ESTIMATION OF SUSTAINABLE SALMON PRODUCTION IN BIG GLORY BAY, STEWART ISLAND

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ESTIMATION OF SUSTAINABLE SALMON PRODUCTION IN BIG GLORY BAY, STEWART ISLAND

A study conducted for MAFFish

by

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INTRODUCTION.

This study was carried out by the Water Quality Centre, DSIR, Hamilton under contract to MAFFish, Christchurch. The objective of the study was to determine the carrying capacity (in terms of sustainable salmon farming production) of Big Glory Bay.

It was agreed not to carry out the proposed work on site characterisation measurements and specific licence areas set out in the Contract Proposal dated 6 November 1987.

The emphasis in this report is to determine the maximum salmon production likely to maintain water quality in Big Glory Bay at a level where it will not prejudice salmon farming in the long-term. This is the primary concern of MAFFish. There may be other constraints placed on salmon farming in the bay (eg to maintain water classification standards, or to protect important biological communities in the bay). The Water Quality Centre has undertaken other studies under contract to the Southland Catchment Board and the Department of Conservation which address these latter aspects of salmon farming operations but the results of that work are not covered here.

The physical characteristics of Big Glory Bay are summarised in Table 1.

CONCLUSIONS & RECOMMENDATIONS.

1. The existing farms cause a detectable increase of nutrient concentrations in Big Glory Bay. A major expansion of salmon farming could cause eutrophication leading to high concentrations of phytoplankton. Farming in Big Glory Bay could cause eutrophication in Paterson Inlet.

2. There are no widely accepted guidelines for the 'safe' concentration of phytoplankton which will not cause problems with sea-cage rearing of salmon.

3. Fish deaths may occur at very low chlorophyll concentrations if toxic phytoplankton are present. Toxic species are present in New Zealand waters but no toxic blooms have been reported in Big Glory Bay. At present not enough is known about toxic algae to predict their incidence.

4. Eutrophic conditions with regular phytoplankton blooms probably pose a long-term threat to the sustainability of salmon farming. A maximum chlorophyll concentration of about 15 mg m^{-3} is indicative of eutrophic conditions and we recommend that this be the maximum concentration for Big Glory Bay.

5. We estimate that maximum chlorophyll concentrations of 15 mg m^{-3} are likely if 'available' nitrogen concentrations approach 300 mg m^{-3} which is likely if total salmon production in Big Glory Bay exceeds 5000 t yr^{-1}. If salmon farming starts in Paterson Inlet then these figures would need to be revised. Allowing a wide safety margin we recommend that total salmon production in Big Glory Bay should not exceed 3000 t $year^{-1}$ without further investigations of eutrophication (cf. present production of 800 t yr^{-1}).

6. Oxygen consumption by waste accumulations on the sea-bed underneath salmon farms is unlikely to cause serious oxygen depletion in mid-water provided there is a minimum separation of about 250 metres between farms (including old farm sites). Oxygen depletion may occur just above the bed when currents are weak and so cages should not be closer to the bed than 5 metres.

7. Oxygen consumption by salmon themselves lower dissolved oxygen (DO) concentrations by up to 1 g m^{-3} at the existing farms. Depletion above 2 g m^{-3} could stress salmon and at sites where the minimum current is 5 cm s^{-1}, such depletion is likely if farms exceed 50 metres equivalent radius. A minimum separation of 500 metres between farms should ensure that DO depletion from one farm does not affect another. At present stocking rates this implies that the

sustainable salmon production is 3400 t yr^{-1}, comparable with our recommended limit to prevent eutrophication.

8. Preliminary modelling suggests that the evolution of toxic hydrogen sulphide from the accumulations of solid waste under salmon farms is a potential problem at all licence sites under worst-case mixing conditions (calm conditions, low currents, and large accumulations of wastes) although no direct evidence could be found of toxicity at the existing farms. It is likely to be a major problem at shallow, poorly flushed sites near the head of the bay. Hydrogen sulphide problems could extend 250 metres down-current from the farms and 7.5 metres above the bed. Further work on hydrodgen sulphide is required.

9. A large amount of biogas is generated by the solid wastes which accumulate under the salmon cages. The gas bubbles have the potential to transport pathogens upwards from the sediments into the cages and could lead to future fish health problems.

10. Dense swarms of jellyfish periodically cause problems in Big Glory Bay; clogging nets, reducing the flow of water and leading to fish deaths by suffocation. The medusae take several weeks or months to develop and hence are unlikely to be derived solely within the bay. Their numbers are unlikely to have increased as a direct result of salmon farming.

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FACTORS LIMITING SALMON PRODUCTION.

Based on existing information, the Contract Proposal identified two factors which were considered most likely to limit salmon production in Big Glory Bay (Weston 1986): eutrophication; and the accumulation of wastes under the pens. Field surveys, laboratory investigations and modelling studies were undertaken to address these two problems.

EUTROPHICATION.

Sea-cage rearing of salmon results in the liberation of nutrients (in the form of soluble excretion products, faeces and uneaten food) which have the potential to increase nutrient concentrations in the waters of Big Glory Bay and to stimulate the growth of phytoplankton. Blooms of phytoplankton affect water colour and clarity; algal respiration can potentially deplete dissolved oxygen concentrations at night; and if toxic algae are present they can kill fish.

During field surveys in February 1988:

(a) water soluble nutrient concentrations at a depth of 5 m were measured in single samples collected at 10 sites along a 400 m transect at each of two salmon farms (Figure 2). Surface currents (10-15 cm s^{-1}) were flowing at the time from west to east.

(b) depth averaged nutrient and chlorophyll concentrations were measured in single samples at 10 sites along a transect through the bay (Figure 3).

(c) nutrient concentrations were measured at 4 depths at the entrance, in the middle, and near the head of the bay.

(d) phytoplankton growth rates were measured using C^{14} uptake.

The surveys were conducted on 23-24/2/88 when moderate westerly winds had been blowing for 3-4 days following a long period of light winds. There was a strong surface flow out of the bay throughout the sampling period and a deep counter-current into the bay.

At both sites soluble phosphorus concentrations were higher at and down-current from the farms than up-current. At site MFL338 soluble nitrogen concentrations were elevated within 20 metres of the farm but there did not appear to be a gradient at site IN52 (Figure 2). Concentrations of soluble nutrient within the bay were higher than concentrations measured at the entrance in deep water flowing into the bay (Figure 3). Note that the surface waters at the entrance were flowing out of the bay under the influence of the moderate westerly wind at the time of these surveys, which caused the depth average concentrations to be comparable with the concentrations in the bay. Thus nutrient concentrations are high in Big Glory Bay almost certainly as a result of excretion by salmon, leaching from food particles and release from waste accumulations under the cages. Edwards (1988) and Gillespie & MacKenzie (1982) also found high nutrient concentrations near salmon farms, especially close to the bed.

Nitrogen is almost invariably the nutrient which is in shortest supply and hence limits algal growth in marine waters. The average ratio of particulate nitrogen to particulate phosphorus in Big Glory Bay during February 1988 was 6.9:1, indicating phosphorus sufficiency in the phytoplankton (Boynton et al 1982). Both nitrogen and phosphorus concentrations in the bay were predicted and compared with observations on 24/2/88 to check the nutrient model (described below) but thereafter only nitrogen predictions were used in estimating phytoplankton yields.

Table 2 summarises estimates of the nutrient inputs made from published data together with measurements made during field studies. Fish nutrient release rates are based on published data which do not distinguish between dissolved nutrients (which directly influence water quality) and particulate nutrients (eg faeces and uneaten food) which eventually settle on the bottom. By including an additional input from the sediments, the total input in Table 2 may have been overestimated. The overall uncertainty in these inputs is high, perhaps of the order ± 50%. Nevertheless they enable predictions to be made of nutrient concentration in Big Glory Bay which can be checked by comparison with concentrations measured during recent field surveys.

Table 1. Physical characterisics of Big Glory Bay.

