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The Effect of a Salmon Cage Culture on the Benthic Community in a Largely Enclosed Bay (Dark Harbour, Grand Manan Island, N.B., Canada)

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Abstract

Dark Harbour (Grand Manan Island, N.B., Canada) is a small, enclosed bay with a narrow tidal connection to the sea. The study included bottom surveys to determine the extent of dispersal and accumulation of suspended solids, the tidal current regime, the influence of the cage system on water flow patterns, and comparisons among cage sites on the severity of benthic habitat destruction are presented. The results indicated a substantial accumulation of bottom sludge, irregular patterns of settling of suspended particles, impaired water movements due to the cage structures, and significant changes of the bottom fauna. Possible improvement, by changing cage arrangements, reducing total biomass and adapting operational conditions (changing over from wet to dry feed) are discussed.

Introduction

Recent investigations show that wastes do accumulate under cage farm sites, especially if these are located in shallow and well-protected bays (Braaten *et al.*, 1983; Bergheim *et al.*, 1982; Eklund, 1986; Beveridge, 1984; Mäkinen, 1984; Rosenthal, 1983; Rosenthal *et al.*, 1988). The fate of

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organic solids, waste food and faeces, will depend on the strength, duration (within a tidal cycle) and direction of the water currents. Wind-generated surface currents are important in mixing surface waters and may, therefore, contribute to the distribution pattern of the less rapidly settling particles, especially during slack tide. Tidal-generated currents, however, move the greatest amount of water and contribute most to the dispersal of wastes below cages. The paper reports on some findings of a preliminary study on sedimentation and settling of suspended solids at a unique salmon cage farm site, located in a largely enclosed bay: Dark Harbour, Grand Manan Island, New Brunswick, Canada. The survey was intended to determine the extent of dispersal of fish wastes and whether their accumulation is restricted to the area directly below the cages. Further, the study describes briefly the differences in severity of benthic habitat destruction between cage sites.

Material and Methods

The culture site

The cage farm site is located in a well-protected bay (Figure 1) on Grand Manan Island, New Brunswick, Canada. Dark Harbour is unusual because of its elevation above mean water levels in the Bay of Fundy; therefore, the tidal cycles are not of equal duration. The length of time from a dead low to a full high tide is approximately 3 hours, whereas from a high to the next low tide is about 9 hours. There is only one tidal inlet, about 20 m wide, to accommodate about 545,500 m^3 of incoming seawater in three hours (approximate area of the harbour is 259,688 m^2 with a water exchange volume at 2.1 m tidal height of 545,350 m^3). This tidal water fluctuation level is relatively low when compared to the surrounding Bay of Fundy. The current velocity through the inlet can reach 4 m/sec. These currents dissipate quickly as the harbour widens and deepens. They also last only for a short time. Ebb currents are weaker since the water drains out of the harbour over a period of about 9 hours. The overall effect of this is that settling of suspended solids may be supported more than wanted for cage farming. The incoming currents are also partly deflected by a fence, two herring weirs and the cage flotillas themselves.

Fish stock

Unfortunately it was impossible to obtain exact data on the actual biomass of fish in the system during the observation period. Many fish were moved during this period from one site to another while other cage units were frequently graded, cleared out or restocked. It can be assumed that about 80% of the cages contained fish at any one time during the study period and stocking densities varied from about 5 to 20 kg/m^3, depending on whether smolts, ongrowing fish, or brood stock were kept in the cages, at its maximum expansion. At one point in time the farm employed a total of about 64 cages. In July 1986 there were about 80,000 fish from the 1985 stock and approximately 50,000 fish from the 1986 stocking.

Measurements

Temperature and salinity

Temperature and salinity were measured at selected stations and depths from June through August 1986. The stations were selected to reflect the range of possible daily and summer seasonal fluctuations. Most stations were sampled twice on the same date, before and after flood tide. Salinity and temperature were recorded using a Beckman RS5-3 envirobridge induction salinometer.

Water currents

In order to obtain an overview on prevailing currents part of the study concentrated on continuously measuring the speed and direction of currents in various places. The meters employed were Markdan models SD – 4. The 16 readings were retrieved from the electronic memory by passing a magnet over a switch encased in the waterproof case. The current range of the meters is 0-100 cm/s with a resolution of 1 cm/s. The compass resolution is 7.5°. Surface readings were taken at 230 cm (mid-cage depth) below the surface and the bottom readings were taken at 150 cm above the substrate (the surface readings were more numerous than the bottom readings). The current speed and direction for flood and the following ebb tide were recorded.

