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MODELLING THE ENVIRONMENTAL IMPACT OF NEW AND EXISTING FISH FARMS IN SCOTTISH SEA LOCHS

P A Gillibrand and W R Turrell

SOAFD Marine Laboratory
PO Box 101, Victoria Road
Aberdeen, AB9 8DB
Scotland, UK

SUMMARY

In Scotland, the fish farming industry has developed over the past two decades to the point where farms are now in production in the majority of Scottish sea lochs. The regulation of the industry is coordinated between several governmental bodies. As part of this process, simple box models have been developed to estimate the quantities of effluent released by fish farms and the residence times of such material within a loch. The models estimate the enhancement of nutrient and chemical levels within loch systems and also attempt to ascertain whether environmental quality standards are exceeded by the fish farms within a loch system. These box models make certain simplifying assumptions about the hydrodynamic characteristics of Scottish sea lochs. A two-dimensional, laterally integrated numerical model has also been developed for Scottish sea lochs. This model has been used to investigate the physical oceanography of various sea lochs in detail and to test the underlying assumptions of the simple models. In this paper, the simple models are described and the use of the numerical model to validate them is also briefly explained.

INTRODUCTION

Fish farms may affect the surrounding environment in a number of ways. Particular concern arose over the effects of particulate nitrogenous wastes produced by the farms in the form of uneaten food and fish faeces (Gowen and Bradbury, 1987; Pearson and Gowen, 1990), the excretion of dissolved ammoniacal nitrogen by the fish (Turrell and Munro, 1988) and the discharge of chemicals, in particular dichlorvos, used to treat the fish for parasite infestation (Anon, 1989). As part of the procedure to license a new farm, or an increase in production of an existing farm, the potential impact of the farm on its environment has to be assessed.

As part of the assessment process, a suite of simple computer box models has been developed. The use of computer models enabled sound scientific advice to be given

consistently for the increasing number of applications. These models were designed for daily use, and therefore had to be quick and simple to apply. While these models were expected to provide basic estimates of nutrient enhancement and chemical dispersion, they contained many simplifying assumptions about the underlying hydrography of the fjordic sea lochs where most of the farms are sited. The validity of these assumptions was examined through a combination of field observations and more complex numerical modelling.

The assessment procedure using box models considers each sea loch system as a whole, rather than treating individual fish farms in isolation. Thus the processing of an application assesses the effect of that farm, in combination with others already existing in the loch, on the water body as a whole. To facilitate this approach, a database of existing fish farms in Scotland was assembled. The database provides details such as annual fish production and location of all known fish farms in all Scottish sea lochs. The database also contains physical details of the sea loch itself, such as length, volume, surface area and tidal range.

In order to look more closely at the dynamics of Scottish sea lochs, a two-dimensional, laterally integrated numerical model has been developed. The model is an extension to the estuarine model of Elliott (1976) and Wang and Kravitz (1980) and has been described by Gillibrand, Turrell and Elliott (1995). The model has been used to examine the tidal circulation (Elliott, Gillibrand and Turrell, 1992) and deep water renewal (Gillibrand, Turrell and Elliott, 1995) in Loch Sunart.

This paper describes the three simpler models used to assist the day-to-day management of the Scottish fish farming industry. The two-dimensional numerical model is also briefly described.

ASSESSMENT MODELS

Fundamental Assumptions

All three of the assessment models make a fundamental assumption; that there exists a characteristic flushing time for each sea loch system. The flushing time has been defined as the time taken to replace ~60% of the water within a sea loch by tidal exchange and is formulated by Edwards and Sharples (1986), based on the tidal prism method (Dyer, 1978). The relationship has been shown to apply to the "non-stagnant near-surface layers" of both Loch Etive and Loch Creran (Edwards and Sharples, 1986).

A second assumption is that there exists a distinct surface layer of fixed depth. Contaminants released into this layer do not mix with the layer below, which can be considered a worst case approach since any vertical mixing will reduce concentrations in the surface layer. A typical depth of 5 m was chosen for most model runs. The models can be run using either a surface layer of specified depth or the full loch volume.

Simple model 1

The first model estimates the equilibrium concentration enhancement (ECE) of dissolved nitrogen occurring within an enclosed body of water that is being exchanged at a fixed rate. In the case of fish farm applications, the contaminant is soluble ammoniacal

nitrogen, which is excreted by the fish. The rate at which the ammonia is released is assumed to remain fixed at 70 kg per tonne of fish per year (Turrell and Munro, 1988; Ackefors, 1986).

The model assumes a flushing rate, Q , based on the volume of the loch (or the surface layer), V , and the characteristic flushing time, T , where $Q=V/T$. With the assumed source rate of ammoniacal nitrogen, S , and the known total consented production of farmed fish in the sea loch, M , the ECE is given by $ECE=(S.M)/Q$. The model then ranks the lochs in the database in descending order of ECE, where the ranking 1 indicates the highest predicted enhancement. This model also directly relates the annual production in a loch to its effective flushing rate, termed the dynamic ratio ($=M/Q$). The dynamic ratio gives an indication of the relative size of the fish production in a sea loch.

Simple model 2

The second model calculates the amount of dichlorvos that could be used over one year such that a proposed annual mean EQS (Environmental Quality Standard) would not be exceeded. This EQS is assumed to be 40 ng/l (or $C_{EQS}=4 \times 10^{-8} \text{ kg m}^{-3}$). The model also estimates the amount of dichlorvos presently being used annually within the loch system based on the total consented production in the loch. This estimate is based on figures for the annual use of dichlorvos by the industry in 1989 and the consented production in that year. In that year, the industry used 0.292 kg of dichlorvos per tonne on consented production.

Again, the model assumes that the water within the loch, (or the surface layer) is replaced every T days. Thus the volume of water replaced over the course of a year, V' , can be estimated and the maximum amount of dichlorvos permitted to be used annually is given by $M_{\max}=C_{EQS} \cdot V'$ kg.

Simple model 3

This is an advection-diffusion model that simulates a treatment of the fish farms within a sea loch and examines the dichlorvos concentration levels that result. Advection is simulated using a particle tracking approach, where the centre of each release of treatment chemical is tracked with time under the influence of the residual drift of the surface layer towards the sea. Tidal oscillations can, if required, be included in the simulation. Diffusion is simulated using a two-dimensional Gaussian equation describing the concentration field from each of the tracked releases.

The model assumes a 5 m deep surface layer with a steady residual seaward flow. The speed, U , of the flow is based on the length, L , of the loch and the flushing time, where $U=L/T$. A single horizontal diffusion coefficient of $0.1 \text{ m}^2\text{s}^{-1}$ is used to describe mixing in the surface layer. The surface layer is assumed to be vertically mixed. The loch is assumed to be rectangular, with the width adjusted so that the length and surface area match those of the real system. Farms are located as close to their real position as possible. A consistent treatment procedure is assumed whereby farms are treated in order, with those nearest the head being treated first.

The model tracks the treatment chemical from each site as it progresses seawards. The spread of each treatment is calculated using the Gaussian diffusion equations and the fields resulting from all treatments in the loch are summed to give the overall

concentration levels. The output from the model consists of the percentage area of the loch that exceeds (and the length of time for which it does so) a range of concentration limits.

