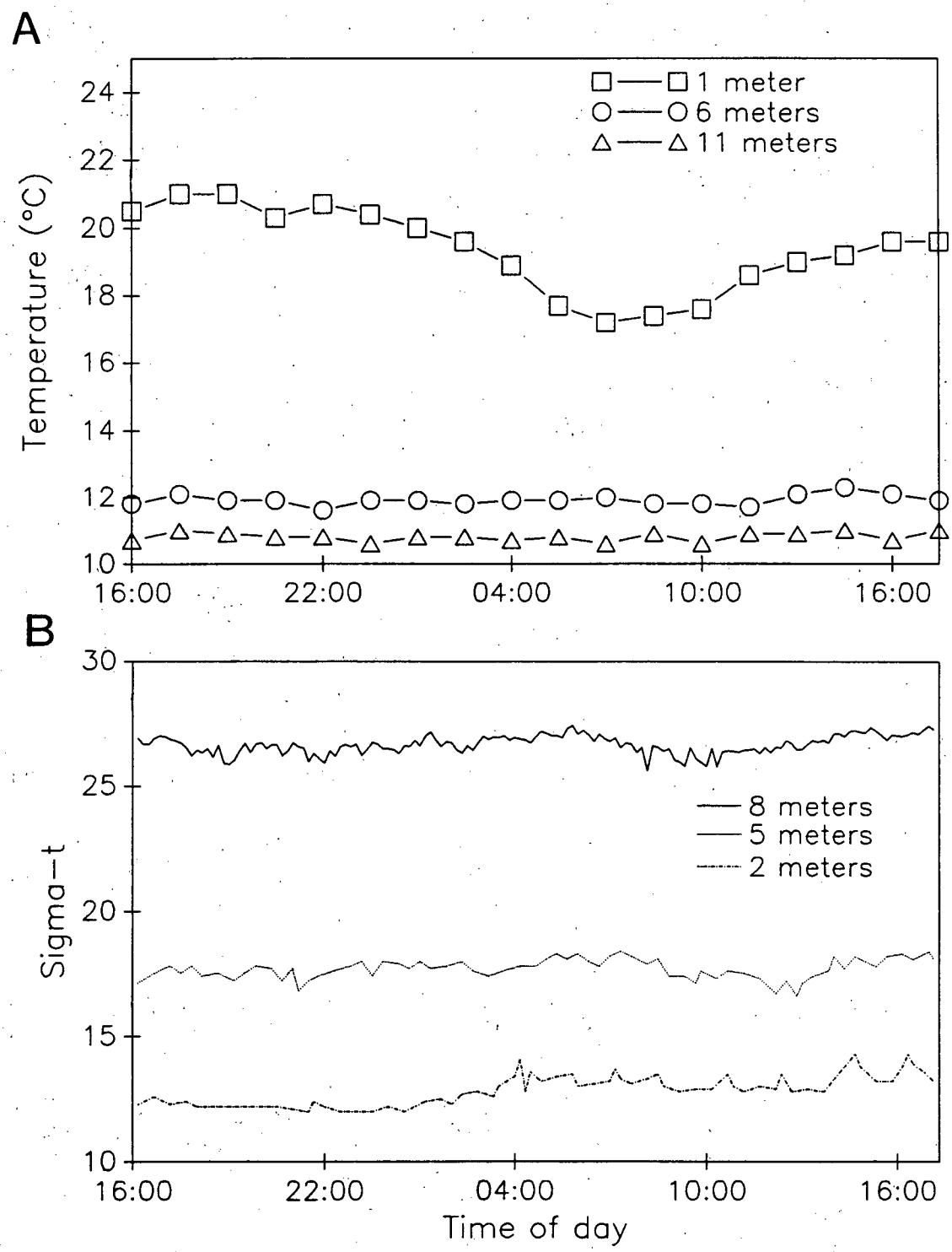


Figure 4. Plots of A) temperature and B) Sigma-t (density) versus time for the indicated depths at the Sechelt Inlet farm site. Data collected using the Hydrolabs instrument to profile the water column inside cage 6. Each point is a single sample - see text for error estimation.

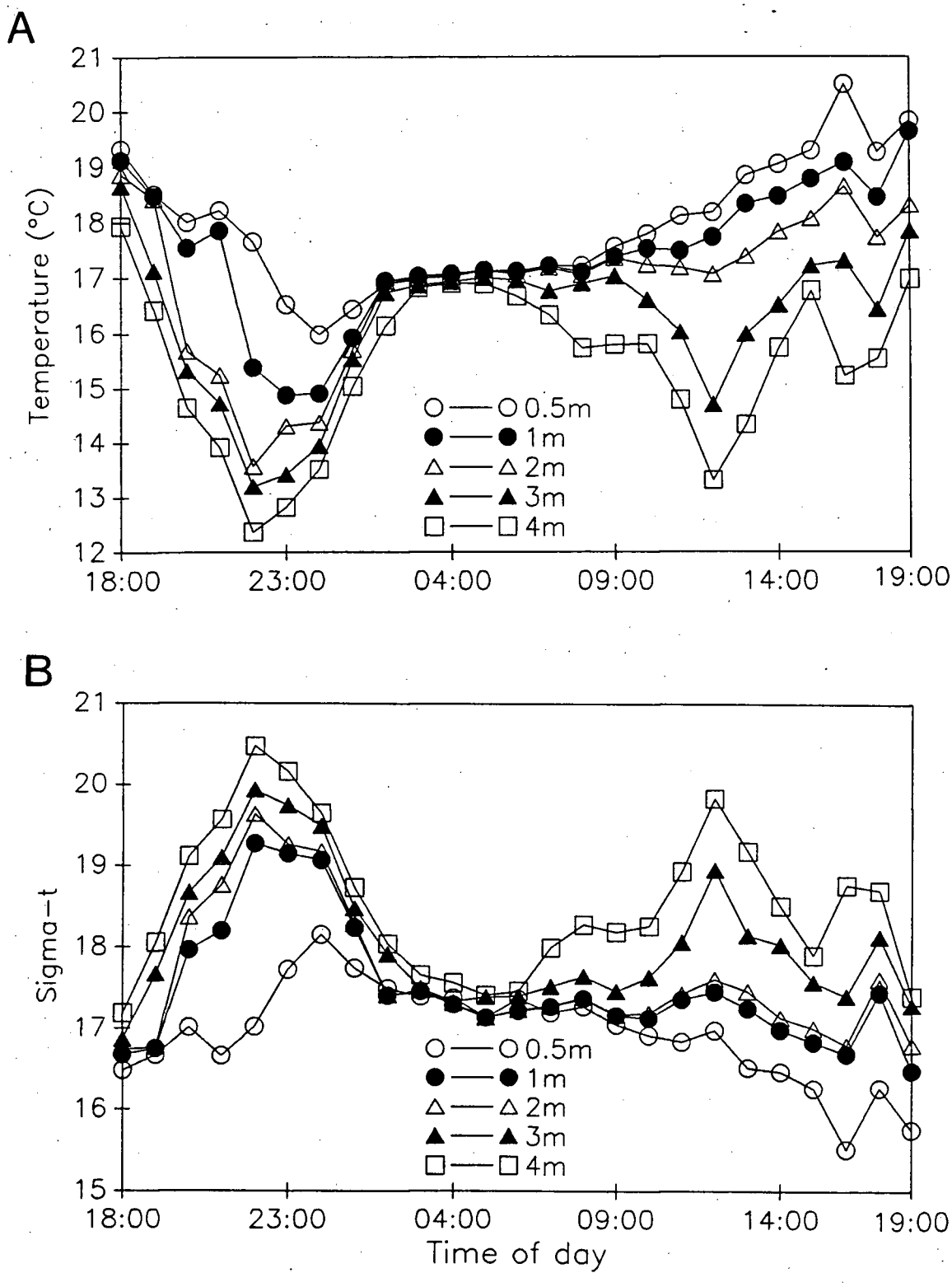
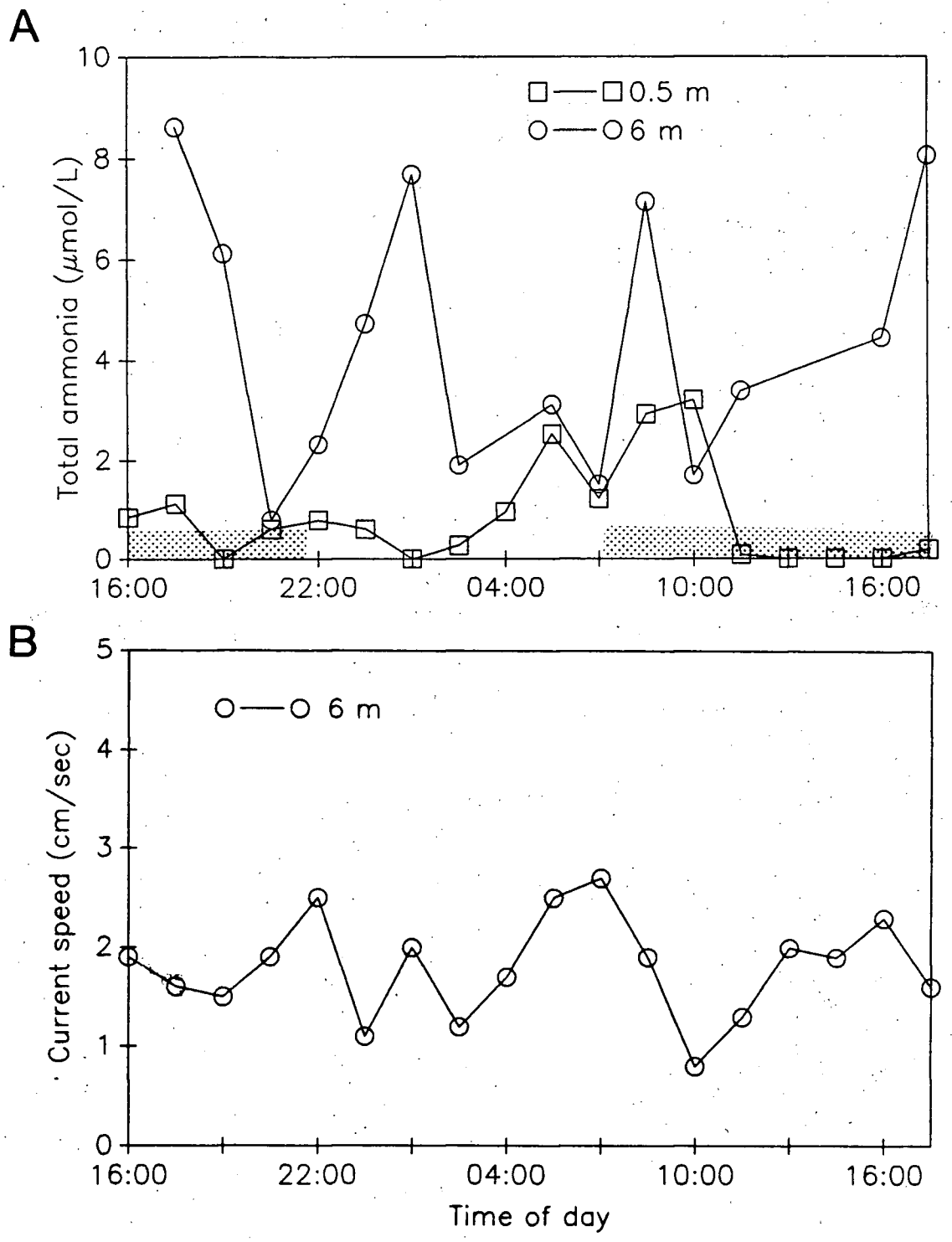


