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 parameters varying in importance at different stages of the process. The authors identified sedimentary oxygen uptake as the primary indicator in macrofaunal recolonisation.

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

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 a recent study did not find a relationship between Slice in sediments and community changes at active sites (Black *et al*. 2005), 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 and Black 2007). Brooks and co-workers argue that copper in enriched sediments is likely to be bound as sulphides and therefore not bioavailable (Brooks and Mahnken 2003; Brooks *et al*. 2004).

More recent approaches to modelling inputs to the seabed from cage farming have yielded an improved understanding of effects on the macrofaunal community. The DEPOMOD model has a benthic component (Cromey, Nickell and Black 2002a; Cromey *et al*. 2002b; Strain and Hargrave 2005), which at present predicts biological responses to organic matter accumulation; current work is focused 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 and Watling 1997); they also noted the potential for increased recovery times due to the presence of heavy metals in the sediment.

The effects of organic flux to the benthos have best been described in qualitative terms by Pearson and Rosenberg (1978, Figure 6.1.7).

A quantitative empirical approach has been taken by Cromey and co-workers (Cromey *et al*. 2002a) who have related predicted organic accumulation[3] , using the DEPOMOD model, to benthic response (Figure 6.1.8, 6.1.9).

Figure 6.1.8 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 pollution (Feeding Group 4). ITI becomes very low at high flux values (Figure 6.1.8). The empirical relationship between flux and total animal abundance (Figure 6.1.9) 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 6.1.8). Direct relationships between flux and number of species are less clear from the dataset that these workers possess.

It can be seen from both Figures 6.1.8 and 6.1.9 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 (EAP). It is sufficient to say that 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 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 that is difficult to sample.

At the Dunstaffnage farm, at the present 700 tonnes biomass, faunal abundance at reference station 2 (REF2, Table 6.1.II) is relatively low compared to typical sea loch benthic samples, but high species diversity (S=58) is indicative of an unperturbed sea loch community. At reference station 1 (REF1, Table 6.1.II), abundance is low as is species diversity, indicating some degree of perturbation – this is unlikely to be caused by fish farm activity owing to the distance from the site (880 m). The most impacted site was found at the cage edge with a relatively low number of species (8) and high abundance. Thus, the previous stocking regime at the site clearly did not breach the Sediment Quality Criterion threshold of less than two abundant species.

6.1.3.4 Consequence Assessment

Logic model

The series of steps and processes, leading from the release of wastes from the Dunstaffnage Farm at the increased biomass through to the change in the benthos below the farm, illustrated in the logic model below (summarised in Table 6.1.III).

[3] 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.

Figure 6.1.8 : Modelled solids accumulation (S_{avail}) plotted against observed Infaunal Trophic Index (ITI). Circles demonstrate the variation in the benthic composition of duplicate grabs and the Envelope of Acceptable Precision (EAP) is defined to take account of this natural variation (88% of stations in EAP, n = 42 stations).