Results

The present status of the 52 Scottish sea lochs included in the database is summarised in Figures 1-4. Each loch has been given a code number. Figure 1 shows the total consented production in each loch and the dynamic ratio of each loch. In Figure 2, the ECE for both a 5 m deep surface layer and the whole loch are presented. It is noticeable that the lochs with the highest ECE and dynamic ratio are not necessarily those with the largest consented production. The flushing time of the loch is a key factor in calculating the ECE.

The estimated annual use of dichlorvos in each loch, and the maximum permissible use, is shown in Figure 3. The ratio of the two parameters (Fig. 3a) closely resembles the surface layer ECE (Fig. 2a). The highest values indicates sea lochs which are being most heavily farmed relative to their capability, and the ones whose ecology might be most at risk.

Figure 4 shows the percentage area of each loch that exceeds various concentration limits during a dichlorvos treatment, as determined by simple model 3. Again, the highest values indicate lochs "most at risk".

RESEARCH MODEL

The flushing time calculation described earlier provides a good first estimate of the rate of replacement of water within a sea loch. The assessment models assume a two layer system, with the surface layer flowing seaward at a steady rate, which represents the classical estuarine circulation. Over the very long term, this is probably a reasonably fair description of the circulation. On shorter time scales, however, this circulation pattern can be disturbed by several mechanisms.

Of prime influence on the residual circulation of a sea loch are wind forcing and freshwater runoff, the coupled effect of which can lead to modification, or even reversal, of the basic circulation and may set up three or more layered flow. The tides also affect the residual circulation through tidal mixing and other processes. The effects on pollutant dispersion of this variability cannot be examined using simple box models, where the circulation is prescribed. In order to investigate the effects of variable wind forcing and freshwater runoff, a more complex numerical model is required.

Model Description

The model was developed from the two-dimensional, laterally integrated semi-implicit model of Wang and Kravitz (1980), which was originally developed for Chesapeake Bay on the east coast of the USA. The model is controlled by the standard hydrodynamic equations for conservation of mass, momentum and salinity, together with an equation of state. The equations are integrated across the width of the estuary channel and are solved using finite difference techniques on a staggered grid. Real bathymetry is included in the model. Boundary conditions include tidal and wind forcing and freshwater runoff.

In order to facilitate the application of the model to Scottish sea lochs, which are radically different from the partially mixed Chesapeake Bay, the model was modified in several ways (Gillibrand, 1993; Gillibrand, Turrell and Elliott, 1995). Grid spacing was allowed to be variable in the vertical so that grid points could be concentrated in the upper layers and the water surface was allowed to move through the grid, a technique first demonstrated by Hamilton (1975). These two modifications allowed the model to simulate the large tides (up to 5 m range) of the Scottish west coast without the loss of near surface resolution. A turbulence closure scheme was also introduced to parameterise the vertical diffusion. This was the level 2.5 scheme of Mellor and Yamada (1982), as used in other coastal ocean models (eg Blumberg and Mellor, 1983; Blumberg and Goodrich, 1990; Galperin and Mellor, 1990a,b).

Other modifications were made to the model and further details are given by Gillibrand (1993) and Gillibrand, Turrell and Elliott (1995).

Model Validation

The model was validated using data from Loch Sunart. Profiles of temperature and salinity were obtained along the axis of the loch in July and August of 1989 and May and July of 1990. In addition, current meters were deployed near the surface and bottom in the upper basin of the loch in both years. In 1989, heavy rainfall during the period between the two surveys caused a marked freshening of the loch. The model successfully simulated this event (Gillibrand, Turrell and Elliott, 1995) and reproduced the salinity field in August. The main features of the current meter data were also reproduced, but some discrepancy occurred, thought to be partly due to three-dimensional effects in the flow.

The model also successfully hindcast all the observed deep water renewal events in both 1989 and 1990 and showed that renewal in Loch Sunart is controlled by the coupled effect of wind forcing and freshwater runoff. The model also indicated that the relatively high frequency of renewal in Loch Sunart is due in part to rapid freshening of the bottom water from recirculation at the sill (Gillibrand, Turrell and Elliott, 1995).

Validation of Simple Model Assumptions

The model was used to assess the validity of the assumptions made by the simple models under a range of environmental conditions. Concern was expressed about the level of fish farming in Loch Fyne (P Singleton, pers. comm.) and this loch was chosen for the exercise (Fig. 5). Typical, tidally averaged, fields of velocity and salinity output from the model are shown in Figure 6. From such output, the mean depth of the surface layer can be estimated by using the first reversal of velocity at each grid column to indicate the bottom of the layer at that position and meaning the depth along the length of the loch. Similarly, the mean surface layer velocity, and hence flushing time (where $T=L/U$), can be estimated. These calculations were carried out for velocity fields produced under a range of wind and runoff conditions. Thus surface layer depth, velocity and flushing time is determined for all wind directions under high and low runoff conditions.

Using a year-long record of wind data from Dunstaffnage (Fig. 5) the actual frequency of occurrence of wind speed and directions can be determined. Then, by combining this distribution with the model results, the actual frequency of occurrence of each surface layer depth (and velocity and flushing time) can be estimated. The results are shown in

Figure 7. In the flushing time diagram (Fig. 7c), the "Pond" group indicates the time when wind forcing has reversed the circulation so that the surface layer is flowing toward the head of the loch. This has important implications on the surface layer salinity, which can be drastically reduced as freshwater entering at the head is held there.

DISCUSSION AND CONCLUSIONS

This modelling exercise has revealed the range of surface layer conditions that can exist in the course of a year. During relatively dry conditions, the circulation is dominated by wind forcing and can be easily reversed, resulting in ponding at the head of the loch and the risk of substantially reduced surface layer salinities and the threat of extra stress to farmed salmon. Under high runoff conditions, from high rainfall or melting snow, the estuarine circulation is more stable and the surface layer depth and velocity is less variable.

The range of conditions that should be expected in Scottish sea lochs, therefore, make assessments of the impact of fish farms using simple models rather difficult. For example, the simple models of Loch Fyne assume a flushing time of 13 days, which is a reasonable median value under normal circulation. However, for 60% of the time, the flushing time of the Loch Fyne is either greater than 20 days or non-existent (ie ponding). Surface layer depth varies regularly between 2-12 m. Thus, a single depth and flushing time will not be representative of the range of surface layer conditions.

It would seem that, in the case of Loch Fyne at least, two assessments using the suite of simple models would be preferable. Thus, the range of potential effects of fish farming could be defined, which would be dependent on prevailing environmental conditions. Alternatively, the worst case should be considered, which in this case results in surface layer ponding. The hydrodynamics of a sea loch during such ponding events should be further considered in order to determine the fate of contaminants released during such conditions. It should be noted that Loch Fyne is particularly susceptible to circulation reversal because of its southerly orientation which is open to the prevailing south-westerly winds. Other sea lochs may not exhibit variability in flushing time to such an extent.

