6 CASE STUDIES

To illustrate the use of the risk assessment protocol presented in Chapters 1 to 4, Members of GESAMP Working Group 31 developed a series of case studies. These case studies are drawn from temperate and tropical coastal aquaculture activities and are concerned with aspects of salmon, shrimp and bivalve culture. They illustrate a variety of potential environmental effects including impacts on macroinvertebrate and macroalgal benthic communities, reduction in the fitness of wild fish populations due to interbreeding between wild and escaped cultured fishes, reduction of the carrying capacity of an embayment for shellfish, development of planktonic algal blooms, and salinisation of agricultural soil.

The examples do not attempt to cover all the types of potential environmental effects, or all types of coastal aquaculture; such a task was beyond the resources available to the Working Group. Furthermore, as pointed out earlier in this document, the choice of critical endpoints will vary (and justifiably so) between jurisdictions. Therefore, no single list of endpoints would satisfy all potential applications of the protocols. The protocols should be applicable to a wide range of situations and combinations of hazards and endpoints, and the case studies demonstrate part of that range.

The case studies also do not illustrate the entire risk analysis process. They focus on the science component, the risk assessment, and present it in a structured way, suitable for use in a transparent and participatory decision-making environment. The case studies do not deal in any depth with the task of the resource manager to select and/or prioritise possible endpoints for investigation. Nor do they deal with the determination of "acceptable degree of change in the receiving environment", which is an important part of hazard identification that requires socio-political input. Risk communication was also excluded from the construction of the case studies as it involves an intimate knowledge of local social and governance issues and mechanisms.

It is hoped that these case studies will useful learning tools for those wanting to apply the protocols. It is also hoped that it will be clear how industry, environmental groups, governmental agencies and stakeholders can all use the assessment as an acceptable common vehicle for discussion to:

- Identify the critical limits of knowledge of the environmental effects of coastal aquaculture, as well as the limits of our knowledge of the mechanisms by which these effects occur.
- set research priories.
- identify further concerns.
- develop management plans and policy.

These case studies were prepared for, presented and discussed extensively by WG 31 Members during the GESAMP Workshop on Environmental Risk Assessment and Communication in Coastal Aquaculture, held 20-24 November 2006 in Rome. Thereafter, the case studies were further revised based on suggestions and comments received during the peer review process prior to and after the 34th Session of GESAMP, held in Paris during 7-11 May 2007.

CASE STUDY 6.1

FISH FARMING EFFECTS ON BENTHIC COMMUNITY CHANGES DUE TO SEDIMENTATION

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6.1.1 Introduction

Marine cage fish farms produce waste organic material that can cause changes to sediment biogeochemistry and benthic community structure that may persist for periods from months to years depending on local conditions. In Scotland, regulations, including Sediment Quality Criteria, have been established to ensure that the degree and spatial extent of change are constrained. In this case-study, we consider waste organic material as a hazard, and we examine the risk that the enlargement of an existing fish farm on the west coast of Scotland will fail to meet the Sediment Quality Criterion "that macrofaunal analysis of replicate grab samples must reveal at least 2 species at high abundance" within the area immediately surrounding the farm (Allowable Zone of Effects, AZE). This we define as the logical end-point. We consider the risks, through a Risk Analysis, in terms of a logical model within the context of a Release-Exposure-Consequence chain.

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, for example, 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. For example, major effects of particulate inputs to sediments on benthic communities are typically restricted to a relatively small area around the farm but may persist for several years (Karakassis *et al.* 1999b; Pereira *et al.* 2004).

In this paper, we develop a risk-based approach, to benthic effects only, using the example of a salmon farm in Scotland that has been operating at about 700 tonnes maximum biomass over the past several years, but which has recently applied for an increased maximum biomass of 1300 tonnes. We restrict ourselves to considering sedimentation of waste organic materials. We do not consider ecological effects from other wastes such as antibiotics, medicines or anti-foulants.

6.1.2 Hazard Identification

Farming fish in open cages produces solid wastes that can cause changes in the benthic community. Effects on benthic macrofauna have been much studied, and the results largely reinforce the paradigm of species succession along organic enrichment gradients established by Pearson and Rosenberg (1978). Briefly, particulate organic material (uneaten feed, faeces and biofouling biomass detached from cage structures, which we define here as the hazard of interest) settles to the seabed where it is degraded by microbes using 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 and Mahnken 2003; Brooks, Stierns and Mahnken 2003a; Brooks *et al*. 2003b; Hargrave *et al.* 1997; Heilskov and Holmer 2001; Holmer, Wildish and Hargrave 2005; Karakassis *et al*. 1999a; Pearson and Black 2001; Pearson and Rosenberg 1978; Weston 1990). Away from the farm, as organic material flux and oxygen demand decreases, animal communities return to background conditions typified by high species diversity and functionality (Gowen and Bradbury 1987; Nickell *et al.* 2003; Pereira *et al.* 2004).