Secchi disk readings

The Secchi disk was 20 cm in diameter and made from white plexiglass, with a 5 cm neutral grey band painted around the periphery. The disk was weighted below, strung through the center then lowered over the side of the boat. Readings were taken on seven dates from July 15 to August 26, 1986. The measurements were taken immediately prior to flood tide.

Benthic observations

All benthic samples were collected by SCUBA diving. A hand-held substrate corer (7.5 cm diameter, 25 cm long; area 85 cm^2) was used for soft substrate samples. For the rock substrate at sites 1 and 2, the contents of a 0.25m^2 quadrat were sampled. The contents of each core were sieved through a 1 mm^2 mesh, which retained only macrobenthos. These samples were preserved in formalin for later analysis. All macrobenthos were counted for each sample collected; however, for the purpose of the present study, only the abundance and percent abundance of two indicator species *Capitella capitata* and *Polydora* spp. (mostly *ligni*) were calculated. *Capitella* is an opportunistic species which tolerates sediment conditions of high organic loadings with low oxygen levels other species would not survive. The presence of *Polydora* in conjunction with a high species diversity and a low percentage abundance of *Capitella* is considered to be an indication of good environmental conditions in benthic soft substrates.

Results

Temperature and salinity

The water temperature ranged from 6° to 7°C in June, and 11° to 12°C in July and August. There was adequate water exchange with the open sea to keep water temperatures in the harbour far below dangerous levels for salmon culture. The highest recorded surface water temperature was 14.4°C.

The salinity of the harbour water below the surface was fairly constant during the observation period in 1986, ranging between 30 and 31‰ S. There was considerable input of fresh water from rainfall and runoff, and surface salinity dropped for only short periods of time; these reductions were substantial in the top 10 cm following heavy rainfall, and on one occasion the salinity was only 13.4‰. The low salinity lens which formed on the surface became more saline as it mixed with incoming water at each successive flood tide.

Secchi disk readings

Secchi disk readings provided some insight into the overall turbidity of the incoming and outgoing water masses, although samplings took place over too short a period of time to observe clear trends. Readings varied between 3 m (white disk) in July, to 4 m in late August. The flood tide made the water more turbid during July; however, in August there was no significant difference in turbidity following flood tide. The poor water clarity in July occurred during periods of heavy rainfall and good plankton growth. The clearer water following flood tides in August indicates that the tidal action was not re-suspending existing settled solids in the harbour.

Current readings

The current readings for flood and the following ebb tide were analyzed for each station. The results are summarized in the maps of Figures 1 and 2, representing typical situations during flood and ebb tide.

The flood current in the harbour flows clockwise but it appears that water currents are deflected at cage site 1, due to impeding cage fences and herring weir structures. The ebb tide flows towards the outlet (Figure 3) but more directly towards the central channel before leaving the harbour.

At site 1 flood currents were frequently weak, often less than 10 cm/s. The dominant current direction was towards the outlet but with much variance. At the southwest side, the mean flood current was 3.8 cm/s (SE ± 0.48) and the ebb current was 1.1 cm/s (SE ± 0.22). The flood currents were strongest at the north side of cage site 1 (Figure 2, meter sites 2 and 2b). The mean flood tide was 2.5 cm/s (SE ± 0.5) and the ebb was 0.4 cm/s (SE ± 0.22 cm). Closer to the channel, the readings resulted in flood means of 4.3 and 4.9 cm/s at the surface, and the ebb values were 1.3 and 1.2 cm/s. The current kept the bottom clear under the side cages so that suspended solids did not accumulate. Meter site 5, at the southeast side of cage site 1, was within 10 m of the cage site and was out of the main current flow of the central channel of the harbour. The mean flood reading was 1.9 cm/s (SE ± 0.82) and the mean ebb reading was 10.8 cm/s (SE ± 0.95). Three readings were taken at the meter site 4, at the south-west side of cage site 1. The mean readings were 1.1, 1.0 and 2.4 cm/s (SE ± 0.31, 0.28, 0.30), indicating the largely reduced current speed was due to location and the cage structure itself. At cage sites 3 and 4 there was only one meter site for this area. The currents here were very low. The mean surface flood reading was 0.1 cm/s (SE ± 0.06), the mean surface ebb was 0.2 cm/s (SE ± 0.14). The currents at cage sites 5, 6 and 7 follow the general pattern of clockwise current flow in the harbour. The dominant flood currents tend towards the south and the southwest, and the ebb currents flow more towards the west. The strength of water currents in this area were weaker than at cage site 2 but were stronger than at cage site 1. In general, current speeds quickly dissipated behind each flotilla during flood tide and ebb currents were reduced even further in speed.

