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Regulating the local environmental impact of intensive marine fish farming
III. A model for estimation of the holding capacity in the Modelling–Ongrowing fish farm–Monitoring system

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Abstract

A model has been developed for estimating the holding capacity of sites for fish farming. Expressed in terms of maximum fish production per month, the holding capacity is estimated with regard to three basic environmental requirements:

(i) the benthic fauna at a farm site must not be allowed to disappear due to accumulation of organic material;
(ii) the water quality in the net pens must be kept high;
(iii) the water quality in the areas surrounding the farm must not deteriorate.

All these requirements must be fulfilled, and the holding capacity is determined by the lowest of the three estimates. The fulfillment of requirements (i) and (ii) depends on local environmental properties such as water depth, the annual temperature cycle and the vertical distribution of current properties, and concentrations of oxygen and ammonium. It also depends on the maximum fish density per unit area, so the physical configuration of the farm is of importance. All these factors as well as feeding rate and feed composition are taken into account in the model.

The model comprises four sub-models which, for a given set of local environmental parameters, compute holding capacity according to these basic requirements. Given the feeding rate, feed

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composition and water temperature, a general fish sub-model adapted for domesticated Atlantic salmon computes the metabolism, growth and feed requirement of a specified fish stock. The fish model also computes emissions of particulate organic matter, i.e., uneaten feed and faeces. A dispersion sub-model computes the distribution of particulate matter from the net pens on the bottom for various sizes of pens and distances between them. A benthic sub-model computes the maximum rate of particulate matter sedimentation that will not result in the extinction of the benthic macro infauna. Water quality in the net pens is expressed as the lowest concentration of oxygen and the highest concentration of dissolved substances potentially harmful to the fish. These are computed by the water quality sub-model that needs input from the fish sub-model concerning the emission of dissolved substances and the consumption of oxygen due to respiration. The holding capacity according to requirement (iii) is computed by means of a previously published model.

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1. Introduction

The impact of fish farming on the environment has been the subject of a large number of studies during the past two decades. Many of its negative environmental effects have now been reduced as a result of better farming practices, improved feeds and the location of fish farms in more exposed areas. Furthermore, a number of precautions have been taken to manage environmental impact, including assessment through standardised monitoring programmes and the use of simulation models (Rosenthal, 2001). Simulation models are needed for rational coastal zone planning and for estimating the holding capacity of sites for fish farming. They are also useful tools for maintaining high water quality in net pens and for evaluating how changes in farm management are likely to affect surrounding areas. Mathematical models have been designed specially for simulations of various aspects of marine fish farming. Rates of water renewal in tanks and net pens, necessary to ensure high water quality, may be computed by models developed for both fry and ongrowing fish (Stigebrandt, 1986; McDonald et al., 1996). A number of papers describe models that simulate the dispersion and bottom deposition of organic particles from fish farms (Gowen et al., 1988; Silvert, 1992; Kishi et al., 1994; Stigebrandt and Aure, 1995; Hevia et al., 1996; Panchang et al., 1997; Cromey et al., 2002). Lately, models that predict the impact of organic material on the sediment or the benthic infauna have appeared (Stigebrandt and Aure, 1995; Findlay and Watling, 1997; Cromey et al., 1998, 2002). Other models have been developed to estimate the eutrophication effects of fish farming on inshore water bodies like fjords and archipelagos that also receive nutrients and organic matter from various other sources (Aure and Stigebrandt, 1990).

Model simulations and monitoring are both essential parts of a management system called Modelling—Ongrowing fish farms—Monitoring (MOM), which can be used to regulate the environmental impact of fish farming. The concept of the MOM system and the monitoring programme has previously been published (Ervik et al., 1997; Hansen et al., 2001). The present paper describes the mathematical model system that has been developed for the MOM system.

2. Premises for the construction of the MOM model system

It is an ultimate environmental objective for the management of sites for fish farming that their impact must not exceed threshold levels that safeguard the well being of both the fish and the environment. In the MOM system, there are three basic environmental requirements that have to be fulfilled in order to ensure long-term use of the sites (Ervik et al., 1993, 1997).

First, the accumulation of organic material under and in the vicinity of the farms must not result in extinction of the benthic macro infauna. This condition is met if the flux of organic matter from the farm is adjusted to local dispersion and resuspension conditions so that the decomposition capacity of the benthic system is not exceeded.

Second, the water quality in the net pens must meet the needs of the fish. This means that the concentration of oxygen is kept above the threshold level and that concentration of ammonium and other potentially harmful substances are kept below the threshold levels. These conditions can be met if the respiration of, and emissions from, the fish are adjusted to the rate of water renewal in the net pens.

Third, the water quality in the areas surrounding the farm must not deteriorate. This requirement is fulfilled if the outlets of nutrients and organic matter from the farm do not contribute to significantly higher algae production in the surrounding surface water or result in low oxygen concentrations in deep water. When the environmental impact is being assessed the contributions of all other sources must also be taken into account, thus considering the total impact.

Fish farming at a site must not violate these three basic environmental requirements. This is the starting point for estimating the holding capacity of a site. In practice, three different holding capacities are computed; one for each of the basic requirements. The holding capacity of the site is then given by the lowest of the estimates. The MOM model system is primarily meant to estimate the holding capacity of new sites for fish farming, but it may also be used to assess the environmental consequences of changes in production on farms already in operation. For the model computations, site-specific environmental conditions such as water depth, current characteristics, concentrations of oxygen and ammonium and the annual temperature cycle need to be known. The holding capacity will also depend on the size and the orientation of the net pens, as well as on the maximum fish density per unit area in the farm, the composition of the feed and the feeding rate.

The MOM model system provides a simulation tool for fish farm managers, consultants, authorities and others. It is cost-efficient and easy to use on a standard PC. Before a farm is established, the MOM model may be used to estimate the holding capacity of alternative sites so that the best of these may be chosen. The model is used to estimate a reasonable fish production at a specific site, and to decide how rigorous the initial monitoring should be. This decision is based on the principle that the closer the fish production is to the holding capacity; the more frequent monitoring should take place. In the course of time, monitoring will reveal the actual impact of the farm and the frequency of monitoring and the maximum permitted fish production can be adjusted (Hansen et al., 2001). Results from monitoring at many sites may also be used to improve our general understanding of, e.g., resuspension and the benthic communities capacity for decomposition, which in turn may be used to refine the model.

3. The structure of the MOM model system

The model system estimates the environmental effects of fish farming on both local (site) and regional scales. This paper describes the local component of the model system, which consists of four process-based sub-models: a fish model, a dispersion model, a benthic model and a water-quality model for the cages. The local model is linked to a previously published regional water quality model (Aure and Stigebrandt, 1990), which estimates the potential effects of fish farming on surrounding inshore water areas such as bays, archipelagos and fjords. It is described in detail in Stigebrandt (2001). An overview of the complete model system is given in Fig. 1. The sub-models are linked by the data they generate, in that the output parameters of one sub-model are used as input parameters for one or more of the other sub-models. An advantage of a modular model is that the sub-models can be altered individually as new knowledge is acquired or as new managing procedures or fish species are introduced. The scope of the model system may also be expanded to include environmental effects of fish farming related to the use of chemicals and medicines.

