Identifying the Risk of Deoxygenation in Scottish Sea Lochs with Isolated Deep Water

A report to
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Executive Summary

Introduction

Oxygen depletion is a naturally-occurring phenomenon in isolated basin waters of fjords, occurring when pelagic and benthic uptake of dissolved oxygen exceeds the supply of oxygen to the basin. The coastline of Scotland contains many fjords (sea lochs) with deep basins, but the frequency and extent of oxygen depletion in these basins is unknown. The goal of this project, which ran for twelve months starting on 1st December 2005, was to develop and apply a rationale to assess whether isolated basins in silled Scottish sea lochs are prone to hypoxia.

The key factor involved in determining whether a basin becomes hypoxic is the ratio of the time scales of deep water renewal, which replenishes the basin with oxygen-saturated water, and the consumption of oxygen by pelagic and benthic biochemical processes (the biochemical oxygen demand, BOD). If deep water renewal occurs more frequently (i.e. the time scale is shorter) than the time taken for the oxygen concentration to fall from saturation to hypoxia, then clearly hypoxia will not occur. Should the renewal time scale be longer, however, then the basin will be at risk of low oxygen levels. To that end, we developed and applied a method to assess the risk of hypoxia in all Scottish sea lochs through four specific objectives:

1. *To estimate the biochemical oxygen demand (BOD) and time scale to anoxia (T_O) for all (silled) Scottish sea lochs as listed in the Sea Loch Catalogue.*
2. *To estimate the rate of basin mixing and the average residence time (T_R), i.e. the time scale between successive deep water renewal events, for all Scottish sea lochs.*
3. *To provide a list of sea lochs in order of those most likely to suffer from depleted oxygen levels.*
4. *To validate predictions of basin water renewal and deoxygenation against available data.*

Methods

Two sub-models were developed to calculate, respectively, the time scales of stagnation periods between successive deep water renewal events in sea loch basins, and the time scales for the basin water to move from oxygen saturation to hypoxia. The theoretical framework of the two sub-models was based on a series of papers over the past thirty years by Stigebrandt and co-workers at the University of Gothenburg who have shown how energy extracted from the barotropic tide is transferred into an internal tide and then works against buoyancy in the deep basins of Scandanavian fjords, mixing deep saline water with the overlying brackish layers and thereby reducing the density of the basin water and ultimately leading to deep water renewal. The effects on oxygen budgets of isolated basin waters were also considered. Evidence exists from Scottish fjordic sea lochs that similar processes are at work, and the method therefore offers a viable approach.

In the present study, an analytical solution to the differential equation describing oxygen depletion is derived, such that the oxygen concentration, $O_2(t)$, at time t following a renewal event, is given by:

$$O_2(t) = O_S - S_O(1 - e^{-\gamma t})$$

where O_S is the saturated oxygen concentration, γ is the diffusive exchange rate, and S_O represents a balance between the BOD and the diffusive supply of oxygen. From this equation, the time scale to hypoxia can be derived simply.

The carbon flux from salmon farms was also considered as an independent biochemical oxygen demand, and the effect of finfish aquaculture on the oxygen budgets of sea loch basins was also investigated.

The model was applied to all silled Scottish sea lochs listed in the Sea Loch Catalogue, and the results were compared to physical data available from a number of published studies of deep water renewal. Some limited data were available on oxygen concentrations in sea loch basins for comparison with the results. Limited data on benthic and pelagic BOD rates were used to force the model.

Results

The model predicted time scales of deep water renewal that corresponded acceptably well with the little available comparative data. Loch Etive was predicted to have the longest time scale of 488 days, and a number of smaller lochs had residence times of ~1 day. Initial results suggested that 28 sea loch basins, out of a total of 135, may be at risk of developing hypoxic conditions, while 64% were predicted to remain oxygenated above hypoxic levels either through frequent exchange or adequate ventilation (diffusion).

A sensitivity analysis found that the pelagic BOD dominated the time scales of oxygen depletion. In addition, both BOD rates, which were obtained from experimental datasets, had to be reduced by 75% in order for the model to reproduce the observed oxygen depletion time scale for Loch Etive. With these parameter values, only 5 sea loch basins were found to be at risk of routinely developing hypoxic conditions. A “worst case” model run, with increased BOD and reduced diffusive oxygen supply, raised the number of basins at risk to 38.

Estimated carbon fluxes from fish farm activity contributed less than 30% of the total BOD in over 90% of the loch basins. However, the additional BOD arising from fish farm carbon is sufficient to cause a predicted risk of hypoxia in a small number (approximately 4) of basins which are predicted to remain oxygenated when fish farms are not present.

Conclusions

All objectives of the project were successfully completed. However, there is a real shortage of data relating to the biochemical oxygen demand in Scottish sea loch basins, which renders the following conclusions somewhat tentative:

- A number of sea loch basins, between 5 and 38 out of 135 basins, may be at risk of routinely developing hypoxic bottom water conditions, mostly caused by natural processes.
- An improved digital database of sea loch bathymetry is urgently needed.
- The pelagic BOD dominates the oxygen depletion rates in loch basins.
- Rates of pelagic and benthic biochemical oxygen demand, obtained from discrete samples, may markedly overestimate the BOD on basin-wide scales. Data from a wider range of locations are required.
- Processes and rates of vertical diffusion of salt and oxygen between basin waters and overlying layers, which contribute fundamentally to basin water renewal and oxygen concentrations, are also poorly understood.
- Carbon fluxes from fish farming may contribute significantly to a predicted hypoxia risk in a small number of sea loch basins (about 4), although the risk itself may be overestimated.

1. Introduction

Commercial production of farmed finfish, primarily Atlantic Salmon, is a strategically important industry for Scotland, and particularly for the fragile economies of the Highlands and Islands where it provides much needed employment and support to remote communities. Production is associated generally with waters on the west coast of mainland Scotland and the Western and Northern Isles. A large array of lochs and waters are used for this purpose ranging from remote inlets only accessible by boat to relatively heavily used waters (Figure 1).

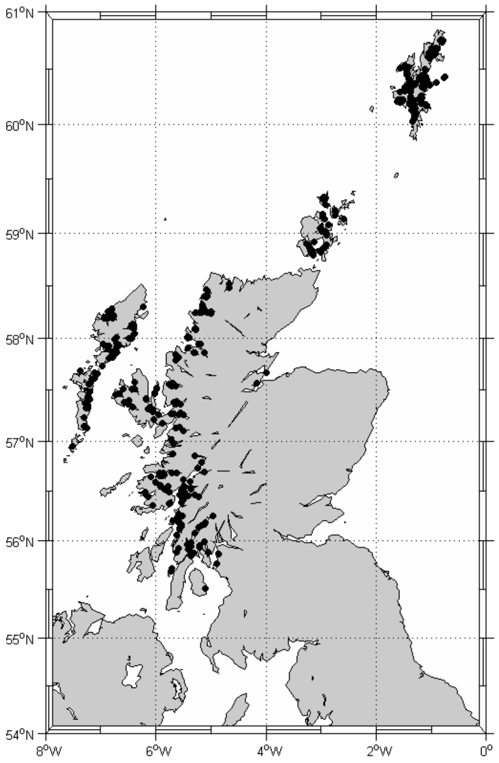

Figure 1. Locations of consented salmon farms in Scotland.

Conventional cage fish farming practice does not involve the treatment of wastes before their discharge to the sea and therefore relies on natural dilution and degradation to assimilate its wastes. The capacity of the environment to assimilate waste is limited by the hydrodynamic and biological characteristics of the recipient water bodies. The waste product of particular relevance here is particulate organic matter (POM), which finfish farms discharge as waste feed and fish faeces. In addition to inputs from fish farms, other sources of POM in the marine environment include phytoplankton growth and decay, bacteria, seaweeds and sea grasses, natural and anthropogenic inputs from rivers and point discharges. The breakdown of organic matter creates a Biochemical Oxygen Demand (BOD), which can lower oxygen levels in the sediment and water column. Lowered oxygen levels occur naturally on a range of spatial scales in the marine environment, including in some deep fjord basins. Extreme lowered sedimentary and/or water column oxygen levels (hypoxia) may have damaging effects on benthos and demersal fisheries (Tett and Edwards, 2002; Anon, 2004). One of the key issues in determining water quality in coastal environments is the ability to measure and/or predict oxygen demand. The decrease in oxygen concentrations leading to hypoxia in stratified waters can severely impact living infauna (Rabouille et al., 2003; Smetacek et al., 1991). The phenomenon of hypoxia has been relatively well studied in the Baltic, the Arabian Sea and the Black Sea as well as in some Norwegian fjordic systems. Mobile fauna such as fish can sense oxygen concentration gradients and avoid these, but less mobile or sedentary species display a range of tolerances to hypoxia and in some cases change their behaviour to compensate. Ultimately species have absolute tolerance limits and are excluded below these limits. Anoxia (i.e. the absence of dissolved oxygen) in bottom waters excludes all metazoan life. Anoxic waters typically have high concentrations of toxic sulphide species and redox sensitive metals such as manganese. Episodic overturning of such waters can result in widespread mortality including fish kills thus exporting the ecological consequences of anoxia (Rosenberg et al., 2001).

Where a sedimentary BOD consumes oxygen from the overlying water column, the resulting concentration of oxygen within the water column is dependent on both the BOD and the rate at which the water overlying the sediment is replaced. Thus in strongly tidal waters, fast tidal streams provide a steady source of oxygenated water which rapidly replaces the oxygen depleted water. Throughout most of the Scottish coastal zone, tidal currents are indeed relatively strong; hence on the zone B scales (CSTT, 1994, 1997) that are of interest here, deoxygenation of the water column is unlikely to occur. However, in the deep basins of fjordic sea lochs, where tidal exchange is restricted, it is possible that the natural BOD, exacerbated by particulate organic inputs from salmon farms, may result in deoxygenation of bottom water.

The likelihood of hypoxia in the basin water of a fjord is determined by two time scales, namely the period between successive deep water renewal events (which provide oxygen-rich water to the basin) and the time taken for all the oxygen in the basin water following a renewal event to be consumed. Clearly, if the latter time scale is shorter than the former, the fjord basin will be prone to hypoxia. If the two time scales are similar, the basin may be subject to oxygen depletion, which may also have deleterious effects. Only in the case where the residence time is much shorter than the hypoxia time scale can adverse impacts be effectively ruled out.

The two time scales are dependent on four key factors:

1. The rate of mixing of the deep water of the fjord basin, which reduces the water density and primes the basin water for renewal (Gade, 1973; Gade and Edwards, 1980; Stigebrandt, 2001) and also provides a source of oxygen to the deep water.
2. The absolute reduction in basin density needed for deep water renewal to occur (Stigebrandt, 2001).
3. The rate of oxygen consumption in the basin water, which is related to the supply of organic matter (Stigebrandt et al., 1996; Stigebrandt, 2001).
4. The volume of the fjord basin and the initial oxygen concentration, which give the mass of oxygen to be consumed.

Combining 1) and 2) provides a time scale, T_E, for the replacement of the deep water. In Scottish sea lochs, T_E varies from the order of a tidal cycle to many months (e.g. Loch Etive, Edwards and Edelsten, 1977). However, the reasons for this variation are still poorly understood, and may be due to differences in either or both of factors 1) and 2) between individual sea lochs. Deep-water renewal in several shallow-silled Scottish lochs occurs during periods of low freshwater runoff and favourable winds, when upwelling of dense water outside the sill is induced (Edwards and Edelsten, 1977; Gillibrand et al., 1995; Allen and Simpson, 1998a). In some, the tidal excursion, related to the spring-neap cycle, is a factor (Edwards et al., 1980).

In the Scandinavian FjordEnv model (Stigebrandt et al., 1996; Stigebrandt, 2001), the required reduction in basin water density for renewal to occur, R_E, is modelled as a simple function of the standard deviation of water density outside the sill at sill depth. In fjords where the external water density is relatively steady (i.e. the standard deviation is small), only a small reduction in basin water density is required for renewal to occur; conversely, where the external density is highly variable, a greater reduction is required on average. Based on empirical data from fjords in western and northern Norway, the value of R_E was specified as the standard deviation multiplied by 1.5. It is not certain that the renewal of deep water in shallow-silled Scottish fjords is so simply related to the variability of coastal water density as Norwegian fjords; however, this approach was adopted in the present model.

The rate of mixing of the deep basin water is dependent on the dissipation of barotropic tidal energy and the processes by which that dissipation is enacted (Stigebrandt and Aure, 1989; Stigebrandt, 1999; Inall et al., 2004). In some fjords, strong tidal jets are generated at the sills, in others strong progressive internal tides dominate, and there probably exists a continuum of possible states where tidal energy is divided between internal tides and tidal jets in different proportions. The rate at which basin waters are mixed depends strongly on the proportion of tidal energy that is converted into the internal wave energy, since tidal jets do not efficiently mix basin water. The transformation of tidal energy into the baroclinic wave field is a function of the basin topography (i.e. basin depth and sill depth), the tidal flow across the sill, and the stratification. The issue of mixing processes and exchange in fjord basins is being considered through a separate SARF-funded project to improve modelling techniques for estimating assimilative capacity.

The other factors that determine the risk of deoxygenation in fjord basins are the rate of reduction of basin water oxygen concentration, itself linked to the supply of organic matter, and the topographic properties of the deep basin (Aure and Stigebrandt, 1989). Unpublished work at SAMS indicates that, for Loch Etive at least, pelagic respiration in the isolated deep basin is a more significant component than benthic respiration. The relationship between oxygen concentration in deep waters and time since last renewal is likely to be topographically driven, but will also be dependent on the rate of carbon supply to deep waters. Loch systems can be ranked in their propensity to deep water hypoxia by computing the time required for hypoxic conditions to develop following renewal; this comparative rate of oxygen depletion relative to the time scale of deep water renewal sets the risk of hypoxia for the basin waters.

The objectives of the study, therefore, are:

1. To estimate the biochemical oxygen demand (BOD) and time scale to anoxia (T_O) for all (silled) Scottish sea lochs as listed in the Sea Loch Catalogue.
2. To estimate the rate of basin mixing and the average residence time (T_R), i.e. the time scale between successive deep water renewal events, for all Scottish sea lochs.
3. To provide a list of sea lochs in order of those most likely to suffer from depleted oxygen levels.
4. To validate predictions of basin water renewal and deoxygenation against available data.

2. Methods

Two sub-models were developed to calculate: (1) the time scales of stagnation periods between successive deep water renewal events in sea loch basins, and (2) the time scales for the basin water to move from oxygen saturation to hypoxia. By comparing these time scales for each sea loch basin, the propensity for the basin water to become depleted in oxygen can be assessed.

Here we describe the theoretical framework of the two sub-models, the data sources used to specify parameter values, and the implementation of the models.

2.1 Sub-Model 1: Time Scale of Deep Water Renewal

Research over the past three decades has shown that deep water renewal in Scottish sea lochs tends to occur in episodic events at variable frequency (e.g. Edwards and Edelsten, 1977; Edwards et al., 1980; Gillibrand et al., 1995; Allen and Simpson, 1998a). Such events tend to be instigated by wind and tidal forcing during periods of relatively low rainfall and river discharge, which together maximise the density of the water at sill depth. A concomitant requirement is the gradual reduction of basin water density by vertical eddy diffusion, which inevitably ensures that the basin water will eventually be no denser than the water entering the basin over the sill and therefore able to be replaced (Gade, 1973). Two processes therefore need to be included in this sub-model: 1. the variability of water density at sill depth; and 2. the rate of reduction of basin water density.