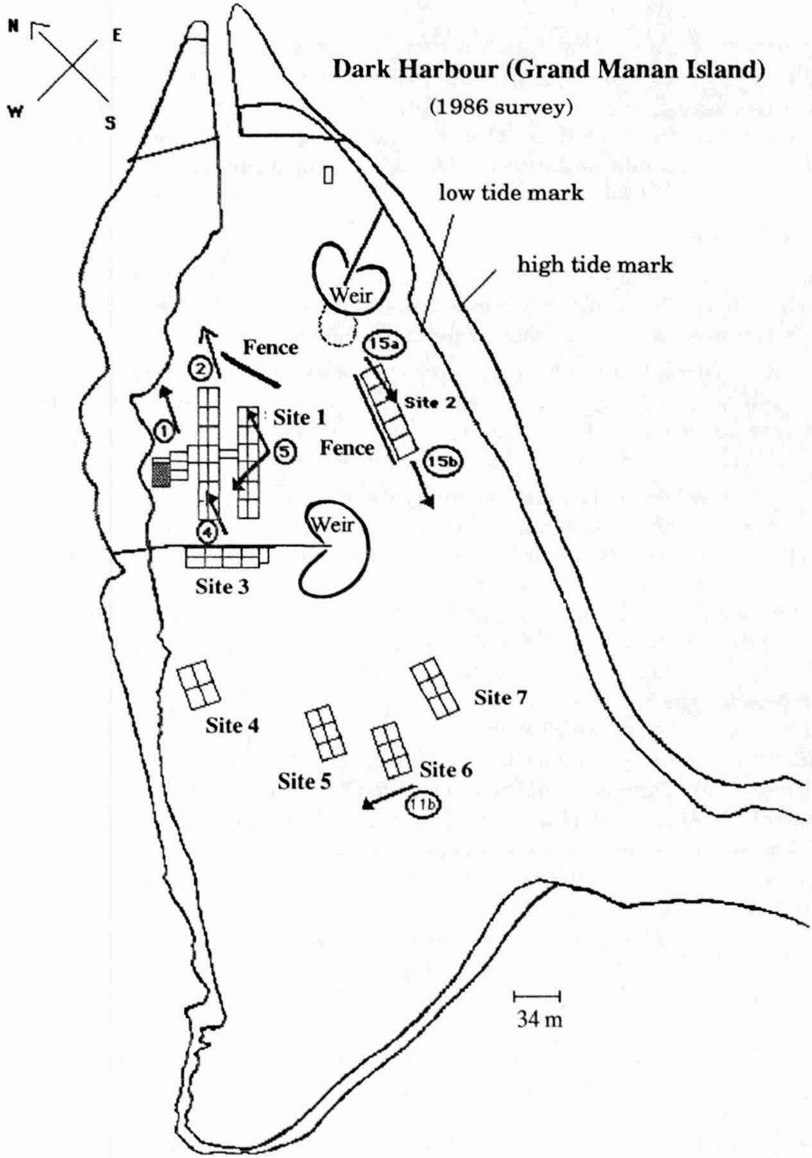

Figure 1: Salmon cage farm in Dark Harbour, Grand Manan Island, New Brunswick. Location of flotillas and average bottom current direction during flood tide. Circled numbers = positions of flow-meters.

