**Salmon Aquaculture Dialogue**

**Working Group Report on Benthic Impacts and Farm Siting**

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**Citation:**

Black, K.D., Hansen, P.K. and Holmer, M. (2008) Salmon Aquaculture Dialogue: Working Group Report on Benthic Impacts and Farm Siting. 54 pages. www.worldwildlife.org/aquadialogues

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This report was commissioned by the Salmon Aquaculture Dialogue. The Salmon Dialogue is a multi-stakeholder, multi-national group which was initiated by the World Wildlife Fund in 2004. Participants include salmon producers and other members of the market chain, NGOs, researchers, retailers, and government officials from major salmon producing and consuming countries.

The goal of the Salmon Aquaculture Dialogue is to develop and implement verifiable environmental and social performance levels that measurably reduce or eliminate key impacts of salmon farming and are acceptable to stakeholders. The group will also recommend standards that achieve these performance levels while permitting the salmon farming industry to remain economically viable.

The Salmon Aquaculture Dialogue focuses their research and standard development on seven key areas of impact of salmon production including: social; feed; disease; escapes; chemical inputs; benthic impacts and siting; and, nutrient loading and carrying capacity.

Funding for this report and other Salmon Aquaculture Dialogue supported work is provided by the members of the Dialogue’s steering committee and their donors. The steering committee is composed of representatives from the Coastal Alliance for Aquaculture Reform, Fundación Terram, Marine Harvest, the Norwegian Seafood Federation, the Pew Environment Group, Skretting, SalmonChile, Salmon of the Americas, and the World Wildlife Fund.

More information on the Salmon Aquaculture Dialogue is available at http://www.worldwildlife.org/aquadialogues.

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## Summary

The Atlantic salmon *Salmo salar* is the predominant culture species in temperate marine waters. Production is almost exclusively derived from culture in floating cages, and the open nature of this culture system allows wastes to participate in external biological, chemical and ecological systems where they may cause unwanted effects.

Regulation of salmon cage culture is largely driven by the potential for disruption of the benthic ecosystem, even though effects on the benthos may not be the most ecologically significant associated with fish farming. This is because the effects may be profound and are relatively easy to detect and quantify, both in severity and spatial extent, at all but the most energetic sites where resuspension is a dominant physical process.

There is a large body of peer-reviewed publications on the processes of benthic pollution at fish farms and significant research has been carried out and published in all the major salmon farming countries except Chile, although the Spanish language literature has not been assessed here.

Benthic macrofaunal communities in sediments receiving normal detrital inputs derived from planktonic production in the overlying water column are highly diverse communities. The oxygen concentration at any point in the sediment is dependent on the rate of its uptake, either to fuel aerobic metabolism or to re-oxidise reduced products released from deeper in the sediment. When the oxygen demand caused by input of organic matter exceeds the oxygen diffusion rate from overlying waters, sediments become anoxic and anaerobic processes dominate.

In marine systems, sulphate reduction is the most important anaerobic process for the degradation of organic material. This is critical for the benthic faunal community as the end-product, sulphide, is toxic. Benthic fauna contribute significantly to organic matter degradation in the sediments and to maintenance of a “healthy” sediment environment through sediment mixing and irrigation processes.

An indicator of anoxic sediments is a cover of the sulphide oxidizing bacteria *Beggiatoa* sp., which form a white mat on the sediment surface. These bacteria derive energy from the oxidation of sulphides from the sediments using oxygen from the water column. If oxygen is depleted in the water just above the sediment surface, the sediment appears black from precipitates of iron sulphides.

Highly organically enriched sediments can occur naturally from large marine or terrestrial inputs of detritus. This may be transient and localised or long-lived and wide scale.

Fish farms release particulate organic material from 2 main sources: uneaten feed and faecal material. Early estimates of feed wastage of up to 20% have been superseded and current estimates are of the order of 5%, but an examination of the literature shows that estimates of feed wastage are based on extremely sparse data. Both the faecal losses and waste feed estimates currently used are insufficiently well constrained for the modern salmon farming industry in any country. There are likely to be large variations in waste feed losses between farms, companies and countries and so all current estimates of loss rates must be treated with caution.

The distribution of waste particles depends on the depth and the current speed: the greater the depth and the greater the current speed, the larger the impacted area but the lower the degree of impact. Once on the bed, particles may be eroded by bottom currents. At all but very quiescent sites, near-bed currents periodically resuspend deposited material and considerable amounts of the vertical flux may be transported away from the farm.

The distribution of cages within a farm is an important factor affecting flux rate per unit area as the depositional footprint of closely spaced cages may overlap. Simulations have shown that the carrying capacity of a fish farm site may double when the cages are scattered compared to when they are situated close together in one unit.

The advective processes that carry particles to the sea bed and later resuspend them are always accompanied by diffusion caused by random fluctuations in current speed and direction. These diffusive processes make it statistically highly improbable that particles will re-concentrate at distance from the farm. An exception to this might be if there is some area down-stream of the farm where current speed is severely attenuated. This could be in the form of a physical feature such as a seabed depression or a change in the substratum that increases the benthic boundary layer depth, e.g. a maerl bed.

Predicting the fate of particulate wastes from fish farms is dependent on being able to describe accurately the hydrodynamic processes that advect particles from the cages to the seabed and also may remobilise such particles by resuspension. Short and unrepresentative current meter measurements, that are typical at present, will likely be superseded by hydrodynamic models in the future.

Farming fish in open cages can cause benthic pollution. Particulate organic material settles to the seabed where it is degraded by microbes utilizing a variety of electron acceptors. Oxygen in sediment porewaters is rapidly depleted and sulphides are generated by sulphate reduction. These effects on sediment biogeochemical processes have profound consequences for the seabed fauna that becomes dominated by a few small, opportunistic species, often at very high abundances, and confined to the upper few centimetres of the sediment. In some cases the complete absence of metazoan life has been reported. Away from the farm, as organic material flux and oxygen demand decreases, animal communities return to background conditions typified by increased species diversity and functionality.

In general, the return of geochemical indicators to near-background levels may take only a few months, recovery of the biological community is highly variable. Typically, recovery is substantial within 2-3 years. Presently, we are not capable of modelling the recovery of the seabed after the cessation of fish farming and so the precise temporal extent of benthic impact cannot be predicted.

Several models exist for the estimation of benthic impacts around fish cages. While modelling of the physical processes is relatively well understood, biogeochemical aspects, including the degradation of organic carbon and the behaviours of benthic animals (e.g. bioturbation) are much harder to model and so ecological outcomes (and biogeochemical indicators) are generally predicted via empirical relationships between predicted organic matter accumulation and some ecological index.

Models are also widely used in regulation of the industry and these can give an indication of the likely scale of farm that could be accommodated at a particular site without unacceptable impacts. Monitoring benthic impacts is mandatory in all salmon growing countries and standards have been set for a wide variety of indicators that require the farmer/regulator to take action if these are breached. Although the indicator set used varies between countries as do the standards, all the standards employed have the objective of retaining a functional benthos beneath salmon cages. This is appropriate given the important role of the benthos in facilitating organic matter degradation.

Coastal zone management and marine spatial planning are increasingly being considered as ways of ensuring the equitable distribution of marine resources between different users and are both linked to conservation or biodiversity goals. However, in many of the salmon growing countries, the practicalities of such planning and management options have yet to be worked through.

The main scientific uncertainties identified in this report are the need for better quantitative information on feed and faecal losses from farms and the requirement for improved biogeochemical/ecological models of the processes affecting the degradation of organic wastes on the seabed.

The rapid increase in the Chilean salmon industry has not been matched by published scientific studies on benthic impacts. However, there is information available in the Spanish language literature and it important that this should be reviewed in order to inform a robust programme of scientific research to underpin policy and regulation to protect the environment.

To be successful in the long term, salmon farming in the future must experience:

- continuously improving environmental performance;
- reduced waste feeds, e.g. through more use of feedback-controlled feeding;
- better matches between benthic assimilative capacity and site biomass;
- common environmental quality objectives across salmon growing countries with appropriate quality standards set to offer a similar levels of environmental protection;
- and high standards of monitoring and enforcement by well resourced regulatory bodies.

It is in the salmon industry's best interests that there is transparency of environmental performance, clear regulation of impacts and strict compliance enforcement to equivalent environmental standards.

# 0 Terms of Reference

The terms of reference agreed between the Salmon Aquaculture Dialogue and the Benthic Working Group, and on which this report is based, are as follows:

The objectives of the group are to:

- Review status of current research and understanding of issues
- Identify significant gaps and/or areas of disagreement
- Identify key research groups
- Identify existing research efforts in the area
- Suggest scope, timeframe and cost for addressing gaps, including draft TORs for key research needs

The specific topics to be considered are:

**Impacts of salmon farming on the benthos:**

- Indicators of impact on benthos (e.g. redox potential, diversity etc.) and the relationships between abiotic and biotic indicators.
- Factors affecting the range and degree of benthic impacts on both coastal environments and lakes
- Cumulative and synergic impacts of multiple activities (salmon farms, agriculture, shellfish farms, water treatment works, industrial effluents) in shared water sheds and water bodies
- Potential for management protocols such as fallowing to mitigate benthic impacts and timeframes required in different environments
- Other mitigation methods and methods of seabed management and their effectiveness
- In dispersive areas, are their factors that might allow accumulation of wastes at a distance from their origin? What are the factors that affect the area of impact over time?
- How good are models of impact and their associated biogeochemical components?
- What are the benthic consequences of changes in feed composition?
- What are the relative merits of regulating on benthic disturbance compared to regulating on the basis of feed inputs?
- Cumulative impacts – how much benthos are we prepared to lose in a basin from multiple stressors? Which other sources of organic matter might be important? How significant is habitat degradation, and consequent loss of ecosystem function?

**Siting**

- Site-selection as a means to minimize key impacts. (Siting will also be addressed within each TWG). What characteristics (currents, geomorphology, proximity to other users, etc) contribute to a benign site?
- Coastal zone management and marine spatial planning
  - Managing multiple users, protect key ecological areas, designated no-farming zones. Are there types of benthos/bottom where farming is not ecologically appropriate?
  - What methods are there for defining the appropriate scale or limit of intensive fish farming in a water body? (e.g. oxygen levels on the benthos)
  - Do different regions have different impact thresholds?

**For both benthic impacts and siting areas examine/consider:**

- Identification of issues that industry will have commercial motivation to address and issues where this is not the case
- Differences from region to region
  - Understanding underlying differences
  - Sharing learning
- Suggest indicators that could be used to measure benthic impacts or siting issues. (A long term goal of the Dialogue is to develop measurable standards or performance levels for farms. As such, we will need to know what to measure in order to indicate impact, as well as what an acceptable level of that might be).
- Trends and causes of improved performance over time e.g. industry and regulatory initiatives.

## 1 Introduction

The Atlantic salmon *Salmo salar* is the predominant culture species in temperate marine waters. Production is almost exclusively derived from culture in floating cages[1], which is essentially an open system. In marine farms the inputs are: juvenile fish; fish feed; medicines; disinfectants and anti-foulants, and the outputs (losses) are: harvested fish; escaped fish; uneaten feed; faeces; excreted metabolic wastes; and effluent chemical species e.g. medicines. The open nature of this culture system allows these outputs to participate in external biological, chemical and ecological systems where they may cause unwanted effects. These effects are often complex, varying by orders of magnitude on temporal and spatial scales.

Regulation of salmon cage culture is largely driven by the potential for disruption of the benthic ecosystem, even though effects on the benthos may not be the most ecologically significant associated with fish farming. This is because the effects may be profound and are relatively easy to detect and quantify, both in severity and spatial extent, at all but the most energetic sites where resuspension is a dominant physical process. Effects on dissolved nutrient concentrations, sea lice transmission to wild populations, escapes, and medicines/chemicals may be more ecologically significant, but the links between cause and effect are hard to quantify and, therefore, often controversial. Benthic effects, unlike algal blooms for example, are generally easy to attribute to the fish farm and, therefore, are amenable to scientifically robust and quantitative regulation.

There is a large body of peer-reviewed publications on the processes of benthic pollution at fish farms and significant research has been carried out and published in all the major salmon farming countries except Chile where very few studies are currently available. While the scientific processes are likely to be predictable, the degree and extent of local impacts in Chilean farms will depend on local factors and further study is required.