Figure 5. Plots of A) ammonia versus time and B) current speed for the indicated sampling depths at the Jervis Inlet site. Stipled area indicates time of feeding. Each ammonia data point is a single sample - see text for error estimation. Current speeds are hourly averages of 6 two-minute sampling episodes.



sunrise, or by the noise made by the empty feeders. The sharp drop at 10:00 then, may have been the result of ammonia excretion rate falling because of insufficient time to process the feed offered at 08:00.

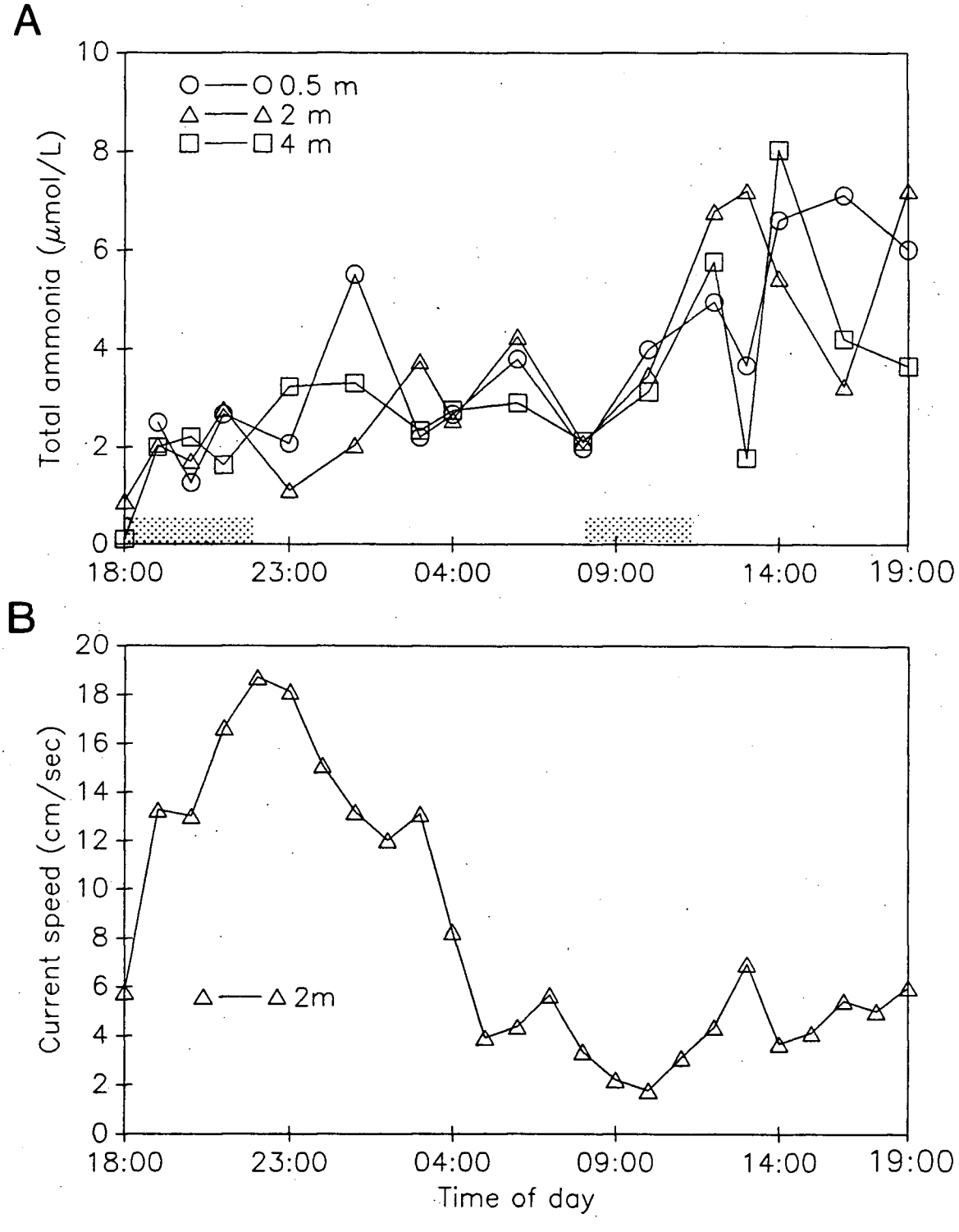
At the JER site, ammonia concentrations at 0.5 m did not follow the expected pattern (Figure 5). Moreover, values were significantly lower than those at 6 m (Table 1). It is suggested that the uptake of NH_4^+ by algae attached to the near surface portion of the JER net-cage may cause the lowering of ammonia concentrations relative to those at 6 m. Furthermore, it may be that these 15 m deep cages, combined with a lower stocking density, allow the fish to escape warmer temperatures near the surface, which would have the effect of concentrating ammonia levels at depth.

Expected ammonia concentration patterns at the SEC site are not apparent at any of the depths sampled (Figure 6). The observed trend is of increased ammonia levels over the 25 h sampling period, while current speed appears to have decreased (Figure 6). It will be shown however, that this relationship is not statistically significant. The overall trend of increasing ammonia over the 25 h period may be due to the sampling procedure disturbing the fish. McLean and Fraser (1974) reported that ammonia concentrations rose noticeably in rearing ponds after a disturbance such as removal of some fish.

Table 1. Comparisons of total ammonia inside cages at the JER and SEC sites. Data were pooled for each depth and location using values collected over the 25 h sampling programs. Order of means is as presented under the Comparison heading. (SD=standard deviation, df=degrees of freedom)

Location	Comparison		1st mean (SD)	2nd mean (SD)	t_{calc}	t-test (df)	p
JER	total ammonia (µmol/L)	0.5 vs 6m	0.9 (1.0)	3.5 (3.0)	3.508	(34)	0.001
SEC	total ammonia (µmol/L)	0.5 vs 2m	3.5 (1.9)	3.4 (2.1)	0.107	(32)	0.915
		0.5 vs 4m	3.5 (1.9)	3.2 (1.7)	0.580	(32)	0.566
		2m vs 4m	3.4 (2.1)	3.2 (1.7)	0.435	(32)	0.666

Figure 6. Plots of A) ammonia versus time and B) current speed for the indicated sampling depths at the Sechelt Inlet site. Stipled area indicates time of feeding. Each ammonia data point is a single sample - see text for error estimation. Current speeds are hourly averages of 6 sampling episodes.



There were no significant differences found among ammonia samples collected at 0.5, 2, or 4 m (Table 1) at the SEC site. The higher stocking density, and shallower cages employed at this site are thought to contribute to the equal distribution of ammonia within the net-cage.

The JER site 6 m ammonia concentrations were also the only ones to show significant variation between pooled samples from inside and outside of the net cage (Table 2). Current meter data indicate that the predominant current flow impinged on the cage sampled at the JER site (Figure 14, which is discussed in Chapter 2) from the outside during a large portion of the tidal cycle, while the sampled cage at the SEC site received much of its water through adjacent cages. The location of the SEC site within a semi-enclosed bay (Figure 2) caused the formation of gyres within the farm which changed in speed and location over the tidal cycle. Thus, because the outside sampling station was subject to waters that had passed through an uncertain number of other net-cages it was considered meaningless as a control. Surface ammonia samples collected periodically from near the shore averaged 0.8 μmol/L (S.D.=0.7, n=13) and ranged from 0.3 to 2.9 μmol/L. These samples indicated that ammonia enrichment was not confined to the fish cages. Background ammonia concentrations are considered to be <1.0 μmol/L for local waters (Dr. P.J. Harrison, DOUBC, pers. comm.).

Table 2. Comparisons of DO, total ammonia, and current speed inside and outside net-cages at the JER and SEC sites. Data were pooled for each depth and location using values collected over 25 h sampling program. (SD=standard deviation, df=degrees of freedom)

Location	Depth (m)	Parameter	INSIDE mean (SD)	OUTSIDE mean (SD)	t-test t_{calc}	(df)	p
JER	1	DO	9.5 (0.8)	9.4 (0.6)	0.294	(34)	0.771
21 July,	6	(mg/L)	7.9 (0.5)	8.3 (0.5)	2.501	(34)	0.017
1988	11		6.5 (0.2)	6.5 (0.2)	0.381	(34)	0.706
		total					
	0.5	ammonia	0.9 (1.1)	0.5 (0.5)	1.272	(34)	0.212
	6	(µmol/L)	4.4 (2.6)	1.7 (1.6)	3.187	(26)	0.004
	6	current speed (cm/sec)	2.0 (1.3)	2.9 (2.5)	3.838	(300)	<0.001
SEC	0.5	DO	9.1 (0.3)	9.0 (0.3)	1.403	(50)	0.167
6 August,	1	(mg/L)	9.0 (0.3)	8.9 (0.2)	0.278	(50)	0.782
1987	2		8.8 (0.4)	8.8 (0.4)	0.572	(50)	0.570
	3		8.6 (0.6)	8.6 (0.5)	0.143	(50)	0.887
	4		8.3 (0.7)	8.4 (0.6)	0.236	(50)	0.815
		total					
	0.5	ammonia	3.7 (1.8)	2.9 (1.2)	1.486	(31)	0.147
	2	(µmol/L)	3.5 (2.0)	3.7 (1.8)	0.302	(32)	0.765
	4		3.1 (1.8)	3.4 (1.5)	0.436	(32)	0.666
	2	current	8.3 (5.4)	7.2 (4.4)	0.776	(48)	0.441
	4	speed (cm/sec)	6.6 (3.6)	5.6 (3.1)	1.042	(48)	0.303

Un-ionized ammonia (NH_3) levels peaked at ca. 0.6 µmol/l (=0.008 mg NH_3/L) at both locations. This value is well below the 0.025 mg NH_3/L reported by Alabaster and Lloyd (1982) to be toxic to salmonids on a long-term exposure basis. Lethal levels are reported to begin at concentrations of 0.2 mg NH_3/L (Alabaster and Lloyd, 1982).