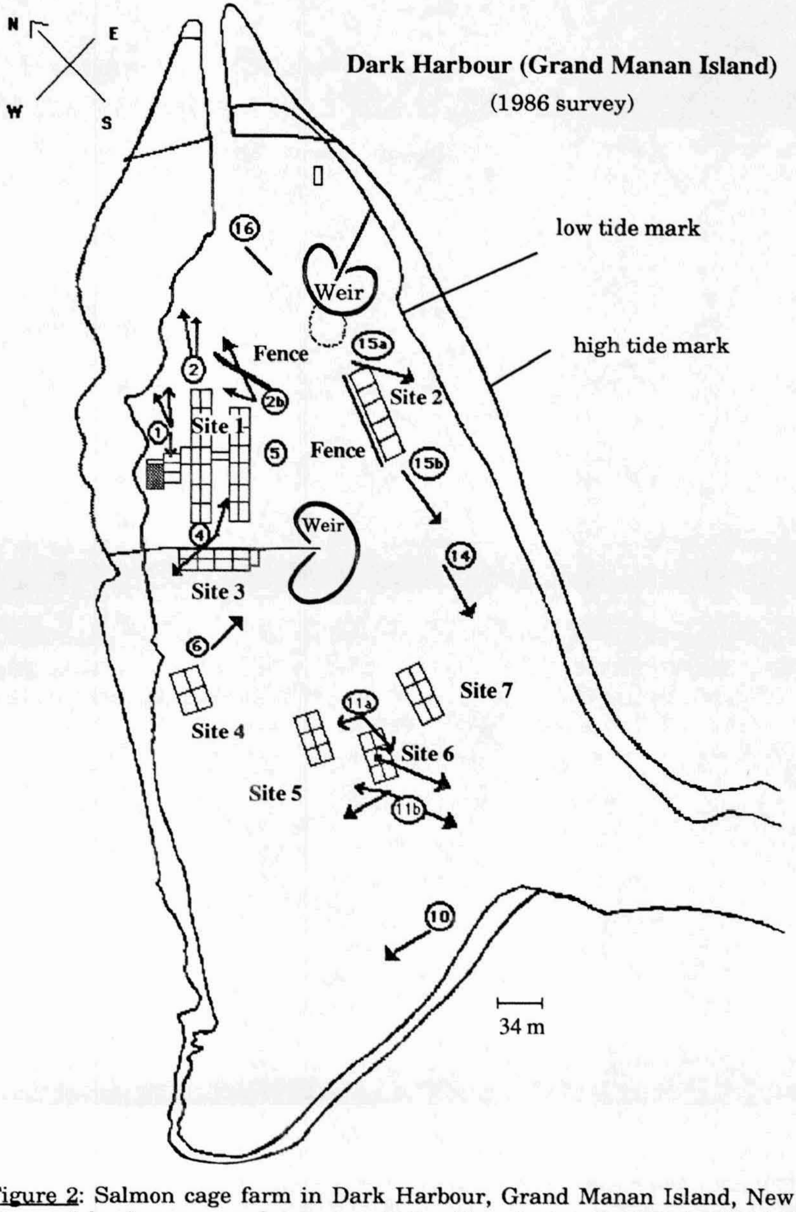

Figure 2: Salmon cage farm in Dark Harbour, Grand Manan Island, New Brunswick. Average surface current direction during flood tide. Circled numbers = positions of flow meters.