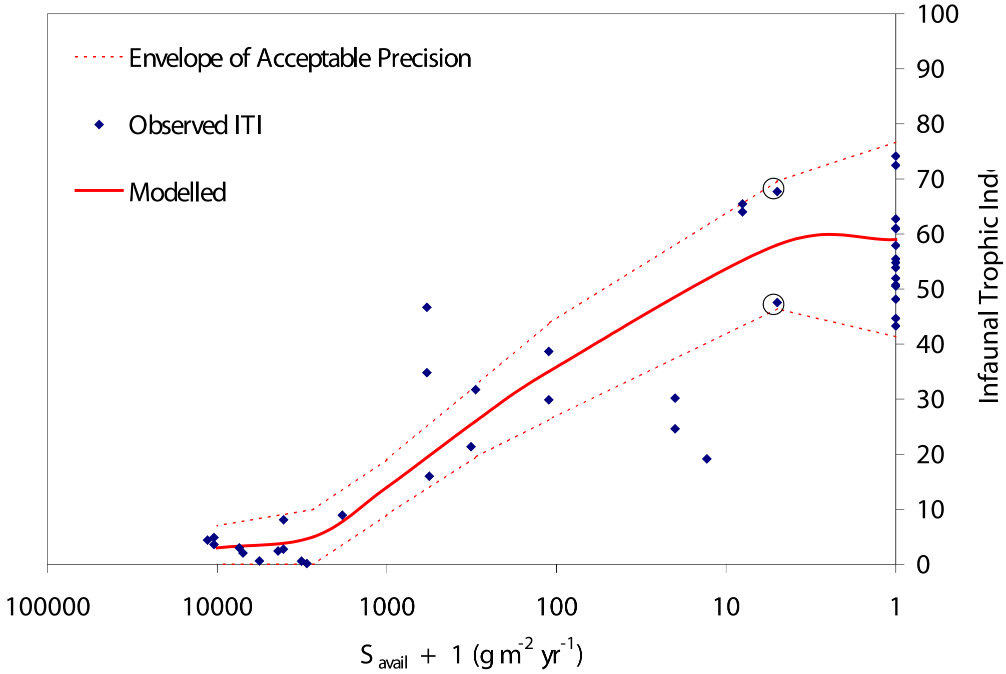
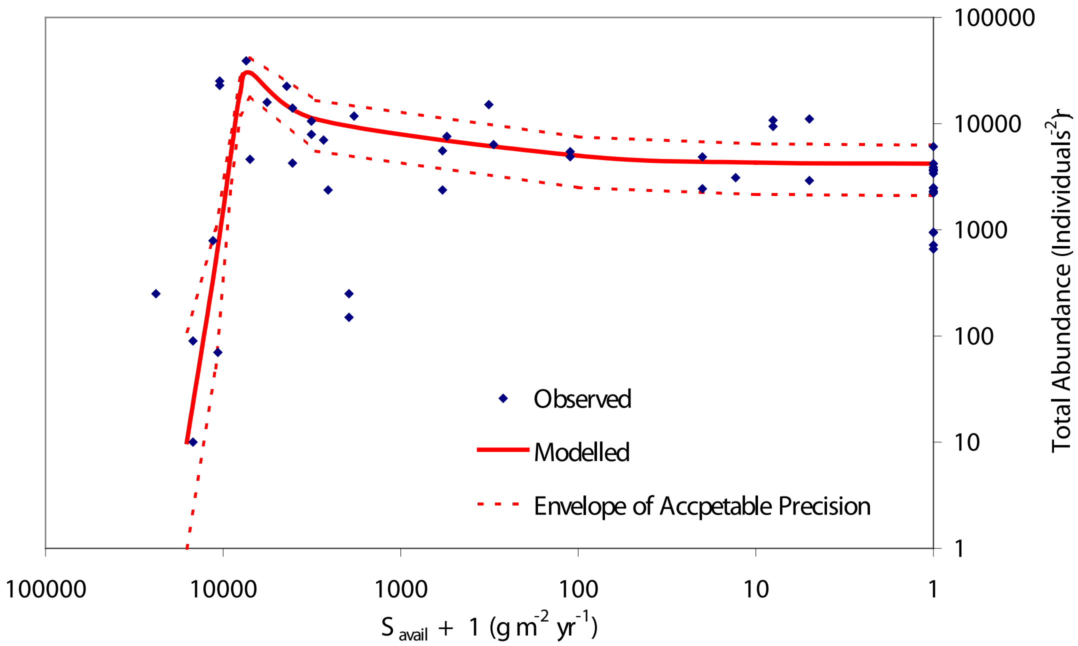


Figure 6.1.9 : Modelled solids accumulation (S_{avail}) plotted against observed total abundance. Envelope of Acceptable Precision (EAP) is shown by the dashed line (68% in EAP, n=50).



Process of concern: Change in the benthic community

End Point of Concern: Macrofauna has less than two highly abundant species.

Logic model steps:

i. Waste food, faecal material and fouling biomass are released from the farm.
ii. Organic wastes intercept the seabed.
iii. Organic wastes accumulate on the seabed and are degraded by sedimentary micro-organisms facilitated by macrofauna.
iv. The benthos is degraded such that there are less than two species with high abundances within the Allowable Zone of Effect (AZE) at peak farm biomass.

The information presented in the preceding sections of this risk analysis allows annotation of each step in the logic model to indicate the likelihood that each step has been, or will be, completed.

i. Waste food, faecal material and fouling biomass are released from the farm

Release of faecal material is an inherent property of fish. Wastage of feed is certain also, but the amount of wastage is not certain. Release of fouling biomass is likely but not quantifiable except to say that it will likely be insignificant compared to faecal and feed wastes. The severity of this effect will depend on the amount of feed actually wasted. Given the assumption of 5% waste feed (moderate intensity) made above, the lilmited geographical distribution on the bottom (low), and the short duration (low) after removal of the farm, we assess the severity of this step as Moderate, as this is a medium sized farm; the probability as High, as a great deal is known about this process; and the uncertainty as Low.

