Regulating the local environmental impact of intensive, marine fish farming

II. The monitoring programme of the MOM system [Modelling–Ongrowing fish farms–Monitoring]

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Abstract

A programme for monitoring the impact of organic waste from marine fish farms is presented. It consists of three types of investigation of increasing complexity and accuracy (A, B and C), which are applied more frequently with increasing environmental impact. The A-investigation is a simple measurement of sedimentation rate beneath the net cages; the B-investigation is a sediment investigation providing a trend monitoring of the sediment condition, and the C-investigation is a comprehensive investigation of the benthic macrofaunal community structure. The A- and B-investigations were designed specifically for fish farming and the latter utilises several parameters in order to make the investigation more robust. The C-investigation employs well-established methods and procedures, which have been used previously in monitoring programmes. Environmental quality standards (EQS) have been set for the B- and C-investigation. The monitoring programme is part of a larger management system in Norway called Modelling–Ongrowing fish farms–Monitoring (MOM). © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Fish farming; Environmental impact; Monitoring; Organic material; Sediment

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1. Introduction

Intensive marine fish farming has a high production per unit area and large fish farms generate large amounts of particulate organic waste, as well as soluble-inorganic excretory waste (Ackefors and Enell, 1994; Einen et al., 1995). Depending on the quantity and composition of the effluents and the susceptibility of the receiving environment, these emissions may have various, and sometimes severe, ecological impacts. They may also influence other coastal zone activities, including negative feedback on the aquaculture activity itself (e.g. Lumb, 1989; Iwama, 1991; Black et al., 1996).

Monitoring investigations of various degrees of complexity have been employed in order to minimise the harmful effects of aquaculture activities (e.g. O’Connor et al., 1991; Hensey, 1992; Henderson and Ross, 1995; Wildish et al., 1999). Reviews of monitoring strategies and methods revealed the need for standardised approaches, which are flexible enough to cover the wide range of environments in which fish farms are located (Cochrane et al., 1994; Codling et al., 1995).

To properly manage the scale of enrichment from fish farming and to ensure that the ecological change does not exceed predetermined levels, monitoring should be regarded as a component of a larger management framework. This should include a system of environmental quality objectives (EQO) and standards (EQS), as well as the means of environmental impact assessment (GESAMP, 1996). Furthermore, guidelines for appropriate actions if the EQS are breached should also be included.

Manuals for procedures and management plans have been developed in Scotland (Mackay, 1998) and in Canada (Anonymous, 1995). In Norway, a management system called Modelling–Ongrowing fish farms–Monitoring (MOM) has been developed to safeguard the long-term use of fish farm sites. The system concentrates on organic enrichment. The concept and the structure of the MOM system have been presented by Ervik et al. (1997). In this paper, we present the monitoring programme and the results of a field trial.

2. Environmental effects

The monitoring of environmental impact of aquaculture is “the regular collection, generally under regulatory mandate, of biological, chemical or physical data from predetermined locations such that ecological changes attributable to aquaculture wastes can be quantified and evaluated” (GESAMP, 1996).

We have applied four criteria in selecting the environmental impact on which to place most emphasis: (1) The impact must have significance for both the natural environment and for the condition of the farmed fish. (2) The impact must be amenable for monitoring. This implies that it must provide a clear signal that can be distinguished from background levels and that the impact should be integrated over time. As the objective of the monitoring is to evaluate and limit biological changes, biological parameters are normally preferable to chemical ones (GESAMP, 1996). (3) Sufficient knowledge must be available to establish adequate EQS. (4) The monitoring must be
cost-effective and convenient to perform by routine methods. The advantage of frequent investigations must be balanced against the scientific benefits of more advanced methods.

2.1. Fish farm discharges and benthic impact

Fish farms generate orthophosphate and nitrogenous nutrients and high concentrations have been observed in adjacent surface waters. However, concentrations decline rapidly with distance from the net cages as a result of dilution and assimilation in phytoplankton or algae growing on net cages and installations (e.g. Aure et al., 1988; Hensey, 1992; Wildish et al., 1993). Widespread surface eutrophication has not been reported in Norway (Skjoldal et al., 1997).