In this report we consider natural processes in coastal marine sediments, the sources of perturbation from salmon farming in cages and their effects, the regulation of salmon aquaculture with respect to benthic impacts, together with some of models that have been developed, the relationships with other coastal users and finally some comments on site selection and some commercial aspects.

## 2 Benthic community and sediment biogeochemistry

[1] Cages are typically comprised of a floatation collar of plastic circles or steel/plastic squares, from which is suspended a net bag, cylindrical or cubic, open at the top and closed at the bottom, held taut by weights. Cages are variable in size, of order 10-25m across and 10-20m net depth, however, the trend in many areas is that both the individual cages and the farms increase in size over time.

Benthic macrofaunal[2] communities in sediments receiving normal detrital inputs derived from planktonic production in the overlying water column are species rich, have a relatively low total abundance/species richness ratio and include a wide range of higher taxa, body sizes and functional types, i.e. they are highly diverse communities (Pearson, 1992). The total productivity of the system is dependent on the availability of food, organic matter, and its quality. Animals have evolved to maximise the utilisation of the available resource by virtue of a wide range of feeding modes and some species can vary their mode of feeding depending on environmental factors. Benthic types include filter feeders that gather detrital material from the water column above the sediment, surface deposit feeders that feed on material deposited on the sediment surface, sub-surface deposit feeders that consume buried organic material by burrowing, and carnivores that prey on other macrofauna. Microbes degrade organic material and are themselves consumed by macrofauna, mediating the transfer of nutrients up the food chain.

A range of terminal electron acceptors are used by different bacterial communities in marine sediments. The oxygen concentration at any point in the sediment is dependent on the rate of its uptake, either to fuel aerobic metabolism or to re-oxidise reduced products released from deeper in the sediment. When the oxygen demand caused by input of organic matter exceeds the oxygen diffusion rate from overlying waters, sediments become anoxic and anaerobic processes dominate. As sediments become more reducing with increasing distance from the water column interface, distinct microbiological processes become successively dominant in the order:

- aerobic respiration, ammonium oxidation (to nitrite) and nitrite oxidation (to nitrate). These aerobic nitrifying processes are inhibited by sulphide and are, therefore, of limited importance in sediments beneath marine fish farms;
- denitrification (producing dinitrogen from nitrate);
- nitrate reduction (producing ammonium from nitrate) and manganese reduction;
- iron reduction;
- sulphate reduction (producing hydrogen sulphide)
- and lastly, under the most reducing conditions, methanogenesis (producing methane).

To some extent, these processes may overlap spatially. In marine systems, sulphate reduction is the most important terminal anaerobic process for the degradation of organic material (Holmer & Kristensen, 1992; Jørgensen, 1982) but is much less important in fresh water due to the normally low sulphate concentration. The dominance of sulphate reduction is critical for the benthic faunal community as the end-product, sulphide, is toxic. Benthic fauna contribute significantly to organic matter degradation in the sediments and to

[2] Macrofauna are operationally defined as those sediment dwelling organisms that are retained on a 500µm sieve.

maintenance of a "healthy" sediment environment (Heilskov, Alperin & Holmer, 2006; Heilskov & Holmer, 2003). Bioturbation is that process of sediment mixing by animals that may expose new substrates to microbial action and allow the movement of oxidants by active or passive pumping of water through burrows, a process known as bio-irrigation (Nickell *et al.*, 2003). Heilskov et al (2006) found that irrigation rate was directly correlated with organic degradation rate and that irrigation velocities increased with organic matter loading, indicating greater fauna-induced oxidation in more enriched environments (Figure 2.1). This implies that a change in faunal structure in fish farm sediments towards smaller opportunistic polychaete species (with lower irrigation potential) will result in slower mineralization rates and, therefore, increased accumulation of organic wastes.

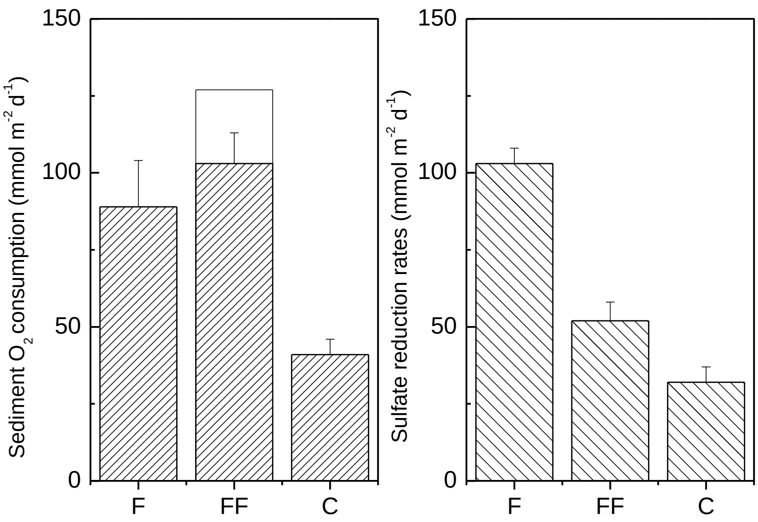


**Figure 2.1.** Sediment oxygen consumption (left) and sulphate reduction rates (right) at a fish farm site (F) and a control site (C) showing the high activity at the fish farm due to organic matter loading of the sediments. Fauna (the polychaete *Nereis diversicolor*) was added to the fish farm site (FF) and the measurements showed increased oxygen consumption enhanced due to re-oxidation of sulphides and animal respiration (open bar). On the other hand sulphate reduction rates decreased due to oxidation of the sediments generally improving the sediment conditions (redrawn from Heilskov & Holmer 2003).

The redox potential (Eh) profile measured down the sediment column to a depth of 10-15 cm gives a useful guide to the relative degree of carbon enrichment in the sediments (Pearson & Stanley, 1979). Positive Eh values are indicative of aerobic and oxidized conditions whereas negative values are associated with anaerobic microbial processes and reduced conditions. Under normal rates of detrital carbon input to sediments, the redox discontinuity level (RDL), i.e. the point at which anaerobic processes become predominant, lies some centimetres below the surface. As carbon inputs increase so does Biological Oxygen Demand (BOD) and the RDL approaches ever closer to the sediment surface. Eventually, under very high detrital inputs, the RDL coincides with the sediment/water interface, where, under low flow conditions, it might even rise into the water column. A sign of anoxic sediments is a cover of the sulphide oxidizing bacteria *Beggiatoa* sp., which form a white mat on the sediment surface. These bacteria derive energy from the oxidation of sulphides from the sediments with oxygen from the water column and, although the bacteria are transparent, the mat appears white due to the precipitation of elemental sulphur inside the bacteria. Eventually, if oxygen is depleted in the water just above the sediment surface, the sediment appears black from precipitates of iron sulphides, and a white cloud in the overlying water indicates the zone where sulphide diffusing from the sediments meets the oxic water column.

Meiofauna are operationally defined as benthic animals that are between 63 and 500µm in size and these have been suggested as good indicators of organic pollution. A recent study in BC (Sutherland et al., 2007) found that meiofaunal kinorhynchs, crustaceans and polychaetes declined in an asymptotically with increasing benthic organic and that the ratio of nematodes to copepods could also be used as a benthic indicator at salmon farms.

It is important to emphasise that highly organically enriched sediments can occur naturally from large marine or terrestrial inputs of detritus. This may be transient and localised or long-lived and wide scale. Hypoxia/anoxia in sediments and overlying water occurs when the supply of new oxygenated water is poor as may be the case, for example, in deep, silled fjordic systems. In such systems, benthic communities are modified and specialist opportunist animals may dominate. Organic rich sediments may also be found in eutrophic waters with re-occurring oxygen depletion events during summer months.

## 3 Sources of perturbation

Fish farms release particulate organic material from 2 main sources: wasted (i.e. uneaten) feed and faecal material. Feed wastage occurs in pulses associated with feeding events, and increases towards the end of a meal as the fish approach satiation. Several feedback systems may be operated at modern salmon farms including video cameras under the cages and sediment traps with particle sensors. These systems reduce feed input during meals on the detection of feed particles passing to the bottom of the cage. Early estimates of feed wastage (Gowen & Bradbury, 1987) of up to 20% have been superseded and current estimates are of the order of 5%. This value is difficult to verify, and feed wastage is rarely measured in the field, but farmers have a strong interest in keeping this to a minimum, as feed is costly and farmers may be judged on the food conversion ratios (FCR) of their crop, which is dependent on low feed wastage: 5% has become an accepted estimate in Scotland. Given the importance of feed wastage rates for benthic impacts, further effort is required to constrain estimates more precisely. See table 3.1 (Chamberlain & Stucchi, 2007) for a list of previous estimates of waste feed and the methods used for their estimation.

**Table 3.1 Estimates of feed wastage (Chamberlain & Stucchi, 2007)**

| Waste feed portion (%) | | |
|---|---|---|
| 20 | Estimated | (Gowen, Bradbury & Brown, 1989) |
| 5–11 | Calculated | (Findlay & Watling, 1994 ) |
| 5(1–40) | Applied (estimates) | (Panchang, Cheng & Newell, 1997) |
| 5–15 | Observed/estimated | (Pearson & Black, 2001) |
| 0 and 3 | Estimated | (Cromey, Nickell & Black, 2002a) |
| 10 | Mass balance calculations | (Perez et al., 2002) |
| 5 or less | Estimated | (Brooks & Mahnken, 2003a) |
| 8 | Calculated average from Findlay and Watling (1994) | (Stucchi et al., 2005) |
| 3 | Applied—from estimates given in Cromey et al. (2002a) | (Corner et al., 2006) |
| 15 | Mass balance calculation | (Strain & Hargrave, 2005) |

Table 3.2 gives harvest data for Scotland for 2005 and 2006 (FRS, 2007) together with mortality losses and feed consumption (from SEPA). The apparent FCR is calculated simply by dividing the feed input by the fish production. The "FCR including mortalities" calculation takes into account that fish feed will have also been consumed by dead fish that do not appear in the production figure. In the table, mortality biomass has been added to production biomass and the calculation performed as before. Next in the table is an assumption of optimal FCR where all the feed is efficiently converted into biomass. As some farmers already report FCRs in the range of 1:1 the figure chosen here of 1.1:1 does not seem unreasonable[3]. Using the FCR of 1.1 we can calculate the amount of feed that is used in fish production and, by difference, the amount of added feed that is not used for fish growth, and this can be expressed as a percentage of total feed added.

The Apparent FCR given in Table 3.2 is not the true Economic FCR[4] as we have not found data on the biomass at the beginning of the year. Rather the assumption is made that the biomass at the beginning of each year is approximately the same, which in turn assumes that across the country the proportion of biomass in year classes is approximately constant over time. This assumption depends on the annual variation in the numbers of smolts put to sea and their survival, shown in Table 3.4. Clearly there is some variation between years that needs to be taken into account when considering the Apparent FCRs in Table 3.2. In addition, to correctly calculate the Biological FCR[5], information on discards and other losses including escapes would be required but such data are not available.

[3] Promotional material by Skretting refers to "the FCR of 1.0 commonly achieved on Nutreco Aquaculture salmon farms" http://www.skretting.co.uk/web/SkrettingUKIreland/InterWeb.nsf/wPrId/9C81F9CB897B6CC380256CDB004BFEE0/$File/Responsible%20practices.pdf

[4] Economic FCR = Amount of feed given / (Biomass(BM) slaughtered + BM in the water at end of period – BM at start of period)

[5] Biological FCR = Amount of feed given /(Biomass (BM) Harvested + BM in the water end of period + BM Mortalities + BM Discarded + BM Loss – BM at start of period)

The concept of FCR includes the efficiency of the animals at maximizing weight gain while minimizing maintenance costs. So we can imagine that the FCR will relate to the metabolic efficiency of the fish which will be a function of fish size, season, maturity and water temperature amongst other things, and also farm factors such as current speed, as fish have to expend energy swimming against a current. Also the quality of the feed will be important. If it is highly digestible and well balanced a smaller amount will satisfy the fish's needs and there will be low faecal losses. If it is less digestible the fish will have to ingest more (with a energy expenditure in so doing) to get the same nutritional content, and faecal losses will be higher.