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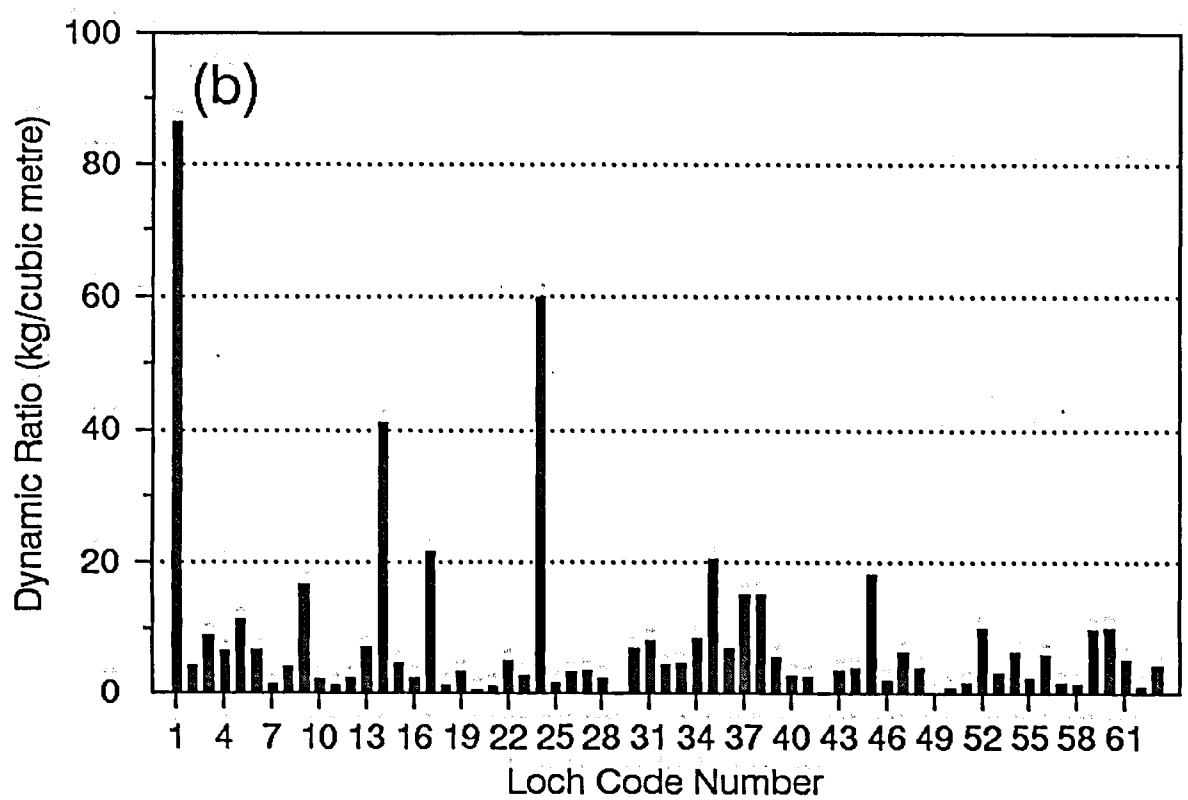
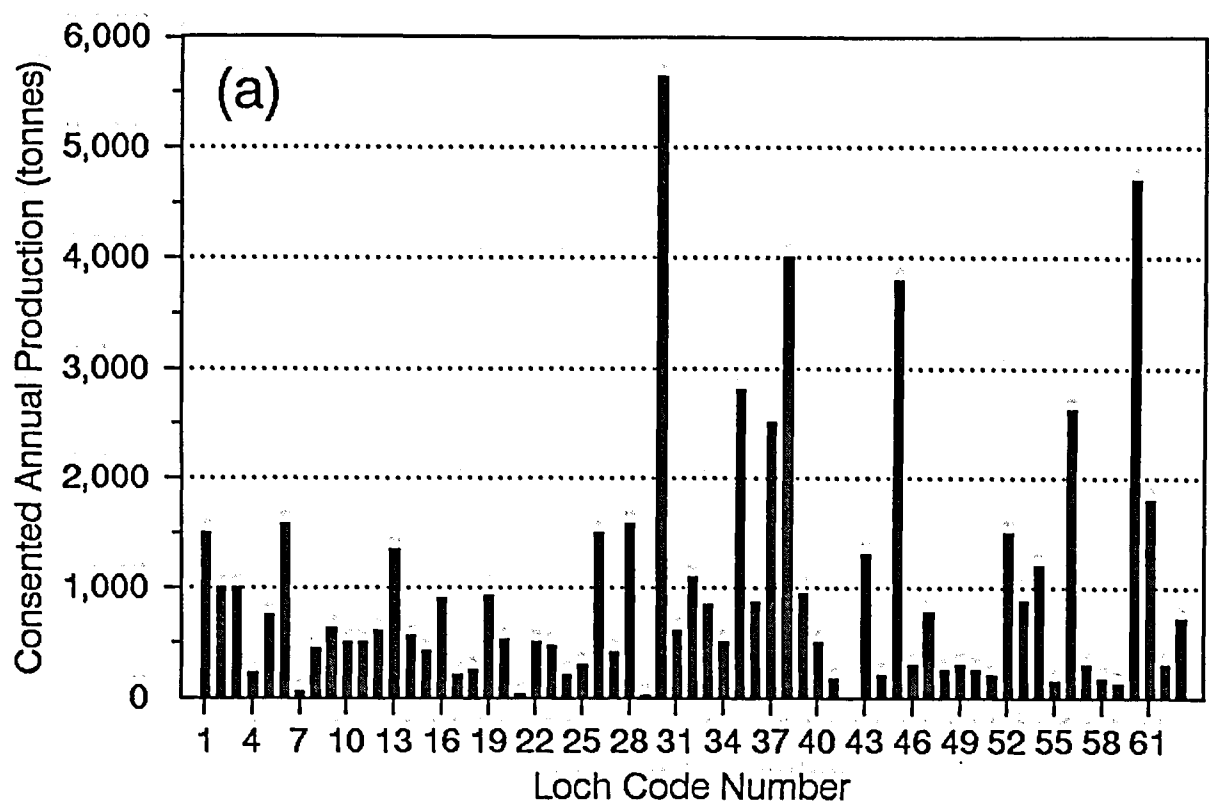


Figure 1 Total consented annual production (a) and dynamic ratio (b) for each loch in 1995. Each loch has been given a code number.