For the computations and the discussions in this paper, it is assumed that all net pens of a fish farm are of the same type and arranged in R rows (1, 2, or 3). It is assumed that the pen form is square, with a side length of L. For non-square pens, L is taken as equal to the square root of the pen area. The pen depth is D, the distance

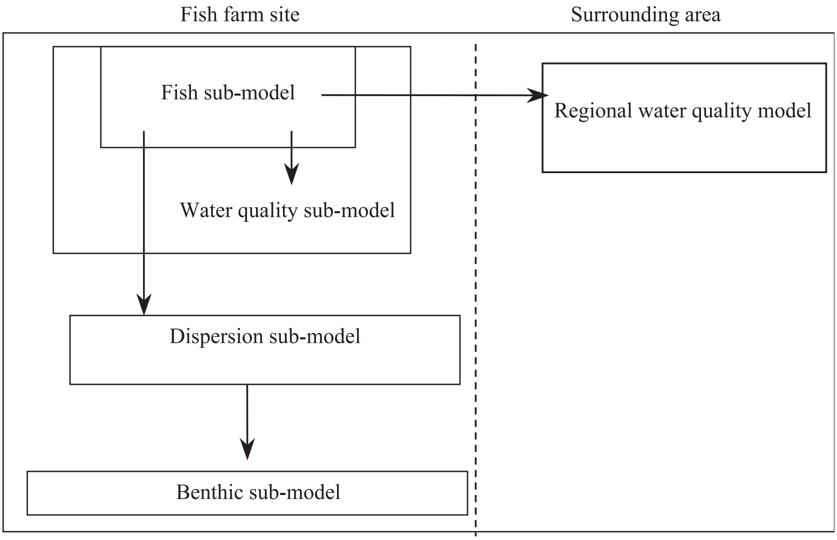

Fig. 1. Overview of the MOM model system. The local site model is linked to a regional (inshore) water quality model (Fjord Environment) (Aure and Stigebrandt, 1990). The output parameters from the fish sub-model are used as input parameters to the water quality sub-model, the dispersion sub-model and the regional water quality model. The dispersion sub-model delivers input parameters to the benthic sub-model. All sub-models require input parameters describing various environmental conditions at the farm site and of the inshore water body.

(separation) between the pens is S, N_F is the number of pens, and the total biomass of fish in the farm is B_M (Kg). The following relationships are used in this paper:

The total area of the net pens in the farm: $A_F = N_F L^2$ (m^2).
The length of the farm: $L_F = N_F/R(L+S) - S$ (m).
The width of the farm: $W_F = R(L+S) - S$ (m).

A list of symbols is given in Appendix A.

4. The fish sub-model

To quantify the impact of a fish farm on local and regional water quality, the turnover and transformation of organic matter at the farm must be known. This is computed by a general fish sub-model that deals with fundamental aspects of fish metabolism and growth. The model is described in detail in Stigebrandt (1999), where references are made to papers on metabolism and growth of fish. In the model energy and matter are conserved. Fish and feed are described by their contents of protein, fat, carbohydrates, ashes and water and their contents of phosphorus and nitrogen. Oxygen consumption due to fish respiration and the emission of various dissolved substances from the fish are computed on the basis of size and number of fish, feed composition, feeding rate and temperature. The emissions of particulate organic matter (uneaten feed and faeces) and plant nutrients (P and N) from a farm are also computed.

In the following, F_p is the protein content, F_f is the fat content and F_c is the carbohydrate content of the feed by weight. Similarly, P_p is the protein content and P_f the fat content of the fish by weight. For all computations presented in this paper, it is assumed that the fish contain 18% protein and 18% fat, i.e., $(P_p, P_f)=(0.18, 0.18)$. In the computer model, the compositions of feed and fish may be chosen freely to fit actual compositions.

The daily rate of feed consumption varies with the composition of the feed, the weight of the fish and the water temperature. The total amount of oxygen and the amount of feed of a certain composition needed to produce a fish of a particular weight from a given start weight, are independent of the temperature at which the fish grows, as are the emissions of particulate and dissolved matter (Stigebrandt, 1999). However, the time required by the fish to reach a particular weight varies with temperature.

Some integrated results from the fish sub-model are presented in Table 1 for two different types of feed, as defined in the table caption. Feed1 contains more protein and less fat than feed2. The amount of feed required for the fish to reach a certain target weight varies with the composition of the feed (Table 1, rows 3 and 6). The assimilation factor of protein in the fish intestine is about 0.90 and the minimum amount of ingested protein required for a given amount of growth therefore equals the amount of protein in the fish divided by 0.90. To reach a weight of 5 kg, a fish thus builds 0.9 kg of protein into its body if $P_p = 0.18$ (see also row 1 in Table 1). It must therefore ingest at least $0.9/0.90 = 1$ kg of protein. It follows that for Feed1 the excess protein is about 0.9 kg (row 4), while for feed2 it is about 0.3 kg (row 7). Thus, the

Table 1
The calculated total amount of feed required to produce a fish of a particular weight (rows 4 and 7), starting with a fish weight of 0.05 kg

	Fish weight (kg)				
	1	2	3	4	5
Protein content of fish (kg)	0.180	0.360	0.540	0.720	0.900
Feedtype 1					
FCR_t	0.834	0.849	0.858	0.866	0.871
Feed required (kg)	0.792	1.655	2.532	3.419	4.313
Protein content (kg)	0.356	0.744	1.139	1.539	1.940
Feedtype 2					
FCR_t	0.729	0.743	0.752	0.758	0.763
Feed required (kg)	0.693	1.449	2.217	2.993	3.775
Protein content (kg)	0.243	0.507	0.776	1.048	1.321

Two different types of feed are considered. Feed1 contains 45% protein, 30% fat and 7% carbohydrates. Feed2 contains 35% protein, 40% fat and 7% carbohydrates. Also shown are the assumed protein content of the fish, the theoretical feed conversion ratio FCR_t for the two kinds of feed and the protein content of the feed. (From Stigebrandt, 1999.)

protein content in both types of feed is higher than necessary for growth. Assimilated protein in excess of the growth requirements is catabolised.

Most of the nitrogen (N) in the feed is tied up in the protein. The phosphorus (P) originates both from the protein and from fish bones that are an integrated part of the fishmeal which provides the protein in the feed. Excretion of both N and P thus increases with the amount of excess protein in the feed (Stigebrandt, 1986, 1999). The fish submodel computes the amount of ingested feed. The ratio between this quantity and the resulting fish growth is called the theoretical feed conversion ratio (FCRt). This ratio varies with the feed composition and increases slightly with increasing fish weight (Table 1, rows 2 and 5). FCR, the factual feed conversion ratio, is the ratio between the amount of feed actually given to the fish and the resulting fish growth. The excess, i.e., uneaten feed, then equals $FCR - FCR_t$ times the fish growth.

The total calculated oxygen consumption, nitrogen and phosphorus excretion and faeces production during the growth of fish to various weights when using Feed1 are shown in Table 2. It is assumed that the fractions of N and P in the assimilated feed that exceed growth requirements are excreted.

Daily emissions of particulate and dissolved matter and the oxygen consumption may be computed using information from Tables 1 and 2, together with information on total biomass, temperature, growth rates and feed supply. As will be discussed below, such calculations need to be done in order to determine the emissions and the oxygen consumption in each net pen. The excess feed in Table 2 is calculated on the assumption that the difference between the factual and the theoretical feed conversion ratios $FCR - FCR_t$ equals 0.3. This means that for each kilo of fish produced, 0.3 kg of the feed supplied is not ingested by the fish. In the computer model, FCR can be chosen freely to fit recorded or assumed farming practice.

