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GESAMP

Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection

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REPORTS AND STUDIES

ASSESSMENT AND COMMUNICATION OF ENVIRONMENTAL RISKS IN COASTAL AQUACULTURE

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IMO FAO UNESCO-IOC WMO UNIDO IAEA UN UNEP

ASSESSMENT AND COMMUNICATION OF ENVIRONMENTAL RISKS IN COASTAL AQUACULTURE

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2008

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ABSTRACT

This GESAMP study focuses on environmental risk assessment and communication in coastal aquaculture. To support effectively an open and transparent approach to sustainable resource use, risk assessment and communication must be able to fit within a broader social, economic and environmental decision-making framework. The communication aspects become paramount in enabling sustainable development in that type of decision-making environment. In today's environmentally conscientious societies, no activity is truly sustainable without social licence. Scientific knowledge has to be developed, presented and communicated in a manner that fully acknowledges the extent and limits of our ability to predict the consequence of development. This applies at all scales, from development of a single aquaculture farm site to the development of a number of sites that may have a cumulative effect that cannot be predicted on the basis of the activities at a single site, and to the initiation of an entirely new industry.

This publication presents a set of objectives, goals, methodologies and a checklist for assessment and communication of environmental risks which may be associated with coastal aquaculture. It is structured to improve risk communication and to ensure that risk assessment is a scientific exercise in predicting environmental change. Suggestions are given on how socio-economic values can be used with environmental risk assessment in open and transparent decision-making for questions of resource allocation. In addition, the risk assessment methodologies are designed to present a clear picture of the role of uncertainty in prediction error. This approach to risk assessment also helps target mitigation and research efforts to ensure knowledge of the causes and effects of environmental interactions of coastal aquaculture.

A set of six case studies is also presented to illustrate the use of the environmental risk assessment methodologies in coastal aquaculture. These examples of environmental interactions span a range of cultured species from fin fish to molluscs and shrimp. The type of effects studied includes effects on carrying capacity, phytoplankton, kelp, benthic fauna, the genome of wild fishes and salinisation of soils.

Key words: coastal aquaculture, environmental risk, assessment, communication, risk analysis, GESAMP.

PREPARATION OF THIS STUDY

The Thirty-first session of GESAMP in 2001 charged GESAMP Working Group on Environmental Impacts of Coastal Aquaculture (WG31) with the task of producing a review report and guidelines for environmental risk assessment of coastal aquaculture, aimed at promoting harmonisation and consistency in the treatment of risk and uncertainty, and improved risk communication. In 2002 FAO invited the preparation of a discussion paper on environmental risk assessment and communication in coastal aquaculture (Hambrey and Southall, 2002[1]). In 2003 this discussion paper was distributed by the FAO Technical Secretary of GESAMP to some 70 experts in the field of environmental risk assessment and coastal aquaculture with a view to inviting comments, suggestions, and contributions to this document. A scoping and planning meeting of a core group of GESAMP WG 31 was held in Rome from 1 to 3 December 2003. Under the chairmanship of Mr E. Black (2005-2007) drafts of sections of this study and six case studies were prepared by members of WG31, and discussed during the GESAMP WG31 workshop (held in Rome from 20 to 24 November 2006). This GESAMP WG31 workshop was attended by C. Bacher, E. Black (Chair of WG31), K. Black, I. Davies, J. Hambrey, R. Petrell, M. Reantaso, H. Rosenthal, D. Soto, S.K.Teng, K.Yin and U. Barg (Technical Secretary of WG31). Following the Rome workshop, the advanced draft of the study report was circulated by F. Haag (GESAMP Officer) to several experts for peer review. The advanced draft study report and the peer reviewers' comments were presented to the Thirty-fourth Session of GESAMP, held in Paris from 7 to 11 May 2007. WG31 revised the study report based on comments contributed by the peer reviewers and GESAMP. On 8 October 2007 GESAMP approved the revised study report for publication. The work of GESAMP WG 31 was sponsored by FAO's Aquaculture Management and Conservation Service. The Secretariat was provided by FAO.

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[1]Hambrey, J. and T. Southall (2002). Environmental risk assessment and communication in coastal aquaculture: A background and discussion paper for GESAMP Working Group 31 on Environmental Impacts of Coastal Aquaculture (71 p.).

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Members of GESAMP Working Group 31 on Environmental Impacts of Coastal Aquaculture

Cedric BACHER (2)
Institut français de recherche pour l'exploitation de la mer IFREMER
29280 Plouzané, France
Tel.(33) 298224215
E-mail: Cedric.Bacher@ifremer.fr; cbacher@ifremer.fr

Edward BLACK (1 ; 2)
Chair of GESAMP Working Group 31
Aquaculture Science Branch
Fisheries and Ocean Canada
12th Floor, 200 Kent Street
Ottawa, Ontario, Canada, K1A 0E6
Tel. (613) 9900272
E-mail: BlackE@DFO-MPO.GC.CA

Kenneth D. BLACK (2)
The Scottish Association for Marine Science
Dunstaffnage Marine Laboratory, Oban, Argyll
Scotland, PA37 1QA, United Kingdom
Tel. (44) 1631559259;
E-mail: kenny.black@sams.ac.uk

Kenneth M. BROOKS (1)
644 Old Eaglemount Road.
Port Townsend, WA 98368
United States of America
Tel. (360) 732-4464
E-mail: brooks@olympus.net

Ian DAVIES (1 ; 2)
Fisheries Research Services Marine Laboratory
375 Victoria Road. Aberdeen AB111 9DB,
United Kingdom
Tel. (44) 1224876544
E-mail: daviesim@marlab.ac.uk

John HAMBREY (1 ; 2)
Crancil Brae House.
Strathpeffer; Ross-shire IV14 9AW;
United Kingdom
Tel. (44) 1997420086
E-mail: john@hambreyconsulting.co.uk

Royann Jean PETRELL (2)
University of British Columbia
2360 East Mall Vancouver
British Columbia, Canada V6T 1Z3
Tel. (604) 8223475
E-mail: petrell@interchange.ubc.ca

Harald ROSENTHAL (1 ; 2)
Schifferstrasse 48. 21629 Neu Wulmstorf,
Germany
Tel. (49) 40-7006514
E-mail: haro.train@t-online.de

TENG Seng-Keh (2)
Block 4, Toh Yi Drive, 09-211,
Singapore 590004
Tel. (65) 64622547
E-mail: tkwy@cyberway.com.sg; skteng@gmail.com

YIN Kedong (2)
Department of Biology, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon
China, Hong Kong Special Administrative Region
Tel. (852) 23587329
E-mail: kyin@ust.hk

FAO staff attending GESAMP WG31 meetings in 2003 (1) and 2006 (2)

Melba REANTASO (2)
FAO Fisheries and Aquaculture Department
Viale delle Terme di Caracalla. Rome,
Italy
Tel: (39) 06-57054843
E-mail: melba.reantaso@fao.org

Doris SOTO (2)
FAO Fisheries and Aquaculture Department
Viale delle Terme di Caracalla. Rome,
Italy
Tel: (39) 06-57056149
E-mail: doris.soto@fao.org

Uwe BARG (1 ; 2)
Technical Secretary of GESAMP Working Group 31
FAO Technical Secretary of GESAMP
FAO Fisheries and Aquaculture Department
Viale delle Terme di Caracalla. Rome,
Italy
Tel: (39) 06-57053454
Email: uwe.barg@fao.org

(1) Attended GESAMP WG31 Scoping & Planning Meeting, 1-3 December 2003
(2) Attended GESAMP WG31 Workshop, 20-24 November 2006

CONTENTS

EXECUTIVE SUMMARY

Aquaculture is an increasingly prominent feature of our coastal environments. Seafood production from capture fisheries has ceased to increase significantly, while demand for their products increases each year. In an effort to fill that demand, aquaculture production has shown marked annual growth. In many areas much of that increase has come from coastal aquaculture activities. However, this adds to the pressures on space, natural resources and environmental services in coastal areas, and potentially to conflicts between different stakeholders and activities in the coastal zone.

The public is demanding a greater role in the management of coastal resources. Many jurisdictions are seeking to use participatory management schemes that include the public and other stakeholders in the processes that lead to decisions on aquaculture (and other) developments. All activities in coastal areas interact with the environment. Coastal aquaculture is no exception, and a wide range of environmental risks associated with coastal aquaculture developments have been described in scientific and other fora, with varying accuracy in their reflection of reality. Reliable assessment of the significance of these risks should provide a sound basis for decisions regarding new developments, mitigation actions, and research needs. However, this must be done in the face of uncertainty in predicting the environmental response to stresses (hazards).

Risk assessments must also communicate risk and uncertainty information to managers and the public in a fashion that meets the information needs of all stakeholder groups and managers at the same time. Scientists must provide information that meets with the requirements of managers for environmental risk management, and of the public and other stakeholders, to enable them to develop.

GESAMP Working Group on Environmental Impacts of Coastal Aquaculture in collaboration with experts of the International Council for the Exploration of the Sea's Working Group on Environmental Interactions of Mariculture has developed an integrated risk assessment/communication protocol that fits within a risk analysis structure for resource management. This report presents a model of ecological risk analysis for coastal aquaculture and guidelines for its application which:

- Is structured to fit into a broader decision making environment which combines social and economic values with science-based predictions of environmental changes and effects;
- Is pre-adapted to enhance the role of risk communication and risk management in the context of transparency;
- Can operate in an open and transparent manner to incorporate information supplied by scientists from government, academia, industry, and stakeholder organisations, and the public;
- Recognises that many of the environmental changes associated with aquaculture activities can also arise from other coastal activities such as industrial and urban development, tourism, agriculture, fishing and stock enhancement; and,
- Clarifies how uncertainty relates to the precautionary principle and affects decision-making.

The document emphasises the role of communication in decision-making, and the need to create risk assessments that meet the needs of, and be acceptable to, stakeholders as well as scientists. The protocol clearly indicates which elements of the decision-making process are derived from social/economic considerations, and where environmental science should provide critical information.

The most common causes of environmental concern from coastal aquaculture are nutrient release, habitat change and loss, effects on wild fish and shellfish populations, chemical pollution, and secondary effects on other production systems. Many of the interactions with the environment are subtle and cumulative, they can be highly dispersed in space and time, and often the magnitude and probability of environmental changes can be unclear. The risk assessment and analysis protocol presented includes processes to identify areas where knowledge is lacking, handles uncertainty (The Precautionary Approach) in an objective and constructive way, and provides an agreeable basis for discussion. The objectives of the risk assessment and analysis protocol presented include the separation of scientific analysis from valuation, transparency, consistency in assessment, non-discrimination, proportionality in risk management measures, monitoring linked into a review and action cycle, all of which are undertaken within the paradigm on sustainable use of coastal resources.

The risk analysis protocol applied to coastal aquaculture includes four main components: hazard identification, risk assessment, risk management and risk communication. The first three are sequential, and are carried out within a comprehensive risk communication strategy.

The risk assessment component is a major focus of this document and is considered in four subcomponents: release assessment, exposure assessment, consequence assessment, and risk estimation. It is recommended that the risk assessment is structured through a logic model that explicitly sets out the steps that lead from the hazard arising from a coastal aquaculture development to the undesirable outcome (endpoint) that is the target of the risk analysis.

The proposed risk analysis protocol is discussed in relation to other procedures established to aid

decision-making on resource use and sustainable development in coastal waters. Particular strengths of this approach are: the inclusion of uncertainty as part of the documentation; the assessment of probability and the uncertainty of the occurrence of each step in the chain of events (logic model) that leads to a change in the environment; and, the potential for a structured risk analysis to be incorporated into existing regulatory processes and contribute a robust and flexible framework for discussions between stakeholders and regulators. The protocol has been developed to work within a participatory management scheme that includes stakeholders and the public. It also helps clarify where research or regulatory approaches best control either the level of anticipated environmental change, or the accuracy of the prediction.

The application of the proposed risk analysis protocol to coastal aquaculture is discussed in some detail, and reference is made to typical sets of environmental concerns arising from aquaculture development proposals. The need for clarity at all stages of the risk assessment process is emphasised, and clarity is identified as an important factor for assisting in the resolution of differences and the handling of uncertainty. Mechanisms are described for combining the outcomes of analyses of several pairs of hazards and undesirable outcomes, as are often raised in relation to coastal aquaculture development.

A common difficulty in decision-making is determining when proposed mitigation measures are sufficient. Mitigation can be used to reduce the severity or uncertainty of an effect. Zero environmental change is unattainable, therefore what constitutes an acceptable degree of change in relation to the anticipated benefits needs to be defined. These are not scientific decisions. They are societal decisions, perhaps political decisions. In order to ensure that the risk analysis can be objective, the valuation process, establishing what is acceptable and what is not, should be carried out at a very early stage in the risk analysis process.

All the processes of risk assessment should be carried out within the framework of risk communication. In some areas, decisions on coastal aquaculture development can be extremely contentious and have in the past led to extreme responses, ranging from encouragement of very rapid exploitation to moratoria on further developments. Advice is offered on the use of experienced facilitators and communicators in avoiding or resolving potential and actual conflicts between stakeholders and other interested parties.

The assessment protocol is applied to a series of case studies covering some of the common causes of concern expressed in relation to coastal aquaculture. These include the effects of the release of dissolved and particulate nutrients on primary production and seabed communities, the potential effects of coastal aquaculture on other local exploitable resources (reductions in sea weed communities, and in the carrying capacity for farmed shellfish), and wider-scale potential consequences of the escapes of farmed stocks for wild populations, and soil salinisation in coastal zones.

1 INTRODUCTION

1.1 Coastal aquaculture in global fisheries context

The growth of aquaculture in coastal and inland waters is one of the success stories of global food production. Demand for fisheries products continues to increase to meet the needs of consumers, reflecting recognition of the dietary benefits of fish and shellfish in both developed and developing countries. The oceans of the world have a finite supply of environmental goods and services available to support human activities and needs. While the world's population continues to grow, the supply of seafood products from marine capture fisheries may be reaching its limit. In fact, global production from capture fisheries has levelled off, and most of the main fishing areas have reached their maximum potential (FAO Fisheries and Aquaculture Department, 2007). In some areas, overfishing and other factors have resulted in a decline in stocks and landings.

Aquaculture has developed to help bridge the growing gap between what the capture fisheries can supply and the growing global demand for fisheries products (Figure 1.1; Table 1.1).

A wide and ever increasing variety of species is produced, and aquaculture maintains its position as one of the fastest growing food production systems. In fact, aquaculture continues to grow more rapidly than all other animal food-producing sectors, with an average annual growth rate for the world of 8.8 percent per year since 1970, compared with only 1.2 percent for capture fisheries and 2.8 percent for terrestrial farmed meat production systems (FAO Fisheries and Aquaculture Department, 2007).

The 2005 contribution of aquaculture to the world aquatic production was about 62.9 million tonnes (excluding aquatic plants). FAO projections (FAO, 2004), indicate that to maintain the current level of per capita consumption, global aquaculture production will need to reach 80 million tonnes by 2050.

Most aquaculture production of fish, crustaceans and molluscs continues to occur in freshwater environments (56.6% by quantity and 50.1% by value). Mariculture contributes 36.0% of production quantity and 33.6% of the total value. While much of the marine production consists of high-value finfish, there is also a large amount of relatively low-priced shellfish such as mussels. Although brackish-water production represented only 7.4% of production quantity in 2004, it contributed 16.3% of the total value, reflecting the prominence of high-value crustaceans and finfish (FAO Fisheries Department, 2006). There can be little question that coastal

Figure 1.1 : Capture fisheries and aquaculture contributions to global food-fish supply 1970 - 2005. AQ share triangles) represent the growing relative share of aquaculture contribution (percent) to total food-fish supply (Subasinghe and Lowther 2007; pers. comm. based on FAO FishStat Plus 2007 data available at: http://www.fao.org/fishery/topic/16073).

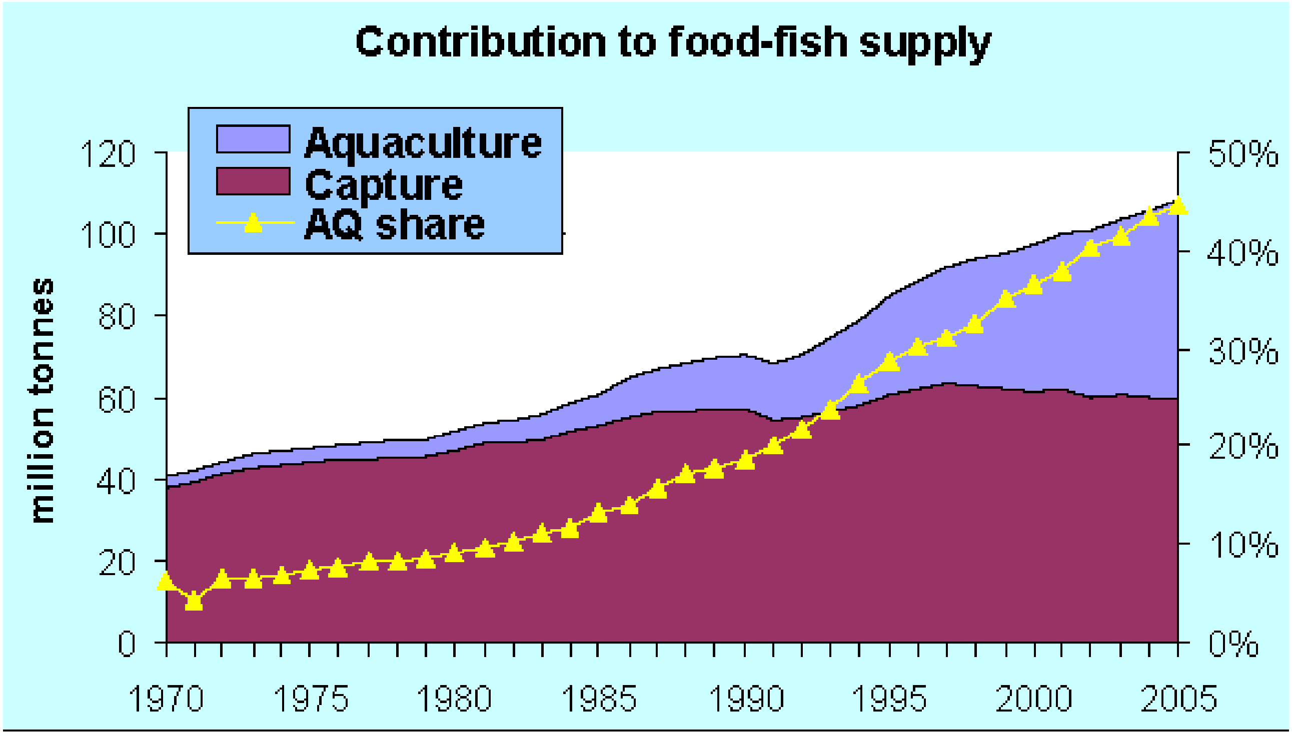
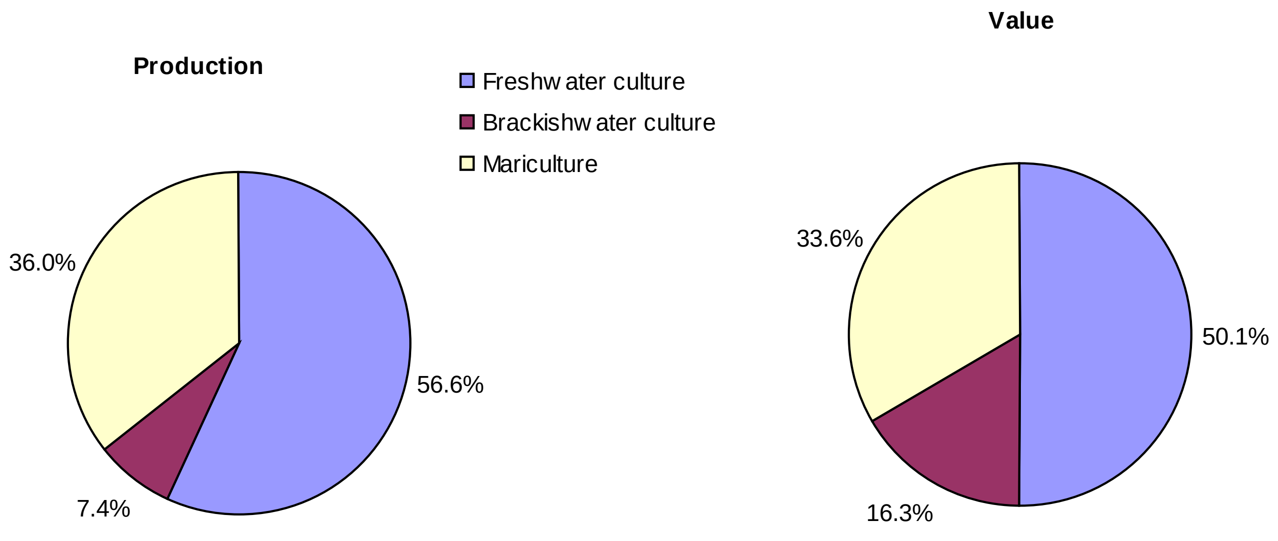


Table 1.1 : World fisheries and aquaculture production and utilization 2000-2005 (FAO Fisheries and Aquaculture Department, 2007).

	2000	2001	2002	2003	2004	2005[1]
	(Million tonnes)					
PRODUCTION						
INLAND						
Capture	8.8	8.9	8.8	9.0	9.2	9.6
Aquaculture	21.2	22.5	23.9	25.4	27.2	28.9
Total inland	**30.0**	**31.4**	**32.7**	**34.4**	**36.4**	**38.5**
MARINE						
Capture	84.6	84.2	84.5	81.5	85.8	84.2
Aquaculture	14.3	15.4	16.5	17.3	18.3	18.9
Total marine	**101.1**	**99.6**	**101.0**	**98.8**	**104.1**	**103.1**
TOTAL CAPTURE	95.6	93.1	93.3	90.5	95.0	93.8
TOTAL AQUACULTURE	35.5	37.9	40.4	42.7	45.5	47.8
TOTAL WORLD FISHERIES	**131.1**	**131.0**	**133.7**	**133.2**	**140.5**	**141.6**
UTILIZATION						
Human consumption	96.9	99.7	100.2	102.7	105.6	107.2
Non-food uses	34.2	31.3	33.5	30.5	34.8	34.4
Population (billions)	6.1	6.1	6.2	6.3	6.4	6.5
Per capita food fish supply (*kg*)	16.0	16.2	16.1	16.3	16.6	16.6

Note: Excluding aquatic plants.
[1] Preliminary estimate

Figure 1.2 : Proportional global production and value of combined fish crustaceans and mollusc aquaculture by environment for 2004 (Source: FAO Fisheries and Aquaculture Department, 2007).



aquaculture, including brackishwater aquaculture and mariculture, is a significant part of worldwide seafood production and that it will continue to be so for the foreseeable future (Figure 1.2).

Aquaculture is a highly diverse activity in terms of the species grown, scale and intensity of operation, technology and management practices. It ranges from small-scale 'back-yard' ponds and hatcheries, to major high technology industrial operations employing thousands of people and numerous individual sites, each producing several thousand tonnes per year. The range of scale, species and technology means that aquaculture can be viewed on the one hand by aid agencies as a useful tool for poverty alleviation, and on the other by large financial institutions as a sound investment area for commercial growth. This diversity can create particular difficulties when drafting regulations or guidelines to apply uniformly across the board.

The recent dramatic growth in coastal aquaculture activity on commercial scales has been concentrated in a few parts of the world, where conditions are particularly suitable for the growth of high value species for local consumption or export. Atlantic salmon production, for example, has developed rapidly in the sheltered cool temperate fjordic environments of Norway, Chile, Scotland and western Canada, whereas tropical shrimp production has developed in coastal areas of tropical Asia and Latin America. The arrival of a relatively new industry to such areas has given rise to concerns and conflicts. The establishment of aquaculture sites may restrict the options available for use of the space that they occupy. This can lead to conflicts with other stakeholders in the coastal zone, such as fishermen, who may see their freedom of action limited.

Environmental impacts and interactions of coastal aquaculture can be particularly contentious. While methods for monitoring local effects of aquaculture (for example, the effects of particulate organic waste on the seabed, or the effects of nutrient release on the availability of nutrients in the surrounding water body) are now well established, other areas of interactions, such as the genetic interactions between escaped animals and wild stocks continue to be hotly debated.

It is these areas, where aquaculture may have the potential to lead to undesirable changes in the surrounding environment and its living resources, which are the focus of this report. Effective management of aquaculture requires understanding of the probability that hazards (such as wastes, or escaped animals) arising from proposed aquaculture developments will lead to consequences that are considered unacceptable in the local or international contexts within which the development would occur. Objective analysis of the ecological risks concerned will facilitate effective allocation of resources to mitigation measures and an open, transparent and even-handed approach to management.

1.2 The scope of this report

As with all other human activities in coastal areas, there are environmental changes associated with coastal aquaculture. The nature of these changes and how to monitor them have been discussed in international science in support of environmental management since the 1980s (for example, Chua *et al*. 1989; Cholik and Poernomo 1987; Ackefors and Enell 1990; Gowen and Bradbury 1987; Hakanson *et al*. 1988; FAO/NACA 1995; Iwama 1991; Kapetsky 1982; Makinen *et al*. 1991; Black 2001; Hargrave 2005; Hambrey and Southall 2002; Mahmood 1987; ICES 1988, 1999, 2002, 2003, 2004, 2005, 2006; GESAMP 1991, 1996, 1997, 2001; Munday *et al* 1992; Nash *et al*. 2005; Pillay 1992; Pullin 1989; Pullin *et al*. 1993; Videau and Merceron 1992).

This report presents a model of ecological risk analysis for coastal aquaculture and guidelines for its application which:

- is structured to fit into a broader decision making environment which combines social and economic values with science-based predictions of environmental changes and effects;
- is pre-adapted to enhance the role of risk communication and risk management in the context of transparency;
- can operate in an open and transparent manner to incorporate information from the broad array supplied by scientists from government, academic, industry, and stakeholder organisations, and the public; and,
- explicitly recognises that many of the environmental changes associated with aquaculture activities can also arise from other coastal activities such as industrial and urban development, tourism, agriculture, fishing and stock enhancement.

The report emphasises the dynamics of risk communication, providing guidelines for communicating risk to environmental managers, stakeholders and the public. To validate the proposed approach to environmental risk analysis, this document presents six trial case studies which use the approach to illustrate its strengths and weaknesses.

The risk assessment protocols in this report are constructed as part of a sustainable development tool (Risk Analysis) which was designed to work hand in hand with risk communication in a decision-making environment that took account of the precautionary principle. The open and transparent application of the risk assessment protocols, and the explicitly documented uncertainty in predicting the outcomes of the interactions of coastal aquaculture with the environment created specific requirements for the methodology. Objectives and principles were developed for the application of the environmental risk assessment and risk communication protocols.

It is recognised that international risk protocols already exist in some other disciplines. For example, the World Animal Health Organisation's import risk analysis protocol which focuses on aquatic animal diseases (OIE 2006), and the international principles and guidelines for the conduct of microbiological risk assessments, as developed by the FAO/WHO Codex Alimentarius Commission (1999). Sumner *et al*. (2004) give an introduction to the application of seafood risk assesmment in the fish industry. This report describes an approach to environmental risk assessment and communication that complements, rather than replaces, those protocols, focusing specifically on coastal aquaculture.

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2 ENVIRONMENTAL INTERACTIONS AND IMPACTS, RISKS AND UNCERTAINTIES ASSOCIATED WITH COASTAL AQUACULTURE

2.1 Environmental interactions and impacts of coastal aquaculture

Most aquaculture production requires clean water with oxygen, pH and nutrient levels at a suitable level to support the farmed species (*see, for example*, Wallace, 1993). Underlying plans for sustainable long-term production is the presumption that these water quality measures will be maintained at levels consistent with environmental conditions that minimise stress for the production species. Past experience shows that sometimes, when aquaculture is initiated, it has been unable to maintain the desired quality in the water or sedimentary environments.

On a global scale, the most common causes of environmental concern include:

- nutrient enrichment: the release of nutrients through uneaten food, faeces, pseudo-faeces and dissolved metabolites to the sediment and water column.

- habitat change and loss: changes in seabed or river bottom habitats due to the accumulation of organic matter or other waste; or the loss of habitat due to modifications of coastal land and wetland to meet the requirements of coastal aquaculture.

- impacts on wild fish and shellfish populations: the escape of farmed fish and their subsequent interbreeding with wild fish; introduction of exotic species (including disease and parasites); increased abundance of pathogens.

- chemical pollution: primarily related to release of therapeutic chemicals used in the treatment of disease, including parasitic infections.

- secondary impacts on other production systems: social, economic and environmental consequences arising from increased demand for inputs (goods and services) such as fish meal, or transportation.

Within these general topics there is a large number of specific environmental interactions. These have been discussed and reviewed in numerous papers and books (for example, Asche *et al.* 1999; Barg 1992; Black 2001; Cognetti *et al.* 2006; GESAMP 1991, 2001; Gray *et al.* 2002; Hindar 2001; Nash *et al.* 2005; Naylor *et al.* 1998; Youngson *et al.* 2001). Although the consequences of the interactions are highly diverse, most share some key characteristics which must be taken into account if improved environmental management is to be achieved:

- many of the consequences of the interactions are subtle and cumulative – often insignificant in relation to a single farm, but potentially significant for a large number of farms producing over a long period of time;

- some of the consequences may be highly dispersed through space and time;

- there is a high level of uncertainty and ignorance associated with many potential consequences.

2.2 Global experience of environmental management of aquaculture

It is generally agreed that aquaculture development needs to be well planned and managed if it is to achieve its full potential as a sustainable use of marine resources (GESAMP, 2001). Many countries already attempt to manage the aquaculture sector through some form of regulation (e.g. licensing associated with design, geographic or operational conditions). This regulation is often *ad hoc*, arising as a result of specific problems or concerns. In some countries, Environmental Impact Assessment (EIA) is applied, this allows for a more thorough appraisal of social and environmental problems, and possible mitigation measures, related to the siting, design and operation of individual farms. Some countries take a more strategic approach through sector level environmental assessment or aquaculture development plans. In a few cases, the management of aquaculture has been addressed within the broader context of Integrated Coastal Management (ICM). There has been some application of Strategic Environmental Assessments (SEA) to coastal aquaculture to help ensure that significant environmental concerns arising from regional or national policies, plans and programmes are identified, assessed, mitigated, monitored and communicated to decision-makers. SEA also can create opportunities for public involvement. Finally, there is increased interest in codes of conduct, for the industry as a whole and for individual farms (FAO Fisheries Department 1997; FEAP 2006; Naylor *et al.* 1998; Phillips and Barg 1999; Hambrey 2000).

Unfortunately, these various regulatory approaches have often proved to be less than ideal, because assessment of the effects of individual farms, through an EIA, can fail to address the cumulative, dispersed, and uncertain impacts of aquaculture development. There are still relatively few examples of sector level assessments or management plans (Thompson *et al.* 1995), or of the effective integration of aquaculture development planning within broader integrated coastal management initiatives (GESAMP 2001), and it is rather early to judge their success. However, there remain some significant constraints to the effective implementation of these approaches.

The more integrated and participatory the planning process is, the longer it takes to develop and agree on development and environmental management plans for the sector. Unfortunately this constraint is most serious in precisely those situations where better planning and management are required – for example, where the sector is developing rapidly and is under little or no control (such as shrimp farming in Asia and Latin America; and salmon farming in more temperate regions).

A related problem is the difficulty in gaining broad stakeholder agreement on what is, or is not, an acceptable level of change in the environment. This problem is compounded when environmental management objectives and associated performance criteria (such as environmental quality standards) have not been previously set or agreed, and where there are high levels of uncertainty associated with possible impacts – as can be the case with aquaculture.

This uncertainty and ignorance has led to calls for moratoria in some countries on some types of aquaculture, such as shrimp and salmon culture. The precautionary principle has often been invoked as the basis and rationale for such moratoria. However, that response is far from ideal. It reflects weaknesses in our ability to make decisions in the face of uncertainty. The effects of moratoria are almost all negative in that they create delays in the development process (where development is appropriate), imply uncertainty as to what is an acceptable level of development, and serve to maintain the state of incomplete scientific knowledge, uncertainty and lack of confidence in decision-making. The problem is the inability of many management systems to support managers making decisions in the face of uncertainty in the relevant risks.

An approach is required that :

- includes processes to clarify areas of ignorance and identify and isolate areas where knowledge is lacking;
- handles uncertainty in a constructive way while balancing realistic concerns and objectives and;
- provides a recognised and agreed sound basis for discussion.

In moving towards such an approach, it is helpful to consider in more detail the nature of risk and uncertainty, how they can be measured, and how regulatory processes have evolved to meet the challenge, for example, through the formulation of the Precautionary Principle.

2.3 Risk and uncertainty

2.3.1 The nature of risk and uncertainty

We constantly make risk assessments in our daily lives. We take responsibility for our actions, however mundane, and the hazards associated with them, based upon an assessment of the likely dangers and probability of undesirable outcomes. Through making such an assessment, we are able to consider simple measures to reduce risk, and where we deem it necessary, alter our actions to reduce the intensity of the hazard, and thereby minimise unnecessary risk.

When selecting a place to cross the road, our assessment may be influenced by the weight of traffic, the distance to a crossing point, our own mobility, our field of vision and in many cases, past experience. This process is a relatively complicated one, but one which we are able to do intuitively with little or no conscious thought. Individuals differ in their willingness to accept risk, for example, display different risk thresholds, and therefore the resulting decision is likely to vary from person to person, and we may find ourselves crossing alone. Similarly, the level of precaution applied to the potential environmental effects of coastal aquaculture is likely to vary according to culture and circumstance, perhaps expressed as national or local policy. It has to be agreed. It cannot be established scientifically, although it may be expressed in quantified scientific terms.

In other situations, the scale and number of factors influencing the assessment add to the degree of uncertainty. All else being equal, higher levels of uncertainty modify our perception of the level of risk, and influence our decisions accordingly. It is in the treatment of uncertainty and lack of information that traditional approaches to risk assessment have fallen down. Although uncertainty has usually been addressed – and is explicitly addressed in classic environmental risk assessment - its nature and importance are not always effectively communicated. In EIA, uncertainty is frequently lost or disguised in the calculations relating to the extent, significance and probability or likelihood of an impact. Since uncertainty is a major feature of many impacts on the natural environment, and since uncertainty is fundamentally different from probability, this is a major weakness.

2.3.2 The measurement or quantification of risk and uncertainty

There is still no universal method for communicating the level of uncertainty or risk and the method chosen will often depend upon the technical sophistication of the communicating parties (Caddy and Mahon 1995).

The general public and experts can view risk from very different perspectives. In a 1987 publication by Slovic, experts and members of the public were given a list of 30 activities to rank according to the level of perceived risk. Slovic (1987) also investigated the attributes of an activity that affected people's view of the associated risks. The attributes broadly divided into two broad groups of factors. One group was typified as describing unknown risks, that is, those that where the activity was new, the associated risks were not generally well covered by science, and where the effect was delayed (after the activity) and the effects were not observable. Examples of these, at that time included: Laetril, microwave ovens, and electric fields. The other group describe a 'dread' of the risk. Those factors included the geographic extent of the effect and its severity (for example, was it globally catastrophic or lethal to humans) the duration of the effect (for example, was it going to affect future generations), was exposure a matter of personal choice, and were the effects controllable. Examples of risk with a high contribution of these factors included: nuclear warfare, nuclear fallout and nerve gas accidents.

If terminology used to express risk is to reflect and integrate differing perceptions of risk by different stakeholders in a participatory management scheme, Slovic's work makes it clear that communication (the topic of Chapter 5) is critical to risk management strategies and that the technical risk analysis performed by scientists must explicitly address issues such as geographic and temporal extent, the duration of the effect, how the effect is generated, and the degree to which it can be controlled.

From a science perspective, a variety of tools are available to measure risk. Typically, these are based on an estimation of the probability of a particular effect arising as a result of a particular action or cause. In more complex cases, a probability distribution may be generated. Depending on the kind of data available, Bayesian analysis may be required to assign appropriate probabilities. These probabilities may be derived from experimental studies, from surveys, from time-series data, or (more subjectively) by expert panels.

Public participation in the decision-making process will, in part, be determined by whether participants agree on the need for an analysis, their willingness to identify the agent of potential environmental change and, the specific mechanism of interaction of those agents with the environment. As mentioned in section 2.1, there are numerous published accounts of specific examples of an agent released by aquaculture (such as the placement of structures that may redirect currents, pathogens, the culture organism or organic matter) and the consequences of interactions involving the specific agent (such as the redistribution of sediments, reduced survival of a wild population due to disease or genetic interbreeding and displacement of bottom fauna). As the references in section 2.1 often demonstrate, most of the effects commonly discussed focus on a single agent and a single outcome. Most decision-making will ultimately is made on the basis of the possibility of one or a very few changes. However, most interactions between human activities and ecosystems are multifactoral and part of the challenge in preparing to make an evaluation of risk is to list the potential interactions and agree on the combinations of hazards and consequences that are of greatest concern. An example of an approach to identifying critical multifactoral causes and ecological effects as part of risk analysis for capture fisheries is presented by Astles *et al.* (2006).

In practice, there is usually a chain of effects arising from a particular action or release of a risk agent. In this case, combining the probabilities down the chain may generate the probability of any intermediate consequence, or of the final consequence. Physical environmental processes may provide only a few cause and effect links, and the probability associated with the final effect may be estimated with reasonable confidence. However, biological and ecological effects, especially in coastal systems, are typically generated through highly complex chains and networks of cause and effect relationships. The uncertainty associated with any probability estimate of an ecological effect is therefore typically very high.

The importance of uncertainty along the chain of effects can be illustrated by considering some of the key types of uncertainty. Measurement causes uncertainty due to inaccuracies in data collection. The natural variations of the process being observed may render observations unreliable and add to uncertainty. Any attempts at modelling, perhaps as part of an ERA process, add further uncertainty due to the limitations of a best-fit interpretation. Finally, implementation and, in particular, the ability to match strategy with action adds to the uncertainty of the effect (Caddy and Mahon 1995).

So can the level of uncertainty be measured in any meaningful way? Scientists use statistical confidence limits, and confidence limits are calculated from probability distributions. To generate a probability distribution for all the links in a typical environmental impact chain is likely to be an unrealistic objective. Where this is possible, confidence limits will in any case be wide for most ecological effects through the necessary combinations of uncertainty down the cause/effect chain.

2.4 A precautionary approach

The need for precaution in environmental management has become increasingly clear in recent decades as the inadequacies of reactive and various *ad hoc* approaches have become apparent. Precautions, or at least enhanced levels of caution, are also a natural and appropriate response to uncertainty in the prediction of the outcomes of actions.

2.4.1 Regulatory approaches based on assimilative/environmental capacity

Industry, and society in general, have had traditional rights of access to, and use of, marine resources. This has been based upon the view that the marine environment has an assimilative or environmental capacity. This presumes that all environments have a finite ability to accommodate exploitation or contamination without unacceptable consequences (Gray 1998). GESAMP described this capacity as "a property of the environment, defined as its ability to accommodate a particular activity or rate of activity without unacceptable impact" (GESAMP 1986).

Traditionally, consent to discharge waste has been given on the condition that monitoring to ensure that the assimilative capacity is not exceeded. The obvious weakness of this approach is that the undesirable environmental consequences may only be evident once the environmental capacity to absorb the waste has been exceeded. This is a particularly dangerous approach to planning and legislation if the effects are irreversible.

It is inevitable, if working to the assimilative capacity through a 'monitor-response' regulatory framework, that measures to reduce potentially damaging inputs to the marine environment will only be implemented once it is too late. Not only is this harmful to the environment, but it can also be expensive, particularly if used in conjunction with the 'polluter pays' principle. Industry may be locked into a repeating cycle of low cost effluent disposal followed by high cost remedial action when the assimilative capacity has been exceeded.

A further criticism of this approach is that it makes little use of available scientific knowledge. Published scientific analysis and case studies provide valuable clues to likely consequences of actions. To be legally sanctioned to ignore this body of evidence and continue discharging to the point where negative impacts show up in monitoring is irresponsible (Gray 1998).

2.4.2 The Montreal Guidelines

In 1985, UNEP attempted to overcome some of the difficulties of existing marine pollution control policy. The Montreal Guidelines (UNEP, 1985) for governments were an attempt to give greater consideration to local variations in the marine environment and tackle the problem of marine pollution from land based sources. The guidelines were based on a need to have strict emission controls and marine quality standards. These should give clear consideration to water and sediment quality, as well as using fish assemblages and biological community structures as indicators of environmental health. The Guidelines also recommend that planning applications should include Environmental Impact Assessments.

These Guidelines build upon some of the principles of assimilative capacity and other existing approaches to marine environmental regulation. However, there were still concerns over the ability of these Guidelines to promote full protection of sensitive marine ecosystems. The principal concerns were over ambiguity within the Guidelines. For example, there was no consideration of ambient conditions within an ecosystem prior to impact, nor was there any quantitative indication of the levels of environmental standards. More particularly, no framework was provided for the process of deciding upon appropriate localised marine standards. Further work was still required for the evolution of an effective regulatory framework (Gray 1998).

2.4.3 The Precautionary Principle

In recent years, the precautionary principle has emerged as a popular approach to deal with uncertainty in science-based decision making. Article 15 of the United Nations 1992 Conference on Environment and Development defined the precautionary principle as "lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation". While the broad sentiment behind the statement is generally agreed upon, the principle has never been accepted as a general principle of international law. A number of factors contribute to the reticence to enshrine the principle in law. The precision of the definition has been problematic. Ronald Doerling, former Vice President of the Canadian Food Inspection Agency, illustrated several of these in an invited plenary speech at Aquaculture 2004 in Montreal, Canada. Among his comments, he pointed out that working interpretations of the principle varied significantly, and that the Swedish philosopher Sandin documented no less than 19 variations in the principle's definition in laws, treaties and academic writings. The versions differed in the interpretation of how scientific uncertainty was evaluated, how severity of consequences is considered, how the costs and risks are to be balanced and, from a legal perspective, how the onus shifts to the proponent to prove (if that is ever possible) that the proposed process or product is safe.

In 1987 at the 2nd International Conference on the North Sea in London, the regulations safeguarding the marine environment were taken a natural step further, by removing the need for concrete scientific proof of cause and effect, and rather shifting the emphasis to precaution. The Ministerial Declaration agreed to "*accept the principle of safeguarding the marine ecology of the North Sea by reducing polluting emissions of substances that are persistent, toxic and liable to bio-accumulate at source by the use of best available technology and other appropriate measures. This applies especially when there is reason to assume that certain damage or harmful effects on the living resources of the sea are likely to be caused by such substances, even where there is no scientific evidence of a causal link between emissions and effects*".

The precautionary principle laid out in 1987 appears to offer improved protection to the marine environment. The spirit of the agreement is widely endorsed, although there are important questions of definition. The terms 'persistent', 'toxic' and 'bio-accumulate' are subject to differing interpretation, and can be assigned to any substance to some degree or other. Virtually all substances will persist to some degree, and can be toxic in high enough concentrations. Conversely, substances may bio-accumulate without causing harm.

Clearly the difficulties lie with the interpretation of the agreement. Nowhere is this more clearly illustrated than in the lack of requirement for a scientific link between cause and effect. This throws open the possibility of suspicion ruling over science, and effluents being unnecessarily banned.

The principle was re-stated and internationally agreed in Principle 15 of the Rio Declaration of the UN Conference on Environment and Development (UNCED):

"*In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation* ".

The principle has since been adopted in Article 174 of the (EU) Treaty of Amsterdam, and has already been used to justify delayed approval for imports of crops containing material from genetically modified organisms, and the banning of imports of beef produced using hormone supplements. It is a major element in the rationale for the more recent UN Cartagena Protocol on Food Biosafety, which aims to regulate the trade in genetically modified products.

A major attraction of the precautionary principle is that precaution is a natural feature of human behaviour. We are all cautious to a greater or lesser extent, and the degree of our caution is related to uncertainty and lack of information, as well as the probability and severity of an undesirable outcome. The principle arose not from developments in environmental science or the philosophy of science, but rather from an awareness of past failures in dealing with environmental risks, coupled with a 'common sense' approach to dealing with uncertainty.

The 4th International Conference on the North Sea, held in Esbjerg, Denmark in 1995 (Oslo and Paris Commissions 1995), in formulating an approach to the control of eutrophication, stated that there should be scientific proof of a lack of eutrophication arising from anticipated nutrient inputs prior to consent to discharge nutrients being granted. In practice, scientifically proving a negative is impossible, especially in complex physical and biological systems.

Notwithstanding this problem, many analysts link the precautionary principle to such a reversal of the burden of proof (although the Rio statement does not strictly imply this). They suggest that it places the burden of proof firmly on the advocates of new technology and developments to show that what they are proposing is safe. It is not for the rest of us to show that it is not (Saunders 2001).

2.5 Interpretation and application of the Precautionary Principle

Applications of the precautionary principle or precautionary approaches, and calls for the application of the principle, have generated much debate and controversy. One problem has been a proliferation of slightly different definitions of the principle. For example, in association with an international grouping of scientists, Greenpeace met in 1998 for a three-day conference at Wingspread, to discuss the implementation of the precautionary principle. The outcome from this conference states that, "*When an activity raises threats of harm to the environment or human health, precautionary measures should be taken even if some cause and effect relationships are not established scientifically*" (Wingspread 1998); a definition that would effectively prevent the implementation of most new technologies. On the other hand, some commentators have suggested that the principle is fundamentally flawed and logically contradictory with suspicion ruling over science (Gray 1998).

However, most people would agree that the spirit of the principle is that we should be careful when embarking on something new; we should be reasonably convinced that no unacceptable harm will come of it; and we should be particularly careful when there is much uncertainty or ignorance about possible outcomes. The principle is not and cannot be a decision criterion, since the word reasonable (as applied to suspicion, proof, certainty, uncertainty etc) is a key word in most definitions. Further, what is 'reasonable' is a question of social values and not definable in the context of the physical, biological or ecological sciences. The principle also does not require developers to prove absolutely that something is safe (Saunders 2001). As noted above, this is impossible from a logical and scientific viewpoint. However, it does require convincing evidence that serious harm is unlikely.

Although many have criticised the principle on the grounds that 'reasonable' cannot be used as a scientific decision criterion, others point out that this is neither implied nor required. As in the case of criminal justice systems, proof beyond reasonable doubt can be established, using as a basis agreed guidelines, precedent, or the opinion of an expert or representative panel (such as a jury). Justice is what society as a whole perceives to be reasonable. The key requirement is that all available evidence is collected and assimilated (either impartially, or by advocates representing opposed factions or positions), the key arguments presented, and a decision is made by some impartial and transparent process. The verdict, while not being prescribed, will be reasonably consistent, at least within a particular national framework or culture.

However, there is always a further dimension to environmental decision-making which is not explicitly addressed in the precautionary principle (although it is implied in the words cost effective). In the face of risk and uncertainty, decision-makers have always balanced possible negative impacts, and their likelihood, against probable or actual benefits. Where the likely benefits are high, and the possible costs of negative impacts low, decision-makers will be less precautionary. Where benefits are limited and costs potentially high, they will be more precautionary. This goes some way to understanding how national differences in the interpretation of the precautionary principle can arise. Developing countries may tend to put more weight on the benefits and less on the risk, especially where the impacts relate to intangible or non-limiting (at least in the short term) environmental goods and services.

The European Commission, in its communication on the precautionary principle (European Commission Press Release IP/00/96, 2 February 2000 and related commentary) qualifies the measures that may be taken under the principle. It proposes five 'guidelines' which should lead to rational and transparent application of the principle. These include:

1. Proportionality: "Measures...must not be disproportionate to the desired level of protection and must not aim at zero risk."

2. Non-discrimination: "Comparable situations should not be treated differently and... different situations should not be treated in the same way, unless there are objective grounds for doing so."

3. Consistency: "Measures...should be comparable in nature and scope with measures already taken in equivalent areas in which all the scientific data are available."

4. Examination of the benefits and costs of action or lack of action: "This examination should include an economic cost/benefit analysis when this is appropriate and feasible. However, other analysis methods...may also be relevant."

5. Examination of scientific developments: "The measures must be of a provisional nature pending the availability of more reliable scientific data... scientific research shall be continued with a view to obtaining more complete data."

In practice this balancing of benefits and costs (as in 4 above), which has always been part, explicitly or implicitly, of development decision making, has tended to favour development at the cost of the environment. Indeed, it is this imbalance which the precautionary principle is designed to alter. However, only an extreme position would hold that this balance should not be taken into account in the application of the principle, albeit with the fulcrum shifted in favour of precaution. A court may convict a criminal, but impose no sentence, in the light of mitigating circumstances. There are measurable risks associated with vaccination, but most would rather accept these risks because they are perceived to be outweighed by the benefits. Invoking the precautionary principle is unlikely to change many such decisions, but it does imply that we need to be generally more cautious, especially when levels of ignorance and uncertainty are high. In essence, we need to make a more informed assessment of risk and place more weight on ignorance and uncertainty as part of this assessment. This implies significant cost in the short term, although if applied correctly it should result in long-term savings and benefits.

The principle has also given rise to debate over the role of science in decision making. Some scientists suggest that the principle is incompatible with science-based decision-making, since science can never prove a negative. Some environmentalists argue that it should supersede conventional scientific risk assessment, since the process lacks transparency, and neither fully admits nor puts sufficient weight on uncertainty and ignorance.

In practice, this is a false dichotomy. Rational precautionary decision making can only be based on evidence provided by good science. But it must be recognised that science cannot provide all the information required for decision-making; and decision -making in an uncertain world is not itself a scientific process. Science should serve decision-making, and the precautionary principle requires that it characterise and communicate the nature of risk and uncertainty more effectively. But this is not enough. Scientific assessment must explicitly address risk and uncertainty, and feed them into a transparent and accountable decision-making process. This process should explicitly link the acceptable level of precaution with the requirements of international agreements and legitimate local needs and aspirations.

Only a socio-political process can determine what is acceptable. Consistent application of these criteria for acceptable environmental change requires that the changes be identified as measurable endpoints (parameters) of environmental significance. The designation of these endpoints is critical to the development of an accurate and effective environmental assessment (*see* EPA 2003) for a discussion on how endpoints may be derived). The endpoints generally will be applicable to the assessment of the environmental effects of a number of industries or activities (including fisheries activities such as stock enhancement or definition of gear types to be used in a particular fishery). To ensure that a particular economic or environmental assessment does not influence the derivation of these endpoints, they should be derived independently and prior to the initiation of a risk assessment.

Improvements to the decision-making processes can be provided through the procedures and protocols of risk assessment in a Risk Analysis framework. In the next section, we examine how Risk Analysis can improve the analysis, characterisation, and communication of risk and uncertainty.

It should be noted that this paper does not address the risks arising from the culture of newly introduced exotic species. The analysis of these hazards is covered by existing guidelines, for example the ICES Code of Practice for the Introduction and Transfer of Marine Species. In the European Union, statutory regulations built on the ICES Code are currently under discussion. Similarly, potential disease interactions are thoroughly covered by the ICES Code and the OIE protocols. Additionally, hazards associated with the quality of the foodstuffs produced through coastal aquaculture are controlled by application of the Codex Alimentarius (1999) and associated international/national legislation.

2.6 Objectives for risk assessment and analysis

The intent of this section is to define the objectives that risk analysis needs to achieve so that it supports effectively governance schemes promoting sustainable resource use that incorporate the precautionary principle as part of the management of the effect of Man's activities on the environment.

1. Integration into Sustainable Use Paradigms: Risk assessment (a science-based assessment) must be integrated into a broader socio-economic decision-making process to determine resource allocation for sustainable use. Risk analysis provides the basis for doing this through use of the table of levels of acceptable protection, as well as a consistent and explicit mechanism for transparent application of the precautionary principle.

2. Separation of Scientific Analysis from Valuation: Risk assessment is a science-based analysis. In itself, it does not determine if a predicted outcome is good or bad, acceptable or unacceptable. Determination of these values can only occur when the predicted outcome is combined with social and economic information.

3. Non-discrimination: Comparable situations should not be treated differently, and different situations should not be treated in the same way, unless there are objective grounds for doing so.

4. Transparency: To optimise the accuracy, effectiveness and social licence for aquaculture activities, risk communication must start early in the Risk Analysis process and communicate the information stakeholders and decision-makers require in a manner they can utilise.

5. Consistency: Measures should be comparable in nature and scope with measures already taken in equivalent areas in which scientific data are available.

6. Proportionality: Risk management measures must not be disproportionate to the marginal change in risk and to the desired level of protection. Coastal aquaculture can represent only minor marginal risk of change when compared with a multitude of other coastal anthropogenic activities). Also, risk management must not aim for zero risk. Where no hazard can be identified, the risk assessment should be concluded and evaluated as non-significant.

7. Ongoing Monitoring of Predicted Effects: Where ongoing monitoring is identified as a necessary component of risk management, the initial analysis should be considered provisional. The availability of more reliable scientific data may lead to changes in our understanding of the mechanisms leading to environmental change and the level of risk (increased or decreased) associated with an aquaculture decrease. A requirement to monitor must be linked to requirements to regularly report on the outcome of the monitoring, and for regulators to make reasoned assessments of the significance of the monitoring results.

2.7 Literature cited

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3 RISK ANALYSIS

3.1 What is Risk Analysis?

McVicar (2004) describes risk analysis as "*a structured approach used to identify and evaluate the likelihood and degree of risk associated with a known hazard. It leads to the implementation of practical management action designed to achieve a desired result regarding protection from the hazard. Actions taken should be proportionate to the level of the risk. This provides a rational and defendable position for any measures taken to allow meaningful use of resources and for the focus to be on the most important areas that can be controlled. Risk management requires that all possible major hazards to the matter of concern should be identified.*"

Risk analysis integrates risk assessment and risk communication, and is structured to support effective risk management. While risk management is not discussed in depth in this document, how the assessment process can link to risk management is illustrated.

Risk analysis has been adopted in a range of international fields affecting aquaculture as a method for integrating risk assessment and risk communication into decision-making. For example, in response to concerns about the transfer and control of diseases of aquatic animals, the World Trade Organisation accepts the risk analysis protocols developed by the Office International des Epizootic (OIE) as the basis for justifying trade restrictions through regulatory actions, including restriction on movements of commercial and non-commercial aquatic animals. The purpose of the OIE protocols was to provide guidelines and principles for conducting transparent, objective and defensible risk analyses in relation to international trade. ICES has embraced this approach in their latest Code of Practice for the Introduction and Transfer of Marine Organisms (hereafter referred to as the ICES Code) (ICES 2005b). One part of the ICES Code is specifically designed to address the "*ecological and environmental impacts of introduced and transferred species that may escape the confines of cultivation and become established in the receiving environment* ".

This document advocates the use of Risk Analysis procedures in assessment of the environmental risk arising from coastal aquaculture developments. Environmental risk assessments are commonly associated with high levels of uncertainty in the probability of outcomes of particular actions, incomplete scientific knowledge, and significant expressions of concern by other stakeholders. Examination of the issues concerned, using a recognized protocol for risk analysis inclusive of good risk communication, is presented as a helpful strategy for developers, regulators and interest groups.

Terms used in fields of human health and environmental risk assessment can have a variety of definitions, depending on their application. These definitions differ subtly and can be a source of confusion.

The definitions for risk and hazard as used in this document are:

Risk: A characteristic of a situation or action wherein two or more outcomes are possible. The particular outcome that will occur is unknown, and at least one of the possibilities is undesired. Risk = Product of the probability of change and severity of change (after Covello and Merkhofer 1993).

Hazard: An agent, medium, process, procedure or site with the potential to cause an adverse effect (EU Commission 2000). A (potential) source of risk that does not necessarily produce risk. A hazard produces risk only if an exposure pathway exists and if exposures create the possibility of adverse consequences (Covello and Merkhofer 1993).

Both the definitions above, of hazard and risk, are linked to what society sees as a negative effect, or an undesirable outcome. In some instances, agents, media, processes or sites may actually result in environmental changes that society considers to be beneficial. For example, increased algal abundance as a result of human release of nutrients into coastal waters is often considered a negative environmental change. In such environments, shellfish culture may lessen the build up of algae. In other, less eutrophic environments, reduction of algal abundance may be seen as threatening the food resources for endemic filter feeding organisms. Thus, in the former case there is no risk of undesirable changes in algal abundance whereas in the latter case such a risk may exist.

3.2 The Structure of Risk Analysis

The risk analysis process is built around the concept that some aspect of the activity under consideration (coastal aquaculture) can lead to the release of a hazard that in turn could lead to an undesirable change in the environment. In the case of coastal finfish aquaculture, an example would be the release of particles of uneaten food and faeces (the hazard) into the environment potentially leading to an unacceptable degree of smothering or alteration of the benthic fauna beneath and around the cages (the endpoint, or undesirable outcome).

Risk analysis can be broken down into four major components:

- Hazard Identification;

- Risk Assessment;
- Risk Management; and
- Risk Communication.

The process and its components are represented in Figure 3.1, in which the relationship between the sequential steps of hazard identification, risk assessment and risk management and the continuous process of risk communication is illustrated. Risk Communication is the most pervasive and important component of risk analysis. It acts to optimise the transparency and openness of the process, as well as maximizing the acquisition of information, and acceptance of the conclusion of the analysis. It has roles to play in the preparation for a risk analysis, during the risk analysis and in some instances as part of the follow-up after completion of the analysis.

Risk analysis provides an objective, repeatable, and documented assessment of risks posed by a particular course of action and answers the following questions:

- What can go wrong? – Hazard Identification;
- How likely is it to go wrong and what would be the consequences of it going wrong? – Risk Assessment;
- What can be done to reduce the likelihood or consequences of it going wrong, or the level of uncertainty in our prediction of the outcome? - Risk Management and;
- How can the analysis process be made understandable, open and transparent to all with an interest in the management of our marine resources? – Risk Communication.

The Risk Assessment component mentioned above is further broken down into four subcomponent steps (Figure 3.2) following the generally accepted protocol proposed by Covello and Merkhofer (1993):

(i) Release Assessment;

(ii) Exposure Assessment;

(iii) Consequence Assessment; and

(iv) Risk Estimation.

3.2.1 Levels of Protection and the Precautionary Approach

The risk assessment phase of a risk analysis provides information on three important aspects of the predicted environmental effect; the severity of change; the probability of it happening, the uncertainty associated with that prediction. The criteria of the desired level of protection are determined by managers, and are compared against the predicted changes. The regulatory response to this information depends on the socio-economic setting in which the decision is made.

Another set of definitions are therefore required prior to initiating a risk analysis. These cover the explicit enunciation of what constitutes an acceptable level of protection for each identified outcome. This will vary from jurisdiction to jurisdiction, as jurisdictions vary in the level of risk they are willing to take depending on their social and economic conditions. In the context of trade restrictions, this is likely to be acceptable as long as restrictions are equally applied to all traders whether the goods and services in trade are created within the jurisdiction, or externally and exported into the jurisdiction. In national or more local regulatory contexts, it implies that regulators can be explicit in the standards that they adopt, and can deliver transparent and consistent decisions from case to case.

Based on the severity and probability of an undesirable outcome being expressed, an explicit table for making decisions can be constructed that illustrates the acceptable level of risk for a jurisdiction. Such a table (*for example*, Table 3.III) could be used to assist resource managers to decide if a licence should be issued (Accept) to operate a farm in a certain location or not (Reject).

This table uses severity and probability to derive consistent and transparent decisions. However, the table does not take account of uncertainty associated with the assigned probabilities. An assessment of a probability as being associated with high uncertainty indicates that the true expression of the risk may differ from the assigned assessment. For example, a risk assessed as of low probability with a high degree of uncertainty may actually be of extremely low or moderate probability. The precautionary principle indicates that such uncertainty should be taken into account in the assessment and decision-making processes. This can be accommodated within the structure described here by considering that if the probability is associated with a high degree of uncertainty, then this should be considered as equivalent to an assessment of a higher probability of occurrence. The decision table above is then modified as shown below (Table 3.IV), which indicates in bold where a higher degree of uncertainty would result in a change of decision from ‘accept’ to ‘reject’.

Risk analysis does not overcome all the shortfalls in the definition and application of the precautionary principle, but it does make the inherent assumptions and value judgments much clearer and explicit. If, however, definitions and the expression of what constitutes an acceptable level of protection are not well made, and made in advance of the assessment, the uncertainties and misuse associated with the use of the precautionary principle also become a threat to the objectivity attainable through risk analysis.

The ultimate purpose of risk analysis is to provide structured and assessed information to underpin a management decision, for example, as to whether or not to permit a particular activity to

Figure 3.1 : The four components of risk analysis and use of levels of protection (L.O.P.) (after OIE 2003).

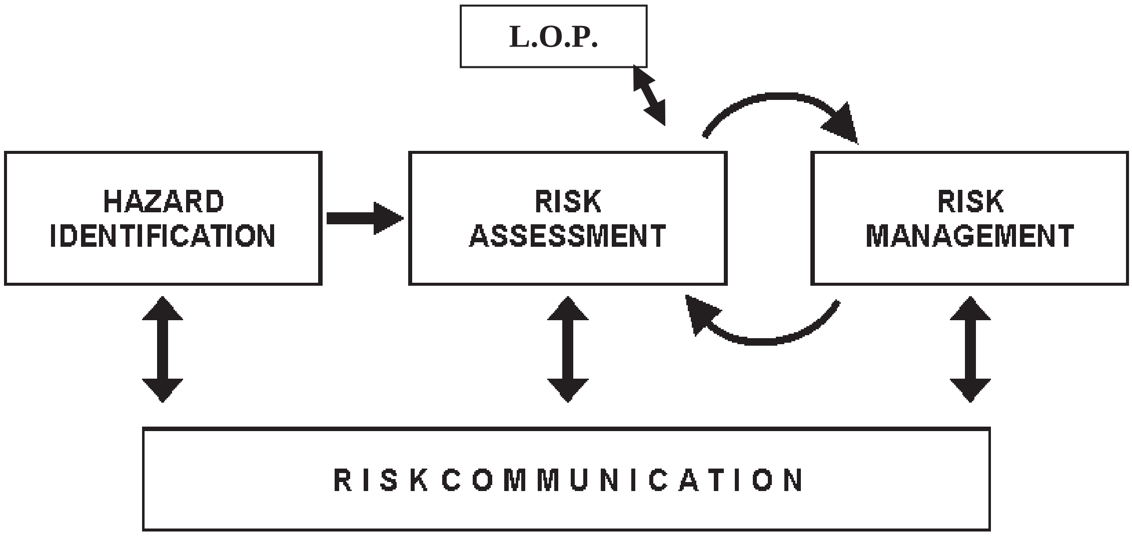


Figure 3.2 : The elements of risk assessment.

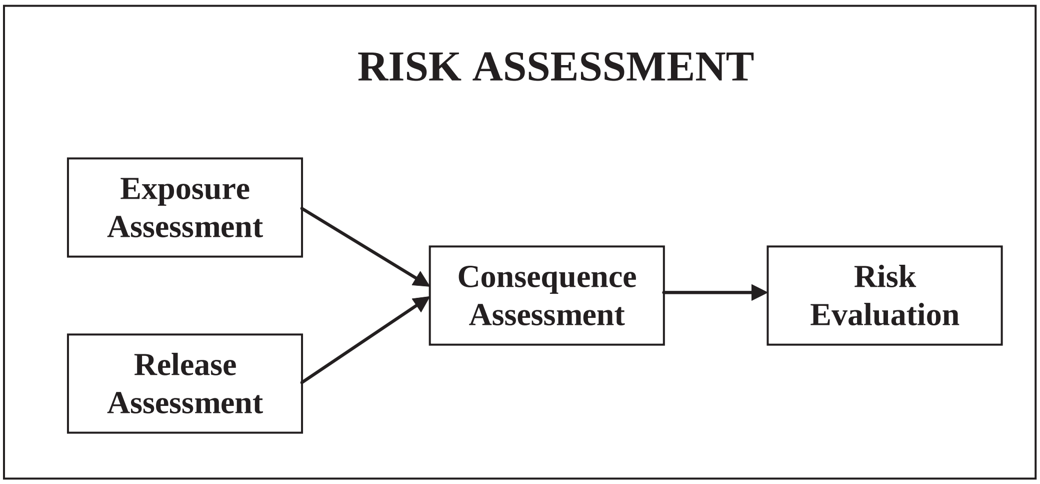


Table 3.1 : Classification of the severity of environmental change. The term 'ecosystems' refers here to water bodies of such size that water quality processes occuring in them largely function independently of the processes in adjoining water bodies. For example, a bay or estuary with relatively short water residence time would not be considered an ecosystem. In contrast, a fjord of an inland sea with a more protracted residence time might be considered an ecosystem for the purposes of these definitions.

Catastrophic:	- irreversible change to ecosystems performance at the faunal-province level or - the extinction of a species or rare habitat.
High:	- high mortality for an affected species or significant changes in the function of an ecosystem. - effects would be expected to occur at the level of a single coastal or oceanic water body. - effects would be felt for a prolonged period after the culture activities stop (greater than the period during which the new species was cultured or three generations of the wild species, whichever is the lesser time period). - changes would not be amenable to control or mitigation.
Moderate:	- changes in ecosystem performance or species performance at a regional or subpopulation level, but they would not be expected to affect whole ecosystems. - changes associated with these risks would be reversible. - change that has a moderately protracted consequence. - changes may be amenable to control or mitigation at a significant cost or their effects may be temporary.
Low:	- changes are expected to affect the environment and species at a local level but would be expected to have a negligible effect at the regional or ecosystem level. - changes that would be amenable to control or mitigation. - effects would be of a temporary nature.
Negligible:	- changes expected to be localised to the production site and to be of a transitory nature. - changes are readily amenable to control or mitigation.

Table 3.II : Definition of assignable qualitative probabilities.

High:	The risk is very likely to occur.
Moderate:	The risk is quite likely to be expressed.
Low:	In most cases, the risk will not be expressed.
Extremely Low:	The risk is likely to be expressed only rarely.
Negligible:	The probability of the risk being expressed is so small that it can be ignored in practical terms

Table 3.III : An example of a table defining the acceptable level of protection

	Severity				
	C	H	M	L	N
H	Reject	Reject	Reject	**Accept**	Accept
M	Reject	Reject	**Accept**	Accept	Accept
L	Reject	**Accept**	Accept	Accept	Accept
EL	**Accept**	Accept	Accept	Accept	Accept
N	Accept	Accept	Accept	Accept	Accept

Severity = C - Catastrophic, H - high, M - Moderate, L - Low, N - Negligible
Probability = H - High, M - moderate, L - Low, EL - Extremely Low, N - Negligible
Reject = Reject a request for a permit to undertake culture
Accept = Accept the risks associated with permitting the culture to be undertaken

Table 3.IV : Table 3.III adjusted to allow for uncertainty in the probability of change

	Severity				
	C	H	M	L	N
H	Reject	Reject	Reject	**Reject**	Accept
M	Reject	Reject	**Reject**	Accept	Accept
L	Reject	**Reject**	Accept	Accept	Accept
EL	**Reject**	Accept	Accept	Accept	Accept
N	Accept	Accept	Accept	Accept	Accept

take place. To be able to implement risk analysis effectively and achieve a desired level of protection against an undesired outcome, it is essential that the terminology used is defined and that, prior to the analysis, there is a clear statement of what would constitute an acceptable level of protection from the outcomes of the hazard(s) being examined. If this framework is established at the outset, these attributes determine the nature of the resultant management decisions and actions. Failure to do so potentially compromises the transparency and freedom from bias that can be achieved through the risk analysis process.

3.2.2 The logic model

As indicated above, risk analysis is built around the concept of the release of a hazard that could lead to an undesirable change in the environment. The processes and conditions by which the hazard can result in the undesirable outcome or endpoint should be linked together in a series of sequential steps, forming a logic model for the combination of hazard and endpoint being analysed. This logic model can be written down as a series of steps, and it is usually very helpful to draw the logic model as a flow diagram, distinguishing between inputs of information, processes, decision points, etc., to ensure that the all parties to the discussion have a sound and consistent basis on which to build the risk analysis.

3.2.3 Severity of effects

To continue the example of a hazard arising from the release of particulate organic waste, the degree of smothering of the benthos or alteration of the seabed can differ from site to site, depending on a wide range of factors. It is important that we can describe the severity of this effect. Terms used in the Australian Import Risk Analysis on Non-Viable Salmonids and Non-Salmonid Marine Finfish (AQUIS 1999) are used here to provide a template for these definitions. In that analysis, there are five categories or levels of severity. The definition of each level of severity is determined by three factors:

- The degree of change experienced in the affected ecosystem or species;
- The geographical extent of the change; and
- The temporal duration of the change (from transient to irreversible).

Attributes of the potential change are often characterised by more than one severity class. The overall severity is expressed as the average of the severity categories. For example, if the predicted effect is high mortality of a subpopulation of a species that would be reversed over a couple of generations then,

- High mortality of a species is an attribute associated HIGH severity.
- As only a subpopulation is affected the level is MEDIUM severity.
- The anticipated duration of a couple of generation is a MEDIUM severity characteristic.

The final assessment of the severity of the change would therefore be the ‘average’ of HIGH+MEDIUM+MEDIUM, for example, MEDIUM.

3.2.4 The probability of outcomes

The assignment of probabilities to particular specific outcomes is a critical part of the risk analysis process. In some cases, a fully quantified approach can be taken but, in most cases, knowledge of the probabilities associated with each of the steps between the initial driver and the final expression of the undesirable effect will not be available. Generally, it will be necessary to adopt semi-quantified or qualitative approaches to estimation of the probability. Previous experience, scientific knowledge, and expert judgment, will be the important factors in assessing the probability of the specific undesirable outcome being expressed. However, there will inevitably be a degree of imprecision and uncertainty in the final assigned probability. For example, monitoring data and modelling indicate that the probability of change due to enrichment of the seabed below fish culture units in Scotland is high, but the same degree of change for the same rate of organic carbon release from fish cages in oligotrophic areas of the Aegean Sea may be less probable i.e. moderate to low probability (Cromey *et al.* 2002).

Expression of the probability of a risk being expressed can be achieved in a number of ways. These may be expressed precisely in numerical form or more qualitatively. As numerical quantification is seldom available, the definitions below (Table 3.II) are of a more qualitative nature. The number of categories used to describe severity and probability of a risk may vary. There is nothing dictating that it should be five; it could be more or less. The greater the number used, the more difficult it will be to attribute clearly any particular risk to a specific category. The fewer the number, the more extreme the final evaluation is likely to be.

3.2.5 Uncertainty in estimates of probability

The assignment of qualitative probabilities to particular outcomes or steps in a logic model inevitably involves elements of expert judgement. We do not have the high level of knowledge that is required before we can have a correspondingly high level of accuracy and certainty in estimates of probability. In making predictions, there are two broad sources of error; imprecision and uncertainty. Imprecision is our inability to measure exactly some input or output or relational coefficient. Uncertainty derives from an incomplete understanding of the forcing factors and mechanisms that determine the consequence of a development. That does not mean that all potential sources of inputs or mechanisms need to be known, but account needs to be taken of all the major ones. Many environmental processes are influenced by a great number of factors. However, significant change in the system is usually determined by a much smaller subset of these factors.

For example, we know that there are many potential sources of mortality that affect fish in a wild population. These could include fishing mortality, human destruction of habitat, disease, predation and competition for scarce resources by other species, and others. Within certain limits, and for short term predictions, one or a limited number of these sources of mortality dominate in determining the abundance of the species. Worldwide fishery harvest levels have been set on that basis, with scientists constantly trying to improve their ability to quantify the abundance of stocks and improve their ability to determine more precisely the coefficient describing the relationship between the spawning stock size and composition and the abundance of fish that will ultimately be harvested. That typifies an approach in response to a problem of errors due to imprecision.

Recently it has become clearer that our models to predict the abundance of fish in some populations are missing critical components. Over longer periods, survivorship seems to vary independent of fishing pressure. Work of oceanographers and biologist to resolve the sources of this error have revealed that sudden changes in ocean regimes that typically occur every decade or so can have a greater effect than fishing on the survival of some species (Beamish *et al.* 2004 a, b, c). Other work (*for example*, Frank *et al.* 2005) has shown that excessive harvesting of top predators from an ecosystem can radically affect ecosystem dynamics causing harvest species to experience an entirely new survivorship dynamic. Errors in our prediction of recruitment due to this lack of knowledge of the mechanism giving rise to the change should be attributed then to uncertainty (completeness of our predictive models).

In the context of risk analysis, qualitative (or sometimes quantitative) models are used to estimate the probability of an event occurring. The expert judgments commonly required to express the probabilities come with an inherent degree of underlying confidence or reliability, and this is the origin of the uncertainty in the predictions. High confidence equates to low uncertainty, whereas high uncertainty implies that the experts have low confidence in their estimates of probability.

It is through the adjustment of decisions in relation to the uncertainty that the precautionary principle is implemented in risk analysis.

3.3 Risk Communication

As noted earlier, Risk Communication is the most pervasive and important component of risk analysis. It is central to the preparation for a risk analysis. It should be a clear and strategic activity during the risk analysis and in working out the conclusions from the analysis. In some some instances, such as the implementation of reporting on monitoring results, it can be a part of the follow-up after completion of the analysis. Risk communication has a number of potential audiences including:

- The individual who has information that can be incorporated in the analysis of risk;
- The individual trying to incorporate the outcome of the risk analysis in their personal view of risks;
- Technical peers who will evaluate and contribute to a risk analysis exercise. (Peer-review of risk analyses is an essential component of risk communication. It ensures the best information is incorporated in the analysis and acts as a quality control function for the final product.);
- The resource manager who may incorporate the results of analysis in his decision making; and,
- The public who define what is an acceptable risk and translate that, via political processes, to the manager who makes resource decisions.

Each of these audiences deal with information differently and their best use of information requires that the information is packaged in the manner that they can best use it. As can be imagined, with such a variety of audiences and needs, risk communication is a complex and challenging task. Chapter 5 addresses this topic. At this point, suffice it to say that the pervasiveness of risk communication in any risk analysis requires a good risk communication strategy to be in place at the start of each risk analysis exercise.

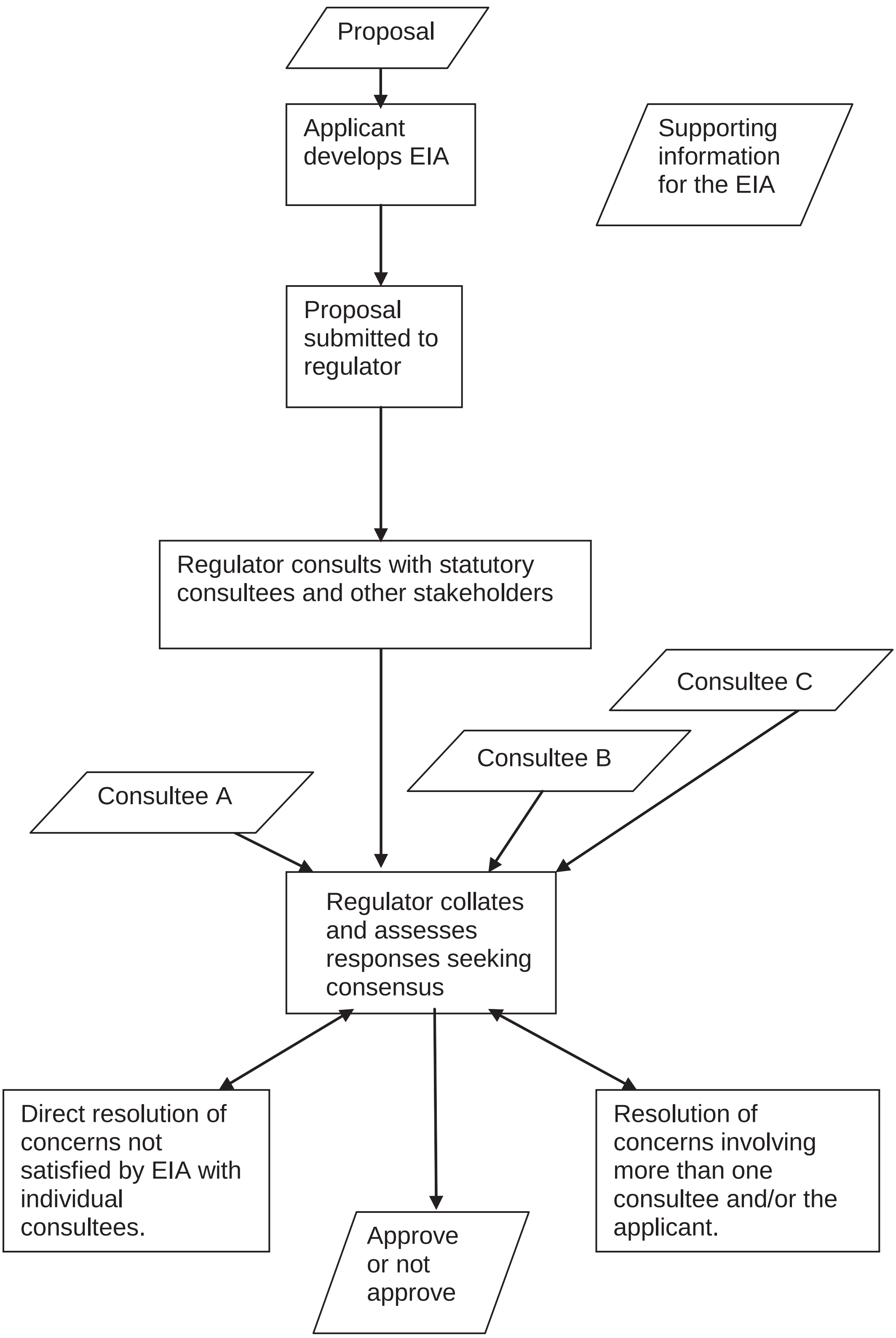
3.4 How can risk analysis contribute to the decision-making process and sustainable development?

3.4.1 Interaction of Risk Analysis with existing decision-making processes

The theoretical discussion above presents risk analysis in isolation from existing decision-making processes. In practice, the true potential contribution available through risk analysis will be achieved through integration with existing processes, rather than in competition with them. These processes operate at a wide range of scales. At the smallest scale, Environmental Impact Assessment and the preparation of Environmental Impact Statements are commonly applied at the scale of the single aquaculture unit. The decisions made will therefore refer to a single development proposal, often in isolation from other similar proposals or from other activities taking place in the coastal zone.

On larger scales, integrated coastal management seeks to find the optimum mix of activities in coastal areas, taking account of the full range of existing and

Figure 3.3 : Flow diagram of a regulatory process involving an initital proposal, consultation, and final approval.



potential activities and stakeholders. On a still larger scale, strategic EIA can address the regional potential for particular developments, for example, the potential scale of use of a coastal sea area for the generation of renewable energy.

Risk analysis can be integrated into processes at all these scales. The key initial step is the recognition of the range of hazards involved and the potential undesirable endpoints. At that point, the consequent cause for concern can be expressed in terms that are consistent with the principles of risk analysis.

As an example, Figure 3.3 illustrates typical steps in the process by which a relatively small-scale proposal is ultimately approved or rejected by a regulator. A typical proposal might be for the creation of a new aquaculture site in the coastal zone. The main stages in the process are:

1. The initial formulation of an outline proposal by an aquaculture enterprise. Generally this part of the process will be the responsibility of the applicant and will include a wide range of considerations, including social and economic factors that are outside the scope of this document. It is recognised that EIAs can be prohibitively costly for very small or artisanal developments. Sometimes governments will undertake a group or class assessment based addressing a common practice (for example, British Columbia Environmental Assessment Act, 2002) and requiring applicants to identify how their proposal differs from the 'standard' practice, and what the implications of those differences would be.

2. In order to develop the proposal to a stage where it can be submitted to a regulator that include environmental factors in their consideration, the proposal will commonly need to be developed to include an Environmental Impact Assessment or similar document. This will require the input of information from external sources.

3. The combined proposal and EIA will then be submitted to the regulator for a decision as to whether the proposal will be approved or not.

4. The regulator will then undertake a consultation exercise involving statutory and non-statutory consultees. Each of these will consider the proposal and the information supplied in the EIA in relation to their own sectoral interests and responsibilities and comment to the regulator as to whether their concerns have been adequately discussed and satisfied.

5. In most cases, some concerns will not have been satisfied at that stage, and it will be necessary for the regulator to engage in bilateral or multilateral discussions aimed at resolving outstanding issues.

6. Once this process has been concluded, the regulator will make their decision.

Risk analysis is not explicitly included in the diagram (Figure 3.3) and it is therefore necessary to consider its potential role in the regulatory process. Clearly, the formal structure of a risk analysis can be a useful framework for the resolution processes described at point 5 above. However, for this to be effective, it would be necessary for the information relevant to the concern being addressed to be presented in the form of a risk analysis. The regulator is unlikely to be in a position to undertake major reformatting or analysis of information at either this stage of the decision process, or prior to their consultation after they receive the application. Therefore, the risk analysis format needs to be established and used in the documents supporting the application, for example, in the EIA document.

Guidance on the content of EIAs for fish farm development is available. The guidance normally lists the primary areas of interest of the relevant regulators, i.e. ensures that information is available for assessment against relevant legislation. Guidance, by necessity, tends to be general rather than specific to each proposal. For example, the guidance will indicate that information is required on interactions with protected areas designated for conservation reasons, rather than listing in detail the conservation designations present throughout the possible development area.

In developing the scope for an EIA, applicants therefore need to consider both the general guidance on EIA content, and also make contact with relevant stakeholders and agencies to ensure that they become aware of the specific concerns in the area of the proposed development, and that these are subsequently covered by the EIA document. It is at this stage that the formal risk assessment structure can be introduced, as a process for clarifying the concerns raised, and the hazards and processes involved. Risk assessment is therefore best introduced into this regulatory/approval process as early as possible, i.e. during the scoping and drafting of the EIA document. These actions are the responsibility of the applicant, and therefore it is for the applicant to instigate the use of risk assessment. Regulators (and consultees) can assist by promoting the use of risk assessment in scoping of EIAs.

The example discussed above is structured round a relatively small-scale proposal and hence is addressed through EIA and similar procedures, which are applicable at the individual project level. It has become recognised that such approaches have limitations when dealing with larger scale issues, and consequently Strategic Environmental Assessment (SEA) procedures have been developed as an assessment tool for establishing the suitability or scale of undertaking of a particular plan or programme. The purpose of SEA is to ensure that significant environmental effects arising from policies, plans and programmes are identified, assessed, mitigated, communicated to decision-makers, monitored, and that opportunities for public involvement are provided.