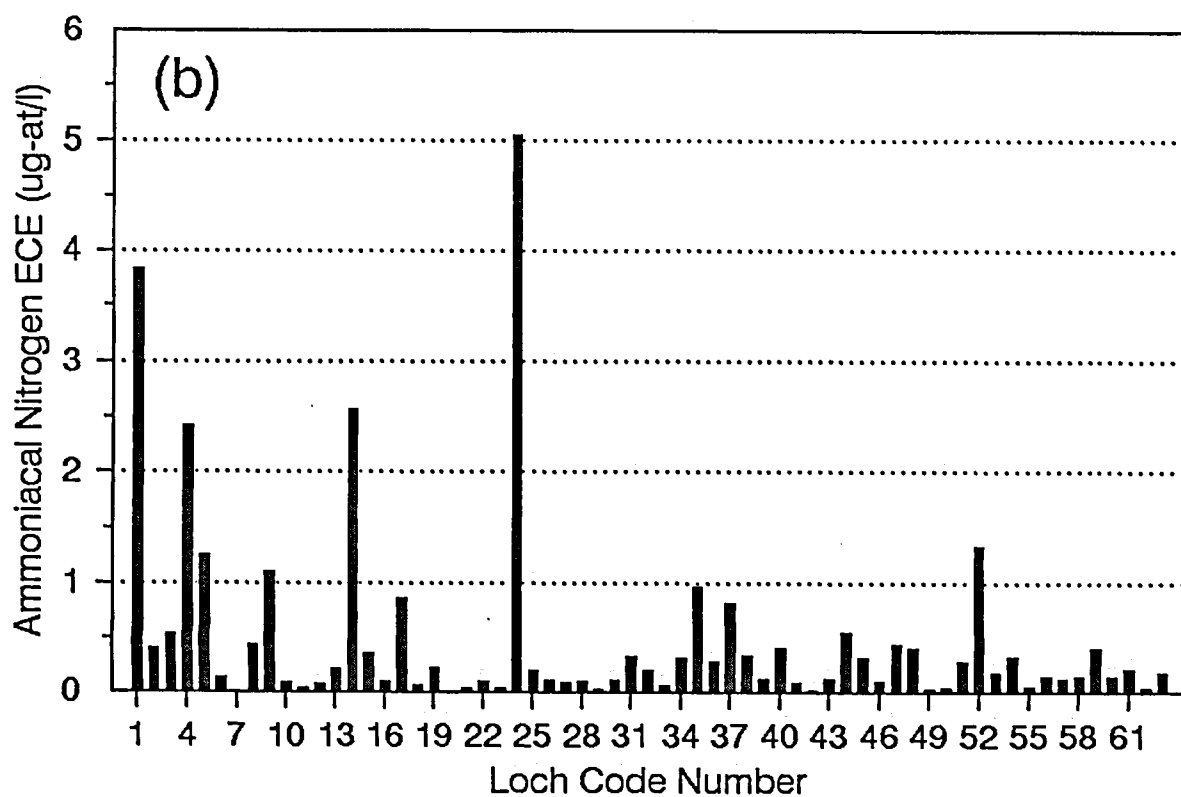
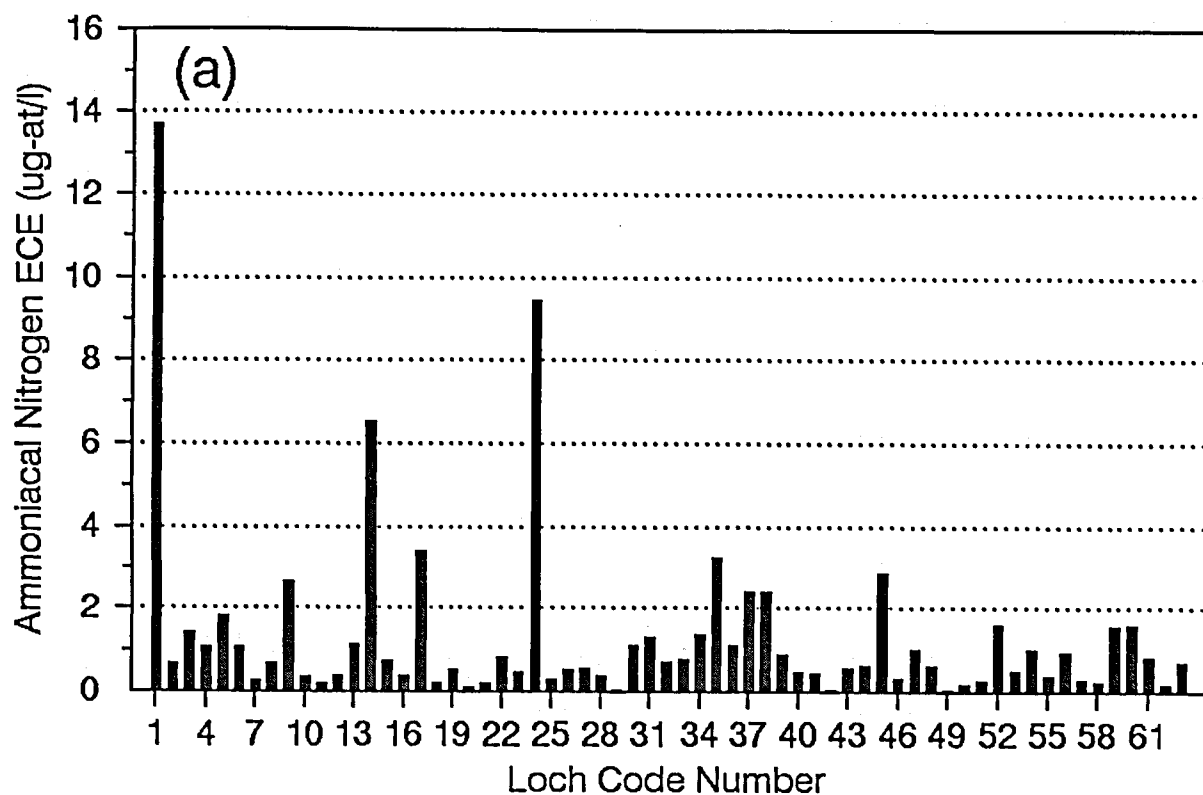


Figure 2 Equilibrium Concentration Enhancement (ECE) for a 5 m layer (a) and whole body (b) of each sea loch in 1995.