In a series of papers over the past thirty years, Stigebrandt has shown how energy extracted from the barotropic tide is transferred into an internal tide and then works against buoyancy in the deep basins of Scandanavian fjords, mixing deep saline water with the overlying brackish layers and thereby reducing the density of the basin water (e.g. Stigebrandt 1976, 1977, 1979, 1999; Stigebrandt and Aure, 1989). The same processes have been observed in Scotland (e.g. Allen and Simpson,1998b; Inall and Rippeth, 2002; Inall et al., 2004, 2005) and can be assumed to modify basin water properties in sea lochs. We follow Stigebrandt's approach here, and calculate the energy transferred from the barotropic (surface) tide into the internal tide and thereby into work done against buoyancy in the basin. This approach has been employed in Scandinavia in the FjordEnv model (Stigebrandt, 2001).

An example of the idealised bathymetry and water column structure of a two-basin Scottish sea loch, as represented in the model, is shown in Figure 2. In this example, the outer basin and outer sill are both deeper than the inner basin and sill; however, multiple variations of sill-basin systems are present in the 110 sea lochs included in the Sea Loch Catalogue (Edwards and Sharples, 1986). The present model can accept any configuration.

The depths of the brackish surface layer and tidal intermediate layer are given by H_1 and H_2 respectively. These values, which represent annual-mean layer depths, are generated from the physical exchange model developed under SARF project 012 (Gillibrand and Inall, 2006). The layer depths are calculated daily in response to varying river runoff and wind stress, and the annual-mean values then calculated. The model was run using averaged annual cycles of river flow and wind stress, based on data from Creran and Tiree respectively. The river flow data were modified for each loch according to the relative catchment areas and rainfall. The depth of the bottom layer is determined by the basin depth. Annual-mean densities for each layer are also generated by the exchange model and used here.

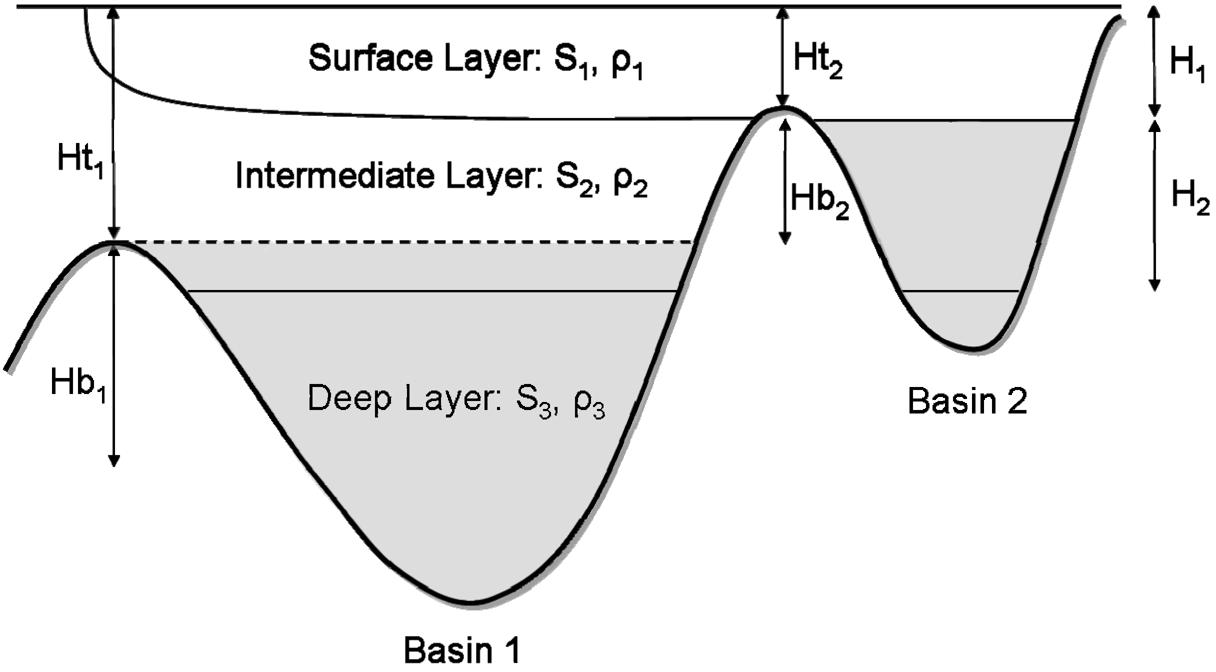

Figure 2. Schematic of the fjord basin model. H_i, S_i, ρ_i *represent the thickness, salinity and density of layer i.* Ht_j *is the maximum depth of sill number j.* Hb_j *is the mean depth of basin j. The shaded volume in each basin indicates the water assumed to be at risk of hypoxia; its upper limit is set by the sill depth (as in Basin 1) or by the surface layer thickness if the layer extends below sill depth (as in Basin 2).*

For a two-layer fjord system, the energy flux into the basin due to M_2 internal tide generation and propagation is given by (Stigebrandt, 1999):

$$E_T = \frac{\rho_o}{2}\omega^2 a_0^2 \frac{A_U^2}{A_M}\frac{H_B}{H_B + H_T}c_i \tag{1}$$

where ρ_0 is a reference density (kg m^{-3}), a_0 and ω are the amplitude (m) and frequency (rad s^{-1}) of the semi-diurnal ($M_2 + S_2$) tide, A_U is the surface area of the loch upstream of the sill (m^2), A_M is the cross-sectional area of the sill, H_T and H_B are the thicknesses of the upper and lower layers respectively. The phase speed of the internal tide, c_i, is given by

$$c_i = \left(\frac{g' H_T H_B}{H_T + H_B}\right)^{1/2} \tag{2}$$

where the reduced gravity $g' = g\Delta\rho/\rho_0$, with g the acceleration due to gravity (m s^{-2}) and $\Delta\rho$ the density difference between the two layers (kg m^{-3}).

Internal sills in sea lochs generate internal tides propagating in both directions (e.g. Gillibrand and Amundrud, in press). For basins with sills at both ends (e.g. Basin 1 in Figure 2), the combined energy flux from both internal waves was calculated.

A small proportion, R_f, of the energy flux due to the internal tide is used to work against buoyancy and reduce the basin water density. Several studies in fjord basins have shown that about 5% of the energy flux is dissipated in this way i.e. $R_f = 0.05$ (Stigebrandt and Aure, 1989, Inall and Rippeth, 2002). The work against buoyancy per unit area of the basin, W (J m^{-2} s^{-1}), is therefore given by

$$W = \frac{R_f . E_T}{A_T} \qquad (3)$$

where A_T is the horizontal planar area of the fjord basin at sill depth (m^2).

In the present model, H_T is set to sill depth unless the surface layer extends below the sill, in which case H_T is set to equal the surface layer thickness i.e.

$$H_T = \max(Ht, H_1) \qquad (4)$$

For the situation shown in Figure 1, the value of H_T in the first (outer) basin is $H_T = Ht_1$, whereas for the second (inner) basin, $H_T = H_1$. We do this on the assumption that the surface layer is thoroughly oxygenated at all times due to exchange across the air-sea interface. The lower layer thickness, H_B, is the mean depth of the water column beneath H_T. The density difference $\Delta\rho$ is calculated using predicted annual-mean densities for the appropriate layers.

From the work being done against buoyancy, W, and the mean depth of the basin water, H_B, the rate of density reduction can be calculated by

$$\frac{d\rho}{dt} = -\frac{C.W}{g{H_B}^2} \qquad (5)$$

where C is a constant with a value C = 2 (Stigebrandt, 2001).

The time scale of deep water renewal, T_E, is given by

$$T_E = {R_e} \Big/ {\frac{d\rho}{dt}} \qquad (6)$$

where R_E is the reduction in density required to obtain a complete exchange of basin water. In the present model, the value of R_E is linked to the standard deviation of the density of adjacent coastal water, as discussed in section 2.4.

Equations 1-6 provide a method of estimating the average duration of basin water stagnation in Scottish sea lochs between successive renewal events. It should be remembered that observations demonstrate that renewal events in Scottish fjords are episodic and irregular, responding to variable and unpredictable patterns of wind forcing and river discharge. We do not expect, therefore, to predict time scales of individual events, but merely the expected time scale on which an event is likely to occur.

2.2 Sub-Model 2: Time Scale of Oxygen Depletion

The depletion of oxygen in sea loch basins was assumed to be due to the combined effect of a pelagic biochemical oxygen demand, BOD_{pel} (mgO_2 m^{-3} d^{-1}), a benthic BOD, BOD_{ben} (mgO_2 m^{-2} d^{-1}), and the oxidation of an additional particulate organic carbon (POC) flux from finfish aquaculture, μF_C ($mgO_2\ m^{-2}\ d^{-1}$), where F_C is the flux of POC. Oxidation of this carbon is assumed to occur with $\mu = 3.5\ gO_2/gC$ (Stigebrandt et al., 1996; Stigebrandt, 2001). This consumption was balanced against a diffusive flux of oxygen into the basin water as a result of the same vertical mixing that reduces the basin water density. The rate of change of the basin water oxygen concentration, O_2 ($mgO_2\ m^{-3}$), is therefore given by

$$\frac{dO_2}{dt} = -BOD_{pel} - \frac{BOD_{ben}}{H_B} - \frac{\mu F_C}{H_B} + \gamma(O_S - O_2) \tag{7}$$

where O_S is the saturated oxygen concentration assumed to be present in the surface layer. The diffusive flux of oxygen into the basin is dependent on the diffusive exchange rate, γ (d^{-1}), and the difference in oxygen concentration between the basin water and the saturated surface layer.

By assuming constant values for the variables BOD_{pel}, BOD_{ben}, F_C, γ and O_S, Equation 7 can be solved for O_2 as a function of time, t, giving

$$O_2(t) = O_S - S_O(1 - e^{-\gamma t}) \tag{8}$$

where

$$S_O = \frac{1}{\gamma}(BOD_{pel} + \frac{BOD_{ben}}{H_B} + \frac{\mu F_C}{H_B}) \tag{9}$$

is the net effect of the oxygen sink terms.

From Equation (8), it is evident that with increasing time the oxygen concentration asymptotically approaches an equilibrium value whereby the sink terms and the diffusive source are in balance. The equilibrium concentration is given by

$$O_{equilib} = O_S - S_O \tag{10}$$

The time scale, T_O, is defined as the time taken for the basin water oxygen concentrations to fall from the saturation value ($O_2 = O_S$), which is assumed immediately following deep water renewal events, to hypoxia ($O_2 = O_{hyp}$). If the equilibrium concentration is greater than the hypoxia value ($O_{equilib} > O_{hyp}$), then hypoxia is never reached and the time scale is infinite; if, however, $O_{equilib} < O_{hyp}$, then the time scale T_O can be derived from Equation (8), so that

$$\begin{aligned} T_O &= -\frac{1}{\gamma}\ln\left(\frac{O_{hyp} - O_S + S_O}{S_O}\right) & O_{equilib} < O_{hyp} \\ T_O &= \infty & O_{equilib} \geq O_{hyp} \end{aligned} \tag{11}$$

2.3 The Contribution of Fish Farm Carbon to Total BOD

The system of equations (7) – (11) allows us to estimate the influence on deoxygenation of the particulate carbon flux deriving from finfish aquaculture activities. The total biochemical oxygen demand, BOD_{total}, is given by (from Eq. 7)

$$BOD_{total} = BOD_{pel} + \frac{BOD_{ben}}{H_B} + \frac{\mu F_C}{H_B} \tag{12}$$

and the percentage contribution from fish farming is therefore

$$BOD_{FF} = \frac{\mu F_C}{H_B . BOD_{total}} .100\% \tag{13}$$

The variable BOD_{FF} was calculated for each loch basin. In addition, the model was run with F_C set to zero for all loch basins and the influence on the equilibrium concentration ($O_{2equilib}$) and the depletion time scale, T_O, investigated.

2.4 Data Sources and Parameter Values

2.4.1 Physical Data

The primary source of physical data was the sea loch catalogue of Edwards and Sharples (1986), which provided essential information on the physical characteristics of each sea loch system e.g. surface area, volume, mean spring tidal range, mean river discharge etc. The physical exchange model (Gillibrand and Inall, 2006) takes these data and derives an approximate hypsography for each system, which was passed to the present sub-models. The catalogue also contains data about each sill in every system, including the upstream surface area, but contains less information on individual basins. For the present model, the surface area of each individual basin was derived from the upstream areas given for each sill (and manually edited for some systems where sills are not axially sequential along a loch). The basin volumes and horizontal areas at subsurface depths were then derived by scaling the hypsography by the surface area ratios e.g. the horizontal area at depth z and the volume of the basin below depth z were calculated as:

$$\begin{aligned} A_{basin}(z) &= A_{loch}(z) \, . \, \frac{A_{basin}(z=0)}{A_{loch}(z=0)} \\ V_{basin}(z) &= V_{loch}(z) \, . \, \frac{V_{basin}(z=0)}{V_{loch}(z=0)} \end{aligned} \tag{14}$$

where the values $A_{loch}(z)$ and $V_{loch}(z)$ are known from the hypsography.

2.4.2 Sub-Model 1

For sub-model 1, the physical parameters required were available either from the catalogue or as output from the physical exchange model (layer thicknesses and densities and the hypsography).

The variable R_E in Equation 6, the reduction in basin water density required for renewal to occur, was linked to the standard deviation of the density of the coastal water outside the fjord. Some limited data from studies of deep water renewal in Scottish fjords were available (Edwards and Edelsten, 1977; Gillibrand et al., 1995; Allen and Simpson, 1998a; SAMS unpublished data) which indicated that average values of R_E varied from 0.16 – 0.65 kg m^{-3} (Table 1). There was some indication that the value of R_E for a basin increased depending on the number of sills between the basin and the open ocean. For instance, data from Lochs Etive and Sunart were obtained in the uppermost basins, in both cases separated from coastal waters by six sills, and values of $R_E = 0.65$ and 0.48 kg m^{-3} respectively were obtained; conversely, data from Loch Linnhe came from the outer basin, with just one seaward sill, and a value of R_E of 0.16 kg m^{-3} was estimated. This apparent variability is not unreasonable, given that cumulative effects of tidal mixing over sills should indeed increase the standard deviation of the density at sill depth along the fjord. To incorporate this effect, the value of R_E for a basin was specified according to

$$R_e = \sigma_\rho . \log_{10}(N_S + 10) \qquad (15)$$

where σ_ρ is the standard deviation of the coastal water density at sill depth, and N_S is the number of sills between the basin and the open coastal ocean. The constant of 10 in the log term ensures that the log value is greater than unity. The formulation of Equation (15) is arbitrary, with the aim of introducing a small amount of variability into the R_E parameter. Site-specific data for each basin would, of course, be preferable but are simply not available. The results of Equation (15) for sea lochs where data on R_E are available are also presented in Table 1.

The same sources of data for R_E, also provided estimates of the average time scale between renewal events, T_E. These data were also used to calibrate the model and the results are presented in Table 2.