Surface area		11.9 km^2
Volume at mid tide		0.189 km^3
Tide range	mean neap	1.34 m
	mean spring	1.95 m
Tidal prism	mean neap	0.0159 km^3 $tide^{-1}$
	mean spring	0.0232 km^3 $tide^{-1}$
	average	0.020 km^3 $tide^{-1}$
Catchment area (including bay)		27 km^2
Mean rainfall at Oban		1500 mm $year^{-1}$
Estimated mean evaporation		500 mm $year^{-1}$
Estimated mean annual freshwater inflow		850 l s^{-1}
Area of existing salmon farms		1-2 ha
Total salmon production in 1987		800 tonne

Table 2. Estimated 'available' nutrient inputs to Big Glory Bay

	Nitrogen $kg\ d^{-1}$	Phosphorus $kg\ d^{-1}$
Rainfall	12	0.2
Freshwater inflow	20	2
Fish nutrient release	220	54
Sediment release	200	100
Total	452	156

Notes:

1. Rainfall. 5 mg(P) m^{-3} &
235 mg(N) m^{-3} (Rutherford et al 1987)
Rainfall=1500 mm yr^{-1}. Area of bay=12 km^2
2. Freshwater. 0.5 kg(P) ha^{-1} yr^{-1} &
5 kg(N) ha^{-1} yr^{-1} (Rutherford et at 1987)
Catchment area=15 km^2
3. Excretion. 25 g(P) kg^{-1}(fish produced) yr^{-1} &
100 g(N) kg^{-1}(fish produced) yr^{-1} (Weston 1986)
Fish production=800 t yr^{-1}(MAFFish, unpub)
4. Sediment. 5 g(P) $m^{-2}d^{-1}$ &
10 g(N) m^{-2} d^{-1} (this study)
Area of waste patches=2 ha.

Nutrient concentrations in Big Glory Bay are affected by the rate of exchange of water with Paterson Inlet, the nutrient concentration in Paterson Inlet, and the nutrient input to Big Glory Bay. A simplified mass-balance model is:

$$V\frac{dN}{dt} = I - QN + QN_o \qquad (1)$$

where: N & N_o=average 'available' nutrient concentration in Big Glory Bay and Paterson Inlet respectively; V=volume of Big Glory Bay; I='available' nutrient input to Big Glory Bay; and Q=nett exchange flow between Big Glory Bay and Paterson Inlet. V/Q is the hydraulic residence time of the bay, also termed the flushing time. Nutrient losses due to sedimentation are probably small compared to the flushing rate and were neglected. The steady-state solution to equation (1) is:

$$N = N_o + \frac{I}{Q} \qquad (2)$$

and the non-steady solution is:

$$N(t) = N_o + (N(t_o) - N_o)\exp\left(-\frac{Q}{V}(t-t_o)\right) + \frac{I}{Q}\left(1-\exp\left(-\frac{Q}{V}(t-t_o)\right)\right) \qquad (3)$$

where: I,V,Q change to new steady values at time t_o, when nutrient concentration is $N(t_o)$.

Nett exchange flows were estimated from field studies in February 1988 using a pair of moored current meters, drogues, and portable current meters. The residence time of water in the bay was found to depend on the wind. The tidal prism is about 10% of the volume of the bay (Table 1) so if the tidal prism were completely renewed then the residence time of Big Glory Bay would be about 5 days. The tidal excursion near the entrance is only about 2 km and during light winds our drogue studies showed that very little of the water which leaves the bay during the ebb tide escapes past the Bravo Islands (Figure 1) and most returns on the flood tide. During moderate and strong winds, however, two things happen. Firstly, a strong surface flow develops at the entrance with a deep counter-current. For example during moderate westerly winds, surface water flowed out of the bay while a deep current flowed in throughout the tidal cycle. Secondly, flow increases through the Bravo Islands, which dilutes water flowing into and out of Big Glory Bay. Thus we estimate that the residence time decreases from 10-13 days during light winds (< 5 m s^{-1}) to 7-9 days during moderate winds (5-10 m

s^{-1}). These are likely upper-bound estimates of the exchange flow and hence yield likely lower-bound estimates of nutrient concentration in Big Glory Bay.

The average 'available' nutrient concentration in Paterson Inlet was assumed to be the concentration measured at the entrance to Big Glory Bay on 24/2/88 in deep water flowing from Paterson Inlet into Big Glory Bay (Table 3). The 'available' nutrient concentration was taken as the sum of the dissolved inorganic and particulate forms. The former is readily absorbed by phytoplankton while the latter is largely incorporated in phytoplankton already.

To test the accuracy of the model, equation (3) was used to make predictions of the nutrient concentration in Big Glory Bay for comparison with the observed concentrations. On 24/2/88, moderate westerlies had been blowing for 4 days following a fortnight of light winds. Observed and predicted phosphorus concentrations are similar (Table 3) but the predicted nitrogen concentrations are slightly lower than observed. Reducing the residence time would reduce the discrepancy in the predicted nitrogen concentration but would lead to over-estimation of the phosphorus concentration. Increasing the nitrogen input to 564 kg d^{-1} (cf. 452 kg d^{-1} in Table 2) removes the discrepancy. This corresponds to an input of 258 g(N) kg^{-1}(fish produced) yr^{-1} from excretion, egestion and sediment release; which is within the range of values reported from overseas farms.

Table 3. Observed and predicted nutrient and chlorophyll concentrations in Big Glory Bay

	Phosphorus	Nitrogen	Chlorophyll
Total input (from Table 2) kg d^{-1}	156	452	-
Paterson Inlet 24/2/88 mg m^{-3}	6	35	0.5
Light winds: residence time 10-13 days			
Steady-state conc mg m^{-3}	17	66	2.3
Moderate winds: residence time 7-9 days			
Steady-state conc mg m^{-3}	13	56	1.5
Non-steady conc mg m^{-3}	15	62	1.8
Observed 24/2/88 mg m^{-3}	16±2	69±3	1.1±0.2

Notes: Steady-state concentration from equation (2).
Non-steady concentration from equation (3) assuming moderate winds for 4 days after a long spell of light winds.
Observed concentrations expressed as mean ± standard error.
Nutrient concentrations are 'available' = soluble + particulate concentrations.

The nutrient concentration determines the maximum concentration of phytoplankton that can occur in the bay if there are no other constraints on phytoplankton concentration. In practice phytoplankton concentrations are lower than this theoretical maximum mainly because of flushing but other factors such as sedimentation, poor water clarity and zooplankton grazing are also important. The effects of flushing were modelled using the methods developed by Pridmore & McBride (1984) modified so that phytoplankton growth was dependent on nitrogen concentration. The model requires estimates of the nitrogen concentration in the bay, chlorophyll concentration in Paterson Inlet, the residence time, and the growth rate of the phytoplankton. These were all measured in February 1988. The model also requires a correlation between nitrogen and maximum chlorophyll concentration, and this was developed using published marine and freshwater data. The model was checked by comparing observed and predicted chlorophyll concentrations (Table 3). The model predicts slightly higher chlorophyll concentrations than were observed. This difference is most likely attributable to an overestimation of the phytoplankton growth rate since night-time respiration losses cannot be measured in sparse phytoplankton populations and must be estimated from daily or maximum production rates. Nevertheless, the match between observed and predicted nutrient and chlorophyll concentrations was sufficiently close to use the models with confidence for making predictions about possible future eutrophication.

The model was used to back-calculate the maximum nutrient input which would maintain acceptable chlorophyll concentrations in Big Glory Bay. From this was estimated the salmon production which would be sustainable in the long-term. First it was necessary to select a figure for the maximum acceptable chlorophyll concentration.

It has been suggested (eg Weston 1986) that during an algal bloom phytoplankton respiration at night can deplete dissolved oxygen in the cages and kill fish. On 24/2/88 we estimated a respiration rate of 0.3 mg(O_2) m^{-3} hr^{-1} when the chlorophyll concentration was 1.1 mg m^{-3} . There are approximately 1500 tonne (wet weight) of salmon in Big Glory Bay occupying 120,000 m^{-3} of cages. The average respiration rate of salmonids is 300 mg(O_2) kg^{-1}(wet weight) hr^{-1} (Weston 1986). For phytoplankton respiration to exceed 10% of fish respiration the former would need to increase over 1000 fold from its current level. Thus only a huge phytoplankton bloom would significantly increase the rate of oxygen consumption in the cages. We could find no documented cases where planktonic algal respiration depleted dissolved oxygen concentrations low enough to cause fish deaths, only statements alluding to the potential for such problems. Oxygen depletion may well be a problem in salmon rearing pens if the flow of water is reduced (eg by jelly-fish 'attacks') but the principal oxygen demand is unlikely to come from phytoplankton in the water column.