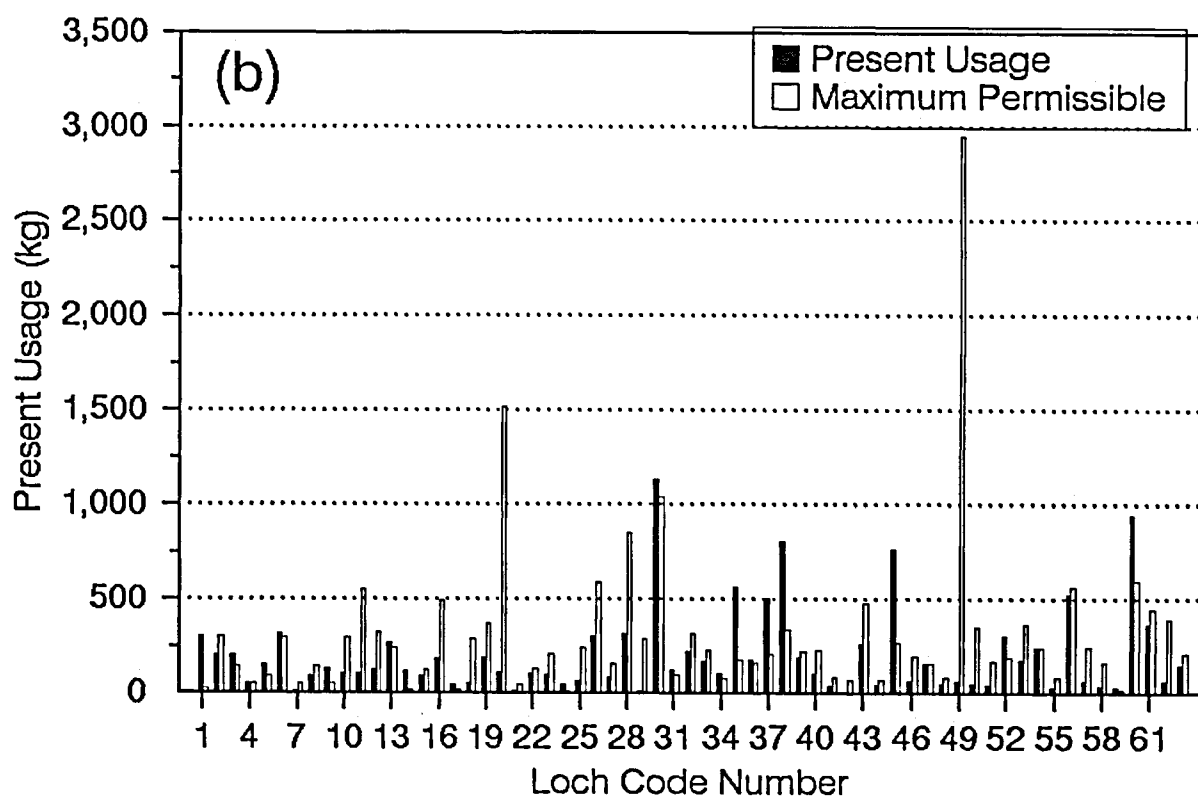
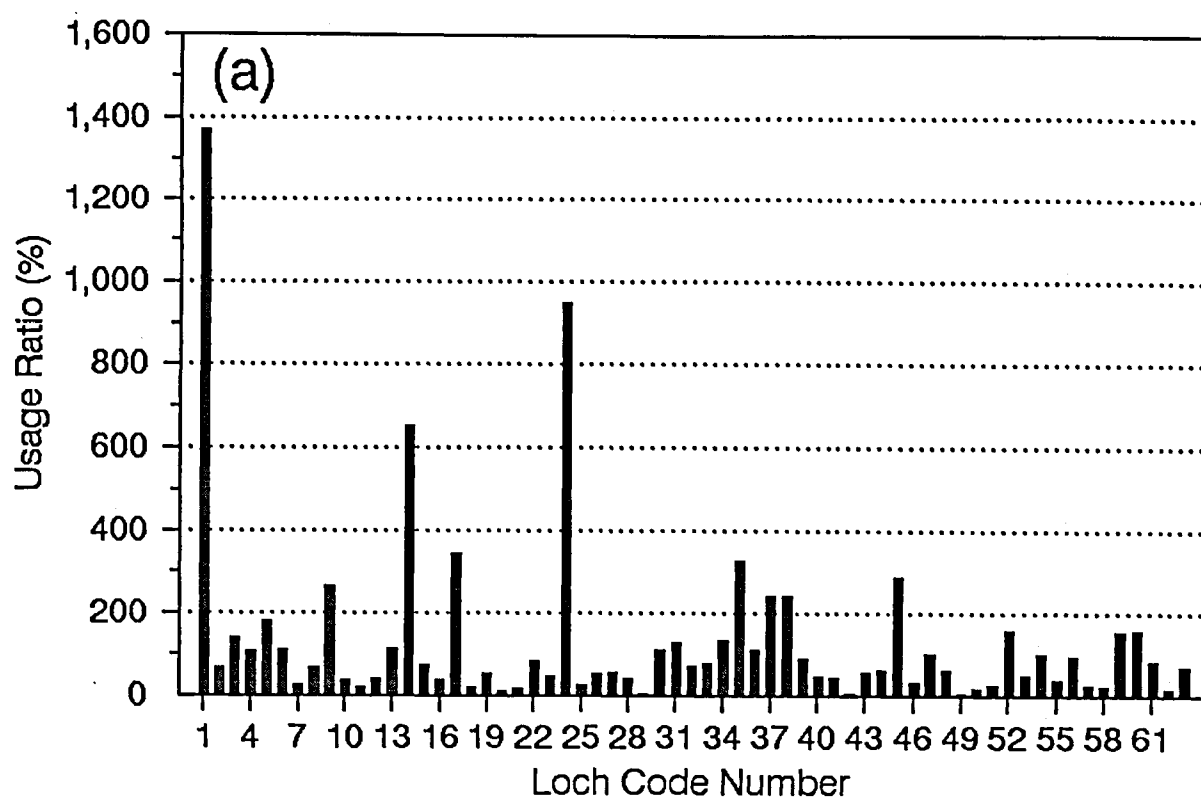


Figure 3 Predicted annual dichlorvos usage in each sea loch in 1995 compared with maximum permissible amount as a ratio (predicted/maximum) (a) and a direct comparison (b).