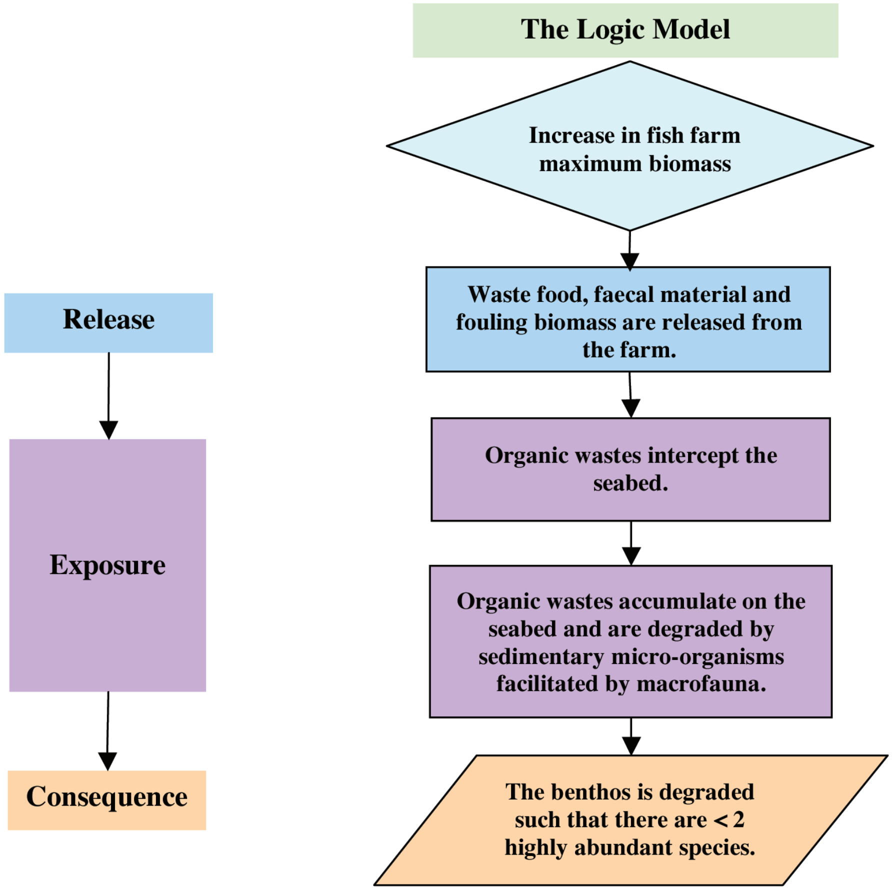
ii. Organic wastes intercept the seabed

The process is driven by the ambient hydrodynamics. The current data indicate that the farm is of medium dispersiveness compared to many other Scottish sites, thus a very significant proportion (intensity - high) of the wastes will intercept the seabed immediately in the vicinity (spatial extent - low) of the farm, and the short residence time of the waste material after removal of the farm (low - duration). This is confirmed by the DEPOMOD model. The Severity is therefore High, the probability is High and the uncertainty is Low. The removal of wastes by wild fish is assumed to be negligible.

iii. Waste food, faecal material and fouling biomass accumulate on the seabed

Resuspension may be an important process as the site is exposed to moderate tidal and wind driven currents. From the near-bed current velocity plot (Figure 6.1.3), it is clear that speeds in excessive of

Figure 6.1.10 : Logic model for benthic community impact from particulate organic wastes from marine fish cage culture.



the DEPOMOD (Cromey *et al*. 2002b) default critical resuspension velocity (90 mms^{-1}) are common. However, some accumulation can be inferred at the existing biomass from loss-on-ignition data, which showed an increased of organic matter (OM) from ~11% at background to ~ 17% at the cage edge. An increased tonnage is likely to increase the rate of production of wastes and increase OM accumulation rate.

The Severity of this step is likely to be Moderate as the degree of change will be incremental on what already exists (Intensity - Moderate), the duration after removal of the farm will likely be no more than a few years (Duration - Low), but the geographic extent will be limited to the area around the cages (Spatial Extent - Low). The probability is High, given the existing data; and the uncertainty is Low, given that a validated model predicts this outcome.

iv. The benthos is degraded such that there are less than two species with high abundances.