If toxic algae are present in a bloom then severe damage to salmon farming operations can occur (Weston 1986). It is presently impossible to predict with confidence the timing and species composition of phytoplankton blooms (Weston 1986, Kaspar 1988). It is possible, however, to use the models outlined above to predict the maximum chlorophyll concentration which is likely to occur during a bloom. Unfortunately, there are no widely accepted guidelines for the 'safe' levels of phytoplankton that will not cause problems in salmon farms. Phytoplankton such as *Chaetoceros convolutus* are known to adversely affect fish populations at very low levels (eg 5 cells ml^{-1}, Caine et al 1987). However, chlorophyll concentrations above 15 mg m^{-3} are usually associated with nuisance blooms having high cell densities and are indicative of eutrophic conditions (eg Relevante & Gilmartin 1978, Harrison et al 1983, Sellner et al 1988). It is likely that the repeated occurrence of such concentrations poses a potential risk to the long-term sustainability of salmon farming. Thus we suggest that a tentative upper limit for the acceptable chlorophyll concentration is 15 mg m^{-3}.

Table 4 summarises nutrient concentrations in Big Glory Bay which would be expected to cause peak chlorophyll concentrations of 15 mg m^{-3}. When the residence time is long (10-13 days) the critical nitrogen concentration is close to 300 mg m^{-3}. Note that these predictions were made assuming that the 'available' nitrogen and chlorophyll concentrations in Paterson Inlet remain at or near their current levels. This is an over-optimistic assumption since the flushing time of Paterson Inlet by coastal water is quite long and it is likely that nutrient and chlorophyll concentrations will increase in Paterson Inlet as a result of salmon farming operations in Big Glory Bay. Not enough is known at this time about coastal nutrient concentrations or the flushing of Paterson Inlet to predict the extent of these increases.

Under worst-case flushing conditions, salmon production of the order 5000 t yr^{-1} would be expected to result in a nitrogen concentration of about 300 mg m^{-3} and a peak chlorophyll concentration of 15 mg m^{-3} . Allowing a wide margin of safety, the sustainable level of production is of the order of 3000 t yr^{-1} (cf present production of about 800 t yr^{-1}). A large safety margin has been allowed because of uncertainties about: the concentration of nitrogen and chlorophyll likely in the long-term in Paterson Inlet and the nitrogen inputs per unit of salmon production. We recommend that if salmon production close to 3000 t yr^{-1} is likely then a more detailed study be undertaken to reassess the potential for eutrophication. Similarly if salmon farming in Paterson Inlet is contemplated then these calculations would need to be revised.

There may be other constraints imposed on total salmon production, for example to ensure that water classification standards (Class SA and SB) are not breached and/or that important biological communities are not damaged.

Table 4. Predictions of critical nitrogen loads to Big Glory Bay

Residence time	Critical chlorophyll conc	Critical nitrogen conc	Critical nitrogen input	Salmon production
days	mg m^{-3}	mg m^{-3}	kg d^{-1}	t yr^{-1}
7-9	15	350	6800	9650
10-13	15	290	3745	5300
Present conditions		70	564	800

Notes: In Paterson Inlet, 'available' nitrogen=35 mg m^{-3}, chlorophyll=0.5 mg m^{-3}.
Nitrogen input from salmon farms=258 g(N) kg^{-1}(fish produced) yr^{-1}

ACCUMULATION OF WASTES.

It is well known that in quiescent areas solid wastes accumulate under salmon farms. These accumulations have the potential to: cause oxygen depletion in the overlying waters; liberate toxic hydrogen sulphide; and generate substantial volumes of biogas.

Oxygen depletion by the bed.

During field surveys in November 1987 and February 1988 measurements were made of:

a Dissolved oxygen (DO) concentrations in the water column near two salmon farms and in the middle of the bay;

b oxygen uptake rates (BUR) by undisturbed cores collected along transects under 5 farms;

c vertical profiles of current speed at several different states of the tide and wind speeds, from which were made theoretical estimates of the depth-averaged vertical and transverse dispersion coefficients; and

d sediment composition along transects under three salmon farms, from which was estimated the distance solid wastes spread from the farms.

The benthic oxygen uptake rate (BUR) (measured using undisturbed sediment cores) averaged 5 g m^{-2} d^{-1} underneath salmon farms and dropped to 'background' levels 1-2 g m^{-2} d^{-1} some 50 metres from the edge of the farms (Figure 4). Other studies in Big Glory Bay have found similar BUR values (Gillespie & MacKenzie 1982; Edwards 1988).

The organic content of the sediments under the salmon farms has a large potential to consume oxygen. The rate of oxygen consumption by the bed is, however, limited by the rate at which oxygen can diffuse from the overlying water into the sediments. The sediments under the farms are black (indicating anoxia very near the surface) and anaerobic breakdown of the wastes occurs with the visible evolution of gas. Clearly the oxygen demand in the sediments exceeds the supply of oxygen. There were no differences in the BURs measured under different farms despite differences in the flux of organic waste matter due to different stocking rates, feeding regimes, water depth and dispersion. Thus BUR appears to be controlled by the diffusion of oxygen into the sediments from the water rather than the rate of supply or breakdown of organic waste matter. One consequence of this is that the BUR at farm sites with sand/mud sediments is unlikely to exceed 5 g m^{-2} d^{-1} even if there are increases of fish stocking and feeding rates. It also means that the BUR is likely to remain high when farming stops at a site. Published oxygen uptake rates by muds and sands seldom exceed 5 g m^{-2} d^{-1} (Hickey 1985) because of diffusion limitations.

The extent of oxygen depletion in the water overlying the bed depends not only on the BUR but also on any nett currents, the rate of dispersion of oxygen depleted water in the water column, and the rate of reaeration at the water surface. Predictions can be made of oxygen deficits using a mathematical model based on the diffusion equation. The model requires knowledge of the currents and dispersion rates. From current meter studies in November 1987 and February 1988, the depth-average vertical dispersion coefficient was found to range from 20-250 cm^2 s^{-1} with the highest rates occuring where the currents were strongest. From the extent of waste accumulations under the cages, the horizontal dispersion coefficient parallel to the current was estimated to be 3200-12000 cm^2 s^{-1}, which agrees with theoretical estimates based on current measurements. Perpendicular to the current it was about 600 cm^2 s^{-1}. Dispersion is likely to be low at the head of the bay. Surface currents (in the top 5-10 metres) throughout the bay are wind-driven and typically 5-10 cm s^{-1}. Deep currents (below 10 metres) are tide dependent: depth-average currents are typically 5-10 cm s^{-1}, while within a few metres of the bed they are often below 5 cm s^{-1}. At slack tide currents drop to 1-2 cm s^{-1} or less and currents at the head of the bay are weak throughout the tidal cycle.

A worst-case analysis of potential oxygen depletion can be made assuming that wastes cover the whole of the bed in Big Glory Bay. Currents and dispersion can then be neglected and the steady-state oxygen deficit is:

$$C(z) = \frac{B}{k_l} + \frac{BH}{D_z}\left(1 - \frac{z}{H}\right) \qquad 4$$

where C(z)=DO deficit at depth z above the bed (g m^{-3}); B=BUR (g m^{-2} d^{-1}); k_l=reaeration rate (m d^{-1}); H=total depth (m); and D_z=vertical dispersion coefficient (m^2 d^{-1}). A typical lower-bound estimate of the reaeration rate in estuaries is k_l=1 m d^{-1} (Bowie et al 1985) which for B=5 g m^{-2} d^{-1} gives an oxygen deficit at the surface of 5 g m^{-3}. The safe DO level for salmon farming is 80% saturation (Davis 1975). At 14°C and salinity S = 33, saturation is 8.4 g m^{-3} and the 'safe' level 6.7 g m^{-3}: a deficit of 1.7 g m^{-3}. The estimated deficit would not be acceptable for the long-term sustainability of salmon farming. This is clearly a worst-case analysis because waste accumulations are only found close to farms.

For a discrete waste patch in a unidirectional current the depth-average dissolved oxygen (DO) deficit is

$$C = \frac{WB}{HU} \qquad 5$$

where: C=depth-average DO deficit (g m^{-3}); B=BUR (g m^{-2} d^{-1}); W=waste patch width (m); H=water depth (m); and U=depth-average current (m d^{-1}). Equation (5) neglects reaeration and transverse mixing, assumes water passes over only one waste patch, and assumes complete vertical mixing over depth H. A worst case analysis is to consider just a thin layer of water near the bed and to neglect exchange between this layer and the water above. Then for a large waste patch (W=200 m), a low current (U=1 cm s^{-1}) and a thin layer (H = 5 m), the average DO deficit predicted by equation (5) is 0.2 g m^{-3}, which is negligibly small. Thus, where there is even a weak nett current, benthic oxygen uptake is unlikely to cause serious DO depletion even in a thin layer near the bed.