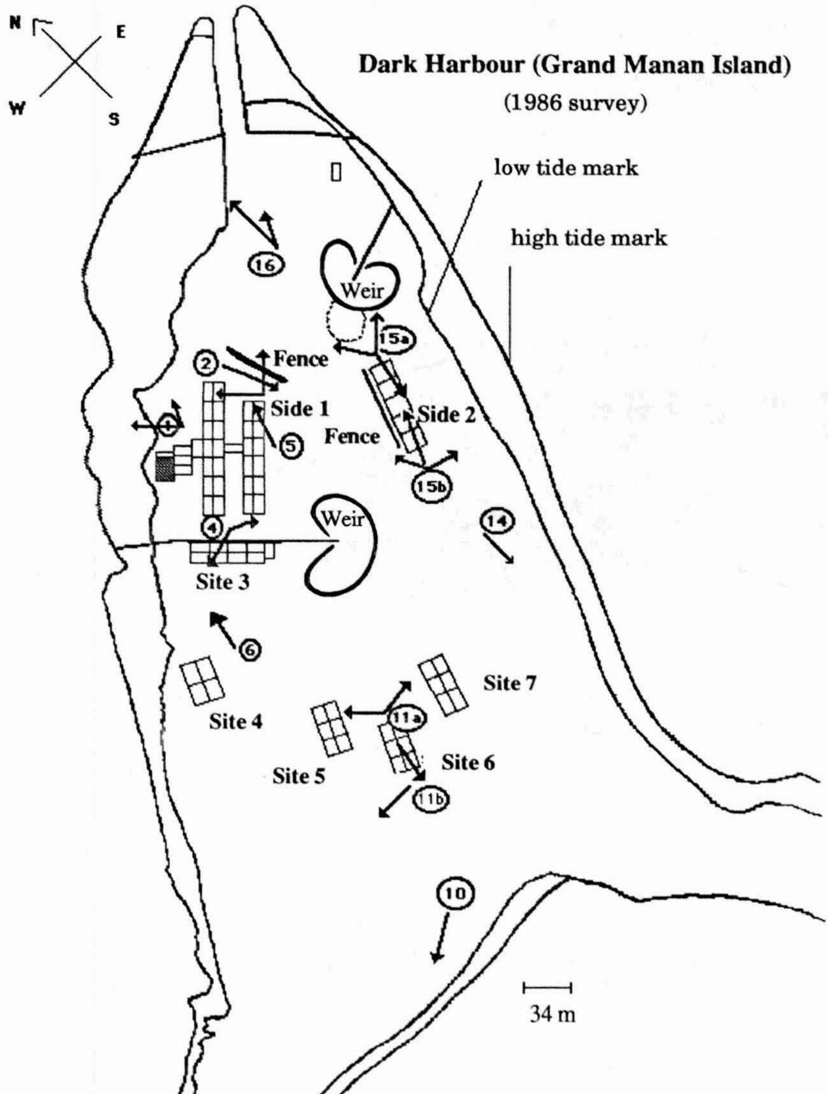

Figure 3: Salmon cage farm in Dark Harbour, Grand Manan Island, New Brunswick. Average surface current during ebb tide. Circled numbers = positions of flow-meters.

Benthic conditions during the 1986 surveys

Site 1 had the poorest benthic conditions of all cage sites in Dark Harbour. Organic loading was also highest at this site, reaching up to 1,633kg of feed per day (as moist pellets); it is also the oldest site, established in 1980. Because of heavy organic loading and low water currents at this site there was a deep layer of anoxic sediment below all the cages, which was covered with a flocculent layer and white patches of *Beggiatoa* colonies. At no time during the summer did an animal benthic community exist at site 1. The effect of the low currents at this site was that the sediment did not disperse beyond the limits of the cages. A poor to good benthic community existed at the northeast and southwest ends of the cage site. A healthy, mixed rock and mud community was found at the north end of the cages.

At site 2, the current kept the bottom clear of accumulated wastes below the six north side cages. Below the other cages, some mud did accumulate; however, the dispersal of waste continued at least 15 m to the east, west and south of the cages. Table 1 represents the data obtained from two surveys (July and September). While the July data show low numbers of *Capitella* and high numbers of *Polydora* at the center of the north end, a much higher abundance of these two species was encountered at the west end of the site. In September, the abundance was relatively high at all sampling points for *Capitella*, while much lower values were encountered for *Polydora*. The diversity index was not as high as one would expect in an area with relatively low waste accumulation. This may be due to the shallow depth of natural sediments for infauna life.

The benthic conditions at site 3 were very poor and nearly as poor as at site 1. Of 11 sample cores, only five yielded any macrobenthic organisms (Table 2). Approximately 75% of the bottom surface of this site, in the northwest direction, had only *Beggiatoa* colonies and a considerable accumulation of anoxic sediments.

Site 4 was used as the brood stock site during the 1986 observation period. Therefore, only a limited number of fish were held in the cages here. Nevertheless, the benthic conditions at this site were very poor; the very shallow waters most likely contributed to the problem, frequently exposing fish to elevated suspended solid loads in near-bottom waters. There was less than 1 m clearance below the cages at low tide. *Beggiatoa* colonies were present at the northeast corner of the site. No sample cores were taken at this site.

At site 5, core samples from the east half of the site were analyzed and data are given in Table 3. Whole pieces of food pellets and faeces were scattered undisturbed on the sea floor under this site but the east side was in good condition. The west side, however, had large patches of *Beggiatoa* and no macrobenthos.