The large values of 15 and 18% of food not used for growth must result from errors in either the optimal FCR used or the waste feed rate or both.

Table 3.3 gives FCRs calculated for the Norwegian industry. The apparent increase in FCR over time is perhaps a consequence of the reducing digestibility of feed as it is increasingly supplemented with less digestible vegetable products (Mundheim, Aksnes & Hope, 2004; Young et al., 2005). If so, this will decrease over time as vegetable formulations become better matched to fish requirements.

Both the faecal losses and waste feed estimates currently used are insufficiently well constrained for the modern salmon farming industry in any country. There are likely to be large variations in waste feed losses between farms, companies and countries and so all current estimates of loss rates must be treated with caution.

**Table. 3.2** Production (FRS, 2007), feed used, mortalities (all kg), apparent FCR, FCR including mortalities, optimal FCR, feed used for fish growth, feed not used for growth (both kg) and the % of total feed not used for growth (data obtained from SEPA).

| Year | Harvest | Feed used | Mortalities | Apparent FCR | FCR Including mortalities | Optimal FCR | Feed used for growth | Feed not used for growth | % |
|---|---|---|---|---|---|---|---|---|---|
| **2005** | 129,588,000 | 174,983,395 | 6,553,946 | 1.35 | 1.29 | 1.1 | 149,756,140 | 25,227,255 | 14.4 |
| **2006** | 131,847,000 | 187,831,476 | 8,385,750 | 1.42 | 1.34 | 1.1 | 154,256,025 | 33,575,450 | 17.9 |

**Table 3.3** FCR for Atlantic Salmon farms according to Norwegian official statistics (Myrseth, 2005).

| Year | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 |
|---|---|---|---|---|---|---|---|---|---|---|
| **FCR** | 1.18 | 1.19 | 1.09 | 1.20 | 1.23 | 1.20 | 1.20 | 1.20 | 1.21 | 1.28 |

**Table 3.4** Annual Scottish smolt input and overall survival (FRS, 2007)

| Year | Smolts to sea (M) | Overall Survival % |
|---|---|---|
| 1995 | 26.786 | 87.8 |
| 1996 | 32.838 | 73.6 |
| 1997 | 42.766 | 76.6 |
| 1998 | 45.87 | 69.1 |
| 1999 | 41.107 | 80.7 |
| 2000 | 45.185 | 79.9 |
| 2001 | 48.643 | 81.6 |
| 2002 | 50.086 | 76.7 |
| 2003 | 43.803 | 76.7 |
| 2004 | 39.041 | 75.5 |
| 2005 | 37.168 | |
| 2006 | 41.09 | |

The settling velocities of a large range of different feed sizes, types and brands have been measured (Chen, Beveridge & Telfer, 1999a; Cromey et al., 2002a) as has the disaggregation of feed pellets after immersion in water (Stewart & Grant, 2002) and their erosion properties (Sutherland *et al.*, 2006). These measurements are of use when modelling processes affecting waste feed (see section 5). Automated feeding systems can provide better control over feed wastage, but systems which blow feed through long pipes from a central hopper to each cage can also fragment and erode pellets before they reach the fish. The fine fragments and dust so produced is seen as a scum on the water surface and on cage structures. Fragments that enter the water and sink may be too small to be ingested by fish. However, efforts have been made to understand the processes of pellet breakage (Aarseth et al., 2006) and design systems to reduce this.

Faecal material is produced in post-prandial pulses. Its amount is related to the digestibility of the feed: modern diets are highly digestible (> 85%). The settling velocity spectrum of salmon faeces from a range of fish sizes is well characterised (Chen et al., 1999a; Chen, Beveridge & Telfer, 1999b; Chen et al., 2003; Cromey et al., 2002a).

The distribution of these particles will depend on the depth and the current speed: the greater the depth and the greater the current speed, the larger the impacted area but the lower the degree of impact. Once on the bed, particles may be eroded by bottom currents: where such currents are very strong, all of the particles can be advected away from the farm; where currents are very weak, the majority of the particles accumulate where they are deposited.

When organic particulate material settling from fish cages intersects the sea bed it either remains where it deposits and degrades, or it is resuspended and is advected, possibly outside the farm area. In flume experiments, waste pellet accumulation enhances the erosion of natural sediments (Neumeier et al., 2007) by preventing the development of a stabilising diatom biofilm although in turbid natural waters with low light penetration this effect may be less important. The critical resuspension velocity has been estimated at about 9 $cm.s^{-1}$ (Cromey *et al.*, 2002b). At all but very quiescent sites, near-bed currents are periodically higher than this and it is likely that considerable amounts of the vertical flux will be transported away from the farm. This is consistent with estimates by Strain and Hargrave (Strain & Hargrave, 2005) where, at a dynamic site, these authors found that the majority of the carbon flux could not be accounted for in terms of the benthic oxygen demand. Such processes are amendable to modelling (Cromey *et al.*, 2002b) (see section 5) and DEPOMOD outputs show that significant accumulation rates are confined to a relatively small area around the farm at relatively quiescent sites (figure 3.1) but are more widely dispersed at more dynamic sites (figure 3.2). These plots show contours of flux (g $m^{-2}$ $yr^{-1}$) and are useful for comparing the severity and spatial extent of the deposition footprints. The relatively dynamic site has a larger but less severe deposition footprint which is also displaced to the SE, showing that the residual current is in this direction. These footprints, which are site specific in their shape and size, are used in regulatory assessments to determine the consented maximum biomass for Scottish salmon farms.

The advective processes that carry particles to the sea bed and later resuspend them are always accompanied by diffusion caused by random fluctuations in current speed and direction. These diffusive processes make it statistically highly improbable that particles will re-concentrate at distance from the farm. An exception to this might be where there is some area down-stream of the farm where current speed is severely attenuated. This could be in the form of a physical feature such as a seabed depression or a change in the substratum that increases the benthic boundary layer depth. For example, a maerl bed may trap waste particulates within its structure (Hall-Spencer *et al.*, 2006). Thus, even in dispersive areas it is necessary to consider changes in the benthic environment at a distance from the farm which may trap particulate wastes and interfere with the normal diffusive processes.

The rate of deposition, particularly of faeces, on the sediments per unit area is a function of the stocking density per unit area (kg $m^{-2}$) of the cages. Thus a farmer may reduce deposition per unit area by reducing the depth of the net while keeping stocking density per unit volume (kg $m^{-3}$) constant or by reducing stocking density by volume while keeping the cage depth constant.

The distribution of cages within a farm is also an important factor affecting flux rate per unit area as the depositional footprint of closely spaced cages may overlap. Simulations have shown that the carrying capacity of a fish farm site may double when the cages are scattered compared to when they are situated close together in one unit (Stigebrandt et al. 2004). Also, the temporal distribution of the organic load seems to have relevance for the benthic impact. Monitoring has shown that the benthic impact at a site is significantly smaller when the organic load is gradually increasing as small fish grow, compared to the rapid increase in load if large fish are moved to a new site (Otto Sandnes, Aqua Kompetanse, pers. com.). Although further work is required in this area, this is likely to be a consequence of the adaptation of the benthic community to increasing load with the dominance of more pollution tolerant species.

At a deep fish farm site producing 2910 tonnes of fish in 19 months, the sedimentation rate was 365 gm$^{-2}$yr$^{-1}$ at 230 m depth during the second year of production, nine times higher than found at a reference station 3 km away (Kutti, Ervik & Hansen, 2007a). The farm was moored at one point which meant that the organic waste was distributed over a larger area than is the case for permanently fixed farms. While the sedimentation rates showed that most of the waste matter settled within 250 m of the farm, the fatty acid composition and δ$^{13}$C isotope ratio of the material in the bottom traps indicated that some components of the organic waste were transported as far as 550 to 900 m, probably due to resuspension of surface sediments. The content of sedimentary organic matter, total organic carbon and total organic nitrogen were not elevated in the sediment around the farm. However, phosphorus was found in higher concentrations in the sediments close to the farm, indicating that organic matter had settled and degraded. The unchanged content of organic matter in the sediment during the production cycle showed that at this site the local resuspension and dispersal conditions and the decomposition capacity of the benthos were sufficient to prevent overloading of the sediments.