In the absence of a nett current, water can pass backwards and forwards across the waste patch and accumulate an oxygen deficit. A more complex dispersion model is needed to make predictions in this case. For a circular waste patch of radius A in which the BUR is uniform with BUR zero elsewhere, the DO deficit at the centre of the waste patch arising from oxygen consumed during a small time interval dt at time t=0 is (after Carslaw & Jaegar 1959)

$$C(z,t) = \frac{B\,dt}{\sqrt{\pi D_z t}}\left(1 - \exp\left(-\frac{A^2}{4D_x t}\right)\right)\exp\left(-\frac{z^2}{4D_z t}\right) \qquad 6$$

where z = height above the bed; and D_x = transverse dispersion coefficient. The solution for a continuous consumption can be obtained by super-position of solutions. Equation (6) applies to infinitely deep water and it is difficult to account for reaeration at the water surface. As a first approximation reaeration can be assumed zero (a worst case) and the boundary condition of zero flux at the surface satisfied by postulating a virtual image source at z=2H. With this boundary condition, the solution for a continuous sink on the bed does not converge but the solution after say 40 days is indicative of how serious DO depletion is likely to be. It is rare for calm weather to persist for more than 40 days after which gales can be expected to dispell any DO deficit that has accumulated.

Predictions of the DO deficit after 40 days of calm weather at various depths near the centre of a salmon farm for several scenarios of total water depth, farm size and dispersion coefficient are summarised in Table 5. Recall that the model assumes negligible reaeration (a worst case). There are no nett currents but the effects of reversing tidal currents are incorporated in the dispersion horizontal coefficient. Dispersion is assumed everywhere uniform at the depth-averaged value, which slightly underestimates oxygen deficits near the bed (where dispersion is lower than average) but does not affect the accuracy of predictions in mid-water or at the surface.

Scenarios 2&3 (Table 5) approximate worst-case and average conditions near the existing farm sites. The waste patches are assumed somewhat larger than the existing farm dimensions because farms are occasionally relocated. Predictions suggest low oxygen depletion even assuming negligible reaeration. This is confirmed by our sampling (Table 6) which found only very slight oxygen depletion at existing farms.

Scenario 1 approximates worst-case conditions at the head of the bay. Serious oxygen depletion in mid-water or at the surface is not predicted here even assuming negligible reaeration. Edwards (1988) and Gillespie & MacKenzie (1982) measured oxygen deficits of 4-6 g m^{-3} and 1 g m^{-3} respectively, very close to the bed at Site IN 51 near the head of the bay. As discussed above, however, the model underestimates the DO deficit very close to the bed because it assumes uniform dispersion coefficients. Predicted and measured deficits in mid and surface water are both small (Tables 5-6).

It can be concluded that the breakdown of wastes on the bed is unlikely to cause oxygen depletion in the overlying water unless a very large area of the bed becomes covered with wastes. Although there is a high organic loading to the bed, the rate of benthic oxygen consumption is limited by diffusion at the sediment-water interface to about 5 g m^{-2} d^{-1}. Provided the farms remain separated, currents and dispersion are sufficiently rapid to counteract the effects of benthic oxygen uptake at this rate.

An estimate can be made of the desirable separation between farms. When the bed is completely covered with wastes and BUR=5 g m^{-2} d^{-1} then the DO deficit at the surface estimated by equation (4) is 5 g m^{-3}, which is unacceptably high. A maximum acceptable deficit as a result of benthic uptake might be 0.5 g m^{-3} which allows a safety margin of 1.2 g m^{-3} for oxygen uptake by fish respiration and incomplete mixing. This suggests that at most 10% of the bed should be covered with wastes. If the average farm diameter is 75 metres then the minimum separation needed is of the order 250 metres. Note that this separation is desirable between recently abandoned farm sites and operating farms since the former are likely to consume oxygen for several years.

DO deficits can be high very close to the bed when currents and dispersion rates are low. Appreciable DO deficits were measured near the bed at site IN 51 (Gillespie & MacKenzie, 1982; Edwards, 1988), although we found only small deficits near the bed at the existing farms even under calm conditions (Table 6). In view of the potential for low mixing and oxygen depletion close to the bed, cages should not extend right down to the bed. Under worst case conditions the vertical and horizontal dispersion coefficients very close to the bed can be expected to be about 1% of the depth averaged values summarised above (Rutherford 1981) viz 1 and 30 $cm^2\ s^{-1}$ respectively. For a BUR of 5 $g\ m^{-2}\ d^{-1}$ and a waste patch of 75 metres diameter, oxygen depletion greater than 5 $g\ m^{-3}$ is unlikely to occur 5 metres above the bed and depletion greater than 1 $g\ m^{-3}$ is unlikely greater than 10 metres above the bed. Note, this is worst case analysis in the absence of any nett current and assuming very little dispersion. At the existing farms 5 metres between the cages and the bed should be adequate.

These predictions are all based on the assumption that BUR never exceeds 5 $g\ m^{-2}\ d^{-1}$. As discussed above, BUR is presently limited by diffusion and if the flux of organic matter to the bed were to increase as a result of increased fish production, BUR is not expected to increase significantly. A remote possibility under a very high organic loading is that increased gas production or some other disturbance could increase the rate of diffusion of oxygen into the sediments and/or the rate of diffusion of reduced compounds out, thereby increasing the BUR.

Another potential cause of oxygen depletion is fish respiration. The average respiration rate of salmonids is 300 $mg(O_2)\ kg^{-1}$(wet weight) h^{-1} (Weston 1986). In Big Glory Bay the average fish stocking rate is of the order of 10 kg(wet weight) m^{-3}. A typical farm has an equivalent radius of 25 m and is 10 m deep. If a current of 5 $cm\ s^{-1}$ flows through the pens, fish respiration would deplete DO by an average of 0.7 $g\ m^{-3}$. This analysis neglects reaeration and oxygen depletion caused by waste accumulations on the bed. In November 1987 DO concentrations measured close to a farm were about 1 $g\ m^{-3}$ lower than concentrations measured in the middle of the bay (Table 6) which substantiates the calculations described above (although note that the waters in the middle of the bay appeared to be super-saturated).

A DO deficit greater than 2 $g\ m^{-3}$ would stress salmon as described above. This could occur if the size of the farms increased to 75 m radius, if fish stocking rates increased by a factor of three, or if the current dropped below about 1.5 $cm\ s^{-1}$. DO would be low for some distance down-current from the farm. For a farm of radius A and depth h,

$$C(x) = \frac{q}{2AhU}\,\mathrm{erf}\left(A\sqrt{\frac{U}{4D_y x}}\right) \qquad 7$$

where C(x) = DO deficit along the line y = 0 a distance x down-current from the farm ($g\ m^{-3}$); q = oxygen removal rate ($g\ s^{-1}$); U = current speed ($m\ s^{-1}$); and D_y = transverse dispersion coefficient ($m^2\ s^{-1}$). For U = 5 $cm\ s^{-1}$, D_y = 600 $cm^2\ s^{-1}$ and A = 25 m, the DO deficit is halved by transverse dispersion some 250 metres down-current from the farm. This analysis mixing. Allowing a safety factor of 2, the minimum desirable separation between farms is probably 500 metres (cf. the 250 metres estimated above). Farms with an effective radius of 25 metres, separated by 500 metres would occupy about 0.7% of the bay. At least 25% of the bay is unsuitable for salmon farming (e.g. the shallows near the head of the bay and exposed sites near the entrance), and 0.7% of the remainder represents 6.3 ha. At present farms occupy about 1.5 ha and produce about 800 t yr^{-1} so an estimate of the sustainable salmon production in the bay is 3400 t yr^{-1}. This compares well with the 3000 t yr^{-1} recommended to avoid eutrophication.