Carbon flux to the seabed below the net cages may be several orders of magnitude higher than natural fluxes in adjacent waters (Gowen et al., 1988; Hall et al., 1990; Samuelsen et al., 1992; Findlay et al., 1995). Increased loads of organic material to the sediment shift decomposition processes from aerobic to anaerobic, and sulphate reduction may predominate (Holmer and Christensen, 1992). Typical features of such sediments are substantially lowered redox potentials and the presence of hydrogen sulphide in the pore waters, mats of sulphide-oxidising bacteria and severe disturbance of the macrobenthic community (e.g. Lumb and Fowler, 1989; Hargrave et al., 1993; Brown et al., 1987). In sediments with severe organic enrichment, methanogenic bacteria proliferate causing gas ebullition (Martens and Val Klump, 1984; Lumb and Fowler, 1989) and a lowering of pH (Schaanning, 1994). Analyses of gas released from such sediments have shown it to consist of methane with up to 1800 ppm of hydrogen sulphide (Samuelsen et al., 1988).

Benthic impact is relevant with regard to both the environment and, depending on the depth of water under the farm, the condition of the fish. Furthermore, since effects are integrated over time, they are convenient for monitoring and the impact can be measured by cost-effective routine methods. In many cases, information on changes in the sediment due to sediment organic enrichment is sufficient to allow decisions regarding reasonable EQS values to be made.

The monitoring system of MOM puts the main emphasis on benthic impact. The monitoring focuses on the area close to the fish farm, where the impact is most pronounced, but it also covers a gradient from the farm into the surrounding environment. Vulnerable sedimentation areas are given special attention.

We have defined the holding capacity of a fish farm site as the maximum fish production that allows a viable macrofauna to be maintained in the sediment. At site level, there are no criteria attached to the faunal community in terms of abundance, number of species or species composition; the only requirement is that macrofauna be present in the sediment. In the surrounding environment, however, less impact is tolerated and the benthic infauna community structure is evaluated using general environmental quality standards set by the Norwegian Pollution Control Authority (see Table 1).

Water column parameters receive little attention in the monitoring programme at the present. However, where deep basins with shallow sills occur in the surrounding
Table 1
Classification of soft bottom fauna in Norwegian fjords and coastal waters (after Molvær et al., 1997)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(I) Very good</td>
</tr>
<tr>
<td>Hurlbert’s index ($ESn = 100$)</td>
<td>&gt; 26</td>
</tr>
<tr>
<td>Shannon–Wiener index (H)</td>
<td>&gt; 4</td>
</tr>
</tbody>
</table>

In the environment, the oxygen concentration of the basin water is monitored. The oxygen concentration in net cages has a direct impact on the well-being of the fish and fish farmers are advised to monitor oxygen separately. Water column parameters may be included in the monitoring programme where appropriate.

3. The monitoring programme

3.1. General design

The monitoring programme consists of three types of investigations (A, B and C), which include a number of variables, providing flexibility and robustness. The A-, B- and C-investigations are of increasing complexity and accuracy and they are performed more frequently as the degree of environmental impact increases. In order to accomplish this, two terms are employed: the degree of exploitation and the level of monitoring. The degree of exploitation is an expression of the amount of impact from the fish farm compared with the holding capacity of the site. The site is overexploited if the holding capacity is exceeded. We distinguish between three rising degrees of exploitation (1, 2 and 3), with three corresponding levels of monitoring, where the investigations are performed at specific frequencies. Thus, the frequency of monitoring depends on the degree of environmental impact. For the A- and B-investigations, the frequencies of monitoring are shown in Table 2. The local environmental authorities will decide the frequency of performing the C-investigation.

Standard procedures have been used wherever possible and other procedures are currently being standardised through the Norwegian General Standardizing Body (NAS).

Table 2
The relationship between the degree of exploitation (DEX) of the site, the level of monitoring (LOM) and the frequency of performing the A- and B-investigations

<table>
<thead>
<tr>
<th>Type of investigation</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEX 1 →</td>
<td>LOM 1</td>
<td>every 3rd month</td>
</tr>
<tr>
<td>DEX 2 →</td>
<td>LOM 2</td>
<td>every 2nd month</td>
</tr>
<tr>
<td>DEX 3 →</td>
<td>LOM 3</td>
<td>every month</td>
</tr>
</tbody>
</table>
3.2. Impact zones

The various emissions from fish farms have different potential for dispersing and influencing the water column and the seabed and various zones of impact around fish farms have been identified (Silvert, 1992; Henderson and Ross, 1995). In MOM, three zones of environmental impact are recognised: the local, the intermediate and the regional. Each zone is characterised by an area of influence and type of impact and each has been assigned monitoring investigations (Table 3). A higher degree of impact is tolerated in the local impact zone than in the intermediate and the regional impact zones and this is reflected in the EQS. Therefore, the investigation performed in the regional impact zone is more comprehensive since it must be able to detect more subtle changes in the environment than the investigation in the local impact zone.