For later use in this paper, we need expressions for emissions of organic matter from the cages. If fish production is T_P, the emission of excess feed is $T_P(FCR - FCR_t)$ and the flux

Table 2
Results from the fish sub-model for fish with a starting weight of 0.05 kg

	Fish weight (kg)				
	1	2	3	4	5
Oxygen consumption—fish (kg)	0.445	0.956	1.496	2.049	2.614
Ammonium excretion—fish (kg)	0.024	0.052	0.080	0.110	0.139
Phosphorus excretion—fish (kg)	0.004	0.009	0.013	0.018	0.023
Faeces production (kg)	0.091	0.190	0.290	0.393	0.495
Oxygen consumption—faeces (kg)	0.159	0.333	0.508	0.687	0.866
N—faeces (kg)	0.015	0.030	0.046	0.063	0.079
P—faeces (kg)	0.002	0.005	0.008	0.010	0.013
Oxygen consumption—excess feed (kg)	0.428	0.893	1.366	1.845	2.327
N—excess feed (kg)	0.018	0.037	0.057	0.077	0.097
P—excess feed (kg)	0.003	0.006	0.009	0.013	0.016

For the computations, Feed1 was used (see the legend of Table 1) and it is estimated that $\mathrm{FCR} - \mathrm{FCR_t} = 0.3$, so the waste feed equals 0.3 kg per kg fish produced. (From Stigebrandt, 1999.)

of faeces is about $0.1T_\mathrm{P}$, cf. Table 2. The total area of the net pens is A_F so the spatial and temporal mean flux $F_{1\mathrm{feed}}$ (g m^{-2} day^{-1}) of excess feed from the pens equals:

$$F_{1\mathrm{feed}} = \frac{T_\mathrm{P}}{A_\mathrm{F}}(\mathrm{FCR} - \mathrm{FCR_t}) \tag{1}$$

The spatial and time mean flux $F_{1\mathrm{faeces}}$ (g m^{-2} day^{-1}) of faeces from the pens is:

$$F_{1\mathrm{faeces}} = 0.1\frac{T_\mathrm{P}}{A_\mathrm{F}} \tag{2}$$

For the computations in Section 6, it is assumed that the carbon content by weight is 50% of excess feed and faeces. The mean carbon emission $F_{1\mathrm{C}}$ from the pens thus equals $0.5(F_{1\mathrm{feed}} + F_{1\mathrm{faeces}})$ (gC m^{-2} day^{-1}).

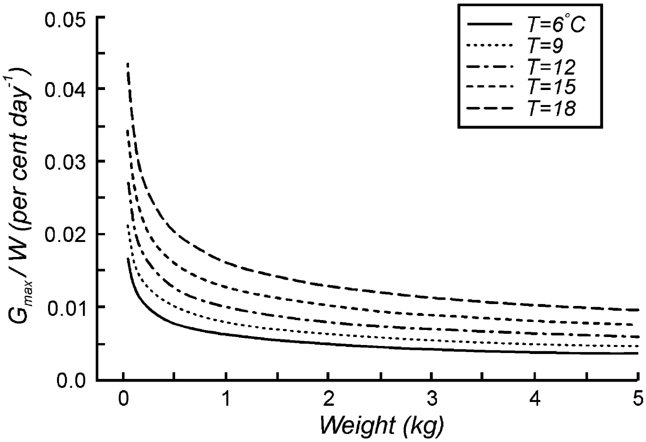

Fig. 2. Calculated normalised daily growth rates (% day^{-1}) of domesticated Atlantic salmon (*Salmo salar*) of different individual weights (>0.05 kg) for different temperatures (*T*). (From Stigebrandt, 1999.)

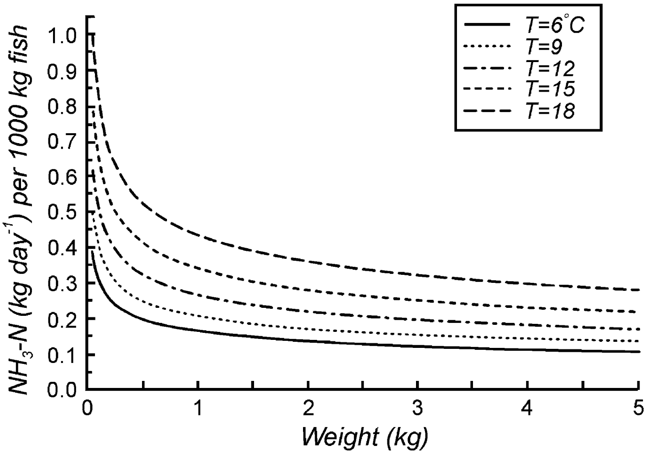

Fig. 3. Calculated emission of NH_3–N (kg day^{-1}) from 1000 kg of Atlantic salmon of different individual weights (>0.05 kg) for different temperatures (*T*). Feed1 was used for the calculation. (From Stigebrandt, 1999.)

The growth rate $G_{\max}$ of the fish varies with temperature and fish weight, *W*. Fig. 2 shows normalised daily growth rates for some temperatures. The model's growth function was calibrated to conform to growth data for domesticated Atlantic salmon (*Salmo salar*) compiled by Einem et al. (1994); see also Stigebrandt (1999). The emission of ammonium–nitrogen and the oxygen consumption of Atlantic salmon of different weights and at different temperatures are shown in Figs. 3 and 4, respectively, for Feed1.

The fish sub-model may also be used to optimise the feeding regime, maximise the fish growth and minimise emissions of nutrients and organic matter. Stigebrandt

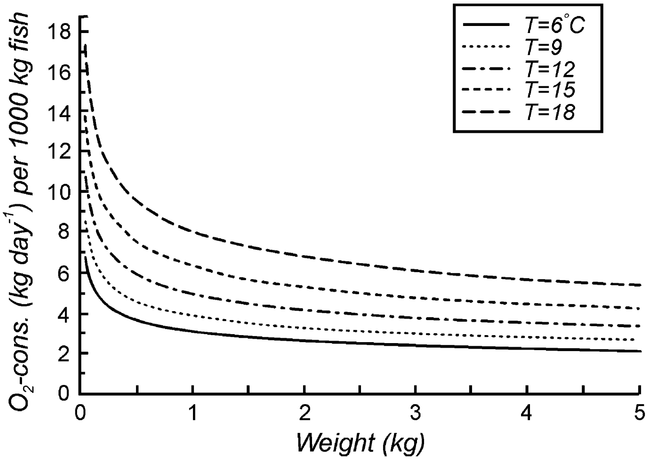

Fig. 4. Calculated oxygen consumption (kg O_2 day^{-1}) by 1000 kg of Atlantic salmon as function of individual fish weight (>0.05 kg) for some temperatures (*T*). Feed1 was used for the calculation. (From Stigebrandt, 1999.)

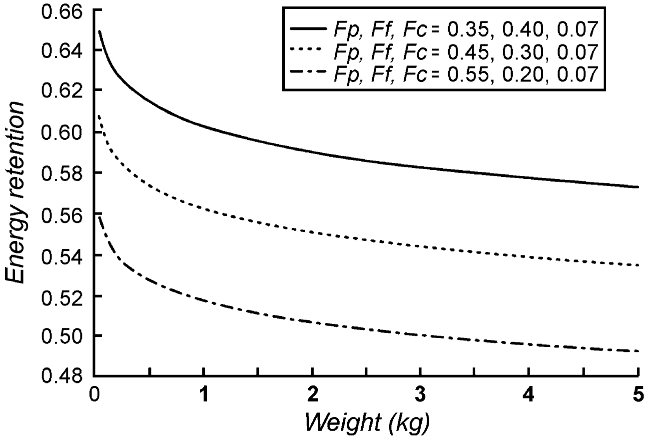

Fig. 5. Calculated energy retention as a function of fish weight (>0.05 kg) for three different types of feed as specified in the legend. (From Stigebrandt, 1999.)