Various sources of data were investigated to evaluate the variability of coastal water density, σ_ρ. SAMS has maintained a mooring in the Tiree Passage since 1981, although both salinity and temperature measurements, from which density can be derived, have been made only since 2002 (Figure 3). The Fisheries Research Services in Aberdeen maintain coastal monitoring stations at various locations around the Scottish coast at which weekly temperature and salinity measurements are made. These sources were all analysed and produced a remarkably consistent pattern of density variability. Density time series from Tiree Passage, Loch Maddy, Scapa Flow and Scalloway all had a standard deviation of $\sigma_\rho = 0.5 \pm 0.04$ kg m^{-3}.

However, some lochs in Scotland do not open out into open shelf water as represented by these time series, for example sea lochs opening into the Firth of Lorne and the Clyde Sea. For this reason, we used a climatology of temperature and salinity for Scottish west coast waters compiled by the UK Hydrographic Office from all known CTD data from the region. This database is held at SAMS, and provides monthly depth profiles of temperature and salinity for an averaged annual cycle. The climatology covers the region 55 – 59 °N 5 - 9 °W at 0.25° resolution (Figure 4). The model identifies the point in the climatology grid closest to each sea loch and uses the standard deviation of density from that location to provide the external value of σ_ρ for that sea loch. The values for four sample lochs are given in Table 1. The climatology does not extend to Shetland, but the closest grid cell in the climatology (the Northeastern-most) lies in essentially the same Atlantic Water that surrounds Shetland, and therefore provides an acceptable boundary condition.

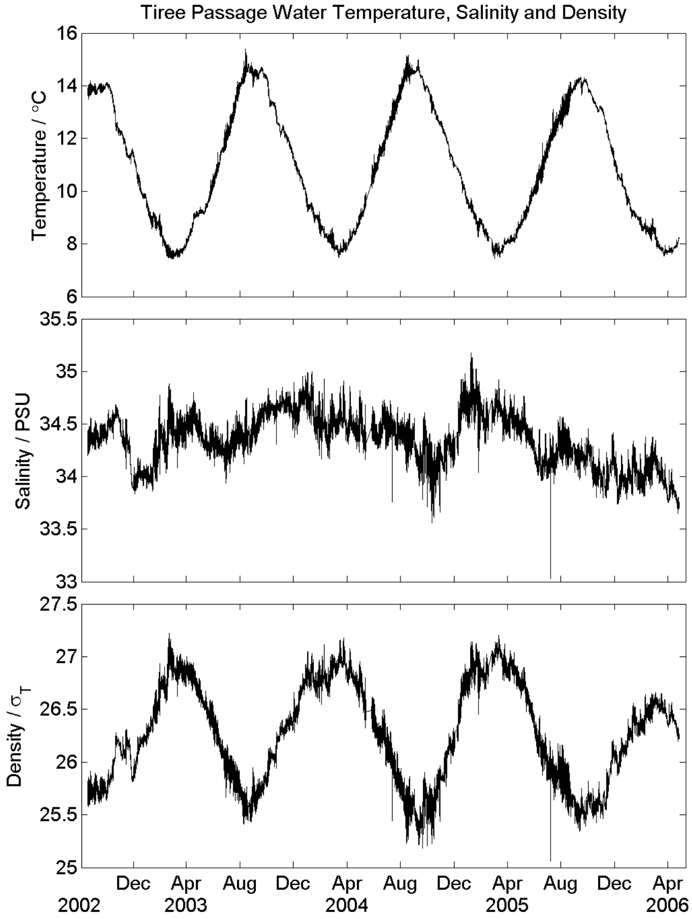

Figure 3. Time series of water temperature, salinity and density in the Tiree Passage between October 2002 – April 2006.

2.4.3 Sub-Model 2

Pelagic and benthic biochemical oxygen demand rates were taken from the literature and unpublished SAMS data. Benthic BOD rates vary in Scottish sea lochs over the range 6.5 – 52.3 mmol O_2 m^{-2} d^{-1} (Overnell et al., 1996; Loh et al., 2002; SAMS unpublished data), with the majority of values falling in the range 7.3 – 23.6 mmol O_2 m^{-2} d^{-1}. Here we used a mid-range value of BOD_{sed} = 14.4 mmol O_2 m^{-2} d^{-1}. The data do not appear to show any obvious seasonal signal and were gathered at varying times of year. The BOD may be modified at low oxygen concentrations, but has been found to be approximately constant for oxygen concentrations down to about 100 mmol O_2 L^{-1} (Overnell et al., 1996).

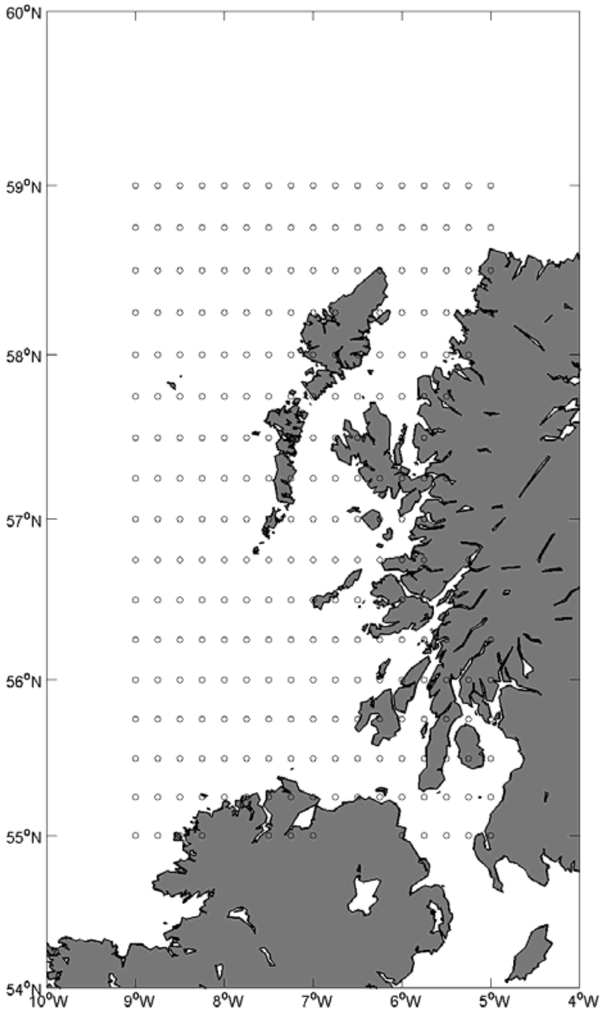

Figure 4. Locations of depth profiles of temperature, salinity and density in the UKHO climatology. Each circle represents the centre of a 0.25° grid square in which all known CTD data are averaged by month.

Pelagic BOD rates also came from unpublished sources at SAMS, with the data gathered from Loch Etive during the Restricted Exchange Environments project in 1999-2000. The value used in the present study was BODpel = 3.7 mmol O_2 m^{-3} d^{-1}. There are no salmon farms in the upper basin of Loch Etive, and the BOD is largely due to non-anthropogenic processes, enabling the carbon flux and resulting BOD from fish farming activities to be calculated separately.

The carbon flux, F_C (gC m^{-2} d^{-1}), was estimated for each sea loch system from the biomass consented by the Scottish Environment Protection Agency (SEPA) as of December 2006. Perez et al. (2002) suggest that a mass of carbon equivalent to about 18% of the fish production is discharged annually; from this a daily mass flux of POC can be estimated i.e.

$$F_C = \frac{0.18.M_C}{365 A_F}.10^6 \tag{16}$$

where M_C is the consented fish biomass (tonnes).

Finally, we have set the criteria for oxygen saturation and hypoxia at 9.2 and 2.5 $mgO_2\ L^{-1}$ respectively. There is no absolute definition of hypoxia, but values of "less than 2-3 milligrams of oxygen per liter of water (mg/L)" have been suggested as appropriate (Ecological Society of America, see http://www.esa.org/education/edupdfs/hypoxia.pdf). In addition, the consultation document published by the Scottish Executive on implementing the Water Environment and Water Services (Scotland) Act 2003 (Scottish Executive, 2006) proposes that transitional/coastal waters with dissolved oxygen concentration of less than 2.4 $mgO_2\ L^{-1}$ should be designated as poor.

2.5 Model Implementation

The sub-models have been developed as Matlab scripts. A further script links the two sub-models, and applies them to each relevant sea loch in the catalogue. Relevant in this sense means that only sea lochs with sills are modelled; those without sills are assumed to be openly exchanged with coastal ocean water and not subject to hypoxia. A further limitation is that loch basins with maximum depths less than 10m are not modelled; here, it is assumed that oxygen exchanged across the air-sea interface is likely to penetrate into the full depth of the water column due to turbulent mixing

In summary then, the models are applied to 68 of the 110 sea lochs listed in the catalogue, with a total of 135 individual basins being modelled.

The calculations of maximum sustainable fish biomass (Equations 12-14) were also performed using Matlab, but are also available as an Excel spreadsheet.

3. Results

3.1 Physical Exchange

The results of the physical exchange calculations for each sea loch basin are presented in Table 3. The table includes sill and mean basin depths, rate of work against buoyancy, the rate of density reduction, the density reduction required for renewal and the time scale of renewal. The predicted values of R_E and T_E for systems from which some data are available are also presented in Tables 1 and 2.

Values of T_E range from 1 day in a number of small basins, to 489 days for the uppermost basin of Loch Etive. There are clearly discrepancies between predicted values and the estimated values from data (Table 2), but the predicted values are at least of the correct order of magnitude, providing some confidence in the first order accuracy of the results.

3.2 Baseline Oxygen Results

Predicted time series of oxygen concentration for all 135 sea loch basins are presented in Figure 5. Depletion rates vary from zero (the basin water remains oxygen saturated at all times) to rapid declines which result in hypoxia occurring within a few days. Predicted oxygen levels in Loch Skiport decline fastest, followed by Loch Airdbhair, Gruting Voe and Stromness Voe (Table 4).

The results in Table 4 have been sorted in order of decreasing T_E/T_O, so the lochs most at risk of hypoxia are listed first and the risk reduces moving down the table. The table presents predicted values of T_E, $O_{equilib}$, T_O and T_E/T_O (see Equations 6, 10, 11). Theoretically, if the value of T_E/T_O is greater than unity for a sea loch basin, the water in that basin is prone to hypoxia. However, given the uncertainties in the estimates of both T_E and T_O, the table is probably best viewed as a relative ordering of the propensity of sea loch basins to hypoxia.

The basin most prone to hypoxia is the upper basin of Loch Etive. Given the anomalously long mean residence time of the basin water (Edwards and Edelsten, 1977), this result is not unexpected. Observations have shown reduced oxygen concentrations in the basin, as low as 1.0 $mgO_2\ L^{-1}$, during the periods between renewal events (Figure 6, SAMS unpublished data 1999-2000). From these data, the rate of oxygen depletion in the upper basin of Loch Etive immediately following the deep water renewal event of May/June 2000 is 0.025 $mgO_2\ L^{-1}\ d^{-1}$. This equates to a hypoxia time scale of T_O = 268 days, much longer than predicted (Table 4). It is possible that the rates of benthic and pelagic BOD used in the model, which are obtained from discrete sediment and water samples and incubated over short periods of time, are not representative of the BOD on the scale of the whole basin. The BOD appears to be over-estimated, and this uncertainty is addressed in the sensitivity analysis.

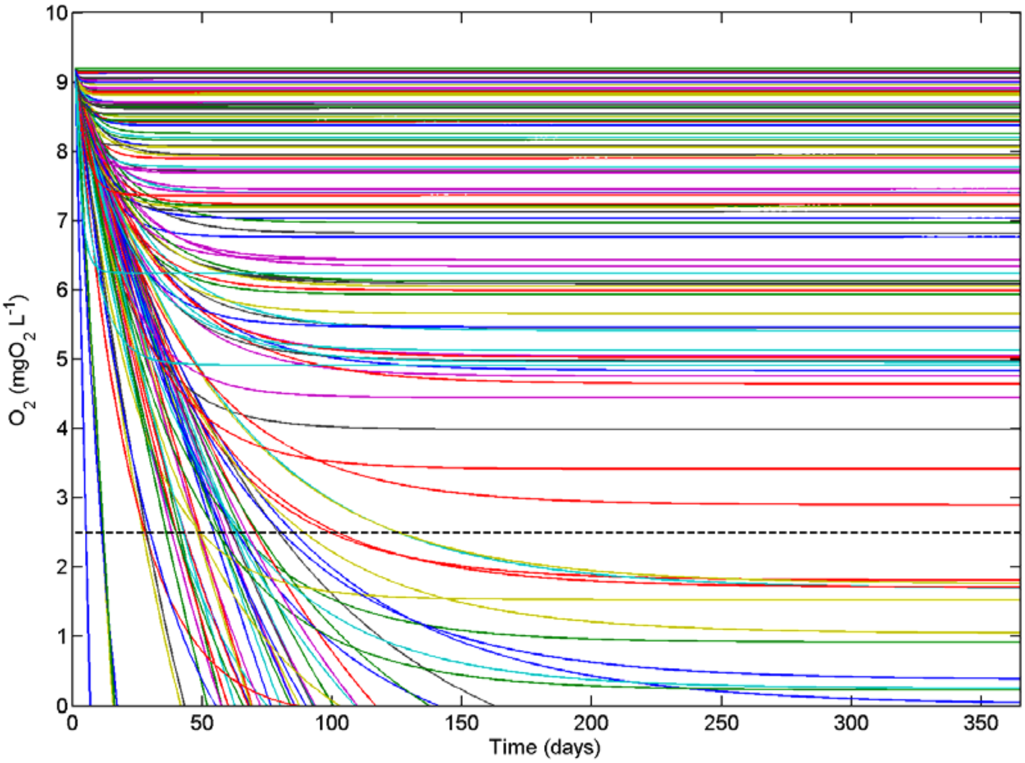

Figure 5. Predicted time series of oxygen concentrations (from Equation 8) for 135 sea loch basins over the course of one year. The vertical scale is cut off at zero, and the dashed horizontal line indicates our defined hypoxia concentration.

Oxygen concentrations as low as 2.5 – 3.2 $mgO_2\ L^{-1}$ have been observed in Loch Fyne (Overnell et al., 1996), and the basin ranks fifth in Table 4. Similarly, Loch Goil has been known to exhibit basin water hypoxia (Overnell et al., 1996) and here the loch is listed thirteenth in the table with a T_E/T_O ration of 1.96.

In total, 28 loch basins have T_E/T_O ratios greater or equal to one. Although, for reasons given above, the ratio value should not be treated as absolute, any future sampling programme designed to evaluate and test these results should focus on at least some of these 28 loch basins.

Notably, eighty-six loch basins (64% of the total) were predicted to remain oxygenated as the diffusive flux of oxygen was large enough to balance the biochemical oxygen demand in the basin before hypoxia was reached. Again, these results should be tested through a targeted sampling programme.

The remaining 21 basins (16%) are predicted to be exchanged frequently enough to prevent oxygen concentrations becoming hypoxic on average. During longer than average intervals between renewal events, however, hypoxia may occur temporarily in these basins.