Linear regressions of ammonia and current speed were not significant at either site (Figures 7 & 8). The slopes are in the predicted direction, however they are not significantly different from zero. The interaction of the tidal cycle (four current reversals in 25 h) and the diurnal periodicity of ammonia production and utilization make this a very complex relationship, and perhaps a linear model is too simplistic. At the SEC site, the influence of the internal tide, may have added considerable noise to the data by alternately increasing and decreasing ammonia concentrations by causing convergences and divergences.

Differences in DO between the inside and outside of the net-cages were significant only at the JER site, and only at 6 m depth (Table 2). This finding perhaps gives further weight to the argument that the bulk of the fish are located in the mid-depths of the cage, hence the greater depletion of DO at this depth. Again, the location of the sampled cage at the SEC location makes inside/outside comparisons meaningless.

Figure 7. Scatter diagram of total ammonia versus current speed for data collected at mid-cage depth (6 m) of cage 23 at the Jervis Inlet site. The line is the least squares regression line with coefficient of determination (r^2) indicated. A t-statistic was used to test significance (p).

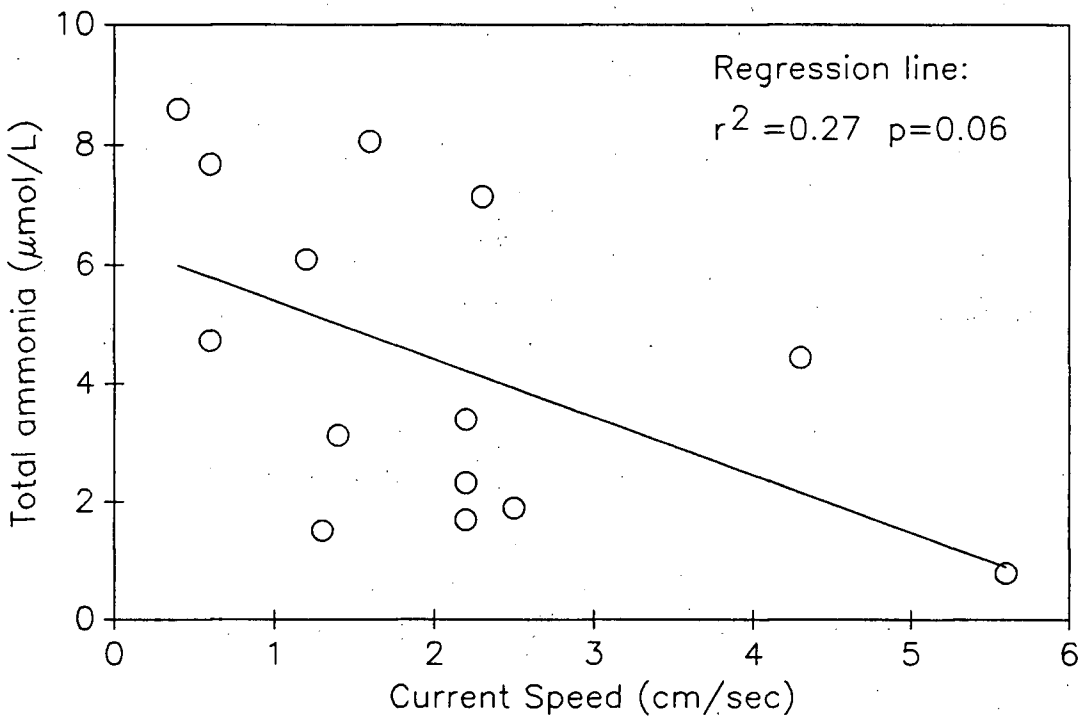
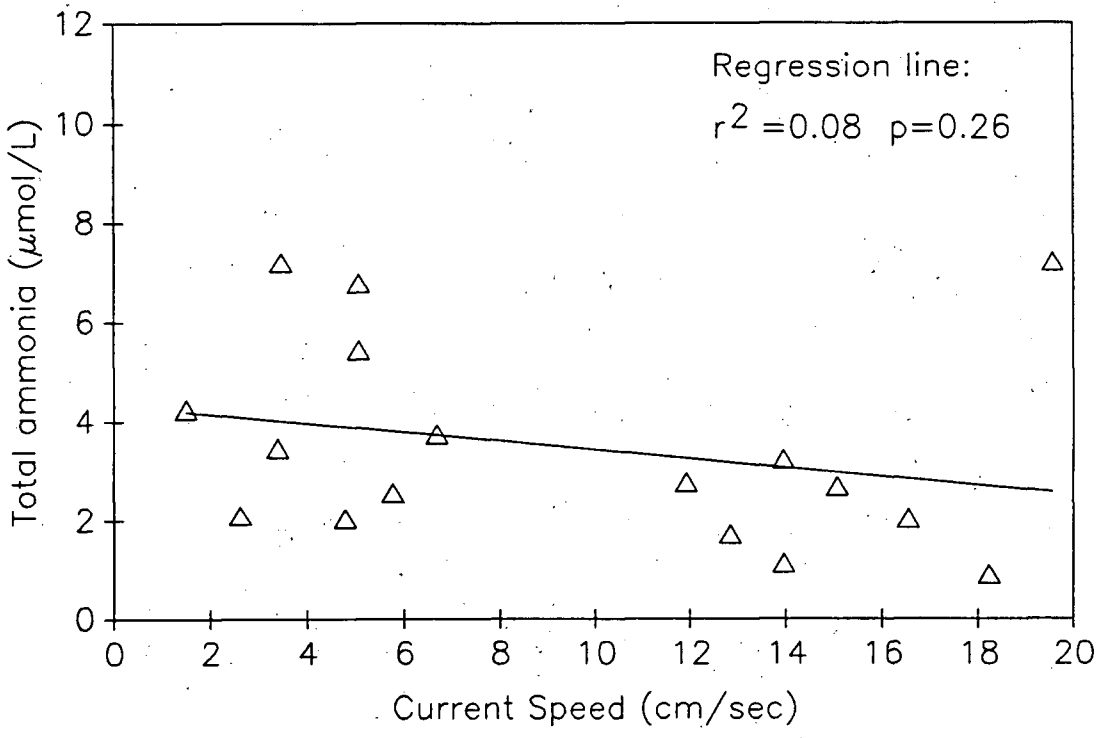


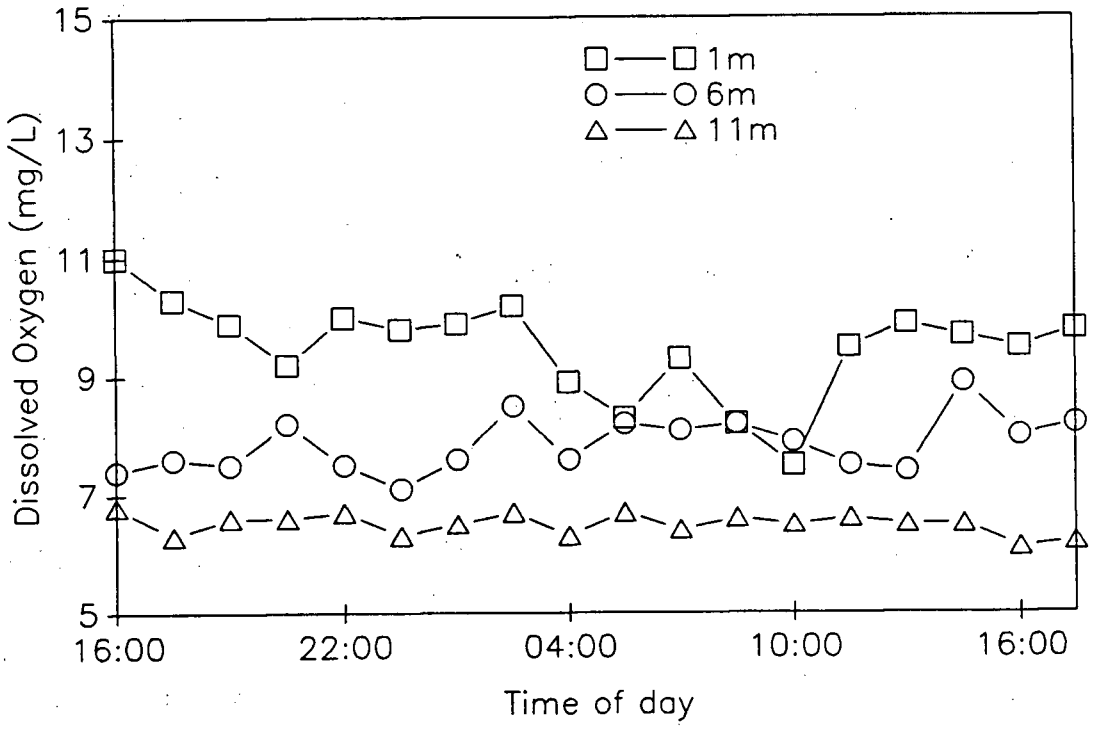
Figure 8. Scatter diagram of total ammonia versus current speed for data collected at the mid-cage depth (2 m) in cage 6 at the Sechelt Inlet site. The line is the least squares regression line with coefficient of determination (r^2) indicated. A t-statistic was used to test significance (p).



Diurnal periodicity of DO at the JER location (Figure 9) is typical of a phytoplankton-driven DO regime at 1 m. Near surface waters (1 m) exhibited photosynthetic production of DO during the daylight hours, with a DO sag occurring during dark hours when respiration by fish, phytoplankton, and other organisms in the water column dominated. The largest sag however, occurred at 10:00 and it was thought that the metabolism of feeding fish may have had some influence as they moved up into the near surface waters to feed.