3.3. The A-investigation

This investigation is a simple measurement of the rate of sedimentation of organic material below the fish farm. It provides the fish farmer with immediate information regarding the load beneath the net cages in order to avoid overloading the site. The sedimentation rate is a function of the amount of organic solid waste, as well as of the current and depth and may vary considerably with the feeding strategy.

The sedimentation rate is measured by deploying two sediment traps 2 m above the seabed at the periphery of the net cages that either contain the most fish, receive the largest amounts of feed or where the B-investigation has revealed heavy impact. Collection lasts for 2 weeks and the frequency of collection at the different levels of monitoring is shown in Table 2.

The A-investigation is performed by each fish farmer as a part of their internal control routines. The investigation is meant to provide a time series of the sedimentation and no EQS has been defined. The interpretation of the results will be based on previous measurements and compared with the results of the B-investigation. The variation in sedimentation rates must be seen in relation to the amounts of feed used and fish produced.

3.4. The B-investigation

The B-investigation is performed in the local impact zone and combines three groups of parameters. It is inexpensive and easy to perform and should be carried out frequently in cases where the impact is severe (cf. Table 2).

For sampling purposes, the local impact zone is considered to be the area covered by the net pens and the area between them. Ten sampling stations are distributed evenly in this area to cover the various sediment conditions. If single net cages are used, at least one sample is taken close to every cage and one between every two cages. If the result of the investigation shows unacceptable conditions, the number of samples may be increased to verify the result. The final result of the B-investigation is the average sediment condition at the site, but the results obtained from the individual samples show the variation of sediment conditions within the site. Control stations are not used in the
<table>
<thead>
<tr>
<th>Definition</th>
<th>Local impact zone</th>
<th>Intermediate impact zone</th>
<th>Regional impact zone</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
<td>Area beneath and close to the farm, where larger particles (waste feed) settle. The extent of the zone depends on the layout of the fish farm, the current regime and the depth under the farm, and will usually extend from 5 to 15 m from the farm.</td>
<td>Area beyond the Local impact zone, where smaller particles (finely divided waste feed and faeces) and resuspended matter from the sediment settle. The extent of the zone varies with depth, current and seabed topography, but will usually not extend more than 100–150 m beyond the local impact zone.</td>
<td>Area beyond the intermediate impact zone to where dissolved substances from the fish farm may be transported.</td>
</tr>
<tr>
<td><strong>Source of impact</strong></td>
<td>Environmental impact is dominated by the fish farm activity.</td>
<td>The fish farm activity is the major source of impact, but other activities may be of importance.</td>
<td>Fish farms are among several sources of impact.</td>
</tr>
<tr>
<td><strong>Potential impact</strong></td>
<td>Major chemical and biological changes in the sediment, reduced oxygen content and elevated nutrient levels in the water.</td>
<td>Some changes in chemical and biological conditions in the sediment. Hypernutrification.</td>
<td>Increased primary production and increased oxygen consumption in deep water. The impact depends on the nature of the recipient.</td>
</tr>
<tr>
<td><strong>Monitoring</strong></td>
<td>Primarily the A- and B-investigations.</td>
<td>Primarily the C-investigation.</td>
<td>The C-investigation, in addition to general coastal monitoring.</td>
</tr>
<tr>
<td><strong>EQS</strong></td>
<td>A-investigation: none. B-investigation: this publication.</td>
<td>“Classification of environmental quality of fjords and coastal waters” (Molvær et al., 1997).</td>
<td>“Classification of environmental quality of fjords and coastal waters” (Molvær et al., 1997).</td>
</tr>
</tbody>
</table>
B-investigation, since it is considered more important to determine the sediment condition at the site in relation to the threshold for unacceptable sediment conditions. The sampling is performed using light equipment operated from the net cage floats or from small craft. Samples are collected by a small gravity core sampler with transparent corers or a modified van Veen grab (> 200 cm$^2$). A portable winch is used at deep stations.

