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Regulating the local environmental impact of intensive marine fish farming I. The concept of the MOM system (Modelling–Ongrowing fish farms–Monitoring)

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Abstract

The paper describes the concept of a management system called MOM (Modelling–Ongrowing fish farms–Monitoring) which may be used to adjust the local environmental impact of marine fish farms to the holding capacity of the sites. The concept is based on integrating the elements of environmental impact assessment, monitoring of impact and environmental quality standards (EQS) into one system. The amount of monitoring is dependent on the level of the environmental impact. Two terms are introduced: (1) the degree of exploitation, which is an expression of how much the site is being utilised, and (2) the level of monitoring, which determines the amount of monitoring depending on the environmental impact. For Norwegian conditions, a monitoring programme, including EQS, has been developed concerning the impact on the sediment under fish farms. It consists of three types of investigations of increasing elaboration and accuracy. A model, which simulates the environmental impact on a site given information about the farm's size and production and the hydrodynamic conditions and topography of the site, has been developed but not yet tested. The model and the monitoring programme with EQS are only briefly described, but will be published later. The MOM system should help to maintain satisfactory environmental

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conditions in and around fish farms and may be a valuable tool in site selection and coastal zone management.

Keywords: Fish farming; Environmental impact; Regulation system; Modelling; Monitoring

1. Introduction

In the past 15 years, there has been a substantial increase in the intensive cultivation of marine species for human consumption, especially in Western countries. During the same period, an increased awareness of the consequences of interaction between intensive fish farming and the environment has emerged (Iwama, 1991). Furthermore, growing numbers of users have competed in the coastal zone, revealing the need for regulation of the individual activities through coastal zone management.

Some of the major environmental consequences that have been recognised with regard to marine fish farming are the effects of effluents on the surrounding marine areas (Braaten et al., 1983; Gowen and Bradbury, 1987). Over the years, research has revealed the type and extent of this environmental impact. The measurable effect on the water phase has mostly been small except in eutrophic areas or in shallow or confined waterbodies (Muller-Haeckel, 1986; Gowen et al., 1988; Iwama, 1991). In many areas, the impact has turned out to be primarily benthic due to the sedimentation of food particles and faecal pellets under and around fish farms (Muller-Haeckel, 1986; Weston, 1986; Aure et al., 1988; Holmer, 1991; Wildish et al., 1993; Wu et al., 1994). The most important benthic impacts include anoxic sediments (Blackburn et al., 1988; Hall et al., 1990; Holmer and Kristensen, 1992, 1996; Hargrave et al., 1993; Wu et al., 1994), impoverished infauna communities or azoic sediments (Brown et al., 1987; Weston, 1990; Tsutsumi et al., 1991), outgassing of methane and hydrogen sulphide (Samuelsen et al., 1988; Wildish et al., 1990a; Hargrave et al., 1993), and long-term residence of fish pathogenic bacteria in the sediment (Enger et al., 1989; Husevåg et al., 1991). When antibacterial agents are provided as medicated feed, they may accumulate in the sediment and lead to the development of resistant bacteria (Samuelsen et al., 1992; Coyne et al., 1994; Kerry et al., 1994).

Monitoring programmes have been designed and applied in various countries to keep the impact under surveillance (Lumb and Fowler, 1989; Wildish et al., 1990b; O'Connor et al., 1991; Rosenthal et al., 1993; Henderson and Ross, 1995). Simulation models have also been developed to predict the dispersion of organic particles from marine fish farms and the effects of effluents on regional water resources (Gowen et al., 1989; Aure and Stigebrandt, 1990; Wallin and Håkanson, 1991; Silvert, 1992). However, to prevent over-exploitation of sites and coastal areas and to optimise the utilisation of the coastal resources, systems that integrate modelling and monitoring and which apply to a set of environmental quality standards (EQS) are needed.

This paper presents a management system called MOM which may be used to adjust the local environmental impact of marine fish farms to the holding capacity of sites. The general concept and the use of the system is described. The model and the monitoring programme with the EQS are briefly described and will be presented in detail separately in subsequent papers.

2. The MOM concept

The concept is based on the appreciation that marine areas are more or less sensitive to effluents from fish farms and therefore have different capacities for fish production. The MOM concept is based on the integration of environmental impact assessment, impact monitoring and EQS a single system, where the amount of monitoring carried out depends on the degree of the environmental impact. The MOM concept is general, and various models and monitoring programmes may be applied in order to accommodate the specific environmental concerns in different countries.