DO values at this site did occasionally reach levels at which some fish would begin to exhibit symptoms of low oxygen stress, particularly at 11 m. Protection level B (Davis, 1975) is set at 6.43-9.00 mg O_2/L, and exposure to the minimal value is considered to pose some degree of risk if extended for more than a few hours. Caveat: instrument error may have been as much -10% in DO readings. A recorded concentration of 6.5 mg O_2/L may therefore actually have been as high as 7.2 mg O_2/L (but was still within level B). To avoid prolonged exposure to low DO, the fish could have moved to near surface waters. Phillips (1985) indicates that farmed *Salmo gairdneri* Richardson (rainbow trout) may alter their position within a net-cage to avoid temperature extremes. He argues further that aggregation of fish in one portion of the cage should not be considered under-utilization of the allocated space, but rather, a provision

Figure 9. Plots of dissolved oxygen versus time for the indicated sampling depths at the Jervis Inlet site. Each data point is a single sample - see text for error estimation.



of a refuge from unfavourable conditions. Thus, it is clear, that any evaluation of water quality within a net-cage must include sampling over the complete depth of the cage as the fish may behaviourally select any portion of the cage in which to reside.

DO concentrations at the SEC site varied greatly over the 25 h sampling period (Figure 10). The effect of the internal wave passing through the site is apparent in the data (Figure 10). For example, DO levels at 4 m are seen to rise from <7 mg/L to near 9 mg/L the during the period 22:00 to 03:00. The only plausible explanation for this increase of DO during the night, is convergence of the water column, caused presumably by the passage of an internal wave through the net-cage.

Linear regressions of DO and current speed were not significant at the JER site (Figure 11) but were significant at the SEC location (Figure 12). In both cases, the slope is in the predicted orientation, that is, as speed increased, DO concentrations increased. However, at the SEC site, an r^2 value of 0.16 indicates that only 16% of the variance in DO can be attributed to current speed. As in the case for ammonia and current speed, the interaction of biological (photosynthesis and respiration) and physical processes cannot be described by a simple linear function. Analysis of more data, collected over the full monthly range of tides, may help to clarify this relationship.

Figure 10. Plots of dissolved oxygen versus time for the indicated sampling depths at the Sechelt Inlet site. Each data point is a single sample - see text for error estimation.

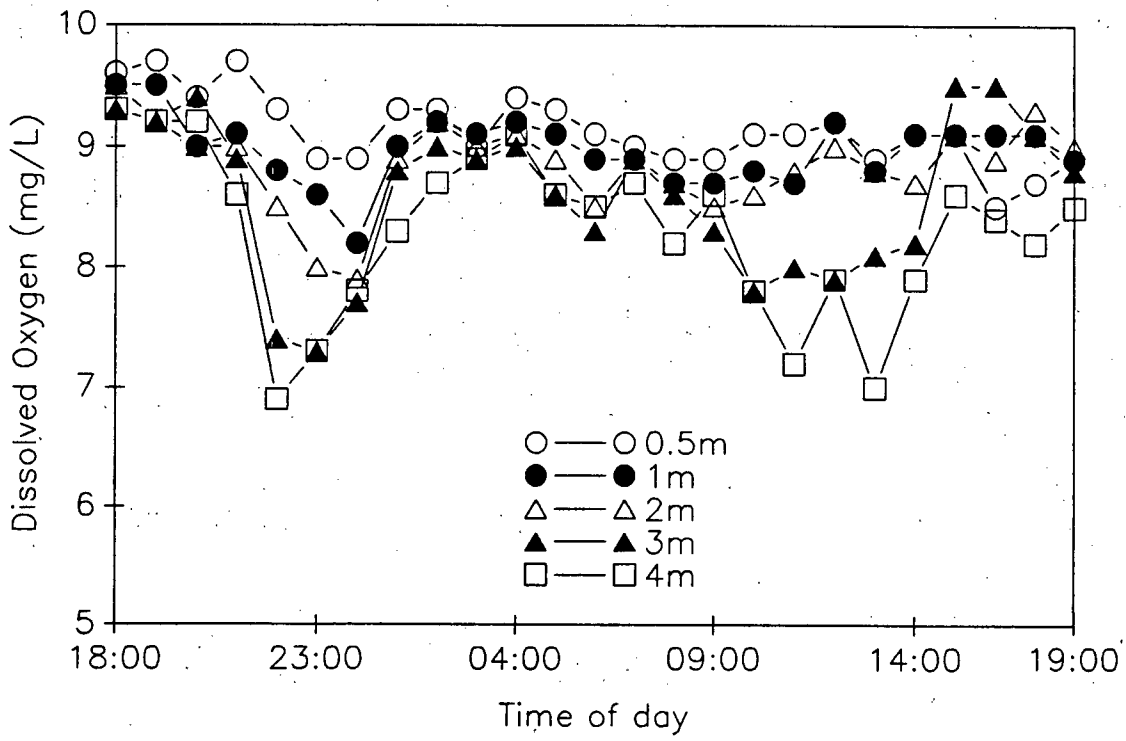


Figure 11. Scatter diagram of dissoved oxygen versus current speed for data collected at mid-cage depth (6 m) of cage 23 at the Jervis Inlet site. The line is the least squares regression line with coefficient of determination (r^2) indicated. A t-statistic was used to test significance (p).

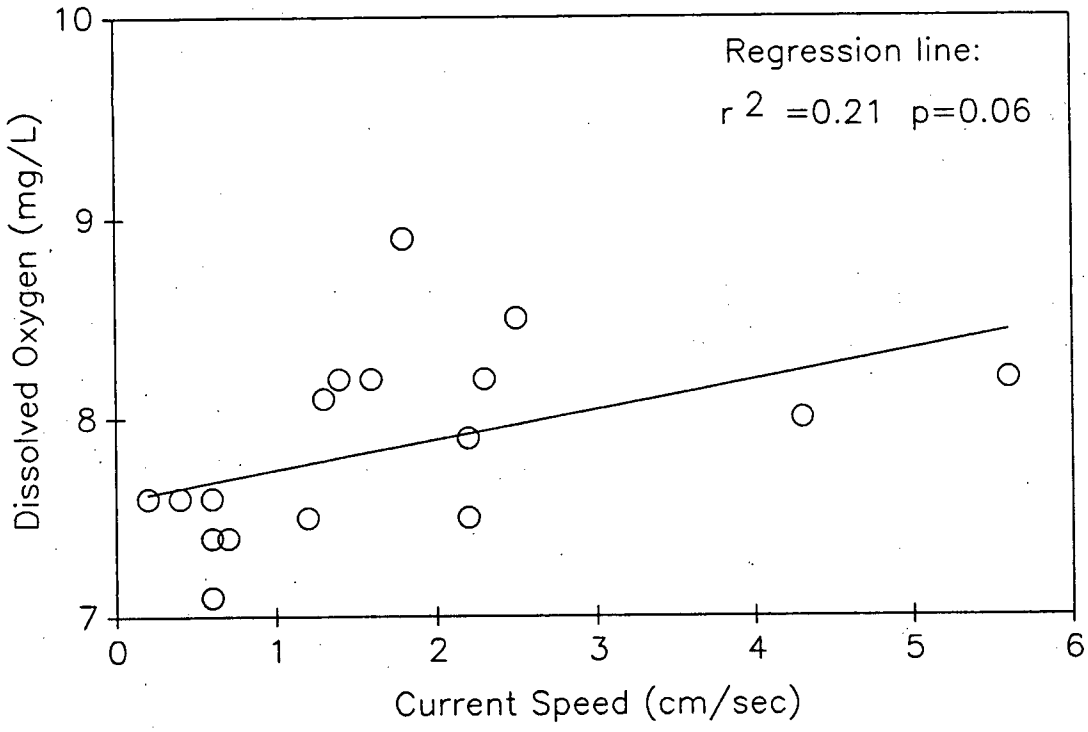
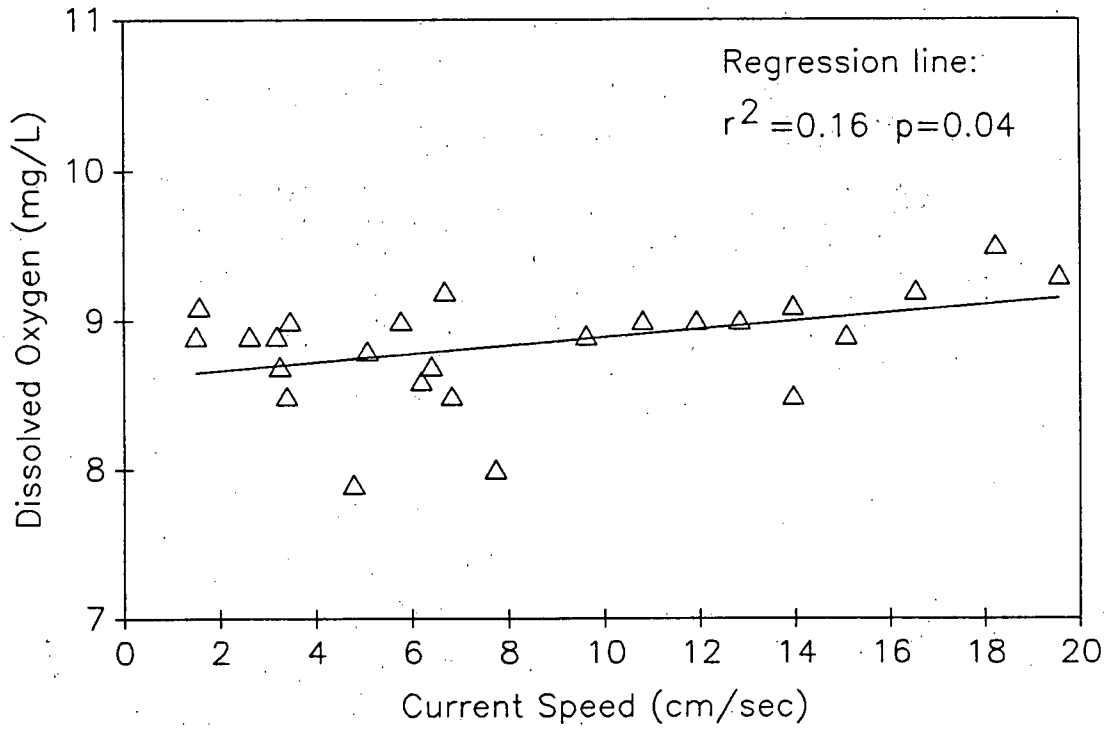


Figure 12. Scatter diagram of dissolved oxygen versus current speed for data collected at the mid-cage depth (2 m) in cage 6 at the Sechelt Inlet site. The line is the least squares regression line with coefficient of determination (r^2) indicated. A t-statistic was used to test significance (p).