The three groups of parameters used in the B-investigation are: biological parameters (macro-infauna) (Group 1), chemical parameters (pH and redox potential) (Group 2) and sensory parameters (Group 3). The use of several parameters makes the evaluation more robust and the results are less sensitive to variation in any one parameter. EQS values have been established for each group, rather than for individual parameters. Four categories of environmental conditions have been defined, in which category four is equivalent to unacceptable sediment conditions. The Group 1 parameter is only used to distinguish between acceptable and unacceptable sediment conditions, whereas Groups 2 and 3 parameters are also used to distinguish between different categories of acceptable sediment conditions. A scoring system has been developed for the three groups of parameters and the lower the score the better the environmental condition. No laboratory work is required for the B-investigation, and the results can be presented to the fish farmer immediately after the investigation has been carried out.

3.4.1. Group 1 parameter

The Group 1 parameter is a determination of whether the sediment contains a macro-infauna and is directly linked to the environmental quality objective, which states that a viable macro-infauna must be present under the fish farm.

The sediment is sieved through a 1-mm mesh sieve and the presence of animals yields a score of 0 and the absence a score of 1 (Fig. 1). If a sample contains little sediment, fauna may not have been collected even if the bottom condition is good. This is often the case where there is hard bottom with little accumulation of fish farm waste. The condition of such a sample may still be acceptable if the results of the other two groups of parameters show either conditions 1, 2 or 3. If a full sample does not contain fauna, the sediment condition is unacceptable, which will also be revealed by the other two groups of parameters. Since fauna cannot always be expected to be found even if the sediment is not impacted, it is accepted that not all samples at a site contain fauna. If the mean score of all the samples taken at a given site is $\leq 0.5$, the sediment condition is 1, 2 or 3, which are all acceptable. If the mean score is $> 0.5$, the condition of the sediment is considered unacceptable (condition 4) according to the Group 1 parameter.

3.4.2. Group 2 parameters

The Group 2 parameters are based on direct measurements of pH and redox potential by electrodes inserted in the sediment immediately after sampling in transparent corers (Hansen et al., 1997). Changes in these parameters are largely controlled by three major decomposition processes in marine sediments: oxygen respiration, sulphate reduction and methane production (Zehnder and Stumm, 1988). Redox potential has been a common parameter for the description of oxygen deficiency in organically enriched
### Sample Level

Parameters to be measured or observed in each core or grab sample

- **Group 1 parameter**
  - Fauna

- **Group 2 parameters**
  - pH
  - Redox potential

- **Group 3 parameters**
  - Gas
  - Colour
  - Odour
  - Thickness of sludge
  - Consistency

### Allocation of scores to the measurements or observations in each core or grab sample

- **Score**
  - 1 (fauna absent)
  - 0 (fauna present)

### Site Level

The mean score of all samples determines the environmental condition of the sediment according to each group of parameters

- **Condition**
  - mean score ≤ 0.5: condition 1, 2 or 3
  - mean score > 0.5: condition 4*

### Determination of the environmental condition of the sediment on the site

- **Condition**
  - mean score ≤ 1: condition 1
  - 1 < mean score ≤ 2: condition 2
  - 2 < mean score ≤ 3: condition 3
  - mean score > 3: condition 4*

- **Condition**
  - mean score < 4: condition 1
  - 4 ≤ mean score < 10: condition 2
  - 10 ≤ mean score < 14: condition 3
  - mean score ≥ 14: condition 4*

Sediment condition on the site = condition given by the three groups of parameters

If conditions determined by groups 1, 2 and 3 differ see procedure in the text

* Condition 4 is equivalent to unacceptable sediment conditions

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Fig. 1. An outline of the procedure to determine the environmental condition of the sediment at a fish farm site based on at least 10 samples taken by grab or core.
sediments (Bagander and Niemistö, 1978; Pearson and Stanley, 1979). It has also been used to assess environmental impacts of fish farms and for developing benthic enrichment index, although it may be difficult in some sediments to attain stable readings from the electrodes (e.g. Hargrave, 1994; Henderson and Ross, 1995; Hargrave et al., 1997; Wildish et al., 1999). However, when the sediment is severely effected by organic material and it becomes more important to be able to distinguish between sediment conditions, the redox potential usually becomes more stable. pH has been less used in sediment investigations. A pH of 7.0 has been defined as the lower threshold of pH in recent anoxic marine sediments (Ben-Yaakov, 1973), but several observations of sediments at fish farms (Schaanning, 1991, 1994; Schaanning and Dragsund, 1993; Cochrane et al., 1994) and more recent studies (Bahr, personal communication; Jarp, personal communication) have shown that pH may fall below 7.0 in samples that contain gas bubbles. Thus, pH appears to be a reliable parameter for predicting the risk of gas ebullition. The gas consists mostly of methane and carbon dioxide, but it may transfer toxic hydrogen sulphide from the anaerobic sediment into the water (Braaten et al., 1983; Samuelsen et al., 1988; Lumb and Fowler, 1989).

pH and redox potential are measured in the water above the sediment and at 2-cm depth intervals in the core sample. If cores cannot be collected, the electrodes may be inserted directly into the grab sample.