The DEPOMOD approach of linking a particle tracking model to an empirical relationship between carbon flux to the bed and indicators of benthic effect is inherently attractive. It has proven to give a good first approximation of the assimilative capacity of a site. However, more subtle factors related to the supply and demand for oxygen are less well understood (Findlay and Watling 1997). According to these authors, an important driver of benthic function is the duration over which supply drops below demand for oxygen. If the drop is sufficiently prolonged, then macrofaunal mortality is expected.

At the Dunstaffnage site, currents rarely drop to zero and then only very briefly (Figure 6.1.3). Developments in DEPOMOD involving its coupling with a biogeochemical sediment model of carbon degradation should allow dynamic predictions of oxygen flux in the future. However, at present we rely on expert judgement of the current record, in conjunction with the DEPOMOD prediction, to estimate risk.

In our judgement, periods of low oxygen supply at this site will not be sufficient (Intensity - Low) to cause episodic (Duration - Low), widespread macrofaunal mortality (Spatial Extent - Low) at the proposed new biomass and consequent organic accumulation rates. Thus we predict that the SQC will not be breached and therefore that the Severity is Low - the effect will be dramatic under the cages but, as mentioned above, the spatial extent will be very limited and the temporal extent probably limited to a few years. The probability of this outcome is Moderate rather than high, as there must remain some possibility that the SQC will be breached given the high predicted accumulation rates. The uncertainty is Moderate because of uncertainty in the representativeness of the current measurements – there are probably more periods of low current speeds during summer than during the winter (when the currents were measured), but also because there is considerable uncertainty in the precise relationship between number of species and abundance at very high accumulation rates.

The consequence analysis is summarised in Table 6.1.III.

The final severity rating (Low) appears reasonable: a significant change to the benthos is predicted but we do not expect that the SQC will be breached. Benthic systems at the highly enriched stage may be relatively resilient to being pushed into azooia as the species remaining are already highly adapted to hypoxia and sulphide. However, the overall probability of this assessment is only Moderate, as is the degree of uncertainty. This is again reasonable, as the increased tonnage is a factor of around two, with a doubling of the input of organic material to the bed. Although we have data from other sites (not given here) that show that high abundances of animals can persist at even higher accumulation rates, the precise relationships between the carbon accumulation and benthic response has significant uncertainties and the hydrographic input data are unlikely to capture the full variability of the dynamics of the site.

6.1.3.5 Risk Estimation

The Company has made applications to the regulator SEPA for the increased biomass but has also been required under the Scottish implementation of the EU Environment Impact Assessment Directive to prepare a detailed Environmental Statement outlining the main potential hazards of the proposed development and mitigation measures that will be used. This Environmental Statement is a public document and is used by the Local Government planning process to elicit comments on the proposal from statutory (Scottish Natural Heritage, SEPA, any local District Salmon Fishery Board and the Scottish Government) and non-statutory consultees (many of whom are stakeholders – a list is given in Annex 2), as well as the general public. The final decision, in the light of any objections or comments, and taking into account the opinion of the Local Planning Department, will then be taken by the Local Authority Planning Committee – a body of elected representatives.

The company employs an environmental management system with comprehensive staff training and submits itself to an independently accredited auditor as part of the Scottish Code of Practice (A Code of Good Practice for Scottish Finfish Aquaculture: www.scottishsalmon.co.uk). Direct control measures involve the careful 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:

Table 6.1.III : Dunstaffnage site Logical model outcomes in summary.

Steps in the logic model	Intensity	Spatial Extent	Duration	Overall Severity	Probability	Uncertainty
Step i. Waste food, faecal material and fouling biomass are released from the farm	M	L	L	M	H	L
Step ii. Organic wastes intercept the seabed	H	L	L	H	H	L
Step iii. Waste food, faecal material and fouling biomass accumulate on the sea bed	M	L	L	M	H	L
Step iv. The benthos is degraded such that there are less than 2 species with high abundances.	L	L	L	L	M	M
Final Rating [4]				L	M	M