Current speeds were generally higher at the SEC location than the JER location (Table 2). This may be due, in part, to the presence of mussels fouling the nets at the JER site to a depth of ca. 4 m. The SEC site had recently replaced, clean nets.

The restriction of the tidal waters through Skookumchuk Narrows, over the entrance sill to the Sechelt Inlet, results in a "turbulent jet" (Lazier, 1963). This "turbulent jet" serves to accelerate the near surface waters and thus current speeds are higher near the sill than at the head of the inlet. No such event occurs over the deep sill at the entrance to Jervis Inlet - where the JER site was located.

It is suggested that proximity of the Sechelt site to a shallow sill has put it under the influence of internal waves generated by tidal action at the sill. These long-period waves propagate along density interfaces, causing convergences and divergences in the near surface waters (Pickard, 1954). The tidal component of these waves can be observed in the twice daily stratification changes seen in the DO, Sigma-t, and temperature plots. Implications of these events to fish farmers are many. As the time of daily tidal events progresses about one hour every day, the time of occurrence of these events also progresses. The temperatures throughout the cages may occasionally become harmful to the fish if, for instance, a convergence occurred during an exceptionally warm period when surface temperatures reached dangerous levels (greater than 21 °C

for chinook; Caine et al., 1987). A rapid increase in temperature may stress the fish, particularly if the change is >5 °C within a 12 h period (Caine et al., 1987). A rapid increase in temperature may also cause gas supersaturation to occur which may lead to fish kills (Weitkamp and Katz, 1980).

Water mass convergences also mean that any harmful phytoplankton in the water column may become concentrated, which may result in fish kills at concentrations that would, in the absence of an internal wave, have been harmless. Early warning networks of phytoplankton watches must therefore add a safety factor into their abundance estimates if internal waves are present in their area. Mitigation of harmful effects imposed by internal tides, or unfavorable near-surface conditions, may be brought about by using deep net-cages, which extend below the depth affected by the internal wave. By employing lower stocking densities fish farmers may allow the fish to behaviourally select the most favourable portion of the water column.

Conclusions:

Defining water quality as the concentration of DO and ammonia present, allows the following conclusions to be made based on data collected at two farm sites during the course of this study.

Dissolved oxygen concentrations were observed to reach levels low enough to have caused stress to some members of the fish population at depths of 6 and 11 m at the Jervis Inlet site and at all depths sampled at the Sechelt Inlet site.

Un-ionized ammonia levels did not exceed the accepted criterion set for avoidance of sublethal effects (0.025 mg NH_3/L) at either location, at any depth sampled, over the 25 h sampling periods.

The presence of a shallow sill near the Sechelt Inlet site, versus a deep sill near the Jervis Inlet site, created marked differences in hydrography between the two locations. The shallow sill, generated internal waves which, upon their passage through the farm site, modified the density structure. Subsequent changes were also observed in temperature and DO profiles over the depth of the cages, and it was proposed that measures, such as increasing cage depth and lowering stocking densities, must be taken by the farmer to mitigate the potential impact of these changes upon fish stocks.

Chapter 2:

Net-cage fish farming in British Columbia: a case study of water circulation and water quality in a large raft of cages

Introduction

This portion of the study was undertaken to observe the effects of the combined periodicity of biological and physical phenomena over a 25 h period, in various positions and depths within a 260,000 kg fish farm. Sampling involved three parts or experiments. Part A, was to measure the water flow as a function of depth in a stocked net-cage which had been submerged for ca. 30 days. This experiment would also indicate whether or not a horizontal velocity shear was present, which would dictate the placement of the current meters for the second phase. Part B examined the water flow patterns within the site. Lastly, in Part C, water quality (DO and ammonia) across the site was monitored in a 25 h sampling program which overlapped concurrent water flow measurements as much as was logistically possible. This last program was designed to test the hypothesis that water quality would be poorer in those cages which were located downstream in the predominant flow direction.

Materials and Methods

The JER site particulars and equipment/methods used in this study are described in the Materials and Methods section of Chapter 1. As it was desired to sample during a period of minimal tidal flow, sampling was scheduled during neap tides (moon in 1st quarter on July 21, 1988). Sampling protocol is outlined below:

Part A

Three current meters were deployed at 2, 5, and 8 m depth inside net-cage 6, while 4 current meters were simultaneously deployed at 2, 5, 8, and 11 m outside net-cage 19, on the north side of the raft (Figure 2). Current meters were programmed to sample for 2 min in every 10 min period, and remained in position for 25 h.

Part B

Based on the findings of Part A, current meters were deployed at 6 m in the locations shown in Figure 2. Sampling rate was as per Part A. Due to logistics, the period of simultaneous records for each instrument was 20:00 20/07/88 to 21:00 21/07/88, which overlapped the water quality sampling program of Part C for a period of 4 h. The daily procession of tides was 1 h for this location, and hence, valid comparisons of water quality and water flow were made by shifting the time scale appropriately.

Part C

Water quality sampling was done inside and outside cage 23 as well as inside cage 15 every 1.5 h for a 25 h period, beginning at 16:00 21/07/88 and ending 17:00 22/07/88. Samples for ammonia analysis were collected at 0.5 and 6 m depth, while the Surveyor® II was used to measure temperature, pH, salinity, and DO at 1, 6, and 11 m.

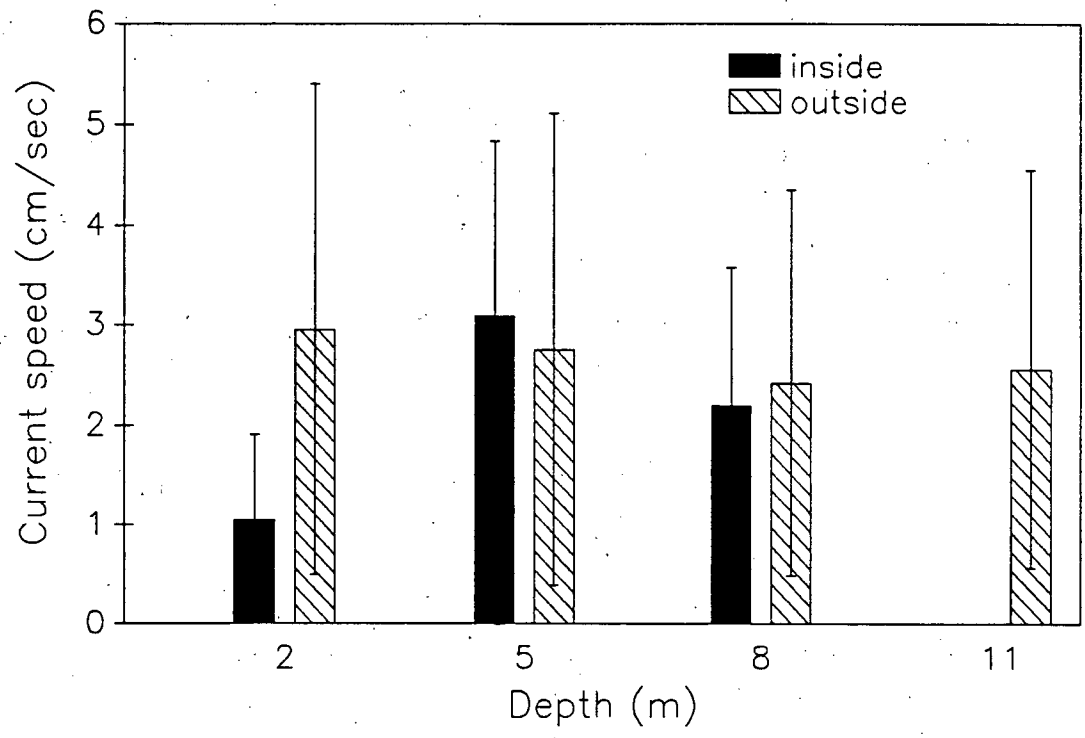
Results

Weather conditions throughout these experiments remained cloudless with virtually no wind. As a result of these nearly ideal meteorological conditions, the seas remained calm which meant that no adjustments to the data were necessary to account for wind driven currents.

Part A

Figure 13 summarizes the findings of the profile experiment. Each bar on the graph is the average current speed over 25 h which consisted of 150-two minute recording episodes. The lack of any strong vertical velocity shear is indicated by the similarity of current speed at all depths outside the net-cages. Current speed at 2 m, inside cage 6, is reduced by 65% relative to that at the northern current meter location. At depths greater than 5 m, current speed inside and outside the net-cages is nearly identical, with a slightly higher speed inside at 5 m and a slightly lower speed inside at 8 m depth. SCUBA divers reported that heavy fouling of the nets by mussels occurred to a depth of about 4 m.

Figure 13. Plot of current speed versus depth for the profile experiment at the Jervis Inlet site. Error bars are one standard deviation.