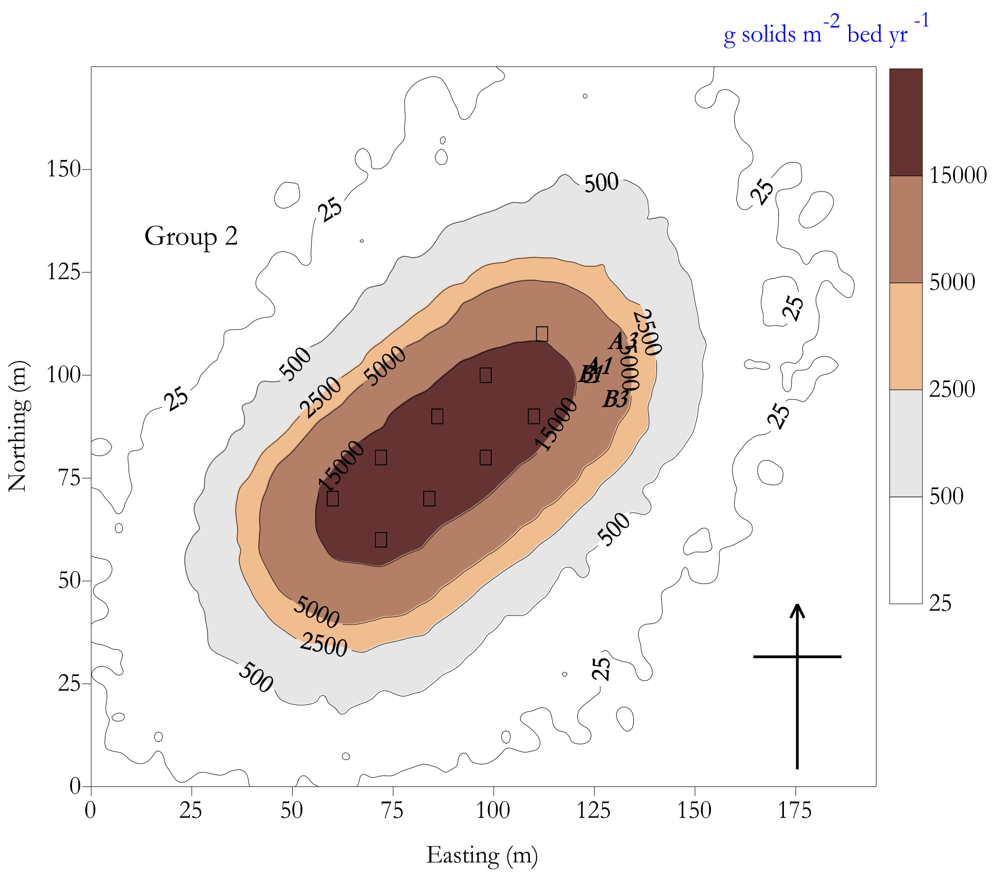


**Figure 3.1** Model output of the organic footprint of a relatively quiescent salmon farm site (Cromey *et al.*, 2002a)

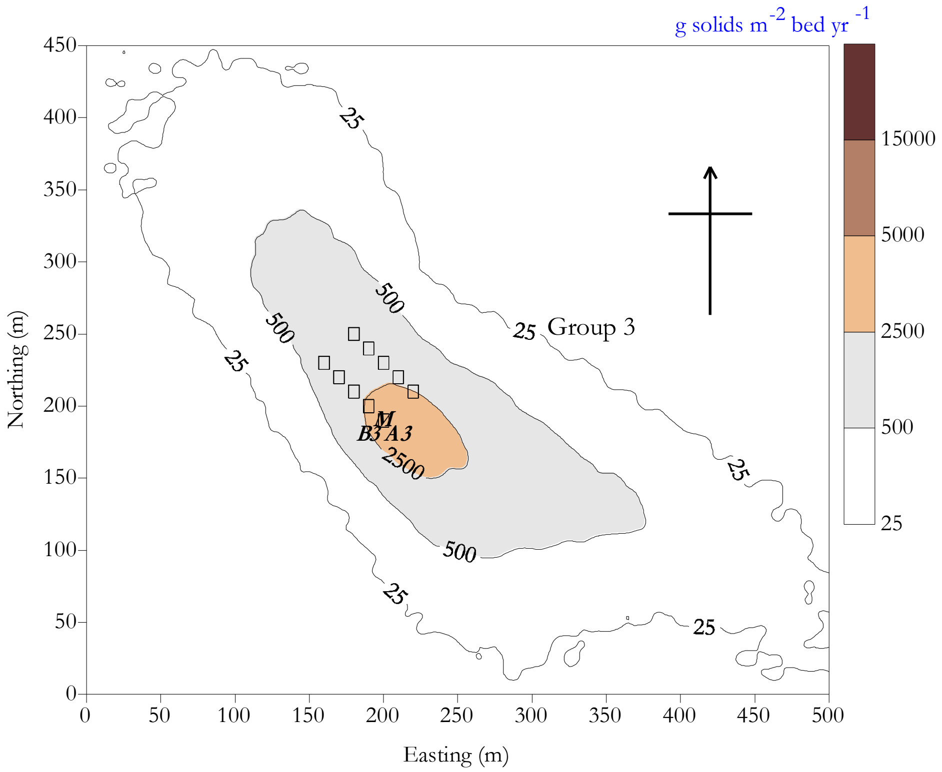


**Figure 3.2** Model output of the organic footprint of a relatively dynamic salmon farm site (Cromey *et al.*, 2002a)

Predicting the fate of particulate wastes from fish farms is dependent on being able to describe accurately the hydrodynamic processes that advect particles from the cages to the seabed and also may remobilise such particles by resuspension. Presently, the Scottish consenting process relies on a 15-day current meter record, from several depths, but at a single fixed point close to the fish farm location (www.sepa.org.uk). This is thought to be the best balance between cost and fitness-for-purpose for sites located in relatively quiescent waters. This is because at such sites a large proportion of particles are retained within a few hundred meters around the farm and so their advection may realistically be described by the measured current record.

As sites become larger, they typically require location in more dispersive areas in order to meet Sediment Quality Standards and other Consent conditions. Increasingly greater proportions of particles are advected outside the area that can be reasonably described by a single current record and benthic impact predictions become unreliable owing to uncertainties in the hydrodynamics.

Another problem is the duration of the current record. The 15-day record was originally chosen as this represents one spring-neap tidal cycle and thus should capture a significant proportion of the variability due to tides. However, in many instances of place and time, tides are not the dominant driver of local currents in the marine environment. Scaling up a 15 day record to an annual record, even while compensating for variations in the strength of the Spring-Neap cycle through the year, can magnify deficiencies in an unrepresentative record. A 206 day record from a Scottish fish farm was analysed for variability in summary statistics for 15-day blocks (Cromey & Black, 2005). Table 3.5 shows that there was high variability between 15-day blocks and the mean. The data used for the consent were from a separate record which showed the lowest mean surface currents and intermediate mean near-bed currents. The long data set shows that this site is actually more dispersive than the data used in the consent (but this will not always be the case).

**Table 3.5** Surface and near bed mean speeds vary depending on the length of deployment time. Currents measured and used for the consent of the site are very different to other periods.

| | Surface mean cm $s^{-1}$ | Near bed mean cm $s^{-1}$ |
|---|---|---|
| **Whole record** | 10.6 | 5.9 |
| **Most dispersive 15 days** | 14.8 | 9.6 |
| **Least dispersive15 days** | 6.4 | 2.0 |
| **Used in consent** | 2.7 | 3.8 |

The best available solution to these problems is the use of a hydrodynamic model rather than a single current record to drive the model. This allows the simulation of the current field in space and time. Hydrodynamic models have in the past been seen as too expensive for fish farm applications but the situation is changing rapidly with access to increasing computing power at lower cost.

## 4 Consequences of organic particulate inputs to sediments

Farming fish in open cages can cause benthic pollution. Effects on benthic macrofauna have been much studied, and results largely reinforce the paradigm of species succession on organic enrichment gradients established by Pearson and Rosenberg (1978, Figure 4.1). Particulate organic material settles to the seabed where it is degraded by microbes utilizing a variety of electron acceptors. Oxygen in sediment porewaters is rapidly depleted and sulphides are generated by sulphate reduction, which is the dominant anaerobic process in coastal sediments (Holmer & Kristensen, 1992). These effects on sediment biogeochemical processes have profound consequences for the seafloor fauna that becomes dominated by a few small, opportunistic species, often at very high abundances, and confined to the upper few centimetres of the sediment (Brooks & Mahnken, 2003a; Brooks, Stierns & Mahnken, 2003a; Brooks et al., 2003b; Brown, Gowen & McLusky, 1987; Edgar et al., 2005; Gowen & Bradbury, 1987; Hargave, 2005; Hargrave et al., 1997; Heilskov & Holmer, 2001; Holmer, Wildish & Hargrave, 2005; Karakassis et al., 1999; Pearson & Black, 2001; Pearson & Rosenberg, 1978; Pohle, Frost & Findlay, 2001; Weston, 1990) and in some cases the complete absence of metazoan life has been reported (Mulsow, Krieger & Kennedy, 2006). Away from the farm, as organic material flux and oxygen demand decreases, animal communities return to background conditions typified by increased species diversity and functionality (Gowen & Bradbury, 1987; Nickell et al., 2003; Pereira et al., 2004).

Recent work at deeper sites (>200m) indicates that the benthic fauna community may become enriched with high numbers of species, abundance and biomass, without the harmful impact on the benthic fauna encountered at shallower sites (Kutti *et al.*, 2007b) presumably as a consequence of the reduced flux per unit area experience by deep sites where dispersive processes have more time to act on sinking particles.

In the 1990's, the size of individual farms increased rapidly from a few hundred tonnes to up to and over a thousand tonnes. But farms were often located in the very sheltered environments required by the previous generation of largely wooden cage collars, and some farms became so polluted that total sediment azooia occurred, and there is more recent evidence of this from the expanding Chilean industry (Mulsow et al., 2006). Such farms were prone to outgassing of methane, carbon dioxide and hydrogen sulphide – a process that has been termed "souring". Hydrogen sulphide is highly soluble and, although it is rapidly oxidised over a few hours, measurable concentrations could be detected in waters overlying the sediments (Black, Kiemer & Ezzi, 1996a; Black, Kiemer & Ezzi, 1996b). Hydrogen sulphide is highly toxic to fish (Kiemer *et al.*, 1995) and has been implicated in both fish kills, and reduced performance, but a causal link is difficult to prove as pathologies are non-diagnostic for hydrogen sulphide poisoning.

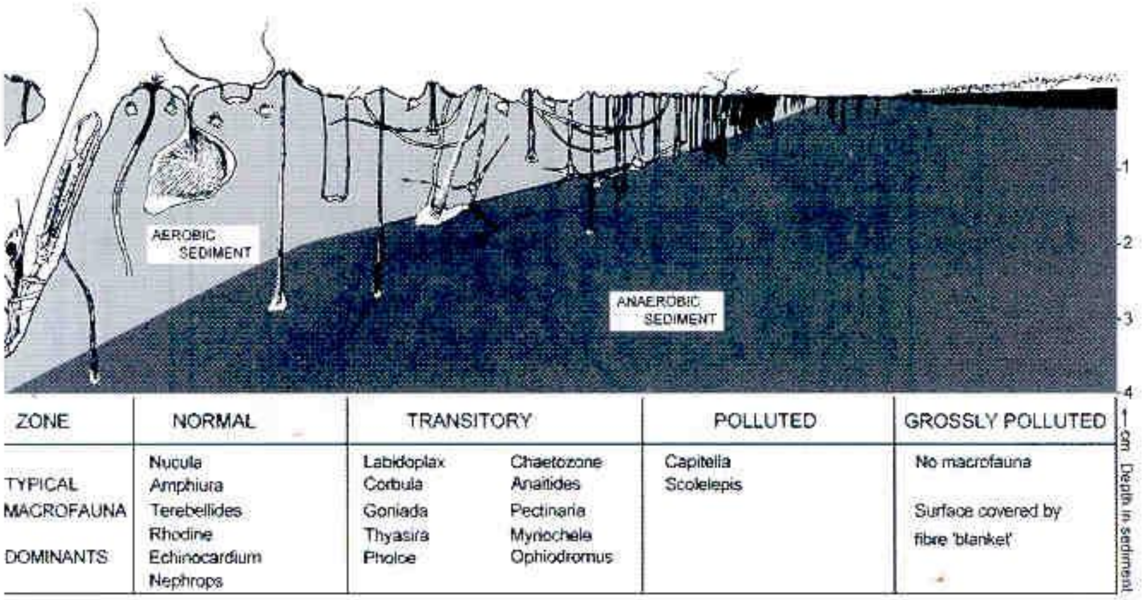


**Figure 4.1** Infaunal succession on an organic enrichment gradient (Pearson and Rosenberg, 1978)

Nevertheless, it is generally true that heavily polluted sites perform less well than relatively clean sites whatever the mechanisms (Black *et al.*, 1996a; Black *et al.*, 1996b), and therefore the protection of cultured fish (and the farmer) from the consequences of excessive benthic impact are an important function of regulation. Anoxic bottom waters and high sulphide concentrations are inimical to metazoan life, and it is likely that were such conditions to be widespread, ecological damage would be done, perhaps at some distance from the farm.

A significant fraction of the particulate material emanating from sea bass/bream cages may be consumed by wild fish. This is well established in Mediterranean aquaculture (Dempster et al., 2005; Dempster et al., 2004; Machias et al., 2005; Tuya et al., 2006) but less is known of fish aggregations around salmon farms (Carss, 1990) owing to the generally low visibility in mesotrophic systems, but also to a lack of research effort. However, the process certainly occurs at salmon farms as evidenced by gut content analysis of wild fish around fish cages (pers. obs., figure 4.2). A recent, and as yet unpublished, study around salmon farms in Norway indicated that > 80% of the diet of saithe around farms was lost food pellets. Cod diets around farms were also modified compared to control fish, although they were less reliant on lost feed (30% of diet) (T. Dempster, pers. com.). Additionally, waste particulates are also consumed by epi-benthic scavengers including fish and crustaceans (Felsing, Glencross & Telfer, 2005), and these species also bioturbate the sediment surface, but again there is little quantitative information on this subject.

Benthic-pelagic coupling is the term used to describe linkages between sediments and the overlying water column. A significant proportion of the nutrient incorporated into sediments is returned to the water column during diagenesis. Several workers have studied this phenomenon owing to the potential contribution to eutrophication and as an indicator of impact (Hall et al., 1992; Hargrave et al., 1993; Heilskov et al., 2006; Heilskov & Holmer, 2001; Heilskov & Holmer, 2003; Holby & Hall, 1991; Holby & Hall, 1994). Between 70% and 80% of the nitrogen added in feed is lost to the environment. The majority (50 - 60% of total N) is lost in dissolved form either directly from the fish or by benthic flux from solid waste beneath the cages.

**Figure 4.2** Gut contents of a mackerel caught near a fish farm in Scotland showing large numbers of feed pellets (photo K. Black, © SAMS).

Presently, we are not capable of modelling the recovery of the seabed after the cessation of fish farming and so the precise temporal extent of benthic impact cannot be predicted. There have been several previous UK investigations into the recovery of the benthos after the cessation of fish farming. The first, a 3 year study (Nickell et al., 1995), considered benthic recovery at 3 sites and concluded that a numerical model that could be used to manage rotation of fish farm sites could not be derived from the data obtained. A descriptive model, based on indicator species and numbers of species, appeared to hold broadly for all three sites giving recovery to 'normal' communities in around two years, even at the most heavily impacted. There was no obvious relationship between recovery times and ambient hydrography, and it appeared that recovery was a complex process which had several drivers that might predominate at different sites and seasons.

The second study of benthic recovery at a Scottish salmon farm (Pereira *et al.*, 2004) was of a shorter (15 month) duration and, at the most impacted station, recovery had not been completed in that time. In contrast to the previous study, organic carbon was not found to be a significant indicator of recovery, with different environmental variables of varying importance at different stages in the process. The authors identified sedimentary oxygen uptake rate as the primary indicator of macrofaunal recolonisation.