Table 1: Results of the benthic survey at Site 2, July 9 and September 12, 1986. Abundance and percent abundance, of total macrobenthos, of *Capitella capitata* and *Polydora* spp., species richness and diversity index (Hs) of each sample.

sample location cage #	abundance/m^2 *Capitella*	*Polydora*	% abundance *Capitella*	*Polydora*	species richness	Hs
15	5453	4658	52	44	5	0.89
7	8747	568	92	6	4	0.35
41	341	0	100	0	1	0.0
10	4203	454	86	9	5	0.53
11	7838	227	92	3	6	0.40
17	3862	227	94	6	2	0.22
16	6589	795	83	10	3	0.57
45	2386	341	88	12	2	0.38
18	4317	114	97	3	2	0.12
21	1363	114	75	6	5	0.91
$\bar{x}$	4510	750	86	10	3.5	0.44
S.E.	17	12	1.2	1.1	0.4	0.17
10m west	1136	2954	23	61	4	1.01
10m east	24878	227	76	1	4	0.66
10m south	2386	341	64	3	4	0.86
				July 9		
centre of	227	4544	4	83	7	0.74
north end	0	0	0	0	0	0.0
west side	2726	5907	29	63	6	0.96
of site	0	0	0	0	0	0.0
$\bar{x}$	738	2613	8	37	3.3	0.43
S.E.	18	28	2	3	1.0	0.35

Table 2: Results of the benthic survey at Site 3, August 21, 1986. Abundance and percent abundance, of total macrobenthos, of *Capitella capitata* and *Polydora* spp., species richness and the diversity index (Hs) of each sample.

sample location cage #	abundance/m^2 *Capitella*	*Polydora*	% abundance *Capitella*	*Polydora*	species richness	Hs
between 68 & X	1590	0	74	0	4	0.83
east cage 25	3749	0	97	0	2	0.13
68	568	0	83	0	2	0.45
east cage X	1022	341	56	19	6	1.33
west cage 25	3976	0	92	0	2	0.28
5	0	0	0	0	0	0.0
between 5 & 54	0	0	0	0	0	0.0
1	0	0	0	0	0	0.0
47	0	0	0	0	0	0.0
between 25 & 47	0	0	0	0	0	0.0
between 25 & 67	0	0	0	0	0	0.0
$\bar{x}$	991	31	37	1.7	1.5	0.27
S.E.	12	3	2	0.7	0.4	0.20

Table 3: Results of the benthic survey at Site 5, September 15, 1986. Abundance and percent abundance, of total macrobenthos, of *Capitella capitata* und *Polydora* spp., species richness and the diversity index (Hs) of each sample.

	abundance /m^2 *Capitella*	*Polydora*	% abundance *Capitella*	*Polydora*	species richness	Hs
	454	454	24	24	8	1.8
	1363	454	52	17	6	1.4
$\bar{x}$	909	454	38	21	7	1.6
S.E.	18	0	3	1.6	0.8	0.4

Site 6 did not exist before July 25, 1986, and was sampled on the day it was established and again on September 15. The high animal diversity, with a mean of 14 benthic species, indicated a healthy bottom fauna before the cages were installed. There were four sample cores taken on September 15; two of them had no animals in them and were excluded from the analysis presented in Table 4. The results from the two remaining samples taken on September 15, indicate the adverse effect within two months on the benthos from the organic loading derived from salmon farming. The poor benthic conditions were observed to extend a few metres around the cage site. However, there was no *Beggiatoa* under site 6, nor immediately around it (within 10 m). There were, however, many flounders – mostly winter flounder - at a rough estimated density of 1 per 4 m^2.

Table 4: Results of the benthic survey at Site 6, July 25 and September 15, 1986. Abundance and percent abundance, of total macrobenthos, of *Capitella capitata* and *Polydora* spp., species richness and diversity index (Hs) of each sample.

sample location cage #	abundance/m^2 *Capitella*	*Polydora*	% abundance *Capitella*	*Polydora*	species richness	Hs
mid-site	909	10906	4	46	21	2.00
"	2954	5794	27	54	7	1.20
"	682	9429	5	66	16	1.40
"	7725	16926	23	49	14	1.50
"	2158	5226	17	40	13	1.80
$\bar{x}$	2886	9656	15	51	14.2	1.60
S.E.	24	31	1.4	1.4	1.0	0.30
			September 15			
east centre	1363	114	92	8	2	0.27
west centre	6134	0	96	0	3	0.11
$\bar{x}$	3749	57	94	4	2.5	0.19
S.E.	41	6	1.2	1.7	0.6	0.24

Brief benthic survey in May 1987

Using SCUBA gear as a follow-up to the 1986 study, an observational survey of selected sites in Dark Harbour was conducted over a three-day period from 29 to 31 May 1987.