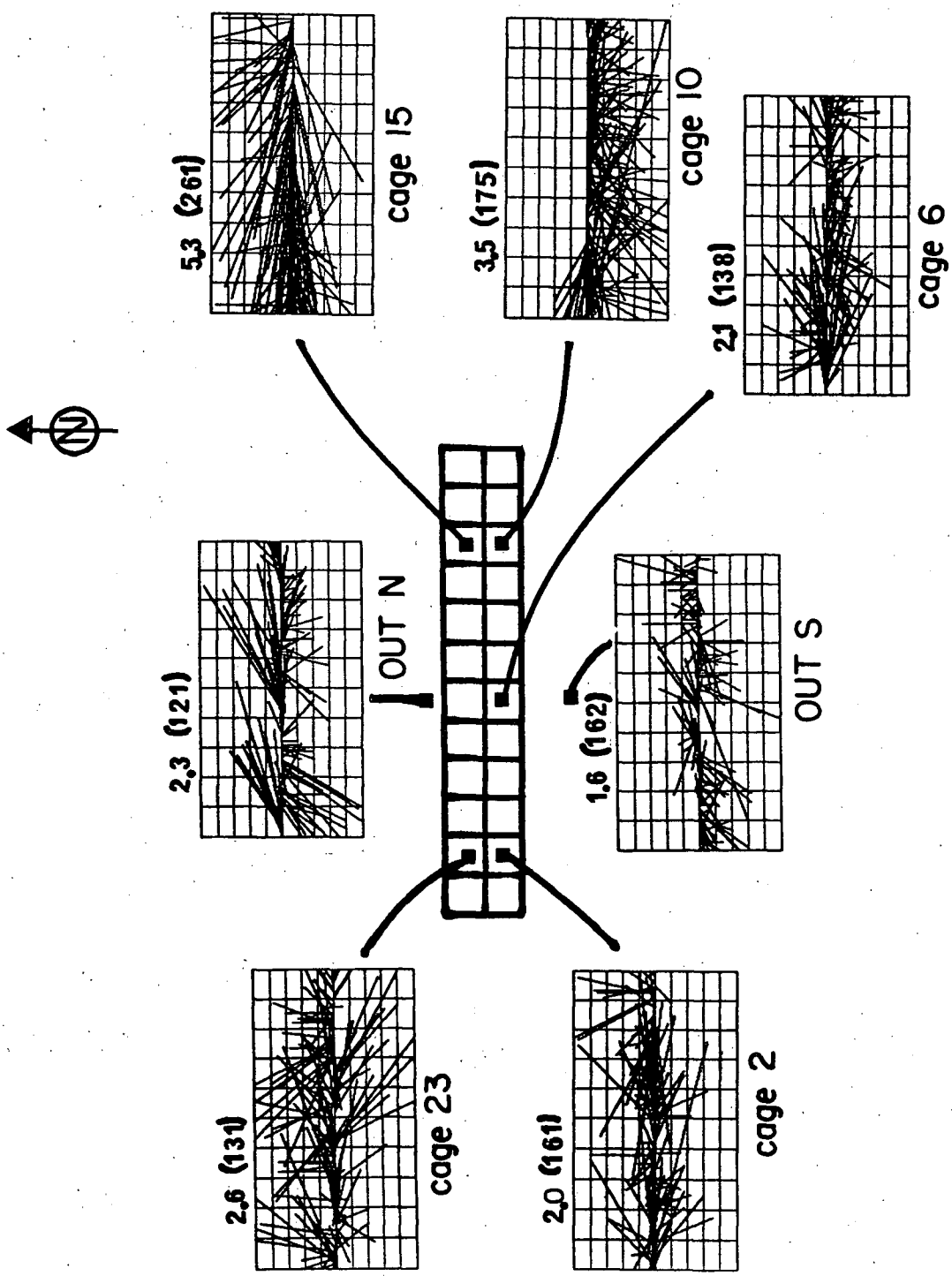


Part B

Current speed and direction over the 25 h sampling period for each of the current meters is illustrated in Figure 14. Each current meter contains its own magnetic compass, which ensures that the horizontal axis for each vector diagram has the same east-west orientation. However, due to the periodic swinging of the raft upon its mooring lines, orientation of the raft's long axis relative to the horizontal axis of the vector diagrams is variable. Nevertheless, visual observations of reference points on the neighbouring island indicated that the raft rotated no more than 10 degrees over a tidal cycle.

The twice daily reversal of the tide is seen in the records provided by the instrument deployed north of the raft (Figure 14). Average diminution of current speed across the site from north to south is approximately 30%. Cages on the southern side of the raft (i.e. cages 2, 6, and, 10) exhibit slower current speeds than adjacent northern cages. Directional changes in flow are evident in all cages relative to the northern outside reference current meter. The greatest directional change is in cage 15, where the tidal signal is masked by a persistent westward flow. Current speed is the highest (ave. 5.3 cm/sec) in cage 15, with the next cage south, cage 10, also exhibiting some of the same pattern of deviation away from typical tidal influence both in speed and direction.

Figure 14. Vector diagrams of data collected at the indicated locations in and around the raft of net-cages at the Jervis Inlet site. Depth of instrument deployment was 6 m for a duration of 25 h. Data was collected simultaneously at each location. The length of each vector is proportional to current speed (1 division = 1 cm/sec), while the orientation indicates flow direction. Figures above diagrams are average speed and (direction) for the 25 h sampling period illustrated in each vector diagram.



Part C

Plots of dissolved oxygen concentrations measured inside cages 23 and 15 for the 25 h data collection period are shown in Figure 15. Diurnal periodicity is seen in the 1 m plots inside both cages. The lowest DO values occurred between 01:00 and 06:00 except for one sample at 20:30 in cage 15. (Sunset occurred at 20:50 and sunrise at 05:30). DO values for both cages were higher near the surface than at 6 or 11 m (Table 3). The only significant difference observed between the two cages was at 6 m depth, where cage 23 showed greater values than cage 15.

The pattern of ammonia concentration changes over 25 h in both cages was similar for the surface sampling depth (Figure 16). Peak values occurred at 10:00 and 05:30 for cages 23 and 15 respectively. No clear pattern of minimum ammonia values for surface waters was apparent. The daily time course of ammonia concentration was even more irregular at 6 m depth. Values are higher at 6 m than near surface waters. There were no significant differences in ammonia concentrations, at either depth, between cages 23 and 15 (Table 3).

Figure 15. Comparisons of dissolved oxygen concentrations versus time for the indicated depths in cage 23 (○) and cage 15 (●) at the Jervis Inlet site.

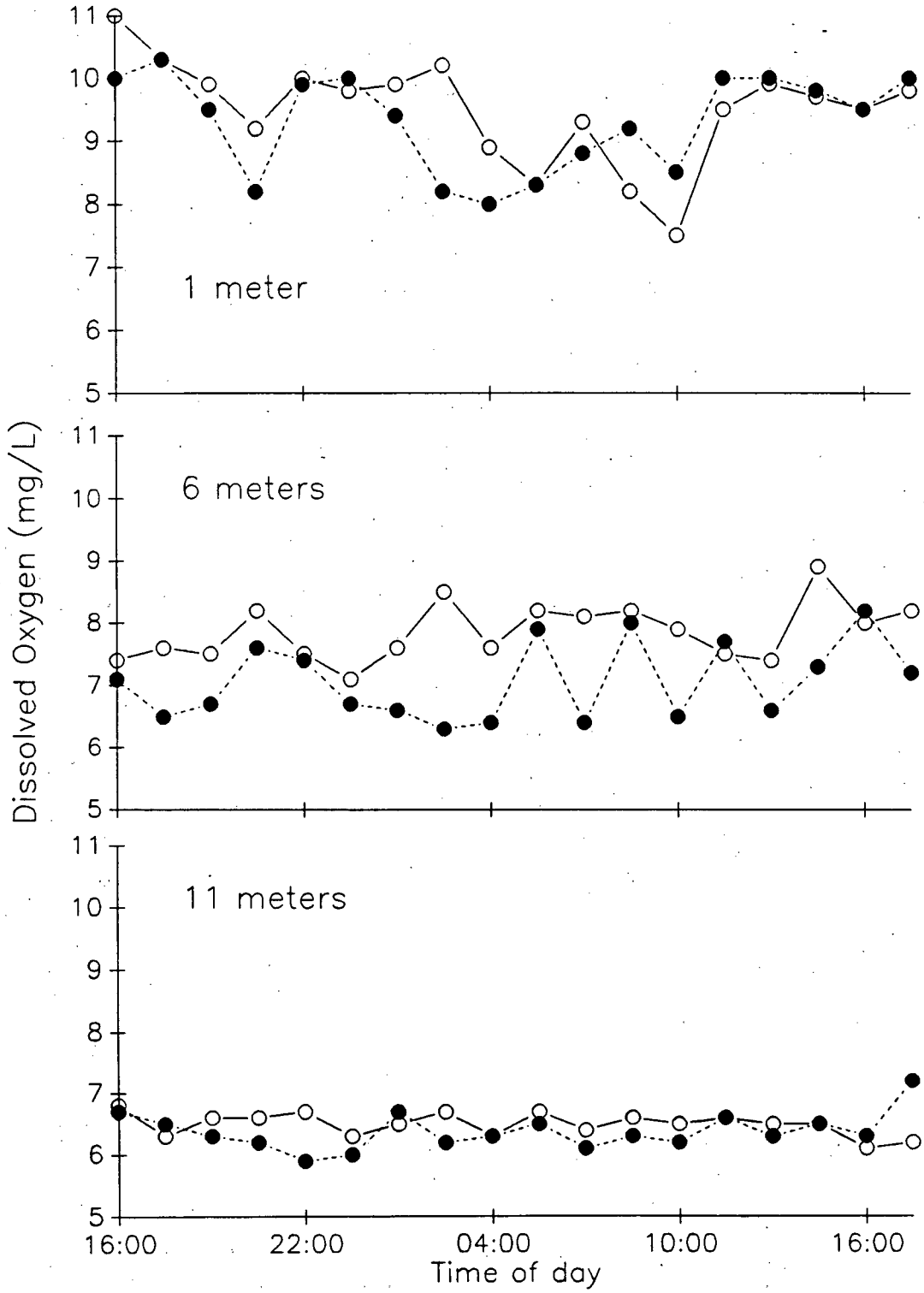
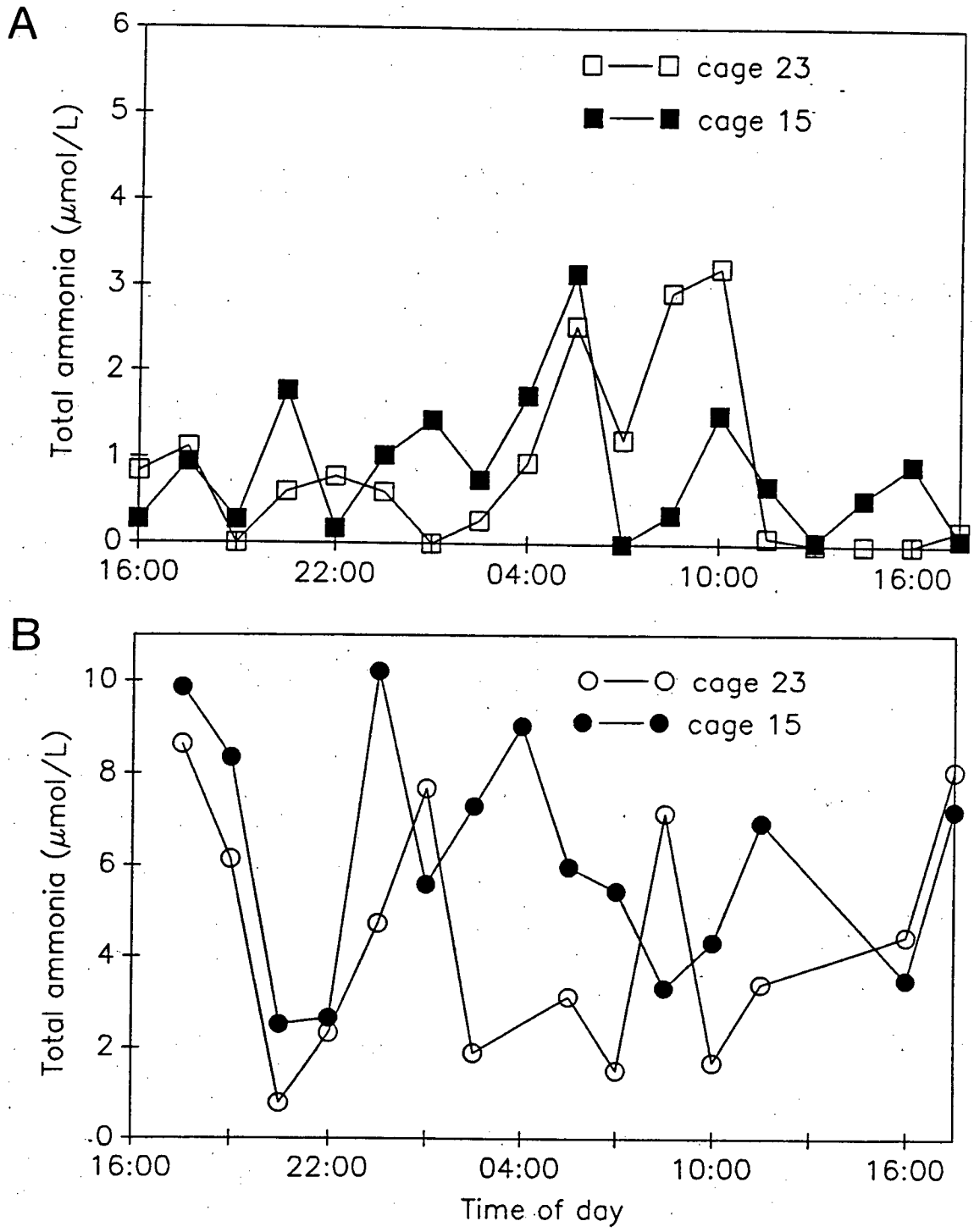