Brooks and co-workers in Canada have probably made the most comprehensive series of recovery studies and have observed a very wide range of recovery rates from a few weeks to 6+ years (Brooks, Stierns & Backman, 2004; Brooks et al., 2003b). They give 2 useful definitions of recovery:

> *chemical* – "defined as the reduction of accumulated organic matter with a concomitant decrease in free sediment sulfide and an increase in sediment redox potential under and adjacent to salmon farms to levels at which more than half the reference area taxa can recruit and survive (free sulfides < 960 μM)", and
>
> *biological* – "defined as the restructuring of the infaunal community to include those taxa whose individual abundance equals or exceeds 1% of the total invertebrate abundance at a local reference station. Recruitment of rare species representing < 1% of the reference abundance was not considered necessary for biological remediation to be considered complete. As an example, if the mean reference station total abundance was 8000 macrofauna/$m^2$, then all of those taxa with a mean abundance of ≥ 80 animals/$m^2$ would be considered necessary for biological remediation to be considered complete."

MacLeod and co-workers have studied recovery processes at salmon farms in Tasmania over several years and have reached some interesting conclusions:

1) macrobenthic recovery was slower than chemical recovery, so chemical methods were not sufficient to define ecological recovery (Macleod, Crawford & Moltschaniwskyj, 2004)

2) recovery of macrobenthic community function (from analysis of life history attributes of dominant fauna) is more rapid than return to community equivalence, and may be a more useful measure of benthic recovery (Macleod et al., 2007)

3) macrobenthic recovery was faster at a more quiescent site than a more exposed site attributed to the greater resilience of the species typically found at such sites and differences in larval supply (Macleod, Moltschaniwskyj & Crawford, 2006).

Since the earlier Scottish studies, salmon aquaculture has changed significantly: cages are bigger, average farm size has increased, more exposed sites have been developed and the in-feed medicine Slice has become widely used. Although recent studies have not found a relationship between Slice in sediments and community changes at active sites (Black *et al.*, 2005; Telfer *et al.*, 2006), its potential to retard recovery has not been studied. Copper is also widely used as an antifoulant and has been detected at very high concentrations in fish farm sediments (Dean, Shimmield & Black, 2007; Smith, Yeats & Milligan, 2005). Brooks and co-workers argue that copper in enriched sediments is likely to be bound as sulphides and, therefore, not bioavailable (Brooks & Mahnken, 2003b; Brooks et al., 2004) but it is possible that recovering sediments may release this copper back into pore waters with the potential to affect recolonisation.

Catching larger falling particles using mesh screens suspended below fish cages to keep them away from the benthos and in oxygenated water has been investigated experimentally and proposed as a method of enhancing recovery times (Buryniuk et al., 2006) although field tests have not yet been reported.

More recent approaches to modelling inputs to the sea bed from cage farming have yielded an improved understanding of effects on the macrofaunal community. The DEPOMOD model has a benthic component (Cromey *et al.*, 2002a; Cromey *et al.*, 2002b) which at present predicts biological responses to organic matter accumulation; current work is focussed on adding a time component using a biogeochemical sediment model and this may be amenable to modelling recovery rates. Morrisey and co-workers (Morrisey *et al.*, 2000) had some success in predicting remineralisation of carbon/recovery rates in New Zealand when using the Findlay-Watling oxygen supply model (Findlay & Watling, 1997); they also noted the potential for increased recovery times due to the presence of heavy metals in the sediment.

There are few published reports on benthic impacts from Chile (Buschmann et al., 2006; Mulsow et al., 2006; Soto & Norambuena, 2004), which is a significant issue given the rapid expansion of that industry. The Spanish language literature on benthic impacts of Chilean farming requires review.

Soto and Norambuena (2004) studied 43 farm sites in southern Chile and found significant differences between control and farmed stations in terms of nitrogen, phosphorus and organic carbon content. Sediment P content was proposed as a potential indicator of fish farm impact. As in other studies, these authors found that relationships between faunal community metrics and geochemical measures were non-linear and variable. No relationships were found between sediment and water column conditions (nutrients and chlorophyll). Mulsow et al. (2006) assessed benthic impacts from fish farming in two Fjords in southern Chile using sediment profile imaging (SPI) and microelectrode profiles of oxygen, hydrogen sulphide, redox and pH. Four from seven stations in Pillan Fjord were severely disturbed with azoic conditions and extremely high oxygen demand (700–1200 mmol $m^{-2}$ $day^{-1}$) whereas, in Reñihue Fjord, SPI images at several stations showed the presence of infauna and burrows and lower oxygen demand (230 to 490 mmol $m^{-2}$ $day^{-1}$). For comparison, Nickell et al (2003) found oxygen demands of 434.9 ± 139.7 mmol $m^{-2}$ $day^{-1}$ at the most impacted station at a Scottish fish farm, that station having a high abundance of small infaunal polychaetes.

The use of indicators of ecosystem state is widely proposed. Gallopin (1997) gives a definition of an indicator as *"An operational representation of an attribute (quality, characteristics, property) of a system"*. In the ECASA project (www.ecasa.org.uk) several indicators relating to aquaculture-environment interactions have been assessed including both benthic and sediment indicators (Table 4.1).

**Table 4.1** ECASA benthic and sediment indicators (consult www.ecasatoolbox.org.uk for descriptions)

| Benthic indicators | Sediment indicators |
|---|---|
| AMBI | Ammonia in pore waters |
| Benthic trophic group | Carbon quality (Rp index) |
| Biomass fractionation index | Heavy metals |
| ITI | MUFAB |
| Macrofauna presence | Nitrifier bacteria |
| Meiofauna sediment test | Oxygen consumption fluxes |
| Meiofaunal diversity | Phosphate in pore waters |
| Multivariate indices | Redox Eh |
| Univariate indices | Sediment flux (traps) |
| | Sulphate and ammonia gradients |
| | Sulphide/oxygen probe |
| | Total Nitrogen (surface) |
| | Total Organic Carbon |
| | Total Organic Carbon (surface) |
| | Total Phosphorous (surface) |

No single "magic-bullet" indicator exists. Rather a suite of indicators should be evaluated in order to correctly interpret the sediment state: if an inappropriate indicator set is chosen then it is quite possible to draw misleading conclusions (Mulsow et al., 2006). A wide range of sediment indicators are used in regulation of aquaculture (section 6) with different legislators choosing different indicator suites. Although this is unfortunate in that it often does not allow direct numerical comparison between countries, in general, similar qualitative information on sediment state (i.e. position on the Pearson –Rosenberg continuum, figure 4.1) can be derived if a sufficiently broad range of indicators have been evaluated.

Integrated or multi-tropic aquaculture is receiving considerable attention. Recycling nutrients between different trophic levels – fish, invertebrates, macrophytes – has some potential to reduce environmental impacts of fish farming while at the same time increasing economic stability by providing secondary products (Chopin et al., 2001; Chopin et al., 2006; Neori et al., 2007; Troell et al., 2003; Troell et al., 1997; Troell, Kautsky & Folke, 1999; Whitmarsh, Cook & Black, 2006). Such systems are intuitively attractive but remain to be fully proven at the large commercial scale and, while the removal of some nutrients from the system through secondary products would be beneficial there may be a local consequence on the benthos through reduced current flows and increased sedimentation/reduced erosion.

## 5 Modelling impacts

Several models exist for the estimation of benthic impacts around fish cages (Cromey & Black, 2005). In general, modelling of the physical processes is relatively well understood. However, biogeochemical aspects, including the degradation of organic carbon and the behaviours of benthic animals (e.g. bioturbation) are much harder to model and so ecological outcomes (and biogeochemical indicators) are generally predicted via empirical relationships between predicted organic matter accumulation and some ecological index.

For example, a quantitative empirical approach has been taken by Cromey and co-workers (Cromey *et al.*, 2002a) who have related predicted organic accumulation[6] using the DEPOMOD model with benthic response (figures 5.1, 5.2).

Figure 5.1 shows this relationship in terms of the Infaunal Trophic Index (ITI):

$$\mathrm{ITI} = 100 - \left[ 33\frac{1}{3} \left( \frac{0n_1 + 1n_2 + 2n_3 + 3n_4}{n_1 + n_2 + n_3 + n_4} \right) \right]$$

where $n_1$ through $n_4$ are the number of individuals found in Feeding Groups 1–4. The coefficients in the numerator of the equation (0, 1, 2, 3) are scaling factors (Word 1979). Feeding groups have been assigned to species on the basis of their feeding mode. ITI becomes very low where species number is low and where the dominants are opportunist deposit feeders associated with organic

[6] Accumulation is what remains of sedimented material after erosion-consolidation processes. The accumulation rate is, therefore, different from the sedimentation rate – a term that is often used erroneously or at least ambiguously.

pollution (Feeding Group 4). ITI becomes very low at high flux values (figure 5.1). The empirical relationship between flux and total animal abundance (figure 5.2) is less tight than for ITI but it is clear that total abundance reaches a maximum value and then crashes to very low numbers at about the same flux rate as ITI (and by inference species number) reaches a minimum (figure 5.1). Direct relationships between flux and number of species are less clear from the dataset that these workers possess. Care must be taken when using indices such as ITI when species numbers are less than 5.

When another useful benthic index AMBI (Borja, Franco & Perez, 2000; Borja, Muxika & Franco, 2003) was calculated using the same data as for Figure 5.1, similar relationships were obtained e.g. outliers were still outliers.

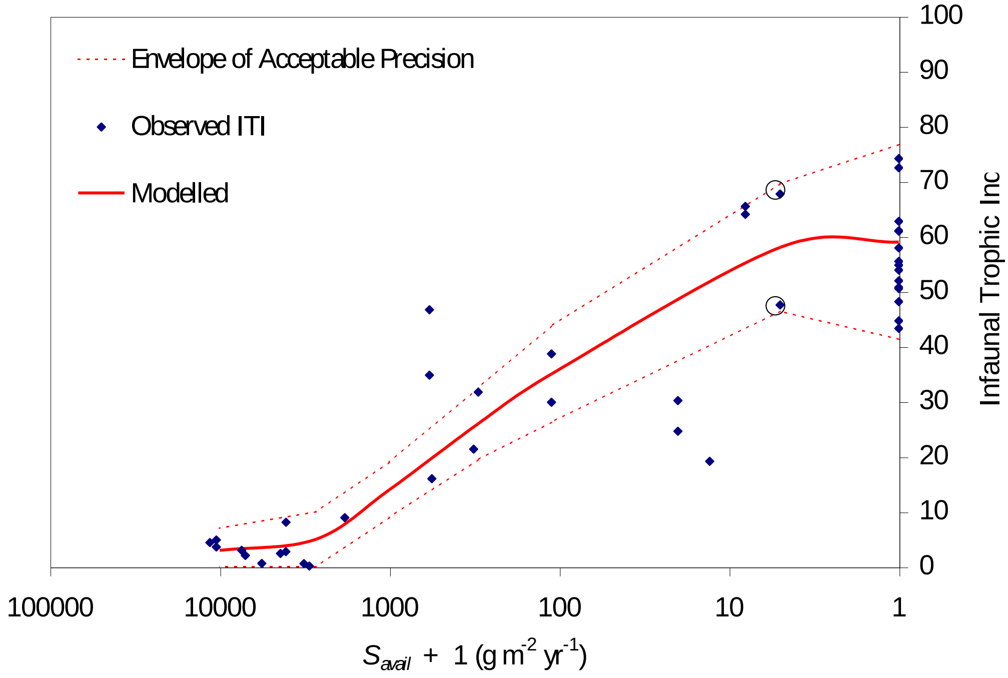


**Figure 5.1** Modelled solids accumulation ($S_{avail}$) plotted against observed Infaunal Trophic Index. Circles demonstrate the variation in the benthic composition of duplicate grabs and the Envelope of Acceptable Precision is defined to take account of this natural variation (88% of stations in EAP, n = 42 stations).