The United Kingdom Department of Trade and Industry describes the SEA as a process that "*identifies those areas of environmental concern that may not be obvious by the consideration of impacts resulting from individual projects or operations in isolation*". For example, the undertaking of an SEA of energy policy would facilitate the consideration of continued exploitation of non-renewable mineral resources against the climatic impacts of burning fossil fuels and the development of renewable energy sources. SEA potentially:

- Encourages consideration of environmental and social objectives at all levels, including those of policy development, plans/programmes and specific project objectives;
- Allows effective analysis of cumulative effects and facilitates consideration of synergistic impacts, which are likely to be overlooked or beyond the scope of individual project EIAs;
- Facilitates consultation between various government bodies and stakeholders, and enhances public involvement in the evaluation of environmental and social aspects of policies, plans and projects;
- Encourages consideration of alternatives that are neither obvious nor practical at the project EIA stage.

Perhaps most importantly, in facilitating spatial planning decisions, SEA helps to determine appropriate and inappropriate sites for projects. Individual EIAs may subsequently be undertaken for projects undertaken in areas considered suitable for development.

The considerations undertaken in the SEA process need not necessarily be limited to environmental issues, as the impacts of polices, programmes and plans upon society are also being viewed with considerable concern. The SEA process can also be used to assess the overarching impact a particular policy, plan or programmes might have upon such socioeconomic factors as:

- Population demographic and distribution;
- Economic conditions;
- Employment;
- Cultural values and assets;
- Overall quality of life;
- Social structure; and
- Societal resources.

Through consultation undertaken with communities and interested parties as part of the SEA process, it is possible to identify the:

- Issues
- Needs
- Concerns
- Values
- Ideas

of those communities and sections of society that may be influenced by a particular policy, plan or programme, and integrate these with identified areas of environmental concern.

The SEA concept therefore contains both the environmental science aspects of large scale proposals, matters of policy and principle often on national scales, but also the concerns and needs of those parts of the national community who either may be directly affected by the proposals, or who have an interest in the proposals from other points of view, for example, their values and perceptions of quality of life.

The Risk Analysis process is structured round the formulation and analysis of logic models leading from hazards to undesirable endpoints. In developing these models, and defining the endpoints, many similar aspects of public opinion and sectoral interests/feelings come into play. Aspects of the perception of risk and consequent responses to it are discussed in Chapter 5 on risk communication, where the need to take into account, and benefit from, both the technical, formal approach to risk and the more subjective factors involved in risk feelings is discussed. In summary, the Risk Analysis process is well suited to application in SEAs, as the scale and complexity of the issues involved are not defined at the outset of the process, but can develop and grow as greater integration is achieved of the inputs and concerns of all interested parties.

3.4.2 Risk analysis and sustainable development

Broader considerations of the sustainability of development require that we match human social and economic goals to the ever-changing natural dynamics of our environment and our interactions with that environment. From our experience with traditional fisheries such as salmon and cod, we are now aware that both natural and human forces can induce rapid quantum shifts in the structure and dynamics of marine ecosystems (Beamish *et al.* 2004 a,b,c; Frank *et al.* 2005). The social expectations and values that provide the backdrop to resource management are also subject to change and variation at the international, national and regional level. Various political processes exist to deal with issues around issues of social values and expectations, and these are outside the scope of this document. Similarly change and evolution of economic systems and expectation are also outside the present exercise. While social and economic issues are not dealt with directly herein, it has to be acknowledged that effective tools for managing sustainable resource use for aquaculture must fit in a decision-making context that integrates social, economic and environmental information.

Allocation of natural resources begins when a proponent (either in the private sector or government) requests some sort of licence, permit or exclusive right to use a resource (#1 in Figure 3.4). Although it some circumstances it may just be a formality to get access to the natural resource in a legitimate way, the very act of requesting a permit is normally an acknowledgement that there is some form of existing or potential future competition for the use of that resource.

Resource managers must then consider what they understand of the social values and expectation they are expected to support (#2a in Figure 3.4) and integrate that with the level of use of that resource which can be maintained on an ongoing basis (#2b in Figure 3.4) plus the probable stream of economic benefits that society is likely to gain from this use as opposed to some other use of the same resource (#2c in Figure 3.4). These factors; social, economic and environmental, define the array of uses within the Sustainable Uses of Resources Envelope (S.U.R.E). Planning exercises can be very useful to the resource manager in that they generally try to integrate some of the social and environmental aspects, but can have difficulty in accurately predicting the sequence and timing of multi-use demand for a resource, especially those used by the private sector, and subject to economic forces. The task is further complicated when the manager must decide on the allocation of the next unit of the available recourse. In addition to not knowing what types of resource use might be proposed in future, the manager is also faced with limited ability to predict accurately the outcome of interactions between aquaculture and the environment.

Risk analysis is a particularly attractive tool for helping to decide the allocation of environmental goods and services, in that it can deal explicitly with errors associated with predicting the environmental sustainability of allocating the next portion of the inventory of resources in an area. It also identifies explicitly how social values and expectations influence decision-making for the allocation of environmental goods and services. Risk analysis does this through an explicit statement of what constitutes an acceptable level of protection for the resource. When rigorously implemented, risk analysis can also help identify knowledge gaps and research topics that would most effectively reduce uncertainty associated with our predictions of environmental change.

3.5 The advantages of Risk Analysis over other decision-support frameworks

As previously noted, the purpose of this document is to advocate the adoption of Risk Analysis procedures in assessment and communication of the risks of environmental change arising from coastal aquaculture developments. Existing relevant frameworks relating to risks and environmental change include Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA). Broader techniques for decision-making drawing on the outputs from such studies include Cost Benefit Analysis (CBA) and Multi-criteria Decision Analysis (MCDA). One of the main objectives of this document is to show how the precautionary approach can be incorporated into decision-making in areas where levels of uncertainty can be high. A precondition for consistent application of the precautionary principle is that there is some standard procedure, framework or checklist for the undertaking the assessment, the characterisation of associated risks and uncertainties, and their communication. The question therefore arises as to why risk analysis offers improvements over these other procedures.

3.5.1 Environmental Impact Assessment (EIA)

EIA is:

"*the systematic, reproducible and interdisciplinary identification, prediction and evaluation, mitigation and management of impacts from a proposed development and its reasonable alternatives.*" (UNEP, 1996)

Guidelines for the application of EIAs to coastal aquaculture have recently been developed (Barg 1992; Hambrey *et al.* 2000; GESAMP 2001, 1997, 1996, 1991) building on widely accepted general frameworks for EIA. It is inappropriate to review the whole process here, but it is informative to examine the conventions for addressing the nature of environmental impacts and associated risks.

Impact identification in EIA is typically based on the use of checklists, matrices, networks and overlays, including Geographical Information Systems. Environmental specialists in consultation with industry specialists normally formulate these tools. The main types of impact considered include:

- Effects on human health, well-being, environmental media, ecosystems and agriculture;
- Effects on climate and the atmosphere;
- Use of natural resources (regenerative and mineral);
- Use and disposal of residues and wastes; and
- Resettlement, archaeological sites, landscape, monuments and social consequences, as well as upstream, downstream and trans-boundary effects.

Identified impacts are then analysed in three stages:

- Characterisation;
- Quantification and prediction; and
- Assigning significance.

Impact characteristics are described in terms of:

- Nature (positive, negative, direct, indirect, cumulative, synergistic with others);
- Magnitude;
- Extent/location (area/volume covered, distribution; local, regional, global effect);
- Timing (during construction, operation, decom-

Figure 3.4 : A schematic of the decision-making environment for competitive allocation of resources. The numbers and acronym are explained in the text above.

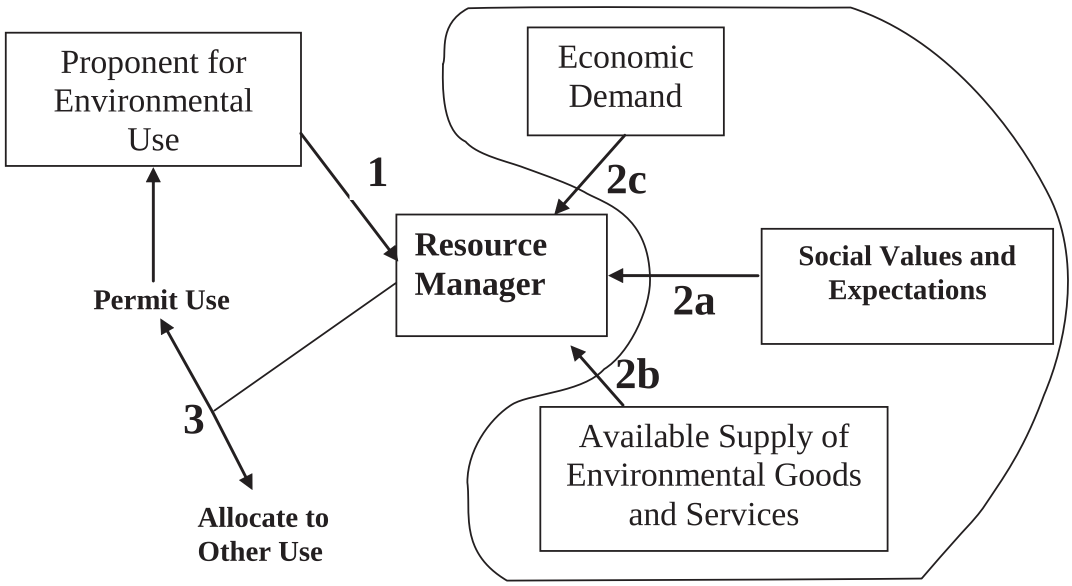
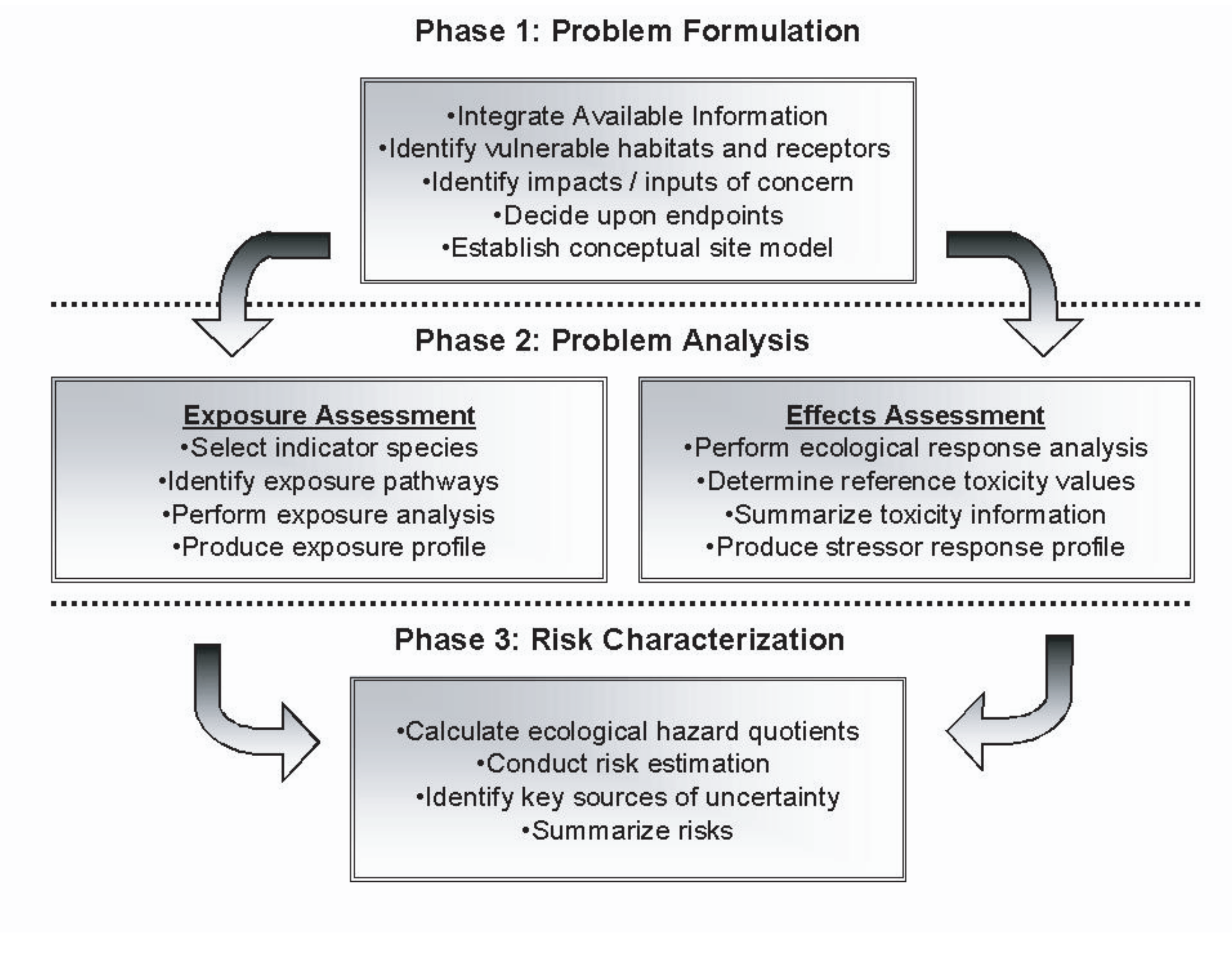


Figure 3.5 : Schematic representation of the ERA process adapted from Asante-Duah (1998).



missioning, immediate, delayed, rate of change);

- Duration (short term, long term, intermittent, continuous);
- Reversibility/irreversibility; and
- Likelihood (risk, uncertainty or confidence in the prediction).

In practice, several of these, and particularly the last, overlap with quantification and prediction and are explored in parallel.

Impact prediction draws on a variety of methods including:

- Professional judgement;
- Quantitative mathematical models;
- Experiments, physical models; and
- Case studies.

In all cases, there will be some degree of uncertainty associated with the predictions or extrapolations, and this must be described, measured if possible, and taken into account in assigning significance.

Assigning significance is a largely subjective process, drawing on a synthesis of the above analysis. Logically, significance can only be described in relative terms, and some agreed standard or baseline (based on science, instinct policy or precedence) is required if it is to have any meaning, utility, or consistency. In practice, such a baseline is often absent, and the assessment of significance depends on the knowledge, values and analytical ability of the EIA practitioner, or in some unfortunate cases, the company commissioning the EIA. In order to minimise the chances of bias, the analysis must be presented clearly and simply, and independently reviewed. This is a major challenge when dealing with complex and, in some cases, hypothetical environmental impacts.

Does EIA tend to under-play uncertainty?

It is argued that, in the past, many EIAs have been weak on characterising impacts in terms of their likelihood, and in terms of the uncertainty associated with the predictions. As noted elsewhere, there is typically very high and often unquantifiable uncertainty associated with many environmental and ecological impacts. In practice, it is probable that the true level of uncertainty is rarely emphasised in EIAs for professional reasons. EIA specialists are paid well to make impact predictions. Few developers or decision-makers want to hear a series of "don't knows" from the experts.

Against this weakness should be set the clear precautionary requirement in best practice EIA. This requires the process to generate an environmental management plan, which, in addition to putting in place measures to minimise possible impacts, also prescribes a monitoring regime and response procedures in respect of possible, but uncertain impacts.

It is clear that more attention needs to be paid to risk and uncertainty within the EIA process. A formal framework for risk assessment is already in wide use – environmental (ecological) risk assessment or ERA. It is arguable that ERA should be an explicit and significant component in EIA.

Other weaknesses

EIA is normally undertaken at farm level, and therefore cannot effectively address cumulative and wider environmental issues, such as nutrient enrichment and interactions with wild species. These need to be addressed at a higher strategic level. While this has been recognised for many years, and strategic, regional or sector level environmental assessment have been recommended, this is rarely undertaken in practice.

3.5.2 Environmental Risk Assessment (ERA)

Environmental Risk Assessment, or Ecological Risk Assessment, is a process for evaluating the likelihood of adverse environmental or ecological effects occurring as a result of one or more environmental stressors, usually of anthropogenic origin (Asante-Duah 1998; Benjamin and Belluck 2001). All available data are collated and, where necessary, more data are assembled to help predict the relationship between stressors and environmental or ecological effects. To date, the process has been applied mainly to the examination of the effects of specific chemicals on soils, aquatic systems and atmospheric systems. It may form a part of an EIA or be undertaken separately in respect of specific chemicals.

The ERA process can be divided into three phases: problem formulation, problem analysis and risk characterisation. The problem analysis stage can be further sub-divided into two distinct sections: characterisation of exposure and characterisation of effect. This means, at least for descriptive purposes, that the risk assessment process has four fundamental elements as illustrated in Figure 3.5.

In spite of this description of the process, the assessment should be iterative. Information that is obtained at a later stage in the process may force a reassessment of an earlier step. In particular, discoveries during the analysis stage may encourage a shift in emphasis in the originally determined endpoints. Rather than being considered a failure of initial planning, this constant reassessment enables environmental risk assessment to be a dynamic process well suited to ecological studies.

A key factor in environmental risk management is determining the scale and nature of potential effects. Although considering all relevant stressors and variables may complicate the process, add increased uncertainty and potentially reduce the confidence in the findings, it adds greatly to the ability of the process to consider and predict for a wide variety of permutations.

Undesirable effects ideally assessed by combining the estimation of exposure with information on the dose-response characteristics (with confidence limits) of key indicator species. The data to generate such curves may be collected experimentally or derived from field survey (ideally both). This then allows for the calculation of a key indicator of negative effects and risk: the hazard quotient or ecological risk quotient. This is calculated as the exposure point concentration, or estimated daily dose, divided by critical ecotoxicity (Asante-Duah 1998).

Determining the nature of unwanted effects can be complicated, as detrimental effects to one aspect of the ecosystem may be beneficial to others. A key attribute of environmental effects to be avoided are those resulting in changes which alter important structural or functional aspects of the ecosystem. The scale, intensity and duration of the impact along with the ecosystem's ability to recover will also be incorporated into the adversity calculation. A well-designed Environmental Risk Assessment should also able to highlight beneficial changes in the ecosystem brought about by anthropogenic interaction.

Environmental Risk Assessments can be sufficiently robust to interpret future potential risks in historically heavily impacted ecosystems. The process can be used as both a prospective and retrospective tool. This enables risk managers to look at likely causal factors of observed effects as well as predicting the outcome of future actions. This aspect is particularly valuable in the natural world where it is almost impossible to begin with a 'fresh canvas' with no prior external impacts. The flexibility of the tool also enables consideration of the chronic and catastrophic effects.

It is widely acknowledged by ERA practitioners that many possible environmental effects cannot be assigned quantitative probabilities to comply with the objectivist ideal. The ERA process therefore allows for qualitative description, which should be highlighted in the conclusion. It has even been argued that the strength of an ERA does not lie in its predominantly objective stance, but instead in the way it treats subjective inputs (Hayes 1998).

The rise in interest in all kinds of risk assessment over recent years is primarily due to its role in informing decision-making. It is particularly useful where there are substantial variables or uncertainties. Cynics, and in particular many environmental groupings, argue that the risk assessment process provides an element of scientific credibility that disguises uncertainty and can be used to add weight to politically motivated decisions. While there is little doubt that the process can be abused, this in no way undermines its strength as a comprehensive framework for assessing effects, quantifying them as far as possible, and describing the risks, uncertainties and probabilities associated with them.

ERA is designed to provide decision-makers and risk managers with comprehensive information relating to the complex consequences of actions in advance of any changes, and the trade-offs between different courses of action.

Potential weaknesses in the ERA approach

Generally, the ERA has been structured to be initiated and applied by experts. It also uses a dose-response type of relationship to describe the interaction between the hazard and the endpoint. As described earlier in Chapter 2 and later in Chapter 5, the public does not formulate its personal valuation of risk in this manner. Consequently, this approach, when used in a participatory regulatory system, starts by expressing the analysis in a format that is more difficult for stakeholders to relate to. When this is done by experts in isolation rather than with the public as part of the formulation of the analysis, this further isolates the public, and leads to possible suggestions of bias in the way the problem is posed. In addition to the public perception of the process, the ERA dose-response model is a poor model for describing many biological systems, particularly where sequential biological interactions may be involved. The phenomenon of multiple thresholds, and rapid quantum shifts in the structure and dynamics of marine ecosystems are described in section 3.4.2.

3.5.3 Cost-Benefit Analysis (CBA)

CBA is a well established tool used in development decision making, principally in relation to large-scale government funded projects. The core of the CBA is the monetary valuation of the costs and benefits associated with a development, so that a benefit/cost ratio can be generated. The assumption is that a ratio greater than one suggests that the project is desirable.

The scope of CBA, in terms of the costs and benefits that it takes into account, is very variable. Increasingly, environmental costs and benefits are included, drawing on the tools associated with environmental economics.

In order to contribute to rational precautionary decision-making, CBA should build on EIA, risk assessment, and financial and economic analyses to provide information to decision-makers on the financial and economic trade-offs between different courses of action. This would allow them to compare these trade-offs with other values and with broader development strategy.

In practice, the emphasis is more usually placed on the generation of simple decision criteria (for example, benefit-cost ratio) to justify a particular course of action. This puts a large portion of the responsibility for the decision in the hands of those conducting the study, since it is typically they who make the subjective assessment of the values of uncertain or non-market costs and benefits. Again, the uncertainty associated with the monetary values generated is rarely emphasised. This uncertainty is typically very high, especially in relation to social and economic costs and benefits.

Cost-benefit analysis is rightly termed analysis rather than assessment, but in practice the criticisms that are levelled at ERA – that it disguises subjectivity in highly questionable numbers, and therefore tends to prejudge what are essentially subjective issues – are also valid. Issues relating to uncertainty need to be given far more emphasis and explained with clarity, so that they can be fully taken into account within an improved precautionary decision-making process.

3.5.4 *International Commission on Radiological Protection (ICRP) Principles*

Risk is a major issue for human health as it relates to environmental and food safety issues. Much work has been done in this area, and it is worth introducing three interactive concepts or principles used in protecting human health against ionizing radiation (ICRP 1997). These principles are relevant to any assessment and decision-making framework related to environmental risks. They have, for example, been applied to waste management (*see* GESAMP 1991b) :

1. 'Justification' states that no practice should be adopted by society unless it can be shown that the benefits outweigh the detrimental effects;

2. 'Optimisation' states that any 'exposures' (in a broad sense) should be kept as low as reasonably achievable;

3. 'Compliance' requires the setting of exposure limits (or standards) which should not be exceeded. There is no reason why similar concepts should not be applied to the development and management of coastal aquaculture (GESAMP has already applied it to waste management. (GESAMP 1991b).

Justification corresponds to thorough cost benefit analysis as described above. Optimisation is a universal common sense principle applicable to any activity. Compliance is a key element in any environmental management system. The principles however do not offer any guidance as to where or how to set precautionary limits (for example, with regard to compliance standards).

3.5.5 *Multi-criteria decision analysis (MCDA)*

This approach is specifically designed to explore trade-offs and consider development options against different criteria. It may also be used explicitly to take account of different perspectives relating to subjective issues, risk and uncertainty. It bridges the gap between analysis (which should be a routine technical process) and precautionary decision-making (which is subjective and political).

The core process of MCDA consists of:

1. Establish the decision context;

2. Identify the options to be appraised;

3. Agree objectives and associated criteria;

4. Score the performance of each option against the criteria;

5. Assign weights to each criterion to reflect their relative importance;

6. Combine weights and score to generate an overall value;

7. Examine and discuss the results and adjust as agreed.

MCDA can be undertaken in workshops involving representatives of different interests and technical specialists, or it can be undertaken using questionnaires sent to a representative sample of the population. Relatively sophisticated statistical techniques have been devised to generate weights and assign preferences.

It is used increasingly for environmental planning and management in different parts of the world, but generally on a small scale. For it to work in an informed way, however, it needs the kind of information generated by SEA, EIA, ERA, CBA, etc. to be effectively communicated to all those involved. It also needs to be brought within an agreed strategic framework if it is to generate consistent decisions.

MCDA and its variants have been widely described (UK-DTLR 2000; Rios 1994; Lootsma 1999).

3.5.6 *Strengths and Weaknesses of these approaches*

EIA and its variants, ERA, and CBA all address important dimensions of decision-making under conditions of uncertainty. They generate information on the nature of the trade-offs associated with development decisions. In some cases, however, they underplay uncertainty and introduce subjective valuation in a manner lacking transparency and accountability. In other words, they go beyond technical analysis into subjective assessment and "pre"-decision making. Since precaution is fundamentally subjective, this is a major weakness.

In order to be more effective, decision-support tools need to place far greater emphasis on risk and uncertainty, and greatly improve the inclusion, presentation and communication of information, so that the various risks and trade-offs can be fully appreciated by decision makers and all stakeholders.

In parallel with this, there is a need to incorporate precautionary approaches into decision-making and environmental management systems, which can also accommodate information on social and environmental effects, associated risks, and costs and benefits. This allows the subjective values associated with precaution to be introduced at a transparent and accountable stage of the process.

Since the emergence of risk assessment as a regulatory tool in the 1980s, the approaches to evaluating environmental risks have been evolving. One of the seminal approaches was put forward by the National Research Council (NRC) of the United States' National Academy of Sciences (NAS) (NAS-NRC) in 1983. This approach was taken up by a number of governmental agencies during the 1990s, including the US Environmental Protection Agency (EPA). Covello and Merkhoffer (1993) reviewed a number of the models (including the NAS-NRC model) in detail. Early applications of risk assessment were in human health, and toxicology. However, by 1992, the EPA (1992) had adapted NAS-NRC protocols for environmental risk assessment, which were designed to be applied to a wide variety of environmental hazards including toxic chemicals.

To date, the application of risk analysis to the environmental interactions of coastal aquaculture has received relatively little attention. In 2005, Nash *et al.* produced a valuable broad overview of many of the hazards and endpoints associated with coastal aquaculture. Nash *et al.* generally followed the EPA NAS-NRC model for risk assessment. Consequently, in many cases, they were not able give detailed guidance on how to link exposure assessment with the characterisation of environmental or ecological effects. This process is important in deriving estimates of the probability of the effect being realised, and of the uncertainty in that estimation. These factors, combined with the predicted severity of the effect are the essential components of the final risk assessment and statement. The report also made little reference to the process of risk communication, or to the affects of uncertainty on the outcome of the analysis.

In 1999, the International Council for the Exploration of the Sea's (ICES) Working Group on the Environmental Interactions of Mariculture started to report on the potential application of risk analysis to environmental interactions of mariculture, and in 2003 joined with a GESAMP initiative to provide guidance on this narrower application of the evaluation risks (Davies *et al.* 2004, 2005). After reviewing potential risk evaluation models, the decision was made to use the Covello-Merkhofer model. A number of attributes made this model more appropriate.

The NAS-NRC model subsumes hazard identification within a problem formulation step rather than as an altogether separate process necessary to justify undertaking a risk assessment. The EPA (1998) model analyses exposure and response in a fashion that is analogous the original dose-response to the NAS-NRC model from which it was derived, rather than clearly indicating the need to define the spatio-temporal relationship (a key component of the public's perception of risk) between the released hazard agent and exposed resource, as described in the Covello-Merkhofer model.

Finally, the sequence of steps in the Covello-Merkhofer model more closely follows the process for the development of effects in nature, in which the evaluation of release and exposure is logically necessary prior to the evaluation of consequences. This also ensures that situations can be identified early where exposure limits, or precludes, strong interactions and a decision can be made to terminate the analysis, and allow the resources required for such an analysis to be directed at more significant threats to the environment.

The Risk Analysis protocol described in this document meets all these requirements and can make a significant contribution to the rigour of debate, the reliability and traceability of development decisions and the receptiveness of the public to decisions based on this process.

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4 RISK ANALYSIS IN PRACTICE FOR COASTAL AQUACULTURE

4.1 Overview of hazards and undesirable endpoints

In this Chapter, we examine in more detail some of the environmental changes associated with coastal aquaculture in order to understand the nature of the hazards, the risks of undesirable endpoints, and how these might be assessed, characterised and communicated through risk analysis. We also examine how the nature of these risks can be accommodated in decision-making and environmental management. Cage culture of salmon is used here to introduce the topic.

The first decision a environmental manager (usually a public official) must make is whether the proposed development warrants completion of risk analysis that includes public consultation. This can be costly and time consuming for complex issues where there is a great deal of public concern and widely varying opinions. For example, in several countries, authorities have been called upon to impose a moratorium on salmon farming, justifying this by recourse to the precautionary principle. Other factors may negate the need for an analysis. For example, a well-located small cultivation unit that is broadly accepted by scientists and the community as not being a threat to the environment, may not require a full risk analysis. The manager must make the decision to institute risk analysis and the precautionary approach in accord with the capacity of government to undertake the process and the potential cost-effectiveness of the process.

Assuming that sufficient concern and adequate resources exist to initiate the process, the first stage in risk analysis is to identify the causes of concern. These will generally be expressed as potentially serious effects resulting from some hazards arising as a consequence of coastal aquaculture. Actual and potential concerns about the interactions of salmon cage culture in coastal waters with the environment are illustrated in Figure 4.1.

A typical selection of concerns raised in relation to salmonid aquaculture may be summarised as:

Hazard	**Concern (undesirable end-point)**
Release of solid wastes (faeces, uneaten food)	Unacceptable change in number of the benthic faunal species
Release of solid wastes (faeces, uneaten food)	Alteration of benthic habitats, reduced oxygen levels, releases of toxic gases from sediment
Escapes of farmed fish	Reduced survival of wild stocks
Release of pathogens and parasites	Reduced survival of wild stocks
Release of dissolved nutrients	Increased occurrence of plankton blooms

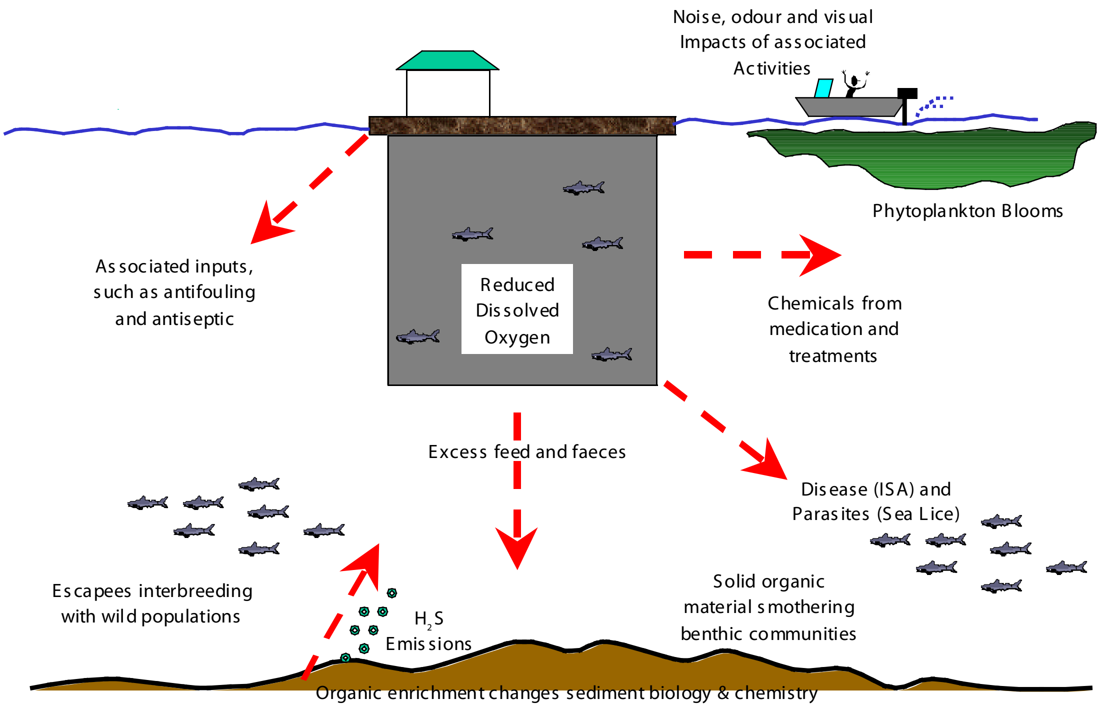
At this initial stage, when concerns are first raised in relation to a particular proposal, it is appropriate to start to adopt the formal approaches of risk analysis to structure the collation and organisation of information.

4.2 Hazard Identification

As outlined in Chapter 3, the initial step in Risk Analysis is Hazard Identification. Hazard Identification should characterise those aspects of the cultured species, site and technology which might facilitate or inhibit the expression of undesirable effects as characterised by measurable endpoints. Hazard identification should include the method of cultivation, in addition to the species, because the physical effects of different methods of cultivation on the environment can be very different. For example, effects of cages or longlines on water movement varies with cross-sectional area, mesh size or density of lines, etc, while effects on wave climate depend on the size and type of supporting structures on the water surface. The endpoints that need to be managed (undesirable effects) are defined by our understanding of the agents (hazards) and their effects on the ecosystems, and equally by policy decisions of regulators. What constitutes valued ecosystem components, and the nature of unacceptable changes, may vary from jurisdiction to jurisdiction. For example, if a society defines the amount and security of food supply as the primary service that it seeks from the marine ecosystem, it may value diversity in the marine ecosystem less than another society for whom marine food supply is a less pressing issue. These are socio-economic valuation issues that, as mentioned earlier, are beyond the scope this paper.

The statement that risk analysis is a tool to help manage the effects of Man's activities on, in this case, coastal biotic resources is deceptively simple. The key point is that the intention is to manage environmental change, not merely individual human activities. For example, there have been calls to control the escape of fish from coastal aquaculture. These, however, often only focus on managing the occurrence of the escapes (the hazard), and do not address the effect of the escapes on ecosystem function or species survival (the undesirable endpoints). The effects that should be managed are the potential effects of escaped fish on the ecosystem or feral fish populations. These target effects constitute the endpoints in risk analysis. Coastal aquaculture escapes are only one component of the processes that may affect wild fish stock abundance, along with fishing, environmental alteration, stock enhancement and other activities and processes (*for example*, climate change).

Fig 4.1 : Main pathways associated with cage salmonid culture



Effective management requires consideration of the context for each decision. Hazard identification should provide the basis for identification of the incremental increase in risk caused by the activity being examined. It is of little value to control the effect of an activity in one location if other activities impacting the same ecosystem ensure that the same effect will occur anyway. For example, a decision might be made to prevent a non-local strain of a marine species from being used in coastal aquaculture because they could escape and subsequently disrupt the genome of a native local population. If however, enhancement of the wild population with a non-endemic strain has already occurred, then disruption of the genome of the local strain has also already occurred, and the incremental change arising from escapes from aquaculture activities may be considerably less significant.

It must be recognised that a full risk analysis is a significant undertaking. Recognising this, and to prevent expending unproductive effort, the analysis should be concluded if hazard identification fails to identify *prima facie* evidence of an increased probability of the occurrence of an undesirable effect. OIE's operational version of risk analysis also recognised this potential waste of regulatory resources and has included termination of the analysis where ever hazard identification fails to find evidence of a risk in its protocols.

4.2.1 *Types of evidence for identification of a hazard that could lead to an undesirable endpoint*

To enable an effective use of risk analysis or risk assessment, a process or mechanism must exist by which exposure to the hazard results in undesirable changes or endpoints. There are several kinds of evidence that can be used to establish that a hazard may be linked to an undesirable endpoint, and thereby justifying the use of resources to implement a risk analysis. The possible severity, extent and duration of the possible change, as suggested by past experiences, will be important in determining whether a full risk analysis is warranted.

The most definitive form of evidence of the need for a risk analysis is evidence that similar changes commonly occur under similar circumstances. Usually, if the endpoint has been expressed frequently, there is a body of correlative evidence and supporting theory on which to base the assessment. The strength of the evidence declines as the number of instances of past occurrences declines. Where the effect has been seen, but only occurs occasionally, and/or the ability to predict its occurrence is limited, uncertainty will play a major role in the risk analysis.

An alternative line of evidence could arise from analogous activities. For example, if the proposed activity were for the culture of steelhead trout in marine waters, an analogous activity for which there is a body of experiential evidence would be the culture of Atlantic salmon. Both species are anadromous fishes and both have been cultured in the marine environment. The greater the difference between the two activities, the greater the likelihood some of the processes arising from the hazards will differ. For example, if the proposed activity is the culture of halibut, any analogy with salmon would be rather weak. Only some of the hazards associated with salmon culture will apply, and others will apply to differing degrees. For example, as halibut have no freshwater component to their life cycle, there would be no hazards to the freshwater habitat to consider.

In cases where there is no experience of the environmental effects of an activity and no analagous experiential body of evidence, the case is less less compelling for identifying that a hazard may exist yet a body of theoretical evidence may exist suggesting that an undesirable effect could result from undertaking the proposed coastal aquaculture development. For example, there is relatively little direct experience of the environmental effects of turbot culture in cages. However, it would be reasonable to anticipate many risks from experience with salmon, and particularly with other marine fish with life histories similar to that of turbot.

Putative or perceived risks of environmental interactions can sometimes arise during two way exchanges of ideas between stakeholders during risk communication. For example, it might be suggested that salmon farming affects the flavour of the products from nearby oyster or clam beds. There is no documented experiential evidence for this, nor is there an analogous or theoretical basis for this assertion. At the same time, there is no evidence that it does not occur. This makes analysis of this potential risk very difficult. In an instance such as this, it is recommended that either a survey or derivation of experimental evidence be undertaken to derive more solid evidence of a risk to inform the need for a formal risk analysis. In the interim however, it must be acknowledged that a lack of evidence of a hazard presents great challenges to undertaking an accurate analysis of this risk.

4.3 Endpoints

The specific undesirable endpoints that need to be managed may be identified in a variety of ways. Some of the endpoints are the result of legislative mandates or international agreements. Others may be derived from special socio-economic concerns. Legislation and policies of the national or regional authority may identify some endpoints that need to be managed. For example, the Canadian Species at Risk Act requires the protection of species or populations designated as being at risk of extirpation. This requires regulatory bodies to protect not simply the species, but also the habitats that support them until such time as they are removed from the list of species at risk. Similarly, the European Union’s Habitats and Birds Directives also require national governments to designate representative areas of various habitats for special conservation management. This includes activities located outside the management areas that may impact on them. International agreements, such as the International Convention on Biodiversity, may also define attributes that require protection. Cultural factors may enter into considerations of what needs protection. For example, clams and salmon are important sources of food, income and cultural activities for the First Nations peoples on Canada’s west coast and therefore cases may be made that they should be protected.

Listed below is a selection of possible endpoints to be examined for links with hazards arising from aquaculture in coastal marine ecosystems. This list should be elaborated to meet the specific socio-economic needs of the country considering implementing a risk analysis protocol. These environmental endpoints are primarily drawn from experience with salmon and shellfish culture in temperate zones over the past 20 – 30 years. Some of the processes and conditions involved in the expression of the endpoints may differ in degree between events and locations. Over time, our understanding of the mechanisms will evolve, and can be anticipated to lead to requirements to examine new parameters to better define the severity and certainty of expression of endpoints. New endpoints could also be identified however, with the historical experience of the environmental interactions of temperate salmonid mariculture gained over a number of continents, over two decades and thousands of farm sites, it seems unlikely that many new types of environmental effects will arise that are unique to newly cultured marine fish species.

Experience suggests that at least five broad categories of environmental effects or endpoints are commonly raised as concerns associated with temperate coastal marine aquaculture.

1) Changes in primary producers
    a) Abundance (i.e. of macroalgae and marine angiosperms)
    b) Composition (i.e. harmful microalgae)

2) Changes in survival of wild populations due to genetic intergradation

3) Changes in composition and distribution of macrobenthic populations

4) Changes in trophic resources

5) Changes in habitat (physical and chemical)

This may also form a starting point for the development of simular lists for new species.

Prior to initiating a risk analysis, it is important to identify clearly the endpoint or characteristic to be managed. Confusion can sometimes arise between predicting the change in the value of a parameter that is part of the sequence of events or processes (logic model) and that of estimating the overall probability (together with its associated uncertainty) of the actual environmental endpoint being expressed. This is well illustrated by the examination of the effect of sea lice on wild populations (McVicar 2004). The true endpoint was the abundance of the wild salmon populations, not the more contentious issue of the abundance of sea lice.

In some geographic areas, very little information may exist on local environments. That does not prevent identification of potential endpoints of concern or the creation of putative logic models to describe a probable mechanism for environmental changes. It does, however, introduce a high level of uncertainty in an analysis. It is recommended that in such situations emphasis be placed on the communication component of risk analysis. There should be early involvement of local communities. Serious consideration should also be given to a recommendation that a monitoring program be put in place to verify the importance of the chosen endpoint(s) and validate the logic model(s). Such a monitoring program will be most effective if local community representatives, industry and government are jointly involved in its derivation and execution. Such monitoring should be reviewed with a frequency that is commensurate with the rate at which the endpoint parameter is likely to change.

4.4 Logic models

The creation of a logic model provides the base on which a science-based Risk Assessment can be built. Often we lack a complete understanding of the processes that lead from the hazard to the change in an endpoint parameter. However, there is usually an understanding of many of the factors involved. To the degree possible, each of the factors that contribute to the change should be explicitly identified, the likely release of the defined hazard outlined, their likely geographical and temporal occurrence elucidated, factors that may modify or prevent the change (modifiers) identified, and the outcome of concern (the specific endpoint) predicted. It is also important to identify which other human activities, as well as natural characteristics and events in the area, might contribute to the expression of the same endpoint.

Endpoints should represent a measurable change that stakeholders or the public would recognise as an unacceptable expression of an effect. For example, the public seldom recognise the hypernutrification component of the eutrophication process but they do recognise that waterways become clogged by macrophytes or changes in the colour of water caused by high abundance of phytoplankton (plankton blooms).

The logic model is a process model that links the released hazard (for example, the release of nutrients) with exposure to the environmental target (algae) to predict the undesired end point (for example, a change in the colour of the water). It outlines steps in the processes linking the hazard and endpoint parameter, and factors that might limit or prevent expression of the effect (for example, the plankton community is light limited, or the receiving water body provides high rates of dilution and/or dispersion). The model should express its outputs in terms of the parameters used to evaluate the severity of change, for example; the duration of the change (from irreversible to an effect that ceases as soon as the release of the hazard ceases) the geographic extent (for example, just at the farm site, over an entire bay or throughout a larger area) and the subsequent possible effect of the outcome (for increased phytoplankton, it might include the possible occurrence of toxic blooms as opposed to the occurrence of a change in water colour without any toxicity). These may be expressed as further sequential endpoints in an extended logic model (for an example of the sequential geographical endpoints, see the case study of escapes of cultured cod in this report, Chapter 6.3).

Once the logic model has been clarified and agreed as the statement of the steps involved in the expression of the undesirable endpoint, it is possible to begin to collate information on the processes operating at each of the steps. This quickly leads to an improved understanding of those steps for which clear information exists, and recognition of those steps for which information is relatively lacking. This can have an immediate effect in directing research or monitoring resources to the areas of weakness in order to improve the knowledge base underpinning the logic model.

4.5 Risk assessment structure

Risk assessment is the science-based core of any risk analysis. It has four component parts. These function to define, as precisely as available information will allow, the probability, extent, duration and degree of change associated with any hazard. As outlined in Chapter 3, the component elements, of the Risk Assessment stage of Risk Analysis, are Exposure and Release Assessments. These are combined to formulate a Consequence Assessment which in turn leads to the Risk Evaluation, as shown in Figure 3.2.

The logical chain of events and processes that link hazard identification, release assessment and exposure assessment to consequence assessment provides the underlying structure for logic models. This should be the basis of a science-based risk analysis process.

The probability, and severity obtained from the risk analysis reflects the consequences of the hazard arising from aquaculture to the local environment. However, each jurisdiction has its own set of regulations and practices, and an aquaculturist may further modify these to increase the efficiency of production or to mitigate risks (Risk Management) to the environment. These modify the level of risk that the hazard presents to the environment and this change represents the shift from a consequence analysis to risk evaluation step.

The outcome of the risk evaluation should be compared to the table of acceptable levels of protection developed earlier to determine if the proposed development should be accepted or disallowed, and, if appropriate, to determine whether additional Risk Management activities might reduce the risk to an acceptable level.

4.5.1 Release Assessment

Release assessment is the description of the strength (abundance), distribution and duration of a hazardous agent (taken in a very broad sense) being introduced to the location under consideration. Release assessment consists of describing the probability of release, as well as the quantity, timing and distribution of a hazard agent in an environment. It should description of the conditions and pathway(s) of events necessary for a 'release' of a hazard into a particular environment. While the terminology 'release' may suggest a physical agent, like a pathogen or solid waste material, is involved. It may also be an activity such as fishing for cultch to support a mollusc culture activity, or in examining the effect of shellfish culture filtering capacity on the carrying capacity of an ecosystem for endemic bivalves.

As some of the hazards may be mobile, as in the case of escaped fish, it is important to capture fully the dynamics of the distribution of the release. For inanimate objects, that might be a matter of describing water flow characteristics. However, for self-propelled objects such as organisms, that description should include the drivers and limiting factors for the behaviour. For example, concerning the interbreeding of escaped cod, the behaviour of cod dispersion to breeding ground is determined by the innate urge to aggregate for breeding, and the pathway is defined by oceanic thermal gradients. This is demonstrated in the cod culture case study documented later in this publication.

If the release assessment demonstrates no significant probability of release, the risk assessment need not continue.

4.5.2 Exposure Assessment

Exposure assessment is the description of the amount, spatial distribution and temporal distribution of the resource feature that may be affected by the hazard. Together, they present a view of the level (intensity/concentration), distribution and duration of any potential interaction between the hazard and the resource. Exposure assessment describes the pathway(s) necessary for the resource of concern to be exposed to the hazard. It should also estimate the likelihood of exposure(s) occurring.

Exposure assessment also includes the form in which the hazard agent is present if this may affect the vulnerability of the target to the hazard. For example, adsorption of contaminants to sediment particles may result in a reduced risk of exposure that would not be evident from simple measures of contaminant concentration. Copper may be present in sediments in the form of relatively large (and uningestible) particles of antifouling paint, and as the copper is released by the paint, it may become bound to sulphides and other sediment components.

In essence, exposure assessment is an expression of the nature of sympatry between hazard and resource. The information in this step should be sufficient to link to the information in the release assessment and support the consequence assessment. If the exposure assessment demonstrates no significant likelihood of significant exposure, the risk assessment should conclude at this step.

4.5.3 Consequence Assessment

The nature of the interaction likely when sympatry does occur is evaluated in consequence assessment. In this stage, the interaction between hazard and resource is analysed as though no other human activities, as well as local characteristics of the area, are likely to interfere with the expression of the endpoint. In effect, this is an estimation of the maximum potential for change that could result from the consequence of the sympatry of hazard and resource in a naive environment (one where this is the only potential agent that could cause the outcome of concern resulting from the interaction between resource and the hazard). For example, if the endpoint being examined is that particulate material may build up on the seabed under a new fish culture site and alter the indigenous macrofauna to an unacceptable degree, the initial assumption would be that there was no other significant either man-made or natural sources of particulate material that would affect the area in question.

In many instances, and for many endpoints, coastal aquaculture many not be the only activity with the potential to cause the expression of the environmental change described by the endpoint. To elaborate, the new site may be near the discharge point of the drainage from some upland development or near an estuary, or natural lagoon/marsh discharge. That activity could also result in the introduction of particulate material that could be deposited on the seabed and affect the benthic fauna. Alternatively, the new site may be close to an existing culture site which is already discharging particulate material which may affect the benthos at the new site.

The net effect of more than one source leading to the expression of the endpoint is that there is already some likelihood that the endpoint will be expressed as a result of Man's activities, whether or not the new coastal aquaculture site is developed. Consequently, the coastal aquaculture activity is only responsible for an increase in the probability of the endpoint being observed, and not the entire likelihood. This incremental increase, or marginal change, in risk is what should be evaluated in the risk evaluation component of risk assessment. Where more than one human activity contributes to likelihood that an endpoint will be expressed, it is possible that expression involves a threshold or trigger-level effect, rather than a continuous increase in probability of expression. Introduction of aquaculture to an area may result in exceeding this trigger. This may be difficult to resolve when resources have already been allocated to existing users.

Finally, under some circumstances a coastal aquaculture activity may actually make a positive contribution to the reduction of the overall level of risk, for example, reduce the risk of an endpoint being observed. For example, a fish farm may be producing particulate material that is distributed over a large area by tidal or other currents. A shellfish cultivation unit located within the plume of particulate waste matter can use this concentration of organic material as a resource for growth, and thereby reduce the extent and severity of the effects of the fish farm particulate material on the benthos. Consequently, instead of increasing the risk to the benthic fauna in the area, the shellfish farm may in fact reduce the probability of adverse effects being expressed. Also, a coastal land-based aquaculture activity that creates water flows with pumps may contribute significantly to the hydrodynamics in brackish water environments, with resultant benefits in oxygen transport in shallow water lagoons. This can be particularly important in regions such as Mediterranean coasts where the limited tide range does not provide a significant driving force for advective water exchange.

Consequence assessment therefore consists of identifying the potential biological consequences of a release of a hazard into the environment. The causal processes that link the hazard to the undesirable changes are expressed as a logic model which lists the stages or processes involved as a series of steps. The logic model steps include key aspects of release assessment, exposure assessment and the consequences for the target endpoints. For each of these steps, the consequence assessment evaluates three attributes; severity of occurrence, probability of occurrence, and the level of uncertainty in the prediction. The assessment of the severity incorporates three aspects: the degree of change, the geographical extent of the expression of the risk, and the duration of the effect.

The next stage therefore is to estimate, from the collated information, the severity of each step in the logic model, and the probability of each step occurring. Steps where good information exists should allow expression of this probability with low uncertainty. Steps where information is relatively sparse may lead to higher levels of uncertainty in the estimated probabilities.

An example of such a collation for the effects of escaped cultured cod through genetic intergradation with wild cod is presented below.

End Point – Significant decline in fitness (survival) due to genetic changes resulting from interbreeding with cultured organisms.

Previous experience – Our primary experiential and experimental knowledge base for evaluation is work that has been done on salmonid populations.

Phenotype is the basis for selection and the effector of fitness. Phenotypic differences between seven species of wild and cultured salmon have been identified for at least a dozen phenotypic traits of potential adaptive significance (Tymchuk *et al.* 2006).

Environment, in addition to genotype, determines expression of adaptive phenotypes. There is evidence that some fitness-related traits (for example, growth, aggression and anti-predator behaviour) are at least in part genetically controlled. However, for some of those traits there is also evidence that in some instances genetics is not the entire basis for differentiation of wild and cultured populations (Tymchuk *et al.* 2006). No evidence has been found that commercially cultured aquatic organisms have novel alleles otherwise absent from feral populations of the same species. However, differences in allelic frequencies have been noted.

With or without interbreeding with cultured fishes, effective selection for long-term fitness of a population cannot be achieved at very low numbers. An indication of whether selection is likely to be effective is available through an examination of the effective population size. The ICES Working Group on the Application of Genetics to Fisheries and Mariculture (ICES WGAGFM 2004) examined the literature on the ratio of effective population size (Ne) to survey population size (N) in their 2004 report (Table 2.1.4.1, reproduced as Table 4.I). They list values and ranges associated with a number of species of interest to coastal aquaculture, including sea bass, Atlantic cod and Pacific oyster.

Published effective population sizes required to avoid the long term effects of interbreeding and genetic drift range from 500 to 5000 (Lande 1995; Franklin 1980; Dannewitz 2003). These are only rough approximations, but give a starting point for evaluation. The relationship between the relative number of cultured fish interbreeding with the wild population and its effect on the fitness of the wild population has not been well quantified.

Interbreeding has been documented between escaped and feral Atlantic salmon. Interbreeding is more likely to occur in areas close to the location of the escape. The effect of intergradation is likely to be proportional to the relative number of wild and cultured organisms interbreeding. The effects of hybridization between wild and cultured salmon are unpredictable and differ between populations, but in general appear to be disadvantageous when hybridization alters potentially fitness-related traits (Tymchuk *et al.* 2006).

Where only a few individuals are involved in hybridisation, the effects on the wild population are likely to be reduced. Where relatively large scale genetic intergradation has occurred, there has been reduced fitness and survival of the feral population. Where studied, hybrids of single interbreeding events rapidly decline (Skaala *et al.* 1996; McGinnity *et al.* 2003) in a feral population and the effect on survival may be largely reversible through natural selection over a period of a few generations. Where repeated large-scale escapes occur, the effects are likely to be greater and the consequences unpredictable.

Metapopulation dynamics are likely to buffer the effects of occasional intergradation events, but may not buffer effects from repeated large-scale events. Where metapopulation dynamics are in effect, it is to be anticipated that some of the populations over time will cease to exist even if they are unaffected by interaction with cultured fishes (Smedbol and Wroblewski 2002). Small populations are at greatest risk of extinction.

This is a complex area to evaluate. Many species are composed of more than a single population and those populations can range in size from a few tens of fish to perhaps 100,000s or more. It is a policy decision as to what minimum size of population should be protected. However, protecting the adaptation of a fish population numbering in the 10s or less presents a special problem. A population of such a small size cannot effectively respond to natural selection and so any differentiation from other populations is likely to be primarily under the effect of non-selection based processes, such as founder effects, genetic drift or inbreeding. It is suggested that an initial step might be to demonstrate that the population in question is able to respond to selection. Regulators may consider tailoring regulatory action to support/protect the fitness of populations that are large enough to effectively respond to natural selection.

It is likely that some level of interbreeding between wild and cultured populations can be tolerated by the wild populations. In the Atlantic, numbers of cultured Atlantic salmon have been found in wild fisheries for

Table 4.I : N_e/N ratios (i.e. ratios between effective population sizes and survey numbers) for selected marine and freshwater species, from the report of the ICES, WGAGFM 2004.

Note: that both the method of calculating N and the definition of N can affect the ratio. (VF Variance in gene frequencies, LD Linkage Disequilibrium, T Temporal Method, MUT mutation drift equilibrium).

Species	**N_e/N**	**Method**	**Reference**
Menhaden	<0.0025	MUT	Bowen and Avise 1990
Black sea bass	0.005	MUT	Bowen and Avise 1990
Pacific oyster	<0.000001	VF	Hedgecock *et al.* 1992
Sea bass	0.27- 0.40	LD	Bartley *et al.* 1992
Chinook salmon	0.0 13 - 0.043	LD	Bartley *et al.* 1992
Steelhead trout	0.73	T	Ardren and Kapuscinski 2003
New Zealand snapper	0.00001	Various methods	Hauser *et al.* 2002
Red drum	0.004	T	Turner *et al.* 1999
Red drum	0.001	T	Turner *et al.* 2002
Vermilion snapper	0.0015 - 0.0025	LD	Bagley et al. 1999
Northern pike	0.03 - 0.14	T	Miller and Kapuscinski 1997
Atlantic cod	0.00004	T	Hutchinson *et al.* 2003
Chinook salmon	0.02 - 0.56	Various methods	Shrimpton and Heath 2003

Table 4.II : Types of data that may be considered in logic models and Risk Analyses of the changes in fitness of wild populations due to genetic intergradation with escapes from cultivation.

Drivers	Proportion of wild population interbreeding with organisms escaping culture
	Relative difference between wild and cultured fish genome
Sources	Shellfish culture activities
	Fish farms
	Strays from other endemic populations
	Genetic effects of - Stock improvement - Transfers - Enhancement - Genetic selection associated with fishing activities
Modifiers	Proportion of genetic or environmental contribution to population differences
	Population size (effects of drift and inbreeding)
	The effects on selection by other human activities such as enhancement activities.
	Meta-population structure
Temporal expression	Where intergradation has an effect on survival it is likely to affect the f1 and to a lesser extent the f2 generation.
	Impacts beyond the f2 generation are unclear.
Geographical extent	Dependent on migratory behaviour and breeding distribution but most likely in areas adjacent to escape.
Outcomes	Reduced fitness of feral population

over a decade. Wild salmon continue to survive, although their survival rate has decreased. The contribution of interbreeding to reduced survival in Atlantic salmon is not clear, as many other factors, such as by-catch, climate change and habitat destruction are also exerting influence, and also would be expected to reduce salmon survival.

4.5..4 Risk Estimation

Risk estimation is the process of characterising the severity and probability of consequences (endpoints). It includes defining the uncertainty associated with prediction of the probability of consequences, and integrating the results with the consequence assessment to produce overall measures of risks associated with the hazards identified at the outset. Thus, risk estimation takes into account the whole of the logic path from hazard identification to unwanted outcome.

The predicted outcomes from the consequence assessment can be further constrained by regulatory or management activities. Local zoning requirements, for example, may require separation of coastal aquaculture from other activities or resources (such as recreational harvesting or habitats of special value such as eelgrass beds) that might be affected by hazards released from aquaculture., Where resource separation is not part of the management of coastal aquaculture, surveillance and control programs (with associated action and limit reference points) may be used to constrain the potential severity and/or distribution of environmental effects.

In risk estimation, qualitative assessments should always be performed and quantitative assessments should be used (where possible) to inform further the outcome of the qualitative assessment. Quantitative analysis is necessarily more focused in nature and has the potential to be more precise (but perhaps less accurate) over all the potential aspects of a hazard. Genetic interaction with escaped fish is an example of an area where quantitative methods might be applicable.

It is sometimes useful to organise data by the kind of information it supplies. Table 4.II provides an example of how that might be achieved.

For a quantitative assessment of genetic interaction, the final outputs may include:

- Quantitative descriptions of the various populations of aquatic animals and coastal aquaculture establishments likely to experience interactions of various degrees of severity over time;

- Probability distributions, confidence intervals, and other means for expressing the error in these estimates;

- Portrayal of the variance of all model inputs;

- A sensitivity analysis to rank the hazards as to their contribution to the variance of the risk estimation output;

- Analysis of the dependence and correlation between model inputs.

In addition to environmental/ecosystem factors, the risk assessment phase of the analysis should also take account of the general supporting framework within which the coastal aquaculture industry operates. In many jurisdictions, risk management actions are already in place in the form of regulatory controls on, for example, the location and scale of coastal aquaculture units. Such controls can be viewed as mechanisms to assist the national industry as a whole to limit their contribution to the occurrence of particular undesirable endpoints. Regulatory structures may also be available, at national or more local levels, to impose particular conditions on specific localities (for example, a bay, or fjord) or farms, and thereby tailor regulation to the special needs of particular areas and developments.

In some jurisdictions, zoning schemes have been used to regulate development. The objective of zoning is to ensure that developments occur in an orderly and planned manner, and that agreed local environmental or societal goals are met, thereby reducing the risks both to the industry and to the receiving ecosystems.

Codes of practice, led by the industry or by regulators, are valuable mechanisms for reducing risk (for example, of disease transfer, or of escapes), provided that individual farm operators recognise the value of the Codes and adhere to them. In the late 1990s, the Chilean salmon farming industry developed a "*Code of Good Environmental Practices for Well Managed Salmon Farms*" that was tied to a system of environmental friendly labelling for products from farms adhering to the Code. Some of these Codes of practice are linked more closely to the achievement of internationally recognised standards, such as the ISO 14000 (Environmental Management Systems) standards and the European EMAS (Eco Management and Audit Scheme) protocol. In British Columbia, approximately 50% of the salmon farming industry has developed corporate environmental management systems that meet and have been accredited to the ISO 14000 standard. Linking the Codes of Practice to quality certification programmes makes conformation to those standards more compelling to the industry, through potentially conferring a market advantage. While Codes of Practice typically include Standard Operating Procedures, the integration of these protocols within the framework of an ISO 14000 Environmental Management System requires that the significant environmental aspects of a coastal aquaculture facility include a quantifiable measure of continual improvement in environmental impact. This is commonly achieved through the implementation of specific environmental objectives/targets, monitoring/research programs, training, record-keeping, and a third-party audit function.

One of the primary considerations in the planning of coastal aquaculture developments is the ease of access to the necessary support infrastructure and services. Farms may be located in remote areas, and this brings the potential for reduced ease of access for veterinarians, maintenance workers, appropriate emergency response following equipment failure, etc. In many cases, the larger companies have become accustomed to these difficulties, and have developed internal mechanisms and resources so that their responses can be quick and effective. However, the absence of such arrangements is likely to increase the severity of any particular incident.

Broader aspects of infrastructural support also need to be taken into account. As noted above, the quality and reliability of transport links can be very important in responding to incidents. Equally, the hazards and potential consequences associated with routine operations such as transport of young stock to grow-out locations increase as the distance increases. In a similar manner, the proximity of the grow-out site to harvesting/processing facilities influences the risk of an operation expressing various endpoints.

4.5.5 Protocol for Estimating Risk

Discussions up to this point have focused on evaluating the probability of exceeding a single endpoint such as "*a high probability of fish farming causing algal abundance to increase to the point that there is a visible change in the colour of the water*". It has also been recommended that linear logic models be used to make the prediction and that regulators/decision makers develop a table of the level of acceptable protection for each type of endpoint prior to initiating a risk assessment.

Situations may arise where a single endpoint is not adequate to meet the manager's need for integrated information on which to make a decision. In such circumstances, policy or the manager must have, prior to the initiation of the assessment, stated this requirement and also whether the decision will be made against individual criteria (failure to meet the acceptable level of protection for any one endpoint will result in a rejected application) or whether some or all of the evaluated endpoints must on average meet some specified level of acceptable protection (LOAP).

Table 4.III is an example of formalised documentation of the outcome of linear logic models, and must be carried out for each logic model for each endpoint identified in the hazard identification. The table is completed, and a brief rationale, with appropriate references, is written to support the ratings given for intensity, geographical scale, duration, probability and uncertainty.

There are however, situations where one or a number of the steps within a linear logic model are evaluated using a subcomponent model. In effect, subcomponent models are being inserted within a larger model. This could result in the evaluation of a step where either condition (Completion of step 1a OR completion of step 1b) can result in the conditions to enable the completion of the next step in the logic model. To ensure transparency in the evaluation, it is recommended that this be made apparent as in Table 4.IV.

Logic models can become more complex when two or more conditions or submodels must achieve a certain probability for the next step in the model to occur. For example, if the endpoint was the occurrence of toxic blooms of the flagellate Heterosigma akashiwo, a linear model might be used to evaluate the probability of the algae attaining some critical level of abundance. However, the occurrence of toxicity and abundance in this species is controlled by different mechanisms. There are instances where blooms have occurred that are not toxic. Thus, the conditions for abundance AND the conditions for toxicity must both be met before a toxic bloom can occur. *See* Table 4.V for an illustration of how this may be formulated in the logic model.

4.6 Risk management and mitigation

The purpose of risk management is either to reduce the assessment of the probability of undesirable environmental change, or to reduce the uncertainty in the assessment of that probability to a level of protection appropriate to the particular jurisdiction and environmental change concerned.

A well executed risk assessment builds the context for the development of risk management. Option identification and evaluation in risk management addresses what might be done to reduce the probability of a risk being expressed, or to reduce the uncertainty in the prediction of the expression of a risk. The logic model discussed above allows identification of the most critical steps in the process that leads to the environmental change and identifies, for all steps, what could be done to reduce the probability of it occurring. This enables rapid identification of the most effective measures to reduce the likely environmental effects, and to improve our ability to predict those effects.

The reduction of the severity or probability of environmental change often entails design of new management or development processes, and their implementation through operational procedures, new technologies or through new siting. In Table 4.VI, under the column headed mitigation, most of these options can be put in place using regulatory or code of practice mechanisms. Some, such as the requirement for geographic limits to the culture of cod (mitigation for logic model step 5), may necessitate a wider planning process.

Where a regulatory approach is taken, care must be given to ensure that only those regulatory measures are taken that are necessary to reduce the level of risk to give an acceptable level of protection. Management for an extreme level of protection, where not required, is contrary to the concept of sustainable development. Suggestions such as moving marine culture to land based facilities (mitigation for logic model step 1) should be considered carefully in this context.

Reduction of uncertainty more often requires research on the environmental or production processes. In this context, one of the advantages of risk analysis is that it can assist in identifying priorities for research and development work. For example, step 5 in the logic model is associated with a high degree of uncertainty. That uncertainty in the decision-making process could be reduced by research that defines gene flow rates between wild populations, and which could do much to

Table 4.III : An example of a linear logic model that might be used in the analysis of the effects of escapes from cod aquaculture industry in Scotland as it may be in 15 years time, producing 25 000 - 40 000 tonnes per year

Steps in the logic model	Components of Severity			**Assessed Attributes**			Stage of assessment
	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity (C,H,M,L, or N)** [1]	**Probability (H,M,L,EL, or N)**[2]	**Uncertainty (H,M, or L)**	
Cod farms are established in coastal waters.	M	M	M	**M**	**H**	**L**	Release
Cultured cod, as gametes, eggs or fish, escape from cages.	M	M	M	**M**	**H**	**M**	Release
Cultured cod interbreed with wild cod.	L	M	M	**M**	**H**	**L**	Exposure
The progeny of this interbreeding (hybrids) show reduced fitness.	M	M	H	**M**	**L**	**H**	Exposure
Sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	M	L	M	**M**	**M**	**H**	Consequence
Genetic interaction caused declines in endemic, evolutionarily significant units (populations), i.e. Genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.	L	M	M	**M**	**L**	**L**	Consequence
Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population, i.e Escapes of cultured cod cause significant decreases in wild/feral cod stocks.	L	M	H	**M**	**EL**	**L**	Consequence

[1] Severity = C – Catastrophic, H – high, M – Moderate, L – Low, N – Negligible.
[2] Probability = H – High, M – moderate, L – Low, EL – Extremely Low, N – Negligible
[3] The final rating for the Severity 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). Note: that the calculation of the final rating follows the multiplication rule of probabilities (i.e., the severity that a given event will occur corresponds to the product of the individual severity). Thus the final value for severity for each specific risk is assigned the value of the lowest individual logic model estimate.

[4] The final rating for the Probability is assigned the value of the element with the lowest level of probability.

Table 4.IV : A hypothetical example of an OR function within the structure of a logic model

Assessed Attributes			
Endpoints	**Severity (C,H,M,L, or N)**	**Probability (H,M,L,EL, or N)**	**Level of Uncertainty (H, M, L)**
1a. Risk of released gametes of cultured fish forming a hybrid zygote wilt wild fish ganetes	H	L	H
1b. Risk of escaped cultured fishes breeding with wild fish	M	H	M
2. Effect of 1a and 1b above	**H**[5]	**L**[6]	**H**[7]
3. Risk of gene flow between wild and cultured population of cod.	**M**	**L**	**L**
4. Risk of Changes in fitness of wild populations due to genetic introgressation (population level)	**M**	**L**	**L**

[5] *For severity when an either/OR evaluation is being made the most severe outcome is selected*
[6] *For probability when an either/OR evaluation is being made the probability associated with the most severe outcome is selected*
[7] *For uncertianty when an either/OR evaluation is being made the uncertianty associated with the most severe outcome is selected*

Table 4.V. A hypothetical example of an AND function within the structure of a logic model

Endpoints	**Severity (C,H,M,L, or N)**	**Probability (H,M,L,EL, or N)**	**Level of Uncertainty (H, M, L)**
1. Risk of Changes abundance of *H. akashiwo*	M	L	L
1. Risk of Changes toxicity of *H. akashiwo*	M	L	H
1. Summary of risk of occurrence of toxic bloom of *H. akashiwo* (combine 1a & 1b)	M	L	**L**

Table 4.VI : Possible mitigation and research activities to reduce the probability of steps in the logic model occuring, or reduce the uncertainty in the estimate of that probability

	Logic Model Step	Probability	**Mitigation** (regulate/design/ modified practices)	Uncertainty	Research/Development
1	Cod farms are established in coastal waters	H	• Where feasible move to land- based production	L	• Develop economically competitive land-based technologies.
2	Cultured cod, as gametes, eggs or fish, escape from cages.	H	• Improve containment design and/ or build in fail-safe measures • Recovery plan for escaped fish	M	• Improve contingency plans for recapture, possibly including prior imprinting, e.g. of prey (pellets)
3	Cultured cod interbreed with wild cod	H	• Use of sterile fish • Harvest fish before maturity	L	• Improve methods of producing sterile fish
4	The progeny of this interbreeding (hybrids) show reduced fitness	L	• For each generation recruit all grow-out stock from juveniles captured in the wild • Retain the wild genome as far as possible	H	• Develop models of the impact of interbreeding on fitness. • Determine if differences are primarily genetic rather than environmental in origin. • Determine if differences are associated with differential survival.
5	Sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	M	• Limit the distribution of cod farming to either proximity to small value stocks or very large stocks.	H	• Identify those population units that have significant potential to respond to selection. • Define rate of gene flow between stocks
6	Genetic interaction caused declines in endemic, evolutionarily significant units (populations), i.e. Genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.	L		L	• Identify those population units that have significant potential to respond to selection. • Define rate of gene flow between populations
7	Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population , i.e. Escapes of cultured cod cause significant decreases in wild/feral cod stocks	EL	• Limit the distribution of cod farming in relation to the distribution of the species or meta population	L	• Identify dynamics of genome at the meta population or species level.

clarify where specific populations may be at risk due to a low rate of gene flow with other components of the metapopulation.

Testable models can be useful in the development of knowledge as well as being of immediate assistance to decision makers faced with uncertainty. A clear weakness in the confidence of the assessment is the lack of information on the likely fitness of hybrids formed by the interbreeding of wild and farmed fish (Step 4), and of the consequences of any reductions in fitness for local and more widespread populations.

The assessments of high probability and/or high uncertainty can be used to guide allocation of resources to those areas where they should be most effective. For example, Step 2 has high probability but, if this can be reduced, the overall risk of adverse effects would be reduced. Actions could be directed at measures to reduce the rate of escape of cultured fish. Combinations of regulatory and developmental research can be very powerful approach to mitigation. The critical event of cod escaping containment (Step 2) is very responsive to such an approach. This applies to both floating cages (mooring, net quality, resistance of the raft to waves, avoidance of predators damaging the nets, choice of locations, etc), and to land-based facilities (screening and treatment of effluents). Development of systems specifically designed to minimise escapes, on land or floating, should be encouraged and, when economically feasible, their use can be encouraged by codes of practice or regulatory tools.

An initial examination of risk management options may consider whether any immediate action is necessary, i.e. is the present risk large enough that some immediate mitigation strategies are appropriate for the proposed development? In the case of the production of cod from the existing Scottish cod aquaculture industry, the wild stocks are protected from the endpoints (undesirable consequences of interactions with escapes from cultivation) by the low probability that there are genetically based phenotypic differences between the wild and cultured cod populations. Furthermore, the small size of the industry and its patchy distribution lead to an extremely low probability that there could be sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is not sufficient to affect population fitness, at the population or meta-population levels. However, there is high uncertainty in the latter assessment. Research, however, takes time, and usually is not available for immediate implementation.

The need and opportunity for mitigation for the Scottish industry as it might be in 15 years time might also be considered to allow for effective research and development to support future growth of the industry. By that time, it is anticipated that expansion of the industry might mean that there would be less protection for wild stocks from adverse consequences of interactions with escapes. Table 4.VI identifies both mitigation and research or development steps that could be used to address risks associated with genetic interactions arising from the predicted future level of cod culture in Scotland.

Implementation of a risk management option should involve a committment to following through on the risk management decision and ensuring that the risk management measures are in place. This should include a planned monitoring and review process to ensure that the risk management measures are audited at an appropriate frequency will achieve the intended results.

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4.8 ANNEX: Principles and a checklist for environmental risk assessment and analysis of aquaculture's environmental impacts

This section provides a list of principles and a summarised checklist of the steps required to undertake a risk analysis of a particular hazard arising from coastal aquaculture. These are constructed to support development of sustainable resource use. The approach also enables inclusive stakeholder involvement in an open and transparent process before during and after the risk assessment. These attributes, plus the design of the approach to fit in an effective communication strategy to enhance the contribution of all parties involved, makes this approach distinct from many of the past application of Environmental Impact Assessment and Environmental Impact Statement procedures.

4.8.1 Principles

1. Optimal management of risk can occur only where there is an open, transparent and inclusive process that integrates effective risk communication with hazard identification, risk assessment and risk management.

2. Implementation of risk management in a resource management scheme requires the output from an environmental assessment to be combined with economic and social values. These social and economic values should not be a part of a risk analysis or risk assessment protocol.

3. Valuation processes (for example, establishing what is acceptable or not acceptable) are not part of risk assessment. Valuation is part of the socio-economic process.

4. It is the role of the resource manager (usually a public official) to deliver a table of acceptable levels of protection for each endpoint. Technical staff undertaking the risk analysis should not be responsible for developing this table.

5. Acceptable levels of protection for each environmental change (as represented by a measurable endpoint parameter) must be created prior to undertaking a risk assessment.

6. Similar levels of acceptable protection should be applied to other human activities that could result in environmental change comparable to those identified as arising from aquaculture hazards.

7. A zero tolerance for potential environmental change is not acceptable in risk management.

8. Identification of a hazard should be based on evidence not opinion.

9. Each hazard should be identified along with the environmental change it might cause.

10. Each potential environmental change should have a measurable endpoint parameter identified that will quantify the severity of change.

11. The precautionary principle is incorporated in uses of risk management through adjustment of what constitutes an acceptable level of protection.

12. The effect of levels of uncertainty on the acceptable levels of protection table must be explicitly stated prior to undertaking a risk assessment.

13. Risk assessment is a science-based predictive process. It can be qualitative or quantitative. The predictive basis can be based on correlative information or on mechanistic models. Mechanistic models are preferable, as there is less uncertainty and broader applicability across geographic regions.

14. Accurate assessment of the increased risk of environmental change due to a new activity (such as a new aqua-farm site) requires a clear understanding of other activities that might contribute to the same environmental change.

15. The risk assessment must present a transparent rationale for the degree of geographic overlap between the released hazard and the resource that might be affected.

16. Exposures (in a broad sense) should be kept as low as reasonably (cost-effective) achievable;

17. The temporal duration of the effect of the released hazard must be clearly enunciated, and include the recovery time upon cessation of culture activities.

18. Development of a logic model that clearly communicates the extent and limits of our understanding of the mechanism by which environmental change occurs are essential to building an open and transparent risk analysis.

19. A cost/benefit analysis should be used to help establish when it is appropriate and feasible to undertake specific management of risk activities.

20. Where monitoring is determined to be a necessary component of Risk Management, regulators must commit to regular publishing of the results of that monitoring along with an analysis of whether the results alter the findings of the initial analysis.

21. No practice should be adopted by government / society unless it can be shown that the benefits outweigh the detrimental effects.

4.8.2 A checklist

1. Make an initial identification of the hazard concerned, and of the consequential undesirable endpoint.

2. Agree a clear statement and decision table expressing what would constitute an acceptable level of protection from the endpoints arising from the hazard being examined.

3. Draw up a logic model describing the processes linking the hazard with the endpoint. Make the logic model as specific as possible to the particular hazard and endpoint being discussed, in the relevant circumstances and location. Express this as a flowchart and also as a tabulation of the steps in the model.

4. Undertake a hazard assessment, drawing on relevant scientific information and experience in similar or related circumstances.

5. Determine whether the hazard released from aquaculture has the potential to increase the probability of the endpoint occurring. If there is no such potential, terminate the risk analysis.

6. Undertake an exposure assessment, i.e. describe the process by which the hazard is released and the probability and intensity of the release in as much detail as possible. Collate information on factors that may potentiate or inhibit exposure.

7. Undertake a consequence assessment. Assess, perhaps model, the process by which the hazard and environment interact leading towards the endpoint. Have particular regard to the probability that the consequence may occur, the scale and intensity of the occurrence, and the uncertainty in the assessment.

8. Tabulate the steps in the logic model and the components of the risk analysis. Ascribe severities to each of the steps in the logic model through consideration of the intensity (or degree) of change, the geographical extent of the change, and the duration or permanence of the change. Estimate the probability of the step in the logic model being achieved, and the uncertainty in that estimation. Record the justification for each of the decisions inherent in creating the tabulation.

9. Use the tabulation to express the severity, probability and uncertainty of each endpoint being expressed.

10. Address areas of weakness where the collated information appears incomplete or inadequate to improve the reliability of the overall assessment.

11. Assess the acceptability of the proposed development through reference to the decision table

Table A4.I - Procedure 1: Evaluating Probability and Severity for a logic model.

Steps in the logic model	Intensity or degree of change **(H,M,L, EL or N)** [1]	Geographical extent **(H,M,L, EL or N)** [1]	Permanence or duration **(H,M,L, EL or N)** [1]	Severity (C,H,M,L, or N) [1]	Probability (H,M,L,EL, or N)[2]	Uncertainty (High, Moderate or Low)
Step 1 of the logic model.						
Step 2 of the logic model.						
Step 3 of the logic model.						
Step 4 of the logic model.						
Etc...						
Final Rating [4]						

[1] *Severity = C – Catastrophic, H – high, M – Moderate, L – Low, N – Negligible.*
[2] **Probability = H** *– High,* **M** *– moderate,* **L** *– Low,* **EL –** *Extremely Low,* **N –** *Negligible*
[3] *The final rating for the* **Severity** *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).* **Note:** *that the calculation of the final rating follows the multiplication rule of probabilities (i.e., the severity that a given event will occur corresponds to the product of the individual vb b severity). Thus the final value for severity for each specific risk is assigned the value of the lowest individual logic model estimate.*
[4] *The final rating for the* **Probability** *is assigned the value of the element with the* **lowest** *level of probability.*

Table A4.II - Procedure 1: Evaluating options for 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	Step 1 of the logic model				
2	Step 2 of the logic model				
3	Step 3 of the logic model				
4	Step 4 of the logic model				
5	Step 5 of the logic model				
6	Step 6 of the logic model				
7	Step 7 of the logic model				

prepared in step 2 above, and determine the need for risk mitigation.

12. Assess the opportunity for risk mitigation, and the need for additional research to reduce uncertainty in the estimations of probability. Draw up a table linking the probability and uncertainty of steps in the logic model with potential risk mitigation actions and research and development opportunities.

5 RISK COMMUNICATION

5.1 Introduction

Most human activities have some interactions with the environment. Coastal aquaculture is no exception, and the interactions should not be ignored. However, as with other industries, the interactions arising from coastal aquaculture occur in specific settings. Risk analysis offers a comprehensive framework for clarifying the processes of interaction that can lead to environmental changes, and the uncertainty associated with the probabilities of the links between hazards and undesirable effects or endpoints being expressed. To be acceptable and useful, risk analysis should be transparent, iterative, and help to build consensus among stakeholders and other interested parties.

5.2 Risk communication objectives

The purpose of risk communication is to provide planners, managers, industry experts, environmental agencies and stakeholders with the information they need to make informed, independent judgements about potential risks to their health, the safety of the operation under consideration, and the potential environmental effects, as well as the economic and social risks that may be associated with a proposed development (Fischhoff 1990; Gow and Otway 1990). Risk communication is an essential tool with the following objectives:

1. Offer stakeholders a sense of ownership of the process, and foster trust in those conducting the exercise.

2. Identify issues of concern, and stakeholder priorities that need to be incorporated into risk identification and risk analysis.

3. Ensure that user knowledge is effectively incorporated into the decision-making process.

4. Provide sound mechanisms by which stakeholders are informed about the nature and strength of links between hazards and endpoints, and the probabilities and uncertainties associated with these relationships.

5. Help the achievement of outcomes that benefit everyone involved, through ensuring that both the proponent and stakeholders understand the problems in advance.

6. Encourages openness through the entire risk analysis process leading to decision-making by effective exchange of information, and by dealing explicitly with perceptions, facts and uncertainty.

7. Ensure that all pertinent and significant data required for the risk analysis are captured, not only from the traditional natural science disciplines that allow assessment of environmental influence or change, but also through stakeholder information on objectives, priorities and perceived risks.

8. Provide mechanisms by which any information generated as a result of the implementation of recommendations arising from the risk analysis (for example, for mitigation or additional research) is also captured.

9. Guarantee that the results of the risk analysis are communicated in a format that is clear and useful to the individuals and organisations that use the information in their decision-making processes.

Of these nine objectives, the last is by far the most complex and challenging undertaking, because the groups receiving the information can have very different levels of understanding of the subject area and of its perceived and real risks. Therefore, a high degree of flexibility is required to ensure good communication between scientists, planners, managers, regulators, developers and the public at both the government and local level. It is almost impossible, without empirical testing, to predict the consequences of effective communication for people’s responses. Experts and laypersons alike often face difficulties associated with communication on subjects related to choice, risk or change. The process of risk communication, therefore, also involves educational steps in order to assess and respond to risks and benefits appropriately (Fischhoff and Downs 1997).

Risk communication is a continuous process, the outcome of which (if well performed) should be sustainable resource development where potential hazards have been identified, risks are assessed and serious risks are controlled even in the absence of full information, in accord with the Rio Declaration, and negativities arising from fear of the unknown are minimised and economic opportunities are maximised within socially agreed ranges of risks.

5.3 The need for better communication

Past experience of the management of coastal aquaculture development has shown that a top-down flow of information will often be met by a reactive response, and that this initial response can lead to long-term resistance. There is a need to improve the quality of discussion and communication of risk characteristics of coastal aquaculture in all relevant areas of environmental effects. This should become a normal and regular input to national policy on aquaculture strategy, and influence the development of regulatory practices as well as any SEA/EIA process, building on planning consents as well as licensing and product labelling initiatives.

Communication in a regulatory context is a two way process, with the objectives of understanding the stakeholders' values, their views of an industry and its products, as well as their priorities. Drawing more extensively on stakeholders' knowledge should lead to better decisions, while also ensuring transparency of the decision-making process.

Within the research priorities of the EU Framework VI, a project has been completed on "Stakeholders in Risk Communication: Risk communication practices in EU Member States, selected other countries and industries" (Wright *et al.* 2006). This survey of approaches to risk communication in the 25 EU member states clearly demonstrated the different ways in which risk communication is handled in most countries, despite the agreed definition by IOS (International Organisation for Standardisation). The conclusions of the project support the concept that risk communication should be seen as a continuum (or as a cycle) in which emergency and crisis communication should be a part. Interestingly, the survey also identified the need for developing generic risk communication plans or guidelines, as already exist in a few countries, favouring "...risk communication at the pre-assessment/assessment stage, since stakeholders, including the public, may bring information that might not otherwise come to light from the experts, and stakeholders will certainly bring their values and opinions, which may well be different from those of the experts and/or risk managers." (Wright *et al.* 2006).

It is precisely for these reasons that Risk Communications MUST gain a much higher profile in the entire environmental assessment process than it has achieved in the past. Commonly practised Environmental Impact Assessment (EIA) and Environmental Impact Statement (EIS) procedures employ a communications process often very late (almost as an inconvenient "attachment" to the entire development process). This has frequently given room for the development of a reactive (and mainly counter-productive) process among stakeholders, while creating fears and perceived risks which can drastically affect not only the efficiency of the process but also result in forced decisions which are not necessarily based on solid facts and real risk. However, a fundamental change in approach is now taking place. Risk Communications should be implemented in the development process right from the outset of any development, thereby minimising the chances for 'distrust' evolving among stakeholders at all levels. One of the major objectives of Risk Communication, therefore, is to build trust among stakeholders, providing a platform for the recognition and articulation of problems, and consensus building as an iterative process in the entire decision path of a development.