(1986,1999) has shown that the oxygen demand and, in particular, the excretion of ammonium and phosphorus by the fish decrease when protein, in excess of growth needs, is replaced by fat. Figs. 5 and 6 show the retention of energy and protein by the fish for three different feed compositions. The differences in energy retention are not very large. However, the retention of protein, the most expensive part of the feed, varies by up to a factor of two, with the highest retention for the feed with the lowest content of protein. Thus, as pointed out in Stigebrandt (1986, 1999), reduction of the protein content in the feed will offer several benefits such as cheaper feed and higher

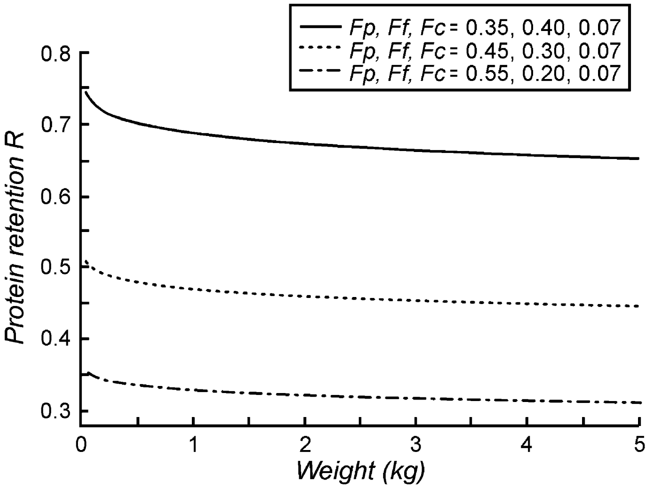

Fig. 6. Calculated protein retention by fish as a function of the fish weight (>0.05 kg) for three different types of feed as specified in the legend. (From Stigebrandt, 1999.)

protein retention and thereby less emission of plant nutrients to the environment. The theoretical necessary minimum content of protein in the feed may be computed by the fish model.

5. The dispersion sub-model

The particulate effluents from a fish farm, consisting of excess feed and faeces from the fish, will be dispersed, and for a large part settle, under or within some distance from the farm. Where and how much will settle depends on the amount and disintegration of the effluent, the sinking velocity of the particles, the current and the water depth. A number of papers have presented computations of the dispersion of uneaten feed and faeces from fish farms using particle-tracking models (Hagino 1977; Gowen and Bradbury, 1987; Fox, 1990; Silvert, 1992). The focus of these models is on spatial boundaries of sedimentation of particulate organic matter and the fish farm is assumed to produce a uniform emission of particles (see Gowen et al., 1994). Hevia et al. (1996) have extended the dispersion model of Gowen et al. (1988) to include, for example, variation in bottom topography and changes in current speed with depth. The model developed by Cromey et al. (2002) allows a detailed description of the farm on a 3D grid. The dispersion sub-model used in the MOM model differs from the other models because the net pen is treated as the basic unit of a farm. The spatial distribution of particle sedimentation under a fish farm then becomes a function of the pen size, the separation between pens and their configuration. The sedimentation from each of the net pens is computed and these may overlap, creating various local accumulation maxima. The dispersion model originally developed by Stigebrandt and Aure (1995) is presented below.

Due to time-dependent variations in current speed and direction, particulate organic waste sinking out of a net pen will be dispersed over an area of the bottom that is larger than the area of the pen. The dispersion process thus implies that the specific sedimentation rate on the bottom beneath a pen F_2 will be less than the specific sedimentation rate based on the area of the pen F_1, given by Eqs. (1) and (2). The sedimentation rate $F_2(r)$ is generally highest beneath the central parts of a pen and decreases with the distance r from the centre. A non-zero long-term mean current displaces the pattern of sedimentation relative to the pen centre, but does not contribute to the dispersion and may be neglected here. Current velocities appear to be approximately normally distributed (see, Stigebrandt and Aure, 1995; Green and Stigebrandt, 2003). This enables us to use the variance, σ^2, to estimate the dispersion of particles. The variance may be estimated from current measurements made on the site, as discussed in Section 8 below. The dispersion increases with the variability of the current and with the sinking time $T=H/w(s)$ of the particles. Here, H is the distance between the bottom of the net pen and the seabed, and w is the sinking velocity of the particles. The dispersion capacity of a location is then given by the dispersion length $\sigma_T=\sigma_H/w$ (m). The sedimentation at distance r from the cage centre, $F_2(r)$ (g m^{-2} day^{-1}), is related to the emission from the net pens F_1 (g m^{-2} day^{-1}) through the relationship:

$$F_2(r) = \mu(r)F_1 \tag{3}$$

The dimensionless dispersion function $\mu(r)$ attains values within the range 0–1. It is called the normalised sedimentation or loading function. With an assumption of no mean current, maximum sedimentation occurs beneath the centre of a net pen ($r=0$).

The normalised loading function $\mu(r)$ for a single cage, as determined by particle tracking techniques, is shown for various values of σ_T in Fig. 7. The sedimentation rate decreases with increasing distance from the centre of the cage, i.e., $\partial\mu/\partial r<0$. The maximum loading $\mu(0)$ decreases with increasing σ_T (Fig. 7) and increases with cage size (shown in Stigebrandt and Aure (1995)). Due to different sinking speeds, uneaten feed and faeces have different values of σ_T, and therefore different dispersions at a site. The simulations shown here are a sub-set of the simulations presented by Stigebrandt and Aure (1995), where the following general conclusions were drawn: (1) The dispersion at a site may be described by the dispersion length σ_T. By using feed with lower sinking velocity or feed which disintegrates easily into smaller particles, the sinking time T may be increased, and thereby the dispersion of excess feed. (2) The sedimentation on the seabed outside the vertical projection of a single net pen increases and the maximum loading $\mu(0)F_1$ beneath the net pen decreases with increasing dispersion length and decreasing pen area. (3) The maximum loading under a fish farm decreases if (i) the separation between net pens is increased, (ii) pen size is decreased, (iii) the number of net pen rows is decreased. The pen rows should be oriented perpendicular to the direction of the strongest currents. The holding capacity

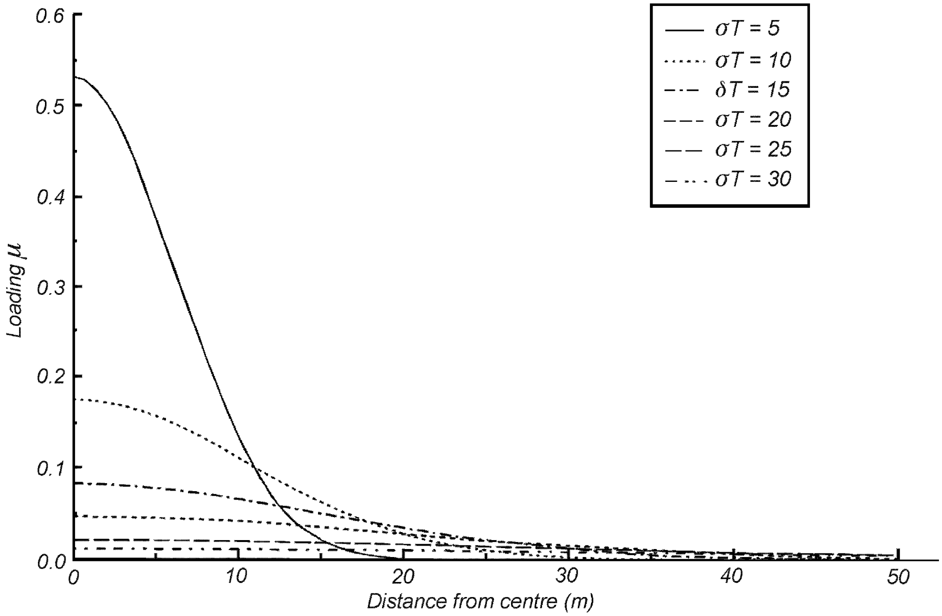

Fig. 7. The normalised loading (sedimentation) function $\mu(r)$ versus distance r from the centre of the cage for different values of σ_T (m) (see legend). The mean current vanishes and the cage size is 15×15 m^2. (From Stigebrandt and Aure, 1995.)

of a site which is limited by the assimilative capacity of the benthic community may thus be increased in several ways.

The greatest risk of extinction of the infauna due to overloading of the seabed occurs where the sedimentation rate is greatest. To compute the maximum sedimentation rate at a certain site, the dispersion sub-model uses filed estimates of the $\mu(r)$ function for single net pens, for the values of σ_T and L that are applicable to the farm. Note that because of its much lower sinking speed, σ_T is much larger for faeces than for conventional feed. The sedimentation rate at any point on the seabed is obtained by adding the sedimentation from all net pens in the farm with specified number of rows R and distance S between net pens. The dispersion sub-model computes the maximum values μ_{feed} and μ_{faeces} for excess feed and faeces, respectively, under the farm. As an example, Fig. 8 displays computed results that show how the maximum specific sedimentation rate on standard fish farms with one, two or three rows of net pens varies with the distance S between net pens. It is evident that the holding capacity of a site might be significantly increased by using larger distances between cages and/or just one row of cages.