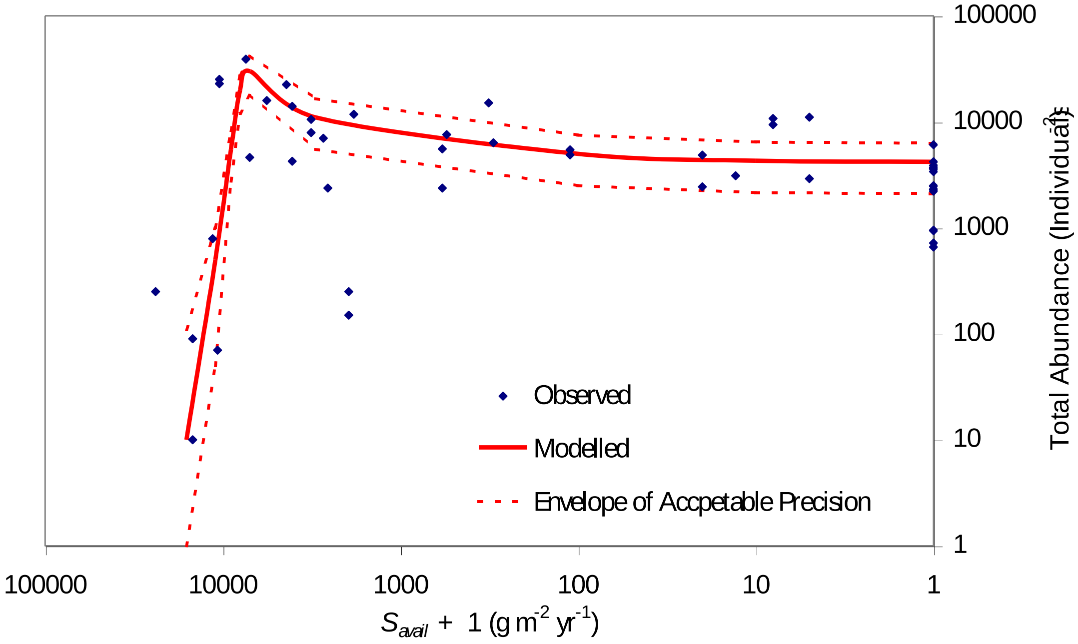


**Figure 5.2** Modelled solids accumulation ($S_{avail}$) plotted against observed total abundance. Envelope of Acceptable precision is shown by the dashed line (68% in EAP, n=50).

It can be seen from both figures 5.1 and 5.2 that the precise level of organic accumulation that will stimulate the crash of animal abundance and the reduction of species number to zero is difficult to predict given the paucity of data, the logarithmic scale and the width of the Envelope of Acceptable Precision. However, at accumulation rates greater than 10kg m$^{-2}$ yr$^{-1}$, highly significant effects on the benthos must be expected. Experience has shown that accumulation rates of 25kg m$^{-2}$ yr$^{-1}$ and above are likely to lead to extremely modified conditions with few or no animals. However, we have few data to support this as farms having such high accumulation rates are now rare (in Scotland). Additionally, such high accumulation rates are likely to be confined to relatively quiescent sites where the most extreme effects will be directly under the cages: an area hard to sample. This model has recently been tested in Canada (Chamberlain & Stucchi, 2007) who found that the existing parameterisation for resuspension of waste feeds was unsatisfactory and led to considerable deviation between model prediction and observation at a highly energetic site. In this case, the critical erosion threshold of 9.5 cms$^{-1}$, which is based on a field experiment designed to study the resuspension of faecal material but not waste feed (Cromey et al., 2002b), resulted in model simulations advecting all of the deposited particles from the model grid. Chamberlain and Stucchi (2007) propose that waste feed particles are dealt with separately and given erosion thresholds in line with those measured by Sutherland et al. (2006). They also determined that the uncertainty in the proportion of waste feed accounted for most of the uncertainty in model predictions (see discussion in section 3 above).

In Norway a model has been developed as part of a management system called MOM (Modelling – Ongrowing fish farms - Monitoring) (Ervik *et al.*, 1997). In the MOM system the environmental objective for the management of fish farm sites is that their impact must not exceed threshold levels that safeguard the wellbeing of both the fish and the environment. The aim of the model is to estimate the maximum production of fish that can be allowed without exceeding the holding capacity at the site (Stigebrandt *et al.*, 2004). The water quality in the net pens must be kept high to protect the fish, the impact on the sediment under the farm must not exceed the EQS, and the water quality in the recipient area must not deteriorate. The model comprises four sub-models (a fish model, a water quality model, a dispersion model and a benthic model) and is linked to a previously developed model on environmental quality in fjords (Stigebrandt, 2001) (Figure 5.3). The model was developed so it can be utilised by both environmental administrators and fish farmers. The MOM model is fully described on the ECASA website (www.ecasatoolbox.org.uk).

The output of the benthic sub-model is a maximum advised production that according to the model simulation will not result in azooic sediments under the farm. The model calculations require information 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 (such as cage size and orientation) of the farm is of importance. These factors as well as feeding rate and feed composition are taken into account in the model. The model simulations are designed to be closely linked to monitoring.

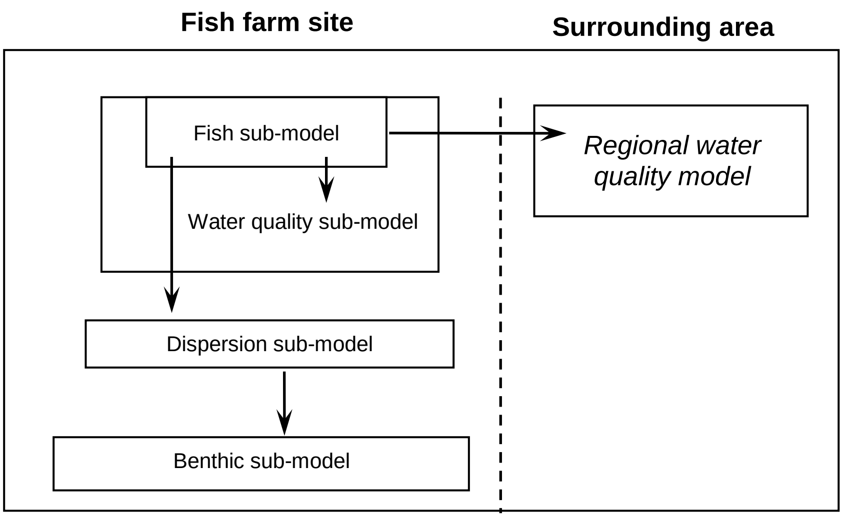


**Figure 5.3** Overview of the MOM model system. The local site model is linked to a regional (inshore) water quality model (Fjord Environment) (Aure & Stigebrandt, 1990). The output parameters from the fish sub-model are used as input parameters to the water quality sub-model, the dispersion sub-model and the regional water quality model. The dispersion sub-model delivers input parameters to the benthic sub-model.

There have been several other approaches to modelling wastes from salmon culture including the modular approach of Silvert and co-workers (Silvert & Cromey, 2001; Silvert & Sowles, 1996) and the GIS framework developed by Ross and Telfer and co-workers (Corner et al., 2006; Hunter, Telfer & Ross, 2006; Perez et al., 2002) but these are not currently used in regulation.

## 6 Regulation and mitigation of sediment impacts

Regulators must ensure that aquaculture developments meet aesthetic, social and economic criteria, and that there is harmonisation between new developments and local infrastructure capacity or other resource use, e.g. tourism. Planners and regulators have duties to ensure that developments do not adversely affect the environment. The objectives of regulation can be separated into three areas:

- protection of legitimate users of the environment, such as tourists or fishermen, so that environmental resources are fairly distributed.
- protection of the environment for its biological structure including protection of important/rare habitats and species
- protection of ecosystem functions such as the recycling of nutrients and the maintenance of oxygen levels

The first of these, which is the subject of Integrated Coastal Zone Management is addressed in the next section.

The second objective, the protection of ecosystem structure, may be intimately linked to the third, protecting ecosystem function, especially where the habitat structures have strong functional roles. For example, mangroves have been shown to have key functional roles in flood protection, in nutrient recycling and as nursery areas (Holmer, 2003; Primavera, 1998; Primavera, 2005). However, habitats may be deemed worthy of protection when their precise contribution to ecosystem function is unknown but they are considered to be rare, or have rare species assemblages, e.g. cold water corals and moves to protect them from trawling damage (Roberts, Wheeler & Freiwald, 2006). As an aside, cold water corals have been found in shelf waters in Scotland (Roberts *et al.*, 2005b) and in Norway near to fish farms, so protection from aquaculture activities as well as fishing must be considered.

Interactions between aquaculture and sensitive habitats or species can be minimised by establishing aquaculture zones in areas with less sensitive/important/rare habitats, or by designations that more closely regulate developments with respect to their interactions with particular features of concern. In Europe, Special Areas of Conservation (SACs) have been established under the Habitats Directive (92/43/EEC) for the protection of specific habitats.

Regarding the third objective, maintaining ecosystem function, regulation has been developed in all salmon growing countries to preserve the capacity of sediments to efficiently recycle organic wastes. Regulators have generally set sediment quality standards to protect the benthic environment around farms from severe degradation. In Scotland, for example, the regulator

(Scottish Environment Protection Agency, SEPA) is required to manage the impacts of fish farming to avoid unacceptable damage to the seabed and its fauna. They have established Sediment Quality Criteria (SQC) as indicators of when they will take action in order to reduce impacts e.g. by reducing the maximum allowable biomass or by entirely revoking the discharge consent. Many benthic indicators co-vary to some extent and together the SQC clearly show what regulators consider to be unacceptable benthic conditions.

In general, fish farming licences have monitoring conditions specified in detail: both their level (i.e. the number of stations, types of measurement and analysis) and their frequency are matched to the perceived risk of the farm. For example, a small farm over a hard substratum with strong currents will be monitored less intensively than a large farm over a soft substratum with weak currents. For Scotland, this process is given in great detail, together with its underlying philosophy and science, in the regularly updated Fish Farm Manual that can be downloaded from the SEPA website (www.sepa.org.uk).

SQCs are set to prevent azooia: for example, in Scotland, at least 2 species at high abundance are required as a mean across all replicates grabs, and not more than one replicate grab sample should contain no macrofaunal animals (Table 6.1). It is well established, although the process is not well understood (section 2), that the presence of macrofaunal animals increase the rate of degradation of organic carbon (Heilskov & Holmer, 2001). Thus, the objective is that farm sediments should contain a high abundance and biomass of bioturbating macrofaunal animals to enhance carbon degradation. This is in accordance with the objectives for Norwegian fish farming (Anon., 1997) and the monitoring programme in use (NSA, 2000) and is also consistent with the approach taken in other salmon farming countries (Wilson, Magill & Black, In press).

In most countries, large salmon farms require monitoring by a full macrofaunal survey and it is highly likely that catastrophic changes to the benthos will be detected by the regulatory process. However, even if the worst happens, the farmer will likely experience problems with fish performance before wide ranging ecosystem damage occurs unless the site is very deep. If monitoring shows that Sediment Quality Criteria have been or are likely to be breached, regulators generally have the right to request a biomass reduction or even the clearing of the site. Sometimes the farm can be moved within the licensed area to allow some benthic recovery for one or more cycles.

The main medicine used for treating sea lice infestation in Scotland is the in-feed Slice (emamectin benzoate), so discharges of organic material are intimately linked with discharges of this chemical, which has clearly defined Environmental Quality Standards (SEPA Fish Farm Manual). Thus it is possible that discharges of particulate organic material are actually limited by the chemical discharge – farmers must be able to treat all their stock sufficiently to ensure that lice levels are controlled to reduce infection of wild salmon and sea trout.

The SQC (or Action Levels, Table 6.1) are levels at which the regulator in Scotland may take action against the farmer. Implicit within the approach are:

- that the farmer is required to monitor the sediments around the farm to measure compliance or otherwise, and that this monitoring may be independently audited, and
- the concept of the Allowable Zone of Effects (AZE) or mixing zone.

The AZE or mixing zone concept is used in many salmon farming countries. The AZE represents an area around the farm where some deterioration is expected and permitted. Thus for several determinands, two SQCs are proposed: one within the AZE and one at any point outside the AZE. The SQC inside the AZE is less demanding than that outside the AZE. The SQC approach thus constrains the level of ecological change while the AZE limits the spatial extent of major changes. In Scotland, the AZE was formerly defined as the area bounded by a line 25m from the cage array perimeter, but now a less arbitrary approach is allowed where the AZE is determined with reference to the dispersiveness of the site using a modelling approach (AutoDEPOMOD) giving site-specific AZEs. This allows larger AZEs, and therefore larger discharge consents, in areas of high dispersion and is driven by the policy goal of encouraging development in more dynamic environments and reducing reliance on sheltered fjordic sites with low currents and, generally, longer residence times.