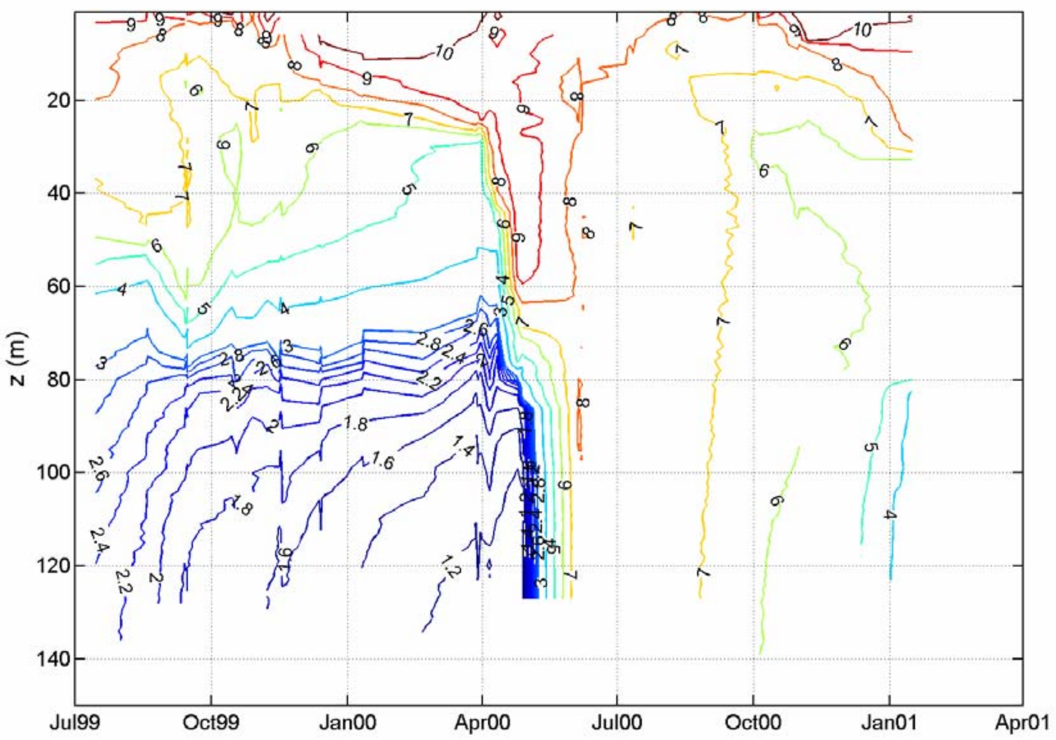

Figure 6. Measured oxygen concentrations (mgO$_2$ L^{-1}) in the upper basin of Loch Etive (station RE5) from July 1999 – January 2001. The vertical axis is depth (m). A deep water renewal event occurred in May-June 2000.

3.3 Sensitivity Analysis

A simple sensitivity analysis was performed. The pelagic and benthic parameters contributing to the total BOD were reduced and increased by 50% in turn, and then both reduced by 75% together. In addition, runs were performed with the diffusive oxygen flux and the oxidation rate of fish farm carbon independently varied by ±50%. The aim of these runs was to establish the most critical parameters in determining the susceptibility of each basin to deoxygenation. Finally, a “worst case” run was performed with the BOD values increased by 50% and the diffusive flux of oxygen reduced by 50%. Eleven model sensitivity runs were performed in total and the parameter values for each are presented in Table 5.

The model was run with the revised parameter values for all sea loch basins in the database, and revised values of T_O and the T_E/T_O ratio obtained for each basin. The ratios of T_O relative to the baseline simulation (Run 1) were calculated for each loch, and the mean and standard deviation of that ratio over 135 loch basins are presented for each sensitivity run in Table 6. For each sensitivity run, the loch basins were ranked in order of decreasing T_E/T_O (a ranking of 1 marks the basin where hypoxic conditions are most likely to be found, a ranking of 135 marks the basin where hypoxia is least likely). The minimum, maximum and median rankings for each loch basin are presented in Table 7.

The sensitivity analysis suggested that the pelagic biochemical demand dominated the time scale of oxygen depletion, with the benthic BOD, by contrast, having a relatively minor effect. Both BOD parameters had to be reduced by 75% (Run 6) for the predicted time scale of hypoxia in Loch Etive to match the observed rate of depletion following renewal (Figure 6). *The sparsity of data available for both these parameters, on basin-wide spatial scales and annual temporal scales, introduces a significant degree of uncertainty into the predictions of hypoxia which will only be resolved by gathering a more extensive dataset from a wider range of locations*. The results from Run 6 are tabulated in Table 8. With these parameter values, hypoxia was predicted for only five basins in Lochs Linnhe-Eil, Etive, Skipport, West Loch Tarbert and Melfort. Lochs Fyne and Goil, which are known to exhibit reduced oxygen concentrations (Overnell et al., 1996) have predicted equilibrium oxygen concentrations of 2.4 and 3.7 $mgO_2\ L^{-1}$ i.e. of similar magnitude to the observed data.

The second largest impact on the hypoxia time scale was due to the enhanced diffusive flux of oxygen, which increased $T_O/T_{Obaseline}$ by 34% on average. This change also had the most variable effect (standard deviation = 0.60) on the ratio of any single parameter change. Modifying the fish farm carbon oxidation rate by ±50% had relatively minor, but variable, effects. The influence of fish farm activity on oxygen budgets is considered in more detail in the next section.

In the “worst case” simulation (Run 11), the time scale T_O was reduced on average by 44%, and the number of basins with $T_E/T_O > 1$ increased to 38. The number predicted to retain oxygen concentrations permanently above hypoxic levels fell to 57 (42%).

The sensitivity of the predicted rankings of the loch basins to parameter values in the model was assessed by comparing the rank of each basin for every sensitivity run. Here, the basin that is most susceptible to hypoxia is ranked 1, and the least susceptible is ranked 135. The minimum, maximum and median rankings for each loch from the 11 sensitivity runs are given in Table 7. The standard deviation of the rankings indicates the variability in the basin rank i.e. it is a measure of the sensitivity of the model predictions to the model parameter values.

Basin 6 in Loch Etive and basin 5 in Loch Linnhe-Eil are consistently ranked 1 and 2 for all sensitivity runs. The standard deviation of 0.29 demonstrates that this ranking is only weakly sensitive to model parameter values. In contrast, basin 2 in Loch Fyne has minimum and median rankings of 4 and 6 respectively, but a maximum rank of 67 indicating that this basin is more sensitive to model parameter values and that the prediction of its susceptibility to hypoxia is therefore less reliable.

At the other end of the table, basin 1 in Loch Torridon ranks consistently at 133-135 with a standard deviation of 0.51, whereas basin2 in the same loch has a median ranking of 135 but a much greater standard deviation, indicating a less reliable prediction.

3.4 The Effects of Fish Farming Activity on Basin Deoxygenation

To investigate the effects of fish farming on basin water deoxygenation, the baseline simulation (Run 1) was repeated but with the fish farm carbon flux set to zero. The effects of the oxygen depletion time scale, T_O, and the T_E/T_O ratio are presented in Table 9. The relative effect of fish farm carbon was estimated by calculating the ratio R:

$$R = \frac{T_O(FF)}{T_O(NoFF)} \tag{17}$$

where $T_O(FF)$ and $T_O(NoFF)$ are the time scale T_O when fish farm carbon is and is not included respectively. The parameter presented in Table 9 is

$$1 - R = \frac{T_O(NoFF) - T_O(FF)}{T_O(NoFF)} = \frac{\Delta T_O}{T_O(NoFF)} \tag{18}$$

where ΔT_O is the change in T_O caused by the inclusion of fish farm carbon. The parameter 1-R is a measure of the effect of fish farming activity on oxygen depletion relative to the undisturbed state.

The loch basins in Table 9 are ranked according to the parameter 1-R. The top five basins all have values of R = 0 (1-R = 1) because $T_O(NoFF)$ is infinite i.e. the equilibrium oxygen concentration without fish farming activity is greater than the hypoxia criteria. The introduction of fish farm derived carbon lowers the predicted equilibrium oxygen concentration below the hypoxia threshold, so that the basins can potentially become hypoxic (according to the model). However, only the top two, Ainort and Portree, are predicted to reach hypoxic conditions ($T_E/T_O > 1$) when fish farming is included, and the uncertainty in the model parameter values precludes firm conclusions about the effects of fish farming in these systems.

The estimated contribution of the particulate organic carbon flux from fish farming activities in each sea loch to the total biochemical oxygen demand in each basin is also presented in Table 9, and the data are summarised in Figure 7. The values range from zero to 73% (Loch Airdbhair). In total, fish farming activity in over 90% of loch basins contributes less than 30% of the *estimated* BOD in that basin, and less than 10% in over 60% of basins. Of the loch basins where fish farm activity contributes more than 10% of the estimated BOD, only six are predicted to become hypoxic as a result of including fish farm carbon, and two of those are marginal cases (Lochs Claidh and Craignish). These six basins are highlighted in Table 9.

The effect of fish farm derived carbon on deep water oxygen levels depends on the flushing rate of the water column. In Loch Airdbhair, for example, the deep water renewal time scale is 3 days, and the high estimated carbon flux does not lead to predicted hypoxia; this was also the case for Stromness Voe and Gruting Voe. But the addition of fish farm carbon to the natural BOD in individual basins of lochs Ainort, Portree, Skiport, Ronas Voe, Claidh and Craignish increases the values of the T_E/T_O ratio from less to more than one i.e. the loch basins are predicted to become hypoxic due to the addition of fish farm carbon (Table 9). In 22 other loch basins where $T_E/T_O > 1$ when fish farm carbon inputs are included, the model also predicts hypoxia without the inclusion of fish farm carbon i.e. the predicted hypoxia events are natural processes. It is important to remember here that the parameter values in the baseline simulation (Run 1) may lead to an overestimated risk of hypoxia and that more data are required to validate and refine these predictions.

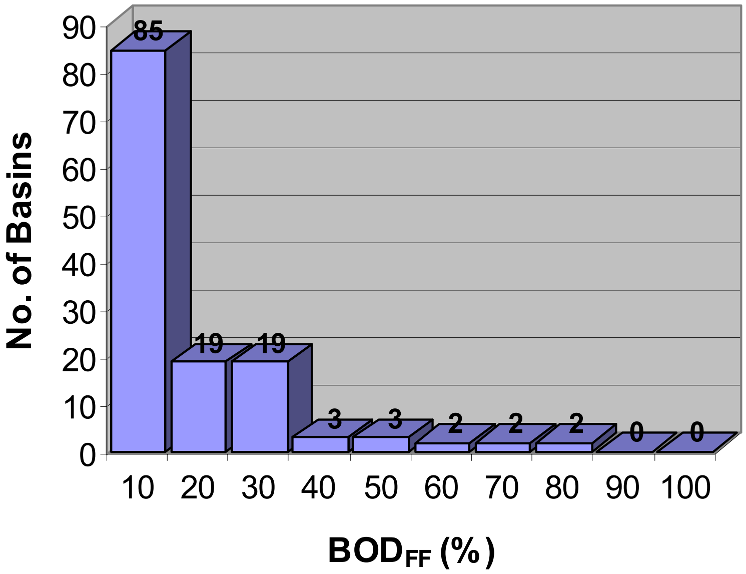

Figure 7. The estimated contribution (%) of fish farm carbon to the total BOD of 135 loch basins.

In order to account for the uncertainty in the model parameter values, the sensitivity analysis described earlier was repeated but with the fish farm carbon source set to zero. Runs 9 and 10, where the oxidation rate of fish farm carbon was varied, were not necessary and so the sensitivity analysis reported here comprised nine simulations. As previously, following each run, the loch basins were ranked according to the value of T_E/T_O and the median values from the nine simulations are presented in Table 10. The median rank from the first sensitivity analysis is shown for reference, and the difference between the rankings with and without fish farming is given. Those loch basins which rank higher when fish farm carbon inputs are included are highlighted. The lochs are ordered according to the ranking generated when fish farming activity is included.

In total, 13 loch basins are ranked higher due to the inclusion of fish farm carbon. However, only two of these lie in the top ten of loch basins predicted to be most susceptible to hypoxia, and only four lie in the top twenty. These results suggest that fish farming in Scotland is unlikely, except in a small number of cases, to contribute significantly to hypoxia events in sea loch basins and that, in the large majority of cases, such events are likely to result from natural processes (i.e. pelagic and benthic BOD). However, it should be noted that in two loch basins, Skiport and West Loch Tarbert Kintyre, which are predicted to become hypoxic in both the baseline simulation and sensitivity run 6, fish farming is estimated to make substantial contributions to the total BOD

Discussion and Conclusions

The results presented here constitute a first attempt to model the basin water oxygen budget for 68 silled Scottish sea lochs, and to assess whether hypoxia is a significant problem in deep loch basins. The two sub-models involved have both been developed in recent years under the present project and a second, SARF–funded project to model assimilative capacity in Scottish sea lochs. The results suggest that there are sea loch basins in Scotland where hypoxic conditions may occur from time to time. It is important to emphasise that the models calculate *average* time scales for deep water renewal and oxygen depletion; a great deal of variability about those averages may be expected. The averaging also applies spatially: basin water volumes are assessed for hypoxic conditions, but hypoxia may develop in localised (sub-basin) volumes of water. Detailed studies of that variability would require more complex numerical water quality models, but applying such models to all Scottish sea lochs rapidly becomes economically unviable. The simpler box-type model described here, that can be applied quickly to a large number of systems, provides a valuable screening tool which may contribute to managing the development of aquaculture in Scottish coastal waters and also steer directed measurement studies to those systems most in need of more careful environmental monitoring and modelling.

The results suggest that the sea loch basins most at risk from hypoxia are those with the longest intervals between renewal events. The link between the T_E/T_O ratio and the renewal time scale T_E is clear (Figure 8). Low oxygen concentrations have been observed in some of the systems predicted to reach hypoxic conditions, providing some confidence in the model predictions. In total, between 5 and 38 loch basins could be prone to hypoxia on occasion, with the remainder predicted to either settle at an equilibrium oxygen concentration greater than 2.5 $mgO_2 L^{-1}$ or to be exchanged sufficiently frequently to prevent concentrations falling so low.