The maximum carbon flux $F_{2\mathrm{Cmax}}$ to the sediment under the farm (gC m^{-2} day^{-1}) is computed as:

$$F_{2\mathrm{Cmax}} = 0.5(\mu_{\mathrm{feed}} F_{1\mathrm{feed}} + \mu_{\mathrm{faeces}} F_{1\mathrm{faeces}}) \tag{4}$$

where μ_{feed} (μ_{faeces}) is the maximum loading with excess feed (and/or faeces) that takes into account contributions from all cages as computed using the dispersion sub-model.

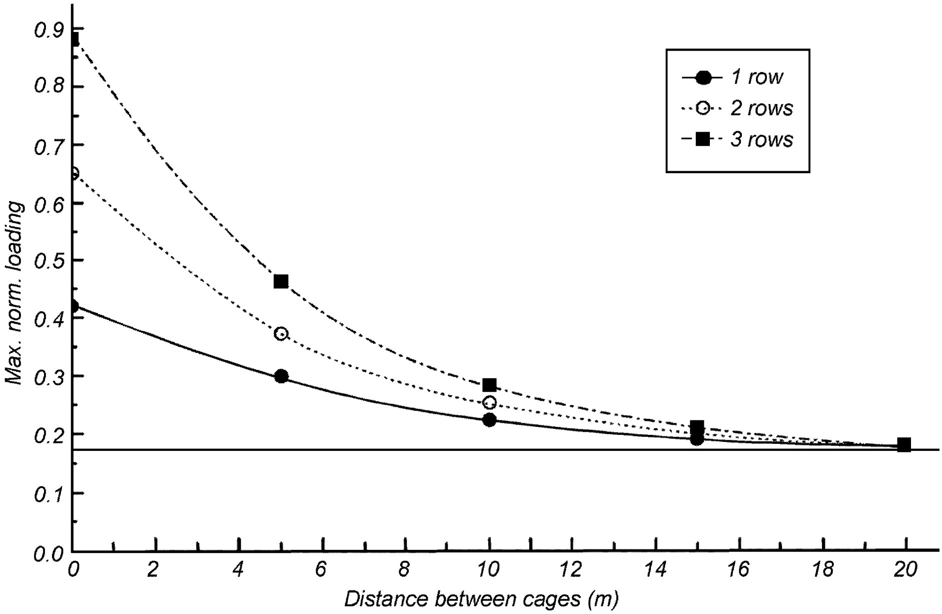

Fig. 8. Maximum normalised loading (sedimentation) versus distance S between cages for a standard farm with 1, 2 or 3 rows (see legend). For these computations, $\sigma_T = 10$ m and $L = 11$ m. (From Stigebrandt and Aure, 1995.)

$F_{1\text{feed}}$ and $F_{1\text{faeces}}$ are defined by Eqs. (1) and (2), respectively. The factor 0.5 accounts for the carbon content of feed and faeces as mentioned in Section 4. In Eq. (4), it is assumed that local sedimentation maxima of excess feed and faeces coincide. This is true only if the mean current vanishes. If not, local sedimentation maxima for excess feed and faeces do not coincide. Eq. (4) then overestimates the maximum carbon flux to the sediment.

If the current speed above the bottom occasionally exceeds a certain threshold value, accumulated organic material will be resuspended and may be transported away from the site. Cromey et al. (2002) estimated that the threshold current value for resuspension of organic matter from fish farms is about 10 cm s^{-1}. This is in accordance with Panchang et al. (1997) who estimated that the threshold is in the interval between 10 and 20 cm s^{-1}. Current speeds in this range should occur occasionally if the variance of the bottom current is 4–6 (cm $s^{-1})^2$, and the frequency of such events should increase with the current variance, as shown in Stigebrandt and Aure (1995).

6. The benthic sub-model

Aerobic decomposition of organic matter in sediments requires that oxygen be supplied to the sediments from the overlying water. Sediments beneath marine fish farms are susceptible to oxygen depletion if the sedimentation rate of excess feed and faeces reaches a critical level. With insufficient oxygen supply to the sediments, anaerobic decomposition will prevail and the sediments may produce high concentrations of hydrogen sulphide, resulting in azooic sediments (Braaten et al., 1983; Hansen et al., 1991). It has been demonstrated that the maintenance of a macrofaunal population, even if this comprises small opportunist species such as *Capitella capitata*, can enhance organic matter decomposition and possibly prevent further accumulation of organic waste (Heilskov and Holmer, 2001). Ebullition from highly reduced sediments may bring bacteria, hydrophobic particles and hydrogen sulphide from the sediments up into the net pens and into contact with the cultivated fish (Storebakken and Olsen 1982; Samuelsen et al., 1988). It is therefore beneficial to keep the organic deposits under fish farms at a level where ebullition is prevented and a viable macrofauna exists in the sediment. As a threshold level for acceptable sediment impact, we have chosen the highest organic load on the sediment that will retain a benthic infauna (Ervik et al., 1993, 1997).

The task of the benthic sub-model is to compute the maximum rate of sedimentation of organic matter that does not lead to extinction of the benthic infauna. Species have different tolerances to oxygen depletion and to hydrogen sulphide, and only the more tolerant species can survive the conditions in reduced sediments (Theede et al., 1969; Tsutsumi et al., 1990; Costello and Read, 1994). In the MOM system, however, the main concern at present is simply to maintain an infauna, without regard to its diversity. The sub-model therefore needs to determine the current speed required to provide an oxygen flux to the sediment that will be sufficient to retain an infauna consisting of more tolerant species. If the infauna is to prevail, the oxygen concentration of the water above the sediment must be sufficiently high over time to sustain the fauna.

Stigebrandt and Aure (1995) developed the benthic impact model used in MOM. They assume that aerobic benthic metabolism is limited by the maximum rate of oxygen delivery to the sediments. They argue that the latter is determined by the turbulent diffusion of oxygen across the turbulent bottom boundary layer. Oxygen consumption by infauna cannot be greater than oxygen delivery and it requires oxygen concentrations to be sufficiently high over time. This determines the maximum rate of sedimentation of particulate matter from the farm. The benthic model of Findlay and Watling (1997) is also based on oxygen delivery and consumption. However, instead of using oxygen delivery calculated from turbulent diffusion across the turbulent bottom boundary layer and the oxygen concentration above this layer they used Fickian diffusion.

Oxygen delivery must be high enough to maintain a minimum oxygen concentration that enables the macrofauna to survive. Furthermore, we consider worst-case scenarios by assuming that the oxygen demand of the sediment equals the theoretical total oxygen demand for complete oxidation of the settled organic matter. It is assumed that the vertical oxygen transfer to the bottom is determined by the dynamic properties of the turbulent benthic boundary layer. However, oxygen conditions in the sediment will depend on the diffusive boundary layer, which is usually less than 1 mm thick (Jørgensen and Revsbeck, 1985; Gundersen and Jørgensen, 1990). It is assumed that most benthic infauna is able to penetrate this layer and obtain oxygen from the overlying turbulent boundary layer. The rate of vertical oxygen transport by the turbulent boundary layer is dependent on the current speed above the boundary layer and the difference in oxygen concentration between just above the boundary layer and the sediment surface. The flux of particulate organic matter from the farm to the sediment must thus not exceed the level at which decomposition causes the oxygen concentration at the sediment surface to sink below a critical threshold value.