Fig. 2 is based on measurements of pH and redox potential in marine sediment beneath Norwegian fish farms (Schaanning, 1991, 1994; Schaanning and Dragsund, 1993). A score is allocated to the pH and redox potential measured in each sample. The score boundaries in Fig. 2 have been determined on the basis of descriptions of organic enrichment (Pearson and Stanley, 1979; Grey, 1981). The method gives high resolution in heavily enriched sediments where the macrobenthic community is absent or severely disturbed. A score of 0 will correspond to a well-oxygenated environment with low organic input and favourable conditions for the presence of viable benthic communities. Increasing input of organic matter will drive the sediment environment through successive stages of increasing oxygen deficits and corresponding changes in microbial communities (Zehnder and Stumm, 1988). A score of 2 frequently represents an environment with hydrogen sulphide, which gives low redox potentials in the pore water (Bagander and Niemistö, 1978). A score of 5 represents an environment with methane gas in the sediment and low pH values. Scores of 1 or 3 are allocated to transition zones.

If measurements are made at several depths in core samples, the lowest pH and the corresponding redox potential are used to assign scores. This implies that in sediments with a redox discontinuity layer, site assessment will frequently be based on values

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As shown in Schaanning (1991), the stoichiometry of sulphate reduction: \( \text{CH}_4 \cdot \text{O} + 1/2\text{SO}_4^{2-} = \text{HCO}_3^- + 1/2\text{HS}^- + 1/2\text{H}^+ \) shows that buffering by \( \text{HS}^- \) at a pH corresponding to the first dissociation constant of hydrogen sulphide \((\text{pK})\) will prevent the pH from decreasing to values much below 7.0, whereas the stoichiometry of methane production: \( \text{CH}_4 \cdot \text{O} + 1/2\text{H}_2\text{O} = 1/2\text{HCO}_3^- + 1/2\text{CH}_4 + 1/2\text{H}^+ \) shows that this process may drive the pH down to values corresponding to the first dissociation constant \((\text{pK})\) of carbonic acid.
Fig. 2. Investigations by Schaanning (1991, 1994) and Schaanning and Dragsund (1993) showed that measurements of pH and redox potentials in fish farm sediments fell within the boundaries of the hatched area. For use in MOM, the hatched area has been divided into five compartments with increasing scores associated with higher organic input and decreasing values of pH and Eh (Fig. 1).

recorded below this layer. As seen from Fig. 2, this may result in the allocation of a lower score than might have been obtained from data recorded at depths closer to the sediment–water interface. In coarser sediment types on the other hand, sharp redox-clines may be absent or present only below the sampling depth of the light grab or core equipment. Furthermore, in sediments that have recently been enriched with organic material, the redox potential gradient may be inverted, so that the potential increases with increasing depth.

The rationale for using the minimum values is based on the following considerations: (1) The simplicity of the rule. (2) The freedom it provides with regard to sample quality and electrode design. (3) The reduction in the variance resulting from measuring in the steep gradients frequently present within the top few millimeters of the sediments.

The sediment condition of the site according to Group 2 parameters is determined using the mean score of all samples collected within the area investigated, as shown in Fig. 1.