5.3.1 Trust, ownership and politics

Trust is only gained over time and can be destroyed by single mishap or mistake. Further, once lost it can take a long time to rebuild. Our social and psychological training/experience also works against developing trust. The 1999 report of the ICES Working Group on the Environmental Interactions of Mariculture identified that the reactive role of environmental managers in dealing with the potential environmental effects of aquaculture, in addition to the long lag required for research to reduce the uncertainty in our prediction of the probability of effects, creates tensions between the scientific and public views of the severity of the risks arising from aquaculture. Not having the foresight to recognise and be prepared to respond to the public need for answers, and thereby not having reliable and convincing answers for the public, fuels the fires of potential distrust.

For a number of other psychological reasons, there is even a further bias against the development of trust (Slovic 1999). These include:

1) Negative (trust destroying) events are more notable than positive (trust building) events;

2) When both types of events come to our attention, the negative ones have greater weight than the positive events;

3) A quirk of human nature is that bad news (negative events) are generally seen as more memorable than good news (positive events); and,

4) Distrust, once initiated, tends to perpetuate distrust, inhibiting the kinds of personal contacts and experiences that are necessary to overcome the distrust.

All of this generates a need for the public to find a champion for their concerns who will act as a hedge against possible lack of concern or unwillingness of resource managers to safeguard effectively environmental quality. Many environmental non-governmental organisations (ENGOs) attempt to fill that role.

5.3.2 Standards and priorities

Hazards and risks are, by definition, issues of concern to the wider population who may be affected directly or indirectly. They will have their own views on the relative importance of different effects or endpoints, and the standards or thresholds which might be applied to them. It is therefore appropriate that they should be engaged in scoping the causes for concern to be assessed through risk analysis, prioritisation of these causes for concern, and the setting of standards against which the undesirability of differing degrees of environmental effect can be assessed.

Some characteristics of risk of concern to the general public (Slovic *et al*. 2004)

- Scale / size / extent / numbers of people affected
- Severity (especially mortaility)
- Catastrophic
- Familiarity
- Quantity of scientific understanding / uncertainty
- Controllability: ease of mitigation
- Naturalness
- Voluntariness
- Fairness (equity)
- Present v. future risk
- Visibility / detectibility
- Cost / benefit
- Nature of the source

Conventional environmental risk analysis only addresses some of these characteristics: decisions arising as a result of the analysis may need to take account of these wider concerns

5.3.3 User knowledge

Those involved in either the use or management of natural resources usually have a good deal of knowledge about natural systems, and the relationships between different elements of them. If practical knowledge is ignored in the process of risk analysis, the analysis will be weaker, and it is unlikely that users will accept its findings. The nature and scope of user knowledge will vary between user groups, for example, the general public, commercial fishers, or indigenous people. Effective communication requires that participants understand the depth of user knowledge, as indicated in written and oral contributions to the risk analysis process, and respond appropriately to this in their interactions. The process of risk analysis should allow for rigorous exploration and testing of scientific information, user knowledge, public concerns, and where appropriate the synthesis of all three.

5.3.4 The perception of risk

In dealing with risk communication, it is important to recognise that members of the public and experts can have different perceptions of risk. This is because, among other factors, they can have different worldviews, experiences, emotional reactions and social status. One of the possible consequences of these differences is that members of the public may find it difficult to trust the scientists' assessment of risk. However, such differences take us into a field known as Risk Feelings.

Proponents of a purely technical approach to risk analysis can tend to view Risk Feelings as irrational, or at least not amenable to rigorous analysis. Several recent studies, however, dispute this view. In fact, the Risk Feelings (an experiential based approach) and the Risk Analysis (a rational approach) operate not only in parallel but often seem to depend on each other for some guidance. Studies have demonstrated that analytical reasoning cannot be effective unless it incorporates experiential forces. In short, rational decision-making requires proper integration of both modes of thought (Slovic *et al.* 2004).

Feelings are the result of a number of experiential forces working in concert. In an attempt to systematically study those forces, Slovic *et al.* (1980) examined 90 hazards using factor analysis. As might be anticipated, one of the most important axes simply describes the number of people exposed to a hazard (*See* box above). The other two axes that 'account' for much of the variation in how risk is felt, demonstrate a much more subtle interplay of factors.

One of those axes has, at one extremity, hazards that were uncontrollable, lethal, dreaded, globally catastrophic, seriously affected future generations, were not easily reduced, involuntary and generally affected 'me'. Hazards at this end of the axis included: crime, warfare, terrorism, nuclear weapons, nerve gas, and nuclear power. At the other extremity of this axis are hazards that are not obvious, but are especially applicable to the particular individual being exposed to them. These hazards are usually controllable, lack dread, are not globally catastrophic, do not have fatal consequences, are equitably distributed across the population (and yet apply to the individual rather than the whole population), present low risks to future populations, are easily reduced, are voluntary and are seen as generally not applying to 'me'. Hazards at this end of the axis exhibit a high level of familiarity, and included bicycles, power tools, home appliances, hair dryers, and cosmetics.

The second axis described many of the hazards that were observable and known to those exposed, had an immediate effect, were 'old' risks and had consequences known to science. At this end of that axis were; bicycles, motor vehicles, police work, dynamite, and crime. The hazards at the other extremity of this axis included items that were not observable, unknown to those exposed, had a delayed effect, were new risks, and had risks unknown to science. Example of hazards with these attributes included cosmetics, food colouring, DNA research, space exploration and nuclear power.

When feelings and analysis fail to satisfy people's needs to accommodate risk in their lives, recent studies have shown that people also use other factors to judge risks. Factors such as gender, race, political worldview, affiliation and trust strongly affect how a risk is judged (Slovic 1999). Clearly most of these factors are not immediately amenable to influence by the risk analysis process, and must therefore be accommodated within that process. Past practices of EIA and EIS failed to incorporate these factors effectively with the consequence that development was unnecessarily delayed or prevented. Thus risk communication is an essential component to the process and plays a central role in fostering a fair and cost-effective decision-making process to the benefit of all stakeholders involved.

Damasio (1994) neatly sums up the dynamic that has to be enabled.

"*The strategies of human reason probably did not develop, in either evolution or any single individual, without the guiding force of mechanisms of biological* *regulation, of which emotion and feelings are notable expressions. Moreover, even after reasoning strategies become established .... Their effective deployment probably depends, to a considerable extent, on a continued ability to experience feelings.*"

To summarise, hazards exist, and our view of the risks is heavily influenced by psychological and social factors. Risk communication must therefore blend science with psychological, social, cultural and political factors. Regrettably, our social and democratic institutions tend to breed distrust, and work against resolving the risk management equation.

When communicating about risk, it must be recognised that logic, used in isolation, is an inadequate communication strategy. Risk, and particularly the perception of risk, is multi-dimensional, with both objective and subjective elements. Risk analysts need to understand the subjective dimensions if they are to focus their work on key concerns and communicate information in ways that address those concerns.

5.3.5 Complexity and uncertainty

Risk analysis is complex and multi-dimensional, dealing with the interface between human responses and complex physical and natural systems. Risk analysis provides a framework for exploring this complexity in a standardised and rigorous framework, and also for incorporating uncertainty in an explicit and clear way. A role of the risk communicator is to use the structure of risk analysis to inform regulators or stakeholders, and others, about the nature of risk, and to attain consensus as to appropriate mitigative actions.

5.3.6 Monitoring

In many instances, the risk analysis will suggest that environmental monitoring should be undertaken after initiation of an aquaculture project, for example, as an element in a cycle involving data collection, assessment, and review of farm operating procedures and conditions. Monitoring can provide information directly relevant to the situation being monitored, and also provide data to assist in risk analyses of other, similar, situations. New assessment technologies are emerging using genomic (transcriptomic) technologies that may allow forecasting of effects on organisms by detecting the up and down regulation of target genes. In some cases, monitoring is a normal requirement of licences/permits to develop/operate fish farms. In some other cases, the uncertainty in the assessed probability of the undesirable outcome being expressed may suggest that targeted monitoring should be undertaken to try to ensure that, if the undesired effect does occur, then corrective measures can be taken.

An example of the latter occurred in British Columbia, Canada, where a decision was made to allow the farming of Atlantic salmon, a species not native to the Canadian west coast. There was a substantial body of experiential evidence from many hundred introductions of this species outside its home range. In no instance was Atlantic salmon able to establish anadromous populations. It was recognised that the salmon were likely to escape containment and enter the marine waters, and that if mature reproductive individuals escaped near a suitable stream, they might reproduce and produce some offspring. However, the available evidence suggested that it was very unlikely that the offspring themselves would survive to reproduce. To help evaluate if that conclusion was accurate, a monitoring program was developed, built around government and stakeholder participation (Figure 5.1). As predicted, a very limited number of juveniles were detected in a few streams close to farms, but there has been no evidence to date that the F1 generation was ever able to complete the life cycle of wild Atlantic salmon and return to breed. While these observations do not provide absolute proof that it cannot happen, the data are now becoming invaluable in assisting to quantify the level of risk of establishing a wild population of Atlantic salmon presented by future individual salmon farms.

5.4 Learning from past experience

5.4.1 A brief history

Historically, risk analysts undertook risk analysis as a technical procedure, at the end of which, results were communicated. Given the lack of explicit recognition and incorporation of the uncertainties inherent in risk analysis, stakeholders often responded negatively to the outcomes. Fischhoff (1995) reviewed some of the approaches used, and attitudes held, in the past and identified a pattern of miscommunication and misconceptions among participating parties that subsequently lead to an attempt to improve communication. He describes seven types of approach ranging from the technocentric "all we have to do is get the numbers right", to genuinely participatory or partnership approaches. These latter recognise not only the importance of transparency and trust, but also the potential contribution of stakeholders to the risk assessment process, and especially to those parts of the process which have significant subjective elements. In accord with Fischhoff (1995), we interprete these categories as follows:

1. "*All we have to do is get the numbers right.*" Risk analysis here is seen as a purely technical process which scientists can undertake before delivering the results to managers. This disregards the fact that such a process involves judgement about issues which may affect many people – and that they need to be reassured about how those judgements are made. It lacks transparency. Simple questions by the media have often undermined this approach.

2. "*All we have to do is tell them the numbers*." Scientists and risk analysts have often been tempted to hand out their conclusions in the simplest possible format – a set of numbers reflecting the conclusions of their analysis. While having some attractions, Fischoff argues that such a straight-forward approach may be met by a feeling in stakeholders that nobody in the planning process seems to care about their view and perspective.

Figure 5.1 : An example of post analysis data collection

3. "*All we have to do is explain what we mean by the numbers*." Scientists often believe that an analytical science approach is all that is needed when conveying complex data analysis in simplified ways. This may not be sufficient and can be difficult where the audience or stakeholders do not share the same conceptual framework or background.

4. "*All we have to do is show them that they already accept similar risks*." This attitude ignores the multiple dimensions of risk perception. In particular, acceptability depends on benefits as well as risks, and also that new risks are less well tolerated than old ones. People can be (apparently) inconsistent for a whole host of reasons.

5. "*All we have to do is show them that it's a good deal for them*." This may be done by considering the expected costs and benefits associated with particular risks or strategies. Explaining benefits can encounter difficulties that are analogous to those involved in explaining risks. For example, logically equivalent ways of presenting the same options can produce systematically different choices (known as 'framing effects').

6. "*All we have to do is treat them nicely.*" If people do not feel respected, then they have more reason to suspect that they are not being fully informed. They also have more reason to fear that risks are not being managed properly on their behalf, and that the risk-management process is part of a larger trend to disenfranchise them. Although sympathetic delivery is no guarantee of respect, it does show that one is recognised as a person with feelings (even if those are being manipulated).

7. "*All we have to do is make them 'partners*'". Stages 1 through 6 involve increasing levels of recognition of the recipients of the message as individuals with complex and genuine concerns. This still implies a one way process – a well researched sales message. However, the understanding is cultivated in order to get across a message whose content has been determined by the communicator. That means seeing recipients as individuals but not engaging with them as such. This stage involves the public as partners in risk management. It means providing them with a seat at the table and allowing them to communicate their own concerns. In effect, it means opening a communication channel in the opposite direction. Care must be taken to establish with the partner/stakeholders how their input will be incorporated into the process. For example, is their invited input only tokenism (it may be perceived as that) or may their input dominate the discussion? What happens to people's input (especially non-experts) once it has been given, especially if it is contrary to expert opinion? The process by which controversial opinions are accepted is a necessary issue which should be addressed early in discussions with partners.

The approaches towards the end of the above list begin to recognise not only the importance of transparency and trust, but also the potential contribution of stakeholders to the risk assessment process, and especially those parts of the process which have significant subjective elements.

5.4.2 *The way forward: a more participatory approach*

As discussed above, our responses to hazards and risk are heavily influenced by psychological and social factors. Risk communication must therefore seek to integrate the scientific aspects of risk analysis with relevant psychological, social, cultural and political factors. However, distrust seems to be an inevitable element of our social and democratic institutions, and this tends to work against the resolution of the conflicts that so often complicate risk analysis and management.

A new approach is therefore needed – one that focuses on introducing more public involvement early in a risk analysis which is transparent and in which it is clear to all involved that the biological and physical sciences have a distinct role from that of the economic and political sciences. The role of the biophysical sciences is to measure and develop the knowledge that will allow prediction of how much change will result from the introduction of a hazard into the environment, its geographic extent and its temporal duration (this is risk assessment). Risk communication takes information from these sources and orders it in a way that speaks to people's concerns, by translating the socio-economic values to the environmental manager and helping to make the science relevant and informative in relation to socio-economic interests. Managers can also supply supplementary post-analysis data from monitoring programs that will allow the risk assessment to be used in an adaptive management protocol.

Work in Europe and North America has begun to lay the grounds for public participation in the deliberative and decision-making process (for example, *see* Renn *et al.* 1991; Renn *et al.* 1995; Stern and Fineberg 1996), and for the creation of tools to improve the effective use of the contributions from stakeholders and other interested groups.

5.5 Developing a Communication Strategy

5.5.1 *Overall considerations*

Risk Communications strategies inevitably differ between situations, even within a single field such as coastal aquaculture. The particular circumstances vary with location, and the mix of concerns will vary with the people affected or concerned about a development. It is therefore not possible to be highly prescriptive in advice on how to undertake risk communication. However, the following sections attempt to identify some themes that are generally applicable, although the scale of effort required to complete the tasks will vary greatly. Communication in relation to a regional or national plan for coastal aquaculture will be a very different challenge to that required for the extension of a single existing production site. The communications strategy mapped out at the outset of the risk analysis process should:

- Define the need and scope of consultation and communication;
- Identify relevant stakeholders, interest groups and experts who should be involved, and their particular interests, knowledge, needs and perspectives;
- Decide on the approach and technique for engagement and communication with respect to each stage of the risk analysis and for each stakeholder group, government, and technical experts.

The details of such a strategy will depend on the issues being addressed, the political or decision-making context, and the nature of the lead organisation. The following guidance should therefore be interpreted with flexibility. Nonetheless there are some general principles which should be applied in most circumstances:

- Engagement with key stakeholders should be undertaken from the outset, to maximise transparency and ownership;
- Specifically seek out, show respect for, and take full account of local and/or user knowledge;
- Consultations should be expertly facilitated by someone seen by all parties as neutral and trustworthy;
- The process should be iterative – consultation informs analysis; analysis informs consultation; consultation generates consensus..... and so on. The number of iterations may range from one to many according to the issues being addressed and the scope of the whole exercise.
- The final assignment of estimates of severity, probability and uncertainty – the core of risk assessment – should not be done by a single individual. Although they may be informed by technical experts, final estimation should be undertaken by an agreed delegated group, including technical experts, and including appropriate or requested stakeholder representatives.

The objective of this process is to maximise the flow of information and the interactions between all involved. It is a continuous process, including not only the risk identification and risk assessment but also the implementation of the decision, its subsequent monitoring and iterative improvement (mitigation) process.

It should also to be emphasised that a risk communicator and/or facilitator is not a public relations official whose primary aim is to limit the possible impact of the Risk Analysis on the development of the project. The risk communicator's main objective is to ensure that stakeholders and the public are equally informed about the risks, and can agree on how to manage the risk. If such agreement is not attainable, the process should lead to a common understanding of the management options.

Irrespective of the degree of consultation and interaction, transparency must be established and maintained. The procedure must be clear; the process must be open; the analysts should be available and accountable; the reporting regular; and the basic analysis should be value neutral.

5.5.2 Step by step development of a communication strategy

Any risk communication strategy will have to undergo a clear planning process and the following sequence has been developed from an amalgamation of several different approaches that have been taken in various jurisdictions, and which contain key elements for successfully building a strategy of risk communication. As an initial step, the communicator/facilitator who will organise the communication process has to be appointed. Thereafter, the strategy should be built gradually, as visualised in Figure 5.2.

The process is not a linear one and may go through several iterative loops between several steps, depending on the number of hazards identified and the complexity of the system. It also can be a short process with all stakeholders and regulatory agencies involved in one meeting (yellow box) dealing with all steps if hazards and risks are clearly identified and well-controlled. If no hazards are identified, the process may end at the scoping meeting.

1) Starting with a scoping process which is based on the documentation provided by the proposer and developed with the respective authority/organisation in charge (in accordance with the existing framework in any of the regional and/or national jurisdictions and their policy or mandatory procedures).

This exercise will have to be well documented, in agreement with the participating parties without peer review. It provides the basis for the next step in the process. If it becomes clear at this early stage that the proposal will be contentious and that resolution might be difficult, it might be advantageous to identify and involve a facilitator (*see* step 3) at this point.

Public involvement may not be required at this stage, unless issues have already been discussed between the proponent and various stakeholders (i.e. NGOs) and the media. If advisable, (case dependant) communications of the status of preparation of the project to stakeholders and the public (including media) should be based on the agreed minutes of meetings or on specifically agreed press releases.

2) Identifying the relevant stakeholders and interest groups and seek and consider their needs

One difficulty is the appropriate and reliable identification of stakeholders. While many are clearly identifiable, some may enter the process later as their interests evolve. There is a need to be alert to such groups and to solicit contacts as early as possible. Another barrier to effective risk communications are conflicts and lack of coordination among stakeholders. The facilitator should anticipate such difficulties during the planning and preparation of the discussion process. It requires a skilful professional to organise effective risk communication strategies, for example selecting the timing and number of meetings, the composition of participants from various stakeholders in one or several subsequent meetings, whether to focus on one specific and complex issue, or on many issues, in a single meeting. Those with a vested interest should be invited to cooperate closely with others who may be affected by the project and may have formulated their own objectives.

For example, when dealing with the expansion of shellfish long-line farming near existing oyster bouchots and bottom cultures (*see* case study 6.2) it might well be advisable to have all stakeholders at the first meeting because (a) the issue may have been already been of public debate via the proponent, or (b) there is a need to ensure that the experts capture all issues that need to be addressed in developing the influence diagram, and (c) the scientists may wish to inform the farmers and authorities of the potential effects and of what needs to be studied. While competition for food (phytoplankton) is one of the key issues, and carrying capacity may have to be established, there are others such as fisheries or boating that may wish to identify their own interests.

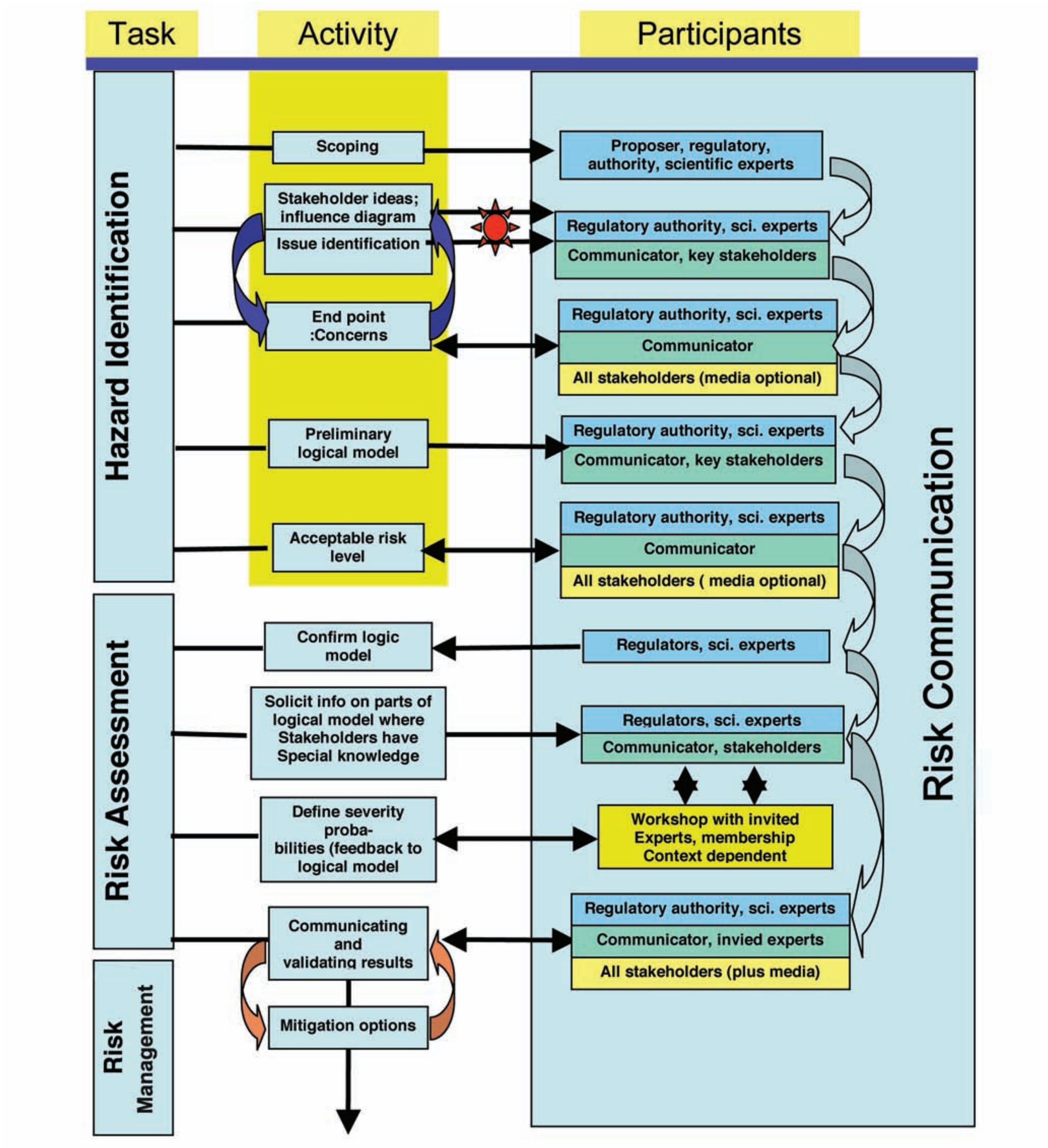
In the case study on benthic deposition under and around a cage farm that it is proposed to expand (*see* case study 6.1), existing knowledge and risks have been well-established. The scale of the effect is among the key issues and therefore may require involvement of only a few experts, the farm operator itself and those next to him.

3) Defining the key issues that must be addressed in relation to risk assessment of the specific project, particularly those which may have not yet been covered by an EIA (if it already exists; in some jurisdictions this is not mandatory)

At this stage, there is a need to involve a facilitator who may not only be able to solicit further ideas from the representatives of the stakeholders but also to facilitate the communication and negotiations with the regulators, governmental agencies and the scientific experts. The process will result in the development of an influence diagram to be used in the mental models approach. The reasoning and agreed outcome of the negotiations should be clearly documented. This may be in form of a protocol or an elaborate document which stakeholders may wish to expose to peer review, for example in cases where risks are complex. An iterative approach to clarifying the issues may be required.

4) Identify key stakeholders who can enable a better community understanding of the risk assessment and management issues

Figure 5.2 : Visualisation of a more generalised scenario of risk communication practices involving various participants in different stages of the communication process. Asterix = early determination of stakeholders to be involved



Among stakeholders, there are always a few (for example, representatives of trade associations) who have particular skills and opportunities to convey messages to other stakeholders who share similar concerns but for some reason (for example, cost, or lack of immediate and direct personal consequences) are not able to have their own representative participating in the risk analysis process. Representatives of key stakeholders should be encouraged to act in some form as facilitator and/or communicator with other stakeholders.

5) Identifying and prioritisation of end points

At this stage (Figure 5.2), all stakeholders should be invited to participate in the meetings and discussions which are facilitated by the communicator. Depending on the complexity of the issues, multiple meetings and discussion for a may be necessary, and an iterative approach may be necessary to make progress. The outcome of these communication exercises should find their expression in an improved influence diagram and finally be reflected in the minutes of the meetings and provided to the experts who incorporate the results into their subsequent report. This report should go through peer review before initiating the next step.

The case study on the effects of escapes from cod cage culture on native populations (case study 6.3) may serve here as an example. Since the genetic influences may be of far-reaching effect in time and scale, those involved in fisheries management must be consulted early in the process. Additional communication exercises are certainly needed with population geneticists who would be able to advice on endpoints (*for example*, scale = number of escapees in relation to natural stock size; potential frequency of outbreaks; genetic impact over time, for example, generations). Each of the stakeholders may have a different view. Through discussion meetings, an iterative process can be initiated that generates more specific endpoints in terms of scale, short-term and long-term impacts of the development of a cod cage farming industry and subsequently helps to determine the complexity of the final logic model.

6) Developing a procedure on how information can be effectively communicated to internal and external stakeholders

The steps to be followed may be sequential to the logic model developed in the risk assessment process, however, there are often scenarios where this is not the case. During discussion, the initial influence diagram can be developed further as long as the logic model has not been finalised.

Taking the case study on the effects of fish farming on kelp (case study 6.4), the kelp harvesters and the wild fisheries (specifically local fishermen and/or first nations) who consider kelp as the ‘kindergartens’ for their fish would be involved together with local scientists to develop mitigation plans that would either eliminate the problem or affect the design and the outcome of the final logic model. Communication with all involved could also help at this stage to get a better understanding of the acceptable risk associated with severity of the geographical extent of he impact.

7) Assess the outcome of the initial information-gathering exercise

At this stage, there is already a need to analyse how successful the informational exercise has been and what has been learned from this discussion. This allows continuous adaptation of the strategy, in particular identification of the points and aspects that may have been missed and how they relate to those items already within the scope of the risk analysis procedure.

8) Introducing the preliminary logic model

This first attempt to draw up a logic model is important and needs to be in place before any level of environmental change can be agreed as reflecting an acceptable degree of change. Certainly, the regulators, planners and experts, as well as the representatives of key stakeholders, should be involved in this process. Again, there may be a need to refer back to previous groups, expand the tasks, or confirm doubts being raised or the approach being taken. Documentation of the development will have to be rigorous but in clear accessible language that is understood by all involved. Peer-review is not needed at this stage.

Presenting the structural components of the logic model diagrammatically will greatly assist the stakeholders to arrive at a logical framework for their subsequent discussion. The influences diagram can be gradually altered during the discussions, starting with key issues and adding to them, building on interactions between stakeholders, communicators and the public. It should have clear structural links to the logic model which is subsequently developed and finalised early in the risk assessment process.

9) Developing agreed views on an acceptable level of change

Clear definition of the acceptable level of environmental change is an essential requirement for a clear and transparent risk analysis. In some cases, environmental regulation may have developed to a stage where environmental quality standards (for example, for impact on benthic fauna, or nutrient releases) are in place. Clearly, these represent *de minimis* standards that need to be met. In other cases, it may be necessary to develop and agree standards or thresholds relevant to the logic models and endpoints under discussion.

This is, in many cases, by far the most complicated process. It should be science driven but will have to reflect the feelings and requirements of many stakeholders who are indirectly affected. Here, the communication process may be simple in cases where the level of uncertainty is low and the risks can be controlled, but difficult where multiple options of high uncertainty prevail. At the end of the process, certainly a full documentation of the decision is required, and the final report should be subjected to peer-review.

10) Finalisation of the logic model and acquiring special stakeholder knowledge

Entering the Risk Assessment phase, the scientific experts and regulators should prepare the final logic model to be used for further elaboration and refinement. Commonly, extended negotiations with key stakeholders will follow to explore the possible gaps which may be filled by specialised stakeholder knowledge.

At this point, key stakeholders may have arranged their own internal communication processes. It is important to assure that all are being adequately informed in time, so that none of the stakeholders feel that they are being excluded or overlooked, or faced with being out-competed by coalitions that have established themselves. The Communicator and/or lead agency has to assure a comprehensive flow of information among all involved.

11) Special workshops, and expert consultations

Depending on the complexity of the project and its potential environmental effects/endpoints (*for example*, large geographical range, long-term effects), external expertise may be required to resolve the questions of assigning appropriate classifications to severity and probability. Special workshops with invited experts may need to be organised and may be held separately or in conjunction with the representatives of stakeholders and/or regulators. Certainly, the resulting report and accompanying documentation will be provided to the regulator, scientific experts, communicator and representatives of stakeholders who will assess and incorporate the material in the decision process.

The case study on the expansion of shellfish farming (case study 6.2) may provide an example again. There may be specific issues that had not previously been addressed because of the need for specific expertise or site specific information. While carrying capacity assessment using hydrodynamic modelling, primary productivity and filter feeding capacity may be sufficient, questions concerning the effects of benthic accumulation of faeces and their fate (resuspension) may become an issue for which a specialist group may have to be called upon either to provide direct advice or gain solid new data through experimental work. There may be a need for several consultations to help design technical aspects of the assessment. Subsequent feedback may be expected to adjust the logical model.

12) Communicating and validating results, considering mitigation measures

Validating the results of the logic model will have to include the identification of the severity of the risk. The use of decision rules and scoring systems described above for the risk assessment should aid validation and communication of results of the risk analysis. There may be a need to fill specific knowledge gaps that have been identified during the final phase of testing the logic model. To gain this knowledge quickly, specific workshops with invited experts to deal with clearly defined Terms of references may be the best approach to make progress within a reasonable time window. These invited experts should meet and discuss the issues independently and discuss their findings with the facilitator and key stakeholders, involving also the identified lead regulatory authority and respective administrators and scientists. It is only after the severity of risk has been clearly identified, a sound sequence of potential mitigation strategies and their efficacy in reducing the severity of environmental risk will be possible. This phase is particularly sensitive and needs to be approached in an iterative process where results from the expert group are communicated to the respective assessment bodies.

5.6 The operational dimension of communication with participants and the media

5.6.1 When to release information

Communication with stakeholders is not a public relations exercise but an undertaking that has to serve all the parties involved, rather than any particular interest group. Timing and careful selection of the issues to be conveyed, however, is important, particularly when dealing with uncertainty. Decisions are needed on when to go to public with information and when to convey messages to different participants first. Good, speedy and effective communications between all parties need to be established early in the process.

The media quickly can have a selective ‘amplifying’ effect, by placing special emphasis on negative points. This can cause discrepancies in the perception of the magnitude of risk between stakeholders, resulting in public perceptions of risks as being much greater than expert assessments would suggest. Covello and Sandmann (2001) identify a long list of so-called outrage factors that may lead to amplification, and thereby influence participants’ perceptions.

Timing can affect the choice of media used. There may be good reasons to release information early in the process. It is understood that people are entitled to be informed on activities that affect their lives. Early release of information also sets the pace for achieving a resolution of the problem. If a long-lasting process is anticipated, it may be advisable to inform people why this is, in order to minimise speculation and reduce negative amplification through interest groups or the media. Delaying the release information can also mean that information may be leaked anyway. If information is leaked to a wider audience, it may be incomplete and/or misleading and have unpredictable, usually negative, consequences.

Being the first to release information gives one the advantage of being able to control it, to ensure its accuracy and refer to it if any distortion is discovered. Early release of information tends to avoid the need to correct information that was improperly conveyed through other channels. It is generally known that people are more inclined to over-estimate risks if information is held back during the risk assessment process and, with few exceptions, an early release of information is generally a positive step.

Appropriate risk communication requires not only good knowledge of the subject but also the proper use of language. While scientific terminology may be confusing to laypeople, it may also lead to misinterpretation and subsequent misunderstanding.

5.6.2 Communication with the public at large and the media

There are many ways of communicating with the public, and each of them requires specific skills. Dealing with newspapers requires careful choice of words and, since journalists mainly use their own language, it might be appropriate to request that text provided to the journalists should be cited as verbal quotation. Radio communication is often done through interviews, with questions and answers and, as in television, time constraints require quick responses.

In choosing the medium to use, one should first decide on the target audience to be addressed. The medium selected as the first platform for disseminating information will influence the spectrum of the public being addressed or informed. The consequences of starting by using a specific type of communication system can be significant. In the case of coastal aquaculture, one may wish to act through local, target-group oriented fixed (landline) telecommunications or through mobile communications (cellular radio) or even satellite communications, which might be initially accessible to fishermen and sailors first rather than the public at large. Amateur radio or specific Internet links or networks contact different audiences. In each case, it is important to realise which audience needs to be informed first. The final decision on any of these considerations is context dependent and certainly needs a case by case approach. Therefore, we are only able to point to these scenarios without giving any preference for any of the case studies outlined in this report.

5.7 Engagement and communication tools

5.7.1 General guidance

There is a need to recognise that building stakeholder relations is very different from public relations activities. As pointed out previously, in public relations, the communicator usually attempts to find the best method to ‘sell’ an idea. In stakeholder relations, the communicator will have to stay neutral, facilitating communication and trying to bring participants to consensus. There are a number of common rules that are well known, but have not often been followed by science experts involved in risk assessment exercises. These are briefly addressed here. :

(a) Build trust among stakeholders and the public

One has to expect that as communications to the public use quite different strategies to stakeholder communications, there is no need to attract their attention. They are already highly motivated, often sceptical and even worried and sometimes impatient to address their particular concerns. Skills are needed by the facilitator to recognise immediately these sensitivities, scepticism or hostility. A method often used to achieve an acceptable working climate in stakeholder relations and at communication meetings is to acknowledge the expressed problems, apologising for any mistakes made and sharing control. It is important to address people’s doubts. Ignoring or downplaying their doubts may reduce trust among stakeholders and with the public.

(b) Simplify language and presentation

It is not advisable to omit information because it seems to be overly technical, even though risk issues may be extremely complex. Participants in communication meetings usually do understand scientific and technical issues easily, if they are properly prepared and presented, mainly through visual aids such as diagrams and graphics. Verbal presentations and printed informational material (*for example*, flyers, posters) should avoid acronyms as well as scientific jargon.

(c) Assure objectivity

It can be difficult to respond in a credible format when opinions are expressed very strongly or even in an intentionally offending manner. It should often be easy to differentiate between opinions and facts. In order to maintain credibility, the facilitator should respond to both opinions and facts in the same manner.

(d) Use proper language

Messages containing negative connotations receive more attention and are remembered longer. This is a well-known fact on which media build their business. However, risk communication is most effective when reporting what has been done rather than what has not been done!

(e) Communicate clearly

Information must be presented at the audience’s level of understanding, otherwise people may feel left out or misinformed and may refuse to accept the information provided. It is important ‘to know the audience’ to be able to convey messages effectively. It is often helpful to use examples that the audience is familiar with. Back these with solid information to help to put the risk in perspective.

(f) Identify and discuss areas of uncertainty

Discuss sources of uncertainty, such as how the data were gathered, how they were analyzed, and how the results were interpreted. Uncertainty should be clearly indicated in logic models or influence diagrams. This demonstrates that the uncertainties are recognized, which can lead to an increase in trust and credibility.

(g) Be cautious when comparing risks

Comparing a risk with another with which the stakeholder is familiar can be helpful. But caution is required, as people's perception of different types of risk depends on a wide range of factors, as discussed above.

(h) Broad participation

Ensure that all key stakeholders and relevant organisations are involved. This will enhance credibility and ownership of the results.

(i) Know your clients

Research the interests and needs of your target audience in relation to the issues being addressed, in order to improve the focus of the risk analysis and the quality of the risk communication process.

(j) Involvement of the media in risk communications

While stakeholder communication meetings normally are designed to deal with relatively small groups, the media play an important role in amplifying risk communication to (a) reach a larger audience and/or (b) emphasise specific issues that are of wide interest. The media are not necessarily interested in solving problems but in selling news, and the best products to sell include (among others) catastrophes, controversies, conflict and fears. The operational modes to be potentially considered in risk communications are outlined below.

5.7.2 Specific tools

The core principle of effective communication is to supply what people feel that they need to know. It is surprising how often this simple concept is neglected in risk communications. Rather than conduct an objective analysis of what the public believes and what information they need to make the decisions comfortably, risk communicators typically ask technical experts what they think are the critical issues people should be told about. Communicators will also often have their own staff or expert advisors to advise on these critical issues. Such advisers may know relatively little about the needs of the stakeholders or interest groups that are the audience at discussion fora, workshops or group meetings as well as recipients of brochures, flyers and communication letters. A useful technique is to have draft communications evaluated by individuals with background knowledge and experiences similar to those who will use them.

Bridging from the public's knowledge and beliefs to an understanding of what information they need to make their decisions is one of the most important considerations in effective risk communication. However, the public's state of knowledge, beliefs and needs are not usually those that are determined by the technical experts. Earlier, we discussed that some of the general and specific knowledge individuals require to make decisions is often the product of social, psychological and economic considerations. Further, risk communications are distributed to larger groups or entire populations and each of these populations has a mix of individuals with different educational and social backgrounds, so the needs of populations will greatly vary.

A further key to effective and credible risk analysis is to clarify known relationships, agree on which are the most important, and identify areas of particular ignorance or uncertainty. A variety of tools can be used to engage stakeholders or other experts in problem formulation, exploring relationships and presenting results. Some of these can feed directly into the risk analysis process.

5.7.2.1 Influence diagrams

An important early requirement in effective risk communication is to develop a conceptual model that can be used as a framework for problem formulation and the exchange of ideas, knowledge, priorities and values. Influence diagrams were developed by decision analysts as a way to summarise information about uncertain situations, allowing effective communication between experts and decision makers in relation to an analysis (Howard and Matheson 1981; Shachter 1988).

At minimum, any communications strategy should include the development of a simple influence model based on the identified chain of events and processes linking a potential hazard to an adverse effect or endpoint. It should be developed in collaboration with expert stakeholders and using simple language. An example is presented in Figure 5.3 and 5.4, where Figure 5.3 explains the symbols used for Figure 5.4. Once the basic chain has been established, the various factors affecting the strength of the links in the chain can be explored. This process will not only provide the analyst with a much better understanding of concerns, issues and user knowledge, it will also assist in giving a sense of 'ownership' of the process to stakeholders and/or other experts. The influence diagram can then be used as a starting point for developing the more rigorous 'logic model' (Figure 5.5) and associated severity, probability and uncertainty ratings used in the risk analysis. It may also be used, modified as required by the logic model, to present the findings of the risk analysis towards the end of the risk analysis process (Figure 5.6). This will ensure that the language and concepts are those understood by the target groups.

Other examples of influence diagrams and logic models can be found in the individual case studies in Chapter 6.

5.7.2.2 Decision trees and decision analysis

Decision trees may be useful where the risks associated with alternative actions or strategies are being explored, where these may result in different endpoints or effects of concern, and where uncontrollable factors may affect the expression of a particular endpoint. The basic approach is very similar to that described above, for example, stakeholders are asked to map out the chain of events which may follow from an activity, but the chain will branch in response to specific events, actions, or choices. The probabilities associated with each branch can then be discussed and explored in more detail later by the risk analyst.

Figure 5.3 : Symbols used in the influence diagram representing different functions such as data input, scenario building, issue identification and degree of certainty

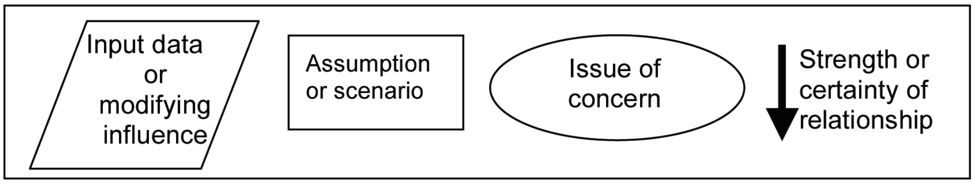


Figure 5.4 : Example of an influence diagram based on a case study presented in this report (See chapter 6.3)

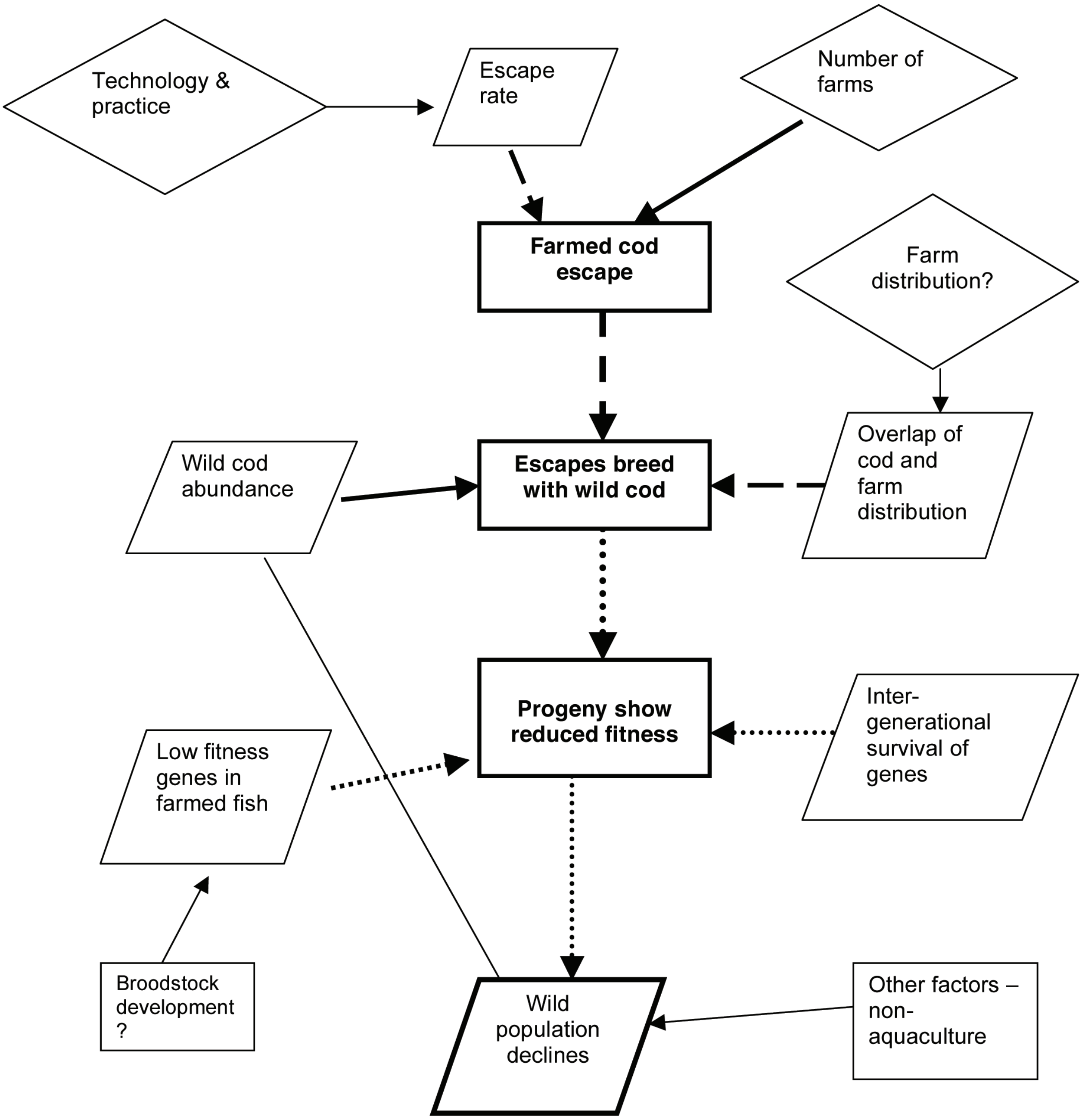


Figure 5.5 : Principle logic model which can be further developed by expert groups and used as a basis for detailed risk analysis (Standard flow chart symbols from http://www.patton-patton.com/basic_flow_chart_symbols.htm).

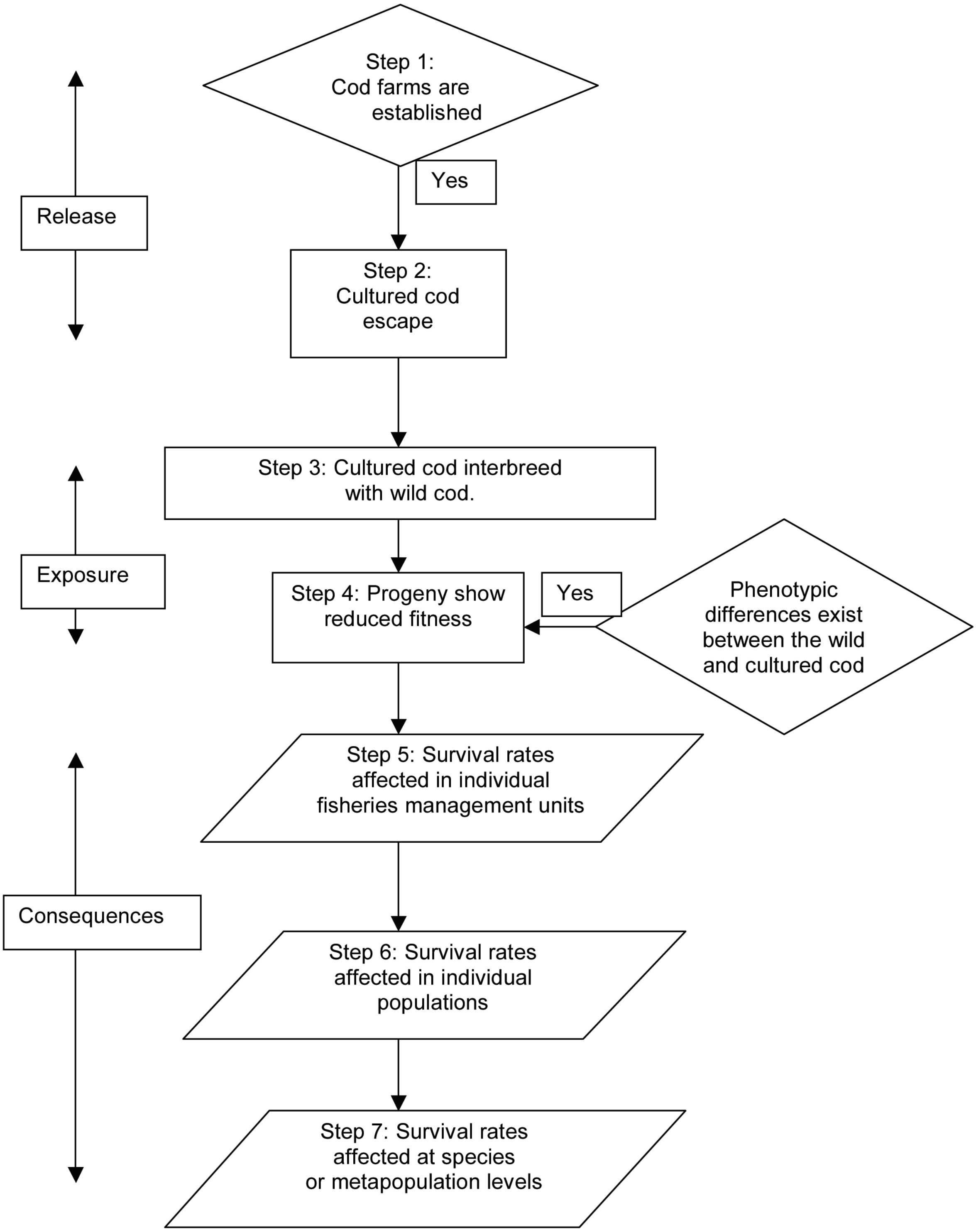
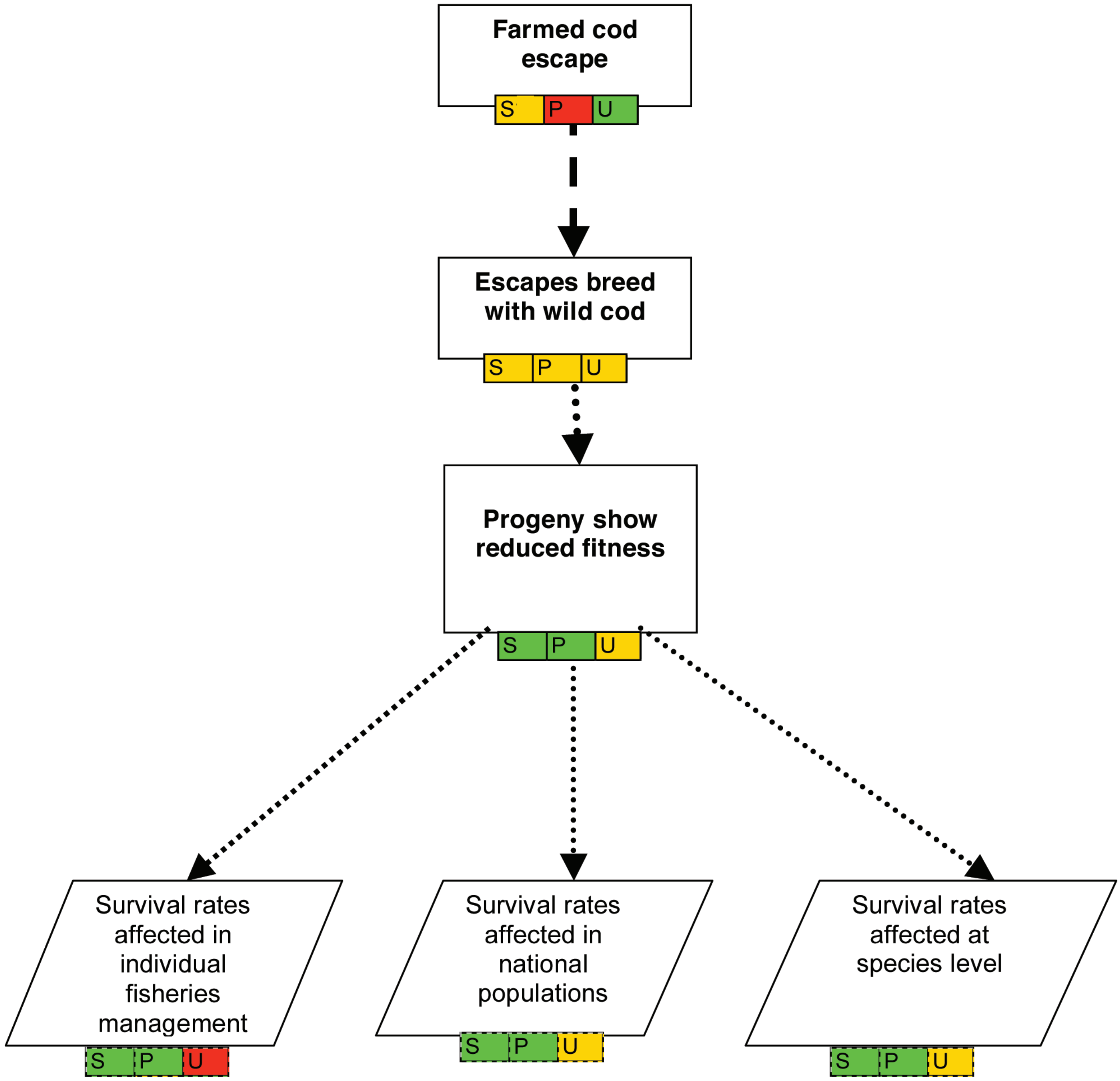


Figure 5.6 : Summary of risk analysis - used as a tool in validating and communicating results.
Colour bars reflect low (green), medium (orange) and high (red) ratings for severity (S), probability (P) and uncertainty (U) and are for illustrative purposes only



5.7.2.3 Mental modelling

A more sophisticated development of the above approaches is a technique called mental modelling (Morgan *et al.* 2002) which may be useful when dealing with more complex issues or sets of issues, where human perceptions are complex and varied, and where significant resources are available. It uses expert knowledge to form a framework which is developed using information from interviews with the target population. Those interviews are not questionnaire based. Such interviews run a real risk of bias by inadvertently communicating the experts' knowledge or providing clues in cases where respondents are unsure or their answer. Instead open-ended interviews are used. These interviews typically begin with very general questions like, 'What makes you choose to buy sea food rather than other types of food?' The intent is to get an immediate expression of whatever comes into the respondent's mind on the topic. Each topic that they raise is subsequently explored in more detail. In the final stage, the interview is more directed to make sure that no major factors have been overlooked. That stage may have respondents sort pictures and indicate which is relevant to the topic and their sorting process. They may be asked to solve problems using their beliefs (rather than just reporting their beliefs) and they may be asked for explicit definitions of terms commonly used.

Mental modelling: the process

1. Develop knowledge framework (detailed influence diagram)
2. Open ended interviews with target population:
   - Framed initially by user perspective (general)
   - Elaborated in response to specific questions
   - Elements of expert framework tested against user (specific)
3. Develop detailed influence diagram
4. Compare expert influence diagram with population defined influence diagram and amend focus of technical risk assessment as appropriate

The complex series of factors and interactions are mapped out in an influence diagram. Unlike the simple influence diagram generated above, corresponding to a single chain of causality, this diagram is likely to have many connections and pathways, representing the range of understanding and perceptions of the stakeholders.

The complexities typical of mental models in such circumstances can be illustrated by the example of an analysis (Figures 5.7a and 5.8a) of Canadians' mental model of the factors influencing their choice to purchase aquaculture seafood products from among the array of food stuffs available (DFO 2006).

Examining Figure 5.7a (for example, the model derived from interviews with experts) the first impression is that this is a daunting, perhaps an incomprehensible representation. This is not an uncommon problem when dealing with such a complex decision process, but patterns and relationships can be identified. To understand the diagram easily, first establish what are the major factors and influences affecting the decision. The larger ovals are factors of major influence. In the experts' model (Figure 5.7b), there are groups of major nodes that have an underlying theme. (These have been outlined in boxes drawn with dashed lines.) For example, Box A concerns risk control, regulations and industry practices. While these factors do not directly affect the choice to buy seafood, they do affect the consumer's access to seafood, which in turn influences the choice to buy seafood. Similarly the quality of communications (Box B) does not, other than point of sale communication, have a major direct influence on the choice. In contrast, Social and Cultural factors (Box D) are major direct influences, as are Perceptions of Environmental Effects (Box E).

In Figure 5.8a, we can see the process as it was revealed to interviewers by members of the Canadian public. This diagram is built as an overlay on the expert model of Figure 5.7a. In this diagram, the degree of influence is indicated by colour rather than the size of the node. Red indicates major influences and uncoloured nodes and the dashed circles and influence lines were not mentioned in any of the interviews with experts. To examine the major factors in the public decision making process, ignore the size of the circles and focus only on the colour of the node as in Figure 5.8b.

As noted earlier in Chapter 2, there are significant differences between the perceptions of the experts and those of the public. One of the first things to note is that the components of Box A were of secondary influence on the decision to purchase (Figure 5.8b), and not a major influence as anticipated by the experts (Figure 5.7b). Interestingly, while a person's social milieu was a major influence on the choice to buy, the perceptions of the socio-cultural impacts of aquaculture activities was not. Further, some factors that experts thought might be of lesser influence on the decision to purchase were actually major factors, among these were cost, access, convenience, and knowledge of appropriate preparation techniques. These are significant differences that should influence the content and delivery of any communications. It is also clear that a large number of factors influence the decision to buy, and a decision to address only one of them would limit the effectiveness of any communication strategy.

5.7.3 Workshop and meeting facilitation

Engaging people effectively in a communications strategy requires expert facilitation. It is vital that the facilitator is seen as neutral, and knowledge and understanding of stakeholders and issues of concern is at least as important as technical expertise, which in any case can also be provided by participants.

How many workshops and / or meetings are required in the decision making process will depend on the number of stakeholders involved, the diversity of subject areas to be covered, and the priorities by which issues have to be addressed. The latter may vary from case to case. In complex situations, it may be advisable to call for an initial meeting at which a simple agenda is set up, providing the opportunity for all stakeholders to get

Figure 5.7a : An experts' mental model of factors influencing consumers decision to buy seafood as seen by a survey of experts (DFO 2006). The size of the oval is proportional to the importance of the factor's influence on the factor (oval) or decision (box). The arrows indicate what decision or factor is influenced. Dashed arrows or ovals indicate influences not identified by the experts as important. Dashed boxes represent logical groupings of factors.

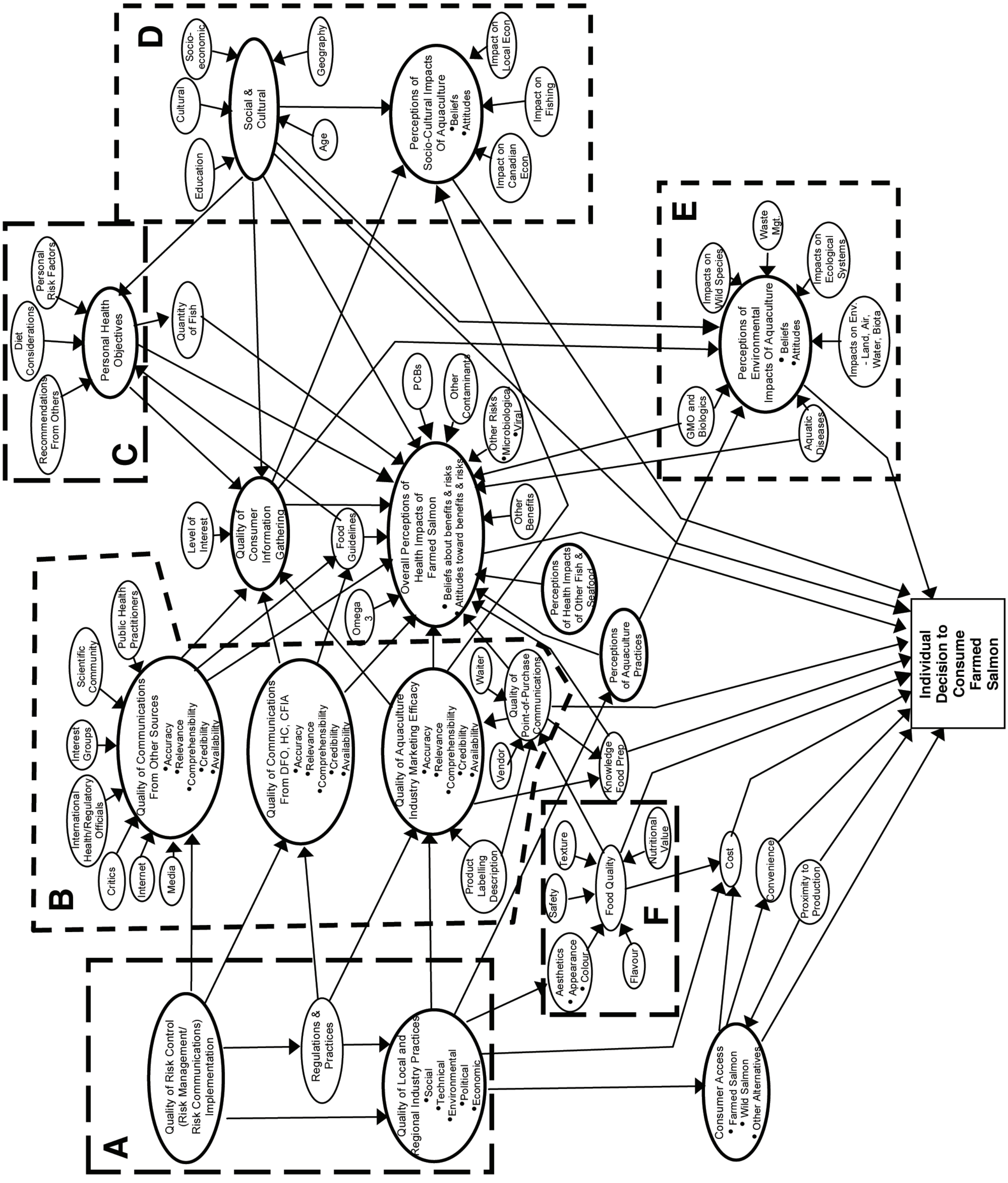


Figure 5.7b : Simplification of Figure 5.7a to emphasise the major nodes (DFO 2006)

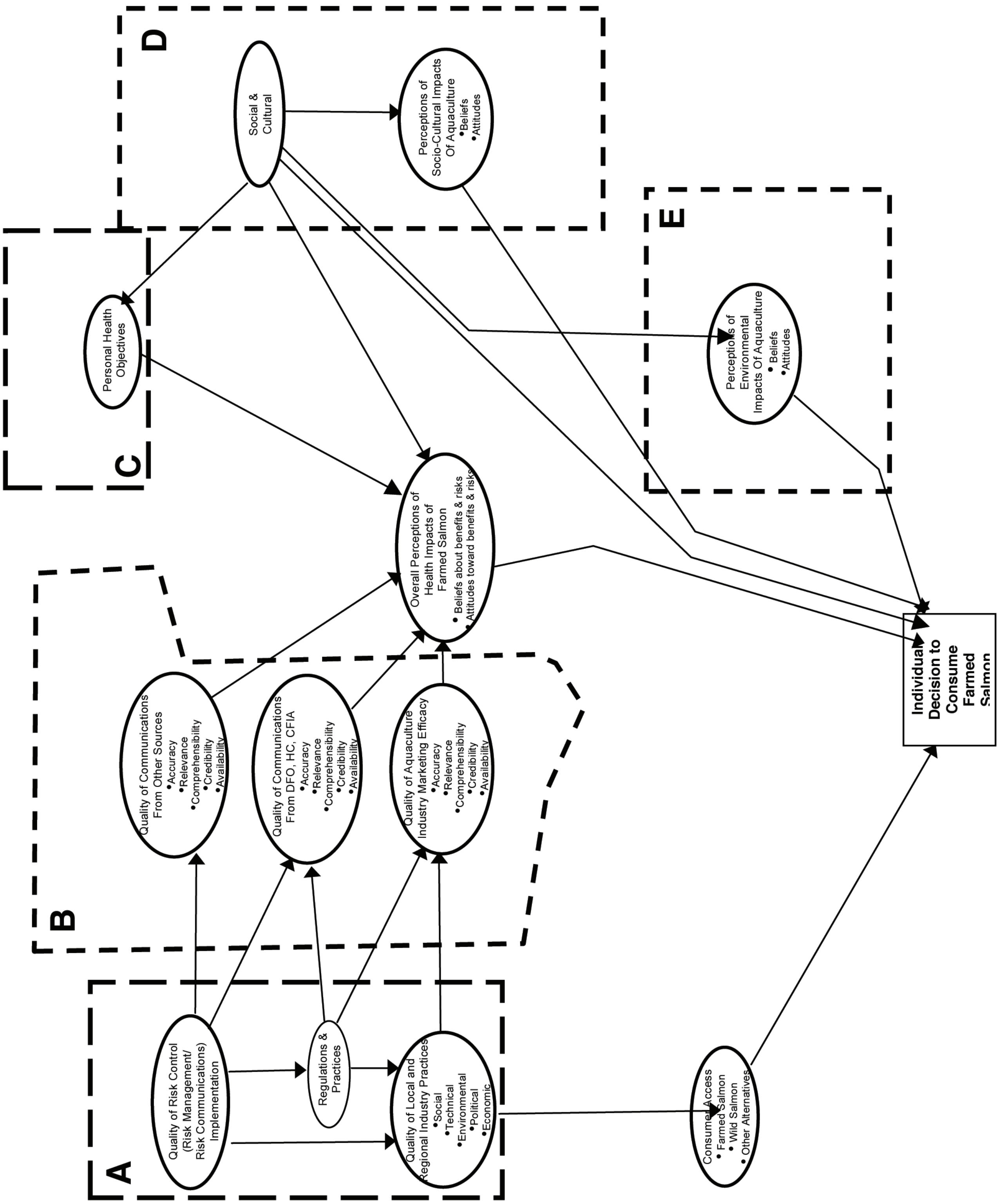


Figure 5.8a : A mental model of factors influencing consumers decision to buy seafood as seen by a representative survey of the public overlaid on the expert model of Figure 5.7.a (DFO 2006). The colour (not the size) of each oval is proportional to the importance of the factor's influence on the factor (oval) or decision (box). The arrows indicate what decision or factor is influenced. Dashed boxes represent logical groupings of factors.

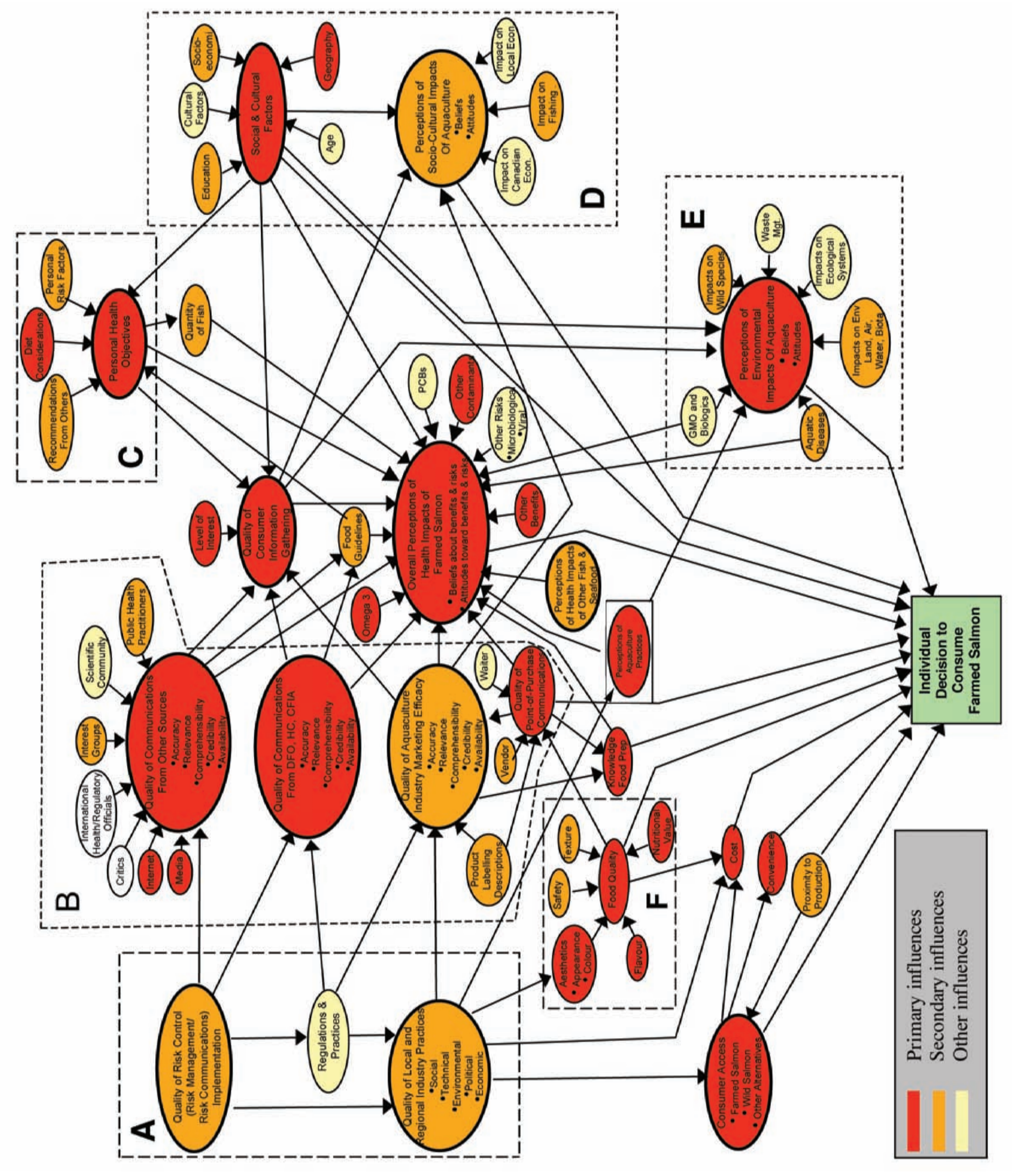
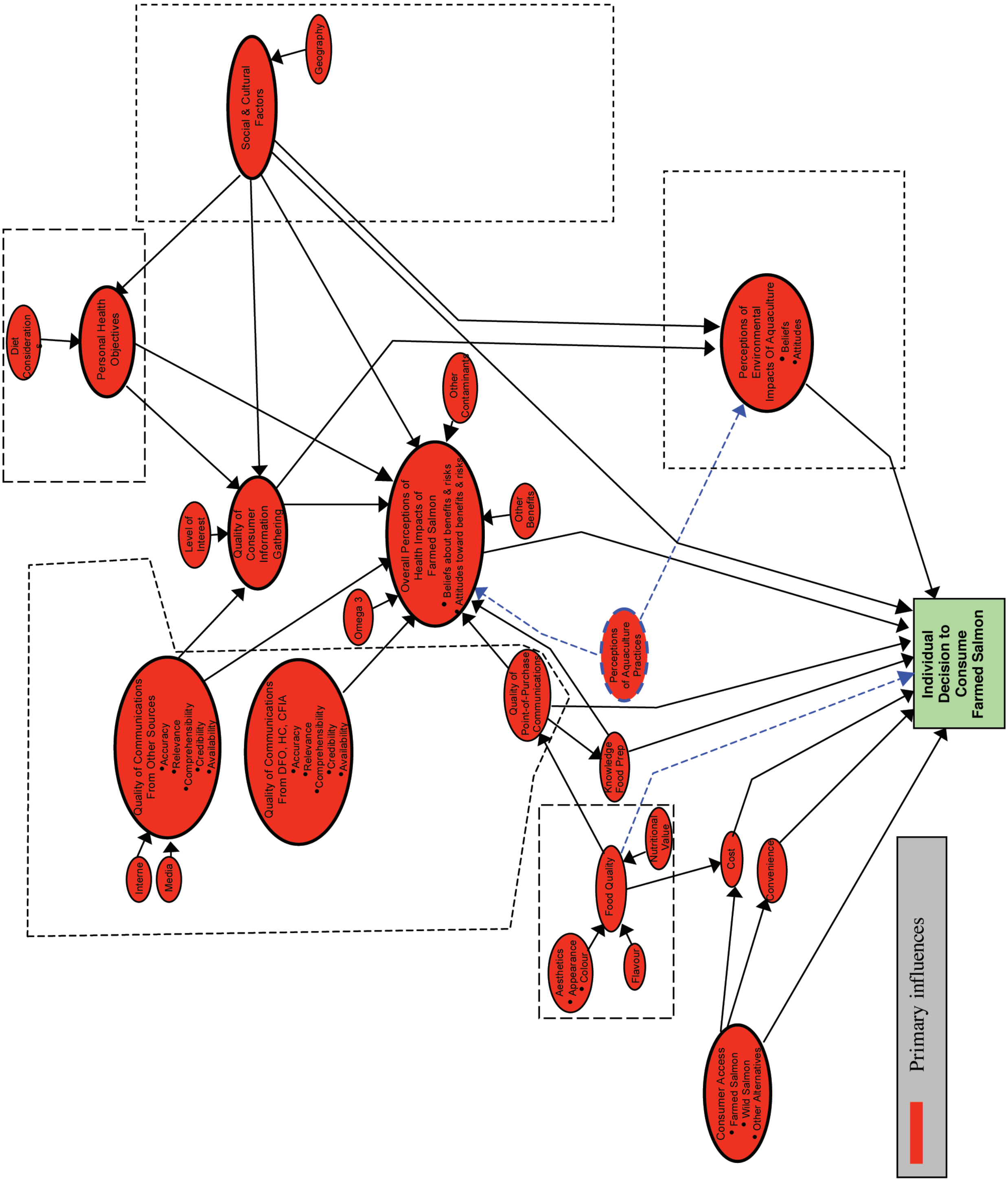


Figure 5.8b : A mental model of the primary factors influencing consumers decision to buy seafood as seen by a representative survey of the public overlaid on the expert model of figure 5.7b (DFO 2006). The colour (not the size) of each oval is proportional to the importance of the factor's influence on the factor (oval) or decision (box). The arrows indicate what decision or factor is influenced. Dashed boxes represent logical groupings of factors.



to know each other, and familiarise themselves with the positions of others. Such meetings can assist in problem formulation while also exploring the relationships among stakeholders. Subsequent meetings may be in smaller groups, on less controversial issues where consensus can easily be reached, followed by full-scale workshops with all stakeholders. At a series of smaller meetings, participants may more easily overcome any reluctance to speak out, feel more comfortable and acknowledge that they are fully recognised in the process. Such strategy can be time consuming but is indispensable. At meetings, stakeholders should be involved in communicating results. This aspect is often overlooked in consensus building.

Much published guidance is available in many languages about facilitation techniques and this should be referred to, as necessary.

5.8. Concluding remarks

Risk communication should play a key role in the decision process of any resource use development and has – in the past – been largely neglected or employed so late in the process that effective and timely progress by an industry and/or in the development of a project was impossible to achieve. Risk communication provides the fundamental basis on which all hazard identification, risk assessment procedures and project implementation steps should be based.

The examples and strategies presented in this document deal with a comprehensive and complete environmental assessment strategy that is applicable not only to coastal aquaculture but is also valid for a variety of other forms of aquaculture, addressing specific issues to demonstrate the way by which development proposals should be handled in terms of potential hazard identification, and risk assessment as well as how these are interlinked with procedures for risk communication to visualize and demonstrate the processes involved.

Based on these considerations, a number of specific case examples have been elaborated and are presented (Chapter 6) in which the incremental steps of the processes have been demonstrated. They cover:

(a) the localised effects of benthic community changes under and around fish cage farms (Chapter 6.1),

(b) the determination of site-specific carrying capacity for the development of additional shellfish raft culture and its potential interaction with already existing extensive mussel farming in the area (Chapter 6.2),

(c) the far-reaching effects of release of fish (effects of escapes from cod farming on cod populations (Chapter 6.3),

(d) considerations of long-term effects on the adjacent macro-algal communities as being potentially affected by the proposed expansion of fish cage farms (Chapter 6.4),

(e) the salinisation of farm land by low salinity shrimp culture (Chapter 6.5), and

(f) the effect of nutrient released from a fish farms on local phytoplankton (Chapter 6.6).

All these examples can be used as model cases to elaborate further the approaches taken to perform an overall Risk Assessment and to apply the results in the decision making process.

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5.10 ANNEX: Principles and Checklist for Risk Communication

5.10.1 Principles

1 Risk communication has to start at a very early date and simultaneously with the initiation of the process for hazard identification to allow a full recognition of the diverse issues that need to be addressed in the development process.

2 Risk communication should be an open, inclusive and transparent process for which the strategy should be developed as the procedures for hazard identification of a particular case evolves.

3 Risk communication methodology must assure that all results of the risk analysis procedure are communicated in formats that are clear and useful to individuals and organisations who use the information in their own decision-making process.

4 Risk communication methods should be carefully selected in light of the type of stakeholders involved and the target population to be addressed, thereby fostering effective involvement and support.

5 Risk communication may involve a step by step approach to issues, recognising that the uncertainty levels may differ between issues.

5.10.2 Checklist

1 Identify an agency or an organisation to lead the risk communication process.

2 Prepare an initial list of potential stakeholders who need to be included into the communication process right from the beginning.

3 Prepare campaigns of open-ended interviews to collect the entire spectrum of views of stakeholders (affected population) while ranking these according to perceived risks (severity, potential for mitigation).

4 Check that all needs of these stakeholders are properly conveyed to and considered by the experts when formulating an influence diagram.

5 Critically check that all risks perceived by stakeholders are expressed, and noted and fully conveyed to experts and decision-makers.

6 Collect detailed information on the key characteristics of risks of concern to the general public which might need the attention of experts and decision-makers in perfecting the influence diagram.

7 Check that both present and future risks are perceived and articulated by stakeholders and the public at large in ways that indicate an appropriate perception of these risks, and ensure that their views are fully conveyed to experts and decision makers.

8 Assure the inclusion of cost-benefit information in the communication process

9 Identify the most effective pathways of communication for each of the stakeholder groups.

10 Assure that the timetable is well prepared, indicating to whom and when information gathered in the risk identification phase, as well as the risk assessment phase, will be released.

11 Prepare and regularly update a list of priority subjects to be discussed and communicated in stakeholder group meetings.

12 Set up a list of criteria specific to each project that identifies the format in which information is released at each stage of the process in relation to (a) scale/size and extent of risks, (b) number of people affected, (c) severity (e.g catastrophic, negligible), (d) quality of scientific understanding of risks and uncertainty, (e) controllability of risks and ease of mitigation, (f) present and future risks, and (h) cost-benefits.

13 Prepare a monitoring tool to ensure that incoming results from the risk identification and risk analysis procedures are communicated adequately and in a timely manner to all participants (directly affected stakeholder, NGOs, or/and the public at large).

14 Monitor the responses from public and stakeholder groups to risk communication and pass this information on to the respective experts and decision makers.

15 Prepare a schedule for meetings between experts and stakeholders, and experts and decision makers, in line with the progress made in the risk identification and risk analysis process.

16 Develop a framework for the negotiation mechanism to be employed to bring the risk assessment to an end and transfer the project to the implementation phase.