The flux of organic material from the farm that settles at the bottom (F_2) does not necessarily represent the amount of organic material being decomposed in the sediment. Some of the material may be transported away by strong bottom currents and by animals and oxidise outside the farm area. The fraction of the particulate organic matter from the farm that is oxidised within the farm area is called α ($0<\alpha<1$). The vertical oxygen flux necessary to completely decompose the settled material will be $\alpha\eta F_2$, where η is the amount of oxygen necessary to oxidise 1 g of organic carbon to carbon dioxide and water. If the specific flux of oxygen to the sediment is F_{O_2} (g O_2 m^{-2} s^{-1}) one expects at steady state that:

$$\alpha\eta F_2 = F_{O_2} \tag{5}$$

Thus, if one knows α, η and F_{O_2}, F_2 can be computed. In the MOM model, we use for η the standard value 3.5 g O_2/gC. The following formula for F_{O_2} is from Stigebrandt and Aure (1995)

$$F_{O_2} = \beta U_{\rm bent}(O_{2\rm i} - O_{2\rm bent}) \tag{6}$$

where $O_{2\rm i}$ is the oxygen concentration just above the turbulent benthic boundary layer, $O_{2\rm bent}$ is the oxygen concentration at the sediment surface and $U_{\rm bent}$ the horizontal current velocity just above the turbulent benthic boundary layer. $\beta U_{\rm bent}$ may be looked upon as the effective vertical velocity that transfers oxygen to the bottom. Theoretically, this should be equal to the effective vertical velocity $C_D U_{\rm bent}$ that transfers horizontal momentum towards the bottom. The coefficient β should thus have a value equal to that of the drag coefficient (C_D). In the MOM model, it is tentatively assumed that $\beta = 2 \times 10^{-3}$.

Maximum oxygen transport to the bottom occurs when the difference $O_{2\mathrm{i}} - O_{2\mathrm{bent}}$ is at a maximum, which for a given $O_{2\mathrm{i}}$ occurs when $O_{2\mathrm{bent}} = O_{2\mathrm{min}}$, the lowest oxygen concentration that will allow the benthic infauna to survive. For the calculations we use the maximum sedimentation rate $F_{2\mathrm{max}}$ (g C m^{-2} s^{-1}) that occurs beneath the cage centres if there is no mean current, as discussed in Section 5. By combining Eqs. (5) and (6), we obtain the maximum acceptable sedimentation on the bottom:

$$F_{2\mathrm{max}} = \frac{U_{\mathrm{bent}}\beta}{\alpha\eta}(O_{2\mathrm{i}} - O_{2\mathrm{min}}) \tag{7}$$

The relationship between measured currents and the dimensioning current velocity U_{bent} used in the model is discussed in Section 8.

An expression for the maximum potential fish production at a fish farm that does not lead to extinction of the benthic infauna, $\mathrm{TPF}_{\mathrm{bentam}}$, can be derived using (Eqs. (1), (2), (4) and (7), thus:

$$\mathrm{TPF}_{\mathrm{bentam}} = \frac{2\beta A U_{\mathrm{bent}}(O_{2\mathrm{i}} - O_{2\mathrm{min}})}{\alpha\eta((\mathrm{FCR} - \mathrm{FCR}_{\mathrm{t}})\mu_{\mathrm{feed}} + 0.1\mu_{\mathrm{faeces}})} \tag{8}$$

where FCR is the actual feed conversion ratio, $\mathrm{FCR}_{\mathrm{t}}$ is the theoretical feed conversion ratio (computed by the fish sub-model, see Section 4), A is the total area of the cages in the farm and μ_{feed} (μ_{faeces}) is the maximum specific loading with excess feed (faeces) accounting for contributions from all cages as computed by the dispersion sub-model. Since μ_{feed} is usually much larger than μ_{faeces} and $\mathrm{FCR} - \mathrm{FCR}_{\mathrm{t}}$ is greater than 0.1, the maximum potential fish production at a certain site is determined essentially by the amount of excess feed and the sinking velocity of feed.

7. The sub-model of water quality in fish cages

High water quality in the fish cages means a sufficiently high concentration of oxygen and sufficiently low concentrations of ammonium and other deleterious substances. In well-flushed farms, the residence time of the water is short and changes in both oxygen and ammonium concentrations are small and harmless as the water flows through the cages. If flushing is sluggish, however, concentrations may reach dangerous levels. It is thus important to estimate the minimum flushing rate of a fish farm at a given site. The water quality sub-model computes the maximum fish production $\mathrm{TPF}_{\mathrm{O}_2}$ that keeps the oxygen concentration above a critical value with the estimated minimum flushing rate. The derivation of the formula for $\mathrm{TPF}_{\mathrm{O}_2}$ is described in detail. The calculation of the maximum fish production $\mathrm{TPF}_{\mathrm{NH}_4}$ that keeps the ammonium concentration below the critical value is quite similar to that for oxygen and therefore only the final formula is given.

To estimate the oxygen supply to the fish farm, the minimum mean current U_{MIN} needs to have been estimated from observations. As shown below, U_{MIN} may be used to calculate the maximum fish production $\mathrm{TPF}_{\mathrm{O}_2}$ that keeps the oxygen concentration above the critical value $\mathrm{O}_{2\mathrm{MIN}}$. The latter is determined by the sensitivity of the fish to low concentrations of oxygen.

The rate of oxygen consumption OX1 of the fish in a farm of length L_{F} and depth D by a current with the speed of U_{MIN} equals:

$$\mathrm{OX1} = (O_{2\mathrm{IN}} - O_{2\mathrm{OUT}})L_{\mathrm{F}}DU_{\mathrm{MIN}} \tag{9}$$

where $O_{2\mathrm{IN}}$ ($O_{2\mathrm{OUT}}$) is the oxygen concentration of the water flowing into (out of) the farm. $O_{2\mathrm{OUT}}$ must not fall below $\mathrm{O}_{2\mathrm{MIN}}$. For given values of U_{MIN} and $O_{2\mathrm{IN}}$, the oxygen supply is at its maximum when $O_{2\mathrm{OUT}} = O_{2\mathrm{MIN}}$. In Eq. (9), it is assumed that the fish may also use the oxygen in the water between the cages. This is thought to be made possible by transversal water motions produced by the fish. Note that U_{MIN} is measured perpendicular to the long axis of the farm. One interesting property of Eq. (9) is that OX1 is at a maximum when L_{F} is at maximum, which occurs when $R = 1$ and the farm only has one row of cages. In this case, the farm is maximally exposed to the current.

Alternatively, the estimate of the minimum oxygen supply required by the fish in the farm may be based on the maximum flushing time $\mathrm{TF}_{\mathrm{MAX}}$, which is the time a water parcel remains in the farm. The mean rate of oxygen consumption by the fish OX2 with a water retention time $\mathrm{TF}_{\mathrm{MAX}}$ in the farm is:

$$\mathrm{OX2} = \frac{(O_{2\mathrm{IN}} - O_{2\mathrm{OUT}})N_{\mathrm{F}}D(L+S)^2}{\mathrm{TF}_{\mathrm{MAX}}} \tag{10}$$

Here, $N_{\mathrm{F}}D(L+S)^2$ is the "effective volume" from which the fish in the farm can obtain oxygen and $O_{2\mathrm{OUT}}$ is the oxygen concentration after the time $\mathrm{TF}_{\mathrm{MAX}}$. Once again, it is assumed that in the event of low flushing rates at the farm, the fish may create a certain amount of local water motion around the cages and thus obtain oxygen from a water volume greater than the volume of the cage.

Putting $\mathrm{OX1} = \mathrm{OX2}$ and $L_{\mathrm{F}} \approx N_{\mathrm{F}}/R(L+R)$, gives the following relationship between U_{MIN} and $\mathrm{TF}_{\mathrm{MAX}}$:

$$U_{\mathrm{MIN}} \approx \frac{W_{\mathrm{F}}}{\mathrm{TF}_{\mathrm{MAX}}} \tag{11}$$

where W_{F} is the width of the farm, defined in Chapter 2. Eq. (11) can be used to calculate U_{MIN} when $\mathrm{TF}_{\mathrm{MAX}}$ is known and vice versa.