3.4.3. Group 3 parameters

The Group 3 parameters are a number of sensory sediment variables, which change with increasing organic enrichment: sediment colour, odour and consistency, gas ebulbition, and thickness of sludge accumulated on top of the original sediment (Fig. 1).
These parameters provide valuable information about the condition of the sediment and have been included as visual observations in sediment studies and in monitoring (e.g. Hall et al., 1990; Codling et al., 1995; Holmer and Christensen, 1996; Dyer, 1998). However, since most of these parameters are observed rather than measured, they have not previously been regarded as suitable for the development of EQS. The information provided by these parameters has been standardised for use in the B-investigation by assigning numerical values to the sensory variables. The more effected the sediment by organic enrichment, the higher the score allocated to the parameter. Sediment colour is allocated a score of 0 if it is light, grey or brown and 2 if it is black or brown due to organic accumulation. The odour and consistency of the sediment are each allocated scores of 0, 2 or 4 depending on the extent to which the parameter is affected as a result of organic enrichment. Gas bubbles in the sediment are either absent, which registers a score of 0, or present, giving a score of 4. If the gas bubbles are too small to see, the pH measurement will probably indicate that methane is being formed. The thickness of accumulated sludge is measured and allocated a score from 0 to 4. The maximum score of 4 is given where accumulations are more than 8-cm thick. The allocation of scores to the individual variables may entail some subjectivity. Therefore, the variables are not considered individually, but the scores from all Group 3 parameters in one sample are added in order to avoid placing too much emphasis on individual observations. The mean score of a minimum of 10 samples is calculated and the sediment condition falls into one of four categories as shown in Fig. 1. A mean score of zero is equivalent to undisturbed conditions while a mean score higher than 14 defines a sediment condition, which is deemed unacceptable.

3.4.4. Determination of site condition

The environmental condition of the site is expressed by combining the conditions determined by the three groups of parameters. Acceptable sediment conditions according to Group 1 means that the environmental condition of the location is 1, 2 or 3. If Groups 2 and 3 indicate the same sediment conditions, then this is considered the condition of the site. If Groups 2 and 3 indicate different conditions, Group 2 takes precedence over Group 3.

Unacceptable conditions according to Group 1 may be caused by unacceptable sediment conditions or by small sample sizes from hard bottoms with little accumulation of organic matter. In the first case, Groups 2 and 3 will also give unacceptable sediment conditions. In the second case, the condition of the site is determined by Groups 2 and 3. If they differ, Group 2 takes precedence over Group 3.

3.5. The C-investigation

This investigation is a study of the benthic community structure along a transect drawn from the fish farm towards sedimentation areas or sensitive parts of the intermediate and regional impact zones. Three sampling stations are used, one close to the fish farm, one at the deepest area in the surrounding environment and one in between. The benthic infauna is sensitive to organic loading (Pearson and Rosenberg, 1978), and investigation of benthic community structure has been widely used to assess
the effect of organic effluents from fish farms, being considered sensitive enough to
detect more subtle impact (e.g. Weston, 1990; Ritz et al., 1989; Johannessen et al., 1994;
Henderson and Ross, 1995; Findlay et al., 1995). However, the investigation is rather
comprehensive, requires qualified taxonomists and therefore is relatively costly. The
C-investigation is used in the intermediate and regional impact zones where changes in
the sediment condition are expected to be less severe than in the local impact zone and
where less impact is tolerated. It is carried out less frequently than the A- and
B-investigations.

The C-investigation is performed according to the Norwegian Standard for sampling
and investigation of benthic infauna (Anonymous, 1998). A set of general EQS has been
developed by the Norwegian Pollution Control Authority (Molvær et al., 1997) and
these are employed for the intermediate and regional impact zones (Table 1).

4. Field trial of the B-investigation

The B-investigation was tested with regard to training of personnel, practicality of
fieldwork and comparison of the three groups of parameters.

Forty-four fish farm sites in Southern, Western, Mid- and Northern Norway partici-
pated in the field trial. The fish farms were located in depths of water between 30 and
100 m, had productions between 90 and 1330 tonnes/year and had been in operation for
at least 1 year at the time of the field trial.

A total of 218 sediment samples were collected. At the time of the field trial, six
sampling stations were established at each site. However, after the trial, the number of
sampling stations was increased to 10 as described in Section 3.4. Samples were
retrieved generally from all stations, but in some cases this was not possible due to the
nature of the seabed. A recent relocation of Norwegian fish farms from sheltered sites to
more exposed locations has resulted in many sites with hard bottom, rock, gravel or
course sand, which are unsuitable for core sampling and sometimes even for grab
sampling. Core samples could be retrieved at nine sites, although not at all sampling
stations, and a total of 30 cores were collected. The other 35 sites were investigated
using a modified van Veen grab (250 cm²) and 188 samples were collected.

4.1. Comparison of parameters

The results from the three parameter groups were compared in order to determine
whether the scoring system and the consequential determination of the environmental
conditions were appropriate.