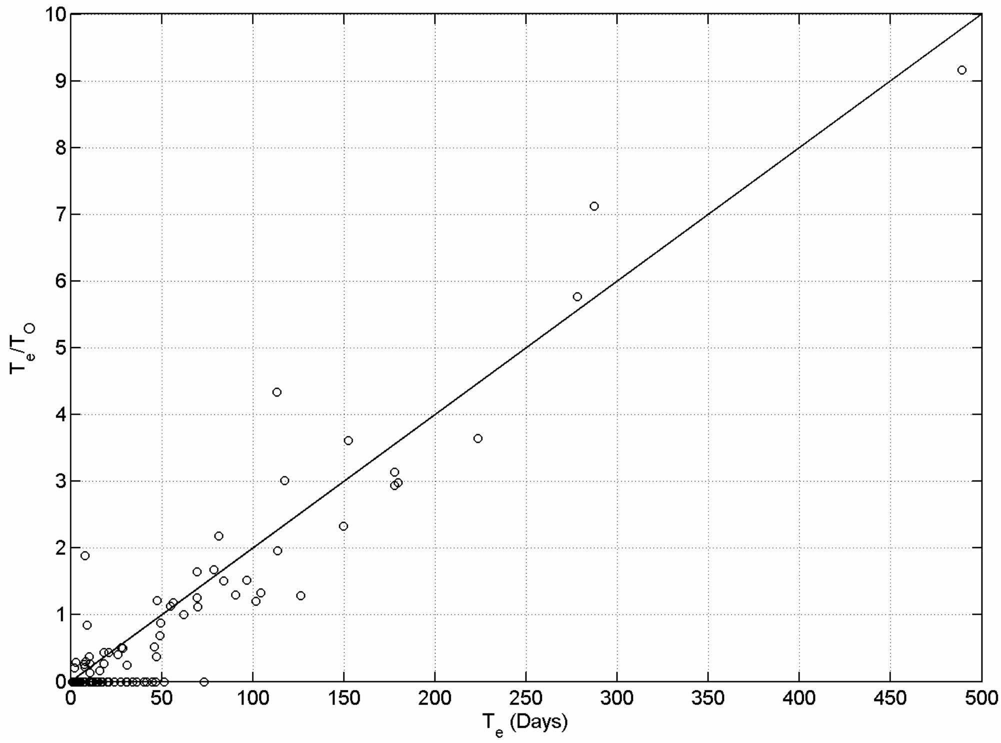

Figure 8. The ratio of deep water renewal and oxygen depletion time scales (T_E/T_O) for 135 sea loch basins plotted against the renewal time scale (T_E).

There are a number of caveats on the results presented here. First, the scarcity of available data on both deep water renewal and oxygen depletion in Scottish systems prevents a robust, thoroughly quantitative, analysis from being performed. Deep water renewal has been studied in a small number of Scottish sea lochs (i.e. Etive, Eil, Sunart, Linnhe, Fyne) but direct observations of vertical mixing have been limited to Loch Etive and the Clyde Sea. Although the mathematical approach used here to estimate vertical exchange is considered reasonably robust, the dataset available to test the model predictions, made for sea lochs and voes throughout Scotland, is clearly limited. More importantly, the values of pelagic and benthic biochemical oxygen demand used in the model are not based on mathematical formulations but are entirely empirical, and again are necessarily derived from just a handful of measurements at a small number of study sites. This is more critical, since the likely variability in BOD, both temporally and spatially, is not accounted for in these results.

The results presented here provide guidance for a targeted campaign of field measurements (*à la* Aure and Stigebrandt, 1989; Stigebrandt et al., 1996) that could be directed at those systems thought to be most at risk from basin water hypoxia, with the resulting data being used to refine the model predictions. The model results suggest that observed values of benthic and pelagic biochemical oxygen demand, derived from discrete incubated samples, could overestimate the basin-scale BOD by a factor of about 4. More detailed modelling of the data from Loch Etive is required to test the robustness of the parameter values, and samples from other (less anomalous) locations would also be beneficial.

A field programme should target those lochs predicted to be at risk of hypoxia with (i) the longest residence times, and (ii) the fastest predicted oxygen depletion rates. For the first type, regular CTDO (conductivity-temperature-depth-oxygen) surveys over a twelve-month period should resolve the rates of oxygen depletion and density reduction in basin waters. For the second type, deployments of moored instrumentation over the timescales of oxygen depletion (typically a few weeks), would resolve the depletion rates. In both cases, process studies of the biochemical oxygen demand and vertical diffusive fluxes of oxygen and salt would be invaluable in increasing the range and scope of the datasets on these processes available from Scottish waters.

The model described here uses an analytical solution (Equation 8) of the differential equation (7), achievable only because we assumed constant values for the BOD and diffusive exchange parameters. If the BOD and diffusive exchange parameters were found to vary temporally, e.g. seasonally, Equation (7) would have to be solved iteratively which, while not difficult *per se*, involves numerical techniques that are inherently less accurate.

The second, and most easily resolvable, caveat concerns the physical characteristics of individual basins, which have been estimated for the present study rather than accurately determined. The catalogue of Edwards and Sharples (1986) contains data on the physical characteristics of whole loch systems, but not on individual basins. To overcome that, we were forced to approximate the hypsography of individual basins by scaling the hypsography for the whole loch (itself estimated) by the relative surface areas of the basin and the loch (Equation 15). Undoubtedly there are differences between the estimated and actual hypsography, some of which may have very significant impacts on the results. A first task to improve the model results presented here is to establish a database of digitised sea loch basin bathymetry, which the Fisheries Research Services in Aberdeen have begun, but not completed; its completion is essential to improve the accuracy of modelled environmental impacts at basin scales.

The model suggests that the majority of Scottish lochs are being farmed for salmon without exacerbating the biochemical oxygen demand such as to produce harmful effects. In a small number (3-4) of loch basins, which are predicted to be susceptible to hypoxia, fish farming provides a significant contribution (9 – 70%) to the total BOD in the basin. Again, however, the considerable uncertainties in the constants and parameter values used in the model caution against unquestioningly accepting these results: the best use of the model predictions will be to steer field sampling to those systems predicted to be most at risk of adverse environmental impact. An additional caveat on this particular subset of the results is that within the model the carbon flux emanating from salmon farms is distributed evenly throughout the loch; thus basins without a salmon farm present still receive an additional carbon input and an elevated oxygen demand as a result. In reality, the particulate carbon flux from fish farms is likely to settle out locally. Conversely, of course, basins with a salmon farm may not receive the full corresponding carbon flux and the total BOD will therefore be modelled at a lower value than it should.

A number of conclusions can be drawn from this study, but it is most important to emphasize the real shortage of data relating to the biochemical oxygen demand in Scottish sea loch basins, which renders these conclusions somewhat tentative.

- A number of sea loch basins, between 5 and 38 out of 135 basins, may be at risk of routinely developing hypoxic bottom water conditions, mostly caused by natural processes.
- An improved digital database of sea loch bathymetry is urgently needed.
- The pelagic BOD dominates the oxygen depletion rates in loch basins.
- Rates of pelagic and benthic biochemical oxygen demand, obtained from discrete samples, may markedly overestimate the BOD on basin-wide scales. Data from a wider range of locations are required.
- Processes and rates of vertical diffusion of salt and oxygen between basin waters and overlying layers, which contribute fundamentally to basin water renewal and oxygen concentrations, are also poorly understood.
- Carbon fluxes from fish farming may contribute significantly to a predicted hypoxia risk in a small number of sea loch basins (about 4), although the risk itself may be overestimated.

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Tables

Table 1. Observed values of the standard deviation of density at sill depth in the external coastal waters at the entrance to each loch (σ_ρ), the mean observed value of R_E for the basins indicated, estimated from the sources listed, and the values of R_E used in the model derived from Equation 16.

		Etive	**Sunart**	**Linnhe-Eil**	**Creran**
External σ_ρ (kg m^{-3})		0.54	0.17	0.43	0.54
Modelled Basin R_E (kg m^{-3})	Basin 1	0.56	0.17	0.45	0.56
	Basin 2	0.61	0.19	0.48	0.61
	Basin 3	0.63	0.19	0.50	0.63
	Basin 4	0.65	0.20	0.51	0.65
	Basin 5	0.66	0.20	0.53	-
	Basin 6	0.68	0.21	-	-
Observed R_E (kg m^{-3}) (Basin Number)		0.65 (6)	0.48* (6)	0.16 (1)	0.25 (2)
Source		Edwards and Edelsten (1977)	Gillibrand et al. (1995)	Allen and Simpson (1998)	SAMS unpublished data

* This value estimated from a modelling study of deep water renewal in Loch Sunart. Density time series data were not available.

Table 2. Estimated mean interval between renewal events from observations and predictions of T_E from the model. Data sources are Edwards and Edelsten (1977), Gillibrand et al. (1995), Allen and Simpson (1998), Overnell et al. (1996).

Loch	**Observed Mean Renewal Interval (d)**	**Modelled Renewal Interval, T_E (d)**
Etive	480	488
Sunart	42	28
Linnhe	21	31
Fyne	365	223

Table 3. Physical exchange parameters. For each sea loch basin, the values of H_T, H_B, W, $d\rho/dt$ (R), R_E and T_E are shown.

Loch	Basin	H_T (m)	H_B (m)	W ($J/m^2/d$)	R ($kg/m^3/d$)	R_E (kg/m^3)	T_E (d)
A' CHAIM BHAIN	1	44.1	13.8	32.07	-0.0342	0.16	4.7
A' CHAIM BHAIN	2	44.1	15.6	4.51	-0.0037	0.17	46.6
A' CHAIM BHAIN	4	26.1	15.3	17.04	-0.0147	0.18	12.5
A' CHAIM BHAIN	5	22.1	18.5	7.10	-0.0042	0.19	44.8
A' CHAIM BHAIN	6	13.4	10.7	6.00	-0.0107	0.19	18.2
AILORT	1	10.0	3.5	18.50	-0.3056	0.27	1.0
AILORT	2	13.2	6.6	59.77	-0.2749	0.30	1.1
AILORT	3	13.2	8.9	0.93	-0.0024	0.31	126.3
AINORT	1	25.0	9.7	1.22	-0.0026	0.25	96.7
AIRDBHAIR	1	3.1	4.2	3.92	-0.0445	0.13	3.0
ALINE	1	3.2	11.6	23.94	-0.0360	0.38	10.6
ALSH	1	18.3	5.4	25.62	-0.1780	0.30	1.7
ALSH	2	18.3	37.2	12.26	-0.0018	0.32	177.8
ALSH	3	18.3	24.1	45.12	-0.0158	0.33	20.9
BAY	1	26.0	14.7	5.12	-0.0048	0.08	17.6
BROOM	1	18.3	7.7	32.32	-0.1109	0.21	1.9
BROOM	2	18.3	19.9	2.51	-0.0013	0.23	177.8
CARRON	1	20.4	17.4	125.38	-0.0843	0.30	3.5
CARRON	2	13.4	12.4	164.51	-0.2196	0.32	1.5
CARRON	3	13.4	22.9	8.34	-0.0032	0.33	101.5
CLAIDH	1	22.0	16.4	1.06	-0.0008	0.04	56.2
CRAIGNISH	1	18.1	9.9	4.91	-0.0101	0.71	69.9
CRERAN	1	12.7	8.9	457.44	-1.1632	0.57	1.0
CRERAN	2	16.7	9.5	19.43	-0.0438	0.61	13.9
CRERAN	3	16.7	7.1	7.47	-0.0306	0.63	20.6
CRERAN	4	11.3	11.1	15.10	-0.0248	0.65	26.1
DUGHAILL	1	18.0	12.7	0.99	-0.0012	0.08	62.1
DUICH	1	18.3	39.9	57.77	-0.0073	0.34	47.0
DUICH	2	18.3	6.3	0.90	-0.0046	0.37	81.3
EISHORT	1	10.2	4.5	3.47	-0.0343	0.26	7.5
EISHORT	2	9.2	8.3	0.80	-0.0024	0.28	117.5
EPORT	1	16.1	3.9	12.96	-0.1723	0.04	1.0
EPORT	2	9.1	3.8	4.76	-0.0686	0.05	1.0
EPORT	3	9.1	5.9	2.15	-0.0124	0.05	3.8
EPORT	4	9.1	6.1	2.33	-0.0126	0.05	3.9
EPORT	5	9.1	3.2	3.53	-0.0713	0.05	1.0
EPORT	6	9.1	3.8	3.57	-0.0516	0.05	1.0
EPORT	7	8.1	2.5	0.76	-0.0241	0.05	2.2
EPORT	8	6.7	3.5	0.44	-0.0072	0.05	7.5
ERIBOLL	1	38.0	14.6	2.58	-0.0024	0.07	27.5
ETIVE	1	9.9	22.3	741.89	-0.3006	0.56	1.9
ETIVE	2	8.9	11.4	918.09	-1.4437	0.61	1.0
ETIVE	3	12.9	23.7	50.77	-0.0184	0.63	34.1
ETIVE	4	24.9	11.1	100.80	-0.1680	0.64	3.8
ETIVE	5	24.9	23.9	44.87	-0.0159	0.66	41.5
ETIVE	6	13.9	30.1	6.19	-0.0014	0.68	488.9
EWE	1	35.2	11.6	30.63	-0.0463	0.15	3.2
EWE	2	31.2	13.1	4.42	-0.0053	0.16	30.5
EYNORT	1	9.1	2.8	170.66	-4.2703	0.08	1.0
EYNORT	2	5.1	4.2	33.87	-0.3966	0.09	1.0
EYNORT	5	6.1	3.7	1.18	-0.0173	0.10	5.7
FEOCHAN	1	5.8	7.5	76.57	-0.2765	0.51	1.8

FEOCHAN	2	5.8	7.5	19.69	-0.0711	0.55	7.7
FYNE	1	43.6	17.3	12.31	-0.0083	0.20	23.9
FYNE	2	43.6	41.5	8.17	-0.0010	0.22	223.4
GARELOCH	1	15.6	5.7	31.72	-0.1987	0.32	1.6
GARELOCH	2	13.2	16.9	6.90	-0.0049	0.34	69.5
GOIL	1	16.0	32.5	14.51	-0.0028	0.32	113.5
GRESHORNISH	1	29.0	10.6	1.39	-0.0025	0.07	27.8
GRIMSHADER	1	3.9	4.7	9.80	-0.0904	0.06	1.0
GRUTING VOE	1	26.6	5.5	0.68	-0.0046	0.05	10.2
GRUTING VOE	2	11.4	3.2	0.29	-0.0057	0.05	8.9
HOURN	1	90.1	31.5	7.94	-0.0016	0.17	104.2
HOURN	2	13.1	28.1	206.62	-0.0527	0.18	3.5
HOURN	3	13.1	22.8	130.11	-0.0506	0.19	3.7
HOURN	4	13.1	28.8	43.99	-0.0107	0.19	18.1
HOURN	5	13.1	4.7	2.10	-0.0191	0.20	10.4
INCHARD	1	24.0	16.0	4.55	-0.0036	0.07	20.0
LAXFORD	1	46.0	7.4	3.12	-0.0117	0.08	7.0
LEURBOST	1	8.0	5.8	1.65	-0.0101	0.04	4.2
LEVEN	1	7.9	13.8	460.55	-0.4898	0.45	1.0
LEVEN	2	25.9	10.1	66.34	-0.1315	0.48	3.7
LEVEN	3	32.9	7.4	27.76	-0.1015	0.50	4.9
LEVEN	4	32.9	7.6	8.64	-0.0307	0.51	16.8
LEVEN	5	5.9	16.6	9.16	-0.0067	0.53	78.8
LINNHE AND EIL	1	19.9	37.6	101.25	-0.0145	0.45	31.0
LINNHE AND EIL	2	16.9	9.3	111.48	-0.2633	0.48	1.8
LINNHE AND EIL	3	12.9	12.5	273.93	-0.3545	0.50	1.4
LINNHE AND EIL	4	32.9	25.1	32.52	-0.0105	0.51	48.8
LINNHE AND EIL	5	32.9	13.0	1.52	-0.0018	0.53	287.2
LITTLE LOCH BROOM	1	40.3	23.9	32.75	-0.0116	0.13	11.1
LITTLE LOCH BROOM	2	39.3	30.4	3.53	-0.0008	0.14	179.8
LONG ALSH	1	5.3	11.7	11.57	-0.0171	0.34	20.2
LONG ALSH	2	4.3	12.3	3.82	-0.0051	0.37	73.3
LONG CLYDE	1	58.6	5.9	7.16	-0.0412	0.32	7.7
LONG CLYDE	2	39.6	11.2	4.56	-0.0074	0.34	46.1
MELFORT	1	36.0	16.7	2.47	-0.0018	0.50	278.2
MOIDART NORTH CHANNEL	1	3.8	5.2	5.37	-0.0404	0.18	4.5
MOIDART SOUTH CHANNEL	2	3.2	4.7	1.78	-0.0167	0.20	11.9
NA CILLE	1	13.0	5.1	0.17	-0.0014	0.21	152.5
NA KEAL	1	50.0	11.2	10.05	-0.0162	0.24	14.6
NEVIS	1	22.2	46.5	31.84	-0.0030	0.27	90.3
NEVIS	2	13.3	46.2	36.75	-0.0035	0.29	83.9
PORTREE	1	18.0	7.7	1.25	-0.0043	0.23	54.9
RONAS VOE	1	16.9	10.4	1.15	-0.0022	0.05	20.9
RONAS VOE	2	16.9	12.3	0.78	-0.0010	0.05	47.6
RYAN	1	7.0	3.7	1.08	-0.0162	0.16	10.1
SCRIDAIN	1	53.0	14.0	3.53	-0.0037	0.11	31.0
SEAFORTH	1	40.1	7.2	17.67	-0.0687	0.04	1.0
SEAFORTH	3	13.5	5.7	64.87	-0.4069	0.04	1.0
SHELL	1	31.1	14.6	4.91	-0.0047	0.05	10.2
SHELL	2	13.5	10.8	3.86	-0.0067	0.05	7.7
SKIPORT	3	9.7	1.2	0.09	-0.0117	0.09	7.9
SKIPORT	4	9.7	10.0	5.82	-0.0117	0.10	8.1
SLAPIN	1	7.0	5.4	0.72	-0.0050	0.26	51.1
SLIGACHAN	1	5.6	9.6	20.16	-0.0441	0.25	5.8
SNIZORT BEG	1	26.0	9.5	2.19	-0.0050	0.07	14.0