To estimate the holding capacity with respect to the water quality in the cages, we estimate the maximum possible production $\mathrm{TPF}_{\mathrm{O}_2}$ at the farm during periods of minimum flushing, without a risk that the oxygen concentration in the net pens falls below the critical value $O_{2\mathrm{MIN}}$. Having estimated this, we can estimate the biomass needed for this level of production. If the mean oxygen consumption per kg fish production is DO_2, it is necessary that:

$$\mathrm{TPF}_{\mathrm{O}_2} = \mathrm{OX1}/\mathrm{DO}_2 \tag{12}$$

Here, the fish sub-model computes DO_2 (see Table 2 for an example). Using Eq. (9), we obtain the following expression for the maximum, or critical, production $\mathrm{TPF}_{\mathrm{O}_2}$ based on oxygen conditions in the farm:

$$\mathrm{TPF}_{\mathrm{O}_2} = \frac{(O_{2\mathrm{IN}} - O_{2\mathrm{MIN}})L_{\mathrm{F}}DP_{\mathrm{F}}U_{\mathrm{MIN}}}{\mathrm{DO}_2} \tag{13}$$

Here, we have introduced the permeability of the farm P_{F} ($0 < P_{\mathrm{F}} < 1$) that describes the reduction in U_{MIN}, as determined from measurements made before the farm was established, due to the resistance to water flow introduced by the cages and floating devices of the farm. If, for example, $P_{\mathrm{F}} = 0.5$, the flushing of the farm is only half of what would be expected using U_{MIN} estimated during pre-farming conditions. In the MOM model, U_{MIN}, P_{F} and $\mathrm{O}_{2\mathrm{MIN}}$ are given as input parameters. It is assumed that $O_{2\mathrm{IN}}$ equals $O_{2\mathrm{SAT}}$, the saturation concentration of oxygen at given salinity and temperature computed according to Weiss (1970). For calculations of DO_2 in the MOM model, the dimensioning fish weight is taken as the median weight of the fish during the production cycle, i.e., the weight halfway through the production cycle. In the computation of the maximum production $\mathrm{TPF}_{\mathrm{O}_2}$, we neglect possible diffusion of oxygen through the water surface. This is a slow process, e.g., Stigebrandt (1991), in particular, during calm (critical) conditions when the rate of flushing of the farm is generally likely to be low. We also neglect the possibility that fish-induced water motions may transport some oxygen from a water layer beneath the cages, which provides a certain margin of safety for the estimated holding capacity.

Eq. (13) shows that increasing the length of the farm L_{F} and/or the depth of the cages D can increase the maximum production $\mathrm{TPF}_{\mathrm{O}_2}$ of a fish farm. Production may also be increased by decreasing DO_2 by using feed with less protein and more fat, as mentioned in Section 4 above. Furthermore, it is important that the net pens should be kept clean in order to ensure that the permeability of the farm P_{F} is as high as assumed in the computations.

We use Eq. (13) as a template to construct a formula to compute the maximum production of the farm, $\mathrm{TPF}_{\mathrm{NH}_4}$, based on the condition that the concentration of ammonium must be lower than a critical value $\mathrm{NH}_{4\mathrm{MAX}}$:

$$\mathrm{TPF}_{\mathrm{NH}_4} = \frac{(\mathrm{NH}_{4\mathrm{MAX}} - \mathrm{NH}_{4\mathrm{IN}})L_{\mathrm{F}}DP_{\mathrm{F}}U_{\mathrm{MIN}}}{\mathrm{DNH}_4} \tag{14}$$

where $\mathrm{NH}_{4\mathrm{IN}}$ is the ammonium concentration in the water flowing into the farm. This value must be estimated from observations and put into the computer program. The fish sub-model computes the mean ammonium production DNH_4 per kg fish production (see Table 2 for an example).

If the actual production of the farm is lower than the maximum production according to Eqs. (13) and (14), the minimum oxygen and the maximum ammonium concentrations in the cages will of course be higher than $O_{2\mathrm{MIN}}$ and lower than $\mathrm{NH}_{4\mathrm{MAX}}$, respectively.

The holding capacity of a location, PROD, is finally determined by the minimum value of the TPFs as computed from Eqs. (8), (13) and (14):

$$\mathrm{PROD} = \min(\mathrm{TPF}_{\mathrm{bentam}},\ \mathrm{TPF}_{\mathrm{O_2}},\ \mathrm{TPF}_{\mathrm{NH_4}}) \tag{15}$$

If possible, PROD is computed on a monthly basis. The computer programme estimates the standing stock necessary to obtain the production PROD. We must remember that the holding capacity PROD must not violate the requirement that fish production at a site is not allowed to lead to a deterioration in water quality in the area surrounding the farm. This is checked using a regional water quality model as discussed in Section 2 above.

The computations in the present version of the MOM model assume that the pens are anchored in fixed positions, i.e., without significant swing. If pens are anchored with appreciable swing, a larger area of the seabed will receive organic waste from the farm and this should decrease F_2 and increase $\mathrm{TPF}_{\mathrm{bentam}}$. At the same time, the flushing of the pens will be less efficient during periods when the pens drift with the current. This tends to decrease $\mathrm{TPF}_{\mathrm{O_2}}$ and $\mathrm{TPF}_{\mathrm{NH_4}}$. Our experience from numerous applications of the MOM model to farms anchored in fixed positions is that $\mathrm{TPF}_{\mathrm{bentam}}$ is usually much smaller than $\mathrm{TPF}_{\mathrm{O_2}}$ and $\mathrm{TPF}_{\mathrm{NH_4}}$. Thus, anchoring farms with large swing might be one method of evening out the TPFs and thus increasing the holding capacity of a site. It should be possible to compute the amount of swing that would give maximum holding capacity PROD of a site, which should occur when $\mathrm{TPF}_{\mathrm{bentam}} = \min(\mathrm{TPF}_{\mathrm{O_2}}, \mathrm{TPF}_{\mathrm{NH_4}})$. Computations of PROD for pens anchored at swing will be included in future versions the MOM model.

8. Required input data for the MOM model system

The current conditions at different depths at a fish farm site are crucial for the farmed fish, the dispersion of particles and dissolved substances, as well as for the condition of the benthic community in the area. The poorest water quality for the fish occurs when the flushing time T_{F} of the pens is long. The water quality at the bottom is dependent on both the variability of currents, which determines the dispersion of particulate matter, and on the minimum current in the bottom layer that determines the supply of oxygen to the benthic animals. How these values are extracted from current measurements is discussed below.

If possible, current records should be obtained from at least three levels: in the surface layer, at an intermediate depth (halfway between the bottom of the cages and the sediment surface) and in the bottom layer. In cases where rotor instruments are used in environments with weak currents, any recorded zeros (due to the current metre threshold) must be replaced by currents extracted randomly from a statistical distribution with the same mean and variance. In Stigebrandt and Aure (1995), this was done and it was shown that the corrected currents in two Norwegian fjords were approximately normally distributed. A recent investigation suggests that non-tidal currents in general are normally distributed in the sea including inshore areas (Green and Stigebrandt, 2003).

The dispersion of particulate matter is determined by the fluctuating component of the current. A measure of this is the standard deviation (σ), which is estimated from the variance sigma squared (σ^2). If a current record consists of M current registrations u_i ($i = 1..M$) and the mean current in the record is u_0, then σ is defined by:

$$\sigma = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(u_i - u_0)^2} \tag{16}$$

Current measurements obtained at mid-depth between the bottom of the pens and the sea bottom should be used for the estimation of σ. Furthermore, the current component perpendicular to the main axis of the farm should be used.