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

Kenny Black and Chris Cromey
Scottish Association for Marine Science, Oban, Scotland. UK

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)

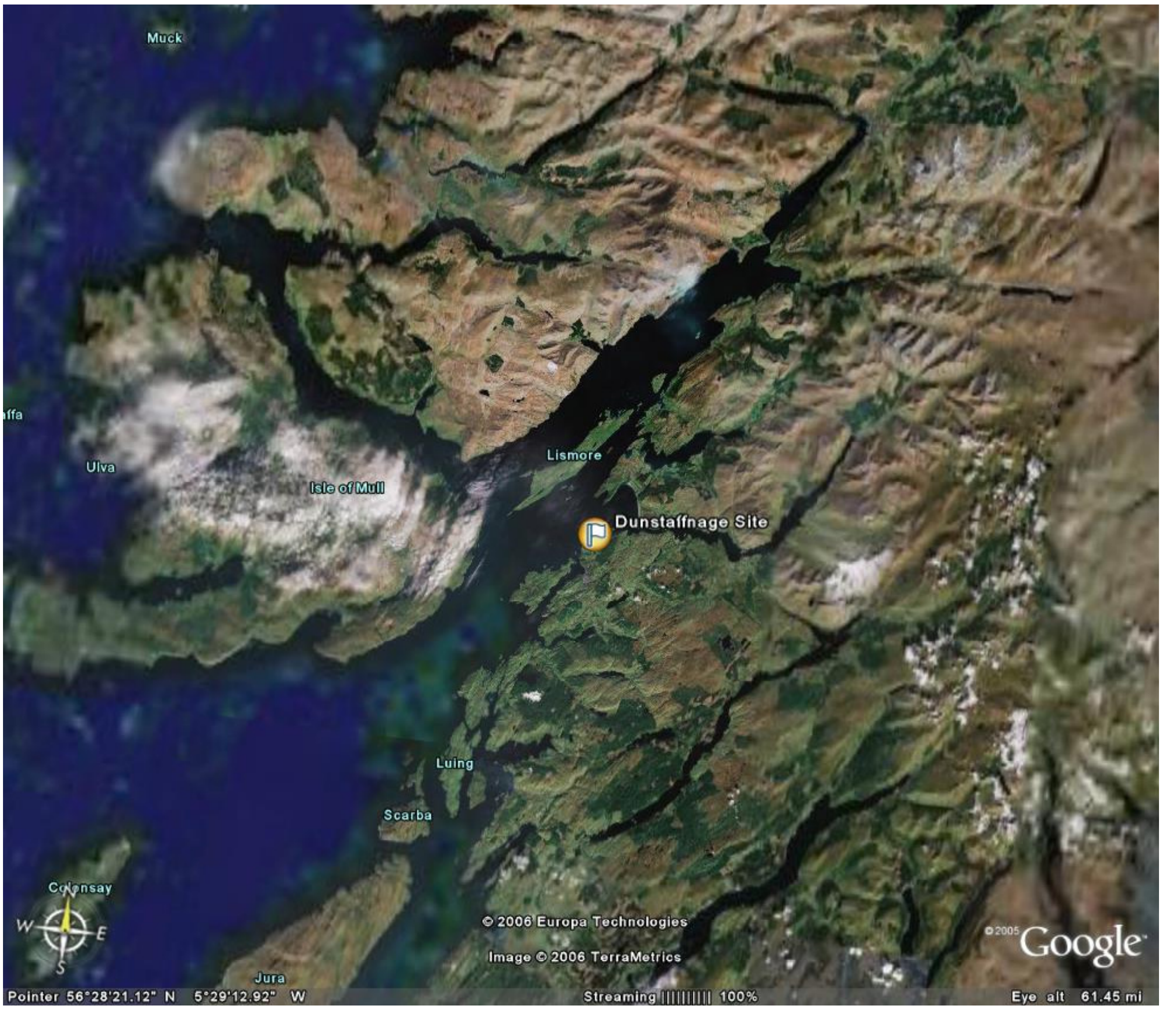


Table 6.1.I : Summary statistics for hydrographic data at the monitoring site (22 day record, 10 minute averages). (Provost, SAMS, Current Speed and Meteorological Measurements at the Dunstaffnage Fish Cage Site, Firth of Lorne, Argyll. Data Report Prepared for Scottish Sea Farms Ltd February 2006)

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

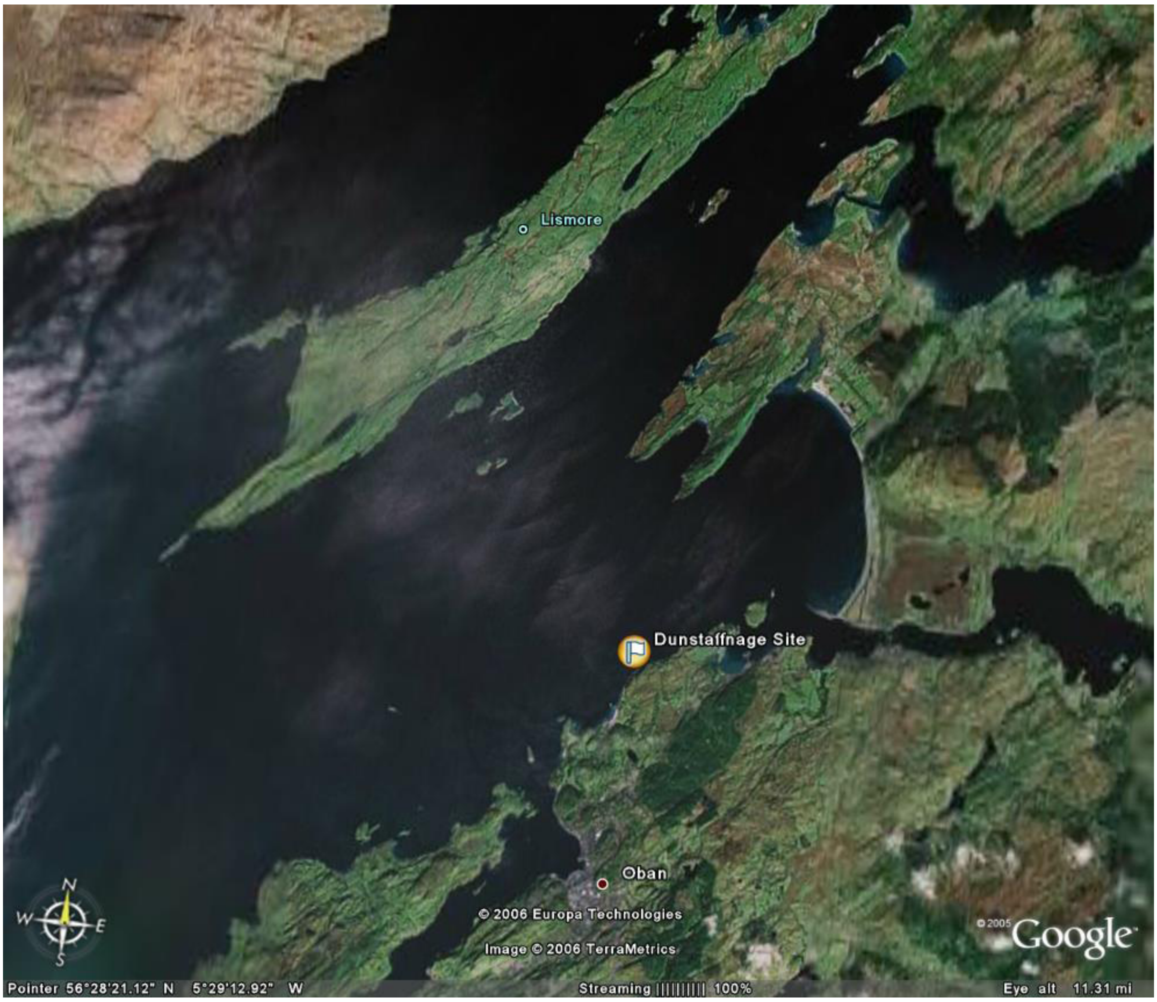


Figure 6.1.2 : The Dunstaffnage site, Oban and the mouth of Loch Etive to the East. (Google Earth)

Table 6.1.II : Summary Statistics, Benthic macrofauna (from Scottish Sea Farms, Biological Seabed Survey at Dunstaffnage, 30th June 2005, report by Hunter Biological)

	South West			North East				
				CAGE				
Distance	REF2[1]	50m	25m	EDGE	25	50	150	REF1[1]
No of Species[1]	58	33	26	8	14	13	27	17
Abundance m^{-2}	1852	1867	830	18126	9200	407	637	378
Evenness[2]	0.8	0.62	0.75	0.19	0.25	0.8	0.86	0.86
Shannon-Weiner[3]	4.7	3.1	3.5	0.6	1	2.8	4.1	3.6
ITI[4]	64	63	57	0	0	28	59	52

[1] REF2 is located 900 m SW of the cage group, REF1 880m to the NE.
[2] Total number of species from 3 pooled 0.045m^2 grabs.
[3] Species Evenness - Pielou's evenness index, j (Pielou, 1966)
[4] Shannon Weiner Diversity - Shannon-Wiener information function, H(s) (Lloyd, Zar and Karr, 1968)
[5] Infaunal Trophic Index (ITI) – defined in section 3.3

Figure 6.1.3 : Current speed (mm.s^{-1}) and water depth (m) measurements for bin 1 (3m above the bed) during the survey period at the Dunstaffnage site. (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)

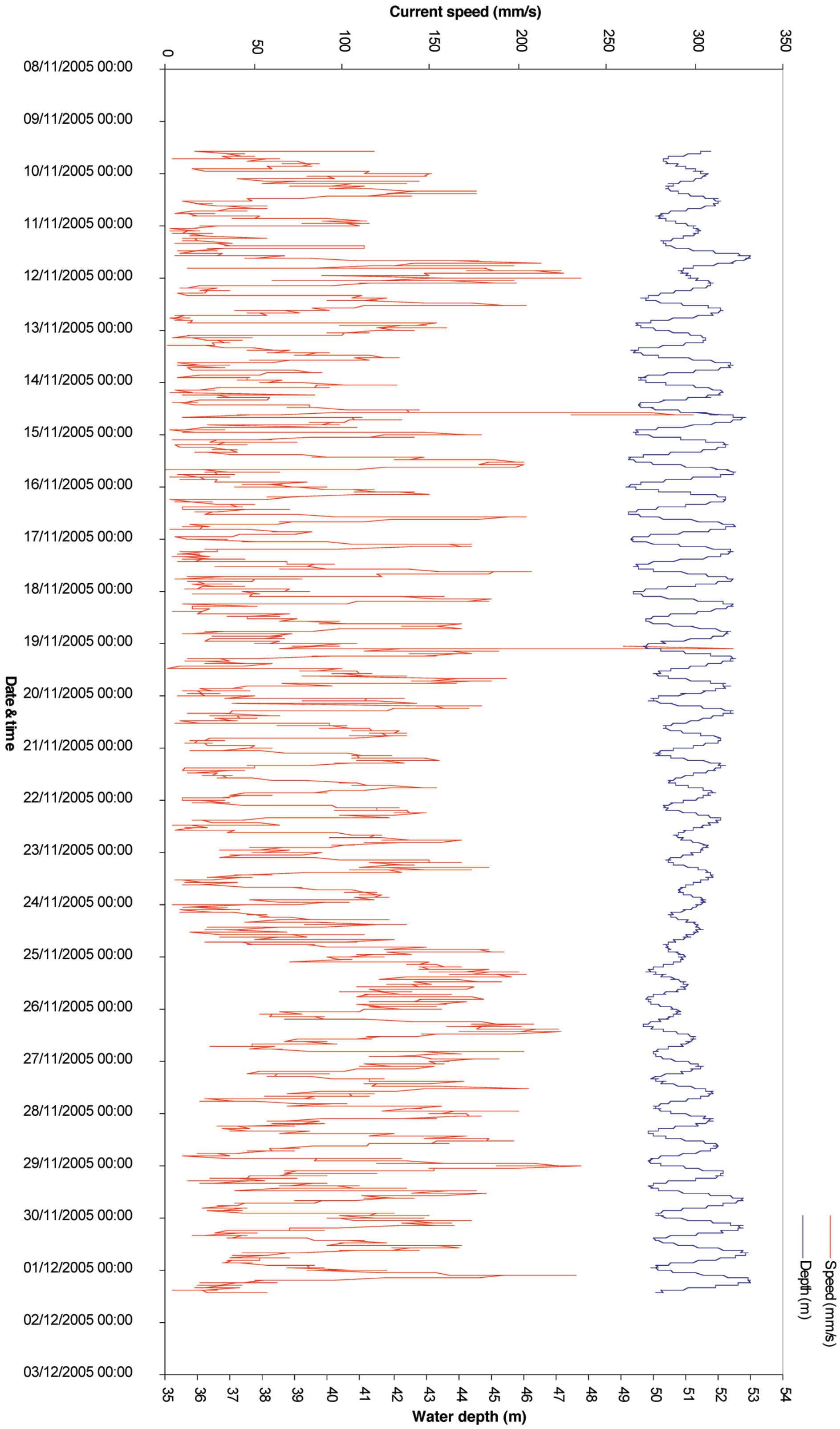


Figure 6.1.4 : Scatter plot of east and north vector components (mm.s^{-1}) measured 3 m above the bed at the Dunstaffnage site (22 day record, 10 minute averages). (Provost, SAMS, Current Speed and Meteorological Measurements at the Dunstaffnage Fish Cage Site, Firth of Lorne, Argyll. Data Report Prepared for Scottish Sea Farms Ltd February 2006)

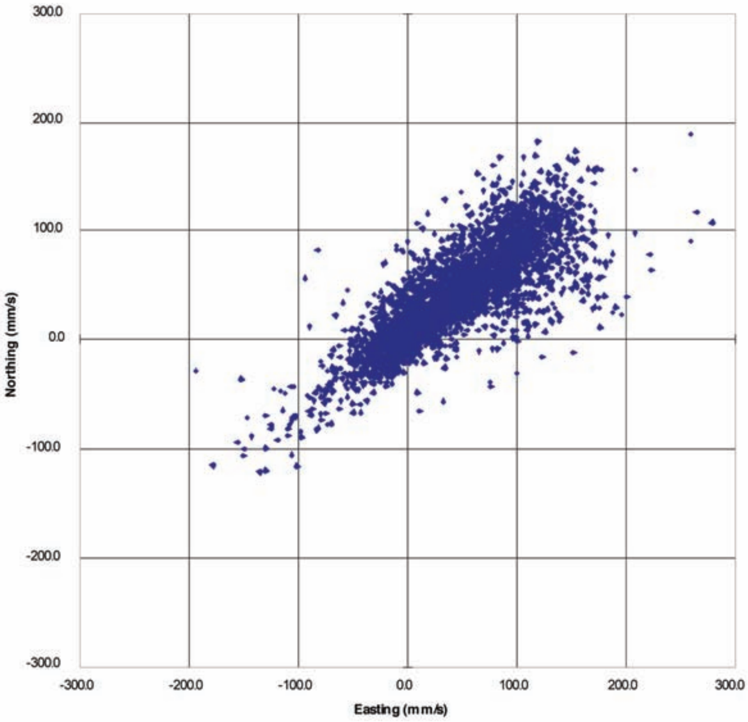
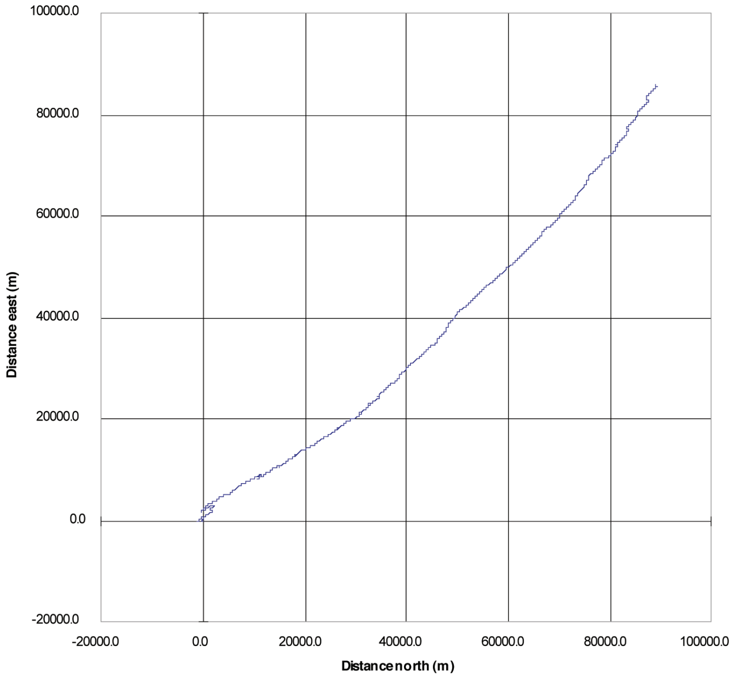


Figure 6.1.5 : Cumulative vector plot (m) for currents measured 3 m above the seabed at the Dunstaffnage site (22 day record, 10 minute averages). (Provost, SAMS, Current Speed and Meteorological Measurements at the Dunstaffnage Fish Cage Site, Firth of Lorne, Argyll. Data Report Prepared for Scottish Sea Farms Ltd February 2006)



operations such as net changing and fish transfers. Slaughtering is done by transferring live fish to a well boat and transporting them to the company's fish processing plant at South Shian on the shore of nearby Loch Creran. There the fish are pumped ashore and slaughtered under controlled conditions with full treatment of blood wastes. Thus, no blood-water is discharged either at the Dunstaffnage site or elsewhere.

6.1.3.2 Release Assessment

Fish farms release particulate organic material from three main sources:

a) wasted (for example, uneaten) feed
b) faecal material
c) detached fouling biomass

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 are typically operated to limit feed wastage 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. Thus, early estimates of feed wastage (Gowen and Bradbury 1987) of up to 20% have been superseded and current estimates are of the order of 5%. Although this value is difficult to verify, farmers have a strong interest in keeping this to a minimum, as feed is costly and farmers are often 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. At some point in the future, farms in Scotland may be consented on the basis of total feed input over the farming cycle as is common in Norway, rather than maximum allowable on-site biomass as at present – this would exert an additional pressure to reduce feed wastage. The settling velocities of a large range of different feed sizes, types and brands have been measured (Chen, Beveridge and Telfer 1999).

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 (Magill, Thetmeyer and Cromey 2006). This is not the case for detached biomass: this occurs when encrusting, fouling organisms are dislodged from cage structures and settle to the bottom. In the Scottish setting, this is likely to be a minor component of the particulate flux from farms, but the subject has received no research attention.

The maximum biomass proposed for the site is 1,300 tonnes. This will probably be attained early in the second year of each two year production cycle, and maintained at that level for the remainder of each cycle by cropping. Thus the total production from the site over a two year period will be much greater than the maximum biomass, probably of order 2,000 tonnes. If a food conversion ratio of 1.2 is assumed, then the total feed input will be 24,00 tonnes. If 5% of this is wasted and 85% of the remainder is assimilated by the fish (thus 15% are lost as faeces), then the total losses of feed and faecal material are 120 tonnes and 342 tonnes respectively.

Wild fish and scavenging epibenthos may intercept particulate material in the water column or on the seabed. This process has been shown to be important in reducing the flux of organic matter to the seabed in fish farms in the oligotrophic Mediterranean Sea (Dempster *et al*. 2004; Dempster *et al*. 2002; Machias *et al*. 2004; Tuya *et al*. 2006) but there has been no attempt to quantify this aspect in Scotland, although it is known to occur (Carss 1990). In the absence of hard evidence, we assume that this is a less important process in mesotrophic Scottish waters.

6.1.3.3 Exposure Assessment

Organic particulate material settling from fish cages intersects the seabed. It either stays where it lands and degrades, or it is resuspended and is advected, possibly outside the farm area. The critical resuspension velocity has been estimated at about 9 cms^{-1} and verified in a specifically designed resuspension tracer study in fish farm sediments (Cromey *et al.* 2002b). At the site considered here, near-bed currents are regularly higher than this and it is likely that considerable amounts of the vertical flux will be transported away from the farm. This is in accord with estimates by Strain and Hargrave (Strain and Hargrave 2005) where, at a more 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) and a DEPOMOD output for the present site (Figure 6.1.6) shows that significant sedimentation rates will be confined to a relatively small area around the farm.

The duration of effect is an important aspect of risk analysis. There have been several previous UK investigations into the recovery of the benthos after the cessation of fish farming. The first, a three year study completed in November 1995 (Nickell *et al*. 1995; 1998), considered benthic recovery at three sites and concluded that a numerical model which could be used to manage rotation of fish farm sites was not possible 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 was shown that recovery was a complex process where dominant associated environmental drivers changed with different sites and seasons.

The second study (Pereira *et al*. 2004) of benthic recovery at a Scottish salmon farm was of a shorter (15 month) duration and, at the most impacted

Figure 6.1.6 : A DEPOMOD output showing predicted solids accumulation rate on the seabed at the increased tonnage (1300 mt) for the Dunstaffnage site (g m-2 yr-1) AMSL (2006)

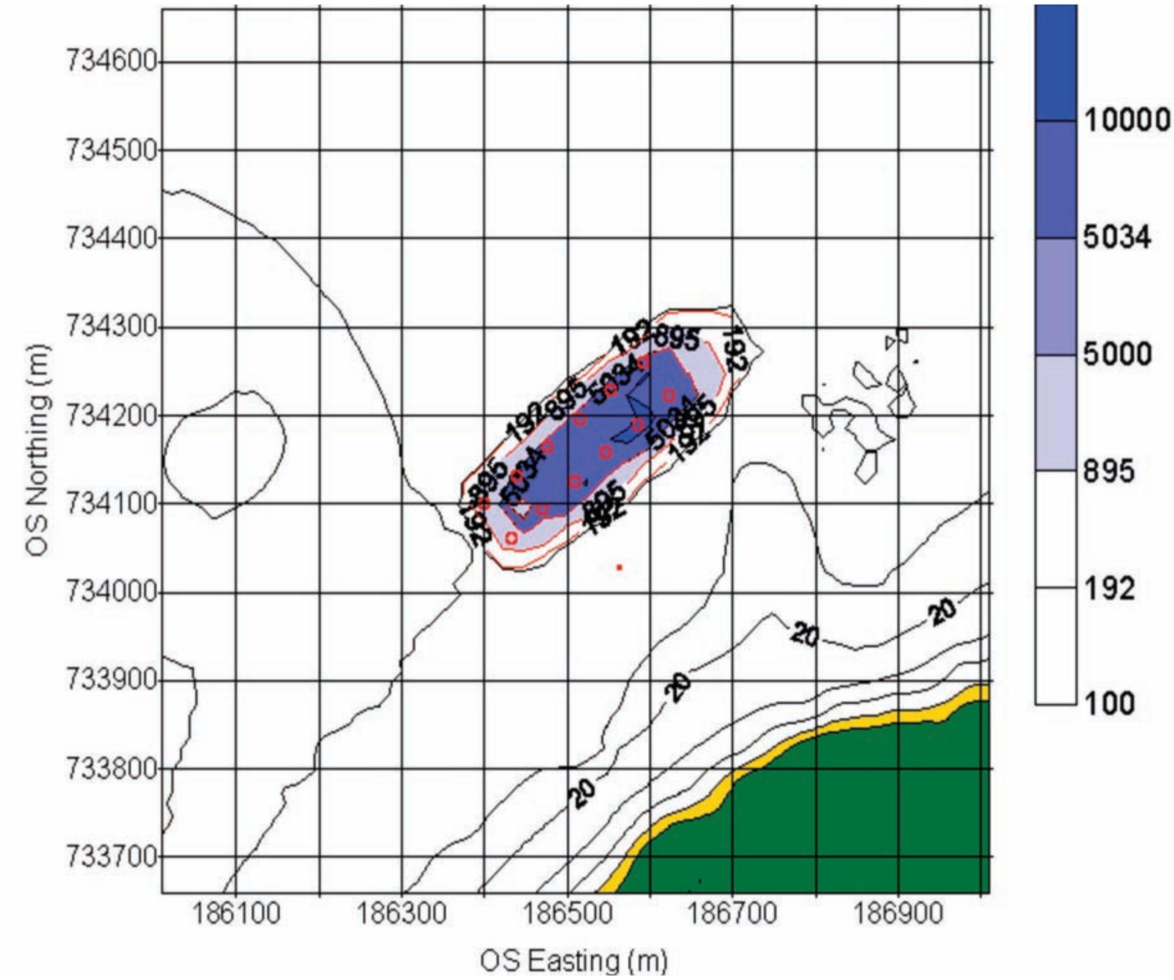
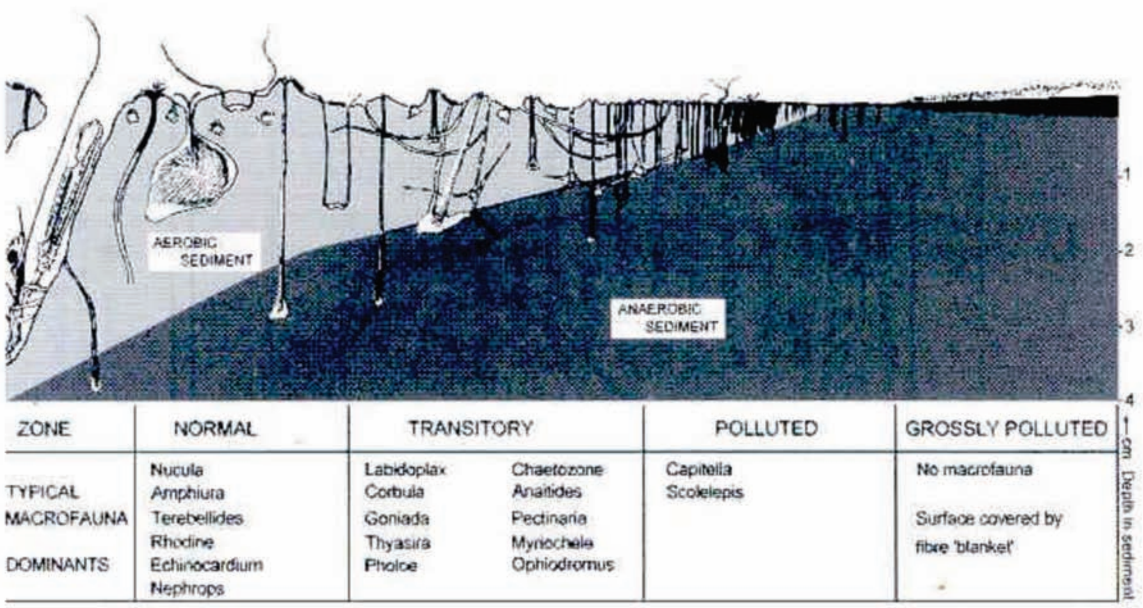


Figure 6.1.7 : Infaunal succession on an organic enrichment gradient (Pearson and Rosenberg, 1978)



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).

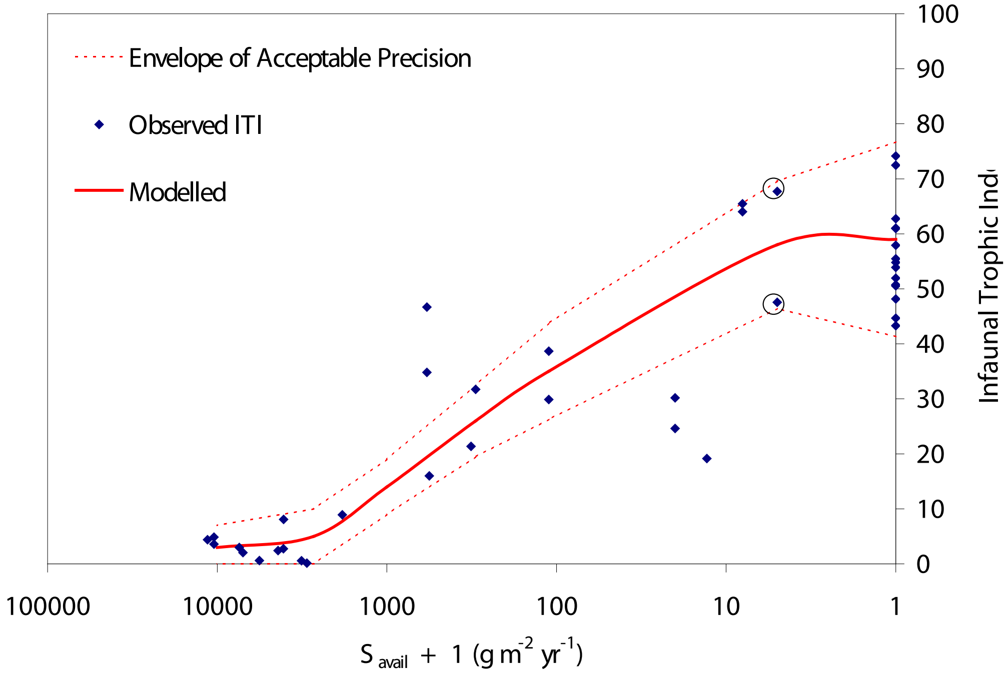
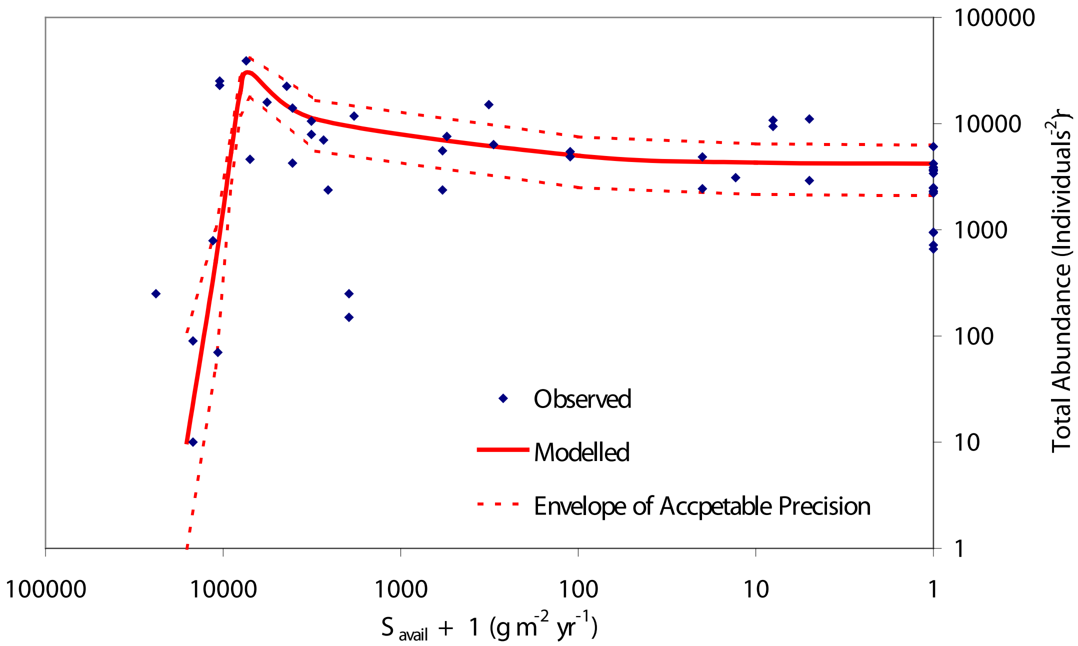


Figure 6.1.9 : Modelled solids accumulation (S_{avail}) plotted against observed total abundance. Envelope of Acceptable Precision (EAP) is shown by the dashed line (68% in EAP, n=50).



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.

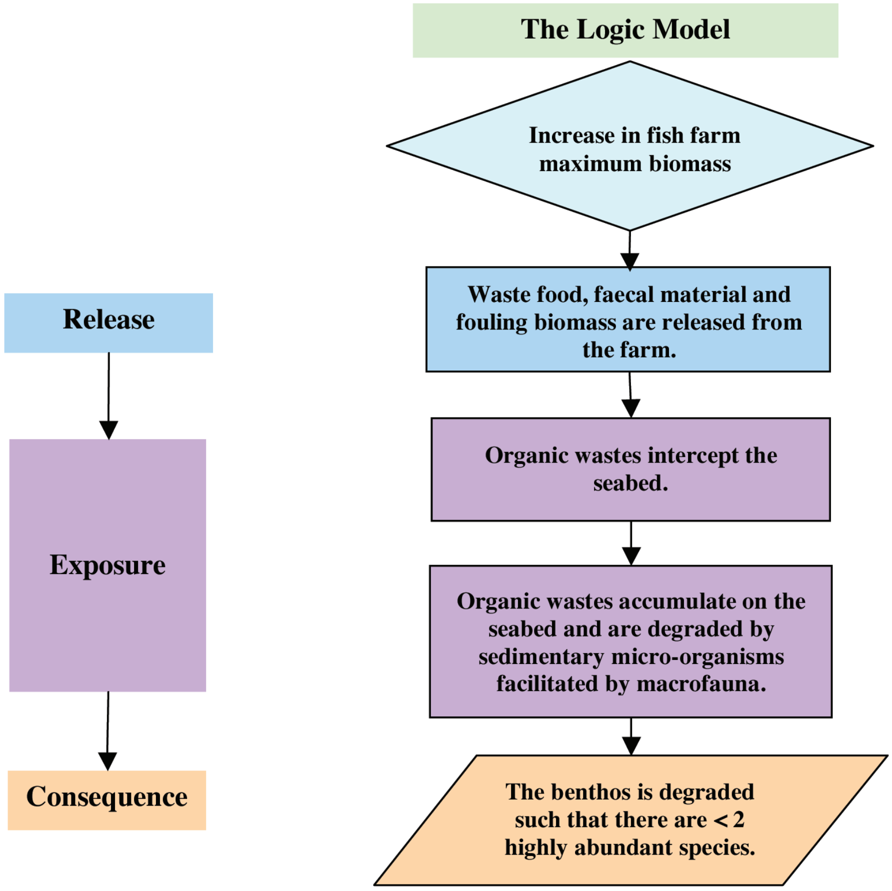
ii. Organic wastes intercept the seabed

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 bevhaviours

- *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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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

CASE STUDY 6.2

RISK ASSESSMENT OF THE POTENTIAL DECREASE OF CARRYING CAPACITY BY SHELLFISH FARMING

C. Bacher[1] and E. Black[2]
[1] Manager of IFREMER Program on Dynamics and Health of Coastal and Estuarine Ecosystems, Brest, France
[2] Senior Aquaculture Advisor, DFO Aquaculture Sciences Branch, Ottawa, Canada

6.2.1 Introduction

This case study considers whether the introduction of a new shellfish farm to a coastal embayment in France would reduce the overall shellfish production in the area. In several areas of France the introduction of new shellfish farming activity is suspected to have affected potential shellfish production, as well as ecosystem productivity and function. Scientists are being asked increasingly frequently to assist regulators in defining appropriate rules to manage the development of coastal aquaculture (Goulletquer and Le Moine 2002). The expansion of mussel aquaculture in Pertuis Breton is used as an example of the assessment of potential loss of productivity in aquaculture areas due to different types of interactions.

6.2.2 Hazard identification

6.2.2.1. Pertuis Breton case study

France has been at the forefront of coastal shellfish aquaculture for more than a century. The possibility of exceeding the carrying capacity of an embayment is a common concern, and examples can be found of how carrying capacity can be managed. France is one of the leading countries in Europe for shellfish production, with an annual harvest of more than 150 000 tonnes of the Pacific oyster (*Crassostrea gigas*) and 60 000 tonnes of mussels (*Mytilus edulis* and *M. galloprovincialis*) (Goulletquer and Le Moine 2002). The Pertuis Charentais ranks first among French shellfish rearing areas, with an annual production of 40 000 tonnes and 15 000 tonnes of oysters and mussels respectively, and standing stock estimated in 2001 at 125 000 tonnes of oysters and 13 000 tonnes of mussels (Figure 6.2.1). This biomass is held on 4 000 ha of leased intertidal areas and 3 000 ha of oyster ponds, which are environmentally sensitive and subject to many recent regulations. Pertuis Charentais is divided into two bays: Pertuis Breton, where most of the mussel culture takes place, and Marennes-Oléron Bay, which is occupied by the major part of the oyster cultivation.

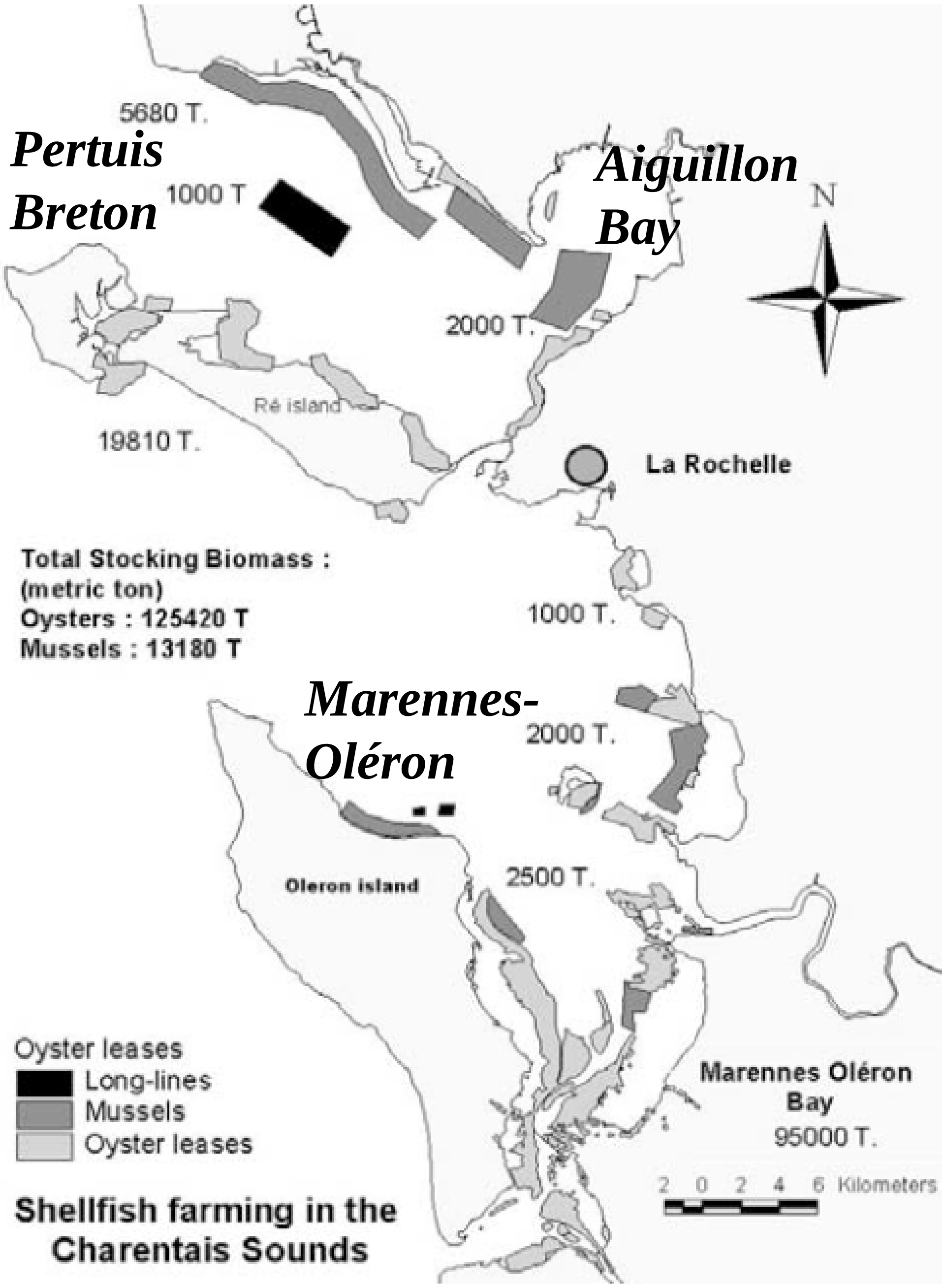
Pertuis Breton is the most important site for mussel culture in France. It is located in a macrotidal estuary of 350 km² with freshwater inputs of up to 100 $m^3.s^{-1}$ in winter, derived from two rivers (Garen *et al.* 2004). With an average depth of less than 10 m, the hydrodynamics of this water body is driven by tidal exchange and influenced by west winds. Its eastern part is covered by large intertidal mudflats accounting for one fifth of the total area. The mudflat substrate is very fine sediment that can be easily resuspended in water and generates high turbidity levels.

Blue mussels (*Mytilus edulis L.*) have been cultivated in the Pertuis Breton area since the 13th century. Mussels are traditionally grown on bouchot, which are rows of wooden poles placed perpendicularly to the shore, anchored in the sandy mud substratum beneath the surficial soft sediment layer. Mussels are collected either as seed attached on collecting ropes, or as juveniles placed in net socks, and then wound around the 2 m poles where they fatten and grow to marketable size within two years. About 337 km of bouchot are used along the Pertuis Breton shoreline.

Environmental constraints limit the potential for new sites or new culture practices. There is no more available space in the intertidal areas to set up bouchot. Long-line culture has been developed as an alternative to the traditional 'bouchot' method (Goulletquer and Héral 1997) of rearing mussels. In contrast, long lines can be used in the central region of the bay, where the hydrodynamics are strong and the primary production high enough to support mussel growth (Garen *et al.* 2004). For technical reasons (for example, accessibility of long-lines to boats, intensity of currents, weight of mussels and ropes), ropes must be separated by a few meters and the mussel density in long-line areas is less than in bouchot culture. As a consequence, one advantage of the long-line technique is that there are large amounts of space available for this culture technique, relative to that available for bouchot. Another advantage is in environmental conditions. Lower concentrations of inorganic particulate matter, and the continuous immersion time of mussels on longlines are more favourable to bivalve growth. Suspended culture on sub-surface long lines began in 1991 to enhance the overall production of mussels in the area and improve mussel spatfall. Two hundred and forty lines of 100 m, each carrying a 4 m mussel rope every 1.2 m, were set up in a 400 ha zone. That now accounts for about 10% of mussel production in the Pertuis Breton.

There is good reason to believe that bivalve culture could affect the carrying capacity of the environment for shellfish production. Héral (1993) established that overstocking was probably responsible for the decrease in growth of oysters in Marennes-Oéron bay. Fréchette *et al.* (2005) and Fréchette and Bacher (1998) have emphasized the role of intraspecific interactions in setting limits on mussel growth. High densities of shellfish in cultiva-

Figure 6.2.1 : Cultivation areas for oysters and mussels in Pertuis Charentais (from Goulletquer and Le Moine 2002).



tion are also likely to affect the size distribution within a culture unit (for example, rope).

These examples suggest that the introduction or extension of shellfish farming activity may result in changes at a local or ecosystem scale. There is therefore good reason for concern among farmers about the optimisation of mussel cultivation in Pertuis Breton, and a desire to locate new farming activities in a manner that will minimise the interactions with existing enterprises. A proposed expansion of farming activities in a new long-line area in the centre of Pertuis Breton is the scenario underlying this risk assessment of the interactions between and within the different farm areas. It is used to identify the underlying processes that might lead to specific types of environmental change and estimate the risk associated to them. In keeping with the definitions given by Inglis *et al*. (2000), the environmental change of concern is that of alteration (reduction) in the "Production Carrying Capacity". An analysis of "Production Carrying Capacity" aims at assessing the stocking density of bivalves at which harvests are maximised. It requires assessment of the available food supply, how it is used by shellfish and how rearing density and cultivation technique can affect food availability and shellfish growth. Below, we review some ways by which aquaculture may affect that productivity.

6.2.2.2 Effects at a local scale

In a survey of mussel growth in one site in Ireland, Karayucel and Karayucel (2000) found differences in the growth rate of mussel that was dependant on the position of the mussels within a raft. Local competition for food resources is the likely cause. Causation is not so obvious in some other studies on rafts, since food depletion arising from shellfish filter feeding depends on a range of factors – for example, current velocity, food concentration and shellfish density.

Several models of shellfish behaviour address seston depletion within the benthic boundary layer with application to bottom culture of shellfish, or to benthic bivalve populations (Campbell and Newell 1998; Newell and Shumway 1993; Roegner 1998; Verhagen 1982; Butman *et al.* 1994; Wildish and Kristmanson 1997). There is little bottom culture in France and it is not a significant production method in the area under consideration. Other studies of interest deal with cultivated species on rafts or long-lines (Rosenberg and Loo 1983; Bacher *et al.* 1997; Heasman *et al.* 1998; Pouvreau *et al.* 2000; Pilditch *et al.* 2001; Bacher *et al.* 2003). All studies stress that food depletion may limit production. However, the degree of limitation depends on the nature of the shellfish population (for example, benthic, or suspended), and on the current velocity, density and size of the stock.

Bacher *et al.* (2003) predicted food depletion as a function of hydrodynamical conditions and established a relationship between current velocity and annual growth of scallop. Strohmeier *et al.* (2005) recently measured depletion of phytoplankton within mussel long-lines in an oligotrophic Norwegian fjord. Similarly, evidence of food depletion was demonstrated by Richardson and Newell (2002) on the western shore of Canada in a study of the carrying capacity of Gorge Harbour for oyster cultivation. A reduction of phytoplankton concentrations within the oyster rafts was measured in relation to the grazing capacity of oysters. The average reduction in phytoplankton concentration was used to estimate the demand of the oyster rafts, and this information was used to estimate carrying capacity at the scale of oyster rafts. In suspended cultures, filter feeder densities range between 2 and 700 g DW m^{-3} (DW: dry tissue weight) and current velocities varies from less than 1 cms^{-1} to 35 cms^{-1}. Food depletion only appears likely to occur at spatial scales over a few kilometers when density is low or current velocity is high (Bacher *et al.* 2003; Newell and Shumway 1993).

Bacher *et al.* (2003) combined an ecophysiological model of *M. edulis* and a box model to simulate growth of mussels reared on long lines. From the model, they developed advice on the appropriate size and density of mussels for the cultivation area. Food transport in the long line area was computed using outputs from a hydrodynamical model. Simulations were carried out for different mussel densities and lease sizes to assess their effects on mussel growth. They demonstrated that actual mussel density and lease size had a minor effect on flows of particulate organic matter and phytoplankton, and would not decrease the food concentration available to other cultivated areas. If lease size and mussel density were increased, they would have a minor effect on mussel growth. Based on these simulations, a threefold increase in either mussel density or lease size would be a safe recommendation for managers willing to increase mussel production without having deleterious effect on growth.

In a very new study, Gibbs (2007) defined an indicator based on depletion of chlorophyll-a concentration in a cultivation area. He gave an example of mapping chlorophyll-a concentration and estimated the footprint of the cultivated area. Estimating the area experiencing a given percentage decrease in chlorophyll-a concentration was used as an indicator of acceptable effect.

In another study, emphasis was put on the importance for food availability of water mixing and hydrodynamics at the scale of estuaries and bays for food availability. A simplified method was used by Guyondet *et al.* (2005) to assess the risk of oyster food limitation in part of the Richibucto estuary and to evaluate the importance of water renewal. A 3D hydrodynamic model was first used to characterise the physical environment in the study area, under different forcing conditions. The corresponding water renewal times were then used in a comparison of bulk parameters defining food supply and demand by oysters and to assess the sensitivity of the depletion index method to the prescribed renewal times. Comparison of depletion indices corresponding to different oyster densities showed that this density could be increased to a certain extent without causing a major risk of food depletion.

Currents patterns can be modified by cages, long-lines or rafts (Grant and Bacher 2001; Boyd and Heasman 1998; Plew *et al.* 2006; Smith *et al.* 2006) with consequent effects on carrying capacity. Aure *et al.* (2007) presented a carrying capacity model with emphasis on flow reduction as a function of farm design. The results showed that the carrying capacity of farms with a given surface area is dependent on the length of the farm,space, the distance between long-lines, seston concentration and background current speed. Reducing the length of the farm and increasing the distance between long-lines would therefore increase the carrying capacity. The authors emphasised the relationship between stocking density and food supply as a key indicator for site selection. Moving a farm to a site with higher background current speeds or seston concentrations would also affect mussel growth. In another study, Richardson and Newell (2002) measured and simulated current velocity in the vicinity of the oyster culture rafts in order to estimate the average amount of water passing through a raft. They found that flow slowed as it passed through the rafts and accelerated beneath and to either side of the rafts. The accelerated flow beneath the rafts brings phytoplankton from deeper waters to the surface in the wake of the rafts. In general, flow velocities within the aquaculture rafts were found to be about 10 times less than flow speeds measured around the periphery of the rafts. In combination with calculation of food depletion due to filtration by oysters, Richardson and Newell (2002) expressed the carrying capacity as a number of rafts which could be supported. The calculation was based on a few data and steps that could be repeated in other cases. The number of rafts was estimated by the balance between the consumption and production of phytoplankton, in a way different to that of Karayucel and Karayucel (2000), which was derived from Carver and Mallet (1990) and Incze (1980).

Survival of shellfish can also be affected by local conditions. Using self-thinning concepts, Fréchette *et al.* (2005) have emphasised the role of intraspecific interactions in growth limitation. High rearing density is likely to affect the size distribution within a culture unit - for example, rope. The density of shellfish would therefore be decreased, as would the growth (Lauzon-Guay *et al.* 2005).

6.2.2.3 Food limitation at the ecosystem scale

Smaal *et al.* (1998) stressed the importance of space and food availability for the carrying capacity of bays and estuaries. Carrying capacity estimates at the ecosystem scale require information on primary production of the system as well as the rate of water exchange with adjacent ecosystems. This contrasts with evaluation of cultivation sites and estimates of optimum densities within cultivation sites which require a much greater emphasis on information about local physical factors.

The relationship between the production and standing stock of oysters in Marennes-Oléron Bay (France) was outlined by Heral (1993), who showed that the production is below its maximum value by using an empirical model based on mortality, growth, production and stock time series. Heral (1993) found that the maximum annual production of the Marennes-Oleron Bay was around 40 000 metric tonnes fresh weight (FW) and that the production is more or less stable above 100 000 metric tonnes FW standing stock. These two values indicate the carrying capacity of the bay and it is assumed that it is governed by the food limitation. This is a restricted assessment of the carrying capacity concept (for a review *see* Kashiwai, 1995), but it is appropriate for ecosystems supporting cultured filter-feeders where typical features such as food limitation, artificial seeding, rearing time and marketable weight have to be considered in the carrying capacity assessment.

In this context, the need to understand the link between the environmental conditions and the growth of filter-feeders cannot be avoided. Dame (1993) emphasised coupling between particle transport, ecophysiology and primary production as a way to understand the relationship between the filter-feeders and their environment in coastal areas. In his scheme, food sources (phytoplankton, detritus) and trophic interactions with filter-feeders are key to the assessment of the growth of filter-feeders and effects on the environment, and motivated a great deal of ecophysiological studies. Ecophysiological studies have been developing for the last 10 years and ecophysiological models have been published recently by Van Haren and Kooijman (1993), Scholten and Smaal (1998), Grant and Bacher (1998), Casas and Bacher (2006) for *Mytilus edulis*, Powell *et al.* (1992) for *Crassostrea virginica* and Raillard *et al.* (1993), Barille *et al.* (1997), Pouvreau *et al.* (2006) for *Crassostrea gigas*. These mechanistic models generally describe and quantify physiological processes which control energy gain and loss, and result in the growth of individual shellfish. The physiological processes are driven by temperature, food concentration (particulate organic matter, phytoplankton) and total suspended matter concentration, which includes organic and inorganic particles and acts on the ability of the individual to ingest or to reject a fraction of the available food as pseudo-faeces.

Not all the available food can be used by the filter-feeders. A fraction is rejected without ingestion because of the high particle concentration in the water. Another fraction of the ingested part is not assimilated, due to short gut passage time. Tidal currents, river flows or the geographical situation of the filter-feeders may also result in a low percentage of food utilisation by the filter-feeder populations. The food sources and their dynamics are, therefore, of primary interest in carrying capacity assessment. Most of the ecosystem models focusing on food-limited growth of filter-feeders include a water transport and mixing submodel, primary production and ecophysiological submodels (Grant *et al.* 2007; Herman 1993; Raillard and Menesguen 1994; Powell *et al.* 1994; Gerritsen *et al.* 1994; Bacher *et al.* 1998; Duarte *et al.* 2003).

The other component often considered in such models deals with the population dynamics of filter-feeders. Powell *et al.* (1992, 1994) used a simple equation based on individual growth rates, mortality and recruitment to represent the temporal variation of cohorts in harvested oyster populations. Gangnery *et al.* (2004a,b) and Bacher and Gangnery (2006) estimated oyster and mussel production using two different modelling approaches to population dynamics. The above description is still valid for those species which are the concern of carrying capacity studies, since the production is the product of the individual weights after a given amount of time (rearing time) and the number of survivals.

6.2.2.4 Logic model and endpoints

From the review above, it is apparent that the most important process to be taken into account is the potential reduction in food availability arising from the filtration activity of the proposed additional shellfish population and the consequent effects of food limitation on growth and mortality at local and wider scales – for example, within farmed areas and between areas in the bay. The risk assessment therefore addresses the adequacy of the food supply and how food use by shellfish can be modified by rearing density and cultivation technique. The endpoint will be the production carrying capacity measured by a combination of indicators of individual growth rate and survival. The hazard agent is the extraction of food due to filtration activity introduced by the new farm. We will first consider how and where this introduction occurs (release assessment). The next step is to assess how farming activity can be exposed to the hazard (exposure assessment) and then to analyse the processes which may modify and alter carrying capacity at various scales (consequence assessment). The effect on carrying capacity will be characterised through the estimation of the severity and probability of the effect occurring and uncertainty associated with the predicted probability. The consequences for the proposed aquaculture extension will be estimated from the characteristics of the ecosystem, the amount of shellfish being added to the system and aquaculture technique (Figure 6.2.2). We assume that, if this type of risk is low, there will be an even lower risk of other types of effect, for example, other processes are unlikely to be significantly affected. Similarly, if the impact on mussel growth and survival within the farm is non-detectable, we assume that the effect on the surrounding environment would be negligible and reversible – for example, any effect would be expected to disappear almost immediately after the removal of the farm.

6.2.3 Risk Assessment

6.2.3.1 Release assessment

Since the hazard agent being ‘released’ is the filtration pressure (extraction of food particles) arising from the bivalves, we first calculate the amount of water pumped by the mussels every day inside the long-line area. Considering the number and length of ropes (Figure 6.2.3), the number of mussels was estimated at about 240 million. If we assume that each adult mussel filters around 3 lh^{-1}, the total volume of water pumped by the actual standing stock is about 17 10^6 m^3 per day and results in a filtration time of 1.4 days. This average value will vary with environment fluctuations and mussel weight changes. Environmental parameters and mussel growth have been monitored over one year and ecophysiological experiments were conducted to assess the availability of food and its use by the mussels. Measurements of the concentrations of Total Particulate Matter (TPM), Particulate Organic Matter, and Chlorophyll-a in the long-line and the bouchot areas showed that trophic conditions in bouchot and long-line sites were different (Garen *et al.* 2004). Chlorophyll-a varied between 1 and 11 gl^{-1} with higher values being found in the bouchot areas than at the long lines, and mean values of 2.0 and 3.2 gl-1 at the two study sites. TPM was also higher in bouchot areas, and values lay between 5 and 50 mgl^{-1}. Average values were 13.1 mg l^{-1} in the long line area and 23.1 mg l^{-1} in the bouchot. Temperature varied between 5°C (December) and 22°C (August). Mussel growth showed very similar pattern in bouchot and long lines (Figure 6.2.4), but was lower in bouchot. Dry weights increased from March until September and decreased slightly thereafter. Maximum mean dry weights were 1.3 g in long lines and 0.8 g in bouchot and the final dry weights were 0.7 g and 0.4 g respectively. Shell weights increased during spring and summer and varied only slightly during the rest of the study period. Final shell weights were 4.7 g in long lines and 3 g in bouchot.

An ecophysiological model derived from Grant and Bacher (1998) was applied to calculate physiological responses to temperature, particulate organic matter, phytoplankton and total suspended matter concentration. Such processes have been studied in detail through experiments and ecophysiological models have been recently published for *M. edulis* including more or less detail of the fundamental underlying processes (Ross and Nisbet 1990; Scholten and Smaal 1998; Grant and Bacher 1998; Casas and Bacher 2006). In the model by Grant and Bacher (1998) for instance, clearance rate (l h^{-1}) of particles is a declining function of TPM. Phytoplankton and POC are both cleared at the same rate, and the proportion of the ingested mass rejected as pseudo-faeces in relation to turbidity is parameterised using a step function: no rejection at 0–5 mg l^{-1}, 20% rejection at the pseudo-faeces threshold up to 10 mg l^{-1}, 40% rejection from 10–40 mg l^{-1}, and peak rejection (85% of ingesta) beyond 40 mg l^{-1}. Phytoplankton is selected preferentially to detritus. In terms of ingestion, phytoplankton and POC are maintained as separate quantities, each with a defined absorption efficiency (AE), and absorption rates are summed to calculate total absorption. Phytoplankton AE is assumed to be 80% and the AE for detrital POC is set at 40%. In contrast to other models that use gut capacity and gut passage time to limit ingestion (Scholten and Smaal 1998), daily ingestion can not be higher than a constant value defined as the maximum daily ingestion. Net energy balance is determined as the difference between rates of assimilation and respiration, and allocated to somatic tissue and shell, which allows the computation of individual growth rate. One consequence of these calculations was that the effective amount of phytoplankton removed from the water column was about 30% of the filtered material initially estimated above.

6.2.3.2 Exposure assessment

In making assessments of carrying capacity, current velocity, primary production and filtration by cultivated shellfish can be combined to estimate food availability and individual growth (Smaal *et al.* 1998). On the local scale, food concentration, current velocity and filtra-

Figure 6.2.2 : Logical model of the risk assessment procedure, considering the process of filtration by the mussels as the hazard agent. Endpoints are mortality and growth within the new farm area in the centre of Pertuis Breton and the growth in other areas distant from this new area. Boxes refer to processes which are assessed at different steps connected with causal links shown by the arrows.

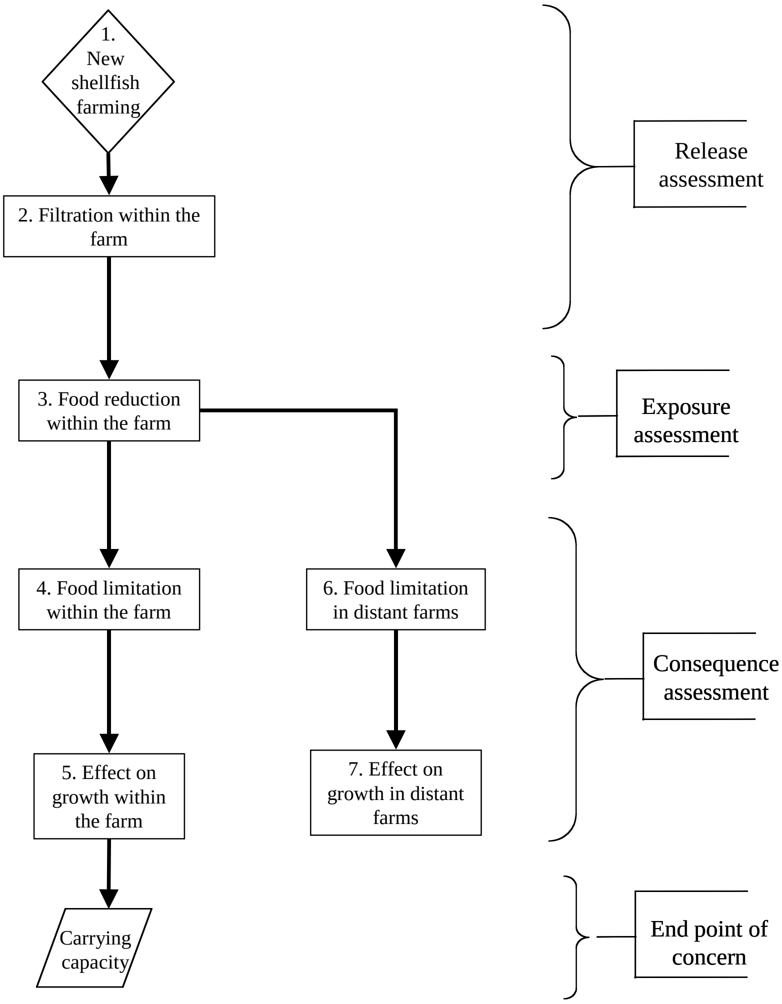
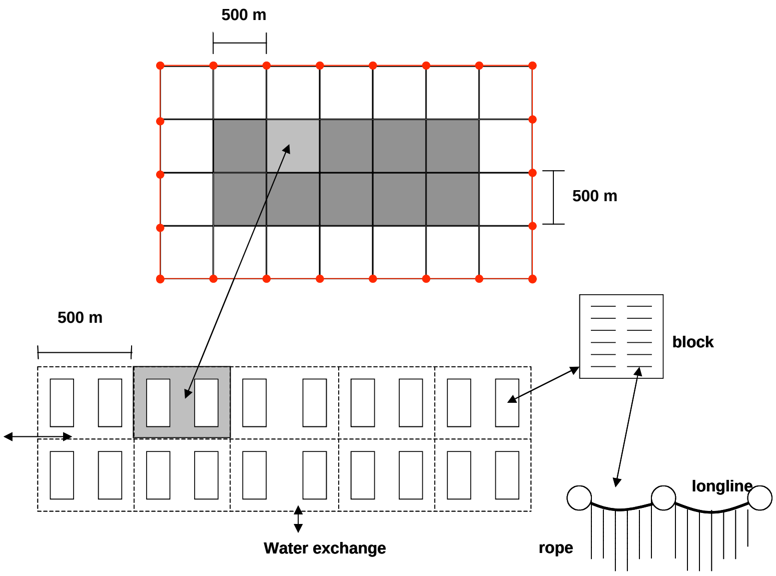


Figure 6.2.3 : Structure of the mussel farm in the center of the Pertuis Breton.



tion rate can limit food availability (Bacher *et al.* 2003). However, all these factors depend on the characteristics of the cultivation site and the species.

In Pertuis Breton, the current velocity field was estimated using a hydrodynamic model (Struski 2005) which predicts water height and current velocity. Water height and tidal currents were simulated for for one complete spring-neap tidal cycle. Maximum current velocity was mapped from this single simulation and showed that the long lines were located in a region of strong water exchange, with maximum current velocities over 1 ms^{-1}. The current velocity was primarily dependent on the tidal coefficient, and maximum tidal currents varied between 0.5 and 1 ms^{-1}. In the long line area, the current direction lie along a northwest/southeast axis and intensive exchange of water occurs at Pertuis Breton straight (Figure 6.2.5). Particle trajectories were computed for one tidal cycle during spring tide using current velocity field derived from the hydrodynamic model. They show that particles coming from the inner part of the bay (Aiguillon bay) exit through Pertuis Breton strait in the west or through La Pallice strait in the south. Trajectories also show that tidal excursion is almost 10 km which supports the suggestion of strong water mixing in the inner part of the bay and thereby probably minimises food depletion. In contrast, in areas with less strong mixing (Bacher *et al.* 2003), particles retained by shellfish in the central part of the bay are available for mussels on bouchot for longer periods of time.

Even though the filtration rate of mussels is affected by a range of factors (for example, temperature, food concentration, individual size and physiology) and on the particular stage of the lifecycle of the bivalve, the high value calculated for the new farm suggests that the exposure must be considered at two different scales; locally within the new cultivation area, and globally by assessing the effect of long-lines on bouchot areas.

A box model was developed to account for competition for food within the long-line areas and to assess whether the farm size and mussel density would affect the carrying capacity. The model couples food transport, food consumption by the mussel population and mussel growth at the scale of a cultivation area. The approach is the same as that used by Bacher *et al.* (2003) except that we assumed that food and particulate matter concentrations were homogeneous within the cultivated area, which was represented as a single box. The transport equation is a mass balance equation that accounts for i) the exchange of water between the box and areas outside the cultivated area (Bacher 1989; Raillard et al. 1994 ; Dowd 1997) and, ii) loss of particles due to extraction by filter feeders. Food consumption by mussels was calculated using ingestion rate of mussels instead of filtration rate, since an important fraction of the filtered particles would be returned to the water column as pseudo-faeces and could be reused by mussels with the same efficiency. Growth rate was based on the eco-physiological model of Grant and Bacher (1998). Details of the equations are given in the Annex to this study.

The box model for the long lines area used standard values of water exchange, box volume and number of mussels and environmental data as boundary conditions. It was expected that increasing the number of mussels would decrease the food concentration and result in a lower individual mussel growth rates. We therefore defined a series of theoretical scenarios combining different mussel densities and sizes of leased area. Nominal lease area was multiplied by a factor L between 1 and 5. If current speed and mussel density were kept constant, this is equivalent to multiplying the cultivation area, volume and total number of mussels by L^2, while the water volume exchange rate and residence time were multiplied by L. We varied the nominal lease size and mussel density, by a factor between 1 and 10.

An exposure indicator was defined from the depletion of phytoplankton computed for the different scenarios and averaged over one year (Figure 6.2.6). It is shown that a decrease of phytoplankton within the farm area by a factor of 10 % would be obtained if the farm size or mussel density was approximately doubled.

6.2.3.3 Consequence Assessment

Using the same box model, consequences of food depletion on growth were assessed for a range of different scenarios. The standard simulation showed only a very small reduction in mussel weight, hardly visible when plotted. It was related to the large flow of POM and chlorophyll-a into the lease area compared to the low food use by the mussel population. An annual carbon budget for phytoplankton showed that filtration was equal to 0.054 mgC l^{-1} d^{-1}, ingestion to 0.048 mgC l^{-1} d^{-1} and inflow to 1.98 mgC l^{-1} d^{-1}. For detritus, the same fluxes equalled 0.55, 0.38, and 19.4 mgC l^{-1} d^{-1}. Less than 2% of the inflow was diverted to the mussel population and the food ration was mainly composed of detritus.

Increasing the lease size or mussel density had similar effects on final mussel dry weight. The minimum final dry weight was less than 0.5 g and was obtained when the lease size was multiplied by 5 and mussel density by 10, in comparison to 0.9 g estimated for the actual density and lease size. However, the effects of lease size and mussel density increase were the same and isolines of final dry weight were symmetrical (Figure 6.2.7).

In a second series of scenarios, we investigated the effects arising from changes in the exchange coefficient alone, in order to assess the effects on mussel growth in areas with lower tidal currents, and to make conservative predictions of the effect of flux reduction on mussel growth. In these series, multiplication factor varied from 0.1 to 1, in order to mimic cases with different current velocities but the same mussel density and lease size. The final dry weight decreased by 15 % in comparison to the actual field situation when water exchange was multiplied by 0.1. The decrease was less than 5 % with multiplication factors above 0.3.

6.2.3.4 Logic model

The steps in the consequence assessment can be deduced from the calculations and available data

Figure 6.2.4 : Monthly progression of shell length of mussels from the 2 locations: long-line (dashed line), bouchot (plain and dotted lines). Data plotted as mean+/-S.E. (from Garen et al. 2004).

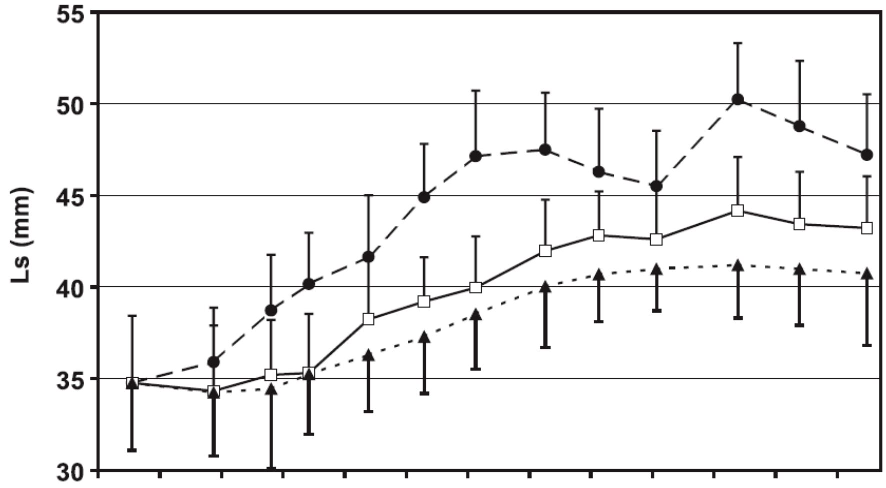
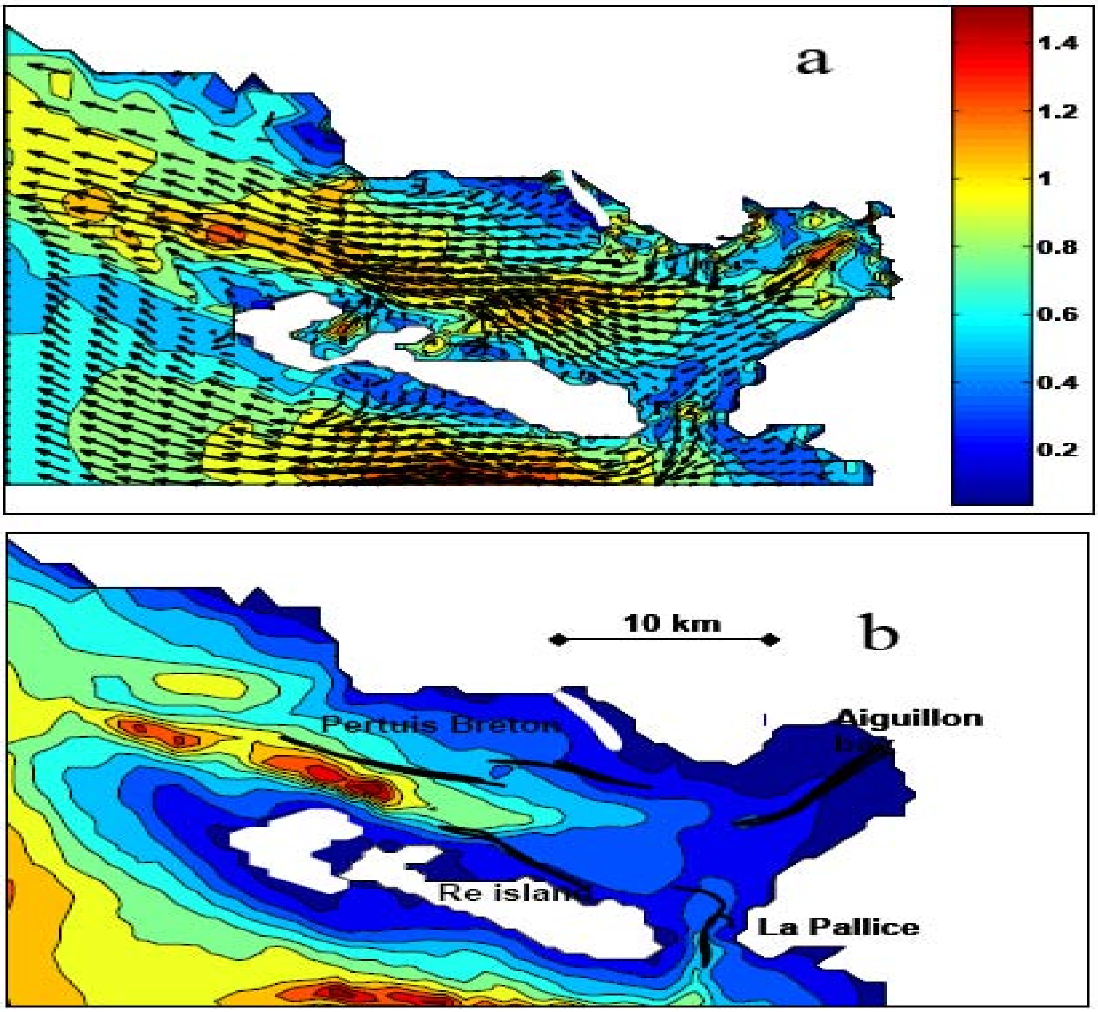


Figure 6.2.5 : Hydrodynamics simulated in Pertuis Breton: a) map of maximum current velocity (m.s-1, in colours), with arrows representing flow direction during the ebb; b) trajectories of particles.



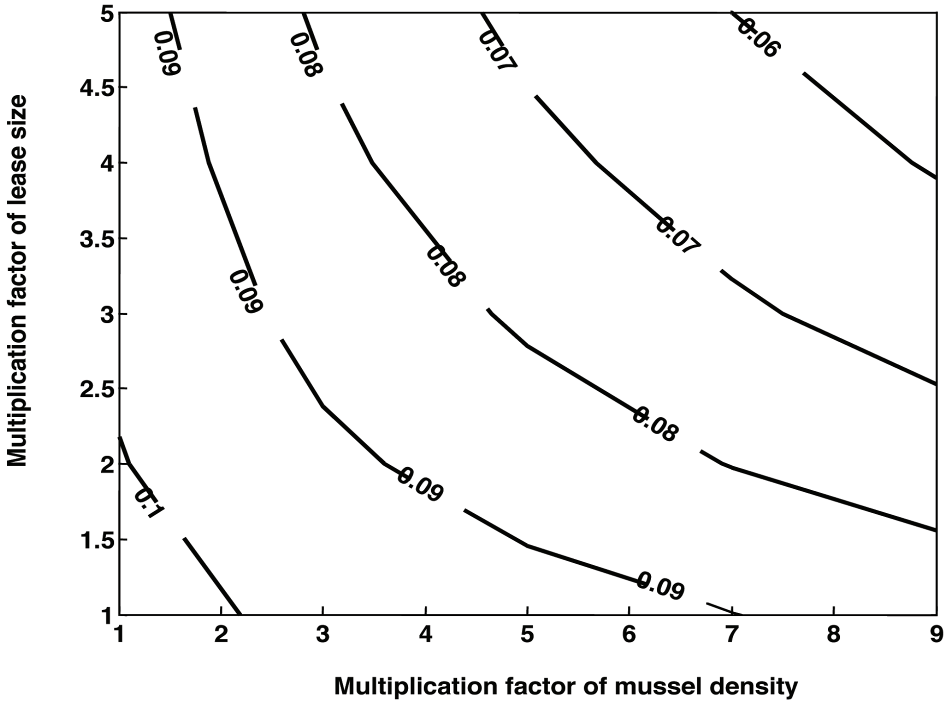


Figure 6.2.6 : Phytoplankton concentration (mg C.l[-1]) shown by the box model with scenarios of increasing density and farm size. The actual situation corresponds to a value of 1 for both multiplicative factors.

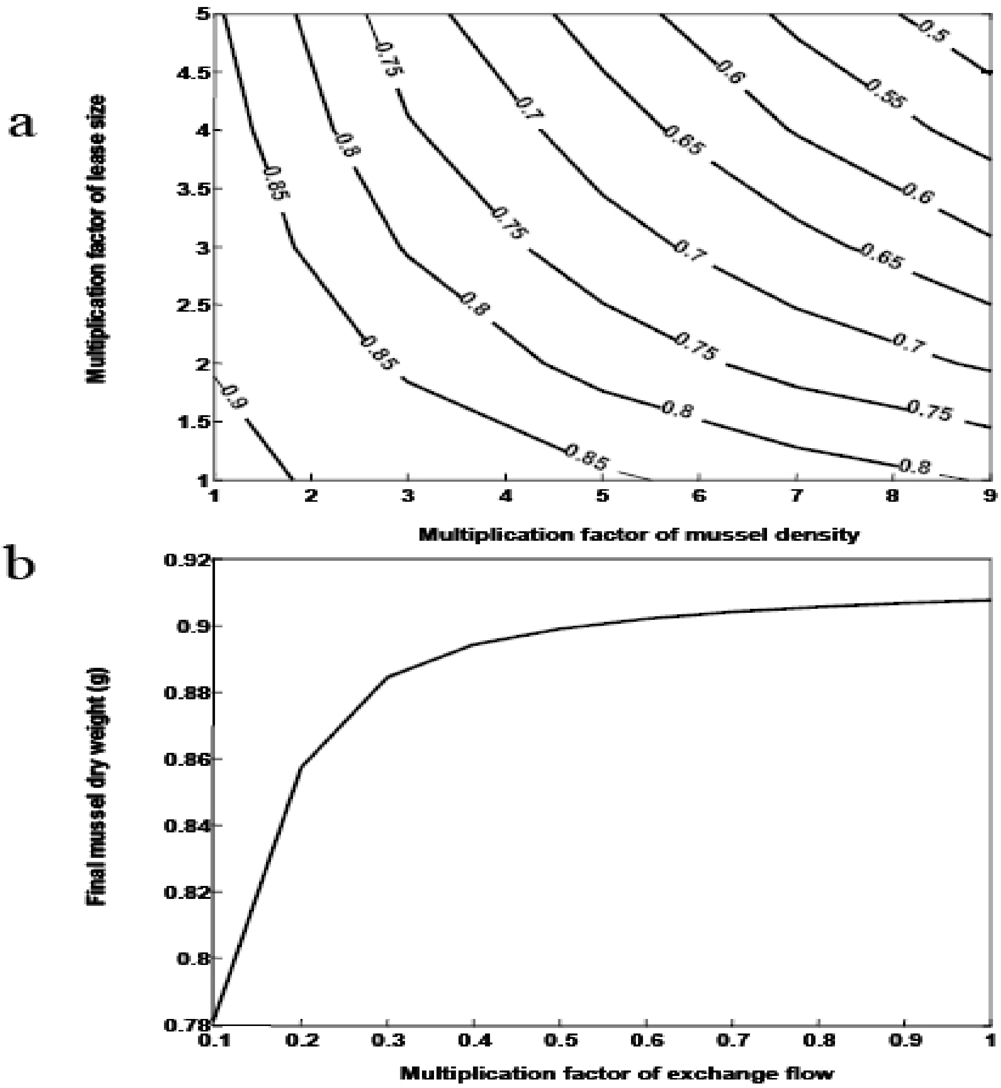


Figure 6.2.7 : Simulation of several scenarios: a) annual mussel growth as a function of density and size of the mussel farm; b) annual mussel growth as a function of water flow.

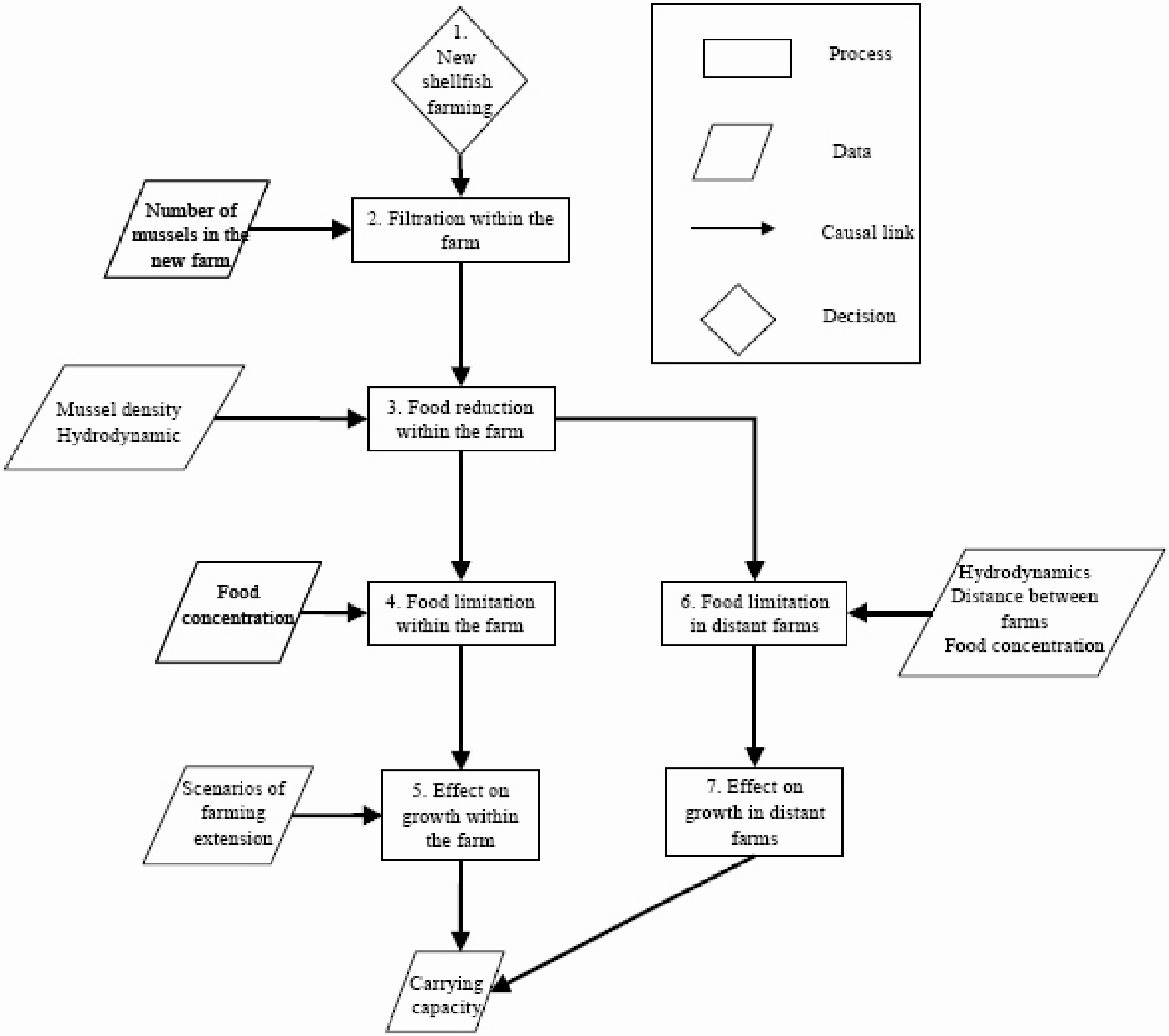


Figure 6.2.8 : Logical model of the risk assessment procedure representing the different processes (rectangles) in relation with input/output information (squeezed rectangles). Arrows represent causal links. Both local and distant effects of farm extension are considered.

according to a logic model (Figure 6.2.8). At each of these steps, probability, intensity and uncertainty of the effect can been assessed.

1. Farming will be expanded.
   Bivalves are probably the largest group of filter-feeders in the area. There are already approximately 9,000 tonnes of cultured mussels and 16,000 of cultured oysters in the Pertuis Breton area and the carrying capacity is probably partly used, which makes the addition of new areas for a 10% increase in production potentially problematic. The intensity of increase is judged to be high given the existing demands of aquaculture. The area of the bay utilised by the new production is moderate. When this new production in the Pertuis ceases, the hazard (filtering) would cease almost immediately (Low). While the area **Severity (intensity+area+duration)** is considered **Moderate**. Given the desire of industry to increase production and the lack of space for traditional production techniques, extension of shellfish farming into long line culture is likely to occur. **Probability of occurance is very High** - for the same reasons given above. **Uncertainty is Negligible**.

2. Filtration in the area of the farm is substantial.
   The estimation of total volume filtration rate in the area suggests the amount of particles present in the long-line area would be substantially decreased if filtration alone was considered. The intensity of filtration on the farm site is considered to be high. Some effect at distance from the farm is probable but it will decrease due to mixing of filtered and unfiltered water and will probably be negligible at a distance of a few kilometers, so the area affected is considered moderate. If production in the new areas ceased, the hazard (filtering) would also cease almost immediately (Low). For these reasons, **severity** is considered moderate and **probability** of occurrence is high. **Uncertainty** related to this calculation is low.

3. Food concentration will be reduced within the farm.
   The box model demonstrated that actual mussel density and lease size had a minor effect on flows of particulate organic matter and phytoplankton within the farm (arial extent is low), and that water exchange was high enough to replace the water and keep phytoplankton food available (intensity is low). The degree of depletion of phytoplankton remained low, even under the various scenarios of farm extension and increased mussel density. If production in the new areas ceased, the hazard (filtering) would also cease almost immediately (Low). **Severity** is therefore low, and **probability** of the scenario occuring is therefore high. Because of assumptions made when the model was used, **uncertainty** is medium.

4. Food availability limits mussel production in the new farm.
   Food concentration and comparison of mussel growth in two different areas indicate that differences in mussel growth may be related to differences in food concentration and other controlling factors which play an important role in ecophysiological responses (for example, particulate inorganic matter). For that reason, the intensity of interaction on the farm site is considered high. The geographical extent of this is believed to be extensive within the farm (high). As the assumption has been that, prior to installation, food availability at the farm site did not limit growth and that after removal of the farm conditions would return to that state almost immediately, post farming duration of feed limitation would be short (low). **Severity** of food limitation can be deduced from these observations as moderate, and **probability** of this occuring is high with low **uncertainty**.

5. Food supply limits growth of the new farm.
   The low degree of food depletion (step 3) implies that the standing stock of cultured mussels could be increased by farmers without consequential reductions in mussel growth. Mussel production could be increased by extending the cultivation area and/or increasing the mussel density without significantly increasing the time needed to attain marketable size or weight. Both factors would have the same tenuous effect on growth. Our results indicate that areas with lower water exchange would also be suitable for mussel production – for example, current velocity 50% lower would not result in a significant negative effect on growth and production over the extent of the site. Therefore, expansion could occur over a large area (high) relative to the present proposal and it is anticipated that there would be little if any effct of food reduction on growth (low intensity of effect). If production in the new areas ceased, the hazard (filtering) would also cease almost immediately (Low). **The severity is Moderate** – The likely degree of change is low but may extent beyond the area of the lease site and immediately downstream of it. If the production was removed, any effect on the system is unlikely to be persistent. **Probability is High** – it is highly likely that the predicted effects (lack of effect on productivity) will permit futher development on the site. **Uncertainty is Moderate** – the variability in environmental forces that have occurred are expected to be representative of the range of environmental variation in the foreseeable future, but precise prediction of that variability is elusive because of the large number of factors affecting variabilty.

6. Based on the above observations, effects, if any, of filtration at the farm site on nearby farms are likely to be negligible (intensity is low). The area affected is also likely to be negligible (geo-

graphical extent is low). As with the previous steps, duration of any effect of the farm once operations cease is expected to be negligible (low). In total, the **severity** of food limitation caused by the new long-line farm site on other nearby farms is expected to be **low**, and the **probability** that this step in the logic model will occur is **high**. Our knowledge of the processes involved in this type of interaction is good enough that **uncertainty** for this prediction is **low**.

7. New production will affect other areas.
When examining potential effects of a long-line farm on larger areas, it is necessary to examine the balance of primary production and the effct of the farm on food concentrations in a larger water body. Primary production varies with meteorological conditions which act on the fresh water and nutrients loadings, light intensity, water temperature and sediment resuspension, and inter-annual variability is probably high. In Marennes-Oléron bay, a comprehensive assessment of primary production showed that primary production is driven by nutrient fluxes, water mixing and light limitation due to turbidity (Struski and Bacher 2006) and its role on carrying capacity has also been assessed (Bacher *et al.* 1998). Although no comparable estimation exists for Aiguillon bay, it is likely that it behaves in the same way because of the similarities between the two ecosystems – for example, macrotidal bays, input from fresh water and nutrients from rivers, sediment resuspension due to currents and waves. Primary production is therefore thought to be a limiting factor for the carrying capacity if mussel production is based solely on primary production at the scale of the bay.

There is also evidence of a relationship between phytoplankton concentration and mussel growth on bouchot in Pertuis Breton (Dardignac-Corbeil 2004) and in Marennes-Oléron Bay (Boromthanarat *et al.* 1988) and growth of suspended culture mussels has been assessed in Pertuis Breton (Barillé 1996). The effect of phytoplankton and turbidity on mussel growth has been assessed by Garen *et al.* (2004) who compared growth in suspended culture and bouchot and showed that mussels on long-lines exhibited the highest growth rate, probably due to differences in immersion time.

Phytoplankton availability is therefore probably the primary limiting factor for growth, but horizontal dispersion probably acts to dilute the available supply of food. The hydrodynamical model implemented in Pertuis Breton and the Marennes-Oléron Bay showed that, in Pertuis Breton, tidal currents frequently exceed 50 $cms^{-1.}$ Compared to other ecosystems where mussel culture takes place, this intense water movement favours the supply of food particles to individual bivalves. However, the residence time of water within the bay has not been accurately estimated and is probably much higher than in Marennes-Oléron Bay, where limitation of carrying capacity has been demonstrated. Increased flushing rates would tend to dilute the concentration of phytoplankton in the water body.

Modelling of food depletion in the long-line area has shown that the actual current velocity and mussel density would not result in significant food depletion, even if the long line area was extended. At the local scale of long-lines or bouchots, primary production is negligible compared to the supply of food through advection of phytoplankton and detritus by currents. Simulations of particle movements and fluxes of bivalve food demonstrated that the actual mussel density and lease size had a minor effect on flows of particulate organic matter and phytoplankton, and that water exchange was high enough to support the additional mussel production proposed.

Interactions between cultivated areas generally occurs when the combination of water residence time, shellfish standing stock and primary production limits food availability (Smaal *et al.* 1998; Guyondet *et al.* 2005; Bacher *et al.* 1998). In Pertuis Breton, long-lines and bouchots are operated in different areas, separated by a few kilometres, which minimises the potential for interactions.