**Table 6.1 Sediment Quality Criteria (SEPA Fish Farm Manual, Annex A)**

| Determinand | Action Level Within Allowable Zone of effects | Action Level Outside Allowable Zone of effects |
|---|---|---|
| Number of taxa | Less than 2 polychaete taxa present (replicates bulked) | Must be at least 50% of reference station value |
| Number of taxa | Two or more replicates with no taxa present | |
| Abundance | Organic enrichment polychaetes present in abnormally low densities | Organic enrichment polychaetes must not exceed 200% of reference station value |
| Shannon -Weiner Diversity | N/A | Must be at least 60 % of reference station value |
| Infaunal Trophic Index ( ITI ) | N / A | Must be at least 50% of reference station value |
| Beggiatoa | N/A | Mats present |
| Feed Pellets | Accumulations of pellets | Pellets present |
| Teflubenzuron | 10.0 mg/kg dry wt/5cm core applied as a average in the AZE | 2.0 µg/kg dry wt/5 cm core |
| Copper | *Probable Effects* 270 mg/kg dry sediment *Possible Effects* 108 mg/kg dry sediment | 34 mg/kg dry sediment |
| Zinc | *Probable Effects* 410 mg/kg dry sediment *Possible Effects* 270 mg/kg dry sediment | 150 mg/kg dry sediment |
| Free Sulphide | 4800 mg $kg^{-1}$ (dry wt) | 3200 mg $kg^{-1}$ (dry wt) |
| Organic Carbon | 9% | |
| Redox potential | Values lower than -150 mV (as a depth average profile) OR Values lower than -125 mV (in surface sediments 0-3 cm) | |
| Loss on Ignition | 27% | |

In Norway, organic waste from marine fish farms is monitored according to Norwegian Standard NS9410 (NSA, 2000) as establish in the regulations by the Ministry of Fisheries and Coastal Affairs in the Aquaculture Operation Regulations (Anon., 2004). The standard is based on the monitoring programme from the MOM system (Hansen et al., 2001; Schaanning & Hansen, 2005). The MOM concept is based on the integration of elements of environmental assessment (model), impact monitoring and Environmental Quality Standards (EQS) in a single system, and where the amount of monitoring carried out depends on the degree of the environmental impact. The EQS set a limit for maximum allowable impact and makes it possible to distinguish between different impact levels.

NS-9410 focuses on methods for determination of sediment conditions at and in the vicinity of fish farms. Traditionally monitoring of benthic impact at fish farm sites has been faunal community analysis. This type of monitoring is maintained in NS-9410, but mainly in the surrounding area and, immediately at the site (equivalent to the AZE), less time-demanding and less costly indicators are evaluated. The scientific benefit of the more advanced faunal community method is balanced against the advantage of a higher number of samples and more frequent surveys. Smaller sampling gear allows sediment samples to be retrieved from between cages in compact cage groups. EQS's for environmental impact are set such that the fish farm sites may be in use over a long period of time and aim to ensure favourable living conditions for the farmed fish as well as to prevent unacceptable impact on the surrounding area. Presently NS-9410 describes monitoring of organic waste but sampling for medicines and chemicals in the sediment may be added.

Two terms are employed to adjust the monitoring to the impact at the site: 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 and the division between acceptable and unacceptable sedimentary conditions is set as the highest level of accumulation within which burrowing bottom fauna can survive in the sediment. The higher the degree of exploitation at a site, the greater the level of monitoring that is required.

At the fish farm site a number of indicators are used to determine how much the sediment is impacted by the farm activity. Because the survey is repeated regularly, at intervals determined by the extent of the environmental impact, trends in the environmental impact can be followed closely. At least ten grab samples are collected at the site and both the average condition at the site and the conditions under different parts of the fish farm are revealed. Three groups of sediment parameters are used: 1) presence or absence of animals larger than 1 mm in the sediment, 2) pH and redox potential and 3) qualitative determination of outgassing, smell, consistency, colour of the sediment, grab volume and thickness of the layer of deposits. All parameters are assigned points, according to the extent to which the sediment is affected by organic material. The points are added and the higher the sum the more affected the sediment. Since many parameters are used in concert the survey is less sensitive to anomalies in individual parameters. EQS have been established which divide the sediment condition into four categories equivalent to the four degrees of exploitation and like the Scottish system (Table 6.1) there are upper threshold limits for allowable effects.

Outside the site area the allowed impact is much less than at the site and primarily biological parameters are used to determine the effects. The main element is a survey of the bottom faunal communities, carried out according to another Norwegian Standard: "Water quality – Guidelines for quantitative investigations of sub-littoral soft-bottom benthic fauna in the marine environment NS-9423", which describes guidelines for sampling and sample processing of macro fauna in soft sediments (Norwegian Standards Association, 1998). In addition, information is obtained on additional parameters that may be used to determine if organic material is of fish farm origin. The pollution control authorities have defined threshold values for environmental quality of fjords and coastal waters (Molvær et al., 1997), and these are applied to the recipient area. However, specific threshold values are provided in NS-9410 when the investigation is used close to the farm.

Most countries (Wilson et al., In press) follow some variant of the approach in Scotland where benthic monitoring is comprehensive, covering a wide range of determinants including a full macrofaunal survey at several stations, usually once every 2 years at the predicted maximum biomass. This is in contrast to the Norwegian MOM system where higher frequency but less extensive investigations are required and full macrofaunal surveys are less common and mainly used outside the AZE.

In Norway, fish farmers have started taking advantage of the deep inshore waters in many regions with farms gradually being relocated to deeper sites, normally exposed to stronger currents. This relocation is still going on and production is now concentrated in fewer but larger farms – a trend followed in several other countries. Furthermore, fish farms use several sites by rotation allowing the abandoned sites to fallow. Today a typical Norwegian fish farm produces 2000 to 5000 tonnes of salmon or rainbow trout within an 18 months production cycle and the normal depth at the sites ranges from 50 to 300 m. The surface currents are still relatively low and are normally on average in the range 2.5 to 3.5 cm $s^{-1}$ but the periods with very low currents are few and short. At such sites, particles are spread over a large area of the seabed, resulting in a reduced sedimentation rate beneath the farms. The grossly polluted impact zone described by Pearson and Rosenberg (1978) is thus seldom found although with constantly increasing production monitoring results indicate that the benthic impact at a number of sites is increasing.

Assimilative capacity is a useful concept for waste generating activities such as farming. In terms of the seabed environment around a cage farm, the assimilative capacity is usefully defined as the maximum rate of input such that benthic communities do not deteriorate beyond minimum criteria even on continuous usage. Salmon are farmed on a 2 year cycle where maximum biomass is achieved and sustained throughout the second farming year. Thereafter, farms are usually cleared for 6-8 weeks before the farming cycle is restarted. Thus every second year the seabed under the cages experiences a high sedimentation rate and every other year starts with a period of no organic input followed by a steady rise to maximal levels as the fish grow.

Fallowing is a term often used for 2 distinct processes: the period of a few weeks between farming cycles when fish are absent from a site after harvesting and before the next restocking – primarily to break disease cycles; and the practice of site rotation where a site may be left empty for one or more years for the sediments to recover. Site rotation has been recommended both by regulators and by scientists (e.g.,Carroll *et al.*, 2003) as a method of reducing benthic impacts by allowing time for recovery. However, there is evidence that such site rotation merely allows an otherwise unsustainable site to remain in production on a periodic basis (Hall-Spencer et al., 2006; e.g., Pereira et al., 2004). A better solution would be to limit the scale of production at any site such that it does not break EQS's even after repeated farming cycles i.e. within the assimilative capacity of the site. However, this may not be a practical option for other reasons, e.g. lack of alternative sites at an appropriate distance from logistical support. The timescale of recovery is discussed above (section 4). While there are certainly site- and regional-scale differences in recovery processes, it seems clear that significant chemical recovery occurs relatively quickly, as labile organic carbon is degraded over a few months. Biological recovery may take years depending on the site, but there appears no reason to require full recovery given that the benthos will be impacted again as soon as the next farming cycle recommences.

As discussed above, regulations are currently focussed on the spatial extent and the degree of benthic disturbance. This means that the farmer has an interest in minimising particulate wastes from the farm. However, the link between increased particulate wastes and increased benthic impact may not become apparent until many months later when a benthic survey is done and the results analysed. A more direct approach at modifying farmer behaviour is to limit the total amount of feed available to a farm over a farming cycle, rather than the maximum biomass that may be farmed. The farmer thus has an even clearer commercial interest in minimising waste feed as this will reduce the total production potential of the farm. Provided that adequate measures are in place to regulate supplies from feed companies and ensure that there is no "black market" trading of feed, this method has the potential to reduce over-feeding and thus reduce benthic impacts. However, it is not a substitute for benthic regulation and monitoring which has the clear focus of assessing the functioning of the sedimentary system.

In contrast to many other salmon farming countries, many farming companies in Scotland have recently submitted themselves to an independently accredited auditor as part of the Scottish Code of Practice[7].

Direct control measures involve the control of feeding using various feedback systems and regular measurements of food conversion ratio. The Code of Practice includes the following:

> *"6.3 Use of Feed*
> *6.3.1. All farmers should have a written feed management plan, which might include (but not exclusively) guidance on the following points:*
> *• feeding the correct feed size for the fish;*
> *• feeding the correct amount of feed to any population of fish, in the proper manner and over the correct period(s) of the day;*

[7] A Code of Good Practice for Scottish Finfish Aquaculture: www.scottishsalmon.co.uk

*• regular monitoring of feed conversion efficiency (following sample weighing), and assessment of whether staff feeding protocols and guidelines are effective; and*

*• the use of 'feedback loop' feeding systems should be considered, since these improve conversion efficiency, decrease environmental impact, and generally ensure that finfish feed is used as efficiently as possible"*

It must be stressed that the code of practice is additional to statutory regulations. Its usefulness will depend on the transparency and independence of the external auditing.

**7 Salmon farming and other users of the coastal resource**

In many salmon growing countries, aquaculture is a major driver of the Integrated Coastal Zone Management (ICZM) agenda as it is a significant user of space, assimilative capacity, and visual amenity, but is also a significant contributor to local economies. ICZM has 8 principles (defra, 2006):

**"a. A broad holistic approach**

The objective of a holistic approach is to forego piecemeal management and decision making in favour of a more strategic approach which looks at the 'bigger picture', including cumulative causes and effects. This means considering the conservation value of natural systems alongside the human activities which take place on land and coastal waters.

Taking a holistic approach will also involve looking at the problems and issues on the coast in the widest possible context, including looking at the marine and terrestrial components of the coastal zone and considering how different issues conflict or interact together.

**b. Taking a long term perspective**

Successful coastal management must consider the needs of present and future generations. Therefore, administrative structures and policies required to manage the environmental, social and economic impacts now, must also be adaptable to take account of, and acknowledge, uncertainties in the future.

**c. Adaptive management**

The … coastline has been subject to constant physical and economic changes over the years, and management of such a dynamic environment requires measures which are able to adapt and evolve accordingly. Successful management should reflect this principle by working towards solutions which can be monitored effectively.

**d. Specific solutions and flexible measures**

Coastal management measures for each stretch of coast must reflect and accommodate the many variations in the topography, biodiversity and local decision-making structures. Integrated management should therefore be rooted in a thorough understanding of the specific characteristics of an area i.e. its local specificity.

**e. Working with natural processes**

The natural processes of coastal systems are continual, so it becomes necessary in some instances to adopt a different approach which works with natural processes rather than against them. By recognising the physical impacts and the limits imposed by natural processes, decisions regarding the human impact on the coastal zone are made in a more responsible manner and are more likely to respond to environmental change.