The benthic condition of site 1 was still poor despite reduced organic loading over the past few months. Below all cages - those empty and those with smolts - and below the former processing shed location, was a heavy accumulation of anoxic sediment with a flocculent layer and white patches of *Beggiatoa* colonies. In 1986 at site 2, there was frequently a strong flood tide water current that kept the six north cages clear of mud. In 1987, a 1-2 cm layer of soft sediment had accumulated under the two northern cages of the flotilla, while the next four cages and the area between site 2 and the new processing shed location were covered with a 3-6 cm thick layer of anoxic sediment, all covered by *Beggiatoa* colonies. Visits to site 5 and 7 indicated that these had further deteriorated since the last survey in 1986. Although there was little anoxic sediment, patches of *Beggiatoa* were found this time between cage sites 6 and 7. The areas north and east of site 7 were surveyed up to about 30 to 40 m from the cage site and up to about 15 m south of the cage site. These areas had seriously deteriorated since they were last inspected in 1986, and the outside areas were covered to almost the same extent as those underneath the cages. The overall situation described above is schematically depicted in Figure 4.

Non-cage site areas

The benthic substrate type throughout most of the sublittoral zone in Dark Harbour was mud and sandy mud as well as some hard bottom, mostly mixed pebbles and boulders. Twenty 0.25 m^2 bottom samples were randomly taken from these areas and the biota was very diverse and typical of hard bottom organisms. The most commonly occurring species included sea urchins, sea stars, sea cucumbers, sponges, barnacles, anemones, tunicates, limpets, chitons, scallops, blue and horse mussels, rock and hermit crabs, and a variety of winkles, whelks, polychaetes and amphipods. Near cage site 1 the substrate ranged from mixed mud and pebbles at the north end to mud only at the south end of the cage site. Along the seawall, from cage site 1 to the southwest corner of the harbour was a rocky littoral zone extending on a steep gradient through the sublittoral until leveling off, at 9-12 m depth (low-water), to a mud bottom. A rich seaweed community exists along the seawall.