The elements and terms employed in the theoretical concept of MOM are described in Table 1. The environmental assessment will be made preferably by a model and must predict the main environmental impact of the fish farm on the site. This prediction will later be confirmed or contradicted by the monitoring. The EQS sets a limit for maximum allowable impact and preferably makes it possible to distinguish between different impact levels. The degree of exploitation is an expression of the amount of impact compared with the holding capacity of the site. The holding capacity has been defined by ICES as the maximum production limited by a non-trophic resource (Rosenthal et al., 1987). If the impact of the production on a farm is close to the holding capacity of the site, the degree of exploitation is high, whereas the degree of exploitation is low if the impact is small relative to the holding capacity. The degree of exploitation may be divided into two or more categories and is linked to the level of monitoring which determines the monitoring frequency. The higher the degree of exploitation, the higher the level of monitoring, resulting in more frequent and more elaborate monitoring.

Fig. 1 shows the use of MOM. For planned fish farms, a model may be used to determine a preliminary degree of exploitation. For fish farms in operation, a monitoring investigation is performed and, provided EQS has been set which can discriminate between different levels of impact, a degree of exploitation can be determined. The level of monitoring then follows directly. Future monitoring may give results which imply

Table 1
Description of the elements and terms employed in MOM

	Description
Model	A mathematical description of the relationship between the amount and type of material released from a fish farm and its impact on the site.
Monitoring programme	Routine measurements of standard variables that describe the impact of a fish farm on its surroundings. Consists of different types of investigations of increasing elaboration and accuracy.
EQS	A group of threshold values for the variables in the monitoring programme and the model. Values above the upper threshold exceed the holding capacity.
Degree of exploitation	The relationship between the impact of the fish farm and the holding capacity of the site. The site is overexploited when the holding capacity is exceeded.
Level of monitoring	The frequency of performing the investigations of the monitoring programme. For every degree of exploitation there is a level of monitoring.

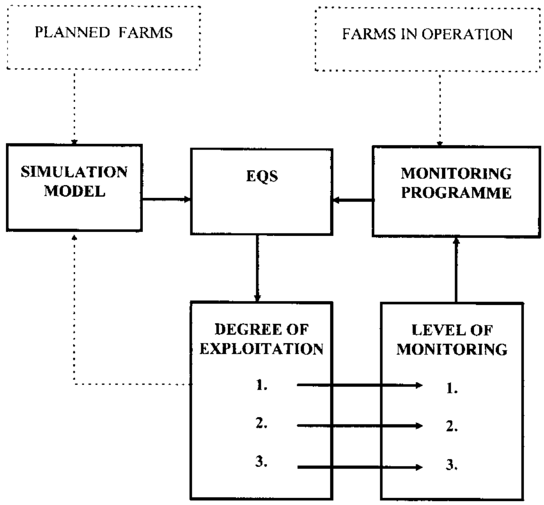

Fig. 1. An overview of the use of the elements and terms of the MOM system. For planned fish farms, a model may be used, and for fish farms in operation, a monitoring investigation is performed to determine the initial degree of exploitation. The level of monitoring follows automatically and through future monitoring, the degree of exploitation can be corrected.

another level of impact, and the degree of exploitation is automatically changed so it is in accordance with how close the impact is to the holding capacity.

MOM has been designed so it can accommodate both changes in environmental assessment and new developments in the industry. The monitoring programme can be altered or substituted by new investigations if these prove to be more adequate. The EQS may be changed in accordance with increasing information on environmental effects. The system may also be adapted to include new species, techniques and legislation.

2.1. Impact zones

The zone of impact around a fish farm and the amplitude of its effects will depend on the natural conditions at the site and the size and management of the farm. In the MOM system, we distinguish between three impact zones with regard to fish farm effluents: (1) local, (2) intermediate and (3) regional. The local impact zone is the area within which most of the food pellets settle mainly under and close to the fish farm. The intermediate impact zone is the main area of sedimentation of smaller organic particles such as faecal pellets, and of deposition of resuspended matter from the local impact zone. The regional impact zone consists of adjacent fjords and water bodies which are mainly influenced by nutrients from the fish farm, although in the case of accumulation areas, they may also be affected by organic particles.