SPELVE	1	13.1	14.6	34.17	-0.0328	0.38	11.6
STORNOWAY	1	10.1	3.2	1.78	-0.0346	0.06	1.7
STORNOWAY	2	10.1	3.2	0.28	-0.0055	0.06	11.5
STROMNESS VOE	1	5.6	6.7	4.23	-0.0194	0.04	2.3
SULLOM VOE	1	18.0	13.5	0.84	-0.0009	0.05	49.5
SUNART	1	72.0	16.7	54.36	-0.0393	0.17	4.4
SUNART	2	72.0	16.8	17.16	-0.0122	0.19	15.3
SUNART	3	71.0	17.0	24.92	-0.0173	0.19	11.2
SUNART	4	47.0	19.2	47.51	-0.0260	0.20	7.7
SUNART	5	17.0	18.3	111.26	-0.0673	0.20	3.0
SUNART	6	13.3	35.5	45.79	-0.0074	0.21	28.4
SWEEN	1	15.8	6.2	5.23	-0.0274	0.21	7.6
SWEEN	2	20.8	6.7	3.94	-0.0181	0.23	12.4
SWEEN	3	20.8	6.6	1.23	-0.0058	0.23	40.2
SWEEN	4	10.6	2.2	1.47	-0.0608	0.24	3.9
SWEEN	5	10.6	0.4	0.09	-0.1162	0.25	2.1
SWEEN	6	10.6	5.1	0.47	-0.0036	0.25	69.4
TAMANAVAY	1	26.0	9.5	0.99	-0.0022	0.04	16.1
TARBERT	1	7.6	6.7	43.21	-0.1978	0.14	1.0
TARBERT	2	7.6	7.6	11.02	-0.0385	0.15	4.0
TARBERT	3	7.6	7.4	2.45	-0.0092	0.16	17.4
TEACUIS	1	10.0	6.2	25.13	-0.1345	0.18	1.4
TEACUIS	2	10.0	3.2	39.84	-0.7934	0.20	1.0
TEACUIS	3	7.0	7.2	10.29	-0.0407	0.20	5.0
TORRIDON	1	81.5	31.3	47.78	-0.0099	0.16	16.6
TORRIDON	2	81.5	29.6	21.12	-0.0049	0.18	36.3
TORRIDON	3	22.5	42.0	10.61	-0.0012	0.18	149.7
WEST LOCH TARBERT KINTYRE	1	8.0	4.2	0.17	-0.0019	0.22	113.3

Table 4. Results from the baseline model run. For each sea loch basin, the values of γ, F_C, T_E, $O_{equilib}$ (O_2), T_O and the ratio T_E/T_O are shown. Values of T_E are presented again to facilitate comparison with T_O. The lochs are listed in order of decreasing T_E/T_O. Where T_O is given as Inf, the equilibrium oxygen concentration is greater than the value used to define hypoxia.

Loch	Basin	γ (d^{-1})	F_C ($gC/m^2/d$)	T_E (d)	O_2 (mgO_2/L)	T_O (d)	T_E/T_O
ETIVE	6	0.003	0.013	488.9	-39.4	53.3	9.17
LINNHE AND EIL	5	0.002	0.075	287.2	-65.0	40.3	7.12
MELFORT	1	0.003	0.017	278.2	-39.1	48.2	5.77
WEST LOCH TARBERT KINTYRE	1	0.019	0.119	113.3	-7.6	26.1	4.34
FYNE	2	0.006	0.025	223.4	-11.7	61.4	3.64
NA CILLE	1	0.014	0.000	152.5	-6.1	42.2	3.61
BROOM	2	0.008	0.030	177.8	-9.4	56.6	3.14
EISHORT	2	0.024	0.211	117.5	-1.9	38.9	3.02
LITTLE LOCH BROOM	2	0.008	0.049	179.8	-8.8	60.2	2.99
ALSH	2	0.007	0.052	177.8	-10.3	60.5	2.94
TORRIDON	3	0.008	0.026	149.7	-8.2	64.3	2.33
DUICH	2	0.011	0.052	81.3	-10.5	37.3	2.18
GOIL	1	0.005	0.000	113.5	-18.0	58.0	1.96
SKIPORT	3	0.017	0.403	7.9	-89.1	4.2	1.89
LEVEN	5	0.005	0.061	78.8	-23.9	47.1	1.67
SWEEN	6	0.013	0.000	69.4	-6.4	42.1	1.65
AINORT	1	0.026	0.141	96.7	0.9	63.4	1.52
NEVIS	2	0.003	0.061	83.9	-28.9	55.4	1.51
HOURN	1	0.013	0.030	104.2	-1.3	78.4	1.33
NEVIS	1	0.010	0.061	90.3	-4.4	69.5	1.30
AILORT	3	0.024	0.021	126.3	1.8	98.4	1.28
GARELOCH	2	0.007	0.000	69.5	-11.7	55.5	1.25
RONAS VOE	2	0.010	0.186	47.6	-10.9	39.1	1.22
CARRON	3	0.016	0.027	101.5	0.0	84.2	1.21
CLAIDH	1	0.008	0.107	56.2	-11.9	47.6	1.18
PORTREE	1	0.043	0.329	54.9	1.5	48.4	1.13
CRAIGNISH	1	0.018	0.034	69.9	-0.9	62.4	1.12
DUGHAILL	1	0.012	0.000	62.1	-3.3	62.2	1.00
SULLOM VOE	1	0.009	0.000	49.5	-7.0	56.6	0.87
GRUTING VOE	2	0.007	0.364	8.9	-88.7	10.5	0.85
LINNHE AND EIL	4	0.013	0.075	48.8	-1.7	70.4	0.69
LONG CLYDE	2	0.020	0.000	46.1	1.0	88.2	0.52
GRESHORNISH	1	0.025	0.192	27.8	0.2	54.8	0.51
SUNART	6	0.006	0.085	28.4	-13.3	56.9	0.50
RONAS VOE	1	0.022	0.186	20.9	-1.1	47.9	0.44
A' CHAIM BHAIN	6	0.008	0.079	18.2	-15.3	41.8	0.43
CRERAN	4	0.022	0.104	26.1	0.3	64.2	0.41
DUICH	1	0.018	0.052	47.0	1.7	124.5	0.38
GRUTING VOE	1	0.046	0.364	10.2	-0.2	27.0	0.38
SKIPORT	4	0.017	0.403	8.1	-8.9	27.5	0.30
AIRDBHAIR	1	0.052	0.740	3.0	-7.1	10.3	0.29
HOURN	4	0.010	0.030	18.1	-4.8	66.1	0.27
HOURN	5	0.018	0.030	10.4	-4.3	38.9	0.27
EPORT	8	0.031	0.103	7.5	-2.1	28.9	0.26
LINNHE AND EIL	1	0.019	0.075	31.0	1.8	125.0	0.25
SHELL	2	0.007	0.172	7.7	-20.5	35.1	0.22
STROMNESS VOE	1	0.007	0.857	2.3	-87.4	10.9	0.21
TAMANAVAY	1	0.022	0.000	16.1	1.7	101.2	0.16

ALINE	1	0.018	0.000	10.6	0.4	79.6	0.13
LONG ALSH	2	0.050	0.000	73.3	6.1	Inf	0.00
SLAPIN	1	0.050	0.089	51.1	4.0	Inf	0.00
A' CHAIM BHAIN	2	0.037	0.079	46.6	4.8	Inf	0.00
A' CHAIM BHAIN	5	0.042	0.079	44.8	5.5	Inf	0.00
ETIVE	5	0.032	0.013	41.5	4.8	Inf	0.00
SWEEN	3	0.058	0.000	40.2	5.9	Inf	0.00
TORRIDON	2	0.030	0.026	36.3	4.7	Inf	0.00
ETIVE	3	0.037	0.013	34.1	5.4	Inf	0.00
SCRIDAIN	1	0.037	0.005	31.0	5.1	Inf	0.00
EWE	2	0.053	0.028	30.5	6.1	Inf	0.00
ERIBOLL	1	0.024	0.018	27.5	2.9	Inf	0.00
FYNE	1	0.054	0.025	23.9	6.4	Inf	0.00
ALSH	3	0.061	0.052	20.9	6.8	Inf	0.00
CRERAN	3	0.097	0.104	20.6	6.8	Inf	0.00
LONG ALSH	1	0.169	0.000	20.2	8.3	Inf	0.00
INCHARD	1	0.036	0.018	20.0	5.0	Inf	0.00
BAY	1	0.048	0.007	17.6	6.1	Inf	0.00
TARBERT	3	0.043	0.000	17.4	5.0	Inf	0.00
LEVEN	4	0.056	0.061	16.8	5.5	Inf	0.00
TORRIDON	1	0.061	0.026	16.6	7.0	Inf	0.00
SUNART	2	0.091	0.085	15.3	7.4	Inf	0.00
NA KEAL	1	0.097	0.031	14.6	7.5	Inf	0.00
SNIZORT BEG	1	0.050	0.026	14.0	5.7	Inf	0.00
CRERAN	2	0.138	0.104	13.9	7.7	Inf	0.00
A' CHAIM BHAIN	4	0.147	0.079	12.5	8.1	Inf	0.00
SWEEN	2	0.181	0.000	12.4	8.2	Inf	0.00
MOIDART SOUTH CHANNEL	2	0.167	0.000	11.9	7.9	Inf	0.00
SPELVE	1	0.038	0.055	11.6	5.0	Inf	0.00
STORNOWAY	2	0.055	0.000	11.5	4.4	Inf	0.00
SUNART	3	0.129	0.085	11.2	7.9	Inf	0.00
LITTLE LOCH BROOM	1	0.116	0.049	11.1	8.0	Inf	0.00
SHELL	1	0.047	0.172	10.2	5.1	Inf	0.00
RYAN	1	0.162	0.000	10.1	7.7	Inf	0.00
FEOCHAN	2	0.056	0.000	7.7	6.0	Inf	0.00
SUNART	4	0.193	0.085	7.7	8.4	Inf	0.00
LONG CLYDE	1	0.109	0.000	7.7	7.4	Inf	0.00
SWEEN	1	0.274	0.000	7.6	8.5	Inf	0.00
EISHORT	1	0.343	0.211	7.5	8.1	Inf	0.00
LAXFORD	1	0.117	0.107	7.0	7.2	Inf	0.00
SLIGACHAN	1	0.041	0.188	5.8	3.4	Inf	0.00
EYNORT	5	0.173	0.004	5.7	7.8	Inf	0.00
TEACUIS	3	0.066	0.000	5.0	6.4	Inf	0.00
LEVEN	3	0.184	0.061	4.9	8.1	Inf	0.00
A' CHAIM BHAIN	1	0.341	0.079	4.7	8.7	Inf	0.00
MOIDART NORTH CHANNEL	1	0.096	0.000	4.5	7.0	Inf	0.00
SUNART	1	0.292	0.085	4.4	8.6	Inf	0.00
LEURBOST	1	0.101	0.000	4.2	7.2	Inf	0.00
TARBERT	2	0.180	0.000	4.0	8.2	Inf	0.00
SWEEN	4	0.224	0.000	3.9	7.7	Inf	0.00
EPORT	4	0.126	0.103	3.9	7.2	Inf	0.00
EPORT	3	0.124	0.103	3.8	7.1	Inf	0.00
ETIVE	4	0.337	0.013	3.8	8.7	Inf	0.00
HOURN	3	0.047	0.030	3.7	6.1	Inf	0.00
LEVEN	2	0.238	0.061	3.7	8.4	Inf	0.00

CARRON	1	0.404	0.027	3.5	8.8	Inf	0.00
HOURN	2	0.048	0.030	3.5	6.3	Inf	0.00
EWE	1	0.463	0.028	3.2	8.8	Inf	0.00
SUNART	5	0.500	0.085	3.0	8.9	Inf	0.00
EPORT	7	0.241	0.103	2.2	7.4	Inf	0.00
SWEEN	5	0.428	0.000	2.1	6.2	Inf	0.00
BROOM	1	0.676	0.030	1.9	8.9	Inf	0.00
ETIVE	1	0.604	0.013	1.9	9.0	Inf	0.00
LINNHE AND EIL	2	0.336	0.075	1.8	8.6	Inf	0.00
FEOCHAN	1	0.218	0.000	1.8	8.4	Inf	0.00
STORNOWAY	1	0.346	0.000	1.7	8.4	Inf	0.00
ALSH	1	0.685	0.052	1.7	8.9	Inf	0.00
GARELOCH	1	0.401	0.000	1.6	8.7	Inf	0.00
CARRON	2	1.053	0.027	1.5	9.0	Inf	0.00
LINNHE AND EIL	3	0.453	0.075	1.4	8.8	Inf	0.00
TEACUIS	1	1.345	0.000	1.4	9.1	Inf	0.00
AILORT	2	2.749	0.021	1.1	9.1	Inf	0.00
GRIMSHADER	1	0.406	0.021	1.0	4.9	Inf	0.00
AILORT	1	3.673	0.104	1.0	8.5	Inf	0.00
CRERAN	1	1.723	0.103	1.0	9.1	Inf	0.00
EPORT	1	0.686	0.103	1.0	9.0	Inf	0.00
EPORT	2	0.713	0.103	1.0	8.7	Inf	0.00
EPORT	5	0.516	0.103	1.0	8.7	Inf	0.00
EPORT	6	2.900	0.013	1.0	8.5	Inf	0.00
ETIVE	2	42.703	0.004	1.0	9.1	Inf	0.00
EYNORT	1	3.966	0.004	1.0	9.2	Inf	0.00
EYNORT	2	0.133	0.472	1.0	9.1	Inf	0.00
LEVEN	1	0.888	0.061	1.0	9.0	Inf	0.00
SEAFORTH	1	0.687	0.159	1.0	8.8	Inf	0.00
SEAFORTH	3	0.558	0.159	1.0	8.7	Inf	0.00
TARBERT	1	0.921	0.000	1.0	9.0	Inf	0.00
TEACUIS	2	7.934	0.000	1.0	9.2	Inf	0.00

Table 5. Details of the sensitivity analysis. In each run, one variable was varied by ± 50%, except in Run 6 when BOD_{pel} and BOD_{ben} were both reduced by 75%. The "worst case" scenario (Run 11) incorporates increased BOD and reduced diffusive flux, all modified by 50% from default values.