Table 3. Comparisons of DO and total ammonia inside cages 23 and 15 at the JER site. Data were pooled for each depth and location using values collected over the 25 h sampling program. (SD=standard deviation, df=degrees of freedom)

Location	Depth (m)	Parameter	Cage 23 mean (SD)	Cage 15 mean (SD)	t-test t_{calc} (df)	p
JER	1	DO	9.5 (0.8)	9.3 (0.8)	0.682 (34)	0.500
21 July,	6	(mg/L)	7.9 (0.5)	7.1 (0.6)	4.358 (34)	<0.001
1988	11		6.5 (0.2)	6.4 (0.3)	1.382 (34)	0.176
		total				
	0.5	ammonia	0.9 (1.1)	0.9 (0.8)	0.059 (34)	0.953
	6	(µmol/L)	4.4 (2.6)	6.1 (2.5)	1.791 (27)	0.085

Figure 16. Comparisons of ammonia concentrations versus time for cages 23 & 15 at the Jervis Inlet site. Depth of sampling was A) 0.5 m and B) 6 m.



Discussion

The profile experiment (Part A) confirmed Inoue's (1972) and Wee's (1979) findings that nets used in construction of net-cages may restrict water flow up to 80%, depending upon the degree to which they were fouled. It was found that current speeds were diminished by 65% at the depths where the net was fouled by mussels and macro-algae, however at depths below the fouling, current speeds were within ±11% inside and outside of the net-cage. In fact, current speed was ca. 11% greater inside the net-cage than outside at 5 m, perhaps due to the swimming behaviour of the fish. Inoue (1972) found that *Seriola quinqueradiata* (hamachi) may cause a rotating current of 1-3 cm/sec when the ambient current speed falls below 4 cm/sec. Salmonids have also been reported to maintain a circular swimming pattern in net-cages, the direction of which was maintained regardless of tide, season, or age of the fish (Sutterlin et al., 1979). Inoue (1972) indicated that this behaviour would result in water exchange being maintained through the net-cage even during periods of little or no tidal flow.

Overall patterns of flow diminishment across the site are in general agreement with the predictions of Weston (1986). Flow was reduced ca. 30% on the south side of the raft relative to the north, which compares well with Weston's (1986) prediction of 50% blockage. Because neither was the direction of current perpendicular to the raft, nor could the influence of biofouling be accurately measured,

these figures are considered to be in reasonable agreement. The surprising finding in this part of the study, was the apparent directional shift and overall greater current speeds observed in cages 15 and 10. Aside from the doubtful speculation that the swimming behaviour of the fish enhances water velocity in these cages, the most likely reason for this apparent anomaly is that local bottom topography influenced the tidal flow patterns. The location of the raft in an area of many bottom irregularities and islets may put it partially under the influence of topographic steering or an eddy (Pond and Pickard, 1986). Either of these phenomena would also produce the observed anomalies in current speed and direction across the raft by subjecting various portions of the raft to different flow streams.

The dynamics of dissolved oxygen over both depth and time are typical for the Jervis Inlet area. Historical values (DOUBC, 1985 and 1986) indicate that DO ranges from 6.1 to 7.9 mg/L for the summer months at 10 m, which compares well with measured values of 6.5 mg/L at 11 m. The near surface DO varied diurnally, presumably with the diurnal periodicity of photosynthesis and respiration as explained in Chapter 1. Cage 15 DO values were lower than those of cage 23 in spite of the greater current speed in the former. Stocking densities were similar in both cages, but the faster current speed in cage 15 may necessitate a greater swimming speed and hence, metabolic rate by the

fish. An increase in metabolic rate would increase the rate of oxygen consumption as well as increase the rate of ammonia production (McLean and Fraser, 1974). Both these changes in water quality were seen in cage 15 relative to cage 23, which experienced slower water speeds. This finding was surprising, since it found in Chapter 1 that increases in water flow would increase DO and decrease ammonia concentrations. Perhaps the inability to detect a correlation between water quality and water speed in this case, is due to a balance between flushing rate and metabolic rate. As current speed increased, flushing rates increased but metabolic rates would have also increased and thus, little change in water quality was observed.

The location of these two cages within the raft, coupled with the observed flow directions indicates another tenable explanation. Cage 15 is the third cage from the eastern end of the raft, and appears to receive water from the two eastern-most adjacent cages throughout most of the tidal cycle. This flow regime advects DO-depleted, ammonia-loaded, waters from the eastern cages, into cage 15. At the western end of the raft, the predominant current flow was from the outside of cage 23, thereby advecting water that has not already been through surrounding net-cages and was consequently of higher water quality.

In order to compare ammonia enrichment of the water column observed in this study with predicted values, a reference to background levels was needed. Sampling

performed outside cage 23 could be considered to be upstream of the raft for at least part of the tidal cycle. In fact, average ammonia concentrations were lower outside than inside the cages (by 0.4 and 2.7 μmol/L at surface and 6 m depths respectively). Weston (1986) predicted a rise in total ammonia concentration of 0.02 mg/L (=1.4 μmol/L) in waters passing through a farm of similar biomass. Values much greater than predicted were periodically observed within the net-cages. However, Weston was predicting the effect by the whole 250,000 kg farm, and it is doubtful, because of mixing by tidal action, and the rapid uptake of ammonium by phytoplankton (Glibert and Goldman, 1981), that these predicted values would be observed at any great distance from the farm itself.

The only significant difference in DO inside and outside of the cages was observed at 6 m in Cage 23 (Table 2). At this depth the 25 h average difference was 0.4 mg O_2/L, which compares favourably with Weston's (1986) prediction of a 0.3 mg O_2/L decrease.

It is suggested that enrichment of the environment in ammonia is occurring within this farm site. Cruise data (Dr. P.J. Harrison, unpublished data) collected on 28 July, 1987 near Active Pass, in the Strait of Georgia, B.C., indicate that ammonium values never exceed 0.47 μmol/L at 12 m depth. Moreover, a station over the Iona Island sewage outfall, yielded values up to 9.42 μmol/L ammonium. Clearly, hypernutrification of the water column is occurring within

the farm site, but even outside of cage 23, values were never as high as inside, indicating that dilution in the surrounding waters is rapid. Black and Carswell (1986) found that ammonia values downstream of a fish farm which was not in use, but fouled with mussels, were similar to values measured at the same distance downstream from a productive farm. This finding would make it very difficult to assess the true impact of fish farming unless a site deplete of fouling organisms could be found (e.g. immediately after net cleaning).

Increases in biomass, length and chlorophyll a content of the green alga *Cladophora glomerata* have been attributed to increased nutrients near fish farms in the Baltic Sea (Ruokolahti, 1988). In the coastal waters of B.C., nutrient depletion is often the limiting factor in regulating phytoplankton blooms (Harrison et al., 1983) and so any input of ammonia to the environment may serve to increase the frequency and magnitude of blooms. No evidence of increasing bloom frequency has been reported for B.C. waters due to salmon farming, however, intensive fish culture in the Inland Sea of Japan has been suggested to be a source of dissolved organic matter, responsible for increasing the occurrence of toxic red tide causing phytoplankton, *Gymnodinium* type-'65 and *Chattonella antiqua* (Nishimura, 1982).

Conclusions:

Water flow and water quality varied with depth inside net-cages, although they appeared to be unrelated. Observed differences in water flow were due to the presence of mussels on the upper 4 m of the net-cage. Good agreement was found between published and observed values for current diminution resulting from fouling. Observed differences over depth, in DO and ammonia concentrations, were speculated to be a result of fish behaviour and metabolism in conjunction with water flow patterns.

It was found that the use of current flow patterns outside of the raft to predict within raft water flow patterns was sometimes misleading. It was speculated that local topography influenced within site flow patterns to such a degree that in some downstream cages, higher current speeds were experienced than those upstream.

For certain locations within the raft, the raft did influence water exchange in the predicted fashion. Comparisons made using the data collected from the two outside stations, indicated slower current speeds on the downstream side of the raft relative to upstream.

Observed variations in dissolved oxygen and total ammonia concentrations were in agreement with the predictions of Weston (1986).