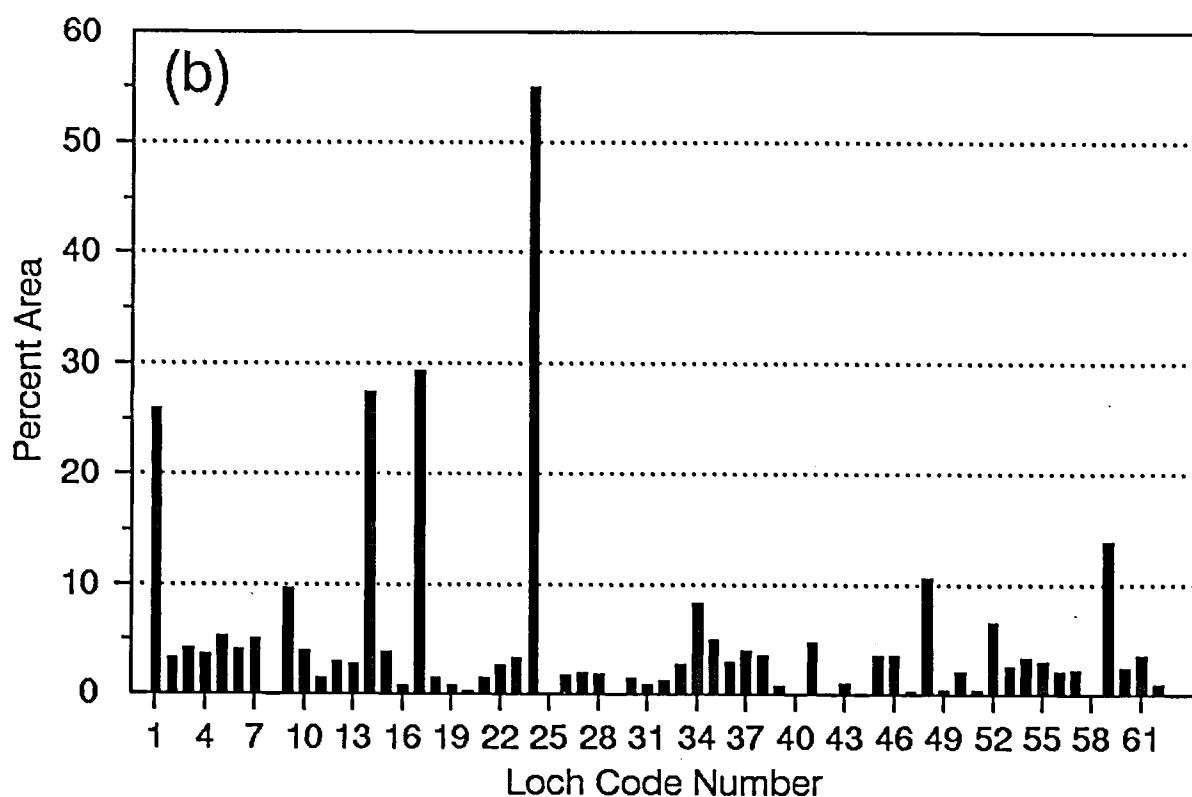
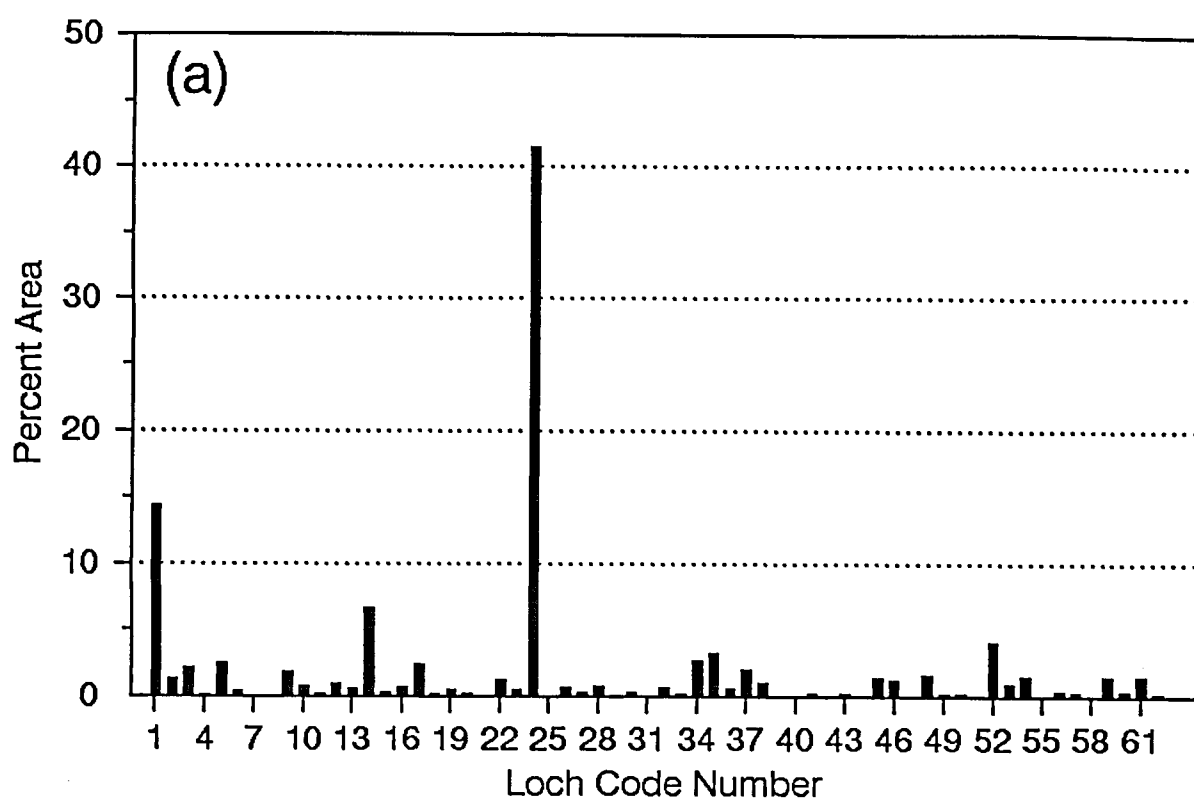


Figure 4 Exceedence areas as mean percentage of surface area of loch for concentration limits of 6.0 $\mu\text{g/l}$ (a), 0.6 $\mu\text{g/l}$ (b), 0.06 $\mu\text{g/l}$ (c) and 0.006 $\mu\text{g/l}$ (d), following a treatment of all farms in a loch.

FIGURE 4 (cont'd)