Table 5. Predicted DO concentrations in the water column under salmon farms

	H m	D_x $cm^2\ s^{-1}$	D_z $cm^2\ s^{-1}$	A m	bottom	mid	surface
Scenario 1	10	250	20	10	0.0	0.0	0.0
				25	0.2	0.1	0.1
				50	0.4	0.4	0.4
				100	1.0	1.0	1.0
Scenario 2	20	1000	100	100	0.2	0.2	0.2
				200	0.5	0.5	0.5
Scenario 3	30	3000	200	100	0.1	0.1	0.1
				200	0.2	0.2	0.2

Notes: 1. DO deficit in g m^{-3}
2. BUR=5 g m^{-2} d^{-1}.Reaeration is neglected
3. H=total depth; D_x, D_z=horizontal & vertical dispersion coefficients;A=waste patch radius

Table 6. Measured oxygen deficits under salmon farms.

Date	Site	Depth m	Bottom	Middle	Surface		Saturation
This study							
18/11/87	MFL319	13.5	8.2	8.3	8.5		8.7
	MFL319	16	8.2	8.6	8.8		8.7
	MFL319	13	8.9	8.6	8.7		8.7
18/11/87	midbay	15*	9.5	9.4	9.5		8.7
* max depth 33 m							
26/2/88	MFL338	27	8.9	9.0	9.2		8.5
Edwards (1988)							
-	IN 51	10	2	7	8	'site 3'	-
	IN 51	10	4	7	8	'site 1'	
	IN 51	10	6-7	8	8	control	
Gillespie & MacKenzie (1982)							
-	IN 51	10	6.9- 7.1	7.9- 8.2	8.1		-

Note: DO in g m^{-3}

Hydrogen sulphide evolution from the sediments.

Under anaerobic conditions bacteria breakdown organic matter and generate hydrogen sulphide. The concentration of sulphate (SO_4) in sea water is about 2700 g m^{-3} and the potential for sulphide production is high. Hydrogen sulphide (H_2S) is toxic to fish at very low levels and poses a potential threat to salmon farming. High concentrations of H_2S were measured in water very close to the bed at site IN51 (Figure 1) by Gillespie & MacKenzie (1982) and Edwards (1988). At the existing farms we observed that the sediments under the farms were covered with *Beggiatoa* sp, a bacterium associated with sulphide producing sediments. Sediments which we collected from under the existing farms smelled very strongly of sulphide. During February 1988 we measured the flux of sulphate into and sulphide out of two cores: one collected underneath a salmon farm at site MFL338 and one collected 50 metres from the edge of the same farm. The measured fluxes were used in a dispersion model, together with observed currents and dispersion coefficients, to predict H_2S concentrations in the water column.

In the two cores studied there was a significantly higher flux of sulphate into the sediments than of sulphide out of the sediments (Table 7) because of accumulation of metal sulphides, elemental sulphur, or H_2S gas in the core. The measured efflux of H_2S under the salmon farm, 0.81 g m^{-2} d^{-1}, is within the range measured by other workers in organically enriched estuarine and marine sediments (Table 8). Sulphide evolution is low 50 metres from the farm as might be expected.

Table 7 Fluxes of sulphate and hydrogen sulphide measured using undisturbed sediment cores

Core	Distance from centre of farm	Incubation time	Length of core	Height of overlying water	H_2S efflux	SO_4 influx
	m	days	cm	cm	$g(S)\ m^{-2}\ d^{-1}$	$g(S)\ m^{-2}\ d^{-1}$
1	0	8	30	4.3	0.81	3.1
2	50	8	30	5.4	0.055	0.65

Table 8. Summary of some published rates of sulphate reduction and sulphide production

Ref.	Locality	SO_4 reduction $g(S)\ m^{-2}\ d^{-1}$	H_2S production $g(S)\ m^{-2}\ d^{-1}$
1	marine sediment	0.005-0.073	-
2	marine sediment	0.28 -0.40	-
3	marine sediment	0.30	0.28
4	marine sediment	0.25	0.05
		>1.3	1.2
5	*Spartina* salt marsh	9.6 -16	-
6	polluted estuary	-	1-10

References
1. Edenborg et al (1987)
2. Iversen & Jorgensen (1985)
3. Jorgensen (1977)
4. Hansen et al (1978)
5. Howarth & Giblin (1983)
6. Bella (1975)

These measurements were used in a simplified computer model, together with measured dispersion coefficients and published values for the oxidation rate of hydrogen sulphide in seawater, to predict hydrogen sulphide concentrations in the water column under salmon farms.

For a circular waste patch, H_2S released over the time interval dt at t=0 results in a concentration at the centre of the waste patch (cf equation (6))

$$S(z,t) = \frac{F\,dt}{\sqrt{\pi D_z t}}\left(1-\exp\left(-\frac{A^2}{4D_x t}\right)\right)\exp\left(-\frac{z^2}{4D_z t}\right)\exp(-kt) \qquad 8$$

where t = height above the bed; S=H_2S concentration (g m^{-3}); F=H_2S flux at the bed (g m^{-2} d^{-1}); H=water depth (m); k=H_2S oxidation rate coefficient (d^{-1}); D_x, D_z=horizontal and vertical dispersion coefficient (m^2 d^{-1}) and A=patch radius. The solution for a continuous source can be obtained by super-position. The H_2S concentration at the water surface was assumed to be zero and a negative image source specified at z=2H. Because of the decay term, the solution for a continuous source converges.

The oxidation rate coefficient of H_2S was taken as k=0.01 h^{-1}, the value given by Millero et al (1987) for sea-water saturated with dissolved oxygen at 10 °C. Slightly lower values of k could occur in waters depleted of oxygen but as discussed earlier severe oxygen depletion is unlikely in Big Glory Bay. The benthic H_2S flux was assumed to be 1 g m^{-2} d^{-1} (see Table 7) and the 'safe' level of H_2S for salmonids was taken as 2 mg m^{-3} (Thurston et al 1979).

Scenario 1 (Table 9) is a likely worst case condition at the head of the bay in shallow water under calm conditions. Predicted H_2S concentrations at the bed, 5-55 mg m^{-3} , are lower than values measured at site IN51 (Figure 1) by Gillespie & MacKenzie (1982), 200 mg m^{-3} , and by Edwards (1988), 74-303 mg m^{-3}. . However, the model was expected to under-estimate H_2S near the bed because it assumes a vertical dispersion coefficient uniform with depth. The model should be accurate at mid-depth, but unfortunately there are no data available from mid-depth to compare with model predictions. The model predictions of zero H_2S in the surface waters match the observations. The model predicts that H_2S concentrations exceed the 'safe' level, 2 mg m^{-3} , at mid-depth for all but the smallest farm. These calculations support the view that H_2S evolution from the bed is a hazard for salmon farms in the shallow and sheltered waters at the head of Big Glory Bay.

Scenario 2 is a worst case in deeper water near the existing farms under calm conditions. No H_2S measurements are available to compare with the model predictions and so the model predictions have a high uncertainty. They suggest, however, that for farms greater than 50 metres diameter, mid-water H_2S concentrations could exceed the 'safe' levels under worst-case calm conditions. Scenario 3 approximates average conditions at a deep site near the existing farms. Predicted H_2S concentrations exceed 'safe' levels only in the case of very large farms (>100 m diameter).

The predictions described here have a high uncertainty. Firstly, the single measurement of sulphide flux made during the present study may not accurately describe conditions everywhere in Big Glory Bay. Secondly, we have chosen values for rates of dispersion from our measurements which may not accurately describe conditions at all farm sites. Nevertheless, the predictions suggest that even at the existing farm sites there is a potential H_2S problem under worst case conditions (calm conditions, with low currents and dispersion) especially for large farms.

During field studies we could find no direct evidence of H_2S toxicity problems. Indeed divers often observed small demersal fish, notably spotties *(Pseudolabrus)*, swimming just above waste accumulations under the salmon farms. Although the tolerance of these fish to H_2S is not known, their presence suggests that H_2S levels were not excessive under the prevailing conditions. It was noticeable that blue-cod did not frequent the waste patches although they were abundant beyond 50 metres from the farms.