Explanatory notes:
Severity = C – *very severe,* **H** – *high,* **M** – *Moderate,* **L –** *Low,* **N** – *Negligible The three components of severity - intensity, the geographic extent, and the duration of the change (in grey) - are separately assessed to inform an overall severity rating.*
Overall Severity = *the highest of the 3 severity sub-components*
Probability = H – *High,* **M** – *moderate,* **L** – *Low,* **EL –** *Extremely Low,* **N –** *Negligible*
Uncertainty = H- *Highly uncertain,* **M** – *Moderately uncertain,* **L** – *Low uncertainty.*
The final rating for the **Probability** *is assigned the value of the element with the* **lowest** *level of probability. The final rating for the* **Severity** *(intensity of interaction) is assigned the value of the step with the* **lowest** *risk rating (e.g.,* **Medium** *and* **Low** *estimates for the logic model steps would result in an overall* **Low** *rating). The final value for severity for each specific risk is assigned the value of the lowest individual logic model estimate. The final rating for the* **Uncertainty** *is assigned the value of the element with the* **highest uncertainty** *level (i.e. the least certainty).*

Table 6.1.IV : Possible mitigation and research activities to reduce the probability of steps in the logic model occurring, or reduce the uncertainty in the estimate of that probability.

	Logic Model Step	Probability	Mitigation (regulate/design/ modified practices)	Uncertainty	Research/Development
1	Waste food, faecal material and fouling biomass are released from the farm	H	Where feasible move to land- based production	L	Develop economically competitive land-based technologies with appropriate waste treatment.
2	Organic wastes intercept the seabed	H	Intercept and recover solid wastes before they reach the seabed	L	Improve cage designs to allow *in situ* waste recovery
3	Waste food, faecal material and fouling biomass accumulate on the sea bed	H	Ensure sites are consented over non-accumulating seabeds i.e. dispersive sites	L	Improve modelling of accumulation of waste materials at dispersive sites using hydrodynamic models
4	The benthos is degraded such that there are less than 2 species with high abundances.	M	No feasible mitigation	M	Improve/develop biogeochemical and ecological models that better predict impacts Improve understanding of infaunal life-histories and behaviours

- *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;*
- *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"*.

As farms of this size require monitoring by a full macrofaunal survey, 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 probably experience problems with fish performance before wide ranging ecosystem damage is possible. If monitoring shows that that Sediment Quality Criteria have been or are likely to be breached SEPA have the right to request a biomass reduction or even the clearing of the site. More likely the farm can be moved within the leased area for one or more cycles to allow some benthic recovery to take place.

Discharges of organic material are intimately linked with discharges of chemicals – for example, the main medicine used for treating sea lice infestation in Scotland, the in-feed medication Slice ™ (emamectin benzoate). Many chemicals, including Slice, have 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 the potential for infection of wild salmon and sea trout. The Dunstaffnage site is near the entrance to Loch Etive, which has significant runs of wild salmonids and thus it is important that the farmer demonstrates that he has enough medicine to keep lice levels low without exceeding Environmental Quality Standards.

In summary, the regulatory and voluntary systems in place in Scotland demand measures to minimise impacts. It is unlikely that the farmer will have to take any additional steps to reduce the risk of breaking SEPA's SQC. However, if such became necessary, the farmer could reduce the stocking density per unit area to reduce the flux rate per unit area. The other important factors that that the farmer has control over are the correct functioning of farming technology (feeders, monitoring equipment etc) by a robust maintenance and replacement schedule, and the training and motivating of staff to reduce wastes to a minimum – an incentive to minimise Food Conversion Ratio would be more environmentally useful than an incentive to maximise production.

Risk management and risk reduction are largely addressed by the regulatory and voluntary processes outlined above. The greatest uncertainties arise where farms are proposed to be located in new environments with rare, vulnerable or protected habitats and species nearby. The regulatory process allows for objections from Natural Heritage interests and, where the habitat is deemed important/valuable etc., developments are not approved. As the Severity of the impact from particulate wastes is low for environments such as the Dunstaffnage site, monitoring is the best method of ensuring that Quality Criteria are not breached.

6.1.4 Risk Management

Possible mitigation and research activities to reduce the probability of steps in the logic model occurring, or reduce the uncertainty in the estimate of that probability are given in Table 6.1.IV. The production of particulate wastes is an unavoidable consequence of fin-fish farming. The only way to avoid effects on the marine environment is to farm fish on land with modern waste treatment capability. At present such facilities cannot compete economically with marine cage farms. An alternative is to attempt to capture some of the particulates before they are lost to the environment. Systems which allow this have been designed. These allow partial containment of the cage and the recovery of all or a fraction of the particulate wastes. Waste feed may be recycled back through the cage (Ervik *et al*. 1994) and faecal material collected for treatment on land. These systems appear to offer some of the benefits of land-based farming with some lower costs, for example, energy for water pumping. At present, such systems require further development and probably a regulatory incentive before they will be taken up widely by the industry.