Regulation of salmon cage culture is to a large extent driven by the potential for disruption of the benthic ecosystem, even though changes in the benthos may not be the most ecologically significant effects associated with fish farming. This is because the benthic 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. At some sites, 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 more difficult to quantify and therefore often controversial. Benthic effects, however, unlike algal blooms for example, are very easy to attribute

[1] Cages are typically comprised of a flotation 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.

to the fish farm and, therefore, are amenable to scientifically robust and quantitative regulation.

In Scotland, as in several other countries, the regulator (the Scottish Environment Protection Agency, SEPA) is required to manage the impacts of fish farming to avoid unacceptable damage to the sea-bed and its fauna. SEPA has gone a little further than most regulators in giving some examples of where it thinks the boundary between acceptable and unacceptable seabed conditions lies. SEPA has established Sediment Quality Criteria (SQC, given in detail in the appendix) as indicators of when it will take action to reduce impacts, for example, by reducing the maximum allowable biomass, or by entirely revoking the discharge consent. The SQC are not the only criteria used – SEPA will accept and consider all the available evidence – but as many benthic indicators co-vary, they do offer a meaningful insight into what SEPA consider to be unacceptable benthic conditions. Discharge consents have monitoring conditions specified in detail: both their level (for example, 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 sediment with strong currents will be monitored less intensively than a large farm over a soft substrate with weak currents. This process is described 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).

The SQCs are useful indicators, but it is important to understand their underlying basis for example, the risk that should be avoided. In the 1990s, the size of individual farms increased rapidly from a few hundred tonnes to up to and over a thousand tonnes. However, farms were often located in the very sheltered environments required by the previous generation of largely wooden cage collars, and sediments at some farms became so polluted that total sediment azooia[2] occurred. 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 within a few hours in an oxic water column, measurable concentrations can sometimes be detected in waters overlying the sediments (Black, Kiemer and Ezzi 1996a; Black, Kiemer and Ezzi 1996b). Hydrogen sulphide is highly toxic to fish (Kiemer *et al.* 1995) and has been implicated in both fish kills and reduced performance at polluted farms, but a causal link is difficult to prove, as pathologies are non-diagnostic for hydrogen sulphide poisoning. 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). Therefore, the protection of cultured fish (and the farmer) from the consequences of excessive benthic impact are one outcome of the application of the SEPA SQCs. 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. Thus on economic, animal welfare and ecological grounds, azooic, outgassing sediments are an outome best avoided.

SEPA’s SQCs are aimed just above azooia: for example, at least two species at high abundance are required as a mean across all replicates grabs taken from the station at the same time, and not more than one replicate grab sample should contain no macrofaunal animals (Table A1). It is well known, although the process is not well understood, that the presence of macrofaunal animals increase the rate of degradation of organic carbon (Heilskov and Holmer 2001). Thus, SEPA’s objective is that farm sediments should contain a high abundance and biomass of bioturbating macrofaunal animals to enhance the rate of organic matter degradation.

For the purposes of this assessment, we use the SQC which requires at least two species at high abundance (Table A1) as the end point beyond which the undesirable outcome of benthic pollution is realised.

6.1.3 Risk Assessment

6.1.3.1 The proposed fish farm development

A major UK fish farm company has applied to the regulator, SEPA, to expand their fish farm at Dunstaffnage from a current maximum biomass of 700 tonnes up to 1300 tonnes. The proposed site will comprise 12 moored circular cages of 70 m circumference with a net depth of 14 m giving a total volume of 65508 m^3. The site has been in operation for at least 15 years but with varying maximum biomass - it has been operating at 700 tonnes maximum biomass for several production cycles. The Dunstaffnage site is located in lower Loch Linnhe (Figure 6.1.1) on the Scottish west coast, north of Oban (Figure 6.1.2).

Compared with many more sheltered sea loch sites, the Dunstaffnage site experiences relatively strong tidal currents (Table 6.1.I; Figure 6.1.3, which shows near-bottom currents only), has a relatively long fetch and is situated on a gently sloping muddy seabed between 30 and 40 m water depth (Figure 6.1.6). The mean spring tidal range is 3.3 m with a pronounced spring-neap cycle (Figure 6.1.3) and the current is highly topographically constrained by the nearby coast with a strong residual flow to the north east (Table 6.1.I, Figures 6.1.4, 6.1.5).

Mandatory benthic monitoring is carried out during every production cycle and a summary of the most recent macrofaunal data is given in Table 6.1.II, which indicates a relatively sparse fauna at the reference sites with fewer species near the cages but at high abundance.

The fish farm is operated by a small team of permanent staff that is supplemented by a mobile work force joining the resident team for major

[2] Azooia (and azooic) is used here to describe the absence of metazoan life.