An estimate can be made of how far from the farms H_2S spreads. A steady line source on the bed transverse to a steady current gives rise to concentrations along a line parallel with the current which passes through the centre of the farm.

$$C(x,z) = \frac{2q}{\sqrt{4\pi U x D_z}} \exp\left(-\frac{z^2 U}{4 D_z x}\right) \operatorname{erf}\left(A\sqrt{\frac{U}{4 D_y x}}\right) \exp\left(-\frac{kx}{U}\right) \qquad 9$$

where x = distance in the direction of the current; z = height above bed; U = nett current; D_y, D_z = horizontal and vertical dispersion coefficients; and k = H_2S oxidation rate coefficient. For a net current of 1 cm s^{-1}, dispersion coefficients near the bed of D_y = 100 cm^2 s^{-1} and D_z = 20 cm^2 s^{-1}, a waste patch with radius A = 25 metres and a sulphide flux of 1 g m^{-2} d^{-1}, equation (9) predicts that H_2S concentrations will exceed 2 mg m^{-3} at the bed for about 250 metres down-current from the edge of the farm and to a maximum height above the bed of about 7.5 metres. There is considerable uncertainty about the rates of dispersion very close to the bed and these calculations are only indicative. They suggest, however, that if H_2S is being generated at rates suggested by our measurements then there is the potential for toxicity problems for distances of the order of hundreds of metres from the farms.

It is not possible to predict with accuracy how the H_2S flux from the sediments might change with time and/or waste loading. The sediments have been observed to give off methane gas (Gillespie & MacKenzie 1982) which indicates that the sediment bacteria utilise sulphate faster than it can be supplied by diffusion from the overlying waters. This suggests that the uptake of sulphate by the sediments is presently limited by diffusion rather than by the rate of supply or breakdown of organic matter. If so then the uptake of sulphate may not change significantly with changes in waste loading in the future. The efflux of H_2S depends not only on the sulphate influx, but also on the retention of metal sulphides, elemental sulphur and H_2S within the sediments. These could change as the organic loading to the sediment changes. In addition the H_2S flux could increase if the rate of evolution of gas increases, thereby increasing the diffusion rates into and out of the sediments. Thus, it cannot be predicted with accuracy whether the H_2S flux from the sediments will remain close to its present value, about 1 g m^{-2} d^{-1}, or whether it will increase. It appears unlikely to exceed 10 g m^{-2} d^{-1} (Table 8).

Table 9. Predicted hydrogen sulphide concentrations in the water column under salmon farms

H m	D_x $cm^2\ s^{-1}$	D_z $cm^2\ s^{-1}$	A m	Height above the bed, m						
				0	5	10	15	20	25	30
Scenario 1										
10	250	20	10	5	3	0	-	-	-	-
			25	20	11	0	-	-	-	-
			50	39	23	0	-	-	-	-
			∞	55	27	0	-	-	-	-
Scenario 2										
20	1000	100	10	0.5	0.5	0.3	0.1	0	-	-
			25	3.0	2.6	1.7	0.8	0	-	-
			50	8.6	7.4	5.1	2.5	0	-	-
			∞	22	17	11	6	0	-	-
Scenario 3										
30	3000	200	10	0.1	0.1	<0.1	<0.1	<0.1	<0.1	0
			25	0.8	0.7	0.6	0.4	0.3	0.1	0
			50	2.7	2.5	2.1	1.5	1.0	0.5	0
			∞	17	14	11	8.2	5.5	2.7	0

Notes: 1. H_2S units=mg m^{-3}

2. H_2S flux=1 g m^{-2} d^{-1}

3. H_2S oxidation rate coefficient=0.01 h^{-1}

4. H=total depth; D_x,D_z=horizontal & vertical dispersion coefficients; A=waste patch radius.

OTHER LIMITING FACTORS.

Gas production at the bed and fish health.

It was observed during the course of the present studies that quite large amounts of gas were produced by the sediments. We measured rates of 127-249 ml m^{-2} h^{-1}. The gas bubbles generally pass through the salmon pens on their way to the surface. The gas comprises methane, nitrogen and carbon dioxide (Gillespie & MacKenzie 1982) which are harmless to salmonids. Gas bubbles do, however, provide a potential vector for transporting pathogens from the waste accumulations under the farms back into the pens and in the longer-term this could lead to fish health problems. It was beyond the scope of this study to examine this question experimentally.

Jellyfish.

Dense swarms of jellyfish are not uncommon in Big Glory Bay and farmers have reported fish deaths as a result of jellyfish clogging cage netting. This reduces water exchange and the fish suffocate through lack of oxygen. There has been speculation amongst farmers that these jellyfish 'attacks' may have increased since farming began in the bay. Although this is incidental to the main concerns of the study, it is worthwhile to consider the possibility that jellyfish attacks may limit farming.

During the February field studies most of the medusae (the bell-shaped life history stage commonly called a jellyfish) in the bay were of the *Aurelia* type, but there are reportedly several species which are problematic. Little is known about these animals and most of our information comes from overseas studies. It is unlikely that the medusae are solely derived from within the bay. The medusa is the final stage of a three part life history and it is more likely that most individuals are merely swept passively in. This is especially so bearing in mind that Big Glory Bay has a residence time of usually less than 10-13 days and the medusae take several weeks or months to develop from the start of their planktonic (ephyra) stage.

Medusae are carnivorous and if their growth is to have been stimulated by the presence of farms zooplankton biomass would need to have increased. Given the small observed increases in nutrient concentrations and the presently low chlorophyll levels it seems very unlikely that zooplankton biomass would have changed. It seems more likely, therefore, that the observed changes in jellyfish abundance are at this stage the result of natural variability. As well as seasonal differences, it is common for such planktonic animals to undergo large year-to-year differences in abundance.

While it is possible that increasingly eutrophic conditions in the future may enhance medusa growth, it would seem that present densities of medusae are normal and the frequency of jellyfish attacks has to be accepted as one of the risks of farming in these waters.

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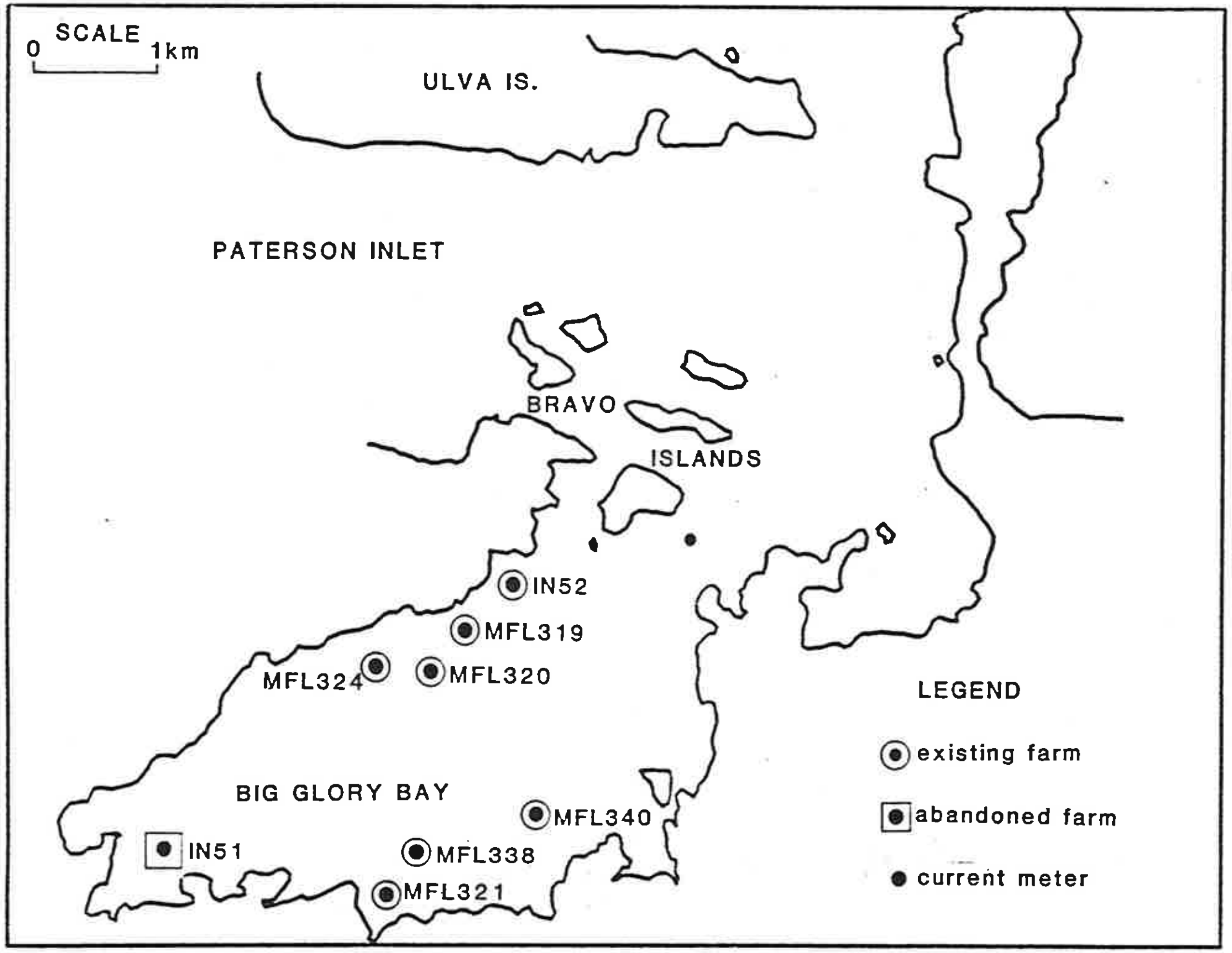