In order to ensure that waste particulates do not accumulate on the seabed once they have been released from a farm, there is a continuing move towards siting farms in areas of high dispersion where wastes are initially spread over a wide area and erosional processes reduce the build up of organic materials. In order to understand better the consequences to the environment of highly dispersive sites, and to improve predictive ability for regulators, particle tracking models that are driven by hydrodynamic models need further development. This is important as near-field current measurements, presently used to drive some particle transport models, may become increasingly unrepresentative with distance and this may limit predictive ability at dispersive sites with large current velocities.

As mentioned above, scientific uncertainties still exist which do not allow us to predict confidently many important benthic responses, for example, the precise determination of the accumulation rate that results in azooia. 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 bio-irrigation 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 (for example, seasonal larval supply) it is also important that we increase our understanding of invertebrate life histories at the species level – an under-researched area.

6.1.5 Acknowledgements

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6.1.6 Literature cited

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Annex 1 Sediment Quality Criteria

In their Fish Farm Manual (available online at www.sepa.org.uk), the Scottish Environment Protection Agency (SEPA) have outlined a range of Sediment Quality Criteria.

Table A1 : 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 ug/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%	

**A detailed description of the derivation of these action levels may be obtained from SEPA on request.*

The SQC (or Action Levels, Table A1) are levels at which SEPA may take action against the farmer i.e. reduce or remove the consent to discharge. Implicit within the approach are:

a) that the farmer is required to monitor the sediments around the farm to measure compliance or otherwise, and
b) the concept of the Allowable Zone of Effects (AZE).

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 the past, the AZE was defined as the area bounded by a line 25m from the cage array perimeter, but SEPA now allow a less arbitrary approach 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.

One consequence of the new method of computing AZE size is that it is theoretically possible that appropriately dynamic sites exist where no practical upper limit in farm biomass can be envisaged. Such sites would be dominated by resuspension and would have extremely large AZEs. Particulates would be deposited over a very wide area but would not breach either inside or outside AZE SQCs. In order to prevent any step-change in farm size prior to achieving sufficient scientific understanding of their impacts more generally (i.e. not only benthic), SEPA have arbitrarily fixed an interim maximum upper limit of 2500 tonnes biomass to any single farm.

In Scotland, the end-points for the risk evaluation are clear – the farm must not breach the SQCs inside and outside the AZE at any point during the 2 year farming cycle. If a site is to be re-used in successive cycles, then it is important that the biomass is such that SQCs will not be broken in future cycles where there is little recovery between cycles. Where monitoring indicates that it is likely that a breach may take place in a consecutive cycle, a “fallow” period of months or years may be agreed.

Annex 2 Non-statutory consultees (from Crown Estate. Environmental Assessment Guidance Manual for Marine Salmon Farmers - http://www.thecrown-estate.co.uk/15_our_portfolio/39_marine/53_fish_farming.htm)

The following list (in alphabetical order) highlights a number of relevant non-statutory parties and other interest groups who can provide advice and information on numerous aspects of marine salmon farming in relation to their own areas of interest. Although consultation with these groups is by no means compulsory, developers will almost certainly benefit from additional information provided and specialist advice given where interests coincide. This information can then usefully contribute to the scoping and screening stages, and throughout the continuing process of EA.

Association of Scottish Shellfish Growers
Association of West Coast Fisheries Trusts
Atlantic Salmon Trust
Fisheries Research Services
HM Coastguard
Health & Safety Executive
Highlands and Islands Enterprise
Historic Scotland
Mallaig and North West Fishermen’s Association
Ministry of Defence
Northern Lighthouse Board
Orkney Fishermen’s Society Ltd
Royal Yachting Association of Scotland
Salmon and Trout Association
Scottish Association for Marine Science
Scottish Executive Development Department
Scottish Federation of Sea Anglers
Scottish Fishermen’s Federation
Scottish Quality Salmon
Scottish Sports Council
Scottish Tourist Board
Scottish Trust for Underwater Archaeology