The likely degree of change (severity) is **low** and limited to the area of the lease site and immediately downstream of it. If the production were removed any effect on the system is not likely to persist even for a short period of time. The **severity** is therefore **Low**. **Probability** that this prediction is correct is high and the **Uncertainty** associated with this prediction is **Moderate** because of a lack of accurate information on some physical parameters such as flushing time. Even so, the variation in environmental forces that are evident in the existing conditions are expected to be representative of the range of environmental variation.

8. Effect on carrying capacity
Mortality of mussels has been monitored at both long-lines and bouchots, and mortallity rates have been at acceptable levels. Given no noticable effect of the new long-line farm on food supply, an increase in mortality is unlikely to occur. The lack of food reduction on the farm site, on nearby farms, or on the carrying capacity of the bay suggests that changes in carrying capacity in the bay due to the new farm will be very small if they occur at all. Furthermore, any effect on the carrying capacity will be quickly reversed should the farm cease to operate. Therefore, the **severity** of effect on carrying capacity will be **low**. The **probability** that this prediction is correct is thought to be **high**. The **uncertainty** associated with this prediction is medium, as some of the physical processes on which it is based (such as flushing times) remain to be fully documented.

Results are summarised in Table 6.2.I. 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. The final rating for the **Uncertainty** is assigned the value of the element with the **highest uncertainty** level. The conclusion of the risk evaluation in both local and distant farms is that the risk of change of carrying capacity is considered as low with a medium uncertainty.

6.2.3.5 Risk estimation

In the earlier description of the potential expansion of farming activities, no special technologies were identified as to be used nor were any specific regulatory requirements mentioned that might reduce the effect of the new farm from that which might be anticipated based on the consequence assessment. For that reason, the risk level identified in the consequence assessment is the same as that for the risk evaluation. Should any of the recommended risk management activities be undertaken, that level of risk may be modified.

6.2.4 Risk Management

Option evaluation in risk management addresses what might be done to reduce the probability of a risk being expressed, or to reduce the uncertainty in the prediction of the expression of a risk. The process therefore identifies, for each step in the logic model, what could be done to reduce the probability of it occurring. These actions would directly mitigate possible effects. A further contribution to increasing the effectiveness of the risk analysis would be to reduce the uncertainty associated with predicting that the step will happen. Usually this involves further research or development. Table 6.2.II identifies both mitigation measures and research or development activities that could address the risks arising from the additional filtration pressure of mussels at a proposed new cultivation site.

Goulletquer and Héral (1997) noted that the shellfish industry was facing several internal and external constraints affecting overall economic yield and sustainability. The development of an integrated coastal management plan for the Pertuis Charentais is likely to be a major objective in the near future, not only to take into account the requirements of sustainable aquaculture, but also to include other users in the management of the coastal area. Ervik *et al.* (1997) developed a comprehensive methodology, combining models and data collection, to minimise the effects of aquaculture in Norwegian waters. General principles for the monitoring of aquaculture effects have been stated only recently by Fernandes *et al.* (2001) who emphasised the role of whole-system environmental assessments in developing frameworks for the sustainable use of ecosystems – for example, whether the effects of an activity on the environment is unacceptable with respect to the objectives/needs of producers, regulators and stakeholders and the desire to be able to use maintain the uses of an area indefinitely. They proposed a set of recommendations concerning the implementation of a more focused approach to environmental monitoring to contribute to the management of sustainable aquaculture.

The effort in identifying and mapping sites suitable for aquaculture, and monitoring existing sites, is therefore key to mitigation and optimisation of shellfish aquaculture. Over the last 10 years there has been an increasing development of Geographic Information Systems (GIS) and models (see http://www.fao.org/fi/gisfish/index.jsp). GIS-based decision support systems (as advocated by Nath *et al.* 2000) constitute a new generation of management tools. Parker *et al.* (1998) organised physical characteristics, such as bathymetry, bottom type, intertidal location, water currents, temperature, and planktonic concentrations into a GIS to predict and map potential growth rates of juvenile shellfish for seeding sites. Similar tools were implemented by Brown and Hartwick (1988), Arnold *et al.* (2000), Congleton *et al.* (1999, 2003), and Vincenzi *et al.* (2006) for shellfish and Pérez *et al.* (2002, 2003, 2005) for fish aquaculture. Most GIS systems are based on maps of environmental data and sometimes outputs from hydrodynamic models are included (Congleton *et al.* 2003). The coupling of biological models to these physical models will allow information and advice on production to be derived (Bacher *et al.* 2003). This will require additional research effort, and the application of ecophysiological, hydrodynamic and ecological models.

6.2.5 Scope of the Risk Assessment

This case study examines some of the effects of shellfish aquaculture at a specific site. The conclusions need be examined by stakeholders and shellfish farmers, fishermen and regulators through a coherent risk communication process. We did not seek to take into account all the possible effects of a new shellfish development, and some uncertainties remain in the assessment. However, the example illustrates how the assessment of potential effects of filtration pressure on shellfish carrying capacity might be undertaken. The output is site-specific but the use of a standardised procedure has several advantages. Any risk assessment must be seen as a continuously evolving process which should take into account new information and changes the input from stakeholders and scientists. These changes can diminish the uncertainty attached to the risk evaluation or refine the definition of the risk. Information developed for one assessment can also often be applied in other contexts and sites and outputs of the risk assessment in one case can bring valuable information to other assessments. Eventually, the methodology leads to a management plan to mitigate any undesirable effects revealed by the risk evaluation, improvements in the good farm management practices and directs data collection and scientific research to critical areas of uncertainty.

Other environmental consequences of shellfish farming can be recognised, and are related to more complex processes which all fall into the broad framework of Ecosystem Carrying Capacity, as defined by Inglis *et al.* (2000). In a recent review, McKindsey *et al.* (2006) emphasised the changes in the flow of nutrients and materials due to shellfish culture. The shellfish filter large amounts of water and remove suspended particulate material. This can be partly excreted in dissolved form or repackaged and released as faeces and pseudo-faeces. These generally differ from other seston particles in aggregate size and shape, organic matter content and cohesive properties. Sedimentation of these

Table 6.2.I : Risk estimation based on the logical model.

Steps in the logic model	Intensity/ degree	Geographical extent	Permanence or duration	Severity (H,M,L)	Probability (H,M,L)	Uncertainty (H,M, or L)	Stage of assess-ment
1. Mussel farming will extend	H	M	H	H	H	N	Release
2. Estimation of filtration indicates that shellfish pump an important volume of water	H	M	H	M	M	L	Release
3. Calculation of food depletion indicator shows that food concentration is decreased by shellfish filtration	L	M	M	M	H	L	Exposure
4. Growth is limited by environmental conditions in the new farm	M	M	H	H	H	L	Exposure
5. Food depletion affects individual growth within the farm	M	M	H	H	L	M	Effect
6. Growth is limited by environmental conditions in areas distant from the new farm	M	M	H	H	H	L	Exposure
7. New production will affect other areas	L	L	L	L	L	M	Effect
8. Change of productivity	L	L	L	L	L	M	Effect

Probability = H – *High,* **M** – *moderate,* **L** – *Low,* **N –** *Negligible*
Severity = H – *high,* **M** – *Moderate,* **L –** *Low,* **N** – *Negligible*
Uncertainty = H- *Highly uncertain,* **M** – *Moderately uncertain,* **L** – *Low uncertain,* **N**- *Negligible.*

particles is likely to occur when current velocity is low, and organic matter would be expected to accumulate on the sediment beneath the cultivation unit. In the field, significant increases in organic matter content and nutrient enrichment have been observed around oyster tables (Sornin *et al.* 1990), oyster reefs (Dame and Prins 1998), mussel beds (Prins *et al.* 1998) and clam beds (Bartoli *et al.* 2001). For instance, in Saldanha Bay (South Africa), biodeposition rates in raft culture were reported by Stenton-Dozey *et al.* (1999). Deposition beneath rafts was attributed to high production of about 105 tonnes wet wt biomass raft^{-1} yr^{-1}, including mussels and associated fouling organisms. The sedimentation rate within the farm was around 300 kg organic carbon m^{-2} yr^{-1} and 45 kg nitrogen m^{-2} yr^{-1}. Chamberlain *et al.* (2006) also estimated biodeposition fluxes due to cultivated mussels in a lagoon in the Saint Laurence estuary (Canada). The maximum biodeposit production recorded was 125.6 mg d^{-1} ind^{-1}. They extrapolated this measurement to estimate the biodeposition rate from a mussel line as 26.4 kg line-1 d^{-1} (365.8 m length; stocking density 575 mussels m^{-1}). The accumulation of this organic matter on the sediment would increase the oxygen demand of the bottom sediments. In some cases, an effect on the environment has been documented and motivated further studies in order to predict when and where these effects would be likely to occur (Chapelle *et al.* 2000). It has been noted that the effect can be exacerbated by environmental factors such as high temperature and slow current speeds, which also increase oxygen demand and depletion in bottom waters. As a consequence, anoxia in the sediment might propagate into the water column and lead to anoxia in the water surrounding cultivated shellfish, with strong adverse consequences for the stock. In a very recent work, Bouchet (2007) showed some effect of oyster culture on sediment quality and macrobenthos communities in Marennes-Oléron Bay due to biodeposition, through processes of recycling of organic matter leading to enhancement of microphytoenthis production, subsequent temporary anoxia and consequential modification of macrobenthos abundance and diversity. The ecological quality was estimated using the AMBI tool which confirmed that the status of the site was medium.

There is no generally applicable statement of the likely effects of shellfish aquaculture on the environment and on the ecosystem carrying capacity. This is mostly due to the recycling capacity of marine ecosystem linked with the fact that shellfish cultivation is always a net sink of nutrients, in contrast to fish aquaculture. Besides, many findings associated with very high densities of shellfish in bottom culture, or at sites with low current velocity (< 20 cms^{-1}) would not apply to suspended culture in places like Pertuis Breton where the intense water mixing will disperse biodeposition and decrease the intensity of the aquaculture footprint on the sediment at the farm site. As a consequence, our example of Risk Assessment is limited to simple cases where our assumptions based on the predominance of food transport and limitation of shellfish growth and production by phytoplankton are valid. More sophisticated tools capable to assess the interactions between all or some

Table 6.2.II : List of mitigation and research or development steps that could be done to improve the risk assessment linked to the identification of new sites for shellfish aquaculture.

Steps in the logic model	Probability (H,M,L)	Mitigation (regulate/design/modified practices)	Uncertainty (H,M, or L)	Research/Development
1. Mussel farming will extend	H	• Map existing cultivated areas and assess standing stock and productivity • Move new sites offshore • Replace existing sites • Define management options and indicators of sustainability	N	• Define acceptable practices of management for a sustainable development of aquaculture, including economic analysis and multi-agents agreement • Improve integrated management of the coastal area, including freshwater and land use
2. Estimation of filtration indicates that shellfish pump an important volume of water	M	• Monitor environmental parameters	L	• Measure primary production and develop numerical model coupling hydrodynamics, nutrient input, sediment resuspension and primary production
3. Calculation of food depletion indicator shows that food concentration is decreased by shellfish filtration	H	• Simulate and map current velocity • Compute water residence time and depletion due to filtration	L	• Map phytoplankton and turbidity with field surveys and/or satellite images • Retrieve bathymetry data and boundary conditions to implement a hydrodynamical model • Estimate the change of hydrodynamics due to long-lines
4. Growth is limited by environmental conditions in the new farm	H	• Assess and monitor the mussel scope for growth	L	• Develop and test ecophysiological model to predict scope for growth as a function of food availability
5. Food depletion affects individual growth within the farm	L	• Compute and estimate residence time of particles over the area in order to assess interactions between cultivated areas	M	• Retrieve bathymetry data and boundary conditions to implement a hydrodynamical model coupled to simple ecophysiological models
6. Growth is limited by environmental conditions in areas distant from the new farm	H	• Compute and estimate residence time of particles over the area in order to assess interactions between cultivated areas as a function of the distance between the farms	L	• Test and validate hydrodynamical model, residence time calculation and particles trajectories
7. New production will affect other areas	L	• Compute and estimate residence time of particles over the area in order to assess interactions between cultivated areas	M	• Retrieve bathymetry data and boundary conditions to implement a hydrodynamical model coupled to simple ecophysiological and primary production models

of the ecosystem components will have to be applied (Chapelle *et al.* 2000; Pastres *et al.* 2001; Gibbs 2004). The effect of larger scale effects due to other coastal activities and environmental change will also have to be taken into account (Marinov *et al.* 2007) and therefore this risk assessment methodology combined with Integrated Coastal Zone Management, mapping and modelling tools will be a great help for decision makers.

6.2.6 Literature cited

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Annex. Box model

The box model couples food transport, food consumption by the mussel population and mussel growth at the scale of a cultivated area. The concept is the same as used by Bacher *et al.* (2003), except that food and particulate matter concentrations are assumed to be homogeneous within the cultivated area, which is represented as a single box. The transport equation is a mass balance equation accounting for i) the exchange of water between the box and the external part of the cultivated area (Bacher, 1989; Raillard *et al.* 1994 ; Dowd 1997), ii) sinks of particles due to consumption by filter feeders:

$$\frac{dC}{dt} = \frac{Q}{V}(C_e - C) - \frac{N}{V}.f(C,w) \qquad (1)$$

where *C* refers to either phytoplankton, organic or inorganic particulate matter within the box, C_e is the outside concentration, *Q* the exchange flow ($m^3\ s^{-1}$), *f(C,w)* the individual food consumption, *N* the total number of mussels, *w* the mussel tissue dry weight (DW).

Food consumption was calculated using the ingestion rate of mussels rather than the filtration (*see* ecophysiological model below) since an important fraction of the filtered particles is assumed to remain in the water column as pseudofeces and would be reused by mussels with the same efficiency.

Equation (1) was coupled to the following mussel growth equation:

$$\frac{dw(x,t)}{dt} = g(C,w,T) \qquad (2)$$

where *T* is the water temperature and *g(C,w,T)* is the growth rate established from the ecophysiological model of Grant and Bacher (1998). Briefly, the model provides two food sources, phytoplankton and detrital POC, where detrital POC=total POC-chlorophyll carbon. Clearance rate ($l\ h^{-1}$) of particles is a declining function of TPM. Phytoplankton and POC are both cleared at the same rate, and the proportion of the ingested mass that is rejected as pseudo-faeces is related to turbidity using a step function : no rejection at 0–5 mgl^{-1}, 20% rejection at the pseudo-faeces threshold up to 10 mgl^{-1}, 40% rejection from 10–40 mgl^{-1}, and peak rejection (85% of ingesta) above 40 mgl^{-1}. Phytoplankton is selected preferentially to detritus. In terms of ingestion, phytoplankton and POC are maintained as separate quantities, each with a defined absorption efficiency (AE), and absorption rates are summed to calculate total absorption. The phytoplankton AE is assumed to be 80% and AE for detrital POC is set at 40%. In contrast to other models using gut capacity and gut passage time to limit ingestion (Scholten and Smaal 1998), daily ingestion can not be higher than a constant value defined as the maximum daily ingestion. The net energy balance is determined as the difference between the rates of assimilation and respiration, and the balance is allocated between somatic tissue and shell. The model predicts changes in both dry tissue weight and shell weight. The respiration equation was modified from Grant and Bacher (1998) to allow a better fit with observations. The model was also applied to the 'bouchot' dataset for validation and, as a further check, ecophysiological functions were compared to measured values.

Long lines cover an area of 2.5 km^2. They are arranged in 20 blocks of 12 long lines each. 85 ropes of 6 m length hang on each long-line and the whole area contains about 240 10^6 mussels. We assumed that mussels were homogeneously spread within the box and that trophic conditions were uniform. Boundary conditions were defined for TPM, POM, and phytoplankton concentrations from the field survey. Temperature time-series were used as a forcing function.

The current velocity field was modeled using a hydrodynamical model developed by Brenon and Le Hir (1999) applied to Marennes-Oléron Bay. This model solves Navier-Stokes equations with a finite difference method using a rectangular grid (Struski 2005) and predicts water height and current velocity. Water height and tidal currents were simulated for one month to cover a full spring-neap tidal cycle. To check the validity of the model, we compared the simulated water height in La Pallice harbour to available observations of water height and we found good agreement. Maximum current velocity was mapped from this single simulation and showed that long lines were located in a region of intensive water exchange, with maximum current velocity over 1 $m.s^{-1}$. Current velocity generally depends on tidal coefficient, and the maximum tidal currents varied between 0.5 and 1 $m.s^{-1}$. In the long line area, the current direction lies along a northwest/southeast axis and intensive exchange of water occurs at Pertuis Breton straight.

Particle trajectories were computed for one tidal cycle at spring tides using the current velocity field from the hydrodynamic model. Particles coming from the inner part of the bay (Aiguillon bay) exit through Pertuis Breton straight in the west or through La Pallice straight in the south. Trajectories also show that the tidal excursion is almost 10 km, which supports the concept of strong water mixing in the inner part of the bay.

Current velocities and water height were used to compute water exchange between the long line area (box) and the outer part of the bay. Average water flow entering and leaving the cultivated area was calculated with the following equation:

$$Q_T = \sum_t \left\{ \sum_{x,y} h(x,y,t) \cdot \left| U(x,y,t) \cdot N(x,y) \right| \cdot L \right\} / n$$

Where *U(x,y,t)* is the current velocity vector at the grid node *(x,y)* located at the box boundary, *N(x,y)* is the vector normal to the lease boundary, *h(x,y,t)* is the water height, *L* is the mesh size used in the hydrodynamics model (500 m), *n* is the number of time steps used for the computation. Due to mass conservation, half of total flow enters the cultivated area and the exchange flow was therefore given by:

$$Q = Q_T / 2$$

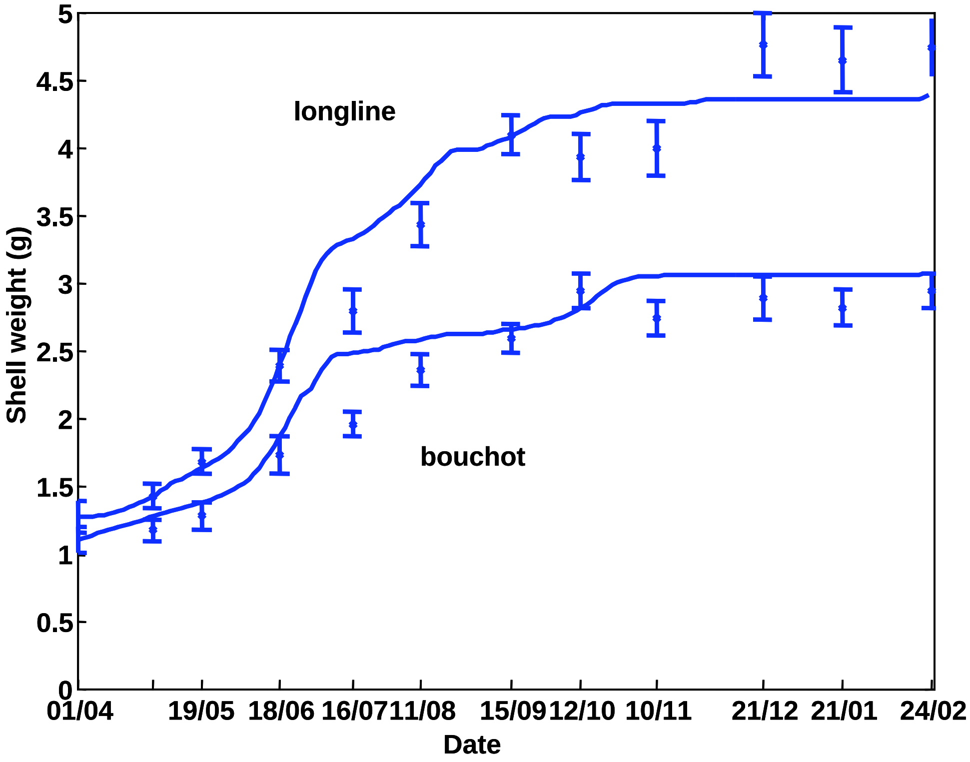
Box volume was equal to :

$$V = \sum_t \left\{ \sum_{x,y} h(x,y,t) \cdot L^2 \right\} / n$$

Where *h(x,y,t)* is the water height of the grid node *(x,y)* located inside the box. Exchange flow was equal to 5.2 10^3 m^3s^{-1} and volume to 2.37 10^7 m^3 which yielded a renewal time of 0.05 days.

Simulated and observed mussel growth is shown in the following figure and illustrates the ability of the model to accurately reproduce the growth patterns at two different sites.

Comparison of simulated and observed shell weight of mussels reared on long-lines and bouchot



Equations, parameters and variables used in the ecophysiological model of mussel growth.

Equations	Description
State variables	
TPM	Total Particulate Matter (mg l^{-1})
POM	Particulate Organic Matter (mg l^{-1})
CHL	Chlorophyll *a*
DW	mussel Tissue Dry Weight (g)
SW	mussel Shell Weight (g)
Forcing functions	
TEMP	Temperature (°C)
Parameters	
chl2c=50	conversion from Chlorophyll *a* to Carbon (gC $gChl^{-1}$)
pom2c=0.38	conversion from POM to Carbon (gC gDW^{-1})
CPHY=CHL·chl2c/1000	Carbon phytoplankton (mgC l^{-1})
CDET=POM·pom2c-CPHY	Carbon detritus (mgC l^{-1})
Clearance rate	
cr1=1.8	
cr2=8.6 10^{-3}	
cr3=0.67	
if TEMP < 5	
frtemp=$e^{((TEMP-5)\cdot 0.07)}$	frtemp=temperature effect
elseif TEMP >5 & TEMP < 20	
frtemp= 1	
else	
frtemp=$e^{((20-TEMP)\cdot 0.07)}$	
end	
CR=CR= (cr1 – cr2·TPM) ·$(DW/0.7)^{cr3}$·24·frtemp	clearance rate (l d^{-1} ind^{-1})
Filtration rate	
FR=CR·TPM	TPM filtration rate (mg d^{-1} ind^{-1})
if TPM < 5	
	rej = rejection rate (no unit)
rej=0	
elseif TPM >5 & TPM < 10	
rej=0.2	
elseif TPM >10 & TPM < 40	
rej=0.4	
elseif TPM>40	
rej=0.7	
end	
Ingestion rate	
IR=FR·(1-rej)	TPM ingestion rate (mg d^{-1} ind^{-1})
ir1=600	
ir2=0.40	
IRmax=ir1·DW^{ir2}	TPM maximum ingestion rate (mg d^{-1} ind^{-1})
IRTPM=min(IR,Irmax)	TPM ingestion rate (mg d^{-1} ind^{-1})
fq=0.8	phytoplankton enrichment factor
IRPHY=IRTPM·CPHYT/TPM/fq	PHYTO ingestion rate (mgC d^{-1} ind^{-1})
IRDET=IRTPM·CDET/TPM	DETRITUS ingestion rate (mgC d^{-1} ind^{-1})
Absorption rate	
ARPHY=IRPHY·0.8	PHYTO absorption rate (mgC d^{-1} ind^{-1})
ARDET=ARDET·0.4	DETRITUS absorption rate (mgC d^{-1} ind^{-1})
AR=ARPHY+ARDET	total absorption rate
Respiration rate	
r1= 6.55	calibrated
r2= 0.454	calibrated
r3=0.75	
RER=(r1+r2·AR)·DW^{r1}	respiration rate (mgC d^{-1} gDW^{-1})
Carbon budget and growth	
Budget=AR-RER	Carbon budget (mgC d^{-1} gDW^{-1})
alloc=0.58	tissue allocation rate - calibrated
w2c=0.4	conversion from DW to Carbon (gC gDW^{-1})
s2c=0.08	conversion from SW to Carbon (gC gSW^{-1})
if Budget>0	
dDW=Budget·alloc/w2c/1000	dDW = dry weight variation (g)
dSW=Budget·(1-alloc)/s2c/1000	dSW = shell weight variation (g)
else	
dDW=Budget/w2c/1000	
dSW=0	
end	
Integration	
dt=1	time step (d)
DW=DW+dDW·dt	dry weight (g)
SW=SW+dSW·dt	shell weight (g)

CASE STUDY 6.3

RISK ANALYSIS OF THE POTENTIAL INTERBREEDING OF WILD AND ESCAPED FARMED COD (*Gadus morhua* Linnaeus)

I. M. Davies[1], C. Greathead[2] and E. A. Black[3]
[1]Principal Environmental Scientist, Fisheries Research Services Marine Laboratory, Aberdeen, Scotland, UK.
[2]Research Scientist, Fisheries Research Services Marine Laboratory, Aberdeen, Scotland, UK
[3]Senior Aquaculture Advisor, DFO Aquaculture Sciences Branch, Ottawa, Canada

6.3.1 Introduction

Cod (*Gadus morhua* Linnaeus) is a predominantly benthic species found on both the eastern and western sides of the North Atlantic from Greenland and south from the Barents Sea to Cape Hatteras and the Bay of Biscay. It feeds on both invertebrates and small fish. Age at first maturity is reported as 3.1 years and the maximum reported age is around 25 years, with males reaching 200 cm and 96 kg, although large specimens are now rare. Cod has a long tradition as an important commercial species, enormous stocks having existed in the past in areas such as the Grand Banks. Stocks in the North East Atlantic have recently declined to a low level, and measures are being taken to attempt to restore them. The traditional popular demand for cod for human consumption, low stock levels, and high growth rate makes the species an attractive target for aquaculture development.

The concern being addressed in this document is that farmed cod in Scotland may escape from cultivation units and genetically interact with wild cod, and that the consequence of this interaction is reduced survival in the wild population at local or larger scales. This concern is addressed through a risk analysis framework that includes: hazard identification, risk assessment (release assessment, exposure assessment and consequence assessment), and risk estimation and management. The analysis is structured around a logic model to clarify the pathway leading from the hazard (escaped cod) to the endpoint (reduced survival in wild populations).

The series of steps and processes leading from the establishment of cod farms in coastal waters to significant decreases in wild cod stocks as a result of genetic interactions between the two groups of cod can be summarized in a logic model, as below:

Process of concern : Changes in fitness of wild populations of cod due to genetic introgression
End Point of concern : Significant decline in survival in wild cod populations due to interbreeding with escaped cultured cod.
Logic model steps :

1. Cod farms are established in coastal waters.
2. Cultured cod, in the form of gametes, eggs or fish escape from cages.
3. Cultured cod interbreed with wild cod.
4. The progeny of this interbreeding (hybrids) show reduced fitness. This is dependent on there being phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons.
5. There is sufficient gene flow to affect survival rates of cod in individual fisheries management units, for example, the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.
6. Genetic interaction causes declines in endemic, evolutionarily significant units (populations), for example, genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.
7. Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population, for example, escapes of cultured cod cause significant decreases in wild cod stocks.

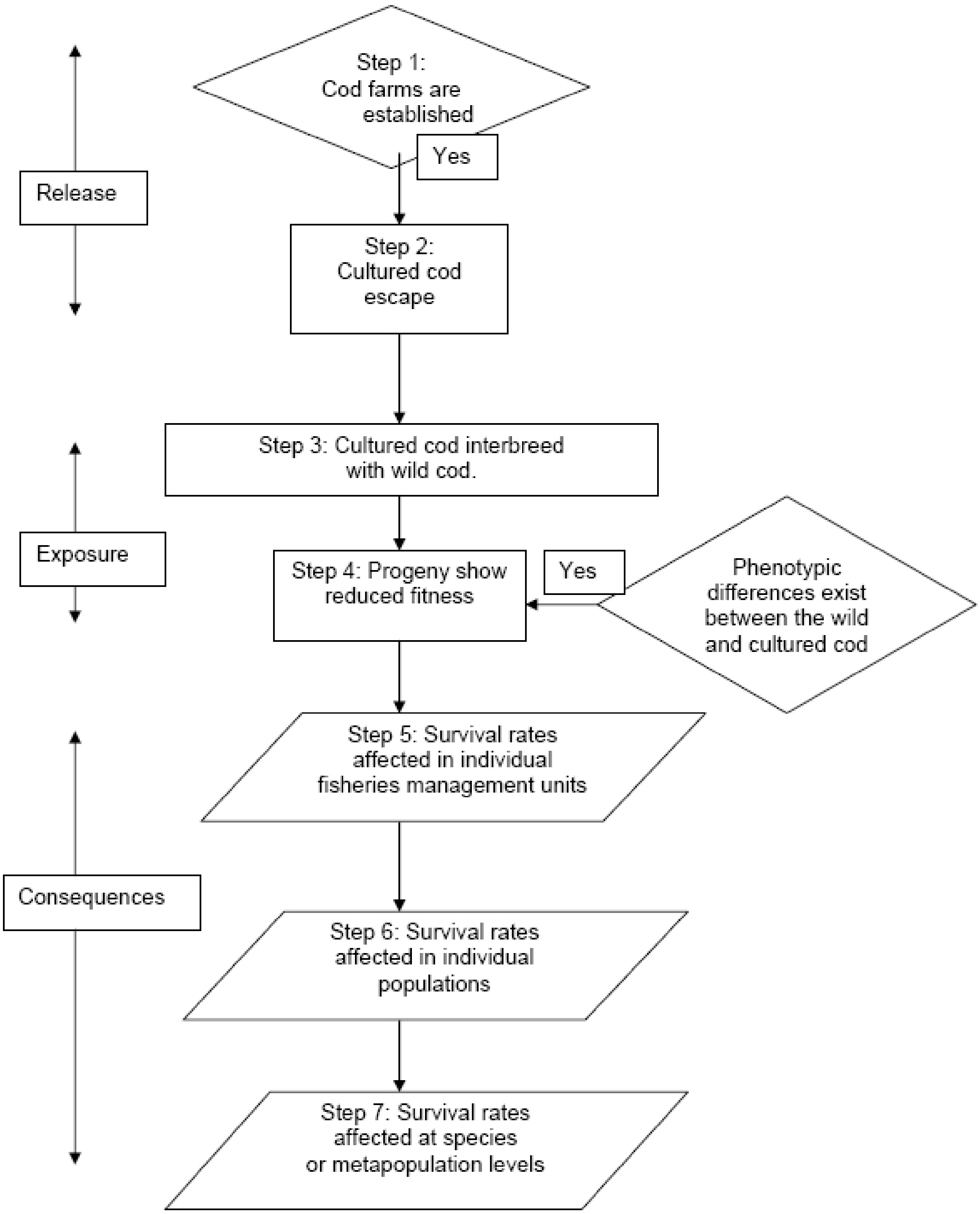
This logic model can be illustrated diagrammatically in Figure 6.3.1. The steps are classified into aspects related to the release of cultured cod into the environment, the exposure of the wild population to the genetic composition of the cultured fish, and the consequences for the wild populations at difference scales from local to the range of the species.

6.3.2 Hazard Identification

The hazard being assessed is the escape of cultured cod, in the form of fish (juvenile or mature), fertilised eggs, or gametes. The authors have not found any published accounts of the effects on wild populations of such escapes. However, cod stock enhancement programmes (for example, intentional releases of large numbers of hatchery-produced cod juveniles to the wild with the purpose of enhancing wild cod stocks) have occurred in several areas, and observations made in these programmes can provide some guidance on the likely interactions of unintentional escapes of farmed cod.

An overview of cod stock enhancement activities along the coast of North America has been compiled by Richards and Edwards (1986). No consideration was given in this review to the potential impact of these releases on natural ecosystems. Further references

Figure 6.3.1 : Diagrammatic representation of the logic model used for the genetic interactions of farmed and wild cod. (Standard flow chart symbols from http://www.patton-patton.com/basic_flow_chart_symbols.htm)



relating to cultured and wild cod interactions include Jørstad *et al.* (1994) and Kitada *et al.* (1992).

Historically, cod stock enhancement has occurred in Norway, Sweden, Denmark, Faroe Islands and North America. Svåsand *et al.* (2000) reviewed the effects of these attempts to supplement wild stocks with cultured cod. Releases involved fish between 8 and 41 cm in length (wild cod in Scotland are ~20 cm long at year 1 and ~50 cm at year 2). The numbers of fish released were relatively small, and varied between 500 and approximately 400 000 fish. Survivability of released cod was highly dependent on the age and size at release. The average rate of mortality of released yolk-sac larvae in Norway was 23% per day during the first 10 days, with only 0.15 % surviving the first 40 days after release. The optimal timing for release is generally after the juveniles have reached the size at which they settle to the benthos.

The occurrence and migratory habits of Baltic cod, together with the changes in their allele frequency, haemoglobin types, meristic characters and otolith types, based on results of extensive tagging trials since the 1950s, were reviewed by Otterlind (1985). About 15 transplantation experiments with tagged cod were conducted to assess the potential homing ability of the fish. The waters along the west of Bornholm constitute an area of hydrographic instability with varying cod migrations and passive transport of fry by currents. Except for local stocks, cod raised in the central and northern Baltic areas migrate mainly to the east of Bornholm, with a varying contribution of the cod from the west of the Baltic Sea. Fish in the latter group migrate primarily southward within the Baltic Sea to spawn, and as adults they usually stay east and north of Bornholm. Results of the transplantation experiments support a strong linkage between cod migration and hydrographic factors. Cod tagged and transplanted to a new area behaved and moved in the same way as the local stock. Indications of 'homing' can be found in areas with suitable hydrographic gradients, such as changes in salinity (*for example*, in Oresund).

Studies from Norway suggest that released reared cod have a variable fidelity to an area. Fish from one resident southern coastal population were fairly stationary when released, with more than 80% of fish recaptured within 5 km of the release site, and no more than 5% dispersing more than 10 km. Reared fish from another northern population had only 45% recaptured within 10 km of the release site. In Denmark, 72% of recaptures were taken within 40 km of the site of release. In the Faroes, more than 50% of the recaptures occurred within 10 km of the release site. On this scale of dispersal (for example, within 50 km of release) Svåsand *et al.* (2000) stressed that results obtained in one area cannot be generalised to other area.

Svåsand (1993) also examined behavioural differences between reared, released and wild juvenile cod, using Floy anchor tags and oxytetracycline markers. While differences in individual behaviour patterns occurred, no differences in migration patterns between wild and reared specimens were demonstrated.

Nordeide and Salvanes (1991) compared the stomach contents and liver weights of reared, newly released cod and wild cod; the stomach contents and abundance of potential predators were also described. During the first three days after release, the reared cod fed mainly on non-evasive prey such as gastropoda, bivalves, and actinaria. This is in contrast to wild juvenile cod, which mainly fed on gobidae, brachyura, and mysidacea. Large cod, pollock, and ling preyed upon the released cod immediately after their release, whereas, during the months following release, the stomach contents of large predators were dominated by labridae and salmonidae, which are also the typical prey of wild cod. The abundance of predators did not seem to increase in the area of release. However, a study by Svåsand and Kristiansen (1985) found no difference in dietary composition of cod five months after release. This suggests that although the foraging behaviour of newly released cod is poorer than wild conspecifics, they adopt similar feeding behaviour to wild fish within five months of release.

Jørstad and Nævdal (1992) and Jørstad (1994) reported an extensive series of investigations of the effects of mass rearing and release of 0-group cod in fjords and coastal areas of Norway. Each year since 1987, pond produced cod have been liberated in Masfjorden, a small fjord north of Bergen. The released cod, as well as the wild fish and those recaptured in the fjord system, have been genetically characterised by electrophoretic analyses of haemoglobin and several enzymes. In 1990 and 1991, about half of the released cod consisted of offspring of broodstock homozygous for a rare allele (Pgi^{-1}(30)). This broodstock was produced by crossing pre-selected heterozygotes for this allele, the homozygotes among the offspring were sorted out on the basis of biopsy sampling of muscle tissue, and when matured, used as parents (Jørstad, 1994). Extensive genetic studies and monitoring were carried out in Masfjorden and Øygarden for both the released and wild cod. Except for the enzyme GPI, the groups of fish did not differ and the patterns of change associated with the GPI frequencies were attributed to genetic drift rather than local adaptation, for example, there was no evidence that the relative survival of the released and wild fish was affected by local conditions.

Svåsand *et al.* (2000) reviewed studies of the ecosystem level effects of large scale releases of reared cod in the Masfjorden and Troms areas of Norway. The Masfjorden studies involved a control fjord and an experimental fjord into which large numbers of reared cod were released. Both sites were monitored before and after the release to detect potential interactions between released cod, its predators (large cod, pollock) and competitors (poor cod, *Trisopterus minutus*), and population characteristics (abundance, growth, condition factor, liver index). The abundance of selected prey species was also monitored. Only minor effects could be ascribed to the releases of cod (Fosså et al., 1994). Recent unpublished data on the poor cod suggests a reduction in size in the experimental area, but not in the control area. For wild cod, however, there was a slight reduction in condition factor and liver index. Higher densities in the experimental fjord became undetectable within 1.5 years. The data suggest that reared cod suffered higher mortality than the wild cod.

In the Troms area experiment, releases did not increase the biomass of cod in the fjord, nor did they reduce prey abundance. A strong year class at that time was believed to have lowered growth rates and may have had an effect on the ecosystem similar to that of an average year class enhanced by released fish.

6.3.3 Risk assessment

The following analysis of the risks of genetic interactions between wild and cultured cod in N.W. Scotland is predicated on the assumption that carrying capacity is not a limiting factor for the abundance of wild cod. Given the historical fishing pressure, low abundance of stocks over more than a decade and the nature of the meta-population structure of cod populations, it is likely to be very difficult to detect carrying capacity effects at the meta-population level. With the potential movement of individuals between sub-populations, it may also be difficult to detect carrying capacity constraints at the sub-population level; but if constraints were occurring they are most likely to be evident at this level.

Our understanding of long term effects of introgression in fishes is limited and has been best studied in salmonid populations. Studies of introgression in marine fishes are almost non-existent. Discussion of the potential effects of introgression between wild and cultured cod must therefore be made in relation to theory and knowledge of the interactions between wild and cultured salmonids.

The concern being addressed herein is that escaped cultured cod may interbreed with wild populations of cod and negate the effects of selection in the formation of locally adapted populations. The consequence of this introgression would be reduced survival in the wild fish population.

Determining what constitutes the size of a managed population is predominantly a governance issue of policy. However, from a scientific point of view it is possible to make some *a priori* estimates of the minimum population size required for the allelic frequency in a population to be effectively determined by selection.

During a protracted period of decline in the size of a populations, there is the possibility that the numbers will become so small that the effects of natural selection will become diluted or nullified by inbreeding and stochastic changes in allele frequencies (genetic drift). Published numbers used for this critical population size vary between effective population sizes (N^e) of 500 and 5 000 individuals (Lande 1995; Franklin 1980 and Dennewitz 2003). In the following analysis, it will be assumed that, if the population has been in decline for a number of generations and the N^e is below 500, then any long term stability in genetic frequencies is not determined by local adaptation. The genetic risk analysis should therefore be performed on the next level, for example, the lowest component level of population structure that exceeds the minimum effective population size for natural selection to be effective.

6.3.3.1 Release assessment

The hazard being assessed is the escape of farmed cod (as fish or gametes) from cultivation sites. Cod gametes may be released by caged cod, and cod have been known to breed during their culture in cages. Further, farms that choose to specialise in the market for larger cod or to maintain fish as a potential brood stock would have large, mature fish in their systems thereby increasing the opportunity for spawning in cages. However, the reductions in growth rate associated with redirection of energy into making gametes has resulted in the development of photoperiod manipulation protocols to delay or suppress maturation (Taranger *et al.* 2006). It is likely that, in the future, farmers will manage their stocks so that very few fish spawn in the cages, thereby reducing the probability of gametes or fertilised eggs escaping from the cages.

While techniques are rapidly developing to control reproduction in cod culture, there is still some potential for cod to spawn in cages. Cod milt and eggs are known to survive for a relatively long time after release, and fertilization of eggs can occur upwards of 60 minutes after release. If present, gametes from wild cod outside net pens could therefore potentially interact with gametes produced by farmed fish inside the cages, although the main spawning areas for wild cod are in more offshore areas.

A similar problem of dispersion of a time-limited viable agent is dealt with in management of diseases on fish farms in Scotland. There the criterion used is the predicted dispersion of an agent over a tidal cycle (12 hrs). That has been translated to a ‘rule of thumb’ of a 5 km separation distance between groups of farms in a disease management unit. If thought necessary, a similar approach might be applied to review the existing locations of cod farms and be part of future planning to separate farms from cod breeding areas. At present, the depth and location of wild cod spawning grounds suggest that the dominate route of interaction between wild and cultured cod will be via escapes of cod from cages rather than via dispersal of gametes.

The inability to reliably produce cod fry for aquaculture has been a significant historical constraint on the development of the industry. In 2002, a breakthrough in the production of cod fry occurred in Norway, when approximately 3 million fry were produced. In addition, survival rates of 87% from hatching to 0.2 g were reported in one hatchery in Scotland. These recent success stories are due to improved knowledge and an increased number of enterprises. A production target of 10 million fry in Norway is expected in the next few years, which will be followed by a subsequent substantial increase in production. As can be seen from Figure 2, intensive fry production is the dominant production method.

Fry production in other countries is less developed. In Scotland, around 50 000 juveniles were stocked in 2002, with 15 tons of cod produced in 2000 and 2001.

Figure 6.3.2 : Total production of cod fry in Norway 1983 - 2002 (Karlsen and Adoff 2003)

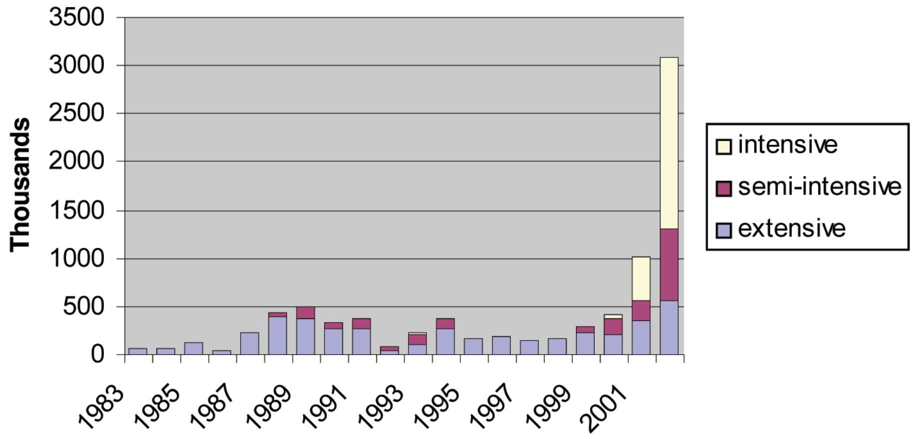
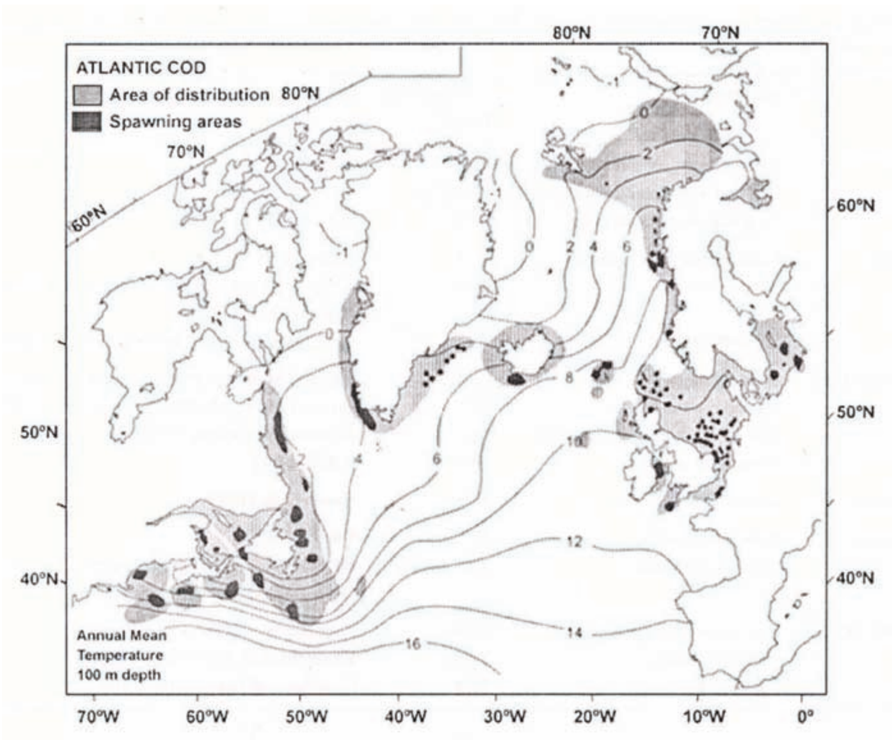


Figure 6.3.3 : Cod distribution and spawning areas (after Imsland and Jonsdottir 2003)



More than 350 tons of production is predicted in 2005. In Ireland, a research fellowship is in place to identify and harness potentially exploitable research and technology so as to enable the establishment of a commercially viable cod hatchery as a preliminary step to developing an industry.

Cod culture in sea cages is currently confined to relatively sheltered inshore areas, compared to salmon culture. The siting, distribution and position of farms 'licensed' to hold cod will be determined by national regulatory bodies (for example, Local Authorities, the Crown Estate Commission and the Scottish Environment Protection Agency in Scotland, and the Ministry of Fisheries in Norway). From the FRS (Scotland) database, 20 out of 483 registered farms have multi-species licences and therefore have the potential to stock and produce cod. No aquaculture licences for cod have yet been issued in Ireland, although several applications are being evaluated. Cod reared in pump ashore facilities, particularly those employing treatment of discharge water (filtration and sterilisation), pose a negligible risk in terms of fish escapes.

FAO data show that the production of farmed cod in 2001 occurred in Norway (608 tons), UK (15 tons), and Iceland (140 tons). More recently, it was predicted (Goodlad, 2003) that cod production may increase from 6000 tons in 2003, to 200 000 tons in 2010, and 400 000 tons in 2020, mostly in Norway. Predictions for Scotland suggest 25 000 tons will be produced by 2012-14. This dramatic increase in cod farming will inevitably lead to an increased risk of escapes.

Rearing trials suggest that sites with water currents in excess of 1m per second are unsuitable for growing cod. Consequently, cod farms will tend to continue to be located in less exposed locations, in terms of both tidal currents and wave action, and thus the risks associated with storm damage will be less than those for salmon (assuming engineering comparability of equipment). Measures such as double netting will further reduce the likelihood of escapes.

There have been no reported escapes of large numbers of farmed cod in Scotland to date (2006), although the industry is still in its infancy. Therefore, there is no specific information available on the rates of escapes of farmed cod under Scottish conditions. However, extensive information is available on rate of escapes from Scottish salmon farms, due to compulsory notification of escapes (Registration of Shellfish and Fish Farming Business and Registration Order 1985). Reporting of escapes is also compulsory in Ireland and Norway. Over the last 5 years, there have been 20-25 escape events per year from Scottish fish farms, mostly from Atlantic salmon farms. The numbers of escapes of salmon from saltwater sites in Scotland have been between 76 000 and 411 000 growing fish (1-4 kg) per year (Table 6.3.I).

This table suggests that the rate of escape is typically around 0.1 – 0.5% of the total number of individuals in cultivation. If this rate is applicable to cod culture, this suggests an escape rate of between 20 000 and 150 000 cod per annum at an annual input to on-growing of around 10 000 000 juveniles per annum.

As a consequence of the fidelity of cultured cod to the area of release, it is likely that cod escaping from the Norwegian industry would mainly join local wild cod in a northern migration to breeding areas, rather than join the fish in the North Sea. As such, it is anticipated that any farmed fish breeding with North Sea cod would mainly be those originating from Scottish farms.

The main causes of escapes from salmon farms have been: human error, equipment failure, bad weather and predator attacks. Cod are currently cultivated using similar equipment (square or circular netting cages with steel of plastic flotation collars in sheltered coastal waters), and therefore these factors could also be considered the main areas of risk with regard to cod farming, with some modifications:

- The generally more sheltered locations of the cod farms at present would lessen the risks of storm damage, but shelter could increase the risk of predator (for example, seal) attacks.
- Human error and equipment failure could probably be regarded has having similar levels of risk as salmon farming.
- Evidence regarding 'nibbling' of nets is currently unclear. It has been reported not to appear to be a significant factor with cod (Scottish Executive Working Group on Escapes), particularly with the use of double nets, but on the other hand observations of 'determined attempts' to escape through netting has been reported in Norway (www.sintef.no).
- Cod can be transferred to sea pens at weights above 5 g, whereas the minimum weight at transfer of salmon smolts to sea is typically 35 g. The risk of escape through minor holes in the net is consequently greater for juvenile cod.
- Unlike salmon, cod shoal rather than school, so the motivation for a contained cod to follow an escaping cod may be less than it would be for salmon in similar circumstances. However, further work is required in this area.

Although outside the scope of this risk analysis, it may be noted that accidentally released fish from culture sites may interact with local wild cod populations at a number of life-cycles through feed competition and behavioural stresses. Behavioural stress will be particularly intense when territorial competition is a key component controlling population density in a given habitat. If a decline in abundance of cod during the 1900s is primarily a consequence of fisheries pressure, it would seem likely that food and habitat resources do not currently limit the survival of cod. This conclusion has been reiterated by Baxter (2000) who states that "unless a small wild population is swamped by large-scale releases (or stocking) of reared fish, it seems unlikely that the reared fish will out-compete the wild fish".

Table 6.3.I : Numbers of salmon smolts put into salt water on-growing units, and numbers of escapes for 1999 – 2004. The percentages are calculated from the smolt inputs in single years. As the production cycle is approximately 2 years, the escape rates expressed against the total fish numbers in cultivation will be approximately one half of the percentages in this table.

	Number (millions) of salmon smolts put to sea	Numbers escaped in salt water (thousands)	% Escapes
1999	41.1	257	0.63
2000	45.2	411	0.91
2001	48.6	76	0.16
2002	50.1	376	0.75
2003	43.8	104	0.24
2004	38.1	83	0.22

6.3.3.2 Exposure Assessment

6.3.3.2.1 Distribution and movements

Studies suggest that, in the North Sea and off the coasts of Canada, Iceland and Norway, cod have differentiated in to a number of subpopulations (Imsland and Jonsdottir 2003; Jorstad *et al.* 2007). Ruzzante *et al*. (1996) have demonstrated that there is genetic differentiation between onshore and offshore populations of cod in Canadian waters off the coast of Newfoundland. Later work by Ruzzante *et al.* (1998) suggested as many as 14 subpopulations may exist if both inshore and offshore populations are considered.

In the Eastern North Atlantic, Neilsen *et al.* (2001) identified three distinct subpopulations (North East Arctic Ocean, North Sea and Baltic). In the North Sea, recent microsatellite DNA studies (Hutchinson *et al.* 2001) suggest that there may be four distinct subpopulations. The amount of information supporting four rather than the traditional three subpopulations is limited and but an EU FP5 project (METACOD 2005) is investigating this issue.

This constitutes a major difference from the structure of salmonid populations, where substantial genetic differentiation can be found over relatively small geographical scales (reviewed by Altukhov *et al.* 2000). This is not unexpected, as salmonids breed in very discrete sites within lakes, rivers and streams and show high fidelity to a spawning site. Those sites exhibit considerable habitat heterogeneity and physical isolation.

Clearly the precise number of genetically differentiated cod populations is an ongoing discussion. Smedbole and Wroblewski (2002) have framed the discussion of cod population differentiation in terms of metapopulations, each composed of a set of local subpopulations. The degree of genetic differentiation among subpopulations may range from slight to almost complete isolation. The spatial patterning of subpopulations within a meta-population is temporally dynamic; subpopulations may undergo extinction and recolonisation, and new subpopulations may develop. Extinction, recolonisation and differentiation of subpopulations will be affected by abundance in the meta-population and recent studies (Beamish 2004a,b,c) suggests that oceanic regime shifts may, on a time scale of decades, have as large an effect on population abundance of marine fishes as fishing pressure.

If, in the course of time, a subpopulation number declines there is the possibility that the numbers will become so small that the effects of natural selection will become diluted by stochastic changes in allele frequencies over time (genetic drift). Under these circumstances, outbreeding to other components of a meta-population provides a degree of stability to the allelic frequencies in the subpopulation. Abundance of cod in NW Scotland is currently so low that the influence of genetic drift and the importance of other subpopulations in stabilising allelic frequencies must be considered.

Given the above complexity, some simplifying assumptions must be made about the structure of cod populations. Currently, the main areas where the aquaculture industry is actively engaged in seeking to develop cod farming are Canada, Scotland, Norway and Ireland. Imsland and Jonsdottir (2003) identify groupings of spawning areas off the east coast of Atlantic Canada, Scotland and Ireland, as well as off the north coast of Scotland. Gene flow between populations is generally expected to be highest between populations whose spawning areas are closer together. These aggregations of spawning areas may therefore form the basis for meta-populations with subpopulations derived and maintained by individual spawning areas within an aggregation of spawning areas. On this basis, for the purposes of this analysis, the cod population structure in the North Atlantic will be assumed to be composed of separate meta-populations in the North West Atlantic, Iceland, Scotland- North Sea (North Sea, NW Scotland, Skaggerak, and English Channel) and Norway (North of Stavanger).

Cod eggs and larvae were found through out the west and north coasts of Scotland during the spawning season (January-April) in the 1970s. By the 1990s, this area had diminished to areas off the west coast off the Western Isles and the northern North Sea (Heath *et al.* 1994). In this area, juvenile cod during their first year are found close inshore or around the mouths of sea lochs and fjords. Recruits to the adult cod population are widely distributed on the west coast of Scotland, mainly in offshore areas where they can occur in large shoals.

East of the UK, after hatching at a length of about 0.4 cm, young fish grow to between 2 and 8 cm by June, and are concentrated mainly in the eastern and northern parts of the North Sea. By the following winter, the young fish are between 13 cm and 26 cm in length and are concentrated in the shallow coastal waters of the eastern North Sea. One and two year old cod can be found all over the North Sea, although by age three they are distributed mainly towards the northern part of the North Sea (The Centre for Environment, Fisheries and Aquaculture Science, pers. comm.).

At the moment there is very little conclusive information on cod nursery areas. The general feeling at the moment is that juvenile cod prefer exposed rocky inshore areas. However, they have also been found on offshore gravel banks in the southern North Sea and sand banks off the west coast of Scotland (EU project METACOD, 2005; and current METAGADOID project). These projects have identified regional populations of cod in the Moray Firth, off Flamborough Head, in the German Bight, in the Southern Bight of the North Sea and in the English Channel that separate during the spawning season and, in some cases, inter-mix during the feeding season. The Clyde Sea has also been identified as a preferred area for juvenile cod. From the evidence of NW Atlantic stocks, we might expect that the different reproductive units might intermix to some extent during the summer.

There is some understanding of the movements of cod to the west of Scotland. As elsewhere, eggs and larvae are dispersed by currents until the young cod move onshore in the spring where they feed and grow in shallow waters for the first year. In late summer, cod move from west of the Hebrides to the north coast of Scotland. In late winter and early spring, they reverse this movement. There is information to indicate that, in the NW Atlantic, cod migrate along clines of preferred ambient temperatures (Rose 1993). Some coastal aggregations of cod appear to show very limited migration and these are most likely to be the most sensitive to interactions with farmed stocks. Cod reach maturity at 2 - 3 years and on the west coast can also spawn at this age. Although maturity at age varies by region, all cod are spawning by six years of age. Non-spawning adult populations can be either migratory or resident.

Results from tagging experiments show that there is a little interchange of cod between the North Sea and areas to the west of Scotland. Tagging studies carried out over several decades have also shown that generally the maximum distance travelled from the release point is about 200 miles, although a few long-distance migrations have been recorded. In one experiment in June 1957, when cod were released in the central North Sea, two fish were recaptured off the Faroe Islands in September 1957 and one fish was recaptured off Newfoundland in December 1961. The available information indicates a degree of uncertainty in understanding of the migratory and other behaviour of cod, and the existence of structure within the overall population to the east of the UK.

Tagging data from Scotland show that there is little exchange of fish between the Firth of Clyde population and those in the Minch, particularly in the North Minch, north of Skye. Cod from the Minch have been caught north of Scotland but there is little apparent exchange between Minch cod and cod in the Moray Firth (NW North Sea).

The above discussion has mainly concentrated on cod stocks round the United Kingdom. Although the appropriate information is not presented, it is considered that the principles and patterns established in this limited area are broadly applicable to cod in other areas, for example, off the Norwegian or Canadian coasts.

6.3.3.2.2 Growth and mortality

Under typical growth rates in Scottish waters, wild cod will reach 20 cm (90 g) after 1 year, 50 cm (1300 g) after 2 years, and 80 cm (5200 g) after 4 years. Data on growth rates of farmed cod transferred to net pens in Scotland at an average weight of 5 g in July are summarised below:

Date	Average weight (g)
July – 1st year	5
October – 1st year	40
December – 1st year	120
February – 2nd year	230
April – 2nd year	350
December – 2nd year	2000
December – 3rd year	3500

A growth trial in net pens carried out on wild cod captured from Bay Bulls in Newfoundland, showed that, when cod were fed on either capelin or two different types of formulated wet diets, they grew on average between 33-34% over a three-month period of the trial (Clark *et al.* 1995).

Predation mortality of cod eggs is predominantly from sprat and herring, as well as juvenile and adult cod cannibalism. The survivability of settling larvae has been linked in many studies to the complexity of the seabed, and is one of the targets of the METACOD project.

Most mortality occurs during the juvenile stages. A significant proportion of the mortality can be due to starvation and cannibalism by older cod, as well as predation by other piscivores. Not surprisingly therefore, different age classes of cod do not aggregate together. After about one year's growth, young cod (in Scotland, at ~20cm length) generally move offshore to feed where they become susceptible to increased fishing pressure prior to recruiting to the spawning stock.

Most cod stocks in the North Atlantic are below the ICES precautionary levels, and in some ICES areas there is a moratorium on cod fisheries. Many of these populations have been in decline for more than a decade, and as the meta-population shrinks and can no longer support all its subpopulations, fisheries have witnessed the disappearance of some local cod populations. Since 1980, the fishing mortality on North Sea stocks has been around 1.0, although it has varied rather more since 2000 (0.5 – 1.2) at a time when stocks have been reduced to such a level that productivity is impaired, and a formal stock recovery plan has been introduced at EU level (ICES 2005).

6.3.3.2.3 Diet

In a study off the west coast of Sweden, Mattson (1990) reported that cod ranging in size from 6 to 97 cm fed at 40-90 m depths. Diets consisted mostly of benthic and epibenthic species (Mattson 1990), with 75% crustaceans and fish. At larger sizes, the proportions of benthic species to copepods increase with size. Young cod up to 1-3 cm size feed exclusively in the water column on copepods, then at 4-6 cm size add benthic prey species such as mysids and amphipods, but copepods remain an important food item. Large cod also consume molluscs, worms and smaller fish.

Juvenile cod are preyed upon by larger piscivorous fish (including larger cod), seals, cetaceans and birds. The proportion of each of the predator types has been shown to vary from year to year. Cannibalism is a large part of predator-prey relations, with larger 0-group cod and older cod consuming smaller ones. Stomach content surveys seem to be most comprehensive in the Baltic Sea. Studies from Newfoundland corroborate these findings. Seals are a significant predator of adult cod; 82% of seal diet in Northern Scotland made up of fish, with 50% sandeel and cod also important prey items. A Canadian study also found that grey seal predation caused 10-20% of mortality in cod stocks.

6.3.3.2.4 Abundance

Cod stocks around Scotland are under severe fishing pressure. Spawning stock levels for both the North Sea and west coast stocks are below safe biological limits. Stocks have been below ICES precautionary levels since 1988. ICES advised the European Commission and national governments that all fisheries which target cod, even as a bycatch, in the North Sea, Skagerrak, Irish Sea and waters west of Scotland should be closed (ACFM 2002).

The ICES ACFM report for 2003 (ACFM 2003) estimates that the spawning stock biomass of cod to the west of Scotland in 2002 was 2,230 tons, with 3 000 000 individuals recruiting at age one. In 2005, the biomass of these stocks was estimated at only 350 tonnes (ACFM 2005). The spawning stock biomass in the North Sea, English Channel and Skagerrak combined was 54,400 tons, with 168 000 000 recruits at age one. The most recent complete data on numbers of individuals present in the North Sea/Skaggerak/English Channel stock assessment area are for January 1, 2003 (Table 6.3.II).

Table 6.3.II : ICES estimates of numbers of cod at age in the North Sea, Skaggerak and English Channel combined, January 1, 2003.

Age	Number of individuals
1	50 037 000
2	63 059 000
3	14 034 000
4	13 234 000
5	1 542 000
6	260 000
7	122 000

The combined average landings of wild cod in the waters off Ireland and UK have plummeted from 75 000 tons per annum to less than 25 000 tons since the mid-1990s (Marine Institute, Stock Book 2001). Around Iceland, there has been low spawning stock biomass and weak recruitment since the mid-1980s.

6.3.3.2.5 Reproduction and spawning

Adult male and female cod form pair bonds, but egg fertilization is external. Females are batch spawners, often producing 15 egg batches over a period of six weeks. One adult female can produce around 4 million eggs (depending on size) per season. Around Scotland, cod may reach maturity at two years of age, but do not spawn until four years old. At age six, all fish are mature. However, most fish are caught in the fishery by the time they are age two.

Data taken from the ICES International Bottom Trawl Surveys, two EU funded projects (Heath *et al*. 2003; METACOD 2005), ichthyoplankton surveys and responses to questionnaires taken from fishermen have found that cod spawn throughout much of the North Sea, although some spawning aggregations do occur. The main spawning areas in the North Sea are in the central North Sea around the Dogger Bank, the southern North Sea, and the German Bight. There is also a center of spawning in the NW North Sea in the Moray Firth (CEFAS). The EU projects are producing much useful information, and FRS has produced a report on North Sea spawning grounds. Spawning aggregations also appear to occur in the Irish Sea and off the NW coast of Scotland. Spawning on the West Coast takes place between January and April, mainly in offshore areas.

The time of spawning is well documented as being between January and April, with the more northern areas spawning later than the more southern areas. Eggs, which are about 1.4 mm in diameter, are found floating in the surface layers over large areas of the North Sea. They typically hatch over a period of 11-30 days, depending on water temperature. *C. finmarchicus* is the staple prey of first feeding larvae of Atlantic cod. Cod juveniles live in the upper water column until around August before settling to a demersal life style, driven mainly by changes in food requirements from predominantly copepods to benthic species.

In Iceland, mature cod in the spawning period were typically found in waters over 300 m in depth, indicating that spawning normally occurs offshore (Begg and Marteinsdottir 2002a, b).

A Canadian study on variation in size-specific fecundity of cod sampled from the Gulf of St. Lawrence and the Georges Bank indicated significant variation that could not be attributed to physiological conditions (McIntyre and Hutchings 2003).

6.3.3.2.6 Genetic structure of wild populations

As discussed above, there is an ongoing debate about the large scale and small scale structure of cod populations. However, to evaluate the potential effects of cultured cod on wild populations, some attempt must be made to outline the likely structure and variability of wild cod populations. Smedbol and Wroblewski (2002) have described cod population genetics as 'meta-populations'. The meta-population structure incorporates concepts of discrete local breeding populations connected by immigration and emigration. Depending on factors such as the distance between areas occupied, geographic or oceanic barriers, and the dispersive ability of the species, the degree of segregation between subpopulations can range from slight to almost complete isolation. However, exchange between subpopulations of the meta-population prevents the development of separate autonomous populations. Begg and Marteindottir (2002a, b) typify a cod meta-population as a composite of local populations (*for example,* spawning components) between which individuals move, and where 'source' populations provide immigrants to less productive 'sink' populations.

No information was found that would allow comment on the rate of straying (and presumably introgression) between subpopulations within a meta-population.

6.3.3.2.7 Synthesis

Genetic interactions between farmed and wild cod depend on escapes of fish from holding facilities. Wild cod can have a protracted spawning period (usually January to June, depending on the area) thus presenting opportunities for a temporal coincidence in the occurrence of wild and cultured cod gametes released from cages. Further, studies have shown that cage reared cod will spawn concurrently with wild cod in the same region. However, wild cod appear to spawn in offshore areas at considerable depth some distance from the present location of cage culture, and therefore it is unlikely that gametes from cages will encounter gametes from wild stocks.

Most adult cod stocks do not frequent the shallow, coastal waters typically used by the salmon industry today, and which will be the location for a developing cod farming industry. As such, direct interaction between caged and wild mature adults will be limited.

Wild, juvenile cod are known to occupy near shore areas where cobbles and kelp can be used for predator evasion and offer diverse feeding opportunities. Eelgrass beds are also known to be important nursery areas where they occur. Escapes in these habitats would probably interact with wild juvenile cod, and give opportunity for escapes to mix into wild stocks, but clearly would not immediately interbreed.

In the event of escapes, the age of the released cod may determine how they adapt to the marine ecosystem. For instance, wild juveniles typically establish schools in inshore, shallow water areas. Escaped juvenile fish may therefore join conspecifics of similar size in inshore waters. On the other hand, adults are found in deeper, more oceanic areas and escaped cod may also follow this migration pattern. Where mature fish escape at the appropriate time of year, they would need to migrate to offshore spawning areas before they could potentially interbreed with wild populations.

Conversely, small juvenile wild cod may enter cages and be exposed to predation during their first year when they have a pelagic life style, but after that it is unlikely that they will be exposed to predation by caged fish. However, the numbers of juveniles lost in this way may not be significant, as juveniles are known not to inhabit the same area as older cod (perhaps to avoid cannibalism) and may therefore actively avoid older cod in cages.

It is not known if adaptation to local environments exists in marine fishes like cod, but if it does, such adaptation will depend on the degree of isolation from other conspecifics. The Danish Institute of Fisheries Research is studying the possible occurrence of local adaptations in marine fishes, and this work should provide useful information relevant to the consequences of escapes of cod.

At least in the first instance, cod farming is likely to occupy the same general areas of coastal waters as salmon farming. Some competition for space may occur, but as farmers seek to grow cod experimentally at established salmon farms, relatively little additional capital will initially be required to establish cod farming on a small scale.

6.3.3.3 Consequence Assessment

The genetic effect of escapes is likely to be minimal if the farmed stock is made up of wild-caught juveniles from a widespread and abundant local stock, which has a regional rather than local population structure. On the other hand, there is a significant potential for change if farmed fish are of non-local origin with low genetic diversity (*for example*, from small populations with a high degree of inbreeding), and subsequently mix with a population that is not differentiated into a series of distinct local populations. Since cod populations are now rather small in many inshore waters, the impacts on wild cod populations may be noticeable if unusually high numbers of non-native farmed stocks repeatedly escaped into depleted local stocks.

Whether cultured for all of their life cycle or only part of it, cultured fish face different selective pressures and a different 'learning environment' than wild populations. Consequently, cultured cod will ultimately express different genetic, phenotypic and behavioural traits than wild cod. A critical question is how significant these differences will be, and to what degree will they impact wild populations when cultured and wild populations interact. Experience with cod culture (as an enhancement activity) dates back to the middle of 1800s. However, actual investigations of the differences between wild and cultured cod are primarily from studies in the 1980s and 1990s. Our knowledge of the differences is further limited by a number of factors including the short time cod have been under continuous selection for culture, the incomplete knowledge of the genetic structure of wild and cultured cod populations, and the fact that, both in culture and in the wild, the selective pressures on the cod genome are constantly changing.

The potential for inter-species hybridisation involving escaped farmed cod is not thought to be a problem (FRS pers. comm.). An extensive e-journals literature search found no reference to any literature on cod hybridization. However, experiences with salmon suggest that further research may be required. Youngson *et al.* (1993) have identified what is likely a behavioural deficiency in escaped farmed salmon that has led to increased levels of hybridization with brown trout. Such hybridization was found to be ten times more frequent among escaped farmed than wild Atlantic salmon females.

Recent studies on NE Atlantic cod conducted by Dr T Svåsand, from the Institute of Marine Research in Norway, included comparisons of wild and cultured cod in regards to behaviour, migration patterns, stomach contents, and growth. Feeding methods, and the efficiency of feeding methods, have been shown to be different in wild and reared cod, with the wild cod generally outcompeting reared cod. Therefore, if feed limits survival, escaped fish are likely to have lower survival rates than wild conspecifics.

The current trend among start-up cod hatcheries in EU countries is to source either eggs or broodstock from established farms that are certified as disease free, thereby minimising risks associated with the use of wild cod of indeterminate health status. Consequently, the practice of introducing non-indigenous cod may increase and accelerate the rate of genetic divergence between farmed and wild cod stocks.

Wild populations can re-adapt following introgression. They do this when individuals from other genetically distinct cod populations (strays who fail to home to the breeding grounds of their parents) interbreed, and presumably can do so when the introgression is with farmed fish. The rate at which the maladapted genes are removed from the population depend on the magnitude of the fitness reductions, the effective population size (Ne) of the wild fish population (a low Ne will reduce the rate of removal of maladapted genes), and the rate of gene flow between the cultured and wild population.

Studies of the magnitude of the reduction of fitness in hybrid cultured and wild cod have yet to be undertaken. Cod, however, have been in culture for a relatively short period and have had little time to genetically differentiate themselves from the wild populations. Cultured salmonids, in contrast, have been raised and selected for culture for many generations. Studies by Skaala *et al.* (1990) and McGinty *et al.* (2003) have shown that maladapted traits in hybrid salmonid populations are removed rapidly over a few generations. It would seem reasonable therefore to expect the same maladapted traits in cod.

Effective population sizes large enough to be free of genetic drift and inbreeding should not experience a reduction in the rate of removal of maladapted genes from the population. Published effective population sizes (Ne) required to avoid the long term effects of interbreeding and genetic drift range from 500 to 5000 (Franklin 1980; Lande 1995). These are only crude approximations but give a starting point for evaluation of the status of wild populations. Hutchinson et al. (2003) calculated the ratio of effective population size to census population size in cod as 0.00004. As noted earlier, estimates of the number of fish recruiting to wild populations that cultured Scottish cod are likely interbreed with (North Sea – Skaggerak – English Channel Metapopulation) is in the order of 100s of millions of fish. One hundred million fish would constitute an effective population size of approximately 4000 fish so it is currently unlikely that the effective population size would limit the rate at which maladapted genes would be removed from the wild population.

The rate of gene flow between wild and cultured populations will, to a large degree, be determined by the proportion of the breeding population which is of cultured origin. Allowing for growth in production to the level of 30-40 000 tonnes per annum in the next 15 years, there would be approximately 10 000 000 fish in cages. Based on earlier discussions of a likely rate of escapes of 0.1 - 1% of the confined population, and all survived to breed, that would suggest that there could be 10 000 – 100 000 escaped cultured fish available for inter breeding. The actual level is likely to be much smaller due to mortalities after escape and before maturity, and there may also be a reduced success of effective breeding by cultured fish due to behavioral or other failures on the breeding ground. If there were 10 000 000 breeding age individuals in the wild, a generous estimate of the gene flow rate would be 1%. Through modeling the effects of gene flow, Theodorou and Couvet (2004) estimated that a gene flow rate of 5% annually each year for 20 years should have only a minor effect on the fitness of the affected population, provided that its effective population size was adequate.

It seems likely then that any introgression between wild and cultured fish at the projected growth of the Scottish farmed cod industry is unlikely to result in a major change in the fitness of nearby wild cod stocks in the next 15 years or so.

6.3.3.3.1 Logic model

The series of steps and processes leading from the establishment of cod farms in coastal waters to significant decreases in wild cod stocks as a result of genetic interactions between the two groups of cod was outlined at the beginning of this document in the form of a logic model as below:

Process of concern: Changes in fitness of wild populations of cod due to genetic introgression

End Point of Concern: Significant decline in survival in wild cod populations due to interbreeding with escaped cultured cod.

Logic model steps:

1. Cod farms are established in coastal waters.
2. Cultured cod, in the form of gametes, eggs or fish escape from cages.
3. Cultured cod interbreed with wild cod.
4. The progeny of this interbreeding (hybrids) show reduced fitness. This is dependent on there being phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons.
5. There is sufficient gene flow to affect survival rates of cod in individual fisheries management units, for example, the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.
6. Genetic interaction causes declines in endemic, evolutionarily significant units (populations), for example, genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.
7. Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population, for example, escapes of cultured cod cause significant decreases in wild cod stocks.

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. This exercise has been carried out for the cod farming industry as it is in Scotland in 2005, and how it might be in 15 – 20 years time, when production is forecast to reach 25 000 – 40 000 tonnes.

1. Cod farms are established in coastal waters.
   Highly probable - Cod farms are already established in Norway and Scotland. The current intensity and geographical range of the small number of farms are low. Considerable growth in production is planned for the coming years. Where active cod farms will tend to aggregate, as salmon farming has done, it is likely that the density of the farms will, over time, increase, but will still occupy only part of the wild cod's coastal habitat. Intensity of development and geographic extent are therefore considered to develop to moderate at the end of the period under consideration. Once in place, the farms tend to become a long term feature of the coastal environment, although they can be moved or removed. (duration - low). For this evaluation, the **severity** of this step is considered to be currently **low**, but may increase to **moderate** with time. Given the market demand for cod and the current limitations on wild fisheries, the probability of this step in the logic model occuring is **high** at present and over the time frame of the assessment.The **uncertainty** associated with this prediction is **low**, as development has already been initiated.

2. Cultured cod, in the form of gametes, eggs or fish escape from cages.
   With the present equipment and husbandry practices used in the industry, it is highly likely (**Probability** is **high**) that some cod will escape from cages. Experience with other species indicates that accidents happen. Data for the period 1999 – 2004 suggest an escape rate of 0.1 – 1.0% of salmon from cages in Scotland. Loss of fish from the cage will be strongly avoided so escape rates are likely to remain at least as low as that of salmon farming (< 1.0%). Currently, this will be of **low intensity**, and limited (**low**) **geographical distribution**. If the farms were totally removed, then, no further escapes of fish or gametes could occur (**Duration - Low**). The resultant **severity** of the interaction of the present scale of production will be limited (**low**), and there is a high probability that this prediction will be realised.

   As the industry grows, numbers of escapes will increase (**Probability - High**), and be spread over a larger area, but will still be small relative to the abundance and distribution of wild cod. The **intensity** and **geographical** spread of this are considered to be **moderate**. As in the previous paragraph, the **duration** will be **low** if cultivation ceases. **Severity** of this effect will therefore move towards **moderate**, and there is **moderate uncertainty** in this assessment.

3. Cultured cod interbreed with wild cod.
   Studies of released juvenile cod in fjord environments in Norway have detected no differences in behaviour (migration patterns) between released and wild cod, and have shown that interbreeding does occur. It is therefore highly likely that escaped fish will interbreed with wild fish (**Probability** - **High**). There is **low uncertainty** associated with this prediction. As the cultured fish genetically differentiate from wild stock, this may result in reduced competence to follow the wild fish to the breeding ground or to maintain the necessary spawning behavior. The intensity of interbreeding is currently assessed as extremely low, and of low geographical extent. The current Severity level of interbreeding is considered Low.

   As the industry expends, the **intensity** and **spread** will increase, although it is considered that it will remain no more than **moderate**. If farms were removed, no further interbreeding between escaped and wild cod could occur (**duration** - **low**). The **severity** of interbreeding in the future is therefore evaluated as **moderate**. The **Probability** of interbreeding in the future is reduced to **moderate** as domestication generally reduces the ability of wild and cultured stock to breed successfully together. **Uncertainty** associated with these predictions is **Low**.

4. The progeny of this interbreeding (hybrids) show reduced fitness.

   There is no evidence to support this contention for cod. For this to occur, it will be necessary for the cultivated fish to show phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons. There is evidence from restocking experiements that cultured juveniles can be selected to show phenotypic differences from the wild stocks. Currently, the industry uses a mixture of captive and wild caught mature adults as broodstock and this will mitigate against genetic differences between wild and farmed fish (**intensity** is **low**). The cod farming industry has a limited distribution in Scottish coastal waters (**geographical extent** has a **low** value). However, as it may take a few years for nature to remove hybrids from the population after removal of the farms, the **duration** of this is considered **moderate**. Therefore the current **probability** of the development of phenotypic differences (and subsequent reduction in fitness) for genetic reasons is **extremely low**.

   It is likely that as cod cultivation systems develop, cod will progressively become more independent of input of genetic material from wild populations. This will make it easier to select broodstock for genetically determined phenotypic traits (intentional or otherwise) desirable for cultured fishes (for example, late maturation). Therefore, the **intensity** of reduced fitness for hybrids will rise to a **moderate** level. Experience with salmonids suggests that as the differences between farmed and wild stocks become more pronounced, the genome of the escaped fish will lilkely be more heavily selected against. The geographical extent of this will probably be linked to the distribution of the farms. Even with suggested expansion of the industry, it is unlikely the industry will be close to most of the Scottish areas occupied by cod, and so the value of **geographical extent** is **moderate**. It is anticipated that if cod farming ceased, the **duration** of the effect of interbreeding now, and in the future, would last as little as a couple of generations and therefore the duration of this step in the logic model is expected to be **moderate**. As a result, the **severity** of this step will also increase to **moderate**. Over time, it is **highly probable** that greater differences will develope between farmed and wild stocks and there will be a reduction in the fitness of hybrids. The **uncertainty** about the fitness of current and future hybrids is considered to be **high** as no studies of hybrid fitness in cod have been undertaken.

5. There is sufficient gene flow to affect survival rates of cod in individual fisheries management units, (for example, the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at managed stock level.)

   Under the current industry conditions in Scotland, it is unlikely (**extremely low probability**) that even localised stocks will be adversely affected. This prediction is **highly uncertain** as it depends on the details of the presently limited distribution (**low** score for **geographical extent**) of cod farms within small areas of largely unknown stock structure. It also depends on the **intensity** of interaction between wild and cultured stock, which is likely to be limited (a **low** score). The uncertainty will decrease as the abundance and distribution of the target population increases. As in the previous step, if farms were removed from Scottish waters, the effects of interbreeding would quickly decline but might last a generation or two. Therefore, the duration of effect is considered to be **moderate**.

   As the industry expands, the probability of change will increase. However, knowledge of the detailed population structure of cod in the Atlantic is incomplete. Currently, stock management is based on large geographical areas (for example, North Sea, Skaggerak and Channel combined). However, there are suggestions that inshore populations in some fjords or sealochs may be to some degree distinct from the more open sea populations. If this is true, the small size of individual inshore populations may mean that sufficient escapees may be available from an expanded industry to significantly change the local wild population genome. At present, the distribution of farms is such that gene flow into these populations is likely to be intermittent, quantitatively small and the genetic differences small, so the **interaction** will be of **very low** intensity. With an increased number of farms in an area this would increase, as has been shown to occur for salmon (McGinnity *et al.* 2003) and brown trout (Skaala 1990) but it will remain confined to a small portion of the range of cod (**Intensity** - **Moderate**, **Geographical Extent** - **Low**). As a consequence, the future **severity** of change will increase to **moderate**. Hybrids will occur for a limited amount of time and so the **duration** involved in this step is seen as **moderate**.

6. Genetic interaction caused declines in endemic, evolutionarily significant units (populations), (for example, genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.)

   The scale of impact required to affect survival in wild cod at population level is greater than that required (in step 5) to affect more localised management units. The present **intensity** of interactions at the population level will be small (**low**), and the **geographic extent** will be very limited (**low**), although, as in previous steps, the duration may be **moderate**. Consequently, **severity** is **low**. The current **probability** that this happen is **extremely low**, and the **uncertainty** is this prediction is also **low.**

   Any escapes from the industry in the future will be interbreeding a population large enough so that the **intensity** of the interaction will remain **low** in spite of the increase in the absolute number of fish interbreeding. A larger industry will likely be more dispersed, and so there will be a **moderate geographic extent** of the interaction in reaction to the geogrphic extent of evolutionary unit. As in previous steps, the cessation of effect of interbreeding will lag behind cessation of the culture activities. from that reason, the **duration** of the effect is considered **moderate** and the consequent **severity** of occurrence will be **moderate**. With increases in the size of the industry, the probability and **uncertainty** of this effect will increase, but is considered to be **low** as the effect of the escapes is spread over a larger wild population.

7. Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population, for example, escapes of cultured cod cause significant decreases in wild/feral cod stocks.

   The current probability of effect on such a large scale is extremely low. The **geographical extent** of the industry is small (**low** score). The **intensity** of the interaction with Scottish farmed fish over the entire meta-population is small (**low** score) through the **duration** of any effect is likely to extend to a **moderate** period of time after cessation of cod farming. The consequent **severity** of interaction is rated as **low**. **Probability** of effects at the level of meta-population is judged to be **extremely low**, with a low level of uncertainty associated with this predication.

   Even the suggested increase in production is not considered to increase the probability of effect above the extremely low level. However, the **geographic extent** of the industry will increase (**medium** score). The **intensity** of the interaction with Scottish farmed fish over the entire meta-population is likely to remain small (**low** score) through the **duration** of any effect is likely to extend to a **moderate** period of time after cessation of cod farming. The consequent **severity** of interaction is rated as **moderate**, and the **uncertainty** associated with this prediction is **low**.

   The outcomes of the risk analyses for the current scale of cod farming in Scotland, and the predicted scale in 15 – 20 years time, are shown in Tables 6.3.III and 6.3.IV.

6.3.3.4 Risk estimation

Without regulations or farm management practices specific to cod farms, there is unlikely to be any difference between the outcome of the Consequence Assessment and that of the Risk Estimation. Risk management may be able to alter the values in Tables 6.3.III and 6.3.IV.

6.3.4 Risk management

Option evaluation in risk management addresses what might be done to reduce the probability of a risk being expresses, or to reduce the uncertainty in the predicted expression of a risk. The process identifies, for each step in the logic model discussed above, what could be done to reduce the probability of it occurring. These actions would directly mitigate possible effects. A further contribution to increasing the effectiveness of the risk analysis would be to reduce the uncertainty in the predicted probability that the step will happen. Usually this involves further research or development.

An initial consideration must be whether any action is necessary, for example, whether the risk is large enough that some mitigation is appropriate. In the case of the Scottish cod industry as it is today, the wild stocks are protected from the endpoints (undesirable consequences of interactions with escapes from cultivation) by the extremely low probability that there are phenotypic differences between the wild and cultured cod populations arising primarily for genetic reasons. Furthermore, the small size of the industry and its patchy distribution lead to an extremely low probability that there could be sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is not sufficient to affect population fitness, at the population or meta-population levels. However, there is high uncertainty in the latter assessment.

The need and opportunity for mitigation is therefore considered in relation to the Scottish industry as it might be 15 years time. By that time, it is anticipated that the expansion in the industry will mean that there will be less protection for wild stocks from adverse consequences of interactions with escapes, although technical developments such as improved containment may mitigate against this. Table V identifies both mitigation and research or development steps that could be in addressing risks associated with genetic interactions arising from cod culture.