Sixteen samples were classified as unacceptable according to Group 2 (pH and Eh)
and Group 3 (sensory) parameters (Fig. 3). Animals were found in more than half of
these samples despite low pH and redox potentials, a strong smell of hydrogen sulphide
and, in some cases, spontaneous gas ebullition. The animals in these samples turned out
to be the polychaete, Malacoceros fuliginosus, a species that is extremely tolerant of
organic enrichment (Costello and Read, 1994). This polychaete appeared to be in the
overlying water or at the sediment surface rather than in the sediment. M. fuliginosus is
commonly found in sediments under fish farms although mostly in sediments less
Fig. 3. The number of samples with fauna (black bars) and without (white bars) in sediment where the environmental condition (see Site Level in Fig. 1) has been determined by Groups 2 and 3 parameters (core samples) or only Group 3 parameters (grab samples).

Fauna was not observed in 23 of the 178 samples taken from sediment classified as acceptable (conditions 1, 2 and 3) by Groups 2 and 3 (Fig. 3). Five of these samples were collected by gravity corer with a small diameter that may not be appropriate for collecting fauna. The others were collected by grab. In some instances, the fauna may have been overlooked, and to minimise this possibility, a small magnifier is now used to examine the sieved sediment samples. Some samples were collected from hard bottoms (rock, gravel) with only a thin layer of sediment, or the sediment was too hard to get proper samples. In these cases, however, there was no accumulation of organic waste and the environmental impact was otherwise acceptable.

Fig. 4a shows a comparison of the sediment condition determined by Groups 2 and 3 parameters for each of 30 core samples. The condition determined by the two groups of parameters agreed in 20 core samples. In six samples, the sediment seemed to be more severely affected when determined by the Group 2 parameters than by Group 3. However, the sediment conditions were all acceptable (conditions 1, 2 or 3). For sediments highly affected by organic material, the Group 3 parameters showed the same or worse conditions than Group 2. Since Group 2 parameters can be measured on a continuous scale, it is expected that these variables will more accurately mirror the sediment condition than the more coarsely determined Group 3 parameters. The Group 3 parameters more readily determine the sediment condition as unacceptable (condition 4) than Group 2; however, in these cases, the sediment was also severely affected (condition 3) according to the Group 2 parameters. Only in one case did the Groups 2 and 3 parameters produce very different results.

The environmental condition of the site is determined for each parameter group before it is finally determined for the site as a whole (cf. Fig. 1). For the nine sites at
which cores could be collected, the environmental conditions according to Groups 2 and
3 parameters were compared (Fig. 4b). These were identical when conditions were very
good (condition 1) and on two sites where conditions were very bad (condition 4). In
five cases, Group 2 yielded a category 1 degree worse than Group 3. There may, thus,
be a risk of underestimating the impact on the sediment if the consistency of the
sediment is such that core samples cannot be collected and the Group 2 parameters are
therefore not measured. However, most sites where the sediment condition was classi-
fied as condition 3 or 4 could be sampled by gravity corer (Fig. 5).

Fig. 4. The environmental condition in the sediment determined by Group 2 parameters plotted against the
condition determined by Group 3 parameters, (a) in individual core samples, (b) at site level. The numbers in
brackets represents the number of samples $n = 30$ (a) and the number of sites $n = 9$ (b) which make up each
point.
With minor modifications, Group 2 parameters may be determined directly from grab samples. In a recent investigation (Schaanning, 1998), pH and Eh were determined simply by inserting the electrodes into the material while it was still in the grab. The bottom substrates ranged from fine-grained soft sediments, through mud accumulated in between stones and gravel, to thin layers of organic waste scraped off steeply sloping rocky bottoms. It is thus possible that the B-investigation may be adapted to employ only grab samples.

5. The application of MOM

The MOM system is presently being implemented through the regulatory framework of Norwegian aquaculture. The A-investigation may be voluntary while the B-investigation will be made compulsory and must be performed at the frequencies shown in Table 2. Many aquaculture companies have already adopted the B-investigation on a voluntary basis and some companies prefer more frequent monitoring than has been proposed in MOM. The application of the C-investigation has not yet been decided. The frequency of this investigation will probably be decided by the local environmental authorities.

At present, feed quotas regulate the production of Norwegian fish farms. In future, feed quotas may still be used to control the production of fish and the MOM system used to manage the environmental impact of fish farms. A database will be established in which the results of the B- and C-investigations can be continuously registered for regulatory purposes as well as for scientific use. After 2 to 3 years of operation, the monitoring programme will be reviewed and modifications may be made in the light of experience.

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