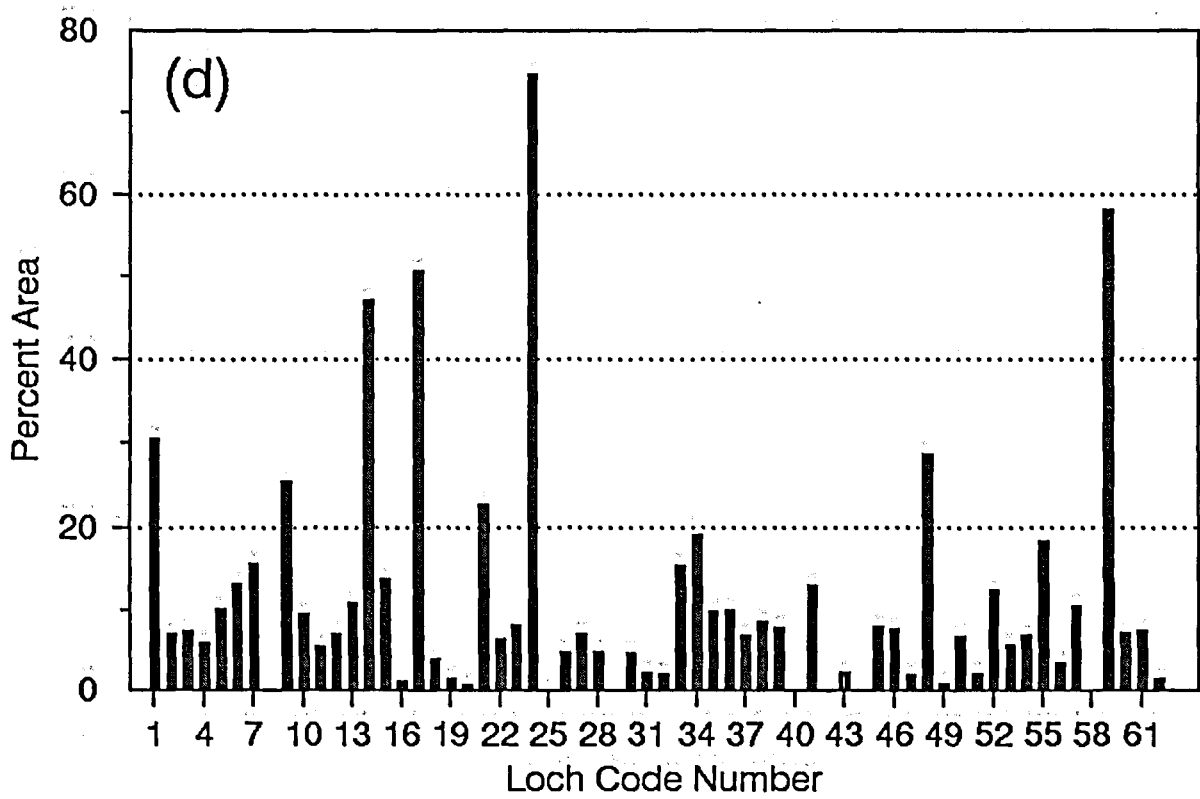
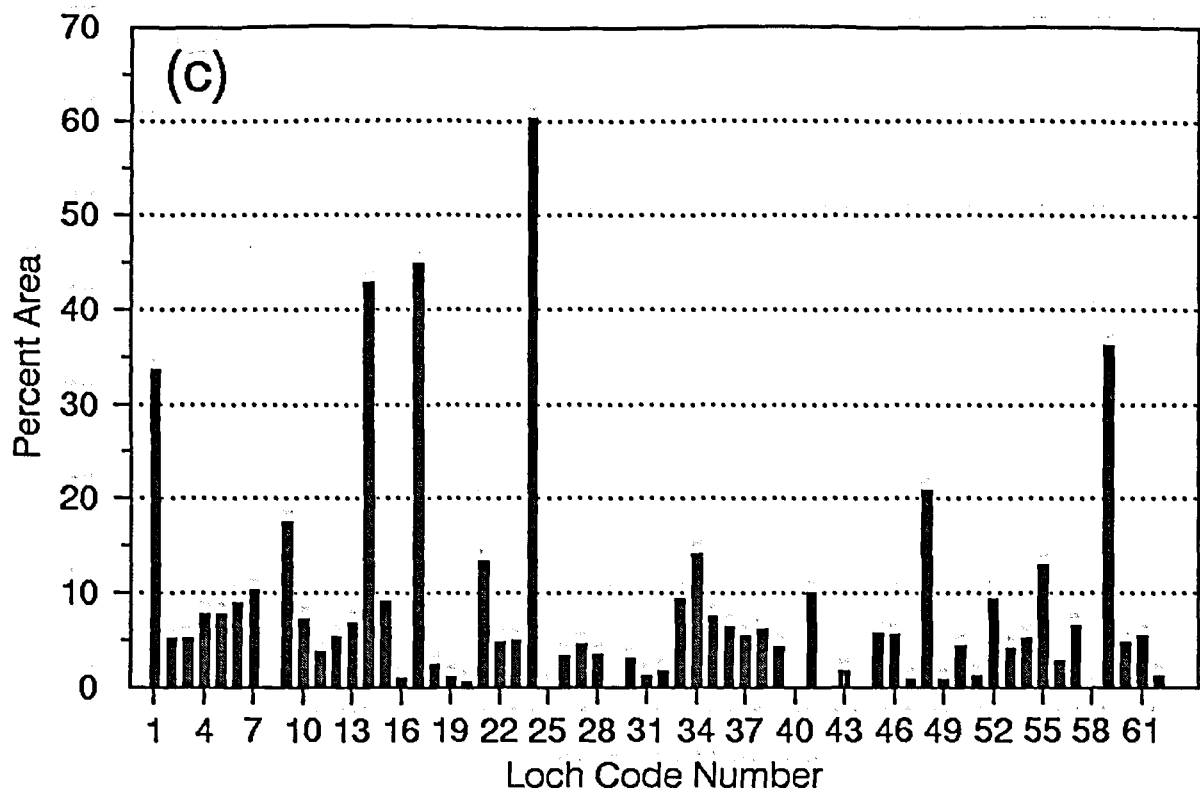
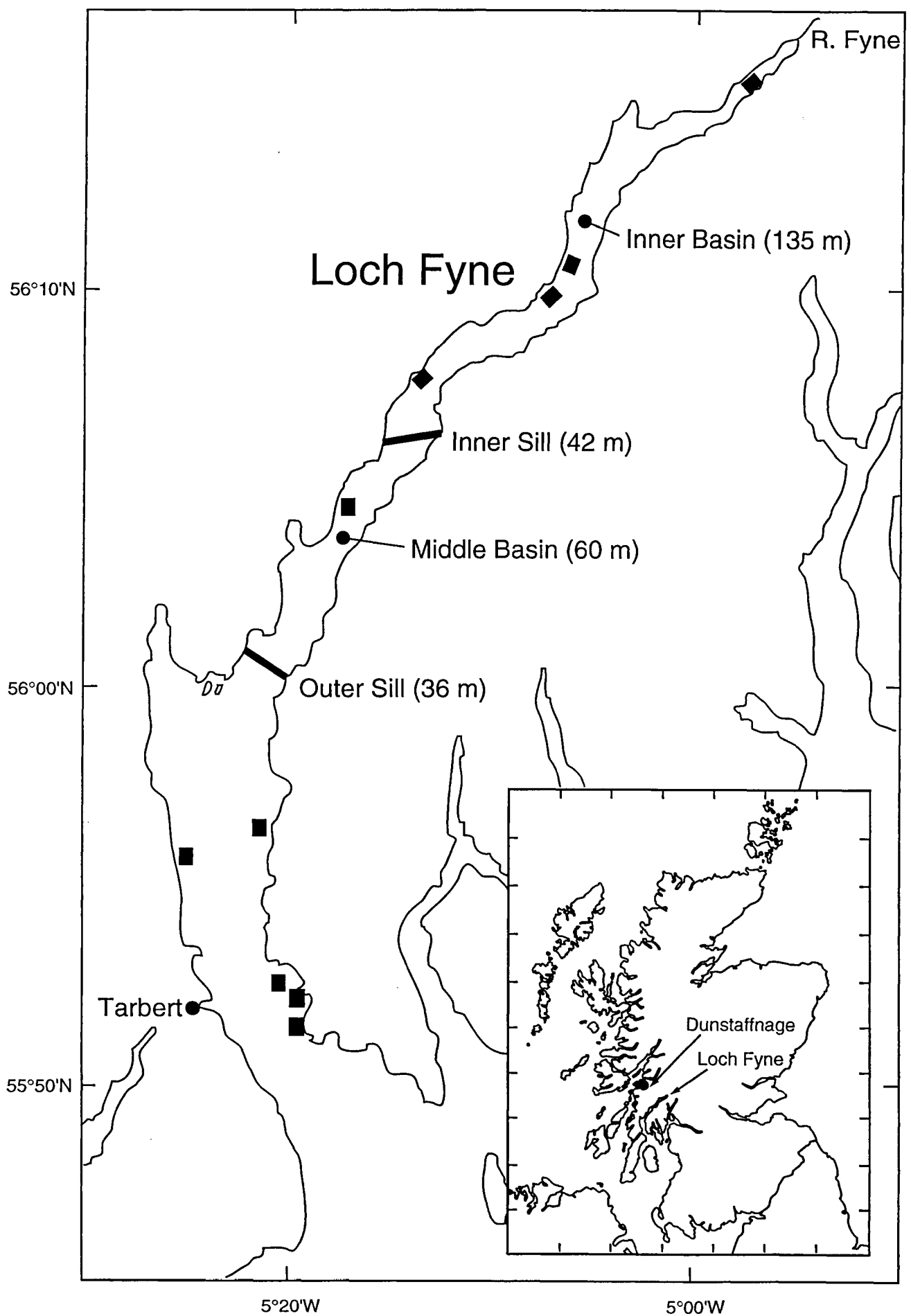


Figure 5 Map of Loch Fyne showing locations of sills and basins. Fish farms in production in 1994 are indicated by solid squares.