3. The MOM system

The monitoring programme with EQS and the model presented below were made to meet the national environmental quality objectives for Norwegian fish farming (Anonymous, 1993). Since the main impact of organic waste in Norway is benthic, a more specific environmental quality objective is to prevent an accumulation of organic matter in the sediment that will lead to the extinction of the benthic infauna. For the MOM system, we have therefore defined the holding capacity as the maximum fish production that will allow a viable macrofauna in the sediment under the farm. When the sediment becomes azoic, the holding capacity is judged to have been exceeded.

3.1. The monitoring programme and EQS

The monitoring programme consists of three types of investigations (A, B and C) of increasing elaboration and accuracy, each of which is carried out at every level of monitoring, but at different frequencies. This allows for less extensive monitoring of sites with a low degree of exploitation compared to sites with a high degree of exploitation.

The A-investigation monitors the organic output from the farm by sampling particles in a sediment trap under the farm. The sediment trap, a plastic cylinder with a L/D ratio of 6, is emptied twice a month. This investigation is relatively easy to carry out, but its usefulness is limited by the degree of uncertainty. With repeated measurements over a period of time, however, it may provide information about the extent of sedimentation under the farm and some information about overfeeding. Environmental standards are not used in the A-investigation. The A-investigation is planned to form a part of the internal control of marine fish farms supervised by the Norwegian local authorities.

The B-investigation will be the core of the monitoring programme since it is inexpensive and simple to perform, and therefore suitable for frequent use. The investigation should offer the authorities and the fish farmer a qualitative impression and some quantitative information on the benthic impact on the site. Sediment is collected by core sampler or by a small grab, and three groups of sediment variables are investigated.

First, there is detection of macrofauna in the sediment by sieving the sediment through a 1-mm sieve. This investigation merely distinguishes between acceptable and unacceptable sediment conditions.

Second, a measurement of pH and redox-potential in the top 8 cm of the sediment is performed. This part of the investigation is based on the results of pH and redox-potential measurements in sediments under Norwegian fish farms (Dragsund and Schaanning, 1993; Schaanning, 1994). The results of the measurements are placed on a pH/Eh diagram which is divided into five categories and given scores, thereby allowing the pH and redox-potential measurements to be compared directly with other sediment variables. The first three categories each corresponds to a degree of exploitation, and the values in the fourth category are considered to describe unacceptable sediment conditions.

Third, a group of qualitative sediment variables such as thickness of accumulated organic material, smell, colour, consistency and gas bubbles are assessed. A score system has been developed, by which these qualitative variables may be quantified. The scores for the individual variables are added, and the resulting number will fall into one of four categories. The fourth category represents unacceptable sediment conditions and should correspond with absence of macrofauna and category four for pH and redox-potential measurements.

The results from the three groups of variables are finally combined and the degree of exploitation of the site is determined in accordance with a set of EQS. If the categories found for the different groups do not correspond, pH and redox-potential measurements take precedence over the third group of variables since the former are quantitative. The B-investigation will be used primarily in sediment under fish farms, e.g., in the local impact zone.

The C-investigation is a benthic macrofauna community study based on fauna investigations of organically enriched sediments (Pearson and Rosenberg, 1978; Pearson et al., 1983; Gray et al., 1992). This investigation monitors long-term environmental changes in the sediment in a transect from the local impact zone into the intermediate impact zone and in accumulation areas in the regional impact zone. The C-investigation is performed more rarely than the B-investigation for all degrees of investigation. The EQS used for the C-investigation is a modified version of "Classification of environmental quality standards in fjords and coastal water" made by the Norwegian State Pollution Control Authority (Rygg and Thélin, 1993).

The monitoring programme and the EQS will be reviewed and evaluated regularly and the results of the monitoring will be sampled and compared in a national database.

3.2. The simulation model

The model is intended as a planning tool both for farms already in operation and for new farms. The task of the model is two-fold: (1) to simulate the environmental impact of a fish farm on a given site, and (2) to determine farming procedures which will prevent the impact from exceeding the EQS. The most important use of the model will probably be in determining relative differences between sites or between various arrangements of net cages in farms. The model consists of five sub-models, two of which existed before the development of MOM started.