Figure 6.1.1 : Lower Loch Linnhe showing Dunstaffnage site location (Google Earth)

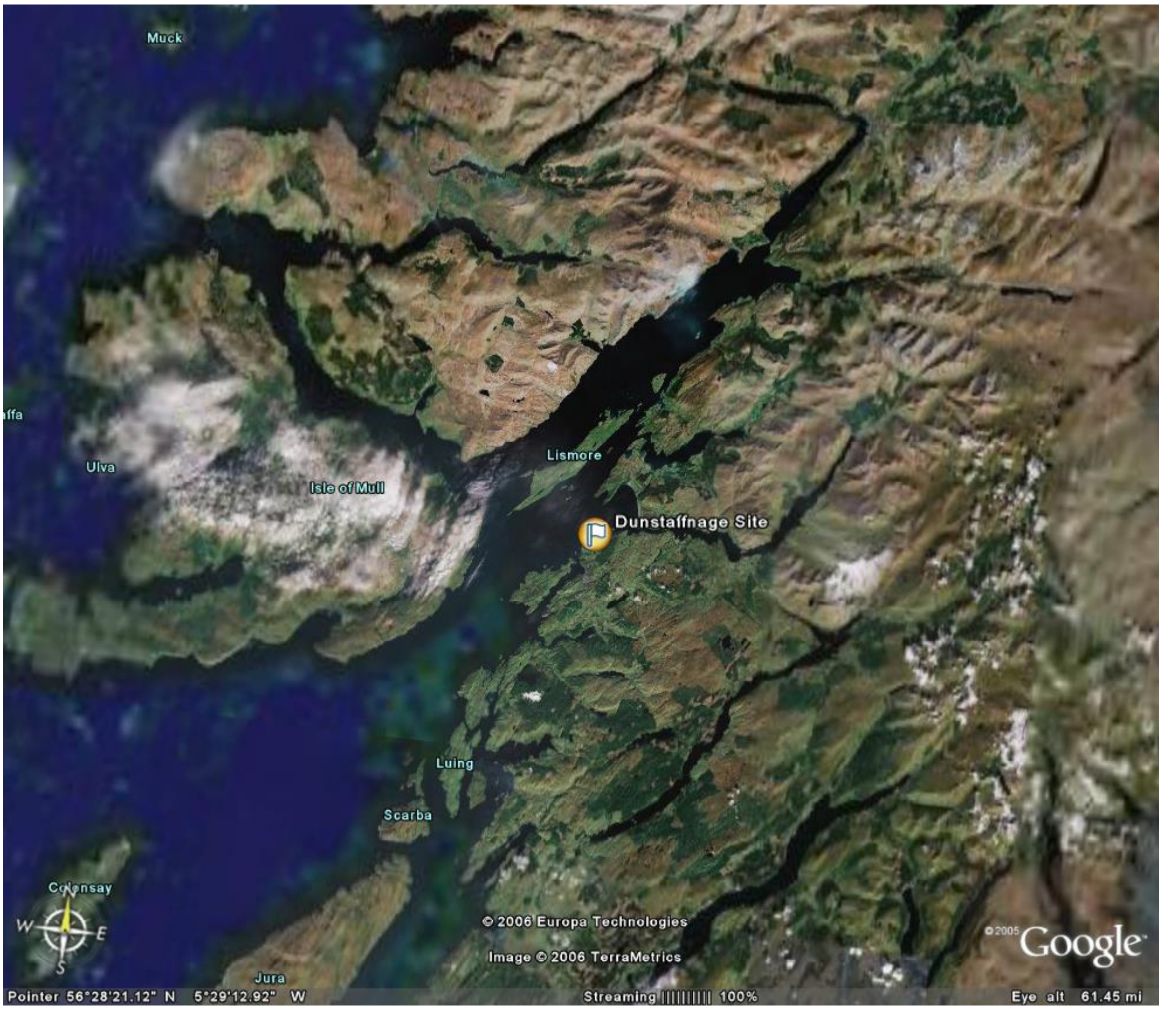

Table 6.1.I : Summary statistics for hydrographic data at the monitoring site (22 day record, 10 minute averages). (Provost, SAMS, Current Speed and Meteorological Measurements at the Dunstaffnage Fish Cage Site, Firth of Lorne, Argyll. Data Report Prepared for Scottish Sea Farms Ltd February 2006)

Depth	Mean speed ($mm.sec^{-1}$)	Max. speed ($mm.sec^{-1}$)	Residual speed ($mm.sec^{-1}$)	Residual direction (°true)
Surface - 35m above seabed	76.9	400.0	42.3	089
Mid-water - 28m above seabed	66.4	285.0	39.8	068
Near-bed - 3m above seabed	83.1	236.0	64.9	046