Figure 1.
Location Map

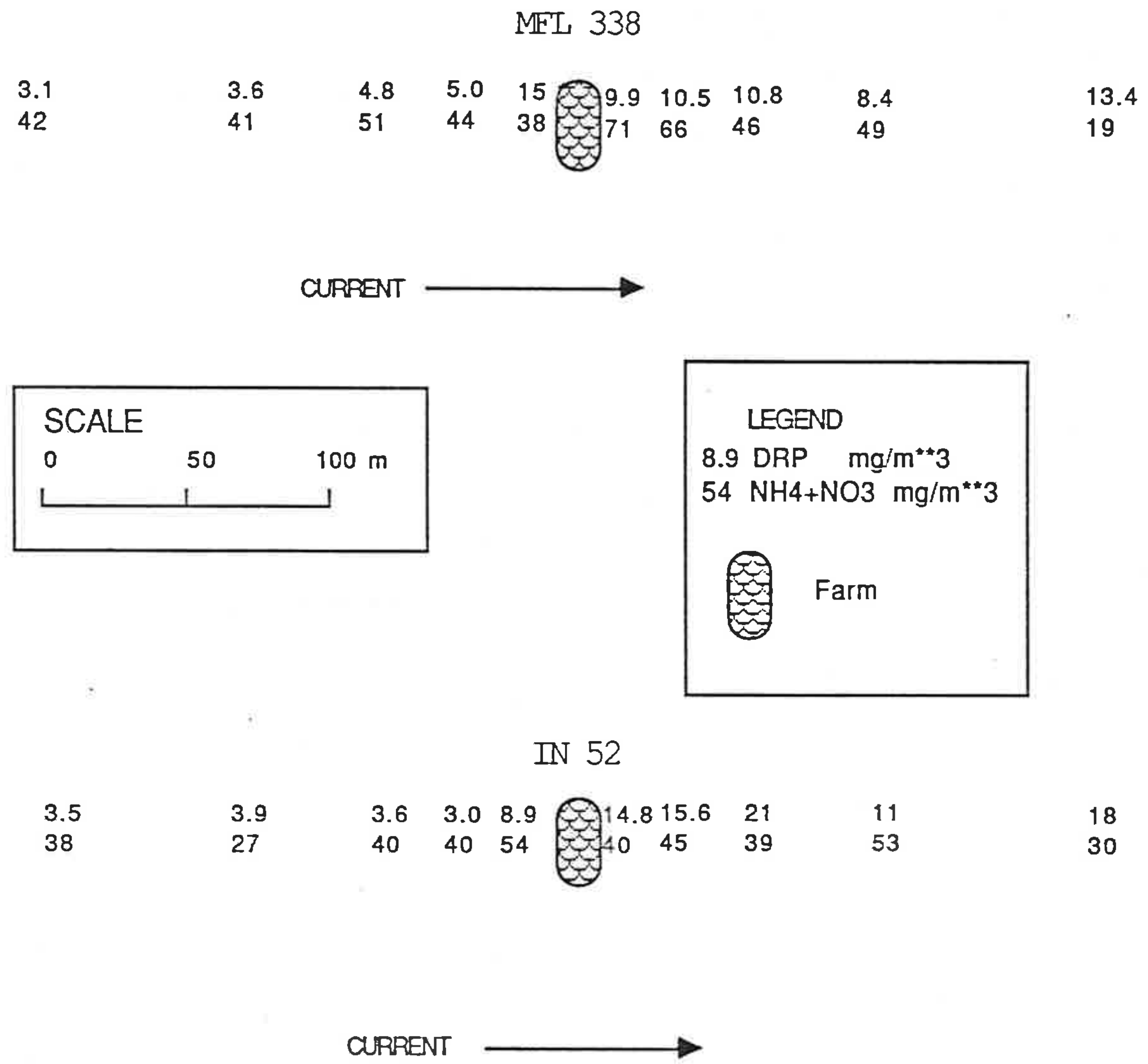
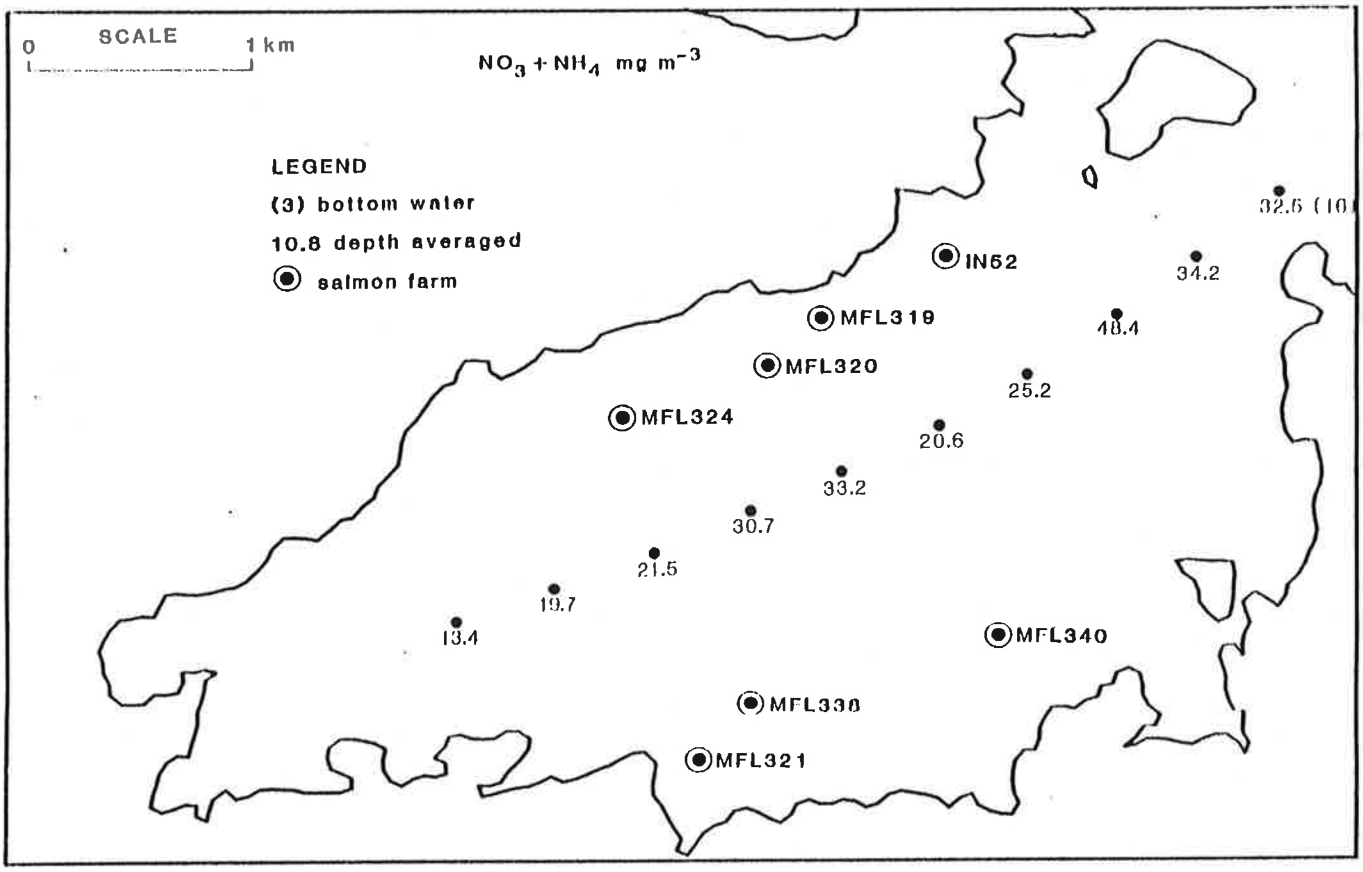


Figure 2.