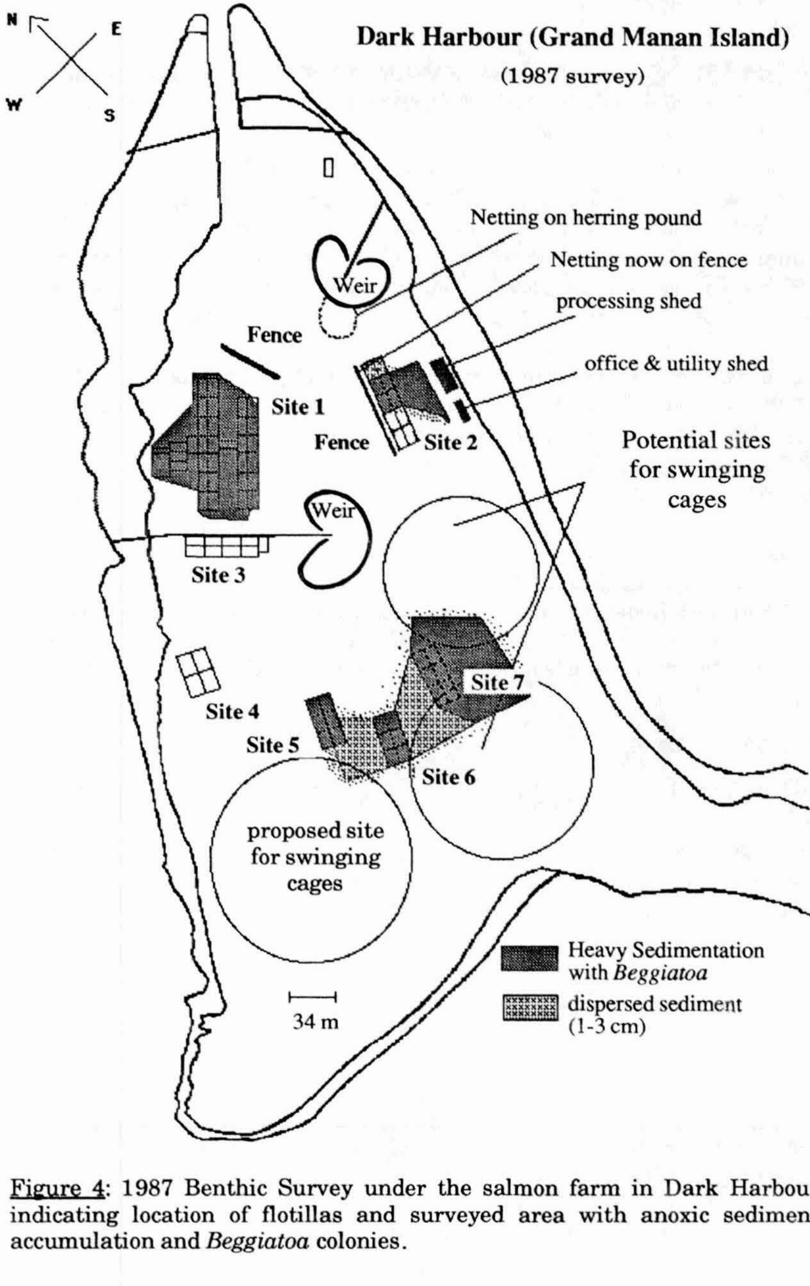

Figure 4: 1987 Benthic Survey under the salmon farm in Dark Harbour indicating location of flotillas and surveyed area with anoxic sediment accumulation and *Beggiatoa* colonies.

Discussion

Although the survey was very labour intensive, time constraints and the limited equipment available at the time put limits on the total area surveyed, the number of samples taken, and the type of data collected. While this was unfortunate from a statistical point of view, in terms of providing a quick picture of the overall benthic conditions and giving advice on how to manage the site in the future, the survey was more than adequate.

The results of the benthic surveys indicate that the heavy organic loading at most cage sites had a detrimental effect on the benthic communities. The use of indicator organisms in this survey provided some means of comparing cage sites. Clearly, cage site 1 was in very poor condition and may have had a direct effect on the health of the salmon. Fish may have suffered some gill damage from hydrogen sulphide bubbles released from the microbial degradation of organic matter. Increased levels of suspended solids in near-bottom waters may have placed additional stress on fish through enhanced oxygen consumption, particularly during slack tide. The build-up of organics and the gas ebulation prompted the management to pump out the sediments at this site, once during the spring of 1985 (5 years after the beginning of operation) and again during the summer of 1986. As revealed by our survey in September 1986, at least 8 cm of newly-accumulated mud was observed, and this just 4-5 weeks after the previous pumping.

Clearly, site 2 was in much better condition in comparison to the problems encountered at site 1; however, the wastes from this site were also exported to the south end of the harbour, contributing to the overall increased loading of the bay.

The poor conditions encountered at site 3 were not really due to an overloading of this specific site, but were mainly caused by the greatly restricted water-flow rates caused by the extented herring weir and the fence installed directly next to the cages.

In general, the water depth (5 to 12 m) in Dark Harbour must be considered as insufficient for permitting long-term cage culture of salmon. Recently recommended depths for salmon culture in protected coastal bays are much deeper (Rosenthal, *et al.* 1988). The existing load of salmon cages in Dark Harbour must be estimated as twice as high as this enclosed bay can possibly handle. This would be realistic only if most of the cages could be relocated to those sites where currents are more steady and longer lasting and where all installations that restrict water movements (weirs and fences) are removed.

Some management plans were already implemented for mitigating environmental effects. The west bank cages on site 1 have been empty since mid-April 1987; restocking of 12 cages of smolts on this site took place as late as early May. It is also the intention to clear out Site 3 in summer, beginning in early June. The processing and grinding sheds were already moved to the shore opposite site 2 in late February 1987. The fish grinding machinery has been dismantled since the recent conversion to exclusively dry feed.

There is a plan to install one set of swivel cages and possibly others at a later date, eventually replacing the fixed cages. It is predicted that the overall effect of the cage farming activity on the environment would not be reduced by using this strategy, unless the total fish biomass in this enclosed bay is substantially reduced.

The inlet of the harbour, however, is too narrow to permit faster currents during the outgoing tide. This narrow channel with its restricted water outflow provides good protection against bad weather conditions but is also the cause for the extended slack tide which critically increases the retention of water masses within the cages and supports settling-out of suspended solids. The pumping of anoxic sediments in 1985 and 1986 and the rapid rate that these sediments returned indicates that excessive loading has already been a problem for several years. Unless the management not only changes the location of the cages but at the same time also reduces the total number of cages and the stocking density, it is predicted that the farm will encounter serious problems in about 2 to 3 years and may have to close down at least temporarily to allow for an extended recovery period.

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