The *fish sub-model* simulates the emission of dissolved and particulate material from the farm. From information on the feeding rate and composition of food, uptake, retention and excretion are calculated in relation to the temperature and the size of the fish. This sub-model, which is essentially based on the long-used model developed by Stigebrandt (1986), provides the boundary conditions for the dispersion sub-model and the sub-model that computes water quality in the net cages.

The *dispersion sub-model* simulates dispersion and sedimentation rates of excess feed and faecal pellets. From the current variability, expressed as the standard deviation, and the estimated sinking time for the organic waste, the model calculates how waste from a single net cage spreads over the bottom. According to the model, the fraction of organic waste deposited under the individual net cages will fall if the area of the cage is reduced. The organic waste deposition beneath a fish farm is computed as the sum of the contributions from all the cages. The maximum deposition under the fish farm decreases with increasing distance between the cages and if the number of rows of cages is reduced.

The *sediment sub-model* simulates the maximum organic deposition on the sediment which will allow a viable benthic infauna. In the model, the maximum decomposition rate of the deposited organic material will depend on the current velocity above the sediment and the difference between the oxygen concentration in the turbulent boundary layer immediately above the sediment surface, which is critical for the benthic fauna, and the oxygen concentration in the water column.

By combining the dispersion and sediment sub-models, one may calculate the maximum fish production that a site can sustain without the benthic infauna disappearing due to oxygen deficit. The dispersion and sediment sub-models were developed specially for MOM and described in detail by Stigebrandt and Aure (1995) and have not yet been tested.

Two *water quality sub-models* exist: (1) for water quality in the net cages, and (2) for water quality in the recipient. Sub-model 1 is an extension of the fish sub-model and calculates oxygen and ammonia concentrations in the net cages on the basis of simulations made using the fish sub-model. Sub-model 2 was developed for fjords and threshold areas by Aure and Stigebrandt (1990). This model simulates changes in Secchi depth and oxygen concentrations in basins in the regional impact zone due to nutrients and organic particles from various sources including fish farms in relation to hydrographic and topographical factors, in the regional impact zone. The model is currently being used by Norwegian authorities and research institutes.

4. The application of MOM

To prevent unacceptable conditions in the sediments under the fish farms, the right combination of site characteristics, production scheme and farm management must be found. Here, the model may be a valuable tool in the future by simulating the outcome of various scenarios. The monitoring programme and the EQS will ensure that the actual farming activity does not exceed the capacity of the site. As a result, a decrease in the stocking density, a more careful distribution of feed, or the selection of a site with a stronger current or a greater depth may be necessary. All of these may have a positive effect on the water quality.

MOM operates primarily at site level but may be linked to more comprehensive management systems which operate at higher geographic levels concerning the coastal zone and involving different activities. In Norway, a system called LENKA was developed to estimate the potential for both freshwater and marine aquaculture (Kryvi et al., 1991). The aim was to identify areas suitable for aquaculture and to avoid conflicts with other users. As a result of the LENKA project, the model for calculating the effect of fish farms on the regional impact zone, which is now a part of the MOM model (Aure and Stigebrandt, 1990), was developed. In many coastal regions, the major problem is not necessarily environmental impact but rather competition for space in relation to other users of the area which limits the number of fish farm sites. By coupling MOM and LENKA, it may be possible to make full use of existing sites.

Other types of environmental impacts such as genetic interference of escaped farmed fish with wild stocks, attacks of sea lice and impact of chemicals or spreading of antifouling compounds are not addressed by MOM. However, with regard to residues of antibacterial agents and other drugs found in the organic waste from the farm, these can easily be incorporated into the monitoring programme. Preliminary attempts are also being made to model the impact of antibacterial agents on bacteria in the sediment. Outbreaks and the spread of diseases are not directly addressed by MOM. However, since the MOM system safeguards good rearing conditions as such, this might limit the risk of outbreaks of disease.

Preventing over-exploitation of sites and adjacent areas and ensuring of good rearing conditions for the fish are important for the production of high quality seafood. In the future, consumers may demand documentation of both the environmental consequences of production, the quality of the fish and their physical rearing conditions. The MOM system offers an opportunity to provide such documentation.

The MOM system is planned to be gradually implemented by the Norwegian authorities from 1998.

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