**f. Participatory planning**

In the past stakeholders may not have had sufficient opportunity to contribute towards the development and implementation of coastal management measures or programmes. Participatory planning incorporates the views of all of the relevant stakeholders (including maritime interests, recreational users, and fishing communities) into the planning process. It can also help to promote a real sense of shared responsibility and coastal stewardship by reducing conflict as real issues, information and activities which affect the coast can be aired more openly.

**g. Support and involvement of all relevant administrative bodies**

Administrative policies, programmes and plans (land use, spatial, energy, tourism and regional development for example) set the context for the management of coastal areas and their natural and historical resources. Addressing the problems faced by … coastal zones will therefore require the support and involvement of all relevant administrative bodies at all levels of government to ensure cooperation, coordination and that commons goals are achieved. It is therefore essential to engage key bodies from the start so that decisions are consistent and firmly based on local circumstances.

**h. Use of a combination of instruments**

Managing the different activities which take place on the coast requires the use of a number of different policies, laws and voluntary agreements. While each of these approaches is important, achieving the right combination is key to resolving conflicts, as these instruments should work together to achieve coherent objectives for the planning and sustainable management of coastal areas."

Relatively few studies have considered cumulative and synergic impacts of multiple activities (salmon farms, agriculture, shellfish farms, water treatment works, industrial effluents) in shared water sheds and water bodies (Strain, Wildish & Yeats, 1995).  In general, for basin scale rather than local scale effects, nutrient budgets are the most important environmental element. In terms of benthic impact, one of the major anthropogenic impacts in the marine environment comes from dredging or benthic trawling (Kaiser *et al.*, 2006) with recent evidence that impacts are long lived and change ecosystem functioning (Tillin *et al.*, 2006) over wide spatial scales (Hiddink, Jennings & Kaiser, 2006). In contrast, while space utilisation in a particular bay might be high, salmon farms occupy only a tiny fraction of coastal seas. By designating areas for aquaculture, or giving farmers exclusive access to sites, it is likely that farms may act as refuges for some species. This is especially obvious with sea bass/bream farming in the Mediterranean, where wild fish aggregate around farms and may experience reduced fishing pressure (Dempster et al., 2005; Dempster et al., 2004). It is thus vital to ensure that fishing is not allowed close to fish farms as this might have the effect of increasing catch per unit effort if target species aggregate there.

Cumulative impacts from farms have typically been considered in terms of the potential for hyper-nutrification. Regarding the benthos, some attention has been given to the potential for particulates from fish farms to cause hypoxia in fjordic basins including a component of the FjordEnv component of the Norwegian MOM system (Stigebrandt, 2001) and a recent study in Scotland (Gillibrand *et al.*, 2006). The latter modelling study concluded that pelagic oxygen demand was more important than benthic oxygen demand in terms of depleting oxygen and in most loch systems this meant that particulate carbon from the farm had little effect on the overall oxygen depletion rate of isolated bottom waters. However, this report acknowledged that understanding in this area is weak as few measurements of benthic and pelagic oxygen demand have been made in such systems. Processes and rates of vertical diffusion of salt and oxygen between basin waters and overlying layers, which contribute fundamentally to basin water renewal and oxygen concentrations, are also poorly understood. In many areas hyperntrification of the water column rather than loss of benthos is likely to be a much more important constraint on industry expansion in semi-enclosed water bodies, but in some fjords the water exchange in the upper layers can be high yet the bottom water stagnant and the deposit of organic fish farm waste directly to the deep area could result in hypoxia.

Marine spatial planning, an element of ICZM, is on the policy agenda for most developed maritime countries (Boyes et al., 2007; Bruce & Eliot, 2006; Cicin-Sain & Belfiore, 2005; Doherty & Butler, 2006; Douvere et al., 2007). Some studies have used GIS tools to determine areas with the appropriate environment for farming while also minimising potential conflicts with other users (Hunter et al., 2006; Perez, Telfer & Ross, 2003).

Recently there has been an examination of truly offshore aquaculture technologies (Colbourne, 2005; Plew *et al.*, 2005) and socio-economics (Skladany, Clausen & Belton, 2007) in the anticipation that such installations will have fewer environmental impacts and be capable of operating at much greater scales. However, a recent report from the UK (James & Slaski, 2006) highlighted “deficiencies in technical capacity, biological understanding and legal impediments that may stifle attempts to conduct aquaculture offshore”.

A variety of regulatory tools exist to prevent aquaculture expansion in areas that are considered environmental sensitive or important (section 7). Some of these are directly focussed on aquaculture (e.g. A et al., 2002) whereas some, such as European Special Areas of Conservation, require an assessment of any human development with respect to the feature that has prompted the designation. In many ways this is a more robust and fair approach and, as there is often an imperfect knowledge of the diversity of benthic species and habitats in the coastal zone, the designation of a percentage of the coastal area for conservation purposes (Marine Protected Areas) should be encouraged without the need to specify the particular conservation feature. Such MPAs should provide protection from a wide range of human activities, including intensive aquaculture, and should ideally form part of a planned network (Gell & Roberts, 2003; Roberts et al., 2003; Roberts, Hawkins & Gell, 2005a; Rodwell & Roberts, 2004).

In the future, environmental impact is expected to gain increasing focus and the competition for space and resources in the coastal zone will increase. Sustainability and integration with other coastal activities are therefore prerequisites for an expanding aquaculture industry. Regulatory systems that can ensure environmentally acceptable operation in the coastal zone are therefore needed. In Norway such a system for aquaculture planning and operations is under development. The aim is to ensure an efficient use of the areas available for aquaculture and to adjust the environmental impact of the industry to the holding capacity of the area. The system called MOLO (MOm-LOcalization) will cover both the planning and the operational phase of aquaculture. In coastal zone planning, GIS systems providing information on local topographical and hydrographical information, as well as an overview of allocation of different uses and environmental status, will be combined with simulation models to site aquaculture activities and to adapt the environmental impact to local and regional holding capacity.

The planning part of MOLO is based to the concept of the LENKA project (Ibrekk, Kryvi & Elvestad, 1993; Levings et al., 1995), where an area capacity is defined as the amount of aquaculture products that can be produced in the area under the current regulations and with regard to other uses and users of the area, and recipient capacity gives information on how much can be produced in the area with regard to the environmental impact without breaching environmental quality standards. Monitoring is an integral part of the operational phase of MOLO.

The expansion of the aquaculture industry depends on its ability to participate as a trustworthy partner in integrating coastal zone management. More emphasis must therefore be but on clarifying the industry’s need for coastal resources like space and recipient capacity. Equally important is the need to further define sustainable and publicly accepted environmental quality standards for aquaculture and to enforce mandatory regulatory systems that can ensure the standards are not breached – a significant challenge in several countries.

## 8 Site selection and commercial considerations

A key commercial constraint is the availability of good sites as in most countries the availability of new sites is strictly limited. In general, a good fish farm site has moderately strong currents (means of 5-10 $cms^{-1}$), is moderately deep (40+ m), has low exposure to large waves (significant wave heights[8] of 2 m or less), is out of sight of tourist facilities and distant from major human habitation, is sufficiently far from other salmon farms as to reduce disease transmission between farms (ideally greater than one tidal excursion distance), and is not in an area of important natural or social heritage. Additionally, sites should not contribute additional nutrients to the water body that would exceed the assimilative capacity taking other sources into account. The site should have access to sufficient medicine discharge permission to reduce the risk of cross-infection between farmed and wild salmonids, and should not be within the immediate vicinity of a river with an important salmon river. No clear advice is possible on this last topic as escaped farmed salmon have been shown to be capable of travelling long distances before entering rivers. In recognition of this, and of the potential damage to wild salmon populations from escapes, farmers are involved in mitigation schemes which focus on appropriate engineering (e.g. NYTEK in Norway[9]) and escape recovery plans[10].

A site with the above characteristics should reduce the risk of significant environmental damage allowing the farmer to operate at a scale that allows economic production in a highly competitive market. There are of course additional commercial considerations: the site must be convenient to human infrastructure such as labour, accommodation, transport facilities, and ideally markets. Operator safety is also a key issue especially where more exposed sites are considered. Aquaculture associations are already interested in assessing their carbon footprint throughout the production cycle and this interest is likely to grow in the coming years as climate change concerns increase along with fuel prices.

Thus there are a very large number of factors that comprise a good site and in general a lack of such sites for the expansion of the industry at least in some countries e.g. Scotland. Compromises are therefore made. Sometimes a farmer may be able to negotiate access to a new site on condition that a more environmentally damaging site is abandoned. Site amalgamations are common as farmers seek to benefit from economies of scale and these can lead to environmental benefits where poor sites are closed but also environmental costs if the assimilative capacity is breached in the process.

[8] The average height of the highest one third of waves recorded in a given period.
[9] www.tekmar.no/tema/ns9415.asp
[10] A Code of Good Practice for Scottish Finfish Aquaculture: www.scottishsalmon.co.uk

Other key issues for farmers at present include:

- Economic sustainability in an expanding global market and industry
- Sustainability of feed supply
- Access to effective sea lice medicines

The first point is beyond the scope of this report but it is often overlooked that good environmental standards have a financial cost and a profitable industry has both more resources and more to lose from a poor public image of environmental performance.

Considerable strides have been taken on reducing the amount of fish meal and oil in fish feed by substitution with vegetable sources (Stubhaug *et al.*, 2005; Torstensen *et al.*, 2005). This may be important given the often higher FCRs achieved with highly substituted diets (Mundheim et al., 2004; Young et al., 2005). More worrying is the situation with sea lice medicines. As the industry moves to larger cages and more exposed environments, the logistics of bath-treatments become increasingly difficult. Thus the industry must rely on in-feed medicines for the future. The in-feed medicine Slice (emamectin benzoate) has a good record in terms of toxicity to benthic invertebrates (Telfer *et al.*, 2006) but there is evidence of a reduction in efficacy over time (Lees et al., 2008). Should resistance to Slice develop, as seems inevitable, and no benign but efficacious successors become available, the prospect of either increased lice burdens or in-feed products with higher ecotoxicity is a serious cause for concern.

## 9 Conclusions and recommendations for further research

As mentioned above, scientific uncertainties still exist which do not allow us to confidently predict many important benthic responses, e.g. the precise determination of the accumulation rate that causes azoia. For this, we require much better understanding of the relationships between organic accumulation, sediment geochemical response, consequences for the faunal community, and the role of bioturbation and bioirrigation in carbon degradation by microbial processes. This requires a combined experimental, observational and modelling approach, with a focus on sediment biogeochemistry. Ideally, such understanding would lead to simple chemical proxies (indicators) of sediment state from which faunal community state could be inferred. However, as recovery processes have a biological dependency (e.g. seasonal larval supply) it is also important that we increase our understanding of invertebrate life histories at the species level – a grossly under-researched area. A better understanding of the effects of sediment contamination with Slice and copper is also required. Further studies on the process of resuspension of farmed wastes should be carried out.

The future for the salmon industry must include:

- continuously improving environmental performance;
- reduced waste feeds, e.g. through more use of feedback-controlled feeding;

- better matches between benthic assimilative capacity and site biomass;
- common environmental quality objectives across salmon growing countries with appropriate quality standards set to offer a similar levels of environmental protection;
- and high standards of monitoring and enforcement by well resourced regulatory bodies.

These objectives can be best met by:

- co-operation between farmers, regulators and scientists, including co-funding of research;
- industry funding of monitoring; state funding of environmental auditing;
- increased transparency of environmental information;
- improved communication between regulators in different countries;
- appropriate training for both farmers and regulators;
- and improved scientific understanding and its application through effective regulatory tools, models and indicators.

The rapid increase in the Chilean salmon industry has not been matched by published scientific studies on benthic impacts. However, there is information available in the Spanish language literature and it important that this should be reviewed in order to inform a robust programme of scientific research to underpin policy and regulation to protect the environment.

It is in the salmon industry's best interests that there is transparency of environmental performance, clear regulation of impacts and strict compliance enforcement to equivalent environmental standards.

## 10. Acknowledgements

The authors acknowledge the contributions of several anonymous reviewers. Kenneth Black acknowledges the contributions of Chris Cromey and Thom Nickell whose comments and contributions have improved this report. Kenneth Black acknowledges the support of the EU FP6 Ecosystem Approach for Sustainable Aquaculture - ECASA project (006540).

Thanks to Katherine Bostick for advice, help and encouragement.

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