Run	BOD_{pel} (mmol O_2 m^{-3} d^{-1})	BOD_{ben} (mmol O_2 m^{-3} d^{-1})	γ	μ (gO_2/gC)
Baseline	3.70	14.38	γ	3.5
2	1.85	14.38	γ	3.5
3	5.55	14.38	γ	3.5
4	3.70	7.19	γ	3.5
5	3.70	21.57	γ	3.5
6	0.93	3.60	γ	3.5
7	3.70	14.38	0.5γ	3.5
8	3.70	14.38	1.5γ	3.5
9	3.70	14.38	γ	1.75
10	3.70	14.38	γ	5.25
11	5.55	21.57	0.5γ	3.5

Table 6. Results of the sensitivity analysis: the mean and standard deviation of the ratio $T_O/T_{Obaseline}$, calculated for 135 sea loch basins (N = 135).

Run	Mean($T_O/T_{Obaseline}$)	Std. dev. ($T_O/T_{Obaseline}$)
Baseline	1	0
2	1.81	0.51
3	0.68	0.11
4	1.20	0.15
5	0.87	0.07
6	4.42	3.36
7	0.81	0.14
8	1.34	0.60
9	1.19	0.33
10	0.90	0.11
11	0.56	0.13

Table 7. Results of the sensitivity analysis. The highest, lowest and median rankings obtained for each loch basin from the sensitivity analysis are given. A ranking of 1 means the loch basin is most likely to exhibit oxygen depletion. The loch basins are presented in order of increasing median value. The standard deviation of the rankings indicates the sensitivity of the rankings to the parameter values in the model.

Loch	Basin	Highest	Lowest	Median Rank	St. Dev.
ETIVE	**6**	1	2	1	0.29
LINNHE AND EIL	**5**	1	2	2	0.29
MELFORT	**1**	3	5	3	0.62
WEST LOCH TARBERT KINTYRE	**1**	3	6	4	0.75
FYNE	**2**	4	67	6	17.71
NA CILLE	**1**	4	97	6	26.25
BROOM	**2**	6	28	7	5.97
EISHORT	**2**	5	44	8	10.46
LITTLE LOCH BROOM	**2**	7	90	9	23.36
ALSH	**2**	8	24	10	4.27
TORRIDON	**3**	10	135	11	35.50
DUICH	**2**	10	14	12	1.35
SKIPORT	**3**	3	24	14	5.96
LEVEN	**5**	7	20	15	3.26
GOIL	**1**	12	16	15	1.35
AINORT	**1**	13	41	17	9.50
SWEEN	**6**	13	125	17	31.34
NEVIS	**2**	9	22	19	3.41
HOURN	**1**	17	83	20	22.76
AILORT	**3**	11	50	21	12.22
NEVIS	**1**	17	99	21	22.48
GARELOCH	**2**	18	69	22	13.71
RONAS VOE	**2**	8	29	23	5.65
CLAIDH	**1**	12	28	24	4.38
CARRON	**3**	18	53	24	11.72
CRAIGNISH	**1**	23	52	25	8.25
PORTREE	**1**	16	106	26	39.86
DUGHAILL	**1**	24	41	28	4.35
SULLOM VOE	**1**	22	113	29	24.63
GRUTING VOE	**2**	6	37	30	8.11
LINNHE AND EIL	**4**	28	96	31	23.83
LONG CLYDE	**2**	31	101	33	29.49
SUNART	**6**	26	119	34	24.91
GRESHORNISH	**1**	32	82	34	19.85
A' CHAIM BHAIN	**6**	16	49	36	8.47
RONAS VOE	**1**	30	101	36	18.96
CRERAN	**4**	36	57	37	7.51
DUICH	**1**	33	58	38	8.36
GRUTING VOE	**1**	26	84	40	16.40
AIRDBHAIR	**1**	11	61	41	12.35
SKIPORT	**4**	14	60	41	11.28
HOURN	**4**	32	76	42	11.27
EPORT	**8**	32	58	44	6.81
HOURN	**5**	33	77	44	11.64
LINNHE AND EIL	**1**	39	94	45	21.50
SHELL	**2**	17	65	46	11.96
STROMNESS VOE	**1**	13	70	47	14.22

ALINE	**1**	22	66	49	10.77
AILORT	**1**	18	79	50	15.05
AILORT	**2**	19	80	51	15.05
ALSH	**1**	23	81	52	14.08
ALSH	**3**	25	73	53	12.33
TAMANAVAY	**1**	44	127	53	37.84
BAY	**1**	26	71	54	10.97
BROOM	**1**	27	82	55	13.52
A' CHAIM BHAIN	**1**	29	83	56	13.33
A' CHAIM BHAIN	**2**	30	59	56	10.32
A' CHAIM BHAIN	**4**	31	84	58	13.03
A' CHAIM BHAIN	**5**	32	61	58	9.30
CARRON	**1**	33	85	60	12.74
CARRON	**2**	34	86	61	12.74
CRERAN	**1**	37	87	62	12.16
CRERAN	**2**	38	88	63	12.16
CRERAN	**3**	39	79	64	9.62
EISHORT	**1**	43	89	65	11.18
ERIBOLL	**1**	41	73	66	12.40
EPORT	**1**	45	90	66	11.00
EPORT	**2**	46	91	67	11.00
EPORT	**3**	47	92	68	11.00
EPORT	**4**	48	93	69	11.00
EPORT	**5**	49	94	70	11.00
EPORT	**6**	50	95	71	11.00
EPORT	**7**	51	96	72	11.00
ETIVE	**1**	54	97	74	10.50
ETIVE	**3**	48	77	75	10.07
ETIVE	**2**	55	98	75	10.50
ETIVE	**5**	40	79	77	13.87
ETIVE	**4**	57	99	77	10.18
EWE	**2**	51	92	79	10.60
EWE	**1**	59	100	79	9.88
EYNORT	**1**	61	101	81	9.68
EYNORT	**2**	62	102	82	9.68
EYNORT	**5**	63	103	83	9.68
FEOCHAN	**1**	64	104	84	9.68
FEOCHAN	**2**	65	97	84	7.71
FYNE	**1**	62	98	85	9.61
GRIMSHADER	**1**	66	89	87	7.44
GARELOCH	**1**	68	105	87	9.13
HOURN	**2**	74	100	88	6.43
HOURN	**3**	75	101	89	6.84
INCHARD	**1**	58	92	90	12.14
LAXFORD	**1**	79	106	92	6.80
LEURBOST	**1**	80	107	93	6.80
LEVEN	**1**	81	108	94	6.80
LEVEN	**2**	82	109	95	6.80
LEVEN	**4**	57	98	96	14.38
LEVEN	**3**	83	110	96	6.80
LINNHE AND EIL	**2**	86	111	98	6.19
LINNHE AND EIL	**3**	87	112	99	6.19
LITTLE LOCH BROOM	**1**	89	113	100	5.96
LONG ALSH	**2**	31	111	101	20.62
LONG ALSH	**1**	91	114	101	5.79
LONG CLYDE	**1**	93	115	103	5.60

MOIDART NORTH CHANNEL	**1**	95	116	104	5.33
MOIDART SOUTH CHANNEL	**2**	96	117	105	5.33
NA KEAL	**1**	98	118	106	5.17
SCRIDAIN	**1**	47	109	107	23.27
RYAN	**1**	102	119	107	4.63
SEAFORTH	**1**	104	120	109	4.27
SHELL	**1**	63	112	110	17.17
SEAFORTH	**3**	105	121	110	4.27
SLAPIN	**1**	26	113	111	32.52
SLIGACHAN	**1**	51	113	112	22.62
SNIZORT BEG	**1**	64	114	113	18.80
SPELVE	**1**	62	115	114	19.04
STORNOWAY	**2**	54	117	116	23.80
STORNOWAY	**1**	111	122	116	2.57
SUNART	**1**	114	123	118	2.09
SUNART	**2**	115	124	119	2.09
SUNART	**3**	116	125	120	2.09
SUNART	**4**	117	126	121	2.09
SUNART	**5**	118	127	122	2.09
SWEEN	**1**	120	128	123	1.93
SWEEN	**2**	121	129	124	1.93
SWEEN	**3**	38	127	125	24.92
SWEEN	**4**	123	130	126	1.71
SWEEN	**5**	67	129	127	17.17
TARBERT	**1**	127	131	128	1.07
TARBERT	**2**	128	132	129	1.07
TARBERT	**3**	55	130	130	28.69
TEACUIS	**1**	130	133	131	0.72
TEACUIS	**2**	131	134	132	0.72
TEACUIS	**3**	75	134	133	16.68
TORRIDON	**1**	133	135	134	0.51
TORRIDON	**2**	44	135	135	34.67

Table 8. Results from model Run 6. For each sea loch basin, the values of T_E, $O_{equilib}$ (O_2), T_O and the ratio T_E/T_O are shown. The lochs are listed in order of decreasing T_E/T_O. Where T_O is given as Inf, the equilibrium oxygen concentration is greater than the value used to define hypoxia.

Loch	Basin	T_E (d)	O_2 (mgO_2/L)	T_O (d)	T_E/T_O
LINNHE AND EIL	5	287.2	-15.8	132.9	2.16
ETIVE	6	488.9	-3.3	274.3	1.78
SKIPORT	3	7.9	-67.0	5.5	1.45
WEST LOCH TARBERT KINTYRE	1	113.3	1.2	92.4	1.23
MELFORT	1	278.2	-3.8	235.2	1.18
GRUTING VOE	2	8.9	-59.6	15.2	0.59
LEVEN	5	78.8	-1.1	219.1	0.36
RONAS VOE	2	47.6	0.4	136.7	0.35
NEVIS	2	83.9	-1.3	290.4	0.29
DUICH	2	81.3	2.3	340.5	0.24
AIRDBHAIR	1	3.0	-3.8	14.1	0.21
CLAIDH	1	56.2	1.8	290.8	0.19
STROMNESS VOE	1	2.3	-66.1	14.1	0.16
SKIPORT	4	8.1	-1.6	57.7	0.14
GOIL	1	113.5	2.4	852.0	0.13
A' CHAIM BHAIN	6	18.2	0.5	194.7	0.09
SHELL	2	7.7	-3.9	98.1	0.08
FYNE	2	223.4	3.7	Inf	0.00
LITTLE LOCH BROOM	2	179.8	4.2	Inf	0.00
BROOM	2	177.8	4.1	Inf	0.00
ALSH	2	177.8	3.8	Inf	0.00
NA CILLE	1	152.5	5.4	Inf	0.00
TORRIDON	3	149.7	4.6	Inf	0.00
AILORT	3	126.3	7.1	Inf	0.00
EISHORT	2	117.5	3.6	Inf	0.00
HOURN	1	104.2	6.4	Inf	0.00
CARRON	3	101.5	6.7	Inf	0.00
AINORT	1	96.7	5.7	Inf	0.00
NEVIS	1	90.3	5.5	Inf	0.00
LONG ALSH	2	73.3	8.4	Inf	0.00
CRAIGNISH	1	69.9	6.2	Inf	0.00
GARELOCH	2	69.5	4.0	Inf	0.00
SWEEN	6	69.4	5.3	Inf	0.00
DUGHAILL	1	62.1	6.1	Inf	0.00
PORTREE	1	54.9	4.7	Inf	0.00
SLAPIN	1	51.1	7.0	Inf	0.00
SULLOM VOE	1	49.5	5.1	Inf	0.00
LINNHE AND EIL	4	48.8	5.9	Inf	0.00
DUICH	1	47.0	7.1	Inf	0.00
A' CHAIM BHAIN	2	46.6	7.7	Inf	0.00
LONG CLYDE	2	46.1	7.2	Inf	0.00
A' CHAIM BHAIN	5	44.8	8.0	Inf	0.00
ETIVE	5	41.5	8.1	Inf	0.00
SWEEN	3	40.2	8.4	Inf	0.00
TORRIDON	2	36.3	8.0	Inf	0.00
ETIVE	3	34.1	8.2	Inf	0.00
SCRIDAIN	1	31.0	8.1	Inf	0.00
LINNHE AND EIL	1	31.0	7.1	Inf	0.00
EWE	2	30.5	8.3	Inf	0.00

SUNART	6	28.4	2.6	Inf	0.00
GRESHORNISH	1	27.8	5.1	Inf	0.00
ERIBOLL	1	27.5	7.5	Inf	0.00
CRERAN	4	26.1	5.8	Inf	0.00
FYNE	1	23.9	8.4	Inf	0.00
RONAS VOE	1	20.9	4.5	Inf	0.00
ALSH	3	20.9	8.5	Inf	0.00
CRERAN	3	20.6	8.2	Inf	0.00
LONG ALSH	1	20.2	9.0	Inf	0.00
INCHARD	1	20.0	8.1	Inf	0.00
HOURN	4	18.1	5.4	Inf	0.00
BAY	1	17.6	8.4	Inf	0.00
TARBERT	3	17.4	8.1	Inf	0.00
LEVEN	4	16.8	7.9	Inf	0.00
TORRIDON	1	16.6	8.6	Inf	0.00
TAMANAVAY	1	16.1	7.3	Inf	0.00
SUNART	2	15.3	8.6	Inf	0.00
NA KEAL	1	14.6	8.7	Inf	0.00
SNIZORT BEG	1	14.0	8.2	Inf	0.00
CRERAN	2	13.9	8.6	Inf	0.00
A' CHAIM BHAIN	4	12.5	8.8	Inf	0.00
SWEEN	2	12.4	8.9	Inf	0.00
MOIDART SOUTH CHANNEL	2	11.9	8.9	Inf	0.00
SPELVE	1	11.6	7.9	Inf	0.00
STORNOWAY	2	11.5	8.0	Inf	0.00
SUNART	3	11.2	8.8	Inf	0.00
LITTLE LOCH BROOM	1	11.1	8.8	Inf	0.00
ALINE	1	10.6	7.0	Inf	0.00
HOURN	5	10.4	4.9	Inf	0.00
GRUTING VOE	1	10.2	3.1	Inf	0.00
SHELL	1	10.2	7.5	Inf	0.00
RYAN	1	10.1	8.8	Inf	0.00
FEOCHAN	2	7.7	8.4	Inf	0.00
SUNART	4	7.7	8.9	Inf	0.00
LONG CLYDE	1	7.7	8.8	Inf	0.00
SWEEN	1	7.6	9.0	Inf	0.00
EISHORT	1	7.5	8.6	Inf	0.00
EPORT	8	7.5	3.9	Inf	0.00
LAXFORD	1	7.0	8.4	Inf	0.00
SLIGACHAN	1	5.8	6.5	Inf	0.00
EYNORT	5	5.7	8.8	Inf	0.00
TEACUIS	3	5.0	8.5	Inf	0.00
LEVEN	3	4.9	8.8	Inf	0.00
A' CHAIM BHAIN	1	4.7	9.0	Inf	0.00
MOIDART NORTH CHANNEL	1	4.5	8.7	Inf	0.00
SUNART	1	4.4	9.0	Inf	0.00
LEURBOST	1	4.2	8.7	Inf	0.00
TARBERT	2	4.0	9.0	Inf	0.00
SWEEN	4	3.9	8.8	Inf	0.00
EPORT	4	3.9	8.3	Inf	0.00
EPORT	3	3.8	8.3	Inf	0.00
ETIVE	4	3.8	9.1	Inf	0.00
HOURN	3	3.7	8.4	Inf	0.00
LEVEN	2	3.7	8.9	Inf	0.00
CARRON	1	3.5	9.1	Inf	0.00