General Discussion

While some of this study involved comparison of conditions within net-cages in B.C. to those in Japan and Europe, the lack of previous data for local farming conditions and practices made this a necessary first step. Results were found to be comparable to the previous studies with relation to diminishment of current speed, utilization of DO, and build-up of ammonia within a fish farm net-cage. From the perspective of the fish farmer, this information may aid in determination of raft configuration, net-cage depth, stocking density, and geographic location.

The influence of hydrography should always be considered in selecting a site (Landless and Edwards, 1976). Moreover, the presence of eddies, topographic steering, and internal waves through a site must also be taken into account. If discovery of any of these topographically derived problems occurs after the farm site is established, mitigation may be as simple as employing deeper nets with lower stocking density, to allow the fish to inhabit the least physiologically stressful portion of the water column (Pickering, 1981). In the case of differing current speeds within the raft, reorientation of the raft with respect to ambient current patterns may also increase water exchange.

In net-cages at the Jervis Inlet farm, temperatures varied markedly with depth, with the near surface waters remaining too warm for optimal growth (Caine et al., 1987). However, the use of 15 m deep nets, allows a refuge for the

fish below the thermocline, thereby decreasing stress, and hence, increasing growth rate.

The concept of a refuge within the net-cage also applies to avoidance of harmful phytoplankton species, such as the diatom *Chaetoceros convolutus* and the dinoflagellate *Heterosigma akashiwo*, which have killed farmed salmon in B.C. (Pennell, 1988). Current husbandry practices during blooms of these species, includes cessation of feeding and lowering of the nets deeper in the water, in the hopes of keeping the fish out of the near surface waters, where these blooms generally occur (Harrison et al., 1983).

No previous studies on the diurnal periodicity of water quality parameters in marine net-cages were found in the literature. This study fills a gap in the knowledge of these events and, as well, indicates a future direction of research. Water quality monitoring programs, mandatory by law (Anonymous, 1988), may benefit from information gained in this study in terms of selecting the most appropriate time and location within a site for sampling. By sampling in the middle depths of a net-cage, during slack water, and at least 4 h after feeding, the highest concentration of ammonia should be found. DO readings should be taken during slack water, and also over the entire depth of the net-cage, preferably just before sunrise, to ensure that the most critical values are monitored. Sampling in this manner will provide the most useful data to both the farmer and the monitoring agency.

Future work should include a time-series analysis of water quality in and around a fish farm under controlled conditions. A time-series analysis would allow identification of the periodicity of the individual components (e.g. tidal exchange, respiration, and photosynthesis) and thus provide the data needed for modelling the environmental impact of fish farming.

Two sites were visited during this study which varied considerably in daily husbandry practices. Further investigation of these factors (e.g. feeding schedule, stocking density, and feed type) is needed to determine the role they may have in influencing water quality.

Sampling was performed in the summer months with the expectation that high seasonal temperatures would make this time of year the most deleterious to fish in terms of increasing metabolic rate and hence ammonia production. The converse argument is that lower photosynthetic rates in the winter may allow dissolved oxygen to fall below critical concentrations. Future studies should therefore be designed to determine whether or not there is a seasonal component to water quality in fish farms.

Bibliography

Alabaster, J.S. and R. Lloyd. 1982. Ammonia. *In* Water quality criteria for freshwater fish, J.S. Alabaster, and R. Lloyd [ed.] Butterworths for FAO, London 279 pp.

Anonymous. 1988. Environmental monitoring program. Manual for marine fish farms. Min. Envir. Parks, Prov. B.C., 40 pp.

Anonymous. 1989. 'A good year' for salmon in B.C. Canadian Aquaculture, 5(2):31.

Beveridge, M. 1984. Cage and fish pen fish farming. FAO Fisheries Technical paper 255. 131 pp.

Black, E.A. and B.L. Carswell. 1986. The impact of salmon farming on the marine water quality. Fish. Dev. Pap. 11, 83 pp.

Bower, C.E. and J.P. Bidwell. 1978. Ionization of ammonia in seawater: effects of temperature, pH, and salinity. J. Fish. Res. Bd. Canada, 35:1012-1016.

Brett, J.R. and C.A. Zala. 1975. Daily pattern of nitrogen excretion and oxygen consumption of sockeye salmon (*Oncorhynchus nerka*) under controlled conditions. J. Fish. Res. Bd. Canada, 32:2479-2486.

Caine, G., J. Truscott, S. Reid and K. Ricker. 1987. Biophysical criteria for siting salmon farms in British Columbia. Aquacult. Comm. Fish. Branch, Min. Agr. Fish., Prov. B.C., 53 pp.

Davis, J.C. 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. J. Fish. Res. Bd. Canada, 32(12):2295-2332.

DOUBC. 1985. Department of Oceanography, Univ. B.C. British Columbia Inlets Cruises. Data Rep. 54, 45 pp.

DOUBC. 1986. Department of Oceanography, Univ. B.C. British Columbia Inlets Cruises. Data Rep. 55, 53 pp.

Emerson, K., R.C. Russo, R.E. Lund and R.V. Thurston. 1975. Aqueous ammonia equilibrium calculations: effect of pH and temperature. J. Fish. Res. Bd. Canada, 32:2379-2383.

Evrik, A., P. Johannessen and J. Aure. 1985. Environmental effects of Norwegian marine fish farms. ICES C.M. 1985/f:37. 13 pp.

Glibert, P.M. and J.C. Goldman. 1981. Rapid ammonium uptake by marine phytoplankton. Mar. Biol. Lett. 2:25-31.

Gowen, R.J. and N.B. Bradbury. 1987. The ecological impact of salmonid farming in coastal waters: a Review. Oceanogra. Mar. Biol. Ann. Rev. 25:563-575.

Harrison, P.J., J.D. Fulton, F.J.R. Taylor, and T.R. Parsons. 1983. Review of the biological oceanography of the Strait of Georgia: pelagic environment. Can. J. Fish. Aquat. Sci. 40:1064-1094.

Hillaby, B.A. and D.J. Randall. 1979. Acute ammonia toxicity and ammonia excretion in rainbow trout (*Salmo gairdneri*). J. Fish. Res. Bd. Canada, 36:621-629.

Holeton, G.F. 1979. Oxygen as an environmental factor of fishes. p. 7-32. *In* M. Ali (ed.) Environmental physiology of fishes. Plenum Press, New York.

Inoue, H. 1972. On water exchange in a net cage stocked with the fish, hamachi. Bull. Jap. Soc. Scientific Fisheries. 38(2):167-176. (Translated from Japanese by Madelon and Louis Mottet).

Kennedy, W.A., W. Griffioen and A. Solmie. 1977. The 1976 crop of salmon reared on the Pacific Biological Station experimental fish farm. Fish. Mar. Serv. Tech. Rep. 726:21 pp.

Kils, U. 1979. Oxygen-regime and artificial aeration of net-cages in mariculture. Meeresforsch 27:236-243.

Landless, P.J. and A. Edwards. 1976. Economical ways of assessing hydrography for fish farms. Aquaculture 8:29-43.

Lazier, J.N. 1963. Some aspects of the oceanographic structure in the Jervis Inlet system. M.Sc. thesis, department of Physics. Univ. British Columbia, Vancouver, B.C., 54 pp.

McLean, W.E. and F.J. Fraser. 1974. Ammonia and urea production of coho salmon under hatchery conditions. Dept. Envr., Env. Protection Service and Fisheries Service, Rep. No. EPS 5-PR-74-5, 61 pp.

Nishimura, A. 1982. Effects of organic matters produced in fish farms on the growth of red tide algae *Gymnodinium* type-'65 and *Chattonella antiqua*. Bull. Plankt. Soc. Japan. 29(1):1-7. (In Japanese with English abstract and figures.)

Parsons, T.R., M. Takahashi, and B. Hargrave. 1984a. Biological Oceanographic Processes - 3rd. ed. Pergamon Press, New York. 330 pp.

Parsons, T.R., Y. Maita, and C.M. Lalli. 1984b. A manual of chemical and biological methods for seawater analysis. Pergamon Press, pp.101-104.

Pennell, W. 1988. More research needed on phytoplankton. Canadian Aquaculture, 4(5):69-70&78.

Perlman, G. 1986. The Third |STAT handbook. Wang Institute of graduate Studies, Tynosboro, MA 01879 U.S.A.

Phillips, M.J. 1985. Behaviour of rainbow trout, *Salmo Gairdneri* Richardson, in marine cages. Aquacult. Fish. Management., 1:223-232.

Pickard, G.L. 1954. Oceanography of British Columbia mainland inlets. III. Internal waves. Fish. Res. Bd. Can. Pacific Prog. Rep. No.98, 13-16.

Pickard, G.L. 1975. Annual and longer term variations of deepwater properties in the coastal waters of southern British Columbia. J. Fish. Res. Bd. Canada, 32:1561-1587.

Pickering, A.D. 1981. Stress and Fish. Academic Press. London and New York.

Pond, S. and G.L. Pickard. 1986. Introductory Dynamical Oceanography - 2nd. ed. Pergamon Press. Toronto, Canada. 329 pp.

Randall, D.J. and P.A. Wright. 1987. Ammonia distribution and excretion in fish. Fish Physiol. Biochem. 3(3):107-120.

Rosenthal, H., D. Weston, R. Gowen and E. Black. 1988. Environmental impact of mariculture. ICES Cooperative Research Report 154. 31 pp.

Ruokolahti, C. 1988. Effects of fish farming on growth and chlorophyll *a* content of *Cladophora*. Mar. Poll. Bull. 19(4):166-169.

Sutterlin, A.M., K.J. Jokola, and B. Holte. 1979. Swimming behaviour of salmonid fish in ocean pens. J. Fish. Res. Bd. Canada, 36:948-954.

Wee, W.K. 1979. Ventilation of floating cages. M.Sc. thesis. Univ. Stirling, U.K. 38 pp.(exclud. tables and figs.)

Weitkamp, D.E. and M. Katz. 1980. A review of dissolved gas supersaturation literature. Trans. Amer. Fish. Soc. 109:659-702.

Weston, D.P. 1986. The environmental effects of floating mariculture in Puget Sound. Wash. Dept. Fish. and Wash. Dept. Ecol. 148 pp.

Williams, P.J. LeB., R.C.T. Raine and J.R. Bryan. 1979. Agreement between the ^{14}C and oxygen methods of measuring phytoplankton production: reassessment of the photosynthetic quotient. Oceanologica Acta 2(4):411-416.