Soluble nutrient concentrations near two salmon farms 24/2/88



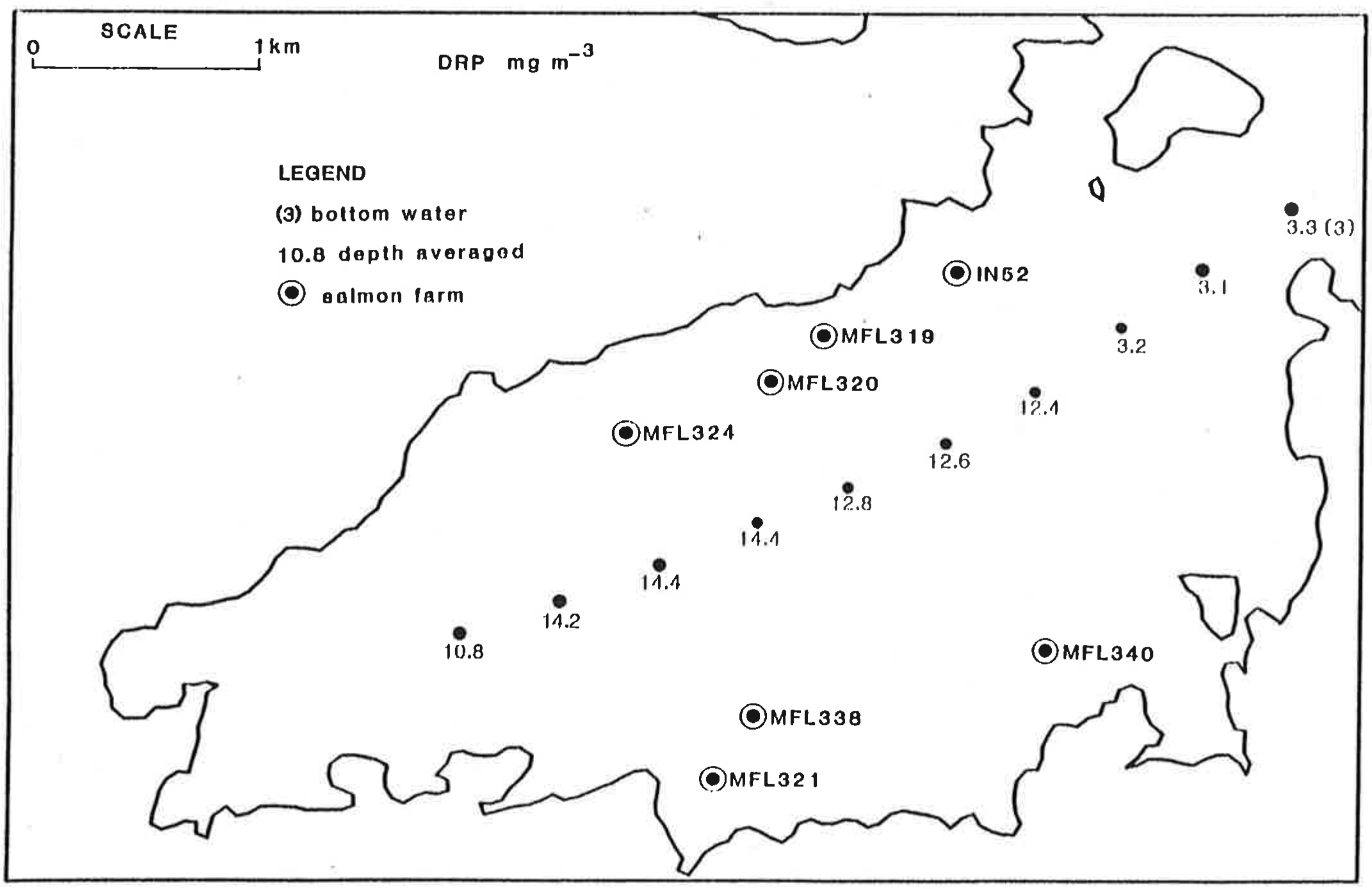


Figure 3.

Soluble nutrient concentrations in Big Glory Bay 24/2/88

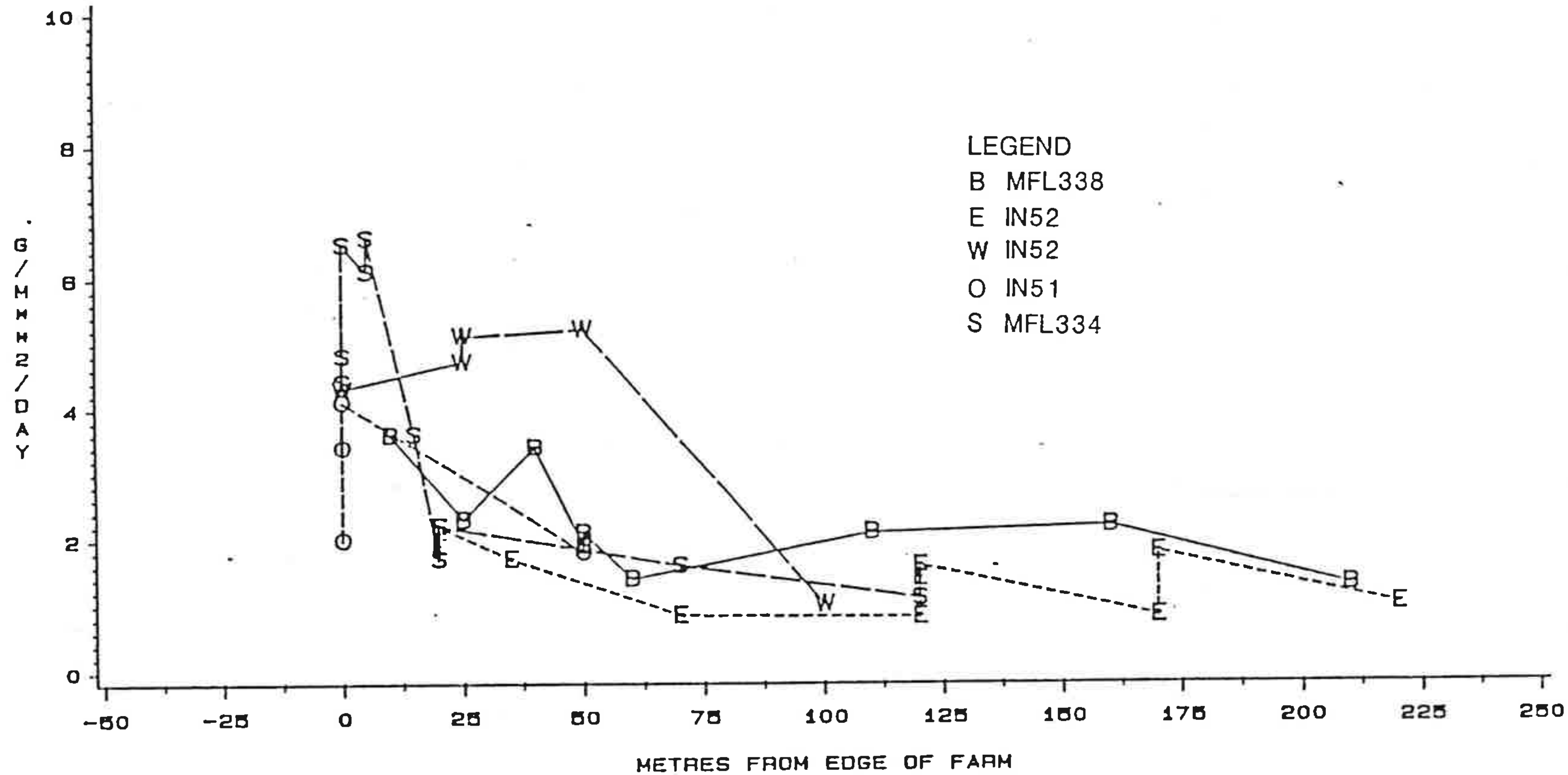


Figure 4.

Benthic oxygen uptake rate measured near four salmon farms.