The dimensioning current in the surface layer is determined from a record obtained in the surface layer. The maximum flushing time $\mathrm{TF_{MAX}}$ of the pens in a farm can be estimated from a time series of the perpendicular current component u_i by computing how long it takes for the current to move a water parcel a distance equal to the width $\mathrm{W_F}$ of the farm. By stepping through the time series one may estimate the maximum number n (max$n$) of consecutive current records needed to just fulfil the condition $L_\mathrm{C} \geq W_\mathrm{F}$, where L_C is defined by:

$$L_\mathrm{C} = \sum_{i=t}^{t+n} u_i \mathrm{d}t \tag{17}$$

Thus, having estimated the value of max$n$, the longest flushing time is given by $\mathrm{TF_{MAX}} = \max n\mathrm{d}t$, where d$t$ is the time interval between consecutive recordings. The dimensioning current is then taken as $U_\mathrm{MIN} = W_\mathrm{F}/\mathrm{TF_{MAX}}$ (see Eq. (11)). Since available records usually cover only shorter times, it is quite likely that the longest possible flushing time has not been recorded. Using the distribution of all estimated T_F, we can estimate the probability for even longer flushing times. For safety, we should therefore multiply $\mathrm{TF_{MAX}}$ obtained from a shorter record by a factor >1 for the computations of U_MIN.

In the bottom layer, the dimensioning current U_bent is taken as the minimum mean speed determined from the bottom current record, corrected for zero recordings. Thus, by stepping through the current record, we can estimate U_bent from:

$$U_\mathrm{bent} = \min\left(\frac{1}{k}\sum_{i=t}^{t+k} u_i\right) \tag{18}$$

The summation starts at time t and consists of k values. Here, k is determined by the condition $k\mathrm{d}t$ = maximum period with zero current tolerated by the benthic fauna. Again, due to the finite length of the record, we should multiply U_bent by a safety factor, which, in this, case is <1.

9. Concluding remarks

The model has been used to compute holding capacity, both with regard to the fish in the cages and to the sediment beneath, on a trial basis at a number of sites in Norway. The monitoring programme of the MOM system is tightly coupled to the model, so in each case the result of the monitoring will either verify or fail to support the model simulations. It is recommended that the model be used in conjunction with the monitoring programme.

The sub-models in the MOM model system are based on basic scientific principles and understanding. The model provides a structured and quantified description of significant environmental aspects of fish farming. It thus provides a possibility to rank various effecting factors according to their relative importance and influence and may be used in future research. The model is presented via a PC Windows application with a user-friendly interface and is convenient for use by many types of personnel.

The next phase of this work will be to integrate the local part of the MOM model system presented in this paper with a regional water quality model for inshore water areas which computes effects of the fish farming upon the water quality in the region. For this it needs the output of organic matter and nutrients for the production PROD as computed by the MOM model. In the present case we will use the model 'Fjord environment' (in Norwegian 'Fjordmiljø') that has been in use in Norway for more than a decade (e.g., Aure and Stigebrandt, 1990). An improved version, 'FjordEnv', with extended geographical applicability is now available as a PC Windows programme (Stigebrandt, 2001).

There is still uncertainty regarding some parameters used in the benthic sub-model. However, data from a growing number of sites in the monitoring programme will be used to lower the uncertainty regarding the values of these parameters. Another uncertainty in the results of the model computations arises from the lack of field data from the sites where the model has been employed. In this case, better field data should diminish the uncertainty. Yet, another area of uncertainty concerns environmental effects not yet included in the MOM model system. These might be environmental effects that will only show up on longer time scales. However, due to its modular construction, the MOM model system can rather easily be extended to handle potential new environmental effects.

Appendix A. List of symbols

A_F	Total area of the net pens in the farm (m^2)
B_M	Total biomass of fish in the farm (kg)
D	Depth of the net pens (m)
DNH_4	Model computed mean ammonium production per kg fish production
DO_2	Model computed mean oxygen consumption per kg fish production
dt	Time interval between consecutive current records
F_{1feed}	Spatial and time mean flux of excess feed from the pens (kg m^{-2} day^{-1})
$F_{1faeces}$	Spatial and time mean flux of faeces from the pens (kg m^{-2} day^{-1})
F_{1C}	Spatial and time mean flux of carbon from the pens (kg C m^{-2} day^{-1})
F_2	Spatial and time mean flux of organic matter at the seabed (kg m^{-2} day^{-1})
$F_2(r)$	Spatial and time mean flux of organic matter at the seabed, r metres from the vertically projected pen centre (kg m^{-2} day^{-1})
F_{2Cmax}	Maximum carbon flux to the sediment under the farm (kg C m^{-2} day^{-1})
F_c	Carbohydrate content of feed by weight
FCR_t	Theoretical feed conversion ratio
FCR	Factual feed conversion ratio
Feed1	Type of feed specified in the legend of Table 1

Feed2	Type of feed specified in the legend of Table 1
F_f	Fat content of feed by weight
F_p	Protein content of feed by weight
G_max	Growth rate of individual fish (kg day^{-1})
H	Distance between the bottom of a pen and the seabed (m)
L	Side length of net pens (m)
L_C	Minimum distance travelled by the recorded flushing current in the time maxndt (m)
L_F	Length of the farm (m)
M	Number of registration in a current record
max$n$	Number of consecutive current records to compute L_C
$\mathrm{N_F}$	Number of net pens in the farm
$\mathrm{NH_{4MAX}}$	Critical value of the ammonium concentration (kg m^{-3})
$\mathrm{NH_{4IN}}$	Ammonium concentration of the water flowing into the pens of a fish farm (kg m^{-3})
$O_{2\mathrm{IN}}$	Oxygen concentration of water flowing into the pens of a fish farm (kg m^{-3})
$O_{2\mathrm{OUT}}$	Oxygen concentration of water flowing out from the pens of a fish farm (kg m^{-3})
$O_{2\mathrm{i}}$	Oxygen concentration just above the turbulent benthic boundary layer
$O_{2\mathrm{bent}}$	Oxygen concentration at the sediment surface
$O_{2\mathrm{min}}$	Lowest oxygen concentration allowing benthic infauna to survive
$O_{2\mathrm{SAT}}$	Saturation oxygen concentration according to Weiss (1970)
OX1	Estimated oxygen consumption by the fish in a farm (kg s^{-1})
OX2	Estimated oxygen consumption by the fish in a farm (kg s^{-1})
P_F	Permeability (porosity) of a fish farm
P_f	Fat content of fish by weight
P_p	Protein content of fish by weight
PROD	Holding capacity of a location (kg yr^{-1})
r	Distance from the vertically projected pen centre (m)
R	Number of rows of pens in the farm
S	Separation (distance) between net pens in the farm (m)
T	Sinking time of particles (s)
T_F	Flushing time of the pens in a fish farm (s)
$\mathrm{TF_{MAX}}$	Maximum flushing time of the pens in a fish farm (s)
T_P	Total fish production (kg yr^{-1})
$\mathrm{TPF_{bentam}}$	Largest fish production (kg yr^{-1}) that does not lead to extinction of the benthic infauna
$\mathrm{TPF_{O_2}}$	Largest fish production (kg yr^{-1}) that keeps the oxygen concentration above $O_{2\mathrm{MIN}}$
$\mathrm{TPF_{NH_4}}$	Largest fish production (kg yr^{-1}) that keeps the ammonium concentration below NH
U_bent	Horizontal current speed just above the turbulent benthic boundary layer
U_MIN	Minimum mean current estimated from observations
u_i	The ith current registration in a record (m s^{-1})
u_0	The mean current speed of a record (m s^{-1})
W	Weight of individual fish (kg)
W_F	Width of the farm (m)
α	Fraction of particulate organic waste oxidised within the farm area
η	Oxygen to Carbon ratio at oxidation of organic matter
β	Coefficient of oxygen transfer across the turbulent benthic boundary layer
σ	Standard deviation of the current (m s^{-1})
σ^2	Variance of the current (m^2 s^{-2})
$\mu(r)$	Dispersion function ($1 \geq \mu(r) \geq 0$)
μ_feed	Dispersion function for excess feed
μ_faeces	Dispersion function for faeces

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