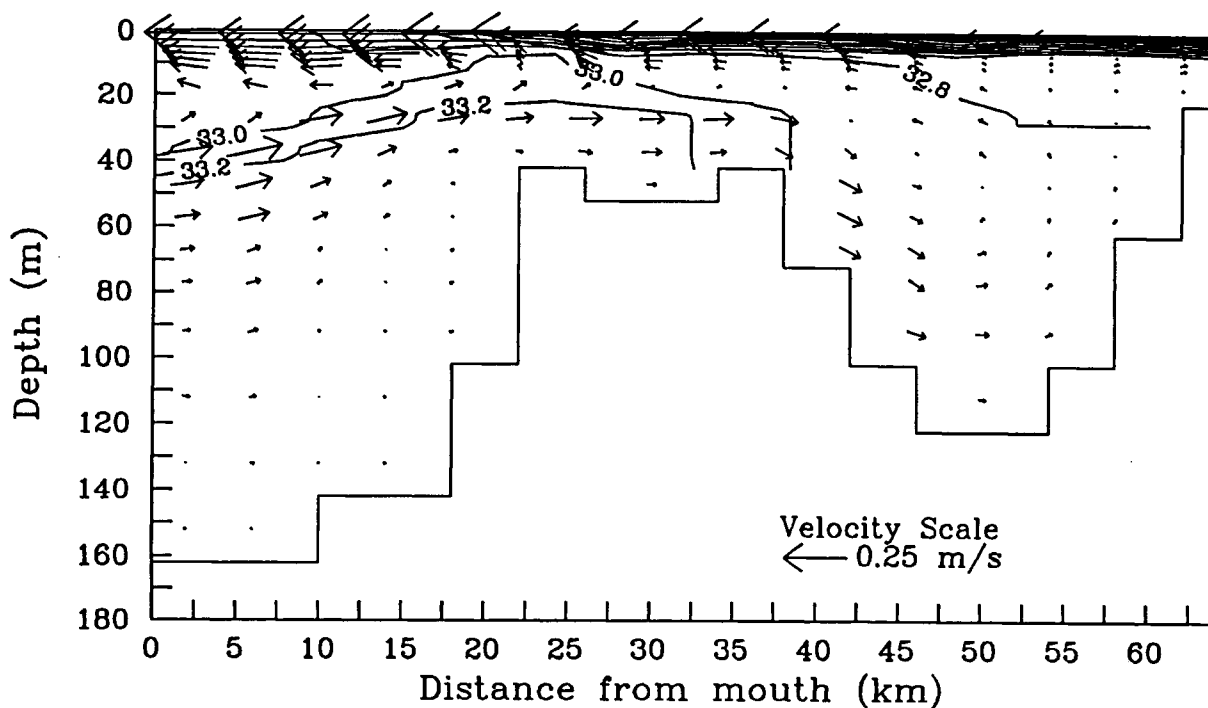


Figure 6 Example of typical velocity and salinity output from the model. The head of Loch Fyne is to the right hand side. The seabed is approximated by a series of vertical steps. The velocity and salinity fields have been averaged over a tidal cycle to remove the effects of the tide. Salinity contours are at intervals of 0.2.

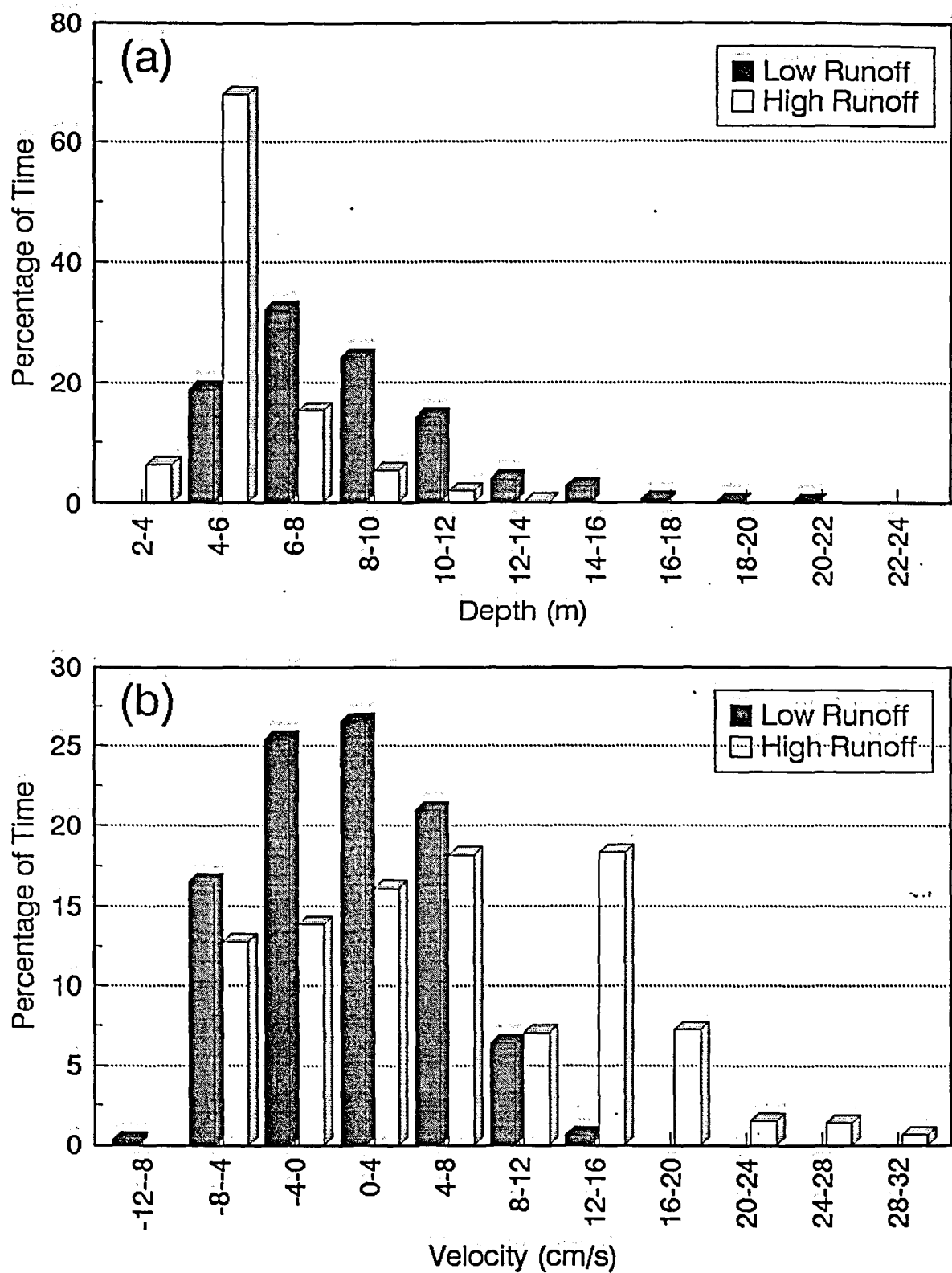


Figure 7 Histograms frequency distributions of surface layer depth (a), velocity (b) and flushing time (c) during low and high runoff conditions.

FIGURE 7 (cont'd)