Whether there will be an impact from escapes from cod farms will depend on the exact nature of the population structure in the wild stock and the genetic nature of the farmed stock. For instance, it could be the impact of escapes would be minimal if the expanded Scottish cod industry reared wild-caught juveniles from local stocks that were widespread and abundant, and showed a regional rather than local population structure. This would be true even if escapes involved relatively large numbers of fish. On the other hand, a significant local impact could occur if the farmed stock were a variety of non-local origin with a narrow genetic base (for example, a high degree of inbreeding), and escapes mixed with a highly structured stock with low numbers in the local population.

The release of genetic material from cod farms (either as gametes or as escaped fish) could be minimised by harvesting fish before they reach maturity; using sterile fish; or using pump-ashore sites where the effluent water can be filtered or sterilised. Use of sterile fish on cod farms would eliminate any possibility of genetic interaction with wild stocks. The use of triploid fish has been investigated in salmon culture; however the cost, relatively poor growth and market acceptability could be problems. More research into other methods of producing sterile fish is required. Studies at the University of St Andrews, Memorial University of Newfoundland, The

Table 6.3.III : Analysis of the cod industry in Scotland as it is today, producing a few hundred tonnes per year.

Steps in the logic model	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity (C,H,M,L, or N)** [1]	**Probability (H,M,L,EL, or N)** [2]	**Uncertainty (H,M, or L)**	Stage of assessment
Cod farms are established in coastal waters.	L	L	L	L	H	L	Release
Cultured cod, as gametes, eggs or fish, escape from cages.	L	L	L	L	H	M	Release
Cultured cod interbreed with wild cod.	L	L	L	L	H	L	Exposure
The progeny of this interbreeding (hybrids) show reduced fitness.	EL	L	M	L	EL	H	Exposure
Sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	L	L	M	L	EL	H	Consequence
Genetic interaction caused declines in endemic, evolutionarily significant units (populations), i.e. Genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.	L	L	M	L	EL	L	Consequence
Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population , i.e Escapes of cultured cod cause significant decreases in wild/feral cod stocks.	L	L	M	L	EL	L	Consequence

Table 6.3.IV : Analysis of the cod industry in Scotland as it may be in 15 years time, producing 25 000 - 40 000 tonnes per year.

Steps in the logic model	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity (C,H,M,L, or N)** [1]	**Probability (H,M,L,EL, or N)**[2]	**Uncertainty (H,M, or L)**	Stage of assessment
Cod farms are established in coastal waters.	M	M	L:	M	H	L	Release
Cultured cod, as gametes, eggs or fish, escape from cages.	M	M	L	M	M	M	Release
Cultured cod inter-breed with wild cod.	M	M	M	M	M	L	Exposure
The progeny of this interbreed-ing (hybrids) show reduced fitness.	M	M	M	M	H	H	Exposure
Sufficient gene flow to affect sur-vival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	M	L	M	M	M	H	Consequence
Genetic interaction caused declines in endemic, evolu-tionarily significant units (populations), i.e. Genetic interac-tion between wild and populations of escaped cultured cod causes sig-nificant declines in survival in wild cod populations.	L	M	M	M	L	L	Consequence
Gene flow is perva-sive and persistent enough to affect fitness at the level of species or meta-population , i.e Escapes of cultured cod cause sig-nificant decreases in wild/feral cod stocks.	L	M	M	M	EL	L	Consequence

Table 6.3.V : 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	Cod farms are established in coastal waters	H	• Where feasible move to land- based production	L	• Develop economically competitive land-based technologies.
2	Cultured cod, as gametes, eggs or fish, escape from cages.	H	• Improve containment design and/or build in fail-safe measures • Recovery plan for escaped fish	M	• Improve contingency plans for recapture, possibly including prior imprinting, e.g. of prey (pellets)
3	Cultured cod interbreed with wild cod	M	• Use of sterile fish • Harvest fish before maturity	L	• Improve methods of producing sterile fish
4	The progeny of this interbreeding (hybrids) show reduced fitness	H	• For each generation recruit all grow-out stock from juveniles captured in the wild • Retain the wild genome as far as possible	H	• Develop models of the impact of interbreeding on fitness. • Determine if differences are primarily genetic rather than environmental in origin. • Determine if differences are associated with differential survival.
5	Sufficient gene flow to affect survival rates of cod in individual fisheries management units, i.e. the population structure of wild cod is such that the rate of interbreeding is sufficient to affect population fitness, at the population or meta-population levels.	M	• Limit the distribution of cod farming to either proximity to small value stocks or very large stocks.	H	• Identify those population units that have significant potential to respond to selection. • Define rate of gene flow between stocks
6	Genetic interaction caused declines in endemic, evolutionarily significant units (populations), i.e. Genetic interaction between wild and populations of escaped cultured cod causes significant declines in survival in wild cod populations.	L		L	• Identify those population units that have significant potential to respond to selection. • Define rate of gene flow between populations
7	Gene flow is pervasive and persistent enough to affect fitness at the level of species or meta-population , i.e. Escapes of cultured cod cause significant decreases in wild/feral cod stocks	EL	• Limit the distribution of cod farming in relation to the distribution of the species or meta population	L	• Identify dynamics of genome at the meta population or species level.

Institute of Aquaculture at Stirling University, and the Institute of Marine Research in Sweden are investigating photoperiod control of maturation in cod. The British Marine Finfish Association website reports that "*Recent research has shown that continuous light can delay sexual maturation and improve growth, making the utilization of photoperiod manipulation a viable option*". This suggests that husbandry practices could significantly reduce the risk of release of viable gametes.

Recently, there has been considerable interest and action concerning the possibility of recapture of escaped salmon, since escaped salmon tend to remain in the area of the cages for some time after escapement. This is thought to be due to their tendency for schooling behaviour, and imprinting on artificial 'prey' (for example, feed pellets). The potential to recapture escaped cod has not been analysed; but is an important area for research. It is also important to discuss this with the public early in a development programme, and to derive the risk management triggers and contingency plans in an open and transparent manner, for each area where a wild cod sub-population can be identified.

6.3.4.1 Risk Mitigation

As indicated in the risk management table above, two broad approaches can be taken to manage these risks. The first is direct mitigation, which generally reduces the likelihood of a step in the logic model being fully realised. These mitigation measures usually take the form of regulatory strictures such as moving culture to land based facilities, or codes of practice used by industry. As can be seen under the column headed mitigation, most of these options can be put in place using regulatory or code of practice mechanisms. Some, such as the requirement for geographic limits to the culture of cod (mitigation for logic model step 5) may necessitate a wider planning process.

Where a regulatory approach is taken, care must be given to ensure that only those regulatory measures are taken that are necessary to reduce the level of risk to give an acceptable level of protection. Regulation for an extreme level of protection, where not required, is contrary to the concept of sustainable development. Suggestions such as moving marine culture to land based facilities (mitigation for logic model step 1) should be considered carefully in this context.

The other approach to managing risk is to reduce sources of high or moderate uncertainty in the risk analysis. In this context, one of the advantages of risk analysis is that it can assist in identifying priorities for research and development work. For example, step 5 in the logic model is associated with a high degree of uncertainty. That uncertainty in the decision making process could be reduced by research that defines gene flow rates between wild populations, and which could do much to clarify where specific populations may be at risk due to a low rate of gene flow with other components of the meta-population.

Testable models can be useful in the development of knowledge as well as being of immediate assistance to decision makers faced with uncertainty. A clear weakness in the confidence of the assessment is the lack of information on the likely fitness of hybrids formed by the interbreeding of wild and farmed fish (Step 4, **High uncertainty**), and of the consequences of any reductions in fitness for local and more widespread populations. Lacroix *et al.* (1998) show modelling approaches to estimate genetic introgression into the genome of wild stocks for salmonids, and such approaches should be considered for application in studies of non-salmonids as well. While it is too early to undertake such research on cod in Scotland (because genetic differences between farmed and wild stocks are currently small) it may be possible to consider the design of appropriate experiments when cod cultivation becomes closed (ie the complete life cycle occurs in cultivation and does not require inputs from wild populations) and selection for desirable traits is established.

It is important to be as inclusive as possible in considering how to control risk. Some control of risk may not directly involve the hazard under consideration (for example, cod farming). For example step 5 talks of sufficient gene flow. That will in part be determined by the relative size of the populations of wild and cultured fishes. The maintenance of sufficiently large wild cod populations (for example, through managing fisheries pressure, stock enhancement schemes, etc.) may be an efficient tool to mitigate the effects of increasing numbers of individuals escaping from aquaculture. That is no mean feat. Even so, there is evidence (Rice and Cooper 2003) that strict adherence to advice from fisheries scientists increases the likelihood of success in this objective. So, healthy wild stocks in and of themselves help to limit the effect of interbreeding with farmed escapes.

The potential impact of escapees will be greater if the local population with which they mix is small. The recent decline in North Sea cod stocks has arisen from a range of pressures, including fishing, but also because of declining recruitment in the area. Proposals have been made to support the natural recruitment of cod through ranching, not to enhance the fishery but to bring the stock back to the size that can be naturally supported in the area while supporting a substantial fishery.

Culture-supported stock support for stock stabilisation (covering the full gene pool in the broodstock to avoid inbreeding or outbreeding depression) could be used to avoid some critically small stock size, i.e. not using aquaculture to produce market size fish, but to produce fish fit for survival in the wild. Such culture-based fisheries could also be considered as a mitigation strategy against the potential effects of escapes.

The assessments of high probability and/or high uncertainty can be used to guide allocation of resources to those areas where they should be most effective. For example, Step 2 has high probability but, if this can be reduced, the overall risk of adverse effects would be reduced. Actions could be directed at measures to reduce the rate of escape of cultured fish. Combinations of regulatory and developmental research can be very powerful approach to mitigation. The critical event of cod escaping containment (Step 2) is very responsive to such an approach. This applies to both floating cages (mooring, net quality, resistance of the raft to waves, avoidance of predators damaging the nets, choice of locations, etc), and to land-based facilities (screening and treatment of effluents). Development of closed systems, on land or floating, could be encouraged and, when economically feasible, their use can be encouraged by codes of practice or regulatory tools.

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CASE STUDY 6.4

RISK ASSESSMENT OF THE DECLINE OF MACROPHYTES DUE TO MARINE FISH FARMING WASTE MATTER

R. Petrell[1] and P. Harrison[2] and E. A. Black[3]
[1] Associate Professor, Chemical and Biological Engineering, University of British Columbia, Canada
[2] Director Atmospheric, Marine and Coastal Environment Program. Hong Kong University of Science and Technology. Clear Water Bay, Kowloon, China Hong Kong, Special Administrative Region
[3]Senior Aquaculture Advisor. DFO Aquaculture Sciences Branch, Ottawa, Canada

6.4.1 Introduction

In this case study, we assess whether hazards released from fish farms could adversely affect adjacent seaweed beds, in particular, kelp beds. This exercise was carried out to identify potential hazards and assess risks. This assessment can be used as an example for carrying out assessments on other forms of macrophytes and marine plants. The analysis starts with the identification of the issue(s) of concern.

6.4.1.1 Introduction and Background Material

Kelps are the largest macroalgae and are members of the order laminariales. They are predominately benthic macroalgae of cold water, and occur throughout the salmon farming areas of Europe and North America where they are valued ecologically and economically in some regions. In Norway, which is one of the largest salmon farming producing countries, wild *Laminaria hyperborea* is harvested and used for the extraction of alginate. Harvesting is restricted to monotypic *L. hyperborea* beds that are only found in completely exposed sites. Currently such sites are unsuitable for salmon farms that must be sited, for structural reasons, in less exposed areas (for example, within a fjord instead of along a completely exposed coastline). Ecologically, a large natural kelp bed protects against coastal erosion (Madsen *et al.* 2001), many animal and algal species are associated with the beds, some fish and bird species feed directly on them, and some fish spawn directly on the fronds. In one study, for example, 387 species were found on its holdfasts (Moore 1971). In a more recent study, 238 species of mobile macrofauna with an average density of almost 8,000 individuals per kelp were found on the *L. hyperborea* sampled along the Norwegian coastline (Christie *et al.* 2003). The largest numbers were found on the largest specimens. Kelps have declined around the world due largely to over fishing of the predators of their major grazers, and excessive sedimentation and nutrients supposedly promoting shading by microalgae (Steneck *et al.* 2002). The areas where kelp beds have completely disappeared due to sea urchins are called urchin barrens (Sivertsen 1997). Over fishing the sea urchin predator has been the suggested cause of the large number of these barren sites, and is thought to be the greatest manageable threat to kelp forest ecosystems over the 2025 time horizon (Steneck *et al.* 2002).

Marine fish farm waste effluent consists of particulate matter as well as dissolved nutrients (Figure 6.4.1). Each fraction has the potential to affect kelp. For example, over accumulation of particulate matter from the fish farms in the benthos leads to an increase in the anoxic zone and over production of sulphide, which is toxic at low concentration to macrophytes and marine plants. As well, young kelp can be buried. Around the world coastal anthropogenic dissolved nutrients input especially nitrate inputs have simulated or over simulated algal growth, especially in areas where background levels limit growth.

The ecological importance and the decline of kelp beds necessitate their protection. From the above information, it is clear that waste matter from coastal marine fish farms is a hazardous substance to kelp (for example, the effluents pose a threat to the health of kelp). But, what is the effect on a local population? To answer this question, we developed a risk assessment model, and tested it on two hypothetical farming sites. The logic model that was developed is conceptualised in summary form in Figure 6.4.2. The model consists of release, exposure and consequence assessments, and risk estimation. The process starts with the question 'is there kelp habitat in the area of interest'. The endpoint to the overall assessment is an estimation of the net change in kelp population. If the answer to the first question is 'yes', the next question to be answered is 'is there a fish farm nearby'. If the answer to this question is 'yes', then we question whether kelp is growing nearby. If the answer to that question is 'no', then the area is possibly barren or once kelp grew there. Note, at this stage of a scoping exercise, it is assumed the hazard did not cause the barren. To be complete, the assessment would, however, have to address the possibility that fish farming effluents are a hazard to kelp recovery as well as to an existing kelp bed. The possibility of a barren site is flagged so that recovery can be considered in risk mitigation. The next stage is a release assessment, followed by an exposure assessment, and culminates in a consequence assessment. In the consequence assessment the severity, intensity and duration of the hazard, exposure and exposure consequence are estimated for each hazard using a logic model. The logic model is developed via analysis of available literature, measurements and/or modelling exercises. The consequence assessment is based on a summary of information derived from experience and as such it describes the likely outcome under 'average' technological and environmental conditions. Each new site may have special regulator restrictions or apply new technologies which may modify the anticipated affect.

Figure 6.4.1 : Conceptual diagram of the pathways of effects of fish farm waste effluents.

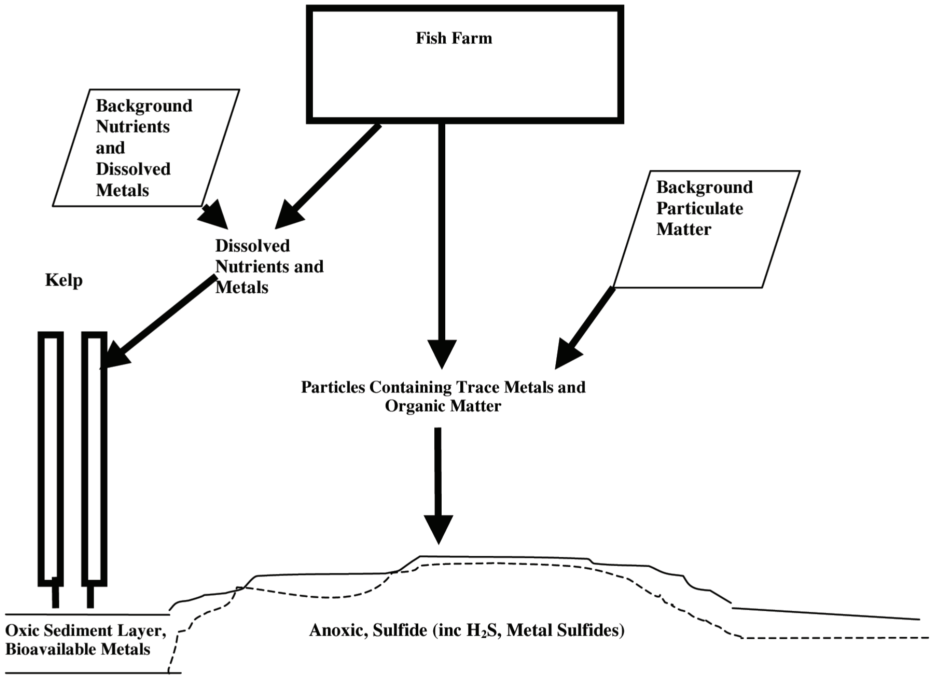
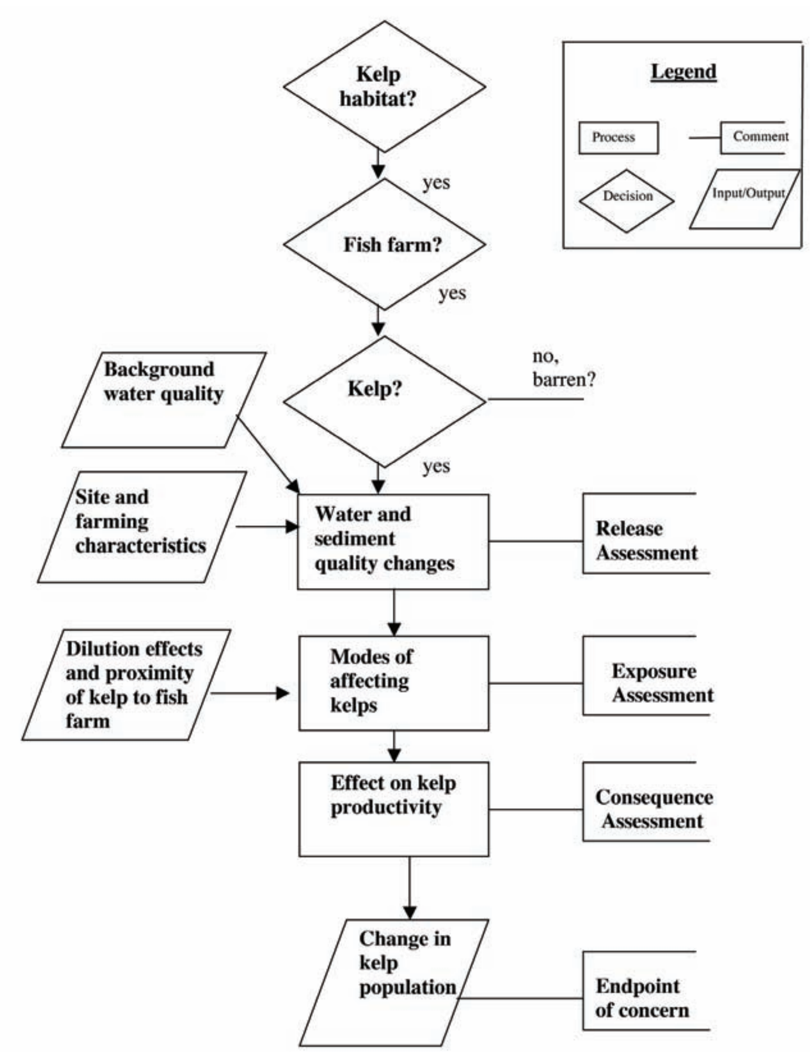


Figure 6.4.2 : Conceptualised logic model used to determine the risk of kelp decline due to fish farming waste.



The risk estimation step in the assessment allows the assessment to modify the nominal outcome accordingly. Risk mitigation, risk communication and management, and how to apply the assessment to other macrophytes are discussed near the end of the document.

Risk management has been defined as a set of activities which if carried out lessens the impact of hazardous substances. We used the term to describe only those activities that follow the risk assessment. The analysis begins with a description of the two fish farm sites, and the kelp life history and basic biology. The latter is used to determine exposure pathways, and describe and quantify the relevant conditions of kelp to risk agents.

6.4.1.2 Site description

For this exercise, we created the two hypothetical fish farming sites in the Lofoten to North Cape region in Norway. This area was chosen because key information such as kelp population, water quality, flushing conditions and salmon farming are available, and back ground water quality is good. Farming sites in Southern Norway could have been examined, but as water quality there is affected by municipal waste, agriculture and industry, it would have been more difficult to separate the effect of just salmon farming waste on kelp. The two fish farms reside at approximately 69 0N and 15 W (Sites A and B, Figure 6.4.3) and within well studied Laminaria resource areas (Sørum *et al.* 1990; Sivertsen and Hopkins 1995; Sivertsen 1997; Rinde and Sjøtum 2005). They are 5 km apart with connecting water currents within a fjord. Table 1 contains a description of the farming sites as taken from Carroll *et al.* (2003) including the production level described using annual fish feed amounts, condition of the substratum, and the current and depth under the cages. Site A is located in a sheltered site, while Site B is a more exposed and deeper site located nearer the fjord inlet. At the time of the study by Carroll *et al.* (2003), a Norwegian aquaculture permit allowed a higher fish production level at less environmentally sensitive sites which were deemed to have higher current speeds, so the fish production at Site A is less than at Site B. Both farms are located approximately 60 m from shore, and orientated parallel to it and the prevailing current. Kelp beds are present near both sites.

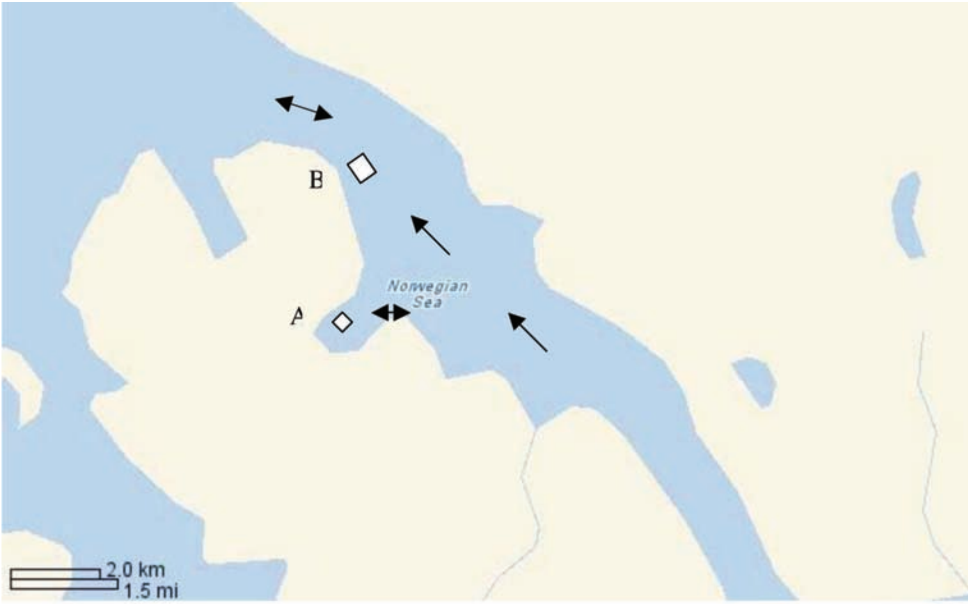
Within the Norwegian coastal region between Lofoten to North Cape, kelp around typical salmon farming sites (for example, sheltered and semi-exposed sites) are highly preyed upon by sea urchins. *L. hyperborea* have optimal growth rates due to favourable temperatures during the growth period and long summer days during the time of carbon production and storage (see section 6.4.1.2 Kelp life history and biology). Rapid growth tends to make them the largest in Norway (Rinde and Sjøtun 2005). The age of maximum growth is 4 years, and the average length is 1.5 to 1.61 m at a water depth of 5 to 8 m.

Coastal currents outside of the fjords in this area where the salmon farms reside move strongly up the coast, and in and out of the fjords (Figure 6.4.4). Within the fjord, surface water of low salinity arising from a river moves outward towards the open sea, while denser Atlantic water moves in below it (Aure and Skjoldal 2004). This is called estuarine circulation. In addition, wind-driven up and down welling just outside of the fjord causes considerable water exchange in the intermediate water layers. Usually basin renewal is yearly in the winter or spring when the density of the water outside of the fjord is at its seasonal maximum. Residence time for surface water and intermediate waters is on the order of days. The water quality in this area has been deemed excellent due to high flushing rates, the lack of large cities and small-scale industries with limited pollution potential (Aure and Skjoldal 2004). There, naturally occurring dissolved nitrogen in the form of nitrate is most available near the upwelling areas at the fjord inlets. Nitrate concentration increases with increasing salinity, and peaks within the Norwegian coastal current in that region in April at 8-14 M, while extreme lows occur in summer during times of high freshwater inputs (Aure and Skjoldal 2004). Salmon farming within the region contributes approximately 50 and 70% of the regional estimated total yearly N (approx. 10,000 tons) and P (1000 tons) inputs, respectively (Aure and Skjoldal 2004), and there are no major point sources of either nutrient. Due to the background nitrate cycle, absence of significant N point sources, and constant supply of N from fish farms, coastal marine fish farms within the area during the late spring and summer potentially provide macrophytes a source of nutrients normally not available to them.

6.4.1.3 Kelp life history and biology

In this case study, both *L. hyperborea* and *saccharina* are considered because they naturally grow together, and are dominant species in the area of interest. Much of their basic biology with the exception of more recent records pertaining to geographical distribution, predation, nutrient uptake and pollution effects is reviewed in Kain (1971, 1979) and Dawson (1966). These three older references are used within this document without further citation. Their life history and basic morphology are depicted in Figure 6.4.5. At maturity (two years for *L. hyperborea* and first summer for *L. saccharina*), the sporophyte (the large plant easily visible to the naked eye), consists of a blade or lamina and a simple cylindrical stipe attached to substrate by a hapteroid holdfast. This plant produces superficial sporangia on sporphylls or sori on its blades. Sori are produced in winter for *L. hyperborea*, and in summer for *L. saccharina* after the blades or laminae have fully developed. These mature in succession and fall out of the blades as irregular plates to end up in the benthos. Meiosis occurs in the developing unilocular (single cell) sporangia, which usually release 16-64 zoospores which attach after a brief period of motility onto solid rock, stones (> 25 cm), loose substrata such as gravel, dead shells, corallines and in the case of *L. saccharina* soft bottom as well (Schaffelke *et al.* 1996). Some species of seaweeds including kelp species are capable of attaching to nets, ropes and buoys on floating fish farms, and grow so densely as to foul them. After attachment, they germinate within a few hours to weeks to grow into tiny haploid gametophytes (Sivertsen and Hopkins 1995; Schaffelke 1996). The spore dispersal range for *L. hyperborea* is at least 200 m from a kelp bed (Sjøtun *et al.* 1995). The fertilized egg secretes a wall and soon undergoes division to begin the development of the sporophyte.

Figure 6.4.3 : Physical location of hypothetical salmon farming sites A and B within a Norwegian fjord.



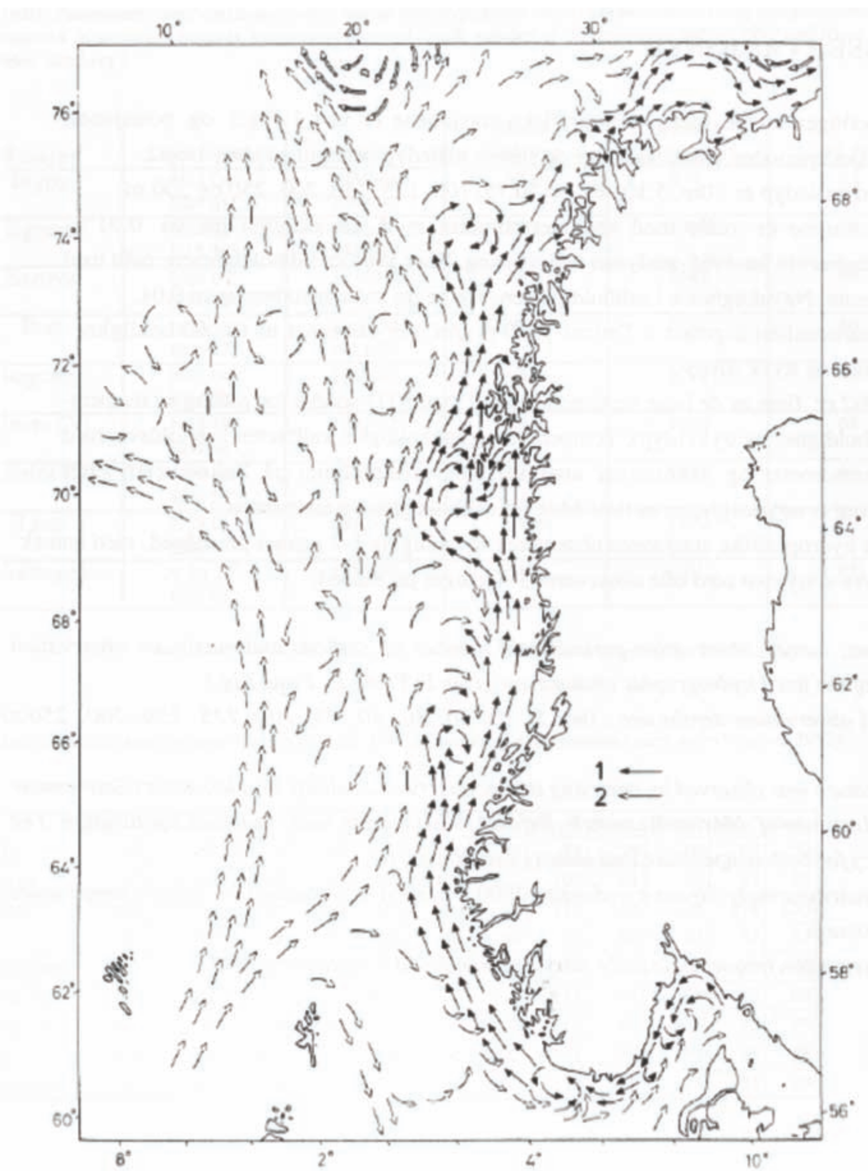
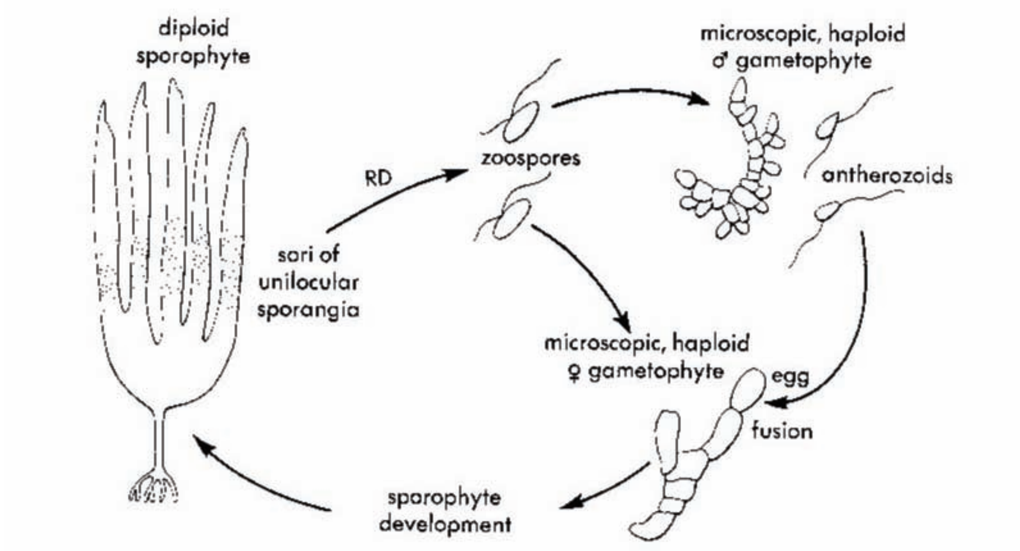


Figure 6.4.4 : Direction of current along Norwegian coastline and near fjord inlets (Aure and Skjoldal 2004, reprinted with permission). It is important to note how the current enters the fjords near our study area. The dark arrows indicated as number 1 in the diagram represents the Norwegian Coastal Current and the lighter arrows indicated as number 2 represents the Atlantic current. The degrees longitude and latitude are indicated on the border of the diagram.

Figure 6.4.5 : Diagrammatic life history of Laminaria *sp. (depicted here is* L. hyperborea*). From Dawson 1966. The sporophyte consists of lamina or blade connected to a holdfast by a stipe.*



Both species can grow at depths between low tide levels to 30 m at wave-exposed to sheltered sites, but the growing depth is actually limited by grazing, irradiance or substratum. Between species, growth patterns are distinct. For *L. hyperborea*, its holdfast and stipe can live 8-20 years, while the blades can break off in severe winter storms. From the stipe just below the old blade, a new blade emerges yearly. If the stipe dies, so does the kelp. The dark period between November and March is its major growth season when it uses C stores obtained during the summer well lit period (Lüning 1971). Sporophyte lengths is 1 to 2 m. Growth rate and mean standing density in shallow winter are approximately 0.94 cm/day and 11-10 kg/m^3, respectively. Average densities of *L. hyperborea* not impacted by harvesting or predation are 20.7 individual/m^2 and 23.9 individuals /m^2 for adult and juvenile specimens, respectively (Sivertsen 1997). The largest kelp originate from new blades that were able to use the nutrients in the blades from the previous year's growth.

In contrast, the holdfast of *L. saccharina* usually lives 3-4 years, while the blades and stipe tend to break off during winter storms. From the holdfast, new blades emerge yearly. If the holdfast dies, so does the kelp. The maximal growth period is between January and June instead of during the winter as for *L. hyperborea*. Ninety-three percent of the linear growth occurs in the proximal 25 mm of lamina during the first four months of the rapid growth period. Lamina length varies from 1 to 2 m. Growth and shallow-water biomasses are 1.7- 4.87 cm/day and 8-20 kg/m^3, respectively. The exception to this growth pattern is found in the high Arctic (74^o 18'N; 20^o 14' W) where blades live 2-3 years, plants longer than 4 years, and blades, as blades of *L. hyperborea* do, elongate during the dark period (Borum *et al.* 2002).

Background nutrient levels are important. In *Laminaria*, ammonia uptake saturation occurs at 10 µM while nitrate uptake has been shown to increase with background levels up to 60 M (Ahn *et al.* 1998; Chapman *et al.* 1978; Harrison *et al.* 1986). Both nitrate and ammonia are taken up simultaneously at nearly equal rates, if available. Chapman *et al.* (1978) observed a linear relationship between the growth of *L. saccharina* and NO^{-}_{3} concentration up to 10 µM and a luxury consumption of NO^{-}_{3} above 10 µM. Laminariales tend to store nutrients during periods of high nutrient levels to use for growth during periods of low availability (for example, Chapman and Craigie 1977).

The main competitor of *L. hyperborea* except near low water is *L. saccharina*. The outcome of this competition is often determined by the substratum. *L. hyperborea* prefers solid rock, and *L. saccharina*, due to its more flexible stipe, can out compete it if attached to substratum that can move in severe weather. In sheltered areas *L. saccharina* out competes *L. hyperborea* (although it can grow there), while generally *L. hyperborea* out competes *L. saccharina* in completely exposed areas. With decreasing wave exposure and current, *L. hyperborea* weakens. In shelter sites, the holdfast is poorly developed with few branched haptera on its holdfast and, as a result, it poorly attaches to rock. In addition, its stipe is short in sheltered sites, and the blade or frond is thin, brittle and easily torn. The morphology of *L. saccharina* also changes with wave and current conditions. Stressors typical of exposed environments (for example, breakage, dislodgement) are viewed as the cause of the differentiating morphological characters (Fowler-Walker *et al.* 2006).

A kelp population has the capacity to recover quickly from a major decline. This has been documented after they have been harvested. In Norway, for example, resource areas for kelp harvesting are large, as exemplified by the harvester size and speed which is 30 tons and 2 tons per minute, respectively (McHugh 2003). Harvesting areas are divided into 5 sections approximately 1.6 km long, and each section is harvested every fifth year after which new recruits would be 1-2 m high (Kitching 1941). The key to rapid recovery is harvesting only older individuals so that the younger individuals living in the under story can grow quickly in the light exposed by the harvest (Christie *et al.* 1998). Unfortunately five years is only a sufficient period for regeneration of the kelp canopy. It does not permit sufficient time for full regeneration of the organisms that once lived upon it (Christie *et al.* 1998).

Abundance of these two species is affected by over grazing by sea urchin (for example, Hjorleifsson *et al.* 1995; Sivertsen 1997); harvesting, sedimentation over young (Devinny and Voise 1978; Walker and Richardson, 1955); increasing water depth and/or light limitation (for example, Kain 1979; Gerard 1988), latitude (Rinde and Sjøtum 2005), current/wave action (Madsen *et al.* 2001; Sjøtun *et al.* 1993; Sjøtun *et al.* 1998); canopy biomass (Subandar *et al.* 1993; Sjøtun *et al.* 1998), nutrients (for example, Chapman and Craigie 1977), and pollution as well as other anthropogenic stresses (Coelho *et al.* 2000; Bellamy 1968; Bellamy *et al.* 1970; Nakahara 1973; Burrows 1971; Burrows and Pybus 1971; Hopkin and Kain, 1978). This information was used to help identify the risks associated with salmon farming waste on *Laminaria*.

6.4.2 Hazard Identification

A hazard produces risk only if an exposure pathway exists and the exposures create the possibility of adverse consequences. This section is used to identify possible adverse consequences of kelp exposed to fish farming effluents.

6.4.2.1 Possible effects of salmon farming effluents on seaweeds

Little research has been carried out on quantifying the effects of aquacultural effluent on wild plants and macroalgae. On the other hand, cultivated seaweed receiving aquaculture effluent has been the subject of many research investigations around the world. In one, Petrell and Alie (1996) showed that kelp cultivated on ropes adjacent to fish farms can act as biofilters of the dissolved nutrients in salmon waste matter. In one study focused on wild individuals growing within a lagoon system, macrophytes and macroalgae species composition changed with distance from the farming operation (De Casabianca *et al.* 1997; De Casabianca *et al.* 2003), and the overall species richness was low (Bachelet *et al.* 2000). These trends are consistent with changes in species composition and richness within a polluted kelp bed (Jones 1971; Bellamy 1968). In one polluted kelp bed, 92% of the kelp biomass disappeared along with a corresponding loss of associated fauna. In a closed lagoon containing shellfish farming, the macroalgae and macrophytes receiving additional nutrients in the effluents were viewed as vehicles for additional sources of dissolved nutrients once they had died and decayed (De Casabianca *et al.* 1997). The growth and N and P nutrient content of *Fucus vesiculosus L.* and associated biomass of epiphytes species were higher close to a fish farm than in a reference site in the archipelago of Aaland, southwest Finland (Roennberg *et al.* 1992). As well, towards the farm, the species composition of algal epiphytes shifted in dominance from brown and red to green algae. These examples provide a reason to examine the risks that nutrients and waste matter from salmon farming might engender for local stocks of *Laminaria*.

We determined after analyzing biological characteristics and other data that *Laminaria*'s growth pattern and reproductive cycle makes it susceptible to the build up of waste matter and dissolved nutrients. Specifically, a *Laminaria* population (numbers, age class composition, growth) is at risk if the waste matter from a fish farm contains high levels of dissolved nutrients that: a) promotes growth of mainly older *Laminaria* individuals, b) promotes growth of algal epiphytes that subsequently negatively affect kelp laminae or its function, and c) modifies the way nutrients are stored for a future generation. A *Laminaria* population is also at risk if the solid waste matter contains particulate matter to levels that cover substratum, gametophytes, holdfasts or blades, or cause a reduction in photosynthesis due to high turbidity. In addition, the population is at risk if the waste matter contained high levels of toxic material. In our analysis, we carefully considered early life stages as a recent review of the anthropogenic effects on the early development stages of seaweeds stresses the importance of the early life stage with regards to the viability of a seaweed bed (Coelho *et al.* 2000). The possible affects of increased nutrients and solid waste matter on sporophyte growth, sori production and regeneration in the benthos that we found are described within this section. The methodology to produce a quantitative measure of the risks is discussed under risk estimation.

6.4.2.2 Possible adverse effects of dissolved nutrients on kelp growth and population

Laminaria growth is highest under low-medium kelp density, adequate nutrients, and mid velocities or level wave action, as under these conditions competition for light and nutrients is low, and nutrient exchange with the laminae is enhanced (Subandar *et al.* 1993; Sjøtun *et al.* 1998; Madsen *et al.* 2001; Hurd *et al.* 1996). An older established bed retards current, restricts light (especially to lower canopy seaweeds) and is more effective due to its larger biomass at removing nutrients to low levels. A high biomass level restricts growth in *L. saccharina* during its rapid growth period and/or the period when nutrients are available for growth and storage. Similarly, high biomass levels during the well lit period could also reduce growth in *L. hyperborea* during its high growth period or winter when it depends on stored carbon from the well lit period for energy.

In general, kelp biomass increases with an increase in nutrient availability to a level where self-shading of the upper story population occurs, shading of younger and smaller individuals in the low stories occurs and/or restricting of flow and nutrient exchange throughout the bed occurs. Light limitation and current reduction have been suggested as the reasons why growth in kelp beds consisting of younger individuals without an upper story of older individuals is higher than the growth in mixed aged beds (Sjøtun *et al.* 1998). In that study, growth of 2-

3 year old individuals declined by half as lamina biomass doubled (from approximately 300 to 600 kg/m^2).

Epiphytes normally grow on the stipe, holdfast and older blade tissue of laminariales. Epiphytic algae type and abundance change due to fish farming (Roennberg *et al.* 1992). Williams and Ruckelshaus (1993) observed that the growth of eelgrass (*Zostera marina*) decreased as epiphytic algae increased. At greater than 80% ambient nutrient levels, epiphytic algae on kelp and eel grass increased relative to background levels (Russell *et al.* 2005). A five hour 200 µmol l^{-1} pulse of nitrate caused an increase in epiphytic algae and a corresponding decrease in growth in the host, while a series of shorter-duration pulses produced no differences (Worm and Sommer 2000). These researchers suggest that the duration of the nutrient pulse and nutrient prehistory on epiphytic algae growth appears to be more important than the nutrient concentration. In summary, the level and duration of nutrient pulses can affect lamina size and function due to an increase in epiphytic algae and salmon farming effluents have been shown to change the type and abundance of epiphytic algae, but research is lacking to show that such changes cause a decline in a local kelp population.

Holdfasts and laminae have been shown to store nutrients for future growth and a new generation, and typically these nutrients are obtained in the early spring in temperate coastal areas when light levels are low and nutrients levels are high. Nutrients stored in the holdfast are obtained from covering soft sediment and passed up to the laminae when needed (Williams 1984; Raven 1981). For nitrate uptake during the spring upwelling period, stored carbon is often used for energy (Raven 1981; Lüning 1971). Typical nutrient uptake and storage characteristics of kelps may, however, be altered in seasonally unusually high nutrient loading conditions. First year *L. saccharina* grown in tanks receiving fish farming effluent under high irradiance did not store N in the blades (Subandar *et al.* 1993). Ahn *et al.* (1998) found that the nutrient uptake kinetic parameters of first year kelp that had originated from a salmon farming net cages were within expected ranges. Like in the previously mentioned study nitrogen did not store in the lamina as a result of the fertilization. In another study, nutrient depleted Laminaria was fertilized and growth was enhanced, but C reserves did not build up in the usual matter (Chapman and Craigie 1977). The possibility exists that the lack of nutrient/carbon reserves in kelp grown in these ways weakens the next individual arising from the remaining tissue from the parent seaweed (Chapman and Craigie 1977). In summary, evidence suggests nutrient fertilization changes the nutrient/energy storage pattern of kelp relative to unfertilized kelp, but as yet, research has not been conducted to determine if such changes could cause a decline in a local kelp population.

The effect of reduced biomass production of sporophytes, whether due to epiphytes, nutrient storage conditions, light limitation, etc., could affect future generations of *L. hyperborea*, as strong new growth on this perennial depends largely on the condition (of energy and/or nutrient stores) and size of the holdfast, stipe or blades (depending on the species) generated from the previous year growth. In addition, adequate growth is important for adequate sori production. Gametophyte and young sporophytes viabilities are considered generally poor so ample sori production is important for Laminariales as a way to ensure future generations. As was previously mentioned, sori production occurs after blades have elongated near the end of the growth season. Thus factors that were mentioned within this section that affect lamina growth and condition would also affect sori production.

6.4.2.3 Possible adverse effects of particulate matter on kelp

Salmon farms using cage technologies produce particulate matter consisting of carbon, nitrogen, phosphorus, sulphur, and trace metals. The particle size ranges from 0.075 to 25 mm for salmon ranging in size from 1 to 5 kg (Buryniuk *et al.* 2006). This matter, along with uneaten fish feed degrade into smaller particles due to current forces and bacterial action. According to basic sedimentation theory and assuming equal particle density for all particle sizes, the largest particles settle out under or close to a fish farm, while the smallest particles settle further away or even remain suspended. The benthic community changes when the degradation rate in the benthos proceeds at a lower rate than the input rate. Through the process of decomposition, oxygen in and above the sediments can become depleted, and under anoxic conditions gases such as nitrogen, carbon dioxide, methane, and hydrogen sulphide can be generated. Direct effects of fish farming particulate matter on natural kelp beds have not been studied. Research has, however, been carried out on other forms of debris and under different cultivation conditions:

Sedimentation over kelp beds has been suggested as the cause for a decrease in the maximum depth of kelp in southwest Ireland, although the causal mechanisms were not known at the time of the study (Edwards 1980). Sedimentation has been shown to affect the development of gametophytes. A small layer of sediment or the amount to just cover the surface of a culture plate reduced the survival of gametophytes of the giant kelp, *Macrocystis pyrifera*, and 108 mg/cm^2 was sufficient to kill them. Water motion further decreased viability (Devinny and Voise 1978). Fletcher (2002) found that fine sediments just 3 mm thick, significantly reduced survivorship of *Fucus* embryos by restricting diffusion of metabolic waste products.

Sedimentation can harm *L. saccharina* if holdfasts are buried to the extent that new stipes and laminae can not emerge. Prior to burial to this level, the kelp would have, however, have already encountered the toxic effects of sulphide (*see* next section). Sediment depositing on top of kelp blades to the level that restricts photosynthetic activity is another avenue of potential harm. Some evidence supports this possibility; tanks containing kelp and receiving fish tank effluents had to be cleaned every two days to remove the debris on walls and laminae (Subandar *et al.* 1993). Sedimentation to this degree (in still water) is, however, unlikely in wave swept environments typical of coastal waters and salmon farms.

Sedimentation in some polluted areas has been sufficiently severe to cause turbidity, light limitation and decline in kelp beds (Bellamy *et al.* 1970; Edwards 1980). Under low to mid current velocities, high kelp biomass can potentially aid in increasing sedimentation rate and reducing turbidity (Madsen *et al.* 2001). Salmon farms are not associated with producing overly turbid water, although, they can be sited within waters that are seasonally quite turbid with Secchi disc reading of approximately 1 m (Ang and Petrell 1998).

In summary, waste particles have the potential to affect seaweeds especially if the particles settle over preferred substratum containing gametophytes.

6.4.2.4 Potentially toxic substances associated with salmon waste

Brown macroalgae are widely noted for their ability to accumulate dissolved potentially toxic heavy metals such as Cu and Zn commonly found in salmon farming effluents, other waste streams and naturally in the marine environment by 10 to over 100 times background levels without known biological effects in adult specimens. The amount accumulated tends to be directly related to growth rate and the concentration in the water (Lobban and Harrison 1994). In a one year old brown alga, *Ascophyllum*, collected on rocks near salmon farms with and without nets, treated with copper as a biofoulant, copper levels varied between 3.4 to 8.7 mg Cu/ kg, and the values for the one non-copper treated site fell to the low range (Solberg *et al.* 2002). The higher values are typical of *Fucus* sp. and *Chondrus crispus* collected near a steel plant wharf (Sharp *et al.* 1988).

Different dissolved heavy metal solutions are more toxic than others (*see* Lobban and Harrison (1994) for information on the factors affecting and mechanisms of metal toxicity). For example, Cu is more toxic to *L. hyperborea* than Zn (Hopkin and Kain 1978). Typical oceanic Cu concentrations need to increase by a factor of three to be toxic to *L. hyperborea* sporophytes (Lobban and Harrison 1994). On the other hand, the respiration rates for *L. hyperborea* sporophytes increased at only very high Zn concentrations of 250 mg/L (Hopkin and Kain 1978). Survival of germinating gametophytes of *L. hyperborea* was reduced in 0.1 mg/L Cu and 5 mg/L Zn, production of sporophytes from gametophytes was delayed 13 days by Cu at 0.025-.075 mg/L and by 2-4 days in Zn at 1000 mg/L. Growth was reduced by Cu at 0.001 mg/L and by Zn at 0.5 mg/L (Hopkins and Kain 1978). In a more recent paper, gametophytes of *L. japonica* could not survive in culture solutions containing more than 50 mg/L Cu and growth was restricted at 5 mg/ L (lowest concentration tested). Toxicity was more pronounced in mixtures of heavy metals (Ye *et al.* 2005).

Heavy metals from both natural and anthropogenic sources are common in marine waters, but they are not always bioavailable. Trace metals concentrations in sediments are largely dependent upon sediment grain size because they are associated with particle surfaces (Rae 1997; Loring 1991). Finer grained sediments, particularly within the clay and silt fractions, are comprised of metal-bearing minerals which may bind with, among others, Cu and Zn. These metals also strongly bind with particulate organic matter like that originating from fish farms (Chapman *et al.* 1998). To be bioavailable, metals must be in the dissolved form as free metal ions. The mobilization of sediment and organic particulate-bound metals into dissolved phase is controlled by oxidation. When particulate organic matter is oxidized (as happens when organically impacted benthos are left to recover between fish farming production cycles), organically-bound metals are released in soluble (bioavailable) form. The effects of metal bioavailability in sediments due to oxygenizing conditions were examined in a study conducted by Trannum *et al.* (2004). In that study, sediments containing high levels of Cu (400–1500 mg/kg) negatively effected colonisation by several taxa when this sediment was removed and positioned at a relatively pristine (well oxygenated) location in an outer fjord.

Hydrogen sulphide is commonly produced in anaerobic sediments where the bacterial community reduces sulphate in the absence of free oxygen, and such anoxic conditions are typical in the benthos below salmon farms after the waste matter has accumulated (for example, Hargrave *et al.* 1997; Johannessen *et al.* 1994). Sulphide is toxic to marine plants at low levels between 0.25-2.5 mM (Raven and Scrimgeour 1997). Toxicity due to sulphide (0.5 mM) had overriding negative impacts on survivorship and growth of the brown seaweed *Fucus* embryos buried by sediment in still water (Chapman and Fletcher 2002).

Hydrogen sulphide and the hydrosulphide anion are the most commonly found sulphide species in aqueous form, and hydrogen sulfide is the most apt to freely cross the membranes of aquatic organisms (Wang and Chapman 1999). Hydrogen sulphide, at a pH typical of seawater (8), forms approximately 9% of the total free sulphides (Erickson *et al.* 2001). Free sulphides can complex with heavy metals such as cadmium, copper and zinc in the sediment pore water, converting the sulphides in the free form into a non-toxic complexed form, and potentially reducing the availability of toxic free metal ions in the sediment pore water (Rittmann and McCarty 2001; Wang and Chapman 1999). Slight increases in sediment redox potential due to oxygenation does, however, cause metals complexed with sulfides to become mobilized and released in dissolved form into the pore spaces of the sediments.

In summary, sulphide generated from decomposition of organic matter affects seaweeds at very low concentrations. The heavy metals associated with sediments below and surrounding fish farms (for example, Zn and Cu) are not likely to be toxic to seaweeds under reducing conditions, but if these sediments become oxygenated, seaweeds within the zone of influence of the farm may be negatively affected by heavy metal toxicity.

Two broad categories of hazards exist, namely dissolved nutrients and particulate matter. From the above analysis, different exposure pathways exist. Depending on the length of the nutrient pulse, epiphytic algae on macrophytes could increase while the growth of the host macrophyte could decrease. The effect of increased levels of epiphytic algae on sori production is unknown, but the effect can be linked to the growth rate of the sporophyte (for example, the sori is directly proportional to the size of the lamina). One could easily assume that if at least 75% of the lamina was covered with epiphytic algae, then sori production would be greatly impaired. Dissolved nutrients can also directly impact kelp tissues by changing how the tissues store nutrients for growth at a later date and by increasing biomass to levels causing light limitation and therefore lower growth rates. A carbon to nitrogen ratio exceeding 20 is generally considered to be nitrogen limiting, so kelp kept at that level during the growing season would eventually die. No one knows what the biomass level is that leads to death, however, doubling the kelp biomass has shown to decrease the growth rate by 50%. This decrease in growth rate could be considered severe in the areas where kelp are under attack by sea urchins. Particulate matter from a fish farm has the potential to bury gametophytes, and increase the likelihoods of exposing kelp to toxic levels of sulphide and heavy metals. Gametophytes buried by 3 mm of sediment, and exposed to 0.25-2.5 mM of sulphide or 50 mg/L Cu die.

No field evidence exists to show that fish farming effluents affect kelp populations; however, there is solid theoretical and experimental evidence to show that there can be adverse consequences to individual macrophytes. Biological and past harvesting information indicates that an affected population would recover if the kelp bed extends over 200 m (for example, the spore dispersal range) from a kelp affected area (Some farm sites are very large, 300 m and longer) and/or only the older individuals are affected (so as to permit younger lower story individuals the opportunity to grow).

6.4.3 Risk Assessment

In this section a systematic process for describing and quantifying the risks associated with fish farming effluents at the two salmon farming sites on kelp is presented.

6.4.3.1 Release Assessment

Waste release from a fish farm depends on the fish number, feeding rate, feed conversion ratio, harvesting rate and fish size. The major factors are fish size, number and feed conversion as they dictate the total digested feed ration at a similar water temperature and feed type. Fish biomass grows nearly exponentially, but due to a decrease in growth rate with age and a changing feed conversion ratio, the amount of solid waste output grows nearly linearly (Figure 6.4.6, Buryniuk et al. 2006). Dissolved nitrogen (mostly ammonium) and phosphorus outputs follow similar trends.

A typical fish production cycle is 60 weeks (faster, or slower depending on the water temperature). Young Atlantic salmon (*Salmo salar*) enter the sites between January and May, and this means the largest biomass (and waste output) would occur before harvesting start dates 14 to 16 months later (April to August). Fish are not harvested all at once, but staggered over an extended period of time. Another production cycle can begin right after all fish have been harvested.

6.4.3.1.1 Zone of dissolved nutrients

The total loading of N and P from a typical salmon farm is 78 and 9.5 kg per ton of fish produced, and 57-86% and 22-46% is ammonium and dissolved P, respectively (Ackefors and Enell 1990, Fivelstad *et al.* 1990). Norwegian aquaculture regulations do not specify that nutrients must be monitored on fish farms (Hansen et al 2001); therefore, empirical data were used to estimate the magnitude and zone of dissolved nutrients that surrounds a fish farm. As nitrogen is normally limiting in temperate coastal waters, we assumed that dissolved N is the only limiting nutrient, and limits kelp production outside of the springtime period. Estimates generated from existing empirical models could have given us daily outputs of dissolved nitrogen, but as they do not consider dispersion and other dilution effects due to wave and current, and cage structure, we could not use them to estimate nutrient levels at the kelp beds. Furthermore, existing models do not consider fluctuations during feeding time in ammonium levels; a variable that plays an important role in algal epiphyte development. The empirical data used to estimate the zone of ammonium are described next.

In a relatively low wave exposed farm site containing approximately 3 kg sized fish with currents averaging 0.024 m/s over a 24 h period, Ahn *et al.* (1998) found that ammonium levels fluctuated during summer between fish feeding and non-feeding times to often exceed 10 µM, while background nitrate levels remained fairly constant at approximately 2.5 µM (Figure 6.4.7). Increases in ammonium near fish cages associated with feeding events were also observed in Chile and elsewhere in Canada (Soto and Norambuena 2003; Wildish *et al.* 1993). Soto and Norambuena (2003) suggested that surrounding the farm, dilution and nutrients recycling must be high, as there was no connection between nutrient conditions in the water column and the levels of N and P in the sediments due to organic waste loading. In the Bay of Fundy, Canada, where flushing conditions are strong, levels of nutrients outside of fish farms during the summer months were indistinguishable from the nutrient poor background conditions (Wildish *et al.* 1993). The authors of that study attributed this to nutrient uptake by microalgae and high flushing conditions.

Available dissolved nutrients from the salmon farm suffer dilution due to dispersion and wave effects. In Petrell *et al.* (1993) existing empirical data on dissolved nitrogen was used to describe the change in its concentration up to 40 m from a salmon farm. The available data appear to indicate that ammonium levels are lowest within the first 10 m of the sea cage and tend to randomly fluctuate up and down within an apparent mixing zone found between 10 to 40 m from the farm (data :Black and Carswell 1987; Korman 1989; Weston 1986). Ammonium between 25 to 40 m from the cage varied from 2.3 to 5.6 µM, and most likely these values depended on the fish biomass and current conditions at the time of sampling. Ammonium levels at 40 m are expected to be higher today because at the time of those investigations, on-farm biomass and farm sites were much lower as compared to today's standards.

Figure 6.4.6 : Estimate of solid waste output (from Buryniuk et al. 2006).

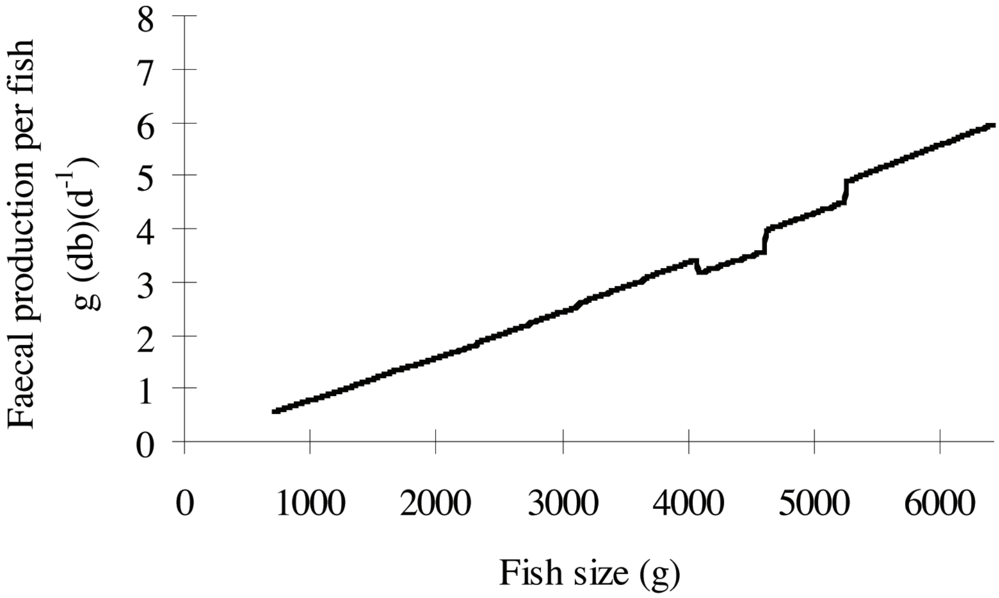
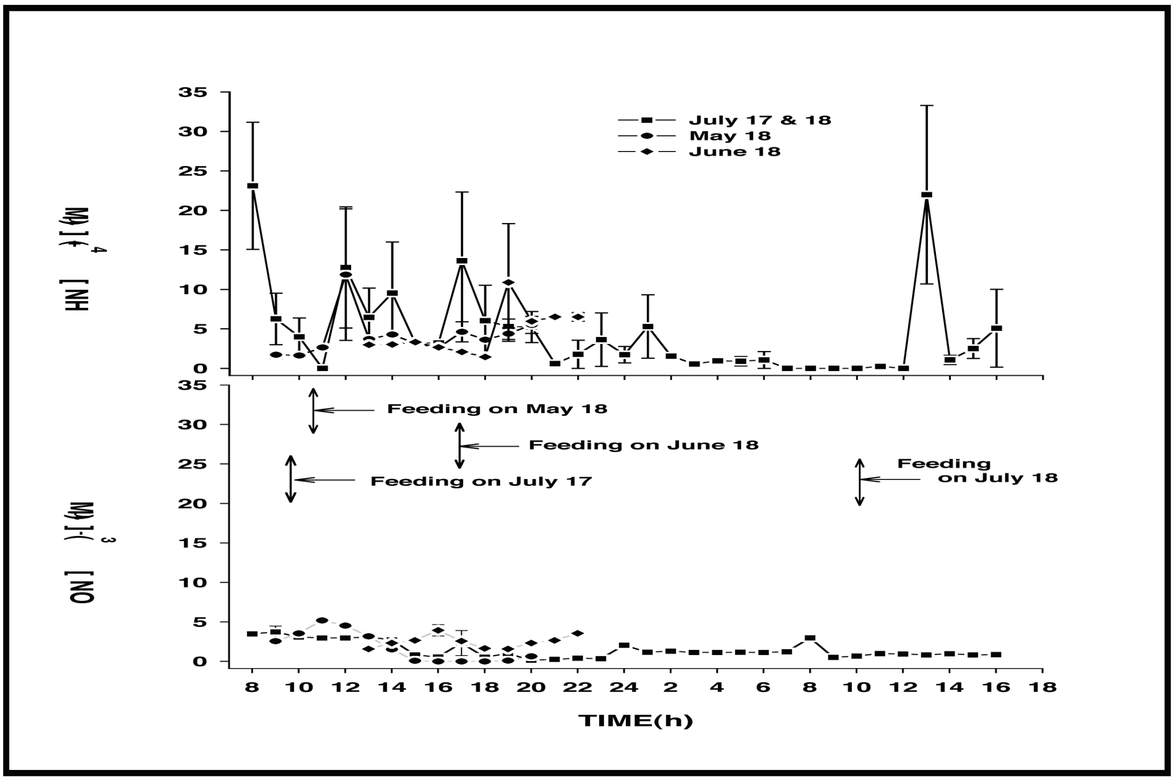


Figure 6.4.7 : Ammonium output at a fish farm (from Ahn et al. *1998).*



Using the above information and references, we estimated the dissolved nitrogen concentration for Sites A and B to be as follows. Between July and September, Site A produces a dissolved ammonium concentration within the cage site when fish are nearing harvest size and four hours following fish feeding time of between 10 and 30 µM. Between 10 and 40 m from the farm site, at the same time, the farm derived ammonium levels fluctuate to always exceed the background nitrogen concentration (2 µM) for that time of year. Fish are fed twice a day during the summer, so this pattern would occur twice daily. Site A with fewer fish produces less ammonium than Site B (Table 6.4.I), but because the current speed or dilution factor is lower at Site A, both sites would have similar ammonium levels surrounding the farm. The ammonium pattern in terms of range and concentration expected at Site B is, therefore, the same as at Site A. Due to lower dissolved nutrients in winter in general and early in the production cycle, we assumed that dissolved nutrients outside of the fish harvesting period would be undetectable anywhere other than within the fish cage.

6.4.3.1.2 Zone of solid waste accumulation

Tests on a number of salmon farming sites in Norway and Chile indicated that neither depth below the site or current correlate with the level of disturbance in the benthos below the farm. As well, below all fish farms, benthic conditions change due to depositing of organic waste material (Carroll *et al.* 2003; Soto and Norambuena 2003). Biological change is evident even at sites with rocky bottoms, although, these sites had been previously considered to be less sensitive to environmental change due to the higher flushing conditions normally associated with rocky bottoms.

Many former investigations were focused on measuring benthic enrichment, while others were focused on developing predictive models for estimating the zone of organic enrichment. Models exist that can be used to predict the amount of solid waste output, and benthic accumulation models have been developed for sheltered sites. Benthic accumulation models have not been proven effective for exposed sites such as Site B, so we used empirical data collected from a number of salmon farms (including Norwegian farms) to assess the accumulation of waste products at Sites A and B. A description of the empirical data follows.

The change in benthos due to organic enrichment from waste matter is evidenced by the presence of organic carbon-tolerant opportunistic species whose range extends to at least 50-100 m from a fish farm perimeter on a down current transect (Brooks *et al.* 2003). In a study of 80 farming sites in Norway, the sediments below 32% of the farms were classified as being poor, or very poor and 10% of the sediments were similarly characterized at 50 to 100 m from the fish site (Carroll *et al.* 2003). Poor in this study meant chemically, structurally (grain size) and biologically altered as compared to a reference site. After comparing site characteristics among the farms, no particular characteristic such as depth or current velocity could be associated with either little change or a major change (poor). Rather, little change in sediments was only associated with fish farms that were left vacate (or fallow) between production cycles.

In terms of heavy metal release from salmon farms, Cu and Zn are normally considered. Copper is incorporated as trace metals in fish feed by manufacturers (for example, 4.8-5.6 µg/g dry weight, Kempf *et al.* 2002) and in anti-foulant paint. In two studies, sediment Cu levels below fish farms were elevated as compared to control sites (actual values: 10-20 µg/g and 100-320 µg/g) (Kempf *et al.* 2002; Uotila 1991). Cu was elevated in most seaweed samples obtained on salmon farms, and this indicates that dissolved heavy metal ions are available for uptake in the water near salmon farms (Solberg 2002). Zinc is included in farmed fish feed in order to prevent cataracts in juveniles. The Interim Marine Sediment Quality Guidelines, produced by Environment Canada, estimate that the threshold level of Zn corresponding to adverse biological effects in marine sediments is 124 µg g^{-1} (Environment Canada 1995). In Finland, Uotila (1991) found zinc to be elevated near the fish farm site (100-500 µg/g). Below a fish farm site in France, it was also elevated (100-200 µg g^{-1}) (Kempf *et al.* 2002). Five years after cessation of fish farming operations at a sheltered site in British Columbia, Canada, Zn levels in the sediments were above background levels 160 m from the farm site, but biological sediment remediation appeared to be completed at 80 m. The initial value below the farm site that had been in operation for seven years, loading conditions was 351 µg Zn/g dry sediment (Brooks *et al.* 2004). Heavy metals in the underlying sediment decrease over time after cessation of fish farming, but it is not clear whether burial or chemical change was the overlying cause of the decrease. At the same site, free sediment sulphides were initially 9410 µM $S^{=}$ and five years later they were still elevated at 1270 (0.1 H_2S) and 225 to 549 µM $S^{=}$ (at 75 m and beyond, respectively). Note: to give meaning to these values recall that we previously mentioned that sulphide is toxic between 250 and 2500 µM.

Table 6.4.I : Salmon farming characteristics (from Carroll et al. 2003).

Site	Current speed, m/s	Depth m	12-mo feed tonnes	Years in operation	Below farm sediment condition
A	0.04-.06	25-50	500	4	Sediment over 0.05 m deep containing coarse and fine grain size fractions
B	0.1-.25	75	1000	10	Rocky, waste debris only in some places

Data on metals and sulphide at four more exposed salmon farming sites in British Columbia Canada are presented in Brooks *et al.* (2003). Unfortunately, no information on kelp at these sites is available, because farms according to B.C. regulations must be at least one kilometer from a kelp bed (Levings *et al.* 1995). At one of the four sites, current speed varied between 0.05 m/s and 0.25 m/s and the substratum was sandy with 30–40% silt and clay. Data from two production cycles interrupted by a four month fallow period indicated that mean sediment free sulphide concentration during the first cycle was 12,375 µM at the farm, 14,213 µM at 30 m, and 3285 µM at least 100 m from the net pens. Two months after the fish were completely harvested, sulphide levels were 40 µM at 100 m, but remained very high at the site. During the second production cycle, fewer fish were produced, and all sulphide levels (farm and 100 m) were below 960 µM. Data from all sites indicated that sulphide levels quickly increase at the site and generally peak at the time of maximum biomass. Elevated levels were observed at 100 m at most sites. Fallowing and farm fish biomass control was seen to be effective at reducing the sulphide levels to a level (960 µM) at which more than half the reference area taxa was found able to recruit and survive. Sediment Zn levels were monitored during and post production. Due to the high levels of sulphides, Zn was deemed not bioavailable at the sites (for example, Zn was most likely bound to sulphide).

Using the above information and references, we estimated the zone surrounding the farm sites reflecting change in relation to sediment grain, sediment heavy metals (Cu and Zn) and sediment sulphide levels. We assumed that the benthos within at least 100 m from the farm at both sites would change as organic particulates accumulate. Further, after the start up of the farm, we assumed that the sediments quickly became organically enriched, and sulphides quickly reached potentially toxic levels. Zinc and Cu deriving from uneaten feed and faecal matter are bound to the sulphides. Species composition changed to the point where only sulphide insensitive species now exist. Sediment quality and taxa would return to approach background levels if sites are fallowed for 4 to 12 months between production cycles. At site A (the sheltered site), without site fallowing between production cycles, sediment remediation would likely require more than five years after the site has been vacated. During remediation, heavy metals would become bioavailable as sediments as the anoxic zone reduces in depth and potentially toxic to kelp. At rocky substratum sites typical of more exposed salmon farming sites (for example, Site B), species composition also changes (although it is not clear what happens at these sites, as waste material does not accumulate).

6.4.3.2 Exposure Assessment

This process consists of a description and quantification of the relevant conditions and characteristics of kelp exposure to the various risk agents in fish farming effluents. Typically (as mentioned in the biological section) at the sheltered Site A, *L. saccharina* would be the dominant kelp species, while at the more exposed Site B both species would be present in varying proportions.

At Site A, kelp could be growing in the benthos over a section of the farm where the water depth does not exceed 30 m. At Site B, kelp would not be growing under the farm site, as the water depth (75 m) is too deep. Likely, they would be growing between 2 and 20 m from the shore in water to a depth of 30 m; this means that the outer edge of the kelp bed would be 40 m from the farm perimeter. Most of kelp at both sites would be restricted to a depth of 8 m, as light tends to limit production at deeper water depth unless the water is very clear, and this means, most of the kelp bed will not be below the farm at Site A.

Waste effluents from Site A have the potential to affect the kelp, because the zones of dissolved nutrients (40 m) and waste particle fallout (100 m) overlap with the kelp bed. Only the particulate waste matter from Site B has the potential to adversely affect the kelp because the zone of dissolved nutrients does not extend to the kelp bed.

6.4.3.2.1 Exposure assessment of kelp to dissolved nutrients

According to the fish biomass/ harvest schedule and background dissolved nitrogen seasonal trends at Site A, dissolved nutrients originating from the farm would be highest just before the fish are harvested. So, bi-yearly during the time naturally occurring nutrients levels are low, the kelp bed has the potential to be fertilized to significant levels by the fish farm. During periods of slack current and fish feeding, or periods when the ammonium concentration would be the greatest, Site A could offer the dominant kelp species, *L. saccharina*, that is below and adjacent to it, a dose of nutrients that could simulate its production to higher than normal background levels (Petrell and Alie 1996). The higher than normal growth would not cause light limitation, as the kelp in this region due to temperature and lighting conditions are already considered to be the largest in Norway (hence they are already known to shade under-story seaweeds). If, however, kelp are absent or reduced in population due to over predation by sea urchins, additional nutrients might provide a benefit for the kelp.

At Site A, the additional nutrients from the fish farm could increase the abundance of epiphytic algae as the duration of the nutrient pulse (twice a day for approximately 4 months) could promote the growth of epiphytes and a corresponding decline in kelp lamina biomass and sori production. A decrease in lamina biomass in the upper story would, however, prevent light limitation and thus promote growth of younger kelp in the lower story. If, however, kelp are reduced in population due to over predation by sea urchins, the adverse effects of additional epiphytic algae could put a restrain kelp recovery.

Sori production could be negatively affected by the increase in epiphytes, and decreased sori production would mean fewer gametophytes. Fewer gametophytes would mean that the kelp would have fewer defences against predation by sea urchins.

The bi-yearly unnatural fertilization scheme at Site A would modify the storage of nitrogen and carbon in

L. saccharina. The laminae in this species break off in winter storms at the holdfast, so unlike laminae of *L. hyperborea*, they can not contribute energy to the next generation. The holdfast can, however, store carbon and nutrients. These nutrients might be obtained from salmon farming effluent, and provide energy and nutrients for a new generation. Under these conditions, the contribution of salmon farming would be positive.

6.4.3.2.2 Exposure assessment of kelp to particulate matter

Toxicity due to hydrogen sulphide and burial of gametophytes is possible at Site A as the zone of particulate fallout from the farm (100 m) overlaps the kelp bed. At the more exposed site and rocky substratum, Site B, the exposed kelp will likely be adversely affected by the organic waste as the zone of particulate fallout from the farm overlaps the kelp bed. The mechanism behind the impact in the benthos is unclear, as previous studies have shown organic matter does not accumulate appreciably at more exposed salmon farming sites. Species diversity does, however, change, and as kelp are sensitive species known to decrease when exposed to organic waste, it is likely kelp exposed to organic particulates from Site B will likewise be adversely affected.

Kelp, are able to trap organic particles from the farm which sink at low to medium velocities; these would settle to the benthos to potentially impact gametophytes via burial and perhaps to the level of toxicity due to hydrogen sulphide.

6.4.3.3 Consequence Assessment

Consequence assessment involves the development of a logic model or a relationship between specify exposures to risk agents in fish farming waste matter and the consequence to the overall kelp population. From the previous section, it was shown that salmon farming waste matter at Site A has the possibility of changing the kelp population dynamics and structures due to dissolved nutrients, sediment burial and hydrogen sulphide toxicity. At Site B, salmon farming waste matter has the possibility of impacting a kelp bed due to sediment burial and hydrogen sulphide toxicity. At Site A, *L. saccharina* is most likely to be affected due to its dominance at sheltered sites, while both *L. saccharina* and *L. hyperborea* could be affected at the more exposed site, Site B. The following is an exercise that will demonstrate the likelihood that these factors change the kelp population. Below, severity at which each step occurs is derived by an examination of three factors, namely, the degree of anticipated change or intensity, the geographic extent of the effect and the duration of the effect after the farm or waste matter is no longer present. Probability is expressed qualitatively. Uncertainty is roughly equivalent to prediction accuracy in a statistical sense. When mechanistic knowledge was incomplete, correlative relationships relating cause and effects were used to make the assessment; when this occurred, our certainty weakened.

6.4.3.3.1 Logic models

The series of steps and processes leading from the establishment of salmon farms in coastal waters to decreases in wild *Laminaria* stocks as a result of waste effluent from salmon farms is conceptualised in the logic models of Figures 6.4.8 and 6.4.9, and formulated below :

Model 1: Dissolved nutrients

Process of concern : Changes in kelp population due to dissolved waste products
End Point of Concern : Decline in survival of kelp beds due to salmon farming
Logic model steps for Site A:

1. Suitable kelp habitat is in the area of interest.
2. A salmon farm is within or close to the kelp habitat
3. Kelp is growing in the area of interest
4. Dissolved nutrients change due to fish farm.

5.1.0 Dissolved nutrients cause an increase in epiphytic algae.
5.1.1 Light limitation occurs.
5.1.2 Lamina production changes
5.1.3 Decrease in kelp productivity
5.2.0 Dissolved nutrients cause an increase in epi phytic algae.
5.2.1 Kelp lamina erosion increases
5.2.2 Sori production decreases
5.2.3 Decrease in kelp productivity
5.3.0 Dissolved nutrients change the way the kelp stores C and N.
5.3.1 Lamina production changes
5.3.2 Decrease in kelp productivity
5.4.0 Lamina grows
5.4.1 Light limitation occurs
5.4.2 Lamina production changes
5.4.3 Decrease in kelp productivity
5.5.0 Lamina production changes
5.5.1 Light limitation occurs
5.5.2 Lamina production changes
5.5.3 Sori production changes
5.5.4 Decrease in kelp productivity
6.0 Change in kelp population

Model 2: Particulate matter

Process of concern : Changes in kelp population due to particulate matter
End Point of Concern : Decline in survival of kelp beds due to salmon farming
Logic model steps for Sites A and B:

1. Suitable kelp habitat is in the area of interest.
2. A fish farm is within or close to kelp habitat
3. Kelp is growing in the area of interest
4. Particulate matter from the salmon farm accumulates in benthos.

5.1.0 Particulate matter affects gametophytes via burial.
5.2.0 Decrease in kelp productivity
5.2.0 Kelp is affected by hydrogen sulphide toxicity.
5.2.1 Decrease in kelp productivity
5.3.0 Exposure to dissolved heavy metals

Figure 6.4.8 : Conceptual model representing the potential impact of fish farming dissolved nutrients waste on kelp. Dashed lines represent the release assessment, and the numbers, steps in the logic model.

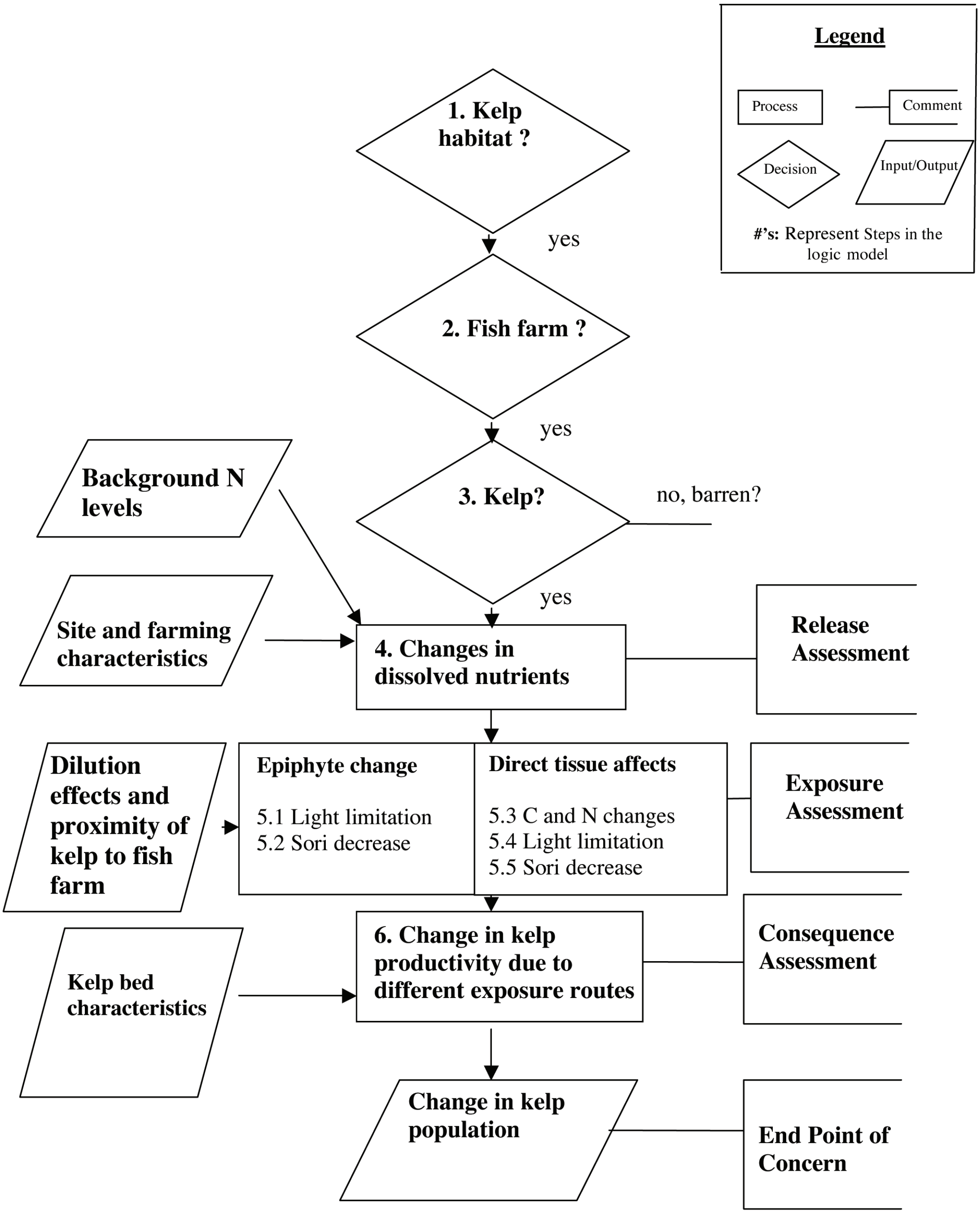
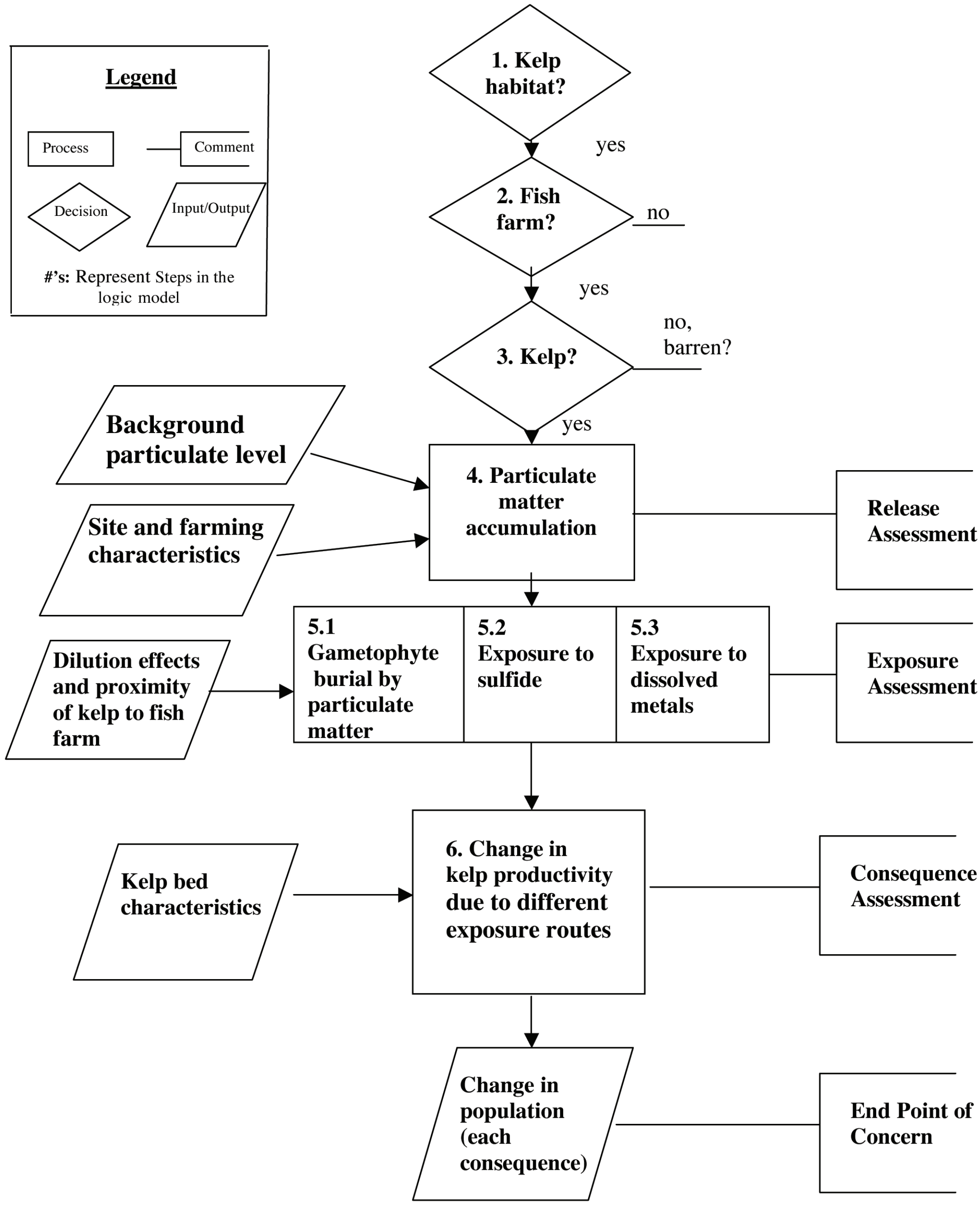


Figure 6.4.9 : Conceptual model representing the potential impact of fish farming particulate matter on kelp population. Dashed lines represent the release assessment, and the numbers, steps in the logic model.