HOURN	2	3.5	8.4	Inf	0.00
EWE	1	3.2	9.1	Inf	0.00
SUNART	5	3.0	9.1	Inf	0.00
EPORT	7	2.2	8.3	Inf	0.00
SWEEN	5	2.1	8.5	Inf	0.00
BROOM	1	1.9	9.1	Inf	0.00
ETIVE	1	1.9	9.1	Inf	0.00
LINNHE AND EIL	2	1.8	9.0	Inf	0.00
FEOCHAN	1	1.8	9.0	Inf	0.00
STORNOWAY	1	1.7	9.0	Inf	0.00
ALSH	1	1.7	9.1	Inf	0.00
GARELOCH	1	1.6	9.1	Inf	0.00
CARRON	2	1.5	9.2	Inf	0.00
LINNHE AND EIL	3	1.4	9.1	Inf	0.00
TEACUIS	1	1.4	9.2	Inf	0.00
AILORT	2	1.1	9.2	Inf	0.00
AILORT	1	1.0	9.0	Inf	0.00
CRERAN	1	1.0	9.2	Inf	0.00
EPORT	1	1.0	9.1	Inf	0.00
EPORT	2	1.0	9.0	Inf	0.00
EPORT	5	1.0	8.9	Inf	0.00
EPORT	6	1.0	8.9	Inf	0.00
ETIVE	2	1.0	9.2	Inf	0.00
EYNORT	1	1.0	9.2	Inf	0.00
EYNORT	2	1.0	9.2	Inf	0.00
GRIMSHADER	1	1.0	6.1	Inf	0.00
LEVEN	1	1.0	9.1	Inf	0.00
SEAFORTH	1	1.0	9.0	Inf	0.00
SEAFORTH	3	1.0	8.9	Inf	0.00
TARBERT	1	1.0	9.1	Inf	0.00
TEACUIS	2	1.0	9.2	Inf	0.00

Table 9. The influence of fish farming activity on the model results for Run 1 (Baseline). The time scales to hypoxia (T_O) and ratio of time scales (T_E/T_O) are given for model runs with and without fish farm carbon inputs. The values of T_E and the contribution of fish farm carbon (BOD_{FF}) to the total basin BOD are given for reference. The lochs are ordered by the ratio, R, of the hypoxia time scales, indicating where fish farming has the greatest *relative* effect (see text for details). Loch basins which have an equilibrium oxygen concentration higher than the hypoxia criteria when fish farming is included in the model (i.e. basins which are unlikely ever to become hypoxic) are not presented in the table. Loch basins where the addition of fish farm carbon changes the prediction of hypoxia from unlikely ($T_E/T_O < 1$) to possible ($T_E/T_O > 1$) are highlighted.

			BOD_{FF}	With Fish Farming		No Fish Farming		
Loch	**Basin**	**T_E (d)**	**(%)**	**T_O (d)**	**T_E/T_O**	**T_O (d)**	**T_E/T_O**	**1 - R**
AINORT	1	96.7	23	63.4	1.52	Inf	0.00	1.00
PORTREE	1	54.9	46	48.4	1.13	Inf	0.00	1.00
GRESHORNISH	1	27.8	28	54.8	0.51	Inf	0.00	1.00
GRUTING VOE	1	10.2	53	27.0	0.38	Inf	0.00	1.00
AIRDBHAIR	1	3.0	73	10.3	0.29	Inf	0.00	1.00
STROMNESS VOE	1	2.3	71	10.9	0.21	40.7	0.06	0.73
SKIPORT	3	7.9	70	4.2	1.89	15.3	0.52	0.73
GRUTING VOE	2	8.9	60	10.5	0.85	28.0	0.32	0.63
EISHORT	2	117.5	34	38.9	3.02	101.9	1.15	0.62
SKIPORT	4	8.1	46	27.5	0.30	69.0	0.12	0.60
RONAS VOE	1	20.9	28	47.9	0.44	105.8	0.20	0.55
EPORT	8	7.5	29	28.9	0.26	58.6	0.13	0.51
CRERAN	4	26.1	17	64.2	0.41	108.2	0.24	0.41
WEST LOCH TARBERT KINTYRE	1	113.3	30	26.1	4.34	43.6	2.60	0.40
RONAS VOE	2	47.6	25	39.1	1.22	57.0	0.84	0.31
SHELL	2	7.7	26	35.1	0.22	49.6	0.16	0.29
LINNHE AND EIL	1	31.0	5	125.0	0.25	160.8	0.19	0.22
AILORT	3	126.3	5	98.4	1.28	124.3	1.02	0.21
CLAIDH	1	56.2	13	47.6	1.18	57.0	0.99	0.16
DUICH	2	81.3	13	37.3	2.18	44.5	1.83	0.16
A' CHAIM BHAIN	6	18.2	14	41.8	0.43	49.9	0.36	0.16
HOURN	5	10.4	9	38.9	0.27	44.9	0.23	0.13
DUICH	1	47.0	3	124.5	0.38	143.8	0.33	0.13
CRAIGNISH	1	69.9	7	62.4	1.12	71.4	0.98	0.13
LINNHE AND EIL	5	287.2	12	40.3	7.12	45.9	6.25	0.12
LINNHE AND EIL	4	48.8	7	70.4	0.69	80.0	0.61	0.12
LEVEN	5	78.8	8	47.1	1.67	51.8	1.52	0.09
SUNART	6	28.4	6	56.9	0.50	61.3	0.46	0.07
CARRON	3	101.5	3	84.2	1.21	89.6	1.13	0.06
LITTLE LOCH BROOM	2	179.8	4	60.2	2.99	63.5	2.83	0.05
NEVIS	1	90.3	3	69.5	1.30	73.2	1.23	0.05
BROOM	2	177.8	4	56.6	3.14	59.3	3.00	0.05
ALSH	2	177.8	4	60.5	2.94	63.3	2.81	0.05
HOURN	1	104.2	2	78.4	1.33	81.9	1.27	0.04
NEVIS	2	83.9	3	55.4	1.51	57.6	1.46	0.04
HOURN	4	18.1	3	66.1	0.27	68.7	0.26	0.04
MELFORT	1	278.2	2	48.2	5.77	49.5	5.62	0.03
TORRIDON	3	149.7	2	64.3	2.33	65.7	2.28	0.02
FYNE	2	223.4	2	61.4	3.64	62.6	3.57	0.02

ETIVE	6	488.9	1	53.3	9.17	54.0	9.06	0.01
NA CILLE	1	152.5	0	42.2	3.61	42.2	3.61	0.00
GOIL	1	113.5	0	58.0	1.96	58.0	1.96	0.00
SWEEN	6	69.4	0	42.1	1.65	42.1	1.65	0.00
GARELOCH	2	69.5	0	55.5	1.25	55.5	1.25	0.00
DUGHAILL	1	62.1	0	62.2	1.00	62.2	1.00	0.00
SULLOM VOE	1	49.5	0	56.6	0.87	56.6	0.87	0.00
LONG CLYDE	2	46.1	0	88.2	0.52	88.2	0.52	0.00
TAMANAVAY	1	16.1	0	101.2	0.16	101.2	0.16	0.00
ALINE	1	10.6	0	79.6	0.13	79.6	0.13	0.00

Table 10. The influence of fish farming activity on the loch basin rankings (Table 6). The table shows the estimated contribution (%) that the biochemical oxygen demand (BOD) from fish farm derived particulate organic carbon flux makes to the total BOD in each basin. The sensitivity analysis was repeated with fish farm carbon input set to zero, and the effect on the ranking of the loch basins assessed. The loch basins are ranked in order of decreasing T_E/T_O including fish farm inputs (as in Table 7). Loch basins which are ranked higher when fish farm carbon is included in the simulations (i.e. Diff > 0) are shaded.

Loch	Basin	Rank (inc FF)	BOD_{FF} (%)	Rank (no FF)	Diff
ETIVE	6	1	1	1	0
LINNHE AND EIL	5	2	12	2	0
MELFORT	1	3	2	3	0
WEST LOCH TARBERT KINTYRE	1	4	30	9	+5
FYNE	2	6	2	5	-1
NA CILLE	1	6	0	4	-2
BROOM	2	7	14	6	-1
EISHORT	2	8	34	19	+11
LITTLE LOCH BROOM	2	9	4	8	-1
ALSH	2	10	5	8	-2
TORRIDON	3	11	2	10	-1
DUICH	2	12	13	12	0
SKIPORT	3	14	70	29	+15
GOIL	1	15	0	11	-4
LEVEN	5	15	8	14	-1
AINORT	1	17	9	26	+9
SWEEN	6	17	0	15	-2
NEVIS	2	19	3	15	-4
HOURN	1	20	2	17	-3
AILORT	3	21	11	15	-6
NEVIS	1	21	3	20	-1
GARELOCH	2	22	0	19	-3
RONAS VOE	2	23	25	27	+4
CARRON	3	24	3	20	-4
CLAIDH	1	24	13	24	0
CRAIGNISH	1	25	7	24	-1
PORTREE	1	26	46	103	+77
DUGHAILL	1	28	0	23	-5
SULLOM VOE	1	29	0	25	-4
GRUTING VOE	2	30	60	33	+3
LINNHE AND EIL	4	31	7	29	-2
LONG CLYDE	2	33	0	29	-4
GRESHORNISH	1	34	28	66	+32
SUNART	6	34	6	31	-3
A' CHAIM BHAIN	6	36	4	31	-5
RONAS VOE	1	36	28	47	+11
CRERAN	4	37	17	36	-1
DUICH	1	38	3	33	-5
GRUTING VOE	1	40	53	82	+42
AIRDBHAIR	1	41	14	48	+7
SKIPORT	4	41	46	57	+16
HOURN	4	42	3	38	-4
EPORT	8	44	29	53	+9
HOURN	5	44	9	36	-8
LINNHE AND EIL	1	45	5	40	-5

SHELL	2	46	26	43	-3
STROMNESS VOE	1	47	71	44	-3
ALINE	1	49	8	41	-8
AILORT	1	50	12	45	-5
AILORT	2	51	11	46	-5
ALSH	1	52	5	49	-3
ALSH	3	53	23	50	-3
TAMANAVAY	1	53	0	51	-2
BAY	1	54	73	51	-3
BROOM	1	55	0	52	-3
A' CHAIM BHAIN	1	56	4	53	-3
A' CHAIM BHAIN	2	56	5	43	-13
A' CHAIM BHAIN	4	58	1	55	-3
A' CHAIM BHAIN	5	58	7	51	-7
CARRON	1	60	4	57	-3
CARRON	2	61	5	58	-3
CRERAN	1	62	19	59	-3
CRERAN	2	63	19	60	-3
CRERAN	3	64	22	61	-3
EISHORT	1	65	43	62	-3
EPORT	1	66	28	63	-3
ERIBOLL	1	66	3	49	-17
EPORT	2	67	29	64	-3
EPORT	3	68	24	65	-3
EPORT	4	69	23	66	-3
EPORT	5	70	30	67	-3
EPORT	6	71	29	68	-3
EPORT	7	72	32	69	-3
ETIVE	1	74	1	71	-3
ETIVE	2	75	2	72	-3
ETIVE	3	75	1	68	-7
ETIVE	4	77	2	74	-3
ETIVE	5	77	1	70	-7
EWE	1	79	5	76	-3
EWE	2	79	5	75	-4
EYNORT	1	81	2	78	-3
EYNORT	2	82	2	79	-3
EYNORT	5	83	2	80	-3
FEOCHAN	1	84	0	81	-3
FEOCHAN	2	84	0	80	-4
FYNE	1	85	3	81	-4
GARELOCH	1	87	0	84	-3
GRIMSHADER	1	87	62	86	-1
HOURN	2	88	3	86	-2
HOURN	3	89	3	87	-2
INCHARD	1	90	3	85	-5
LAXFORD	1	92	22	91	-1
LEURBOST	1	93	0	92	-1
LEVEN	1	94	9	93	-1
LEVEN	2	95	11	94	-1
LEVEN	3	96	14	95	-1
LEVEN	4	96	14	94	-2
LINNHE AND EIL	2	98	14	97	-1
LINNHE AND EIL	3	99	12	98	-1
LITTLE LOCH BROOM	1	100	5	99	-1
LONG ALSH	1	101	0	100	-1

LONG ALSH	2	101	0	99	-2
LONG CLYDE	1	103	0	102	-1
MOIDART NORTH CHANNEL	1	104	0	103	-1
MOIDART SOUTH CHANNEL	2	105	0	104	-1
NA KEAL	1	106	6	105	-1
RYAN	1	107	0	107	0
SCRIDAIN	1	107	1	106	-1
SEAFORTH	1	109	30	109	0
SEAFORTH	3	110	33	110	0
SHELL	1	110	22	110	0
SLAPIN	1	111	22	111	0
SLIGACHAN	1	112	29	112	0
SNIZORT BEG	1	113	5	113	0
SPELVE	1	114	8	114	0
STORNOWAY	1	116	0	116	0
STORNOWAY	2	116	0	116	0
SUNART	1	118	11	118	0
SUNART	2	119	11	119	0
SUNART	3	120	11	120	0
SUNART	4	121	10	121	0
SUNART	5	122	10	122	0
SWEEN	1	123	0	123	0
SWEEN	2	124	0	124	0
SWEEN	3	125	0	124	-1
SWEEN	4	126	0	126	0
SWEEN	5	127	0	126	-1
TARBERT	1	128	0	128	0
TARBERT	2	129	0	129	0
TARBERT	3	130	0	130	0
TEACUIS	1	131	0	131	0
TEACUIS	2	132	0	132	0
TEACUIS	3	133	0	133	0
TORRIDON	1	134	2	134	0
TORRIDON	2	135	2	135	0