5.3.1 Decrease in kelp productivity
6. Change in kelp population

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

6.4.3.3.2 Likelihood of occurrence

The material below is summarised in Table 6.4.II.

Steps in logic Model 1.

1. Good kelp habitat is in the area of interest.
High probability - Different species of macrophytes require different substratum for attachment, and the type of substratum necessary for *L. saccharina* and *hyperborea* can be found near salmon farms. As well, water temperature and lighting requirements are met there. In addition, they grow in sheltered to completely exposed sites to a depth of 30 m; although they tend to be more robust in more exposed sites, and weaker in more sheltered sites. More habitat is available for kelp due to suitable water profiles at Site A than B. The geographical extent of the suitable habitat can be large at both sites, as kelp habitat tends to follow coast lines. The habitat is not expected to change as this would imply a change in substratum and climatic conditions not associated with fish farming. The combined effects of depth and current supports the case for a intensity value of medium for both sites. Uncertainity is low, as published reports indicate that kelp habitat is in the areas of interest.

2. The fish farm is within or close to kelp habitat.
Highly probable - *Laminaria* and salmon share same habitat requirements, namely non toxic water, and similar water temperature and salinity requirements. In Norway no regulations exist that stipulate how far a fish farm must be from a kelp bed. The salmon farming intensity at Site A is lower than at Site B, because fewer fish are produced at Site A than at Site B. Kelp habitat extends to below the farm at Site A, and to 40 m from the farm at Site B, hence, the geographic effect of the farm is greater at Site A than at Site B. The likelihood that the farms will remain in the area is very high. Atlantic salmon is considered a stable in the regional diet and is well distributed over the Europe. Growth in salmon farming is not being planned for the coming years, but growth in the production of other fish species is being planned. Aquaculture offers the population a source of employment. The uncertainty associated with this prediction is low, as is it reported that both kelp resources and fish farming are in the area of interest.

3. Kelp is growing in the area of interest.
Medium probability - In Norway, *Laminaria* grow in sheltered and semi-exposed areas where salmon farms are often sited as long as their preferred substrate is available. They will grow to a depth of 30 m in clear water. We considered the probability to be medium because as kelps in the area of interest are highly impacted by sea urchins, there is a possibility that there are no or few kelp growing there. As well, it has been reported that in many sheltered and somewhat exposed sites there are many urchin barrens. Recovery of these kelp beds has been said to be unlikely within a 25 year time frame, so that situation is expected to endure for some time. We considered the maximum intensity of the kelp beds at both sites to be medium due to the following reasoning. At the sheltered Site A, substratum and depth would provide a large resource area, but as individuals are weak at sheltered sites, the maximal population size is expected to be lower than at completely exposed sites. At Site B, site depth limits the extent of the kelp resource area, but the individual plants are expected to be more robust than those at Site A. The combined conditions of plant density, shelter and depth make the intensity values the same for both sites. The uncertainty associated with this prediction is low because of the predicted 25 year wait period for the sea urchin predators to return and permanence of site conditions.

4. Dissolved nutrients in the area change due to the salmon farm.
Highly probable at Site A - Kelp are right underneath the farm, and the bed extends 60 to the shore. Background water quality is considered excellent in the area in spite of measurable changes in sediment and water quality surrounding the salmon farming sites due to the high flushing conditions in the area and strong dissolved nitrogen limitation in the water column. Background nitrate levels are highest in the spring, so any contribution of dissolved N from the farm would be minimal then. During the later stages of the fish production cycle when fish biomass is maximal, the output of farmed-derived dissolved nutrients would be measurable in the water during late summer to early fall. This would occur biyearly as long as the fish farm remained in the area and if the site was not stocked with fish in between cycles. At this time, at least 40 m from the farm site the contribution of dissolved nutrients from the farm would elevate the available dissolved nitrogen levels to exceed the growth saturation level for kelp at least twice a day after the fish have been fed. The geographical effect is considered medium as only that part of the kelp bed closest to the farm would receive additional nutrients. Intensity is considered to be high as the nutrient concentration would permit adequate kelp growth conditions.

5.1.0 Dissolved nutrients from the salmon farm at Site A are sufficient to enhance the growth of epiphytic algae.

Table 6.4.II : Table summarising risk estimation for logic model.

Steps in logic model 1 (Site A only)	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity**	**Probability**	**Uncertainty**	Stage of assessment
1.Suitable kelp habitat is in the area of interest	M	H	H	M	H	L	
2.A salmon farm is within or close to kelp habitat	M	H	H	M	H	L	
3.Kelp are growing in the area of interest	M	M	H	M	M	L	
4.Dissolved nutrients change relative to back-ground levels	M	M	M	M	H	L	Release
Release summary				M	M	L	
5.1 Dissolved nutrients increase epiphytic algae on kelp	M	M	L	M	H	L	Exposure
Change in epiphytic algae promote light limitation in kelp	L	L	L	L	H	L	Exposure
Light limitation promotes change in lamina production	L	L	L	L	M	L	Exposure
Exposure Assessment				L	M	L	
Change in lamina production decreases kelp productivity	L	L	L	L	H	H	Consequence
Consequence Assessment				L	M	H	
5.2 Dissolved nutrients increase epiphytic algae on kelp	M	M	L	M	H	L	Exposure
Epiphytic algae increase lamina erosion	L	L	L	L	H	L	Exposure
Lamina erosion promotes change in sori production	M	L	L	L	H	L	Exposure
Exposure Assessment				L	H	L	
Change in sori production changes kelp productivity	M	L	L	L	H	H	Consequence
Consequence Assessment				L	H	H	

Table 6.4.II. Table summarising risk estimation for logic model (continued).

Steps in logic model 1 (Site A only)	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity**	**Probability**	**Uncertainty**	Stage of assessment
5.3 C and N storage pattern changes	M	L	L	L	M	H	Exposure
Lamina production changes	M	L	L	L	L	H	Exposure
Exposure Assessment				L	L	H	
Change in C and N changes kelp productivity	M	L	L	L	L	H	
Consequence Assessment				L	L	H	
5.4 Dissolved nutrients affect lamina growth	L	L	L	L	H	L	Exposure
Increase in lamina growth causes light limitation	L	L	L	L	H	L	Exposure
Light limitation promotes change in lamina production	L	L	L	L	H	L	Exposure
Change in lamina production changes sori production	L	L	L	H	H	L	Exposure
Exposure Assessment				L	H	L	
Change in sori production changes kelp productivity	L	L	L	L	H	L	Consequence
Consequence Assessment				L	H	L	
5.5 Sori production changes as a result of changes in lamina production	L	L	L	L	H	L	Exposure
Exposure assessment				L	H	L	
Kelp productive changes as a result of changes in sori production	L	L	L	L	L	L	Consequence
Consequence Assessment				L	L	L	
Overall risk of a drop in local kelp population (highest severity and probability)				L	L	H	

1. **Probability = H** – High, **M** – moderate, **L** – Low, **EL –** Extremely Low, **N –** Negligible.
2. **Severity = C** – very intense, **H** – high, **M** – Moderate, **L –** Low, **N** – Negligible. There are three components of severity that should be considered: the duration of the activity, the degree of change, and the geographic extent of the change.
3. **Uncertainty = H-** Highly uncertain, **M** – Moderately certain, **L** – Low Uncertainty.
4. The final rating for the **Probability** is assigned the value of the element with the **lowest** level of probability.
5. 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.
6. The final rating for the **Uncertainty** is assigned the value of the element with the **highest uncertainty** level (i.e. the least certainty).

Highly probable - Kelp beds are within 40 m of the salmon farm, and therefore close enough to receive some nutrients. Fish biomass is sufficient to produce sufficient nutrients bi-yearly in the summer when background levels are low. The intensity and geographic extent is medium because it is likely that only the section of the kelp bed nearest the farm would receive nutrients. Increases in epiphytic algae occurs when background nutrient levels increase by 80% for extended periods of time during periods of high light, and this is 4.5 µM at this site (summertime). For one quarter of the production cycle of this value is exceeded when fish biomass peaks (approximately 4 months). Uncertainty is low, because this has already been shown to occur on seaweeds in proximity to the salmon farms.

5.1.1 Epiphytic algae promote light limitation.
Highly probable - Once laminae are covered with organisms, photosynthesis is impaired. Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire bed is not affected. Researchers have only found an increase in epiphyte abundance and a decrease in photosynthesis in the host with nutrient pulses. In addition, the high nutrient pulse occurs only four months every second year. Uncertainty is low, because scientific evidence supports a decrease in photosynthesis with shading.

5.1.2 Lamina production changes due to light limitation caused by epiphytic algae.
Medium probability - Late spring and early summer is the rapid growth period for *L. saccharina*. When the nutrient pulses are highest at summer end, it is, therefore, likely laminae have already grown to their maximal extent. Therefore, a reduction in photosysthesis would not greatly affect kelp production. Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire kelp bed is not affected. The cycle of high nutrient pulses from fish farms repeats bi-yearly. Uncertainity is medium, as researchers have examined both nutrient pulses, epiphytic algae and seaweed growth, but not at the time of maximal fish farming dissolved nutrient releases.

5.1.3 Kelp productivity changes as a result of changes in lamina production from epiphytic algae.
Low probability - Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire bed is not affected. Researchers have only found an increase in epiphyte abundance and a decrease in photosynthesis in the host with nutrient pulses. In addition, the high nutrient pulse occurs only four months every second year. Furthermore, a decrease in lamina biomass in the upper story would open light up to lower story younger individuals thus promoting growth of younger kelp in the lower story. Uncertainty is high, as population decline due to epiphytic algae has not been actually studied.

5.2.0 Blade erosion increases due to epiphytic algae increases.
Highly probable - This has been documented in previous research investigations. Researchers have only found an increase in epiphyte abundance and host erosion due to an increase in dissolved nutrients (not total lamina coverage). Intensity and geographic extent are low, because the entire lamina is not covered with epiphytic algae and the entire bed is not affected. The cycle of high nutrient pulses from fish farms repeats bi-yearly. Uncertainity is low as this has been documented in previous investigations.

5.2.1 Sori production changes due to blade erosion
Highly probable - At the time of the nutrient pulse from the salmon farm, *L. saccharina* is producing sori. Intensity of impact is medium. Researchers have only found an increase in epiphyte abundance and host erosion due to an increase in dissolved nutrients (not total lamina coverage). If the epiphytic algae grow over sori tissue or areas where sori would have been produced, and this tissue is consumed, then, sori production would be restricted. Impact is not high, as the kelp can live three to four years and the pulse occurs twice in four years. Uncertainity is high, because no one has correlated epiphytic algae with host sori production.

5.2.3 Kelp productivity changes as a result of changes in sori production.
Highly probable - Intensity of impact is low because most likely only the section of the kelp bed nearest the salmon farm would be impacted by dissolved nutrients. The nutrients would be taken up by the kelp and epiphytes at the front of the bed leaving few nutrients for the kelp in the reminder of the bed. As well, the high nutrient load during adequate lighting occurs only four months every second year, whereas kelp live three to four years. Gametophytes have a wide dispersal range (possibly greater than 200 m), so if the affected kelp did not produce sori, it is likely that new recruits would be obtained from the unaffected kelp outside of the range of the fish farm. This would be the case in a healthy population. In a population affected by sea urchin limited sori production could set back attempts to maintain or restore kelp populations. Uncertainty is high, as the effect of epiphytes and dissolved nutrients on kelp population decline due to limited sori production has not been examined in the field.

5.3.0 Dissolved nutrients affect C and N storage

Medium probability - Under normal circumstances in the region, *L. saccharina* grows during the high light period until nitrogen stores are depleted. At the same time, carbon is stored so that dissolved nitrate can be stored during the dark period that occurs the following winter and early spring. Biyearly on the salmon farm, the kelp receives farm derived nutrients. Then it can grow without the need to consume its nitrogen stores. It continues to grow until the end of its growth period when sori are produced. Some evidence exists that indicates that carbon is not stored when kelp is fertilized in this way. Intensity is expected to be medium because the ammonium from the fish farm would be taken up by the kelp at the front of the bed to leave few nutrients for the rest of the bed. This pattern will occur as long as the fish farm is in the area. Uncertainty is high, as little field work as been done in this area.

5.3.1 Lamina production changes due to changes in C and N storage.

Low probability - Carbon that is stored in Laminaria in the summer is used for nutrient uptake in the spring and for growth under low light conditions. If carbon is not stored, the production of the new laminae may be decreased. Intensity is expected to be medium because the ammonium from the fish farm would be taken up by the kelp at the front of the bed to leave few nutrients for the rest of the bed. Therefore, most of the bed would not be affected by the nutrients. This pattern will occur bi-yearly as long as the fish farm is in the area. Uncertainty is high, because researchers have not investigated the effect of low C stores on regeneration in perennial kelp.

5.3.2 Kelp productivity changes as a result of changes in lamina production.

Low probability - Little information exists relating to the fitness of *Laminaria* without suitable carbon stores at the time of nitrate availability due to upwelling. Intensity is expected to be medium because the ammonium from the fish farm would be taken up by the kelp at the front of the bed leaving few nutrients for the kelp in the rest of the bed. In addition, the effect is expected only once every two years, but it will endure as long as the fish farm is present. Uncertainty is high due to the general lack of information in this area of research.

5.4.0 Dissolved nutrients affect lamina growth.

Highly probable - In the area of interest, *L. hyperborea* are the largest in Norway. We can also expect that *L. saccharina* would also be the largest, as temperature and lighting is favorable for them too. Growth is expected to be good in spite of fish farming nutrients because of the adequate available background nutrients from spring upwelling conditions, and optimal temperature and lighting conditions. Due to the optimal environmental conditions, in this area, severity of this effect on kelp would be marginal. Uncertainty is low because the knowledge level concerning kelp and background nutrients is high.

5.4.1 Increase in lamina growth causes light limitation.

High probability - Previous research investigations have clearly shown that increases in lamina production can cause self shading of upper story individuals and shading of lower and younger story individuals. Intensity is expected to be low, because the size of the kelp in the bed in this area is already considered to be the largest in Norway due to adequate nutrients, lighting and optimal temperature. Uncertainty is low due to the level of understanding and available information.

5.4.2 Lamina production changes due to light limitation.

Highly probable - It is well known that light limitation negatively affects kelp growth unless carbon stores are adequate. Intensity is expected to be low, because the size of the kelp in the bed is already considered to be the largest in Norway due to adequate nutrients, lighting and optimal temperature. Uncertainty is low due to the high level of understanding in this area.

5.4.3 Kelp productivity changes as a result of changes in lamina production.

Low probability - In the area of interest, kelp are already the largest in Norway. Lamina production is expected to be optimal in spite of fish farming nutrients because of the adequate available background nutrients from spring upwelling conditions, and optimal temperature and lighting conditions. Hence, dissolved nutrients from the fish farm would not greatly affect the kelp. Uncertainty is low because the knowledge level concerning kelp and background nutrients is high.

5.5.0 Sori production changes as a result of changes in lamina production

Highly probable - Sori are produced on lamina, so it is logical to assume that sori production will change if lamina production changes. Intensity is expected to be low, because the size of the kelp in the bed is already considered to be the largest in Norway due to adequate nutrients, lighting and optimal temperature. Uncertainty is low due to the high level of understanding in this area.

5.5.1 Kelp productivity changes as a result of changes in sori production.

Low probability - In the area of interest, kelps

Table 6.4.III : Table summarizing risk estimation for logic model 2.

Steps in logic model 2 (Sites A and B)	Intensity or degree of change	Geographical extent	Permanence or duration	**Severity**	**Probability**	**Uncertainty**	Stage of assessment
1. Suitable kelp habitat is in the area of interest	M^{A} H^{B}	H^{A} H^{B}	H^{A} H^{B}	M^{A} H^{B}	H	L	
2. A salmon farm is within or close to kelp habitat	M^{A} H^{B}	H^{A} M^{B}	H^{A} H^{B}	H^{A} H^{B}	H H	L L	
3. Kelp are growing in the area of interest	$M^{A,B}$	$M^{A,B}$	$H^{A,B}$	$M^{A,B}$	M	L	
4. Particulate matter from the fish farm accumulates in benthos	H^{A} M^{B}	H^{A} M^{B}	H^{A} H^{B}	H^{A} M^{B}	H H	L L	Release
Release summary (Logic model steps 1-4)				$M^{A,B}$	M	L	
5.1 Gametophytes are affected by sulfide toxicity	M^{A} L^{B}	M^{A} L^{B}	H^{A} H^{B}	M^{A} M^{B}	H	H	Exposure
Exposure summary				M^{A} M^{B}	H	H	
Decrease in kelp productivity	M^{A} L^{B}	M^{A} L^{B}	H^{A} H^{B}	M^{A} M^{B}	M	H	Consequence
Consequence summary				M^{A} M^{B}	M	H	
5.2 Particulate matter affects gametophyte via burial	M^{A} L^{B}	M^{A} L^{B}	H^{A} H^{B}	M^{A} M^{B}	M	M	Exposure
Exposure Assessment							
Decrease in kelp productivity	M^{A} L^{B}	M^{A} L^{B}	H^{A} H^{B}	M^{A} M^{B}	M^{A} L^{B}	H	Consequence
Consequence Assessment				M^{A} M^{B}			
5.3 Heavy metals reach toxic concentration	L^{A}	L^{A}	L^{A}	L^{A}	L^{A}	H	Exposure
Decrease in kelp productivity due to heavy metal toxicity	L^{A}	L^{A}	L^{A}	L^{A}	L^{A}	H	Consequence
Overall risk of a drop in local kelp population (highest severity and probability)				M	M	H	

Explanatory notes:

1. **Probability = H** – High, **M** – moderate, **L** – Low, **EL –** Extremely Low, **N –** Negligible.
2. **Severity = C** – very intense, **H** – high, **M** – Moderate, **L –** Low, **N** – Negligible. There are three components of severity that should be considered: the duration of the activity, the degree of change, and the geographic extent of the change.
3. **Uncertainty = H-** Highly uncertain, **M** – Moderately certain, **L** – Low Uncertainty.
4. The final rating for the **Probability** is assigned the value of the element with the **lowest** level of probability.
5. 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.
6. The final rating for the **Uncertainty** is assigned the value of the element with the **highest uncertainty** level (i.e. the least certainty).

A: Site A B: Site B

are already the largest in Norway. Sori and lamina productions are expected to be optimal in spite of fish farming nutrients because of the adequate available background nutrients from spring upwelling conditions, and optimal temperature and lighting conditions. Hence, dissolved nutrients from the fish farm would not greatly affect the kelp. Uncertainty is low because the knowledge level concerning kelp and background nutrients is high.

Logic Model 2.

The following material is summarised in Table 6.4.III.

4. Particulate matter from the salmon farm accumulates in benthos.
Highly probable - Benthic change in Norway due to salmon farming has been shown to occur in over 80 salmon farms that were monitored in a study. Benthic impact occurs within two months of the introduction of fish. The site depth and current speed are not correlated to biological change in benthic conditions right under the farm. That is, the benthos are expected to change at both sites A and B. The zone of benthic change extends to at least 100 m from the farms. The magnitude of benthic changes decreases with distance from the farm. Benthic faunal change toward more sulphide resistant species persists as long as the site is farmed, and beyond five years post farming in sheltered sites. Severity is moderate, as the zone of major benthic change is generally localised. Uncertainty is low, because much data exists on benthic impact.

5.1.0 Hydrogen sulphide kills gametophytes.
Highly probable - As documented in research investigations, sulphide after the start of farming operations quickly reaches toxic levels for aquatic plants (2.5 µM) below and at a distance exceeding 100 m from a salmon farm. This low tolerance to sulphide has been suggested as the reason that kelps are not commonly found in muddy anaerobic substratum. The potential particulate fallout zone covers the kelp bed on both farms (Sites A and B). Intensity is expected to be low to high because the geographical distribution of the waste, sulphides, kelp and gametophytes are not uniform. Kelps that are furthest away would receive fewer waste particulates and depending on the kelp density, the kelp closest to the farm would intercept most of them. Following these trends, initially waste accumulation followed by sulphide production would start at the front of the kelp bed, and over time proceed to the back of the bed. The latter statement would depend on the density of the kelp bed. At Site A due to the lower current velocity, the effect would be more pronounced. Duration of the effect lasts as long as the farm remains in the area. Uncertainty is high; because researchers have studied the ability of kelp to settle particles but not the associated formation of sulphides, and no research on this topic has been carried out on fish farms.

5.1.1 Kelp population decreases.
Medium probability - In the area of the salmon farm at Site A, *Laminaria* are heavily preyed upon by sea urchins so survival depends on recruitment. Recruits would be killed if they fell upon sediments containing low concentrations of sulphide (2.4 µM). As deposition is heaviest in that part of kelp bed closest to the farm, gametophytes would not survive there. Over time, kelps would die off in the frontal zone. As the kelps are continuously devoured by sea urchins, and not replaced due to gametophytes lost to sulphide, kelp further back in the bed could trap more of the organic waste, accumulation of which would lead to formation of sulphide and so on until the kelp bed is gone, or insufficient particles are trapped, and the remaining bed is left unaffected. The latter event depends on the distance from the farm. Intensity is low to medium depending on the site. Intensity is limited to the zone of influence of the farm and would be highest in the sheltered site, Site A, as there the zone of influence over the kelp bed is greater than at the more exposed site, Site B. The effect would occur as long as the fish farm is in the area, and several years after closure at Site A. Uncertainty is high. It is known that only a low level of sulphide is required to kill the gametophytes but research has not been conducted on this scenario (for example, particulate waste and salmon farming).

5.2.0 Organic waste particles bury gametophytes.
Medium probability - Kelp are known to have the ability to trap particulate matter, which then settles within the bed. Only a small cover of debris is known to kill gametophytes. Intensity is expected to be low to medium depending on the site because the geographical distributions of the waste, kelp and gametophytes are not uniform. As well, burial is expected to be most intense at the edges of the kelp bed where most of the particles are trapped. The latter statement would depend on the density of the kelp bed. Uncertainty is medium; because researchers have studied the ability of kelp to settle particles, but they have not done so near salmon farms.

5.2.1 *Laminaria* population decreases.
Low to highly probable depending on the distance from the salmon farm. In the area of the salmon farms, *Laminaria* are heavily preyed upon by sea urchins. Therefore, their survival depends on new recruitment. New recruits would be buried at the front of the kelp bed closest to the farm, but as the kelp are devoured by sea urchins and not replaced due to gametophytes, kelp in the interior of the

bed would trap particles with associated burial of gametophytes and so on until the kelp bed is gone, or insufficient particles are trapped, and the remaining bed is left unaffected. The latter event depends on the distance from the farm. Intensity is low to medium. Intensity is limited to the zone of influence of the farm and would be highest in the sheltered site, Site A, where the zone of influence over the kelp bed is greater than at the more exposed site, Site B. The effect will persist while the farm is in operation, and several years after closure. Uncertainty is medium. It is known that only a small amount of sediment over gametophytes is needed to kill them, but research has not been conducted on this scenario (for example, particulate waste and salmon farming).

5.3.0 Heavy metals in the sediments reach toxic levels for gametophytes.
Low probability - Heavy metals such as zinc and copper are bioavailable in sediments under oxygenated conditions; this condition is not expected when the fish farm is active. Sediments are only expected to buildup at site A. In the area of the salmon farm, *Laminaria* are heavily preyed upon by sea urchins. Therefore, their survival depends on new recruitment. New kelp recruits would attempt to colonize the sediments affected by salmon farming between production cycles or post farming. At these times, sediments can be come oxygenized, and dissolved heavy metals can become bioavailable, and potentially toxic to the recruits. Toxicity would be most pronounced at the front of the kelp bed closest to the farm. Severity is low. It is unlikely the benthos would become sufficiently oxygenized between production cycles. Uncertainity is high, as little research has been conducted on heavy metals during times of sediment recovery.

5.3.1 *Laminaria* population decreases.
Low Probability - Heavy metals can be released from sediments but it is unlikely the affected area would greatly affect a local kelp population. The affected kelp would be those attempting to colonise under the fish farm (a small area). The depth prohibits good kelp density, and the sheltered site, produces weak kelp. Uncertainity is high, as there has been little research conducted on heavy metals during times of sediment recovery.

From the risk estimation (Tables 6.4.II and 6.4.III), ammonium from the fish farms does not appear to be a significant hazard to adjacent kelp beds. The only possible concern related to dissolved nutrients is epiphytes affecting sori production on kelp that are being heavily preyed upon by sea urchins. Although the likelihood of occurrence is low, this effect combined with heavy sea urchin predation can set back attempts to maintain or restore kelp populations especially at sheltered sites. It is important to point out that the kelp stocks that would be affected would be very low, a small amount of the kelp along the entire coast line.

From the risk estimation, the particulate matter from the fish farms has the potential to bury and kill the gametophytes. In addition, waste deposition also has the potential to kill seaweeds via sulphide formation at sheltered sites. As the kelps that we studied are perenials, it is likely the affects would take years to be noticed, but once the population declines, recovery would be slow because of lingering toxic effects. Our assessment was, therefore, effective at pointing out a potential future problem. It is important to point out that the number of afflicted individuals would represent only a tiny fraction of the total number growing in the area.

Information relating to this assessment should ideally be communicated to local and national fish farming associations, local fishers, regional science and environmental officers, and the Norwegian Ministry of Fisheries and Coastal Affairs. Fishers might enquire if the kelp near the fish farm serve as important nursey grounds for fish. If so, some of the ratings given to severity and intensity could be changed to reflect their concerns. As much of the assessment in terms of procedures and results is relevant to other species and areas, it should be published if possible in science and trade journals and given to international environmental groups, such as the World Wildlife Federation.

We also found potential benefits of waste. In the sheltered sites where *L. Saccharina* predominants, the waste material has the potential to increase kelp production and at both exposed and sheltered, dissolved nutrients could help aid in kelp recovery from predation via fertilization. These benefits could, however, be overshadowed by the negative effects of the solid waste.

6.4.3.4 Risk Estimation

In the earlier discription of the farm no special technologies were identified as in use nor were specific regulatory requirements mentioned that might reduce the effect of that farm from that which might be anticipated based on past experience with this type of development. For that reason the risk level identified in the consequence assessment is the same as that for the risk estimation. Should any of the recommended risk management activities be undertaken that level of risk may be modified.

Table 6.4.IV : Summary of risk mitigation and research derived from the analysis.

	Logic Model Step	Probability	Mitigation (regulate/design/ modified practices)	Uncertainty	Research/Development
2	Salmon farms are established near Laminaria beds in coastal waters.	M	Where feasible site farm 200 m away from established or barren kelp grounds. This is the dispersion distance for gametophytes, and generally benthic changes due to salmon farming is low at this distance.	L	Verify the distance a salmon farm should be from a kelp bed.
4	Particulate matter from the salmon farm accumulates within kelp bed.	H	See step 2 above.	M	• Determine the ability of kelp to trap and settle waste particles. from salmon farm • Develop ways to trap sediment on site.
5.1	Organic waste particles promote the formation of sulfide in kelp bed.	H	See step 2 above.	M	Determine whether sulfide can form in a kelp bed due to the accumulation of organic particles from a salmon farm.

6.4.4 Risk Management

Option evaluation in risk management addresses what might be done to reduce the probability of a risk being expressed, or to reduce the uncertainty in the prediction of the expression of a risk. This can be addressed through consideration of the series of steps in the logic model discussed above. The process identifies, for each step, what could be done to reduce the probability of it occurring. These actions would directly mitigate possible effects. A further contribution to increasing the effectiveness of the risk analysis would be to reduce the uncertainty associated with predicting that the step will happen. Usually this involves further research or development. Table 6.4.IV identifies both mitigation and research or development steps that could be considered in addressing risks associated with waste effluent, particularly solid waste effluent) from salmon farms on *Laminaria* populations.

Whether there will be an impact from waste material from fish farms on kelp will depend on how close the kelp beds are to the farm and the size of the kelp bed. For instance, it can be envisaged that the impact would be minimal if farming remained distal from kelp beds (greater than 200 m from frontal edges to take into consideration spore dispersal and waste fallout zones). Also if the salmon farm remained distal from barrens, the farm would not impact the remediation of kelp beds over preyed upon by sea urchins. Site fallowing, a farming practice that is often mentioned to be a suitable method for benthic remediation, is not useful if sulphide levels increase to toxic levels during production cycles.

Much information is still unknown. For example, kelp beds are probably capable of trapping tiny particles from the farm that normally would not otherwise settle within the vicinity. As a result, over a period of time, effects of burial and sulphide toxicity may appear on the fringe of the kelp bed, and move back into the bed over time as the frontal individuals die off. The size of the particle capable to be trapped and its relationship to fish farming waste needs to be ascertained. The abilities of kelp to trap particles and provide a surface for their degradation, as well as to remove dissolved nutrients should, also, be explored. Particle entrapment could be done with suitable cultivated stock grown on ropes, and placed adjacent to a sea farm site. The cultivated stock must be locally obtained, so as not to affect the genetics of the wild stocks. The integrated cultivation of seaweed and fish in open systems was suggested as early as 1993 (Petrell *et al.* 1993), but was not accepted by industry due to difficulties associated with marketing kelp and work related issues associated with the handling two very different species. With more help with marketing, cultivated kelp may be grown to protect the wild ones.

To reduce the effects of waste sedimentation, several methods have been developed to prevent the particles from entering the environment. An expensive and energy demanding method is close containment. As an alternative, particles might be managed on site after they have been trapped on a screen (Burynuik *et al.* 2006). As well, a seaweed curtain as describe above may be effective. Others are experimenting with mussels and other species. The correct choice must be based on issues related to long-term sustainability.

6.4.4.1 Risk Mitigation

As indicated in the risk management table (Table 6.4.IV), two broad approaches can be taken to manage risk. The first is direct mitigation which generally reduces the likelihood of a step in the logic model being fully realized. These mitigation measures usually take the form of regulatory strictures such as enforcing a set distance between a salmon farm and a kelp bed. The second approach can be placed *via* a code of practice. This approach is seen when fish stocking considers output of nutrients and solid waste.

The other approach to manage risk is to reduce sources of high or moderate uncertainty. In this context, one of the advantages of risk analysis is that it can assist in identifying priorities for research and development work. For example, research might be used to confirm that only a small portion of a kelp bed is affected by particulate matter or dissolved nutrients, and hydrogen sulphide never builds up to toxic levels. Further research is needed to answer these questions. As well, research might find that a kelp bed is highly effective at trapping particulates, and the overall environment improves as a result. That research could be used to develop artificial kelp beds.

6.4.5 Evaluation of risk assessment model

The assessment was successful in identifying new risks associated with fish farming. This scoping exercise was difficult to carry out due to the large amount of information that had to be acquired and analyzed. In fact, we chose Norwegian sites largely because of the amount and quality of available information on fish farms, kelp resources, basic biology, oceanic currents, water quality and predators of kelp. Without this large database, the study would have been too difficult and costly, and uncertainty would have increased. Fortunately, this assessment can be applied to other sites and macrophytes. This is because the major effects relate to solid waste, and these affects appear to be independent of the species of macrophyte.

In this assessment, although several exposure paths relating to solid waste were ruled out due to dilution or temporal effects, they were still all examined. Local science officers can use this extensive review, and basic and generally available knowledge concerning the biology of local macrophytes to determine what exposure pathways are pertinent to the macrophytes in their areas of concern. For example, annual species capable of growing near a coastal fish farm could experience an immediate loss in recruitment if a thin layer of solid waste covers them or farm-derived nutrients causes them too grow to the level where they block the light needed for further growth. The latter effect, although not a major concern in our test sites due to the ideal growing conditions there, could decrease the growth of perennial species in non-ideal areas. The latter effect could also occur to *L. hyperborea* and *saccharina* in other parts of Norway where the growth conditions are not as ideal as they are in our test sites.

In general, much was learned in the process, and new knowledge and research paths were created. To protect macrophytes, we suggest that fish farms are sited at least 200 m from a macrophyte bed.

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CASE STUDY 6.5

RISK ANALYSIS OF THE SOIL SALINIZATION DUE TO LOW-SALINITY SHRIMP FARMING IN CENTRAL PLAIN OF THAILAND

Seng-Keh Teng
Bari Aquatech Sdn Bhd, Level 3, Wisma Chinese Chamber, 258 Jalan Ampang, 504450 Kuala Lumpur Malaysia

6.5.1 Introduction

In Thailand, commercial shrimp farming such as the farming of tiger shrimp (*Penaeus monodon* - Figure 1) was first concentrated in coastal mangrove areas of the provinces (for example, Samut Sakorn, Samut Songkram and Samut Prakan) along the upper Gulf of Thailand; this region accounted for more than 40% of the country's total shrimp farming area (Boromthanarat and Nissapa 2000). During the market boom in 1990s, shrimp farming in Thailand expanded very rapidly into areas along the southwestern coast adjacent to the Andaman Sea (Smith 1999) and later into the Chao Phraya Delta as well as the eastern part of Thailand (Lindberg and Nylander 2001; Szuster 2003a). As a result of the rapid expansion in farming areas, production of farmed shrimp in Thailand significantly exceeded that for captured shrimp : in 2003, 330,000 tonnes for farmed shrimp, compared to 67,000 tonnes for captured shrimp (DOF 2004).

Like many countries in the tropics, rapid growth of shrimp farming in Thailand during the last two decades has given rise to numerous adverse environmental changes which include:

a) Loss of mangrove habitat that used to be the nursery grounds for larval shrimp and fish as
b) Eutrophication of coastal areas due to the presence of excessive nutrients in the effluents discharged from shrimp ponds;
c) Salt water intrusion into the water table of nearby agricultural land and land subsidence due to over-extraction of both fresh and brackish groundwater to reduce the water salinity in coastal shrimp ponds; and
d) Increased turbidity in receiving waters due to uncontrolled discharge of pond sediments from the surrounding shrimp farms (Boyd and Musig 1992; Avault 1993).

Among these changes, the loss of mangrove forests has received the most attention due to the advocacy and scrutiny of international non-government organisations (NGO's). Thus, in the early 1990s, following the discovery that shrimp farming destroyed mangrove forest areas, the Thai government imposed a ban on the further development of shrimp farms in coastal mangrove areas. To cope with the problem that only limited coastal mangrove areas are now available for shrimp farming in saline water due to the ban, low-salinity shrimp farming techniques were developed as shrimp farmers discovered that black tiger shrimp (Figure 6.5.1) post-larvae could be acclimatised to grow in low salinity environments (Szuster and Flaherty 2000). The farming techniques, which involve mixing high salinity water with fresh water to give a final salinity to as low as 3-5 part per thousand (ppt), have also been proven to be technically and economically viable. The low-salinity farming techniques were found to provide the opportunity for producing two or even three crops of shrimp per year and thus developed rapidly. As a result, low-salinity shrimp farms were found in inland areas as far as 200 km from the Gulf of Thailand, covering large areas of completely freshwater agricultural land deep inside the Central Plain region (for example, in the provinces of Lopburi, Isingburi and Ang Thong) (Figure 6.5.2).

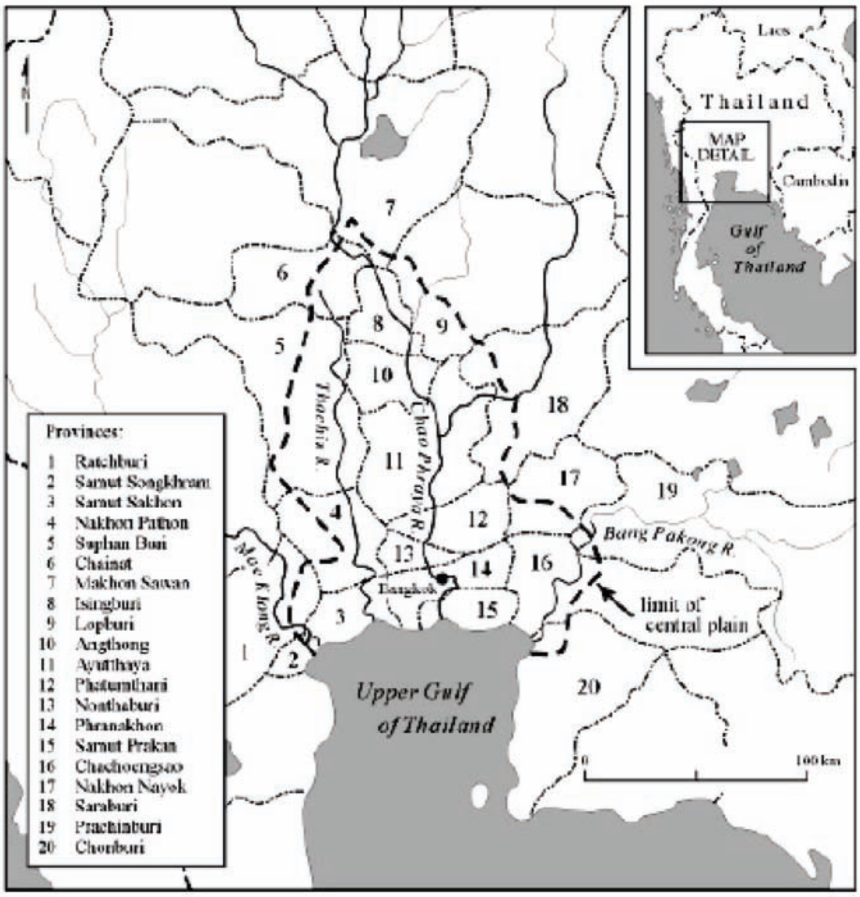
The Central Plain region in Thailand is a vast plain consisting of mainly the Chao Phraya River basin fed by a large network of canals and rivers. It is a lush, fertile valley supporting vast fields of rice, sugar cane, pineapples and other fruits. It is the richest and most extensive rice-producing area in the country and is known as the 'Rice Bowl of Asia' (Figure 6.5.2). Low-salinity shrimp farming in the Central Plain region of Thailand started in early 1980s when the mobility of shrimp farming operations became increasingly constrained owing to:

a) the lack of suitable sites remaining along the coast;
b) the increasing control on the use of mangrove forests by Thai government agencies; and
c) the sharp increase in land values due to competition with other coastal users (Flaherty *et al.* 1999; Flaherty *et al.* 2000).

To cope with the problem of limited availability of coastal areas for shrimp farming in saline water, innovative farmers, supported by relevant government agencies, developed low-salinity shrimp farming techniques in early 1990s. The first low-salinity shrimp farms, evolved through a process of experimentation by small-scale farmers and hatchery operators, appeared along the estuaries of the main rivers draining into the upper Gulf of Thailand. Subsequently, inland low-salinity shrimp farming expanded rapidly after the farming techniques were proven to be technically feasible and economically viable (Szuster 2003a). Successful inland low-salinity shrimp farms can produce around 4-5 tonnes/ha of shrimps twice a year yielding a profit up to 16 times that from farming rice in the Central Plain of Thailand. Because of this high return compared to rice cultivation, rice farmers who can raise the investment capital are usually willing to opt for shrimp farming. Rice farmers who are unwilling or unable to invest may lease their

*Figure 6.5.1 : Black tiger shrimp (*Penaeus monodon*). (source: Thongsawad 2005)*

Figure 6.5.2 : Location of the Central Plain of Thailand.
(Source: Szuster & Flaherty 2000)



paddy land areas to outside investors since the rents, in general, greatly exceed what they can get by growing rice (Szuster 2003b).

The largest concentration of inland low-salinity shrimp farms is in the provinces of the lower Central Plain including the Chao Phraya River Delta where rice irrigation infrastructure has been extensively developed (Figure 6.5.3). With ready access to fresh water supplies because of the well-developed irrigation system and the potentially very high profits of shrimp production relative to rice production, a large number of farmers in this area turned their irrigated paddy fields into shrimp ponds (Flaherty *et al.* 2000). An inventory conducted by the Department of Land Development in the late 1990s identified 22,375 hectares of agricultural land devoted to inland low-salinity shrimp farming in the provinces within the Central Plain region (Table 6.5.I). Inland shrimp farming has been found to be most popular in the provinces of Chachoengsao, Prachinburi, Nakhon Pathon, Nakhon Nayok, Chonburi, Suphanburi and Samut Prakan where the pace of inland shrimp farm expansion is beginning to mirror the explosive growth of shrimp culture that occurred along the coast about two decades ago.

The practices for inland low-salinity shrimp farming are generally similar to those for farming the shrimps in coastal mangrove areas. Shrimps are grown in high stocking densities with aerated pond water and commercially-available pelleted feeds and chemo-therapeutants are used. The main difference is the salinity level maintained in ponds during the grow-out period. Coastal shrimp farms maintain pond salinity between 15-30 ppt throughout the grow-out period while the inland farms begin the grow-out phase at pond salinity between 4-10 ppt and use fresh water to offset evaporation and seepage losses, which can reduce pond salinity to near zero by the time of harvest. In order to increase the salinity in the freshwater pond to 3-5 ppt for shrimp farming, about three truckloads (total = 45 tonnes) of salt water at 60 ppt are required for each hectare of the pond area to produce one crop of the shrimp. This results in a salt loading of roughly 2.7 tonnes per hectare per crop of shrimp production. This salt loading figure has been derived by the calculation that there is 60 g of salt in one litre of 60 ppt salt water and for one tonne of 60 ppt saltwater, the salt content would be 60 kg. For 45 tonnes of 60 ppt saltwater the salt content should be around 2,700 kg (60 kg x 45) or 2.7 tonnes, thus the salt loading of 2.7 tonnes. Since almost all inland shrimp farms in the Central Plain region produce two crops per year, annual salt inputs are ~5.4 tonnes per hectare per year (Szuster 2003b; Thongsawad 2005). This figure is substantially higher if the shrimp farms maintain pond salinity level at 10 ppt throughout the grow-out period, and so 5.4 tonnes per hectare annual salt loading figure should be considered conservative.

6.5.1.1 The issue of concern

Rice is the major crop production in the Central Plain of Thailand. Rice is not only the mainstay of the Thai diet, but also has been Thailand's largest single foreign exchange earner for over a century. Rice exports provided the foundation for Thailand's economic development and have been the vanguard for the country's integration into the global economy. The Central Plain is the richest and most extensive rice-growing area in Thailand.

Inland low-salinity shrimp farming could result in large-scale areas of soil becoming saline and unsuitable for rice production. The effects of salinity on the production of rice are well established. Almost all rice varieties are sensitive to salinity as it reduces the growth of seedlings and seed yield of the rice plants, even at low external salt (NaCl) concentrations. Likewise, concern over the salinisation of paddy lands adjacent to shrimp farms has existed in Thailand, particularly in the Central Plain region, for some time. In these areas, rice paddy fields are typically located behind the dense band of shrimp ponds. Complaints were frequently received from local people about low rice yields and the contamination of groundwater aquifers rendering large areas of land unsuitable for rice cultivation due to salinisation.

The conversion of rice paddy fields to shrimp ponds can be viewed as another example of the restructuring and intensification of agriculture, as farmers switch to higher-value crops. For the people living in rural communities, the potential impacts of low-salinity shrimp farming can be seen from two perspectives. On the one hand, shrimp farming holds the promise of improved welfare through direct participation or employment. On the other hand, the farming practice also raises serious concerns over the potential for environmental degradation, resulting in increased marginalisation, exclusion, and reduced economic welfare for local populations. The development of shrimp farms often occurs in areas where incomes from rice farming are low, indebtedness is high, and limited off-farm employment opportunities exist. Rice farmers are therefore under high pressure to choose short-term exploitation and a high profit potential that benefits relatively few people, in preference to long-term resource stewardship. More agricultural land areas are likely to be converted into shrimp farms.

6.5.2 Hazard identification

The rapid expansion of inland low-salinity shrimp farming within rice growing areas of the Central Plain in Thailand has raised concerns regarding the potential adverse environmental changes as well as the suitability of this farming activity within highly productive freshwater agricultural areas. Specific environmental changes include soil salinisation due to leaching of salt from the shrimp pond; water quality degradation as a result of effluent disposal; water pollution; and competition for freshwater resources between the agricultural and aquacultural farmers (Flaherty *et al.* 2000; Pongnak 1999; Jenkins *et al.* 1999). Among these adverse environmental changes, soil salinisation resulting from low-salinity shrimp farming, is the most critical issue due to its potential to cause long-term damage to agricultural areas (Ministry of Science and Technology 1999).

Soil salinisation has negative effects on rice crop productivity, and all rice varieties are sensitive to varying degrees. Salinity can inhibit the growth of rice seed-

Figure 6.5.3 : Low-salinity shrimp farms in Chao Phraya River Delta of the Central Plain Region, Thailand in 2001. (Source : Szuster 2003a)

Table 6.5.I : Area of Low-salinity Shrimp Farms in the Central Plain Region of Thailand in late 1990s. (Source: DLD 1999a)

Province	Area (ha)
Chachoengsao	8375
Prachinburi	4577
Nakhon Pathon	2204
Nakhon Nayok	1752
Chonburi	1631
Suphanburi	1359
Samut Prakan	518
Ayutthaya	451
Ratchaburi	350
Phetchaburi	322
Pathum Thani	244
Samut Sakhon	206
Ang Thong	193
Lopburi	48
Chai Nat	46
Nakhon Sawan	44
Nonthaburi	22
Saraburi	16
Isingburi	12
Samut Songkhram	5
Total	**22,375**

lings, reduce yields, and increase vulnerability to insect pests (Salim *et al.* 1990). Studies conducted by the Thai Department of Land Development (DLD 1999) and the Thai Ministry of Science and Technology (Ministry of Science, Technology and Environment 1999) indicated that seepage of effluents discharged from an inland shrimp farm may increase salinity of soil up to 50 meters or more from the edge of shrimp ponds. Soil salinisation can be a difficult and expensive environmental change to reverse.

Anthropogenic salinisation process has been found to affect 180,000-290,00 ha of agricultural land and it has become a major constraint on agricultural production. Not surprisingly, it puts the objectives of the National Action Plan for Food Security in Thailand (Im-Erb and Anecksamphant 2002; Thailand Development Support Committee 1990) at risk. The following, therefore, provide analyses of risks associated with soil salinisation due to the practice of low-salinity shrimp farming in inland areas of the Central Plain region of Thailand.

6.5.3 Risk assessment

6.5.3.1 Release Assessment

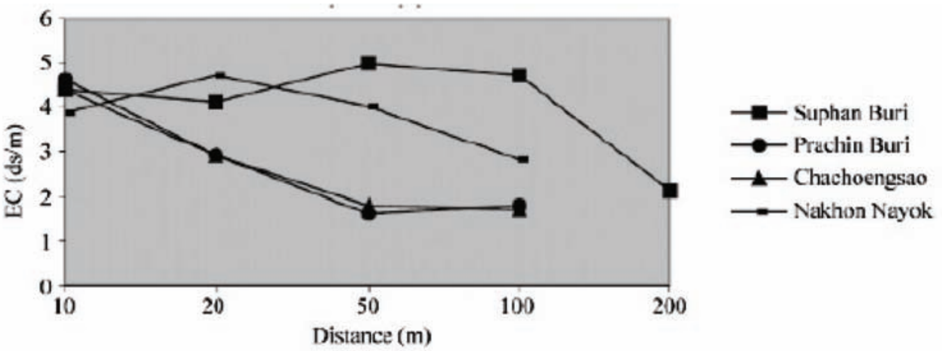
Soil salinisation due to low-salinity shrimp farming can occur directly through the deposition and accumulation of salts in soils located immediately beneath the pond enclosure, or indirectly as a result of seepage into adjacent agricultural areas. The salinisation process is generated by :

a) discharge of wastewater from the shrimp ponds into canals,
b) saltwater leakage or overflow from the shrimp ponds, and
c) leakage from sludge piles in the shrimp farm during rainfalls (Thongsawad 2005).

Indirect soil salinisation can occur through the disposal of saline effluents from shrimp ponds into streams or irrigation canals, which are subsequently used to irrigate rice paddies or orchards. In an earlier study conducted by Braaten and Flaherty (2001), soil salinisation was assessed by analysing the salt balance for an inland shrimp farm in Chachoengsao Province of the Central Plain during May-July 1999. Field data on water fluxes and pond salinities collected from nine ponds in this shrimp farm over one shrimp grow-out cycle were used to model the salt balance. Results indicated that during the grow-out period of shrimp production, seepage represented 38% of the total volume of pond water, which was equivalent to 11.5 tonnes of salt loss per ha per shrimp crop; the pond discharge was at 33% total pond water volume or at 9.7 tonnes salt loss; and the accumulation in pond sediment accounted for 6% total pond water volume or 1.8 tonnes salt loss. The majority of the salt (84% on average) from the shrimp ponds was discharged to the irrigation canals. Much of the salt in the pond sediment was leached to the canal system through flushing of the ponds after the shrimp harvest. Pond discharge caused increases in salinity in the receiving canal water above levels that would impact on yields of irrigated rice and orchard crops. It has also been found that elevated salinity in soil and water in adjacent rice fields was probably related to lateral seepage from the shrimp ponds. Even with shrimp ponds operated at a zero effluent discharge, almost half (~45%) of the initial pond salt content was exported to neighbouring rice fields through seepage, with another 6% of the pond salt content deposited in the pond sediments. It has been found that for an average-sized inland shrimp farm (3-5 ha), the total amount of salt lost to the surrounding environment through seepage, pond water discharge and pond sediments was estimated to be around 23 tonnes per crop of shrimp production; amount of salt loss by lateral seepage through pond walls accounted to 11.5 tonnes per shrimp crop; and the direct discharge of saline water to irrigation canals, the most significant salt transfer pathway, was estimated to be around 9.7 tonnes per shrimp crop (Braaten and Flaherty 2001).

In other studies, criteria for defining the salt-affected area are based on the EC (electromagnetic conductivity) value of 2 dSm^{-1}, for example, any land area that recorded an EC value more than 2 dSm^{-1} is considered to be a salt-affected area and is not suitable for crop production (Im-Erb and Anecksamphant, 2002; Tanavud *et al.* 2000). Twenty shrimp ponds were selected for each of the four provinces in Central Plain for the study; the chosen shrimp ponds had already practiced the shrimp farming for at least three years. The electromagnetic terrain conductivity (EM-38) method was employed to determine EC values in both horizontal and vertical directions and measurement was made at the distances of 0, 10, 20, 30, 40, 50, 100 and 200 m from the shrimps ponds in five provinces in the Central Plain region (Im-

Figure 6.5.4 : EC values of ground water in shrimp ponds in Suphan Buri, Prachin Buri, Chachoengsao and Nakhon Nayok provinces at the distances of 10 - 200 m away from the shrimp pond. *(Source : Im-Erb and Anecksamphant 2002)*



Erb and Anecksamphant 2002). Results of the study showed that the level of soil salinisation, as indicated by the EC values, decreased substantially with the distances away from the shrimp pond. For instance, in Suphan Buri Province, the ranges of the EC values of soil were 2.5-4.2, 2.7-4.3, 2.3 -4.2, 1.9-4.2, 1.7-4.6, 1.5-3.9 and 1.7-3.0 dSm^{-1} for distances of 0, 10, 20, 30, 40, 50, 100 and 200 m away from the shrimp pond, respectively; similar trends of decreasing EC values with distance from the shrimp pond were found in other provinces such as Prachin Buri, Chacheongsao and Nakhon Nayok (Figure 4). Tanavud *et al.* (2000) studied the effect of soil salinisation on the productivity of soil for crop production due to low-salinity shrimp farming in Songkla Lake Basin of southern Thailand. Results of their study indicated that inland low-salinity shrimp farming did cause soil salinisation as far as 100m away from any shrimp pond, with EC values varying from 4.42 dSm^{-1} to 5.24 dSm^{-1}.

6.5.3.2 Exposure Assessment

The expansion of shrimp farming in the freshwater area of the Central Plain and its potential impact on rice cultivation has been a serious concern in Thailand since the first boom of pond shrimp farming occurred during the late 1980s (Thailand Development Support Committee 1990). Results of earlier studies indicated that the total area of salt-affected soils in Thailand, by both natural phenomena and anthropogenic processes, amounted to 3.4 million ha of which the Central Plain region accounted for 0.18 million ha, and in that area salinisation was mainly induced by shrimp farming (Szuster 2003b; FAO 2006).

As mentioned earlier, Im-Erb and Anecksamphant (2002), in their studies on low-salinity shrimp farming and soil salinisation, indicated that soils were highly saline with EC values exceeding 2 dSm^{-1} even in the area within 50m away from the inland low-salinity shrimp ponds in the Central Plain region. Studies on the effects of soil salinisation have suggested that saline soils with EC values greater than 2 dSm^{-1} occured to all agricultural land converted to shrimp ponds (Committee on Inland Shrimp Farming 1998; Im-Erb and Anecksamphant 2002). It has been estimated that the total area of soil affected with salt in five provinces (Suphan Buri, Prachin Buri, Nokhon Si Thammarat, Nakhon Nayok and Chacheongsao) of the Central Plain was approximately 90,650 ha including the areas of the shrimp farms. The total area of soil affected by the salinisation process in the whole Central Plain region is likely to be 2-3 times the 90,650 ha (for example, 190,000-280,000 ha) when shrimp farming areas in the other 15 provinces of the Central Plain (Im-Erb and Anecksamphant 2002) are included in the estimate.

Most of the lands in the Central Plain region are highly productive for rice farming (Szuster 2001) and their soil quality has been negatively affected by conversion into shrimp farms. The issue of soil salinisation within the freshwater areas of the Central Plain region is highly controversial because many low-salinity shrimp farms have been sited within highly productive rice growing areas.

6.5.3.3 Consequence Assessment

Soil salinisation has negative effects on rice crop productivity since all rice varieties are sensitive to varying degrees of salinity which can inhibit the growth of rice seedlings, reduce yields, and increase vulnerability to insect pests (Salim *et al.* 1990). Accumulation of salts in soil can occur to the extent that results in degradation of vegetation and soil quality. Salinity can affect all stages of crop growth by:

a) changing the osmotic potential of soil water and toxicity of specific ions;
b) increasing ion concentrations within the plant, interfering with plant growth; and
c) affecting soil aeration and cation exchange (Greenland 1997).

As a result of these changes, the following effects on the growth of the plants can be observed:

(i) morphological and anatomical changes in leaf anatomy and succulence;
(ii) changes in microscopic and sub-microscopic structure of leaf, stem and root growth; and,
(iii) physiological, metabolic and biochemical changes in enzyme activities.

In saline conditions, the solute concentration of soil water increases, which in turn reduces or reverses the soil to root osmotic gradient which may lead to difficulty in extraction of water by the plants where water molecules tend to move to the areas of lower free energy. These changes can reduce growth or cause death of the plants growing in saline soil (Yadav 2005).

In Thailand, saline soil with EC values exceeding 2 dSm^{-1} can render productive land unsuitable for arable crop production. By comparing the characteristics of saline and normal soils, Tanavud *et al.* (2001) found that saline soil with EC value exceeding 2 dSm^{-1} has significantly lower organic carbon and total nitrogen content (key nutrient components indicating fertility of the soil), clay content and water retention capacity. Thus, inland low-salinity shrimp farming results in large-scale soil salinisation, and causes the soil to be unproductive for agricultural crop production (Tanavud *et al.* 2001).

Agricultural yields in coastal areas of Thailand tended to be rather low, due to marginal soil conditions, and this situation was aggravated by saline seepage from shrimp ponds or saltwater intrusion produced by groundwater withdrawals for shrimp culture (Phillips *et al*. 1993). The destruction of sugar palms, originally planted in coastal rice fields which later became salinized due to the practice of low-salinity shrimp farming, is a highly visible reminder of the aquaculture-induced soil salinisation problem (Phonga *et al.* 2000). It is anticipated that further expansion of inland low-salinity shrimp farming in the Central Plain is likely to aggravate soil salinisation and degrade water resources rendering these natural resources unsuitable for rice and other agricultural crop productions (Braaten and Flaherty 2001).

In Thailand agricultural production is the main source of national revenue. Since soil salinisation associated with inland low-salinity shrimp farming is a critical environmental issue that affects rice production, the issue warrants an analysis of the hazard of salinisation due low-salinity shrimp culture. Below, the logic model concept is used to identify the causes and effects of the soil salinisation resulting from the practice of low-salinity shrimp farming in the Central Plain region of Thailand. A series of steps and processes leading to the occurrence of soil salinisation resulting from inland low-salinity shrimp farming are, therefore, summarised in a logic model shown below.

The Logic Model:

Process of Concern (Hazard): Low-salinity shrimp farming in agricultural land in the Central Plain of Thailand

End Point of Concern: 180 000-290 000 ha of soil in agricultural land in the Central Plain of Thailand are made unsuitable for rice production with an EC greater than 2dSm^{-1}.

Logic Model Steps:

1. Development of low-salinity shrimp farms in agricultural land of Central Plain in Thailand.
2. Practices of the low-salinity shrimp farming will introduce significant quantities of salt.
3. There will be an increase of soil salinity due to low-salinity shrimp farming.
4. Large areas of soil in agricultural lands will be affected.
5. Productivity of soil in agricultural land of the Central Plain decreased.
6. At least 180,000-290,000 ha of soil in agricultural land in Central Plain of Thailand are made unsuitable for rice production.

The causal relation of the logic model steps is presented in Figure 6.5.5.

1. Development of low-salinity shrimp farms in agricultural land of Central Plain in Thailand.

Inland low-salinity shrimp farming has developed in the Central Plain region mainly due to the lack of suitable sites remaining along the coast and the sharp increase in land values due to competition with other coastal users. The farming practice developed rapidly and production in mid-1990s represented as much as 30-40% of Thailand's total production of farmed shrimps. The farming area accounted for around 22,375 hectares of agricultural land in the provinces within the Central Plain region. The pace of expansion of inland shrimp farms mirrors the explosive growth of shrimp culture that occurred along the coast in Thailand about two decades ago. The farming techniques are well-developed and produce higher profits than rice cultivation, so, without further government intervention, this type of cultivation will expand.

Probability of the risk of the further large scale development of low-salinity shrimp farms is considered to be relatively high, due to the pressure of factors including: (a) in Thailand, shrimp farming plays an important role in its national economy; (b) government authorities have been supportive of shrimp farming, encouraging farmers to raise more shrimps for export (c) the area used for such shrimp culture is large; and (d), should it be considered, removal of the industry would require a protracted period to allow for adjustment in the communities that have come to rely on the income from shrimp farming. The Severity of change is therefore High, the probability that this outcome will be realised is High and the uncertainty is Low.

2. Practices of low-salinity shrimp farming will introduce significant quantities of salt.

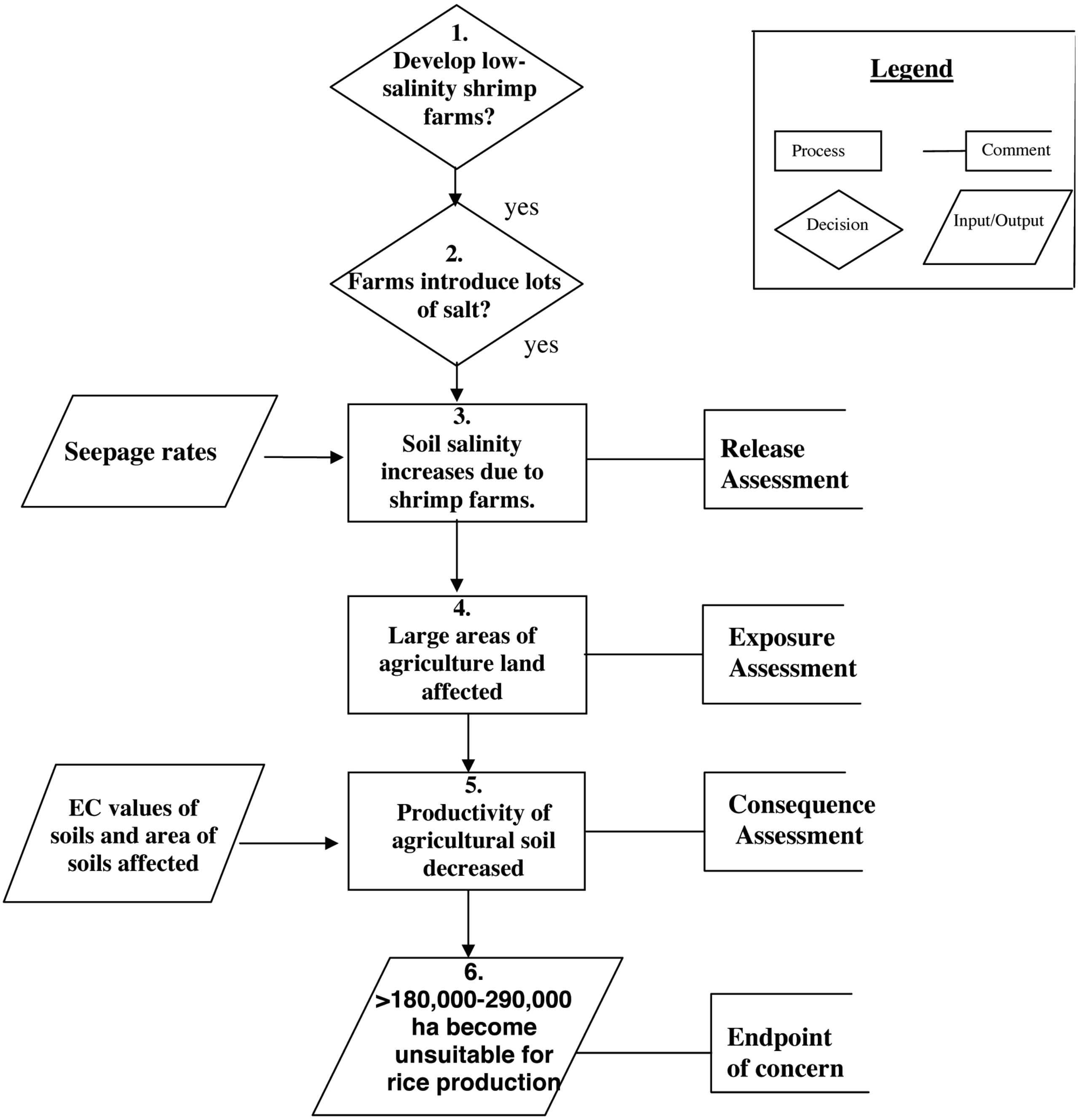
In the conventional coastal shrimp farming, the salinity of the pond water varies according to the salinity of the incoming water, usually in the range of 15-30 ppt. For inland shrimp farming, more complex management of pond water salinity is practiced. To maintain a low salinity of 3-5 ppt in each shrimp pond (1.0 ha), three truckloads (15 metric tons each truckload), for example, 45 metric tons of salt water at 60 ppt are required. Since about 30% of the pond water will be replaced with new water of similar salinity level (3-5 ppt) every 10 days, about three truckloads of 60 ppt salt water will be required per water change for the whole farm. The total volume of high salinity water required per month would be 135 metric tons; the volume for the whole grow-out period (four months) would be 540 metric tons. The total volume of high salinity water required for one production cycle for the farm would be 585 metric tons. Salinity in the grow-out ponds can range from 3 to 8 ppt at the end of the acclimation period, depending on a variety of factors including pen size, water depth, and initial salinity levels. Reservoir ponds are used to store low-salinity water for water exchange in the grow-out ponds. The shrimps are harvested after four months of rearing. Two crops of shrimps can be produced each year. These farming techniques have been well-developed and are known to be commercially viable.

The quantities of salt introduced to the soil by shrimp culture are high relative to other sources of salt. The area over which this occurs is also large. No other commercially proven technology has been developed for raising these shrimp species in low salinty water. Consequently, it is highly likely this type of shrimp culture will continue for the foreseeable future. The Severity of change is therefore High, the probability that this outcome will be realised is High, and the uncertainty is Low.

3. There will be an increase of soil salinity due to low-salinity shrimp farming.

The process of causing the increase of soil salinity due to low-salinity shrimp farming in the Central Plain of Thailand can be either of

Figure 6.5.5 : Logic model for risk of soil salinisation due to low salinity shrimp farming. Numbers in each box refer to a logic model step used in the assessment.



primary or secondary nature. In the primary salinisation, the natural process of parent material weathering is relatively small compared to the secondary salinisation. In the secondary salinisation, accumulation of salt in the soil is caused by mobilisation of stored salt from the soil profile and/or ground water due to human activities. Soil salinisation due to low-salinity shrimp farming could be categorised under the secondary salinisation process. Past experience has shown that a significant portion of the salt from the shrimp ponds enters the surrounding agriculture lands.

Soil salinisation of the agricultural land in the Central Plain region is highly likely to continue. The area of the farms from which the salt originates is large and, as indicated above, is likely to continue for the foreseeable future. The Severity of change is therefore High, the probability that this outcome will be realised is High and the uncertainty is Low.

4. Large areas of soil in agricultural land will be affected.

   In Thailand, saline soil with EC (electromagnetic conductivity) value exceeding 2 dS/m has been known to render productive land unsuitable for arable crop production. It has been estimated that the total area of soil affected in five provinces (Suphan Buri, Prachin Buri, Nokhon Si Thammarat, Nakhon Nayok and Chacheongsao) of the Central Plain region is approximately 90,650 ha, including the area of the actual shrimp farms. The total area of soil affected by the salinisation process due to low-salinity shrimp farming in the Central Plain region is likely to be 2-3 times of the 90,650 ha (for example, around 190,000 - 280,000 ha) if shrimp farming areas in other 15 provinces of the Central Plain are included. Therefore, the degree to which the rice growing agricultural soils are modified (relative to thresholds for rice culture) is high, the area affected is large and given the pattern of development in these areas, the salinisation of farm land likely to last for a considerable period. The Severity of change is therefore High, the probability that this outcome will be realised is High and the uncertainty is Low.

5. Productivity of soil in agricultural land of the Central Plain decreased.

   Salinisation as a result of the low-salinity shrimp farming has caused serious and severe decline in soil productivity and crop yields. Salinity has been found to reduce efficient use of water (for example, crop yield per unit of water) causing reductions in the return from capital investment and labour inputs. Salt-affected soil is:

- more fragile and subjected to other forms of degradation such as reduction in land green cover and becoming vulnerable to wind and water erosion;

- less responsive to any other input, for example, the soil crop yield response to fertiliser is less, as salinity is a limiting factor; and

- less flexible for alternative land use as farmers are forced to cultivate only salt-tolerant crops which are not always be the high income cash crops.

   It has been found that in the Central Plain region, saline soil with EC value exceeding 2 dS/m has significantly lower organic carbon and total nitrogen contents (they are key nutrient components indicating fertility of the soil), clay content and water retention capacity. The rehabilitation of saline soil also needs high investment, and in economic terms the cost of rehabilitation may reach 65% and 100% of the total crop production value in moderate to severe conditions, respectively. Large areas of soil in the Central Plain region will have highly reduced productivity, so long as the low-salinity shrimp farming continues. The probability in this respect is high with little uncertainty.

6. At least 180,000-290,000 ha of agricultural land of Central Plain in Thailand are made unsuitable for rice production (end-point of concern).

   More agricultural land areas are likely to be converted into shrimp farms, although the individual lease areas to be converted to shrimp production may be small. It has been estimated that the total area of soil already affected by salt (with EC value exceeding 2 dS/m) in five provinces (Suphan Buri, Prachin Buri, Nokhon Si Thammarat, Nakhon Nayok and Chacheongsao) of the Central Plain region is approximately 90,650 ha including the area of shrimp farms proper. The total area of soil affected by the salinisation process due to low-salinity shrimp farming in the Central Plain region is likely to be 2-3 times the 90,650 ha (for example, around 190,000 - 280,000 ha) if shrimp farming areas in other 15 provinces of the Central Plain are included. The Severity of change is thought to be close to the endpoint threshold established before the analysis and is therefore Moderate. The probability that this outcome will be realised is High and the uncertainty is Low.

   The severity, probability and uncertainty of risks associated with the logic steps in the analysis of soil salinisation resulting from the practice of inland low-salinity shrimp farming in the Central Plain of Thailand have been assessed. Results of the assessment are summarised in Table 6.5.II.

Table 6.5.II : Logical model outcomes.

Steps in the logic model	Intensity	Spatial Extent	Duration	Overall Severity	Probability	Uncertainty
Step 1. Development of low-salinity shrimp farms in agricultural land of Central Plain in Thailand.	H	H	H	H	H	L
Step 2. Practices of the low-salinity shrimp farming will introduce significant quantities of salt.	H	H	H	H	H	L
Step 3. There will be an increase of soil salinity due to low-salinity shrimp farming.	H	H	H	H	H	L
Step 4. Large areas of soil in agricultural lands will be affected.	H	H	H	H	H	L
Step 5. Productivity of soil in agricultural land of the Central Plain decreased.	H	H	H	H	H	L
Step 6. At least 180,000-290,000 ha of soil in agricultural land in Central Plain of Thailand are made unsuitable for rice production.	H	M	H	H	H	L
Final Rating [4]				H	H	L

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).

6.5.3.4 Risk Estimation

In order to deal with the problem of soil salinisation in the Central Plain region, the Royal Thai government has banned the expansion of inland shrimp farming in Thailand's irrigated rice growing areas in the late 1998s on the basis of a recommendation from the National Environment Board (Srivalo 1998). Governors in coastal provinces were subsequently instructed to designate land as freshwater area where shrimp farming would be prohibited, or as brackish water area where shrimp farming could continue.

However, in spite of the prohibition on shrimp farming within freshwater provinces over the past decade, concerns continue to exist over the capacity for enforcement of the ban, the manner in which brackish water and freshwater areas have been designated, and the possibility that the ban on inland shrimp farming could be relaxed (Flaherty *et al*. 2000). These concerns are reinforced by factors such as: (a) in Thailand, shrimp farming plays an important role in its national economy; and (b) government authorities have been supportive of shrimp farming encouraging farmers to raise more shrimps for export. With the further development of shrimp farming in Thailand's coastal areas increasingly constrained by high land values, more effective protection of mangrove forests, and concerns over the risk of disease owing to poor environmental conditions, renewed pressure is likely to develop for the expansion of shrimp farming into freshwater areas (Vandergeest *et al.* 1999; Thamrong and Laura 2003).

Concurrently with the ban on inland shrimp farming on designated freshwater area, the Thai Government also introduced plans to reclaim the land affected by shrimp farming to be reused for agricultural purposes (Im-Erb and Anecksamphant 2002). At the same time, the Thai shrimp farming industry lobbied strenuously for a reversal of the ban on shrimp farming in freshwater areas mainly in the Central Plain region. While it appeared for a time that the restriction on shrimp farming in freshwater areas would be relaxed, intense opposition from environmental groups and support from His Majesty King Bhumibol of Thailand may finally convince the National Environment Board to re-affirm its original decision and maintain the ban (Szuster 2003b).

With regard to soil salinisation, the Thai government has imposed aquaculture zoning strategies which are being developed to mitigate the environmental impacts of shrimp faming on agricultural land use. A proposal by Thailand's Land Development Department (1999) would restrict shrimp farms in the Central Plain region to designated brackish-water zones within three coastal provinces (Samut Prakarn, Bangkok, and Samut Sakhon). Farm construction within these provinces would be limited to regions possessing soil parent materials with a conductivity of 2 dSm^{-1} or greater (measured at 1.5 m below the surface). This would restrict shrimp farms to less productive areas with saline sediments located relatively close to the surface (Szuster 2003b). Shrimp farms within approved areas would also be required to install perimeter ditches and / or pond liners to mitigate indirect salinisation effects, and the disposal of saline pond effluent during periods when rice farmers are accessing irrigation water supplies would be controlled (Boyd 2001). Enforcement of these measures has been slow and inconsistent, and it remains to be seen whether all shrimp farms within restricted areas will cease production or switch to alternative crops. However, restricting shrimp farming in fresh water zones still represents a prudent strategy for preserving agricultural land, and the implementation of this strategy in the Central Plain region of Thailand should represent a high priority for the Government of Thailand (Szuster 2003a)

6.5.4 Risk Management and Mitigation

The risk(s) associated with each of the logic steps could be mitigated through a number of modifying practices as well as the research and development (R&D) activities taken by the relevant authorities. Such activities for each of the logic steps were analysed and results of the analysis are summarised in Table 6.5.III.

6.5.5 Summary and Lessons Learned

The practice of commercial low-salinity shrimp farming in the Central Plain region of Thailand was technically and economically viable. As a result, rapid development of low-salinity shrimp farms occured in the inland agricultural lands, which are used for rice production. Although inland low-salinity shrimp farming could reap short-term profitable returns, it is considered to be an environmental hazard that introduces soil salinisation to a large area. The anthropogenic salinisation process has been found to degrade soil resources causing long-term damage to agricultural areas and it has become a major limitation on agricultural production, likely to place at risk the National Action Plan for Food Security in Thailand. Agricultural land, once it is salinised and its soil quality is damaged, may be difficult and expensive to reverse. Soil salinisation resulting from the practice of low-salinity shrimp farming does introduce risks for the agricultural development and affects the agricultural production, particularly rice production, in the Central Plain region, which isthe richest and most extensive rice-producing area in Thailand. The expansion of shrimp farming in freshwater area of the Central Plain and its potential impact on rice cultivation has become a serious concern in Thailand since the first boom of pond shrimp farming occurred during the late 1980s. Soil salinisation, therefore, has negative effects on rice crop productivity since all rice varieties are sensitive to varying degrees of salinity which can inhibit the growth of rice seedlings, reduce yields, and increase vulnerability to insect pests. An estimated 180,000-290,000 ha of soil in agricultural land of the Central Plain in Thailand could become unsuitable for rice production due to the practice of the inland low-salinity shrimp farming. A risk analysis to elucidate the causal relationship of these processes of environmental interactions was attempted.

The protocol of risk analysis adopted herewith was based on the initial framework of the environmental risk analysis for mariculture developed by the ICES WGEIM. The protocol essentially involves first the elaborated description/explanation of 'Hazard identification' and the three components of the risk assessment - release assessment, exposure assessment and consequence

Table 6.5.III : A summary of risk mitigation and research options.

<table>
<tr><th>Steps in the logic model</th><th>Probability</th><th>Mitigation</th><th>Uncertainty</th><th>R&D</th></tr>
<tr><td>Step 1. Development of low-salinity shrimp farms in agricultural land of Central Plain in Thailand.</td><td>H</td><td>Implement ban on further development of low-salinity farming in Freshwater arable land</td><td>L</td><td>R&D on alternative freshwater technologies for shrimp production or alternative freshwater species for culture</td></tr>
<tr><td>Step 2. Practices of the low-salinity shrimp farming will introduce significant quantities of salt.</td><td>H</td><td>Permit only fully freshwater cultivation technologies</td><td>L</td><td rowspan="3">Implement new wholly freshwater technologies for shrimp production and/or new freshwater species for profitable culture</td></tr>
<tr><td>Step 3. There will be an increase of soil salinity due to low-salinity shrimp farming.</td><td>H</td><td>Permit the use of only zero discharge technologies.
Avoid building saltwater reservoir in area where it might enter groundwater.</td><td>L</td></tr>
<tr><td>Step 4. Large areas of soil in agricultural lands will be affected.</td><td>H</td><td>Permit the use of only zero discharge technologies.</td><td>L</td></tr>
<tr><td>Step 5. Productivity of soil in agricultural land of the Central Plain decreased.</td><td>H</td><td>Implement zoning that restricts shrimp farming to designated areas.
Create impermeable drainage conduits and/or lined dams that allow water reuse.
For inland areas encourage use of salt tolerant plant species such as Acadia ampliceps or Azadirachta indica to lower groundwater levels. In coastal areas use dikes to prevent saline water intrusions.</td><td>L</td><td>R&D to identify the soil process in order to enhance the ability to manage the problem and to develop remedial measures for improving the saline soils.</td></tr>
<tr><td>Step 6. At least 180 000-290 000 ha of soil in agricultural land in Central Plain of Thailand are made unsuitable for rice production.</td><td>H</td><td></td><td>L</td><td></td></tr>
</table>

assessment. The analysis is further strengthened by the development of a logic model which may represent the analysis of one hazard and is consisted of several simple steps. The logic model steps may represent a summary of the earlier elaborated description on the risk assessment for a particular hazard but contains clear pathways on how risks produced from the hazard may exert the impacts on the environment - including human and physical environment. The logic model also provides the basis for deriving the risk evaluation, risk management and risk communication. In the present case study, the concept of the above risk analysis protocol was successfully applied to analyze the environmental risks due to the occurrence of the environmental hazard ¨ the practice of low-salinity shrimp farming in agricultural land of the Central Plain of Thailand ¨ and how these risks could be evaluated and mitigated.

6.5.6 Literature cited

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CASE STUDY 6.6

RISK ANALYSIS OF COASTAL AQUACULTURE : POTENTIAL EFFECTS ON ALGAL BLOOMS

Kedong Yin[1,2,4], Paul J. Harrison[2] and Edward Black[2]
[1]Associate Professor, Australian Rivers Institute, Griffith University, Brisbane, QLD, Australia
[2]Director and Professor, Atmospheric, Marine and Coastal Environment Program, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, China, Hong Kong Special Administrative Region
[3]Senior Aquaculture Advisor, DFO Aquaculture Sciences Branch, Ottawa, Canada
[4]South China Sea Institute of Oceanology, CAS, Guangzhou, China

6.6.1 Introduction

In this case study, waste effluents released from a fish farm are assessed for their capacity to significantly increase phytoplankton production in Tolo Harbour, Hong Kong SAR, China.

6.6.1.1 Issue of concern

The demand for seafood increases as the world's population grows. Because wild fish stocks are stable or declining, commercial fish aquaculture has become an increasingly common activity in developed (*for example*, Norway, Chile, Scotland/UK and Canada) and developing countries (for example, China and many countries in Southeast Asia). These fish farms discharge nutrients and organic wastes into the surrounding waters. The cultured fish are fed trash fish or manufactured feeds. The conversion of these feeds to fish (the ratio of feed supplied to the fish versus the increase in fish weight) is never 100%. Particulate matter in the form of feed not consumed by the fish or in the form of fish faeces is released, sinks and is deposited on the seabed sediment. This unused solid material breaks down into small particles that are decomposed by bacteria into dissolved organic matter and inorganic nutrients. Dissolved organic matter is eventually remineralised to inorganic nutrients. Dissolved organic and inorganic nutrients are also excreted directly by fish. Phytoplankton growth can be stimulated by the release of these nutrients, and may then result in a number of environmental consequences such as an increased frequency of phytoplankton blooms, a change in phytoplankton species diversity, and the depletion of dissolved oxygen in the bottom waters, as summarised in Figure 6.6.1.

Fish farm effluent may be an environmental hazard if it causes undesirable environmental changes. For many countries, the changes in water colour are associated with other undesirable changes in the aquatic environment such as a loss of fish, reduced property values, closures of swimming beach, etc. This study assesses one particular fish farm site to determine if the conditions there would be capable of generating a significant change in phytoplankton abundance.

A simple conceptual model for possible environmental consequences of nutrients effluent from fish farm on phytoplankton growth is presented in Figure 6.6.1. In this analysis, it serves as the basis for the risk assessment. The model consists of release, exposure, and consequence assessments, and risk estimation. The process begins with the identification of question as 'Is there a fish farm development in the area of interest?' and the endpoint to the assessment is: 'Are probable changes in phytoplankton biomass large enough to cause a visible discolouration of the water…an algal bloom?'.

6.6.1.2 Formation of a phytoplankton bloom

A phytoplankton bloom is a rapid accumulation of phytoplankton biomass in a water body. The bloom is an outcome of the balance between growth and loss rates in phytoplankton population. The growth rate is determined by light, nutrients, temperature and other physiological factors affecting phytoplankton, while the loss rate is driven by physical dilution processes (horizontal exchange and vertical mixing), sinking and grazing (Cloern 2001). A sufficiently slow exchange rate with surrounding waters (for example, a long residence time) helps to minimise the constraints on the growth of the algal population. A stable water column (stratification) can also help prevent light limiting algal growth. Both conditions are generally required for a bloom to occur (Mann and Lazier 1991). When stratification of the water column is relatively shallow, the concentration of the most limiting nutrient determines the amount of phytoplankton biomass (Parsons *et al.* 1984). Thus, fish farms can act as a source of nutrients and may result in algal blooms when the surrounding waters are not flushed or vertically well mixed. In any algal bloom, a concentration of chlorophyll a (chl *a*) exists above which discoloration of the water is apparent to the naked eye. When this happens, people residing in the area generally express concern and consider it to be an indication of poor water quality.

6.6.2 Hazard Identification

6.6.2.1 Sources of nutrients

Caged fish farming releases uneaten fish feeds, faeces, and soluble fish wastes into the environment (Tacon *et al.* 1995), as shown in Figure 6.6.2. Feeds are usually made of dry pellets or trash fish (small, low commercial value fish). The dominant type of feed varies among fish farms. On farms where feeds are usually

Figure 6.6.1 : A simple conceptual model for environmental consequences on phytoplankton resulting from nutrients from fish farm operations.

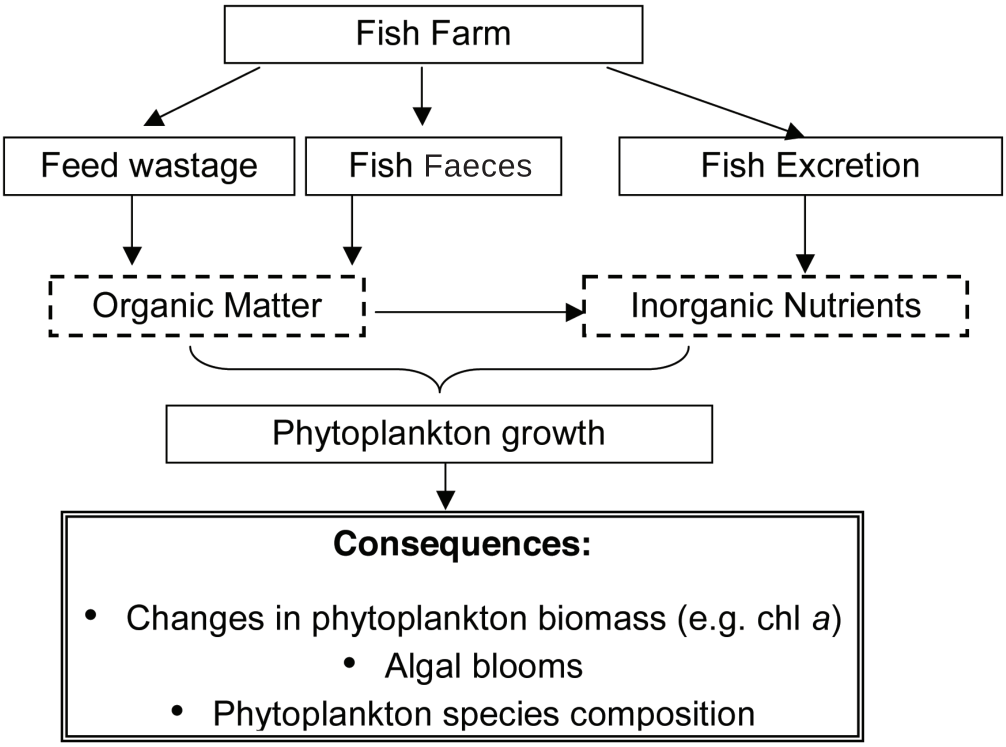
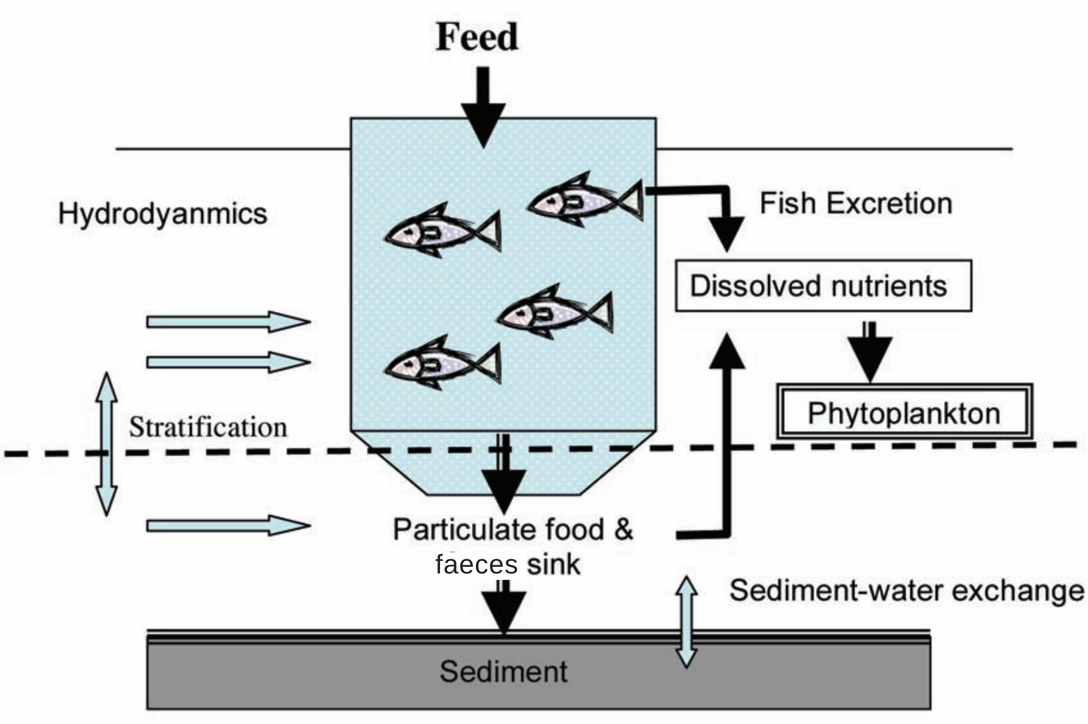


Figure 6.6.2 : Pathways of nutrients by fish farm operations to phytoplankton in water column. Exposure of nutrients depends on hydrodynamics, stratification and sediment-water exchange.



not of high quality and feed delivery systems tend to be imprecise, resulting in relatively poor feed conversion (Islam and Tanaka 2004). Marte *et al.* (2000) described fish cultivation in the Philippines, using trash fish as the main ingredient of feed for caged grouper, sea bass and snapper. FCR (feed conversion ratios = weight of feed supplied/harvest weight) values were generally between 2 and 2.8. The FCR varies depending on management practice and technology, with an average of two being common.

Feeds are generally supplied twice per day for adult fish, and 3 or 4 times daily for small fish. Some of the feed supplied is not captured by the fish and not all of the feed that the fish capture is digested. Faeces and uneaten feed are lost to the environment. Loss rates can be as high as 75–80%, depending on the culture system and the degree of feed management applied (Islam 2005). The waste feed and faeces sink in the water column, settle to the seabed, and are decomposed by bacteria and converted into dissolved organic matter that is remineralised into inorganic nutrients. Fish also excrete nutrients such as ammonium and urea directly into the water. These solid and soluble wastes form the basis for potential changes in water quality, sediment geochemistry, and aquatic and benthic ecology.

6.6.2.2 Changes in water quality and Phytoplankton biomass

The environmental effects of nutrient enrichment are site-specific and largely depend on the prevailing physico-chemical and biological features of the receiving environment. The input of soluble nitrogenous and phosphorous compounds from urban and agricultural runoff have been shown to cause hypernutrification (increases in nitrogen above ambient levels in the environment) in coastal waters as a precursor to algal blooms. The influence of fish farming is less clear. The effects of effluents from cage culture on phytoplankton depend primarily on the annual level of production, volume of the water body, depth of the water column, and water residence time (Phillips *et al.* 1985; Huang 1997). When the residence time of water near fish farms is longer than the doubling times of a phytoplankton population, phytoplankton biomass can accumulate and form blooms, which may cause discolouration of the water.

Waste food and faecal material contain organic nitrogen and phosphorus. That waste feed and faecal material sinks to the bottom in the vicinity of a farm (Figure 6.6.2) and is remineralised. Studies in many parts of the world have shown elevated levels of nutrients such as nitrate, nitrite, ammonium and phosphate associated with higher phytoplankton densities near fish culture (Wu 1995, Leung *et al.* 1999). Enell (1987) also showed that about 80% of the nitrogen input from fish farms was in the dissolved form (ammonium and urea). Ammonia and urea are readily taken up by phytoplankton and therefore most of the dissolved nitrogen released to the environment is readily available for phytoplankton growth in the photic zone. While nitrogen is generally considered the limiting nutrient in marine waters, enhanced levels of dissolved inorganic phosphate have also contributed to eutrophication of waters (Cloern 2001; Islam and Tanaka 2004). The phosphate in fish farm wastes is mainly held in the solid wastes on the bottom and is released by bacterial activity. Under conditions where algal growth is P limited, that phosphate may stimulate increases in algal abundance (Porrello *et al.* 2003).

Given this background, it is reasonable therefore to consider that nutrient wastes from fish farms represent an environmental hazard that in some circumstances might result in augmentation of algal abundances and possibly lead to an undesirable discolouration of waters.

6.6.3 Risk Assessment

Increased nutrient concentrations around fish farms may result in increased phytoplankton biomass (chlorophyll a can be used as a proxy), that may lead to algal blooms (Smith *et al.* 1999). The probability and magnitude of these risks depends on the natural nutrient assimilation capacity of the water column. That assimilation capacity is determined by the coupling between biological and physical processes. The biological processes include natural variability of nutrients, dissolved oxygen, phytoplankton biomass and species composition. The physical processes involve horizontal exchange between waters in which the caged fish are situated and open waters where exchange is less restricted, as well as the vertical mixing of the water column. Phytoplankton growth rate depends on water clarity and inorganic nutrients concentrations, derived either directly from fish excretion or from the decomposition of organic nutrients (feed waste and fish faeces). Since high concentrations of phytoplankton biomass can cause a change in water quality, plankton ecology and potential bottom water hypoxia, large increases in phytoplankton biomass are also a significant environmental phenomenon.

6.6.3.1 Study site

6.6.3.1.1 Tolo Harbour fish production

Fish are a major source of animal protein in Hong Kong. In 1997, the annual per capita fish consumption in Hong Kong exceeded 33 kg, compared to the world average of 16.1 kg (FAO 2000). Fish farms in Hong Kong consist of fish cages and the farms are small, covering about 250 m^2. Fish start as fry and grow to marketable size in about 1.5-2 years (Li 1996). During the annual production cycle of the farm, the fish biomass on site increases and nutrient releases increase along with the biomass. Common species cultured include green grouper, brown-spotted grouper, Russell's snapper, mangrove snapper, cobia and pompano (AFCD 2006, Chau 2004). Currently, there are 26 fish culture zones (Fig. 3) occupying a total sea area of 206 ha with some 1,125 licensed operators. Total marine fish culture production in 2005 amounted to 1,539 tonnes, valued at $76 million (AFCD 2006; June press release on www.afcd.gov.hk).

Tolo Harbour has two fish culture zones (Fig. 6.6.3, numbers 25 and 28) Also there is fish culture zone No. 10 in Tolo Channel. Fish Culture Zone No. 25 (FCZ25) is Yim Tin Tsai, which is separated from No. 28 by land and there is no direct water exchange between them

(Fig. 3). It has an area of 134,400 m^2 (480 m x 280 m) and between 2001 and 2005 produced 175, 133, 220, 126 and 149 tonnes of fish respectively, with an average production of 160.6 tonnes (data provided by AFCD).

6.6.3.1.2. Tolo Harbour geographic features

Tolo Harbour is a semi-enclosed bay connected to Mirs Bay via Tolo Channel to the east of Hong Kong (Fig. 6.6.3). The main harbour and channel is about 16 km long and 3 km wide, on average. The total surface area is about 50 km^2 and the water column is up to 10 m deep in the harbour. There are two fish farms in the Tolo Harbour designated as the Fish Culture Zone (FCZ) under the Marine Fish Culture Zone Ordinance and the Fish Culture Zone No. 25, Yim Tin Tsai FCZ, is used as the case study in this document. Water quality is good in Mirs Bay, but is poor in the inner harbour which receives riverine inputs and sewage effluent. Fresh water input and tidal cycles drive the flushing process and the average residence time is estimated to be 28 days (Lee and Arega 1999).

6.6.3.2 Release Assessment

The maximum nutrient input to Tolo Harbour from the farm may be estimated from : (1) annual fish production (AFP), (2) feed conversion ratio, FCR, (3) total N or P concentration in the feed (this value depends on the type of feed used), (4) total N or P concentration in fish, and (5) a seasonal modifyer, which adjusts for the fact that there is a seasonal pattern in fish growth and feeding. In this analysis, we divide the year into only two periods 'summer' and 'winter', each six months long.). Total nutrient loadings can also be estimated as the total feed nutrient minus the nutrients in the harvested fish.

6.6.3.2.1 Fish Farm Feeds in China,Hong Kong Special Administrative Region

In many temperate and developed regions, cultured carnivorous fish like salmon and cod depend on expensive, high-protein feeds. The protein for that feed is commonly derived from catches of small pelagic fish. In other regions, feeds derived from low-cost, low-protein agricultural by-products or wastes are widely used to reduce the cost of production. The feed conversion ratio (FCR) is an important indicator of how much waste is released to the environment.

The type of feed used and the feeding practices vary with different regions, for example, Korea RO (Kim 2000), Philippines (Marte *et al.* 2000), and Tasmania (Gooley *et al.* 2000). Fish farms in Hong Kong use three main types of fish feed: mixed feed, moist pellet feed and dry pellet feed. Mixed fish feed is composed of trash wild fish, mainly relatively small juveniles of commercially important fish species, or other adult pelagic fish (Willmott 2000). They typically include clupeidae, carangidae, leionathidae, engraulidae, siganidae and scombridae (Wilson 1997; Sadovy 1998). Moist pellet feed consists of mixed fish, fish meal, a vitamin mixture and binder (Wong 1996; Chu 2002). Dry pellet feed is the dried form of moist pellet feed. Mixed fish feed is the most common feed used at Tolo Harbour fish farms, with nearly 99% of farms using mixed fish feed, composed mostly of small fish (Chau 2004). For this reason, mixed fish feed will be used as the basis for estimates in this case study.

Chau (2004) estimated the average feeding frequency and feeding volume by interviewing fish farmers. He found that feeding frequency varied from daily to weekly and he estimated that average weekly feeding frequency was 3.7 times in summer and 2.2 times in winter. The weekly feeding volume also varied with seasons. The average feeding volume per cage of fish per 'meal' was 84 (2.1 pans) and 56 kg (1.4 pans) in summer and winter respectively. Information on feeding volume per cage per week was calculated by multiplying the feeding frequency and volume. The weekly feeding volume per cage was estimated to be 8.8 and 3.3 pans of mixed fish feed in summer and winter respectively, which is equal to 213 and 80 kg, respectively. Thus, each cage received, on average, 30.4 kg of mixed trash fish per day in summer and 11.4 kg per day in winter. Over a full year, 73% of the feed was delivered in one half of the year and 27% in the other half. These two percentages will be used to estimate the release of nitrogen during summer and winter periods in the next section.

6.6.3.2.2 Discharge of nitrogen from fish farms

Areolate grouper, *Epinephelus areolatus*, is the most common fish species cultivated in fish farms in Hong Kong. Leung *et al.* (1999) conducted a detailed study on N budgets in both laboratory experiments and at open-sea fish cages. They gave a structured account of the N budget, which is shown in simplified form in Figure 6.6.4.

The maximum possible loading of nutrients from a fish farm would occur if all nutrients not retained in the fish were discharged to the environment. In a typical open cage farm in Hong Kong, this would amount to losses of approximately 320.6 g N/kg dry fish production (2, Table 6.6.I). Fish Culture Zone No. 25 in Tolo Harbour produced 160.6 tonnes annually (C in Fig. 6.6.4) on average during 2001-2005 (AFCD). This fish production is equivalent to 160,600 kg x 30.8% = 49,464.8 kg as dry weight. Using this amount x 320.6 g N/kg =15,858.4 x 103 g N y-1 (3, Table 6.6.I), gives the amount of N that is potentially discharged annually (D+E in Figure 6.6.4) to the surrounding waters of the fish farms. Based on the feeding practice in Hong Kong (Chau 2004), the relases in summer and winter would be 11,580 x 103 and 4,280 x 103 g N 0.5y-1 (4, Table 6.6.I) respectively.

We do not know exactly the nutrients loadings from other sources. We do however, know ambient concentrations of nutrients, and from this we can estimate the potential maximum effect of nutrient releases from fish farms on nutrient levels in the surrounding waters. If we take the inner Tolo Harbour area to be roughly 1/4 of the total Tolo Harbour area, for example, 50 km^2 (Lee and Arega, 1999), and assume that the N additions are evenly mixed into the top 4 m (5, Table 6.6.I), then the annual fish farm contribution would be about 22 µM (6, Table 6.6.I). This breaks down as 16.5 and 6.1 µM, respectively, for the summer and winter periods (7, Table 6.6.I). When these two values are divided by 180 days,

Figure 6.6.3 : Yim Tin Tsai Fish Culture Zone (No. 25) in Tolo Harbor, connected with Tolo Channel (separated by the dotted lines). Other numbers 1-29 show other designated fish culture zones. The sampling stations, TM2, TM3 and MM17 are also shown.

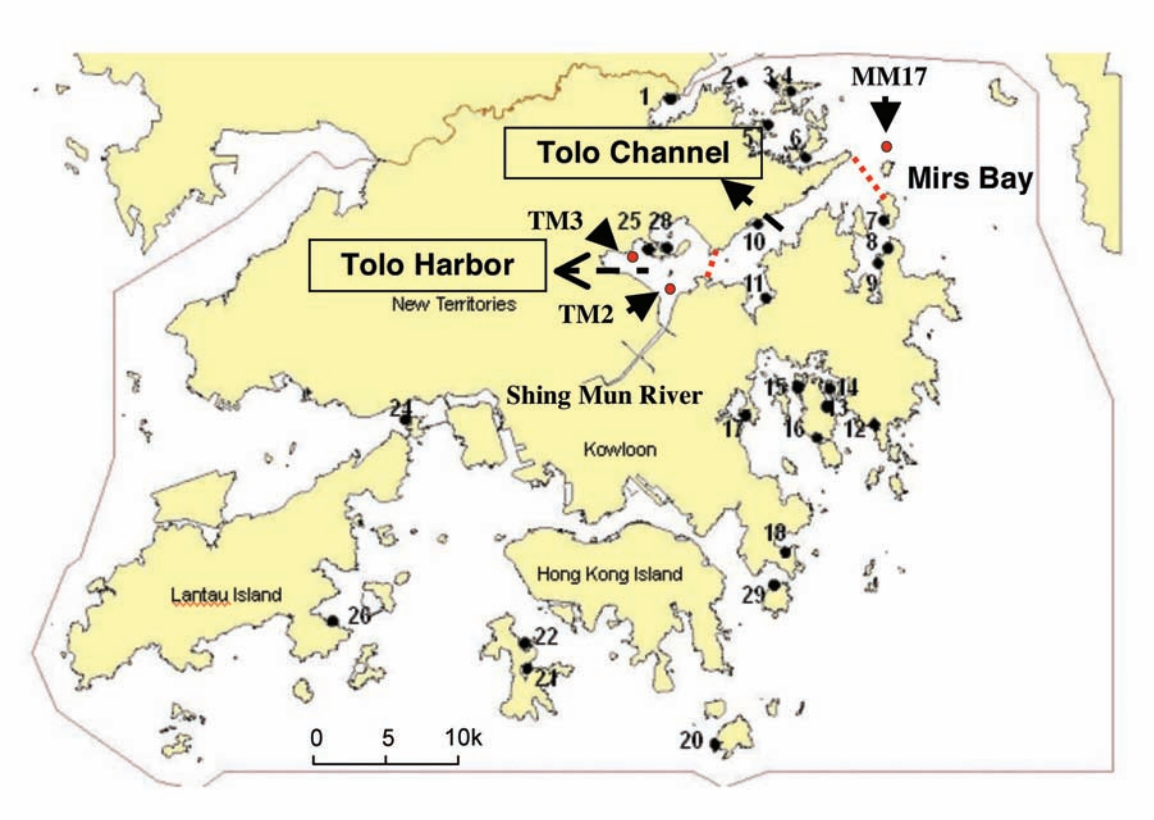


Figure 6.6.4 : A simple conceptual flow diagram for a nutrient budget for a cage fish farm.

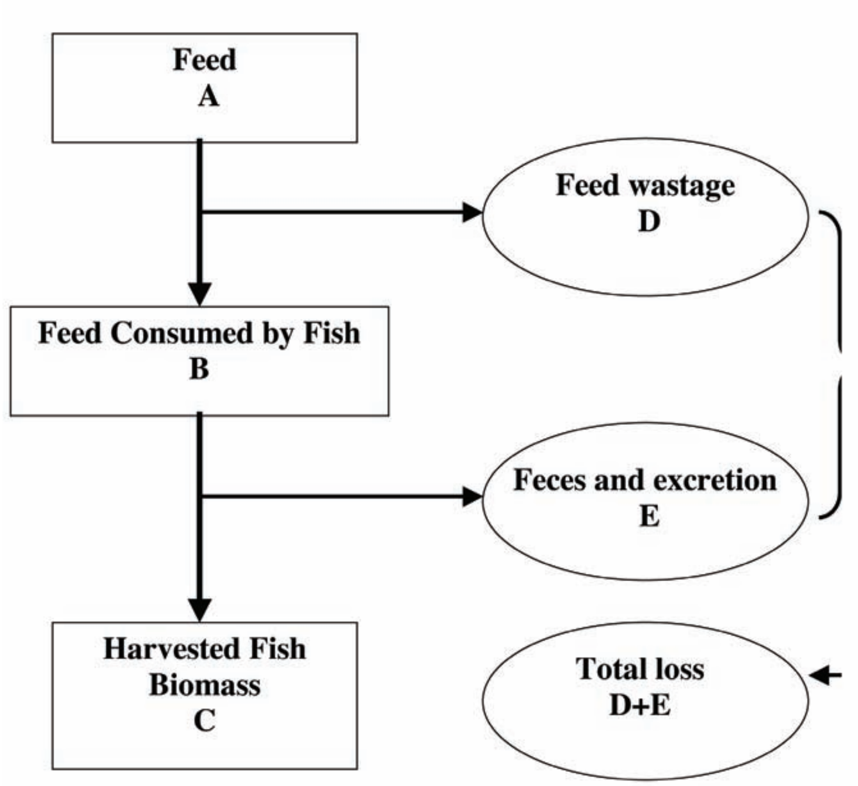


Table 6.6.I : Estimate of N additions (final concentrations) from fish farms FCZ25 to the surrounding waters. Letters, B, C, and D+E in the bracket correspond to ones in Figure 6.6.4. Final N additions are based on the assumption: N additions are distributed evenly in the top 4 m of the Tolo Harbour (1/4 of the Tolo Harbour and Channel area 50 km²).

	Parameters	Quantity	Unit
1	Fish Production	160.6	Tonnes/yr
	Wet weight	160.6 x 10^3	kg/yr
	Dry weight (x 30.8%) (C)	49,465	kg/yr
2	N loss /kg fish production	320.6	g N / kg fish production
3	Total N loss to the environment (D+E)	15,858 x 10^3	g N/yr
4	Feed Addition Summer (73% B) Winter (27% B)	11,576.6 x 10^3 4,281.8 x 10^3	
5	Tolo Harbor volume in top 4 m (1/4 x 50 km² x 4 m)	50 x 10^9	Litre
6	Annual N addition	22.6	µM/year
	Summer addition 73% Winter addition 27%	16.5 6.12	µM/0.5 year
7	Annual daily N addition	0.063	µM/day
	Summer daily	0.092	
	Winter daiy	0.034	

the daily added N concentration is 0.092 and 0.034 µM for summer and winter, respectively. This means that fish farms in No. 25 fish culture zone contribute daily, 0.092 and 0.034 µM N in summer and winter, respectively, to the top 4 m of Tolo Harbour. Relative to phytoplankton half-saturation uptake coefficients for N and P discussed below, this is a very low value. It is worth pointing out that waste feed N, which comprises 43% of the total N loading (Leung *et al.* 1999), may not be totally dissolved in the water column and therefore may not be fully available to phytoplankton. In reality, the water in Tolo Harbour will also exchange to a small degree with adjacent waters. Therefore, the estimates used here are the potential maximum assuming no water dilution occurs.

6.6.3.3 Exposure Assessment

Exposure depends on the spatial scale and intensity of the nutrient addition, the residence times (tidal flushing and dilution), and vertical mixing. Fig. 6.6.2 provides a schematic illustration of basic concepts related to the nutrient effluents from fish farms and their dispersion, which may lead to a visible change in the pelagic ecology including increased phytoplankton biomass (see, for example, Enell 1994; Håkanson *et al.* 1988; Holby & Hall 1991; Mäkinen 1991; Stigebrandt *et al.* 2004).

The contribution of fish farms to ambient conditions of nutrients needs to be examined. Whether an increase in phytoplankton biomass arising from nutrient inputs from fish farms is significant depends on the ambient nutrient concentrations from other sources. Fortunately, the Environmental Protection Department (EPD) of Hong Kong maintains a regular monitoring program, which provides nutrient data that can help in this analysis.

6.6.3.3.1 Environmental conditions in Tolo Harbour

During the summer, there is a two-layer circulation in Tolo Harbour; a surface water outflow of less saline waters and a deep return inflow of more saline water from Mirs Bay (Yin 2002). This is evidenced by the high salinity in August at MM17 (Fig. 6.6.5). The circulation is probably driven by fresh water (lowest salinity in July, Fig. 5) collected from the Tolo Harbour watershed when rainfall is high in summer. Mirs Bay is also subject to the southwest monsoon in summer, and therefore receives pulsed inputs of oceanic waters from South China Sea (Yin 2002). The deep bottom oceanic waters are relatively poor in nutrients and may serve as a within-season flushing mechanism that reduces cumulative eutrophication effects (Yin 2002). This oligotrophic flushing, and the stratification, is likely to limit the impact of phosphorus in bottom waters on algae in surface waters.

The Environmental Protection Department has maintained a water quality monitoring program in Tolo Harbour and Mirs Bay since 1986. Station TM3 is near the fish culture zone, and water quality at TM2 is more likely to be dominated by the effects of waters from the Shing Mun River. MM17 in Mirs Bay at the entrance of Tolo Channel (Fig. 6.6.3) was selected to reflect conditions of the incoming waters. The following water quality parameters are monthly averages during 1986-2000 and describe the conditions in the fish culture zone and provide background conditions for assessing fish farm effects.

Salinity (Fig. 6.6.5): The monthly average surface salinity At MM17 is 32.3 in January. It starts to decrease in April and drops to the lowest value of 30 in July. At TM2 and TM3, the salinity in January is 30.4 and 31, respectively. The lowest salinity is 27 at TM3 in July, and 27.5 at TM2 in May. The salinity can occasionally decrease to 16 (data not shown) at TM2 and TM3, but generally does not go below 28. Salinity near the bottom at all three stations is higher in most months and stratification is present, though weakest in the October-March period and strongest during April-September. The salinity in Tolo Harbour appears to fluctuate synchronously at TM2 and TM3, except for June and July. As the correlation in salinity between the two stations is significant (r=0.86 n=310), this suggests that the two stations may be subjected to the influence of the same waters. This could be important for the distribution of nutrients.

NO_3 (Fig. 6.6.6 - 6.6.7): At MM17, NO_3 is generally below 4 µM in the water column. At TM2, NO_3 is >13 µM in January, and decreases to the lowest concentration (6 µM) during summer (June-September). At TM3, the temporal distribution of NO_3 is very similar to TM2, with the lowest concentration in May when bottom NO_3 is generally <2 µM. NO_3 often decreases below 2 µM at the 3 stations, mostly at MM17, and less frequently at TM2 (Fig. 7). When NO_3 is the sole source of N, concentrations of 1 - 2 µM NO_3 are usually considered to be limiting for marine phytoplankton growth (Parsons *et al.* 1984).

NH_4 (Fig. 6.6.8 - 6.6.9): At TM2, surface NH_4 in winter (December-March) is about 18 µM at TM2, and 8-10 µM in summer months (Fig. 8). At TM3, surface NH_4 is 16 µM in winter, and decreases to 8 µM in summer except for July with a peak of 12 µM. The temporal distribution of surface NH_4 is very similar between TM2 and TM3 (if the July peak is omitted). NH_4 at MM17 is low (<4 µM) all the times. NH_4 frequently decreases to <2 µM, mostly at MM17, and much less frequently at the other two stations (Fig. 9). An NH_4 concentration of 1 µM is considered to be the limiting level for phytoplankton growth if NH_4 is the sole source of N (Parsons *et al.* 1984).

Chl *a* (Fig. 6.6.10 - 6.6.11): Between 1986 and 2001, the monthly average for chl *a* in waters surface at MM17 was <3 µg l^{-1} during all months. Although average chl *a* is higher (around 20 µg l^{-1}) at TM2 than at TM3 (around 16 µg l^{-1}), chl *a* appears to vary synchronously between the two stations. Also, chl *a* at the bottom is approximately 10 µg l^{-1} at TM2, and approximately 5 µg l^{-1} at TM3. Yearly average chl *a* at the surface is the highest at TM2 and the lowest at MM17. However, while chl *a* >20 µg l^{-1} occurs frequently at both TM2 and TM3, there are only two occasions when chl *a* exceeded 20 µg l^{-1} at MM17.

TIN/P (Fig. 6.6.12): The average cellular N:P ratio for phytoplankton is 16:1 (the Redfield ratio). When the ambient N:P ratio is >16:1, P is potentially limiting and when N:P<16:1, N is potentially limiting, the surface TIN/P ratio remains around 16:1 at TM2 and TM3, but there is a peak of 64:1 in July at the other two stations. However, this is the period of lowest algal concentrations, suggesting that P availability does not increase algal abundance. TIN/P at MM17 is usually <16:1.

6.6.3.3.2 Contribution of fish farms to ambient N concentrations

The Total N loading from two urban wastewater treatment plants in Shatin and Taipo was approximately 4,000 kg d^{-1} in 1995 (Lee and Arega 1999). This rate of input would be 28 times the release of N from fish farms in the fish culture zone No. 25 (Table 6.6.I, 51,488 kg N per year) if, as in the past, this was released into Tolo Harbour. The total N loading in Tolo Harbour has been reduced since the treated effluent from the treatment plants is now diverted to other areas in Hong Kong. However, TM2 still has high nutrient concentrations. TM2 receives Shin Mun River Channel water which is heavily polluted. NO_3 N in the river near Tolo Harbour is over 100 µM most of the year, as shown in the water quality monitoring data and sometimes NO_{3-}N can reach about 250 µM (3.5 mg l^{-1}) (http://epic.epd.gov.hk.htm).

The riverine flux of nutrients was estimated to be 58,450 kg y^{-1} for total inorganic nitrogen (TIN), and 6280 kg y^{-1} for PO4-P from four streams entering Tolo Harbour in 1986 (Hodgkiss and Chan 1986). The TIN input from the streams was over three times that of the annual fish farm N loading of 15,860 kg N y^{-1}. The riverine flux may have been reduced since there were no livestock farms remaining in the catchment areas of any of the ten rivers in the Eastern New Territories by the mid 1990s after the implementation of the Waste Disposal Ordinance of the Livestock Waste Control Scheme introduced in 1988, which banned livestock farming in the new towns and urban areas (EPD 2006, 20 Years of Marine Water Quality Monitoring in Hong Kong, http://www.epd.gov.hk/epd/misc/river_quality/1986-2005/textonly/eng/4_eas_nt.htm).

6.6.3.4 Consequence Assessment

There are different sources of nutrients, such as runoff, river channels and discharges which carry sewage effluent. The nutrients from the different sources are eventually distributed in the coastal waters, and increase the ambient concentrations. Therefore, it is important to compare the N additions from a fish farm with ambient concentrations in order to assess potential consequences of nutrients introduced by fish farms in comparison with contributions by the other sources. This way, we can evaluate the incremental change in risk arising from the releases from fish farms, how effective our regulative management of fish farms is, and whether there is any advantage to be gained from implementing risk management or mitigation measures.

6.6.3.4.1 Comparison between ambient concentrations of nutrients from others sources and additions from fish farms

Tidal flushing is weak in Tolo Harbour. Some water from Mirs Bay moves into Tolo Harbour and 70% of that comes back out (Lee and Arega 1999). In other words, 30% of tidally-driven intruding waters remains in the harbour and dilutes the Tolo Harbour water during a tidal cycle. The yearly average total N concentration in

Figure 6.6.5 : Monthly average salinity at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

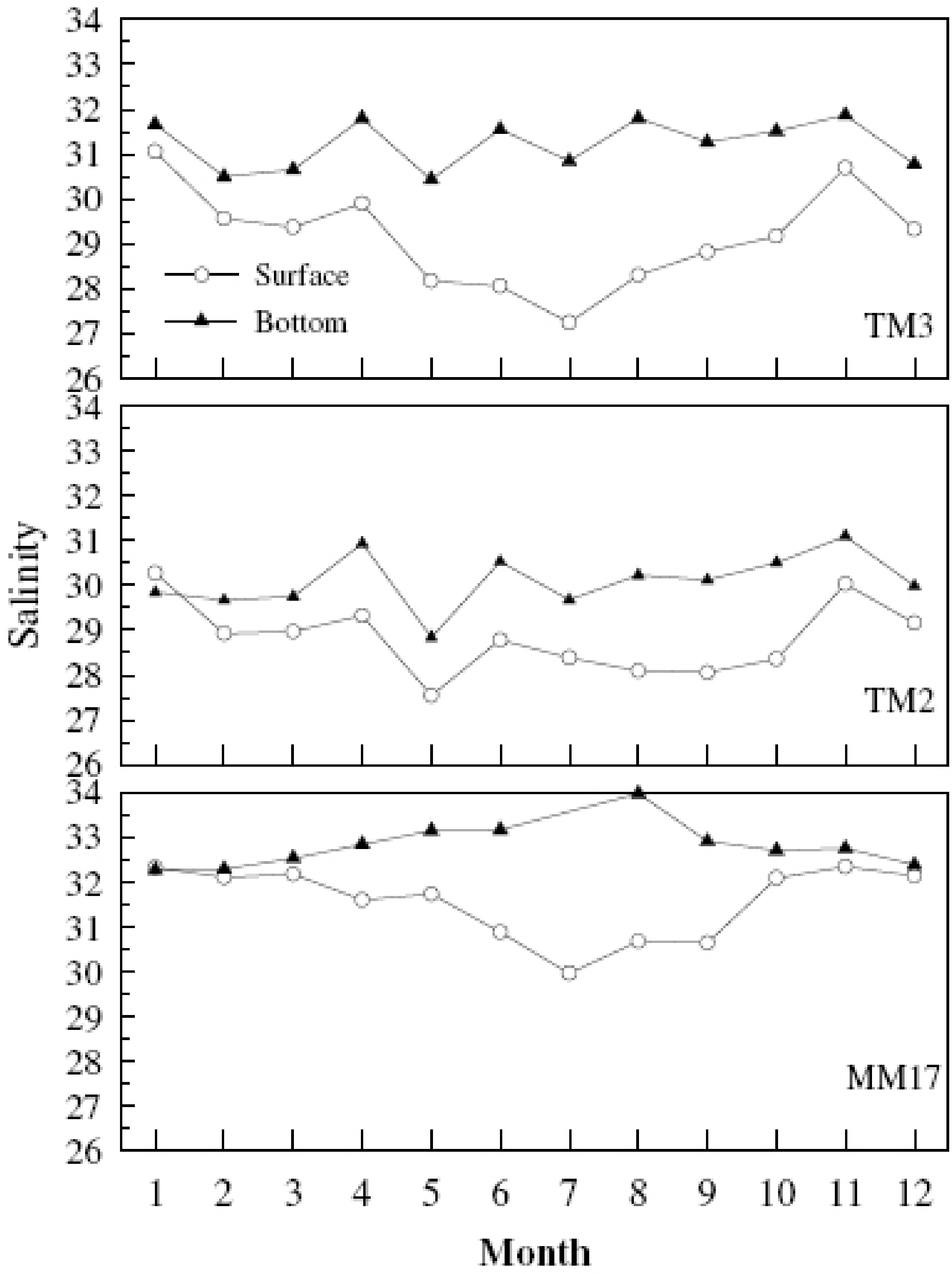


Figure 6.6.6 : Monthly average NO_3 at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

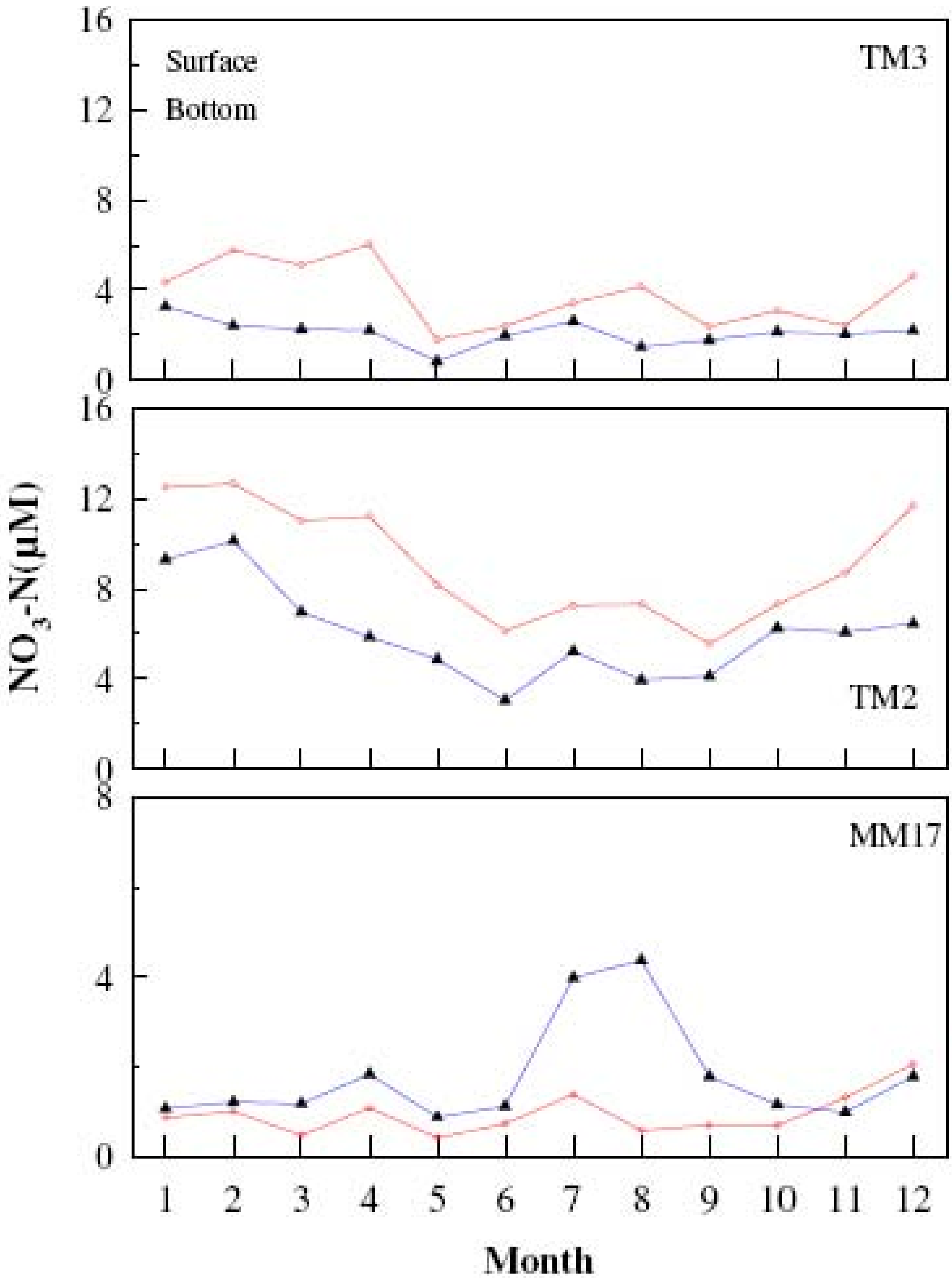


Figure 6.6.7 : Time series of NO_3 showing concentrations < 5 µM at the surface during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

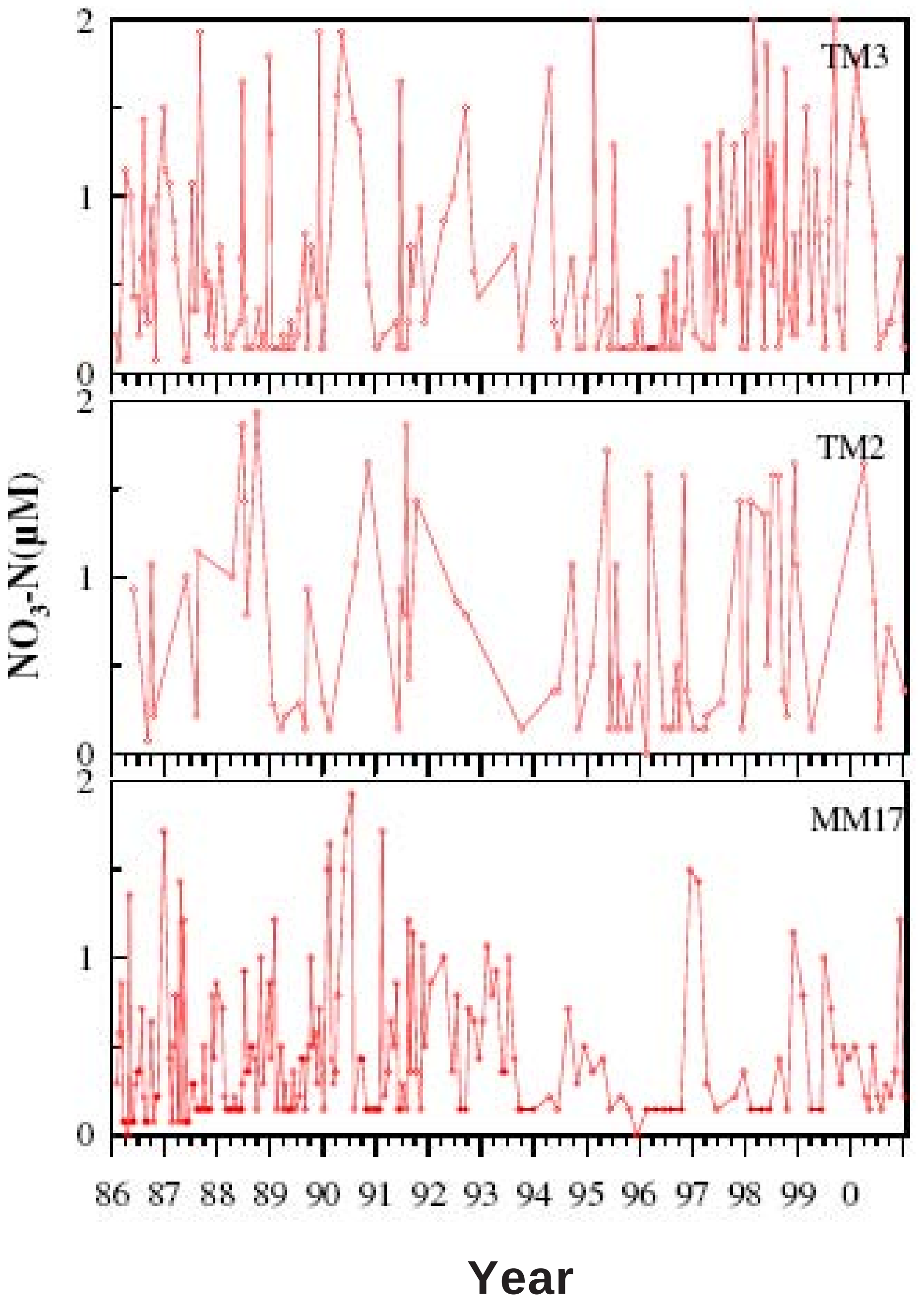


Figure 6.6.8 : Monthly average NH_4 at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

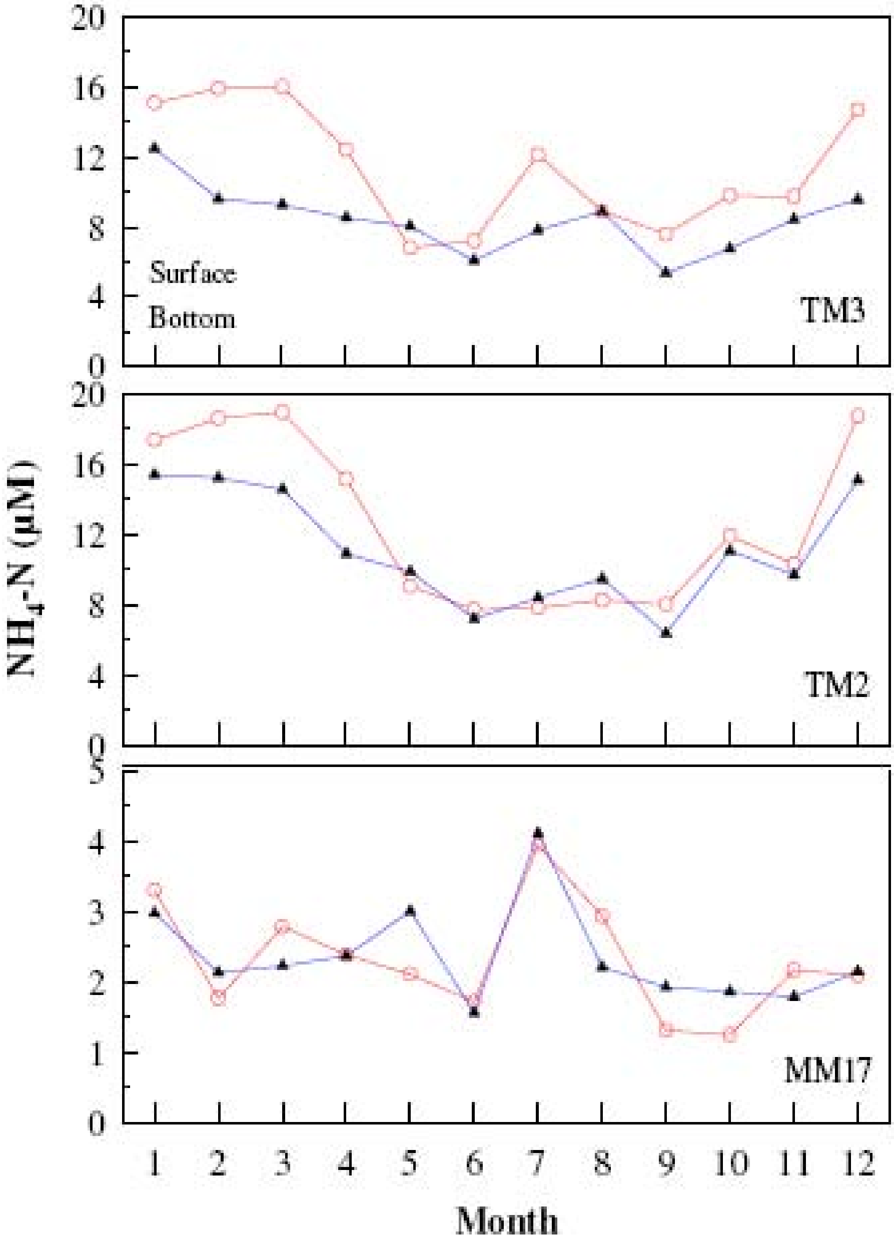


Figure 6.6.9 : Time series of NH_4 showing concentrations < 5 µM at the surface during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

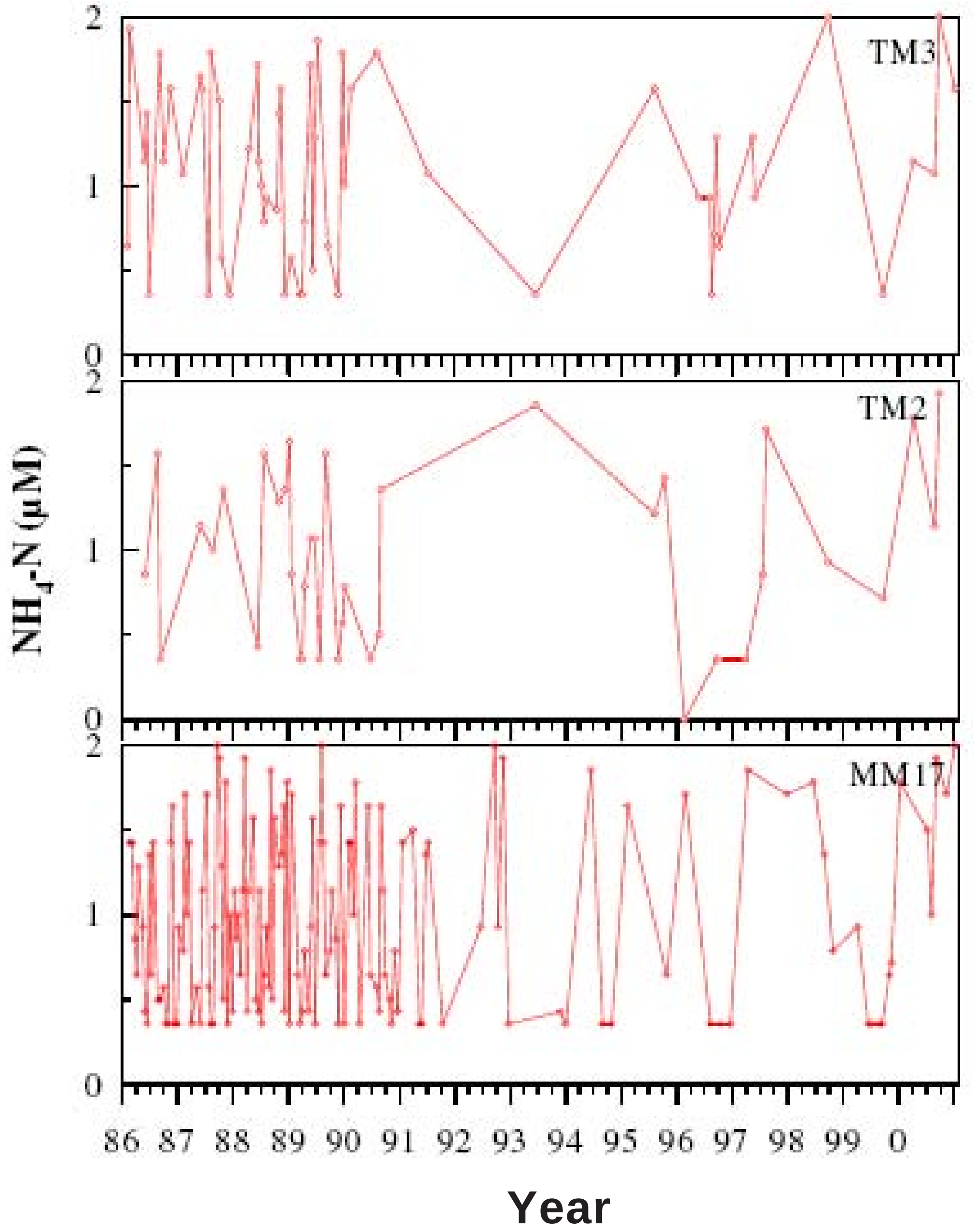


Figure 6.6.10 : Monthly average chl a at the surface and bottom during 1986-2000 at TM3 (near the fish farms), TM2 and MM17.

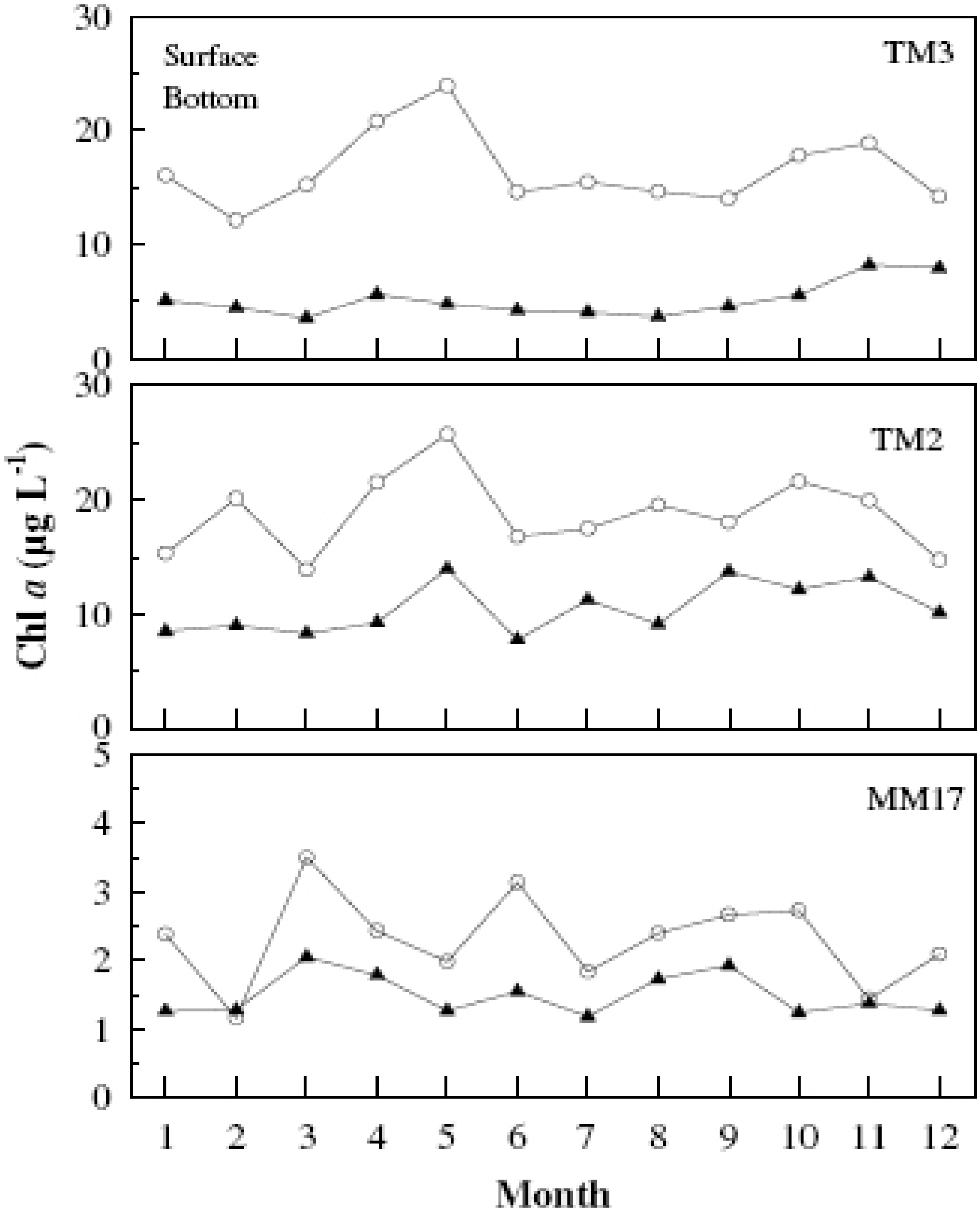


Figure 6.6.11 : Time series of Chl a showing concentrations >20 µg L-1 at the surface during 1986-2000, at TM3 (near the fish farms), TM2 and MM17.

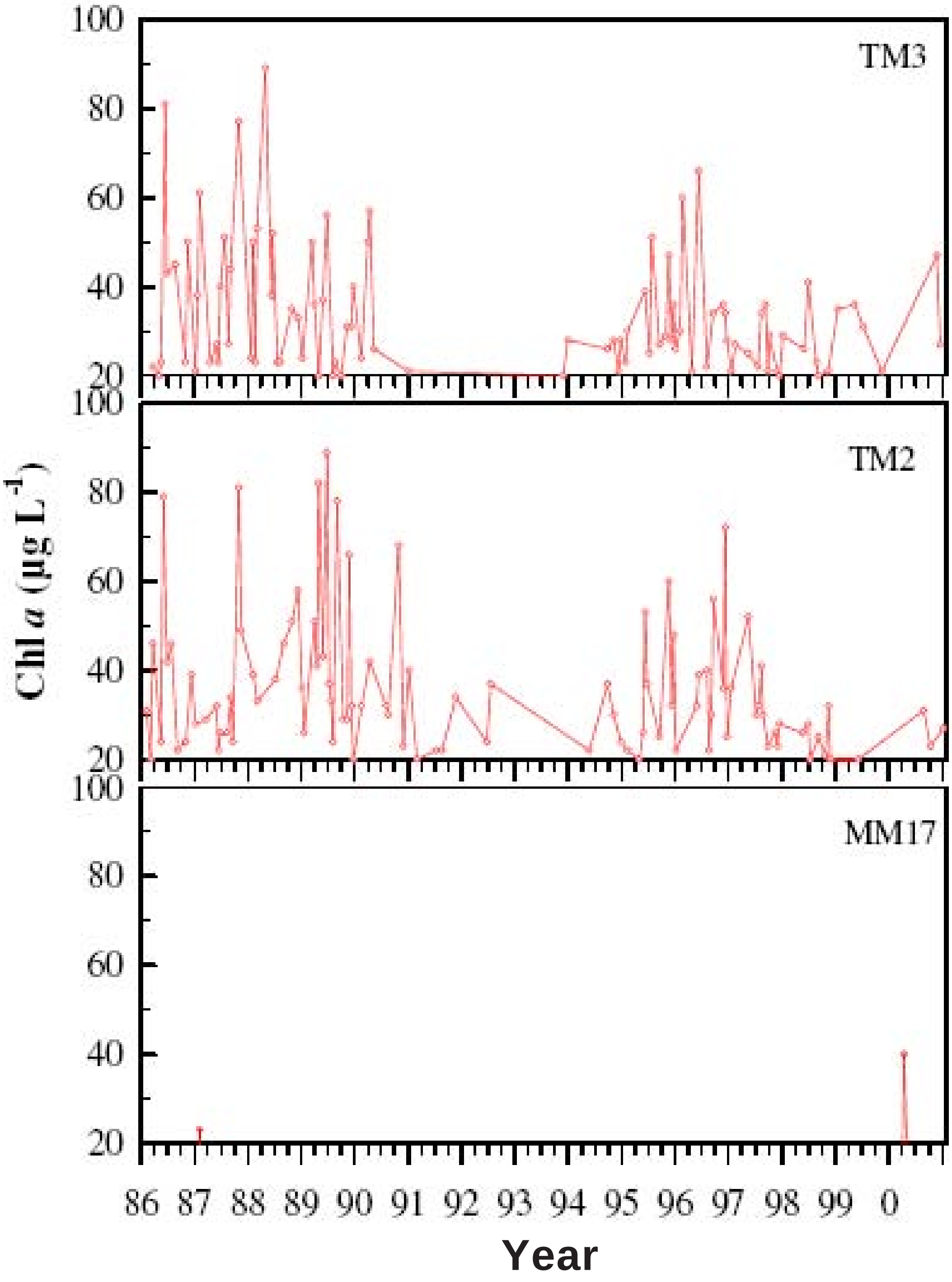
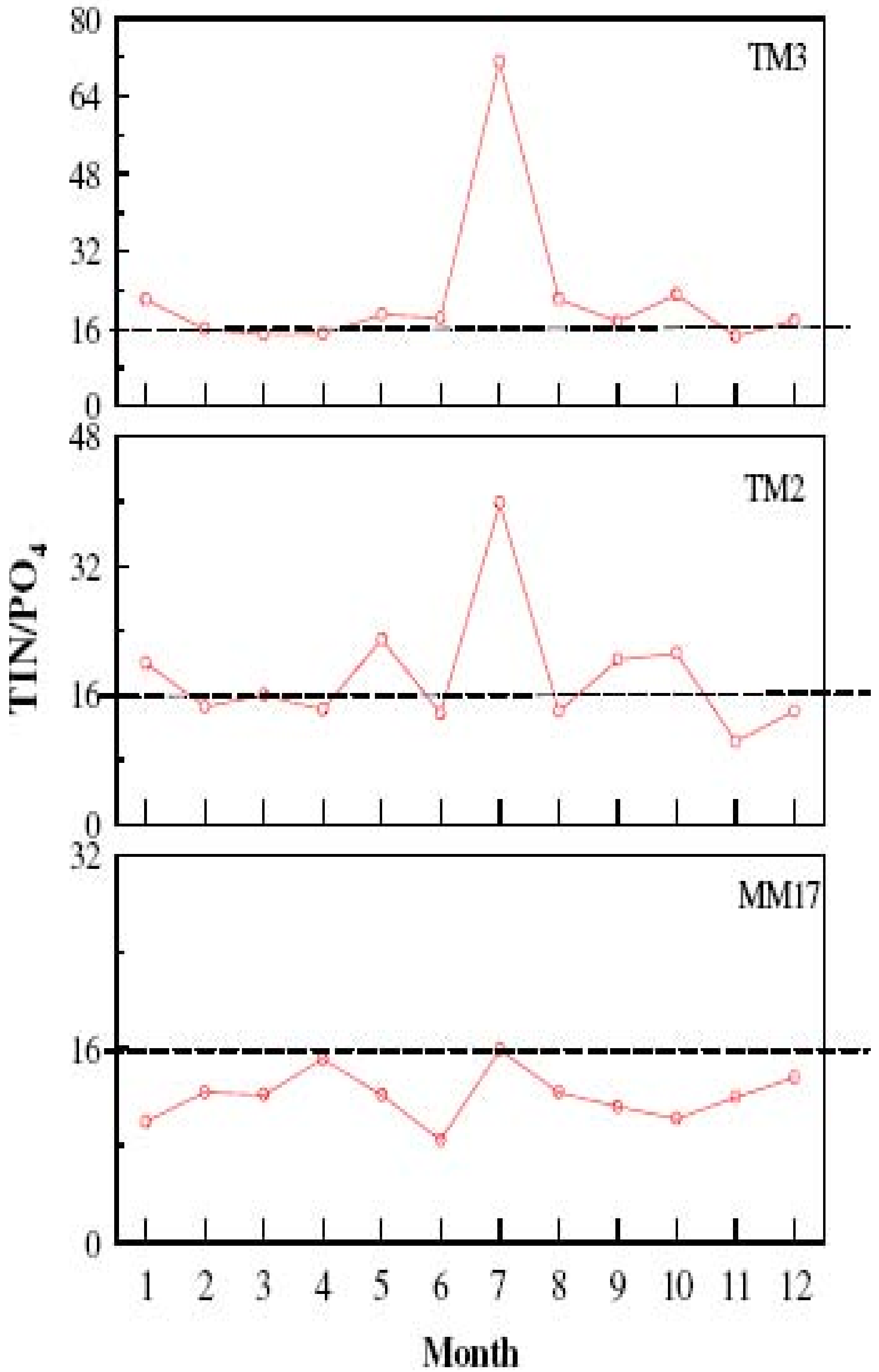


Figure 6.6.12 : Monthly average TIN/PO_4 ratio at the surface and bottom during 1986-2000, at TM3 (near the fish farms), TM2 and MM17. The dashed line is the N:P ratio = 16:1 required for phytoplankton growth.



the water column in Mirs Bay is 4.1 µM with only a small seasonal difference and chl *a* is 1.76 µg l^{-1}. Even if the Mirs Bay water is used as the background water for the fish farms in Tolo Harbour, the background ambient N concentration of 4.1 µM from Mirs Bay is still high compared to the fish farm daily input concentrations of 0.09 and 0.03 µM in summer and winter, respectively. Fish farms contribute only about 0.7 – 2.2% in winter and summer respectively, when compared to Mirs Bay ambient N concentrations. Mirs Bay concentrations are also high in comparison to the phytoplankton half saturation uptake concentrations of 1-2 µM.

Based on the monthly average of TIN at TM3, the average ambient total dissolved inorganic N in the water column (surface-bottom average) near the fish farm is 11.9 µM and 15.5 µM in summer and winter, respectively. These values represent daily concentrations present in ambient waters near the fish farms and can be used as ambient N concentrations for comparisons with N additions from the fish farm. Thus, fish farm FCZ25 contributes only 0.8% (summer) and 0.2% (winter) to the ambient concentrations resulting from all other sources.

Background concentrations of N are also high compared to the nitrogen uptake half saturation coefficients of 2µM that are common for phytoplankton species, suggesting that nitrogen is unlikely to limit phytoplankton growth in Tolo Harbour.

The N/P ratios do not suggest P limitation except in July. Stratification in Tolo harbour is strongest, and Chl *a* are near their lowest at this time. The substantial supply of P from the rivers does not seem to elicit a numerical response in the phytoplankton population. This would support a supposition that phosphorus generated by fish farm effluents is likely to be primarily generated in the sediments below the pycnocline and be largely isolated from phytoplankton in the euphotic zone.

Tidal flushing is weak in Tolo Harbour, and the residence time of 28 days is sufficient for phytoplankton blooms to occur. Phytoplankton blooms do occur frequently in Tolo Harbour, as phytoplankton biomass frequently exceeds 20 µg L^{-1} chl *a* (Fig. 6.6.12). Red tides frequently occur in Tolo Harbour and Tolo Channel (Fig. 6.6.13) (Yin 2003). Our estimates indicate that fish farms contribute very little to the ambient nitrogen concentrations in Tolo Harbour, as the maximum estimated accumulative concentration is a very small fraction of monthly average N concentrations. This conclusion agrees with other studies which found that the spatial footprint for nutrients from fish farms are usually confined to a rather small area. Marine aquaculture cages are generally located from 100 m to 1.5 km offshore in water depths ranging from 15 to 30 m (Gooley *et al*. 2000). These would be the areas primarily susceptible to the effects of cage aquaculture (Pe´rez *et al.* 2002). The spatial scale of the effects of aquaculture effluents depends on a number of factors including the area used for culture, the degree of intensification, production level and the profile of the water body. Guo and Li (2003) reported that the effect of cage culture only extended 20 m outside the cage area in a lake in China with a fish production of 16 metric tonnes using 20,000 m^2 of cage area.

In the consequence assessment, a logic model can be used to describe sequential steps in the mechanism that links specific exposures to nutrients in wastes (the hazard) produced by fish farming to the specific effect of fish farming on overall phytoplankton abundance. The logic model demonstrates how each step contributes to the potential development of bloom conditions.

The steps in the logic model are illustrated in Figure 6.6.14, and summarized below:

6.6.3.4.2 Logic model

The risk: fish farm causes an increase in nutrients, leading to a significant increase in algal biomass, leading to discoloration of the water body.
End point: Chlorophyll a increases to above 20 µg l^{-1}.
Logic model steps:

1. Establishment of fish farms
2. Feed usage by fish farms
3. Release of nutrients
4. Phytoplankton growth
5. An increase in phytoplankton population biomass
6. On the basis of fish farm nutrients, phytoplankton blooms occur

6.6.3.4.3 Evaluation of consequence using the logic model

In the consequence assessment, using the logic model each step in the process is assessed for severity, probability and duration of change (Table 6.6.II).

1. Establishment of fish farms.

Fish farms either already exist, or are in the proposal stage. The intensity of fish farm establishment is thought to be high, their geographic extent is spreading and, once established, fish farms tend to remain in operation for a long time. Consequently the severity of this step is judged as high (H). Therefore, the probability for an establishment of a fish farm is high(H) with low uncertainty (L) in general.

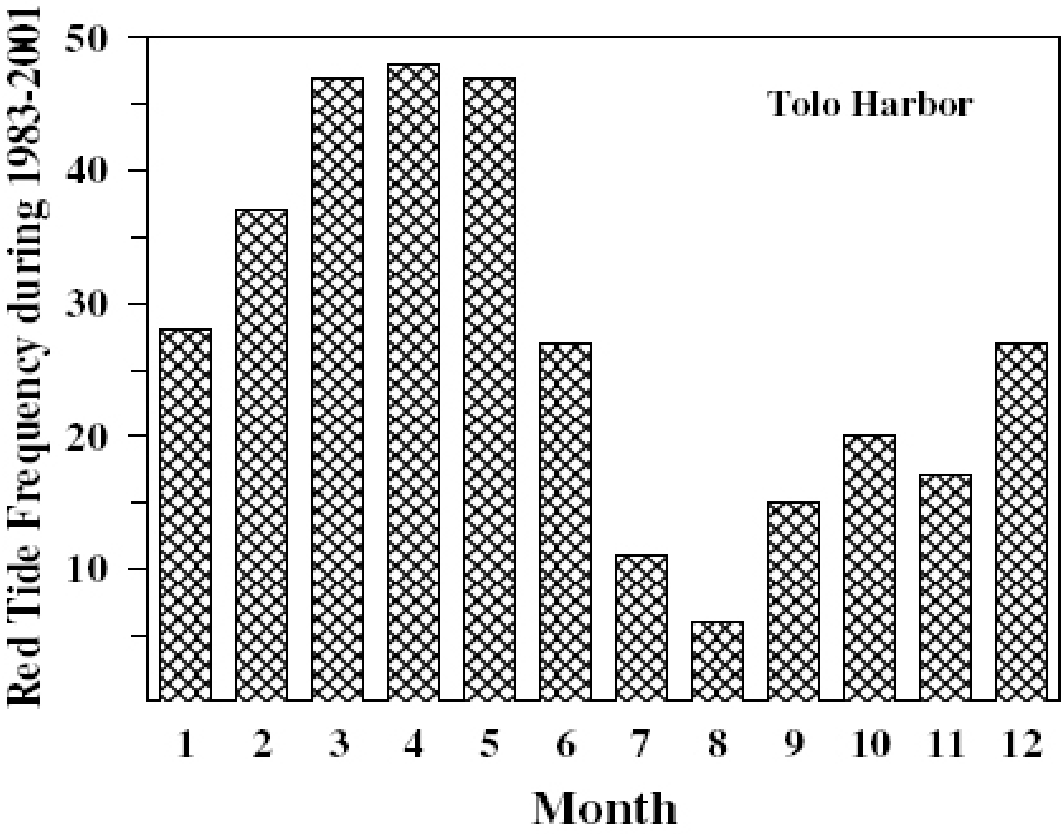
2. Feed usage by fish farms

All operating fish farms provide feed to fish. Intensity/quantity of feed is daily (H), limited to fish farms (geographic extent, L) and feeding continues as long as the fish are in cages, although once the farm ceases to operate feeding ceases (temporal duration, L). The severity of feeding is therefore considered Low(L), and the probability is very high (H). Uncertainty is low (L).

3. Release of nutrients

Intensity (H) of the release is high. The geographic extent (H) of feed wastage distribution can be large as the uneaten feed is quickly

Figure 6.6.13 : Monthly average occurrences of algal blooms (red tides) reported by AFCD (Agriculture, Fisheries and Conservation Department) during 1983-2001, in Tolo Harbor and the Tolo Channel.



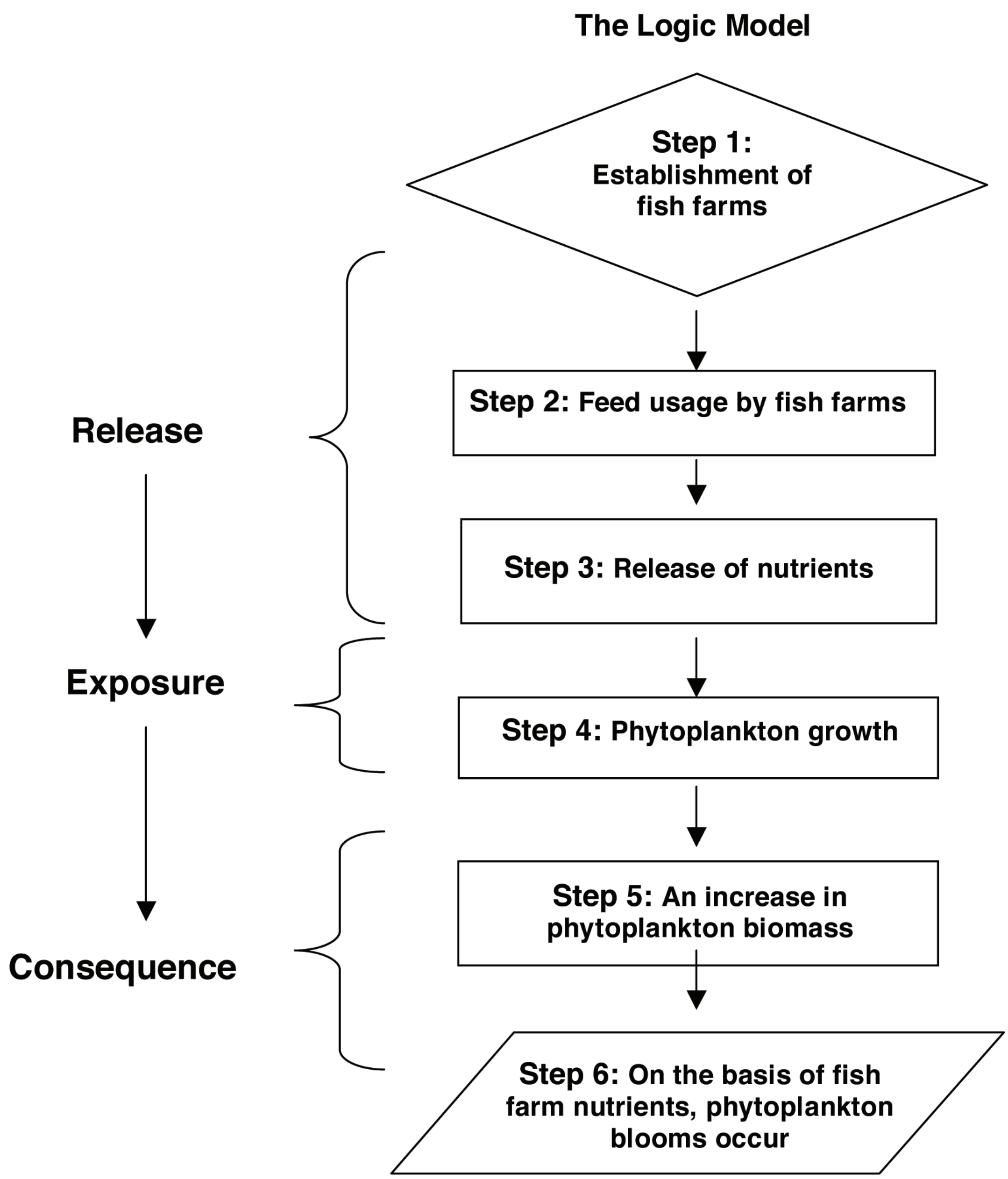
distributed over a large area of the surrounding water before settling on the seabed, and thus there is a constant release of nutrients via fish excretion. The duration of nutrients in the harbour after removal of the fish farm would likely be in the order of a year or two, a relatively moderate length of time (M). The severity of this step of the logic model is therefore high (H); there will be a release of nutrients in active fish farms (probability is H) and uncertainty is low (L).

4. Phytoplankton growth

Phytoplankton will be exposed to nutrients released from fish farms. Nutrient ratios are an indicator of which nutrients are likely to limit phytoplankton growth. For phytoplankton, the nominal N:P ratio (by atoms) is 16 N:1 P (called the Redfield ratio) whereas N:P ratios in fish feeds are generally lower than the Redfield ratio, i.e. are relatively rich in P (Islam 2005). In marine waters, N is usually considered to be the limiting nutrient for phytoplankton growth (Hecky and Kilham, 1988). Further, most of the P in fish farm waste is in the solid component which can be trapped below the pycnocline in stratified waters and be unavailable for phytoplankton growth. Thus, nitrogen excreted by fish will probably enhance phytoplankton growth. In Mirs Bay, the N:P ratio is <16:1, suggesting potential for N limitation of phytoplankton growth. Therefore, we focus on the N budget in Tolo Harbour.

Using N concentration as the basis for phytoplankton growth, the potential intensity of phytoplankton growth is high because of exposure to pre-existing high nutrient concentrations. The farm's proportional contribution to the total supply of nutrients is however not significant (L). The geographical extent of the contribution will in all likelihood remain close to the farm and is judged to be low (L). Temporal persistence of the nutrient contribution after the farm ceases operation will arise from sediment remineralisation, which will probably continue over a time scale of a few years. Only a proportion of the nutrients remineralised from sediment will enter the photic zone and contribute to phytoplankton growth. The duration is thus judged to be medium (M). In this case study, the severity is judged as low (L). The probability of fish farm nutrients contributing to individual alga will be proportional to their contribution to the nutrient pool (L). The uncertainty of whether some phytoplankton will use farm nutrients is low (L).

Figure 6.6.14 : The logic model steps for risk assessment of fish farms. The assessment of severity, probability and uncertainty for each step of the logic model is presented in Table 6.6.II.



5. An increase in phytoplankton biomass

An increase in the biomass or abundance of the phytoplankton population requires a stable water column, for example, long residence time of the water column with little horizontal dilution and weak vertical mixing. When tidal flushing is strong, the phytoplankton biomass gained will be diluted either via horizontal exchange or vertical mixing. When flushing and vertical mixing are not significant, phytoplankton growth and densities will be determined by the most limiting growth factor (nutrients or light).

N and P in Tolo Harbour are only occasionally drawn down to levels that would be considered to be growth limiting. The average water residence time of 28 days permits considerable accumulation of biomass if nutrients are not limiting. However, the frequency of red tides (visible discolouration of the water) (Fig. 6.6.13) suggests that, at high phytoplankton biomass, light may occasionally become a limiting factor for phytoplankton growth. Even so, there are many periods when chlorophyll levels are lower and there may be potential for further population growth.

The intensity of likely increases in phytoplankton biomass is low (L) as nutrients do not seem to be generally limiting. The geographical extent of the increase, in the same fashion as proportion of contribution of farm nutrients to population growth, is expected to be low (L). The duration of the contribution after the farm ceases operation is at best moderate (M) and will regulated by physical processes affecting stratification of the water column. The consequent severity is therefore low (L) and probability is low (L), and the uncertainty is moderate, as we can not predict physical processes or state with absolute authority that light is the limiting factor.

6. On the basis of fish farm nutrients, phytoplankton blooms occur

When phytoplankton biomass accumulates to a certain level, it can discolour the water. Blooms have frequently occurred in Tolo Harbour since 1983 (Fig. 6.6.13). If chl *a* > 20 µg l^{-1} is considered to represent a phytoplankton bloom, phytoplankton blooms have occurred every year at the fish farm (TM3) except for 1991-93, and every year except 1993 at the Tolo Harbour control site (TM2). There is no evidence that the time averaged concentration at these sites is different. In the same period, blooms have occurred only twice at the oceanic control site MM17.

When a phytoplankton bloom occurs, nutrients, including NO_3, and NH_4, can be temporally drawn down to limiting levels (Fig. 6.6.7 and 6.6.9). However, this high concentration of chl *a* > 20 µg l^{-1} is not primarily supported by N concentrations released from fish farms. Therefore, nutrient input from fish farms does not appear to be related to the occurrences of large phytoplankton blooms or to a significant increase in phytoplankton biomass in Tolo Harbour.

Once the factor supporting blooms development (in this case possibly the fish farm) ceases to be present, blooms of phytoplankton last on time scales of days to weeks and so the duration is considered low (L). The contribution of the farm to the intensity of a bloom under the conditions present in Tolo Harbour is low (L) and the geographic extent is low (L) as nutrients are diluted rapidly at most farms. Consequently, the severity and probability of fish farm nutrients leading to a bloom in Tolo Harbour are both low (L), but there is considerable uncertainty in this prediction (H). When water near the fish farms is not moving due to the lack of currents or wind, the nutrients from the fish farm may accumulate and result in a highly localised rapid increase in phytoplankton biomass. If those conditions persist for a week in a subtropical environment, a bloom may occur at the farm site.

Natural waters surrounding the fish farms in Tolo Harbour have background nutrients and phytoplankton biomass that have temporal (seasonal) fluctuations. Even so, fish farm operations in the Tolo Harbour contribute a small nutrient load to Tolo Harbour compared to the loading from other sources of nutrients. The additional nutrient load from fish farms may pose an environmental risk to phytoplankton biomass in Tolo Harbour only when N or P is exhausted during phytoplankton blooms, but rather than contributing to the development of a bloom directly it may only contribute to a longer duration of a very small portion of possible phytoplankton blooms.

6.6.3.5 Risk Estimation

In the earlier discription of the new expansion of farming activities, no special technologies were identified to be used nor were specific regulatory requirements mentioned that might reduce the effect of that farm from that which might be anticipated based on the experience used to development the consequence assessment.

In order to reduce nutrient pollution in Hong Kong waters, the Water Pollution Control Ordinance was enacted in 1980 and was amended in 1990 and 1993. It provides the main statutory framework for the declaration of water control zones to cover the whole of Hong Kong and the establishment of water quality objectives. A licence is granted, with terms and conditions specifying requirements relevant to the discharge, for example, the discharge location, provision of wastewater treatment facilities, maximum allowable quantity, effluent standards, self-monitoring requirement and keeping records. In 1982, the Marine Fish Culture Ordinance was implemented. The ordinance requires all marine culture operations to be conducted at sites within gazetted fish culture zones.

Table 6.6.II : Severity, probability and uncertainty for each step of the logic model. (NA = not applicable)

	Logic Model Step	Intensity or degree of change	Geographical extent	Permanence or duration	Severity	Probability	Uncertainty
1	Establishment of fish farms	H	H	H	H	H	L
2	Feed usage by fish farms	H	L	L	L	H	L
3	Release of nutrients	H	H	M	H	H	L
4	Phytoplankton growth	L	L	M	L	L	L
5	An increase in phytoplankton population biomass	L	L	M	L	L	M
6	On the basis of fish farm nutrients, phytoplankton blooms occur	L	L	L	L	L	H

Probability = H - High, **M** - moderate, **L** - Low, **EL -** Extremely Low, **N -** Negligible
Severity = C - very intense, **H** - high, **M** - Moderate, **L -** Low, **N** - Negligible. There are three components of severity that should be considered: the duration of the activity, the degree of change, and the geographic extent of the change.
Uncertainty = H- Highly certain, **M** - Moderately certain, **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

In Tolo Harbour and the Channel water control zone, the water quality objective is <20 µg chl *a* l^{-1}. There does not appear to be a water quality objective for total inorganic nitrogen, but only a reference level between 0.2 and 0.4 mg N l^{-1}, which is equal to 14.3 and 28.6 µM, respectively.

EPD acknowledges the need for a mixing zone around outfalls of other types of effluents where pollutants are first diluted and accepts that the water and seabed are changed from their normal state within this area, known as an allowable zone of effects (AZE). It is defined as: 'The area (or volume) of seabed or receiving water body in which EPD will allow some exceedance of the relevant environmental quality standard or some damage to the environment'. The concept is fundamental to the Hong Kong system of environmental management. It follows that any modeling approach used in regulating effluent discharges must allow appropriate boundaries to be set, defining the extent of the AZE and therefore where EPD expects the EQS to be achieved, taking into account the natural processes of dispersion and degradation of the various types of wastes. In the case of fish farms, AZE is usually quite small compared with that typical for domestic sewage effluent discharge.

These controls alone seem unlikely to limit phytoplankton proliferation in Tolo Harbour. For that reason, the risk level identified in the consequence assessment is the same as that for the risk evaluation. Should any of the recommended risk management activities be undertaken, that level of risk may be modified.

6.6.4 Risk Management

Risk management addresses what might be done to reduce the probability of a risk being expressed, or to reduce the uncertainty in the prediction of the expression of a risk. This can be addressed through consideration of the series of steps in the logic model discussed above. For each step, the process identifies what could be done to reduce the probability of it occurring. These actions would directly mitigate possible effects. A further contribution to increasing the effectiveness of the risk analysis would be to reduce the uncertainty associated with predicting that the step will happen. Usually this involves further research or development. Table 6.6.III identifies both mitigation and research or development steps that could be employed in addressing risks associated with algal blooms arising from fish culture.

Although Tolo Harbour is a special case where ambient concentrations appear to exceed nutrient concentrations contributed from fish farms, in order to assess these risks, we need to set up a set of criteria for those parameters and address questions such as, at what level is a change in each parameter considered to be a risk and what is the probability (how frequently) that this level will be achieved.

Table 6.6.III : 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	Establishment of fish farms	H	Where feasible move to land-based production	L	Develop economically competitive land-based technologies with appropriate waste treatment.
2	Feed usage by fish farms	H	Intercept and recover solid wastes before they are decomposed and dissolved	L	Improve cage designs to allow *in situ* waste recovery
3	Release of nutrients	H	Use more efficient feed to increase FCR, practice efficient feeding frequency and intensity	L	Improve hydrodynamic modeling dispersal of particles near fish farms Investigating rates of decomposition from feed particles to dissolved form
4	Phytoplankton growth	L	No feasible mitigation	L	Conducting physiological ecological study to understand dominant species growth characteristics
5	An increase in phytoplankton population biomass	L	No feasible mitigation	M	capability of predicting the depth of euphotic zone and its residence times
6	On the basis of fish farm nutrients, phytoplankton blooms occur	L	No acceptable mitigation, but clays have been used in Korea and Japan.	H	Develop biological-physical coupling model to understand the bloom dynamics and to project occurrences of blooms

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