Application of risk analysis to environmental issues in aquaculture

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ABSTRACT

Global production from aquaculture is growing, and future growth will be essential to support human food demands. The development of aquaculture as a newly emerging food production sector poses some risks to the natural environment and human health, as detailed in various publications and studies over the past 20 years. The use of risk analysis to identify hazards and to assess and manage environmental risks associated with aquaculture development is, however, relatively new. This review identifies potential environmental hazards related to aquaculture and outlines methods for assessing, managing and communicating risk. As the risk analysis approach is rather new to the aquaculture sector, recommendations for further action are also provided. Reference is also made to the recent work on risk analysis by the GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Working Groups on Environmental Impacts of Coastal Aquaculture (Anon., 2007) that has helped to explore and define approaches and options for environmental risk assessment and communication in coastal aquaculture.

INTRODUCTION

Global production from aquaculture has grown substantially, contributing significant quantities to the world's supply of fish for human consumption. This increasing trend is projected to continue in forthcoming decades. The sector is envisioned to contribute more effectively to food security, poverty reduction and economic development by producing –with minimum impact on the environment and maximum benefit to society – 83 million tonnes of aquatic food by 2030, an increase of 37.5 million tonnes over the 2004 level (FAO, 2006).

The recognition by government of the need for sound aquaculture policies, population growth, increasing purchasing power of people, opening of new markets facilitated by trade liberalization, and technological advances bring greater opportunities for further development of the sector. The stagnating level of capture fisheries; strengthening of institutional capacity; increasing consumer demand for diversified, safe and quality aquatic products; increasing environmental concerns; the scarcity of land and water resources; and supporting small-scale farmers all pose major challenges to the sector.

The development of aquaculture as a newly emerging food production sector poses some risks to the natural environment and human health, as detailed in various publications and studies over the past 20 years. The use of risk analysis to identify hazards and to assess and manage environmental risks associated with aquaculture development is, however, relatively new. The purpose of this review is to identify potential environmental hazards related to aquaculture and outline methods for assessing, managing and communicating risk. As the risk analysis approach is rather new to the aquaculture sector, recommendations for further action are also provided. Reference is also made to the recent work on risk analysis by the GESAMP (IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection) Working Groups on Environmental Impacts of Coastal Aquaculture (Anon., 2007) that has helped to explore and define approaches and options for environmental risk assessment and communication in coastal aquaculture.

In most countries, environmental impact assessment (EIA) is the main existing and legally required assessment tool, and many of the elements of risk analysis are already included in the EIA process, although associated with somewhat different terminology. Risk analysis should therefore be part of EIA and strategic environmental assessment, rather than considered as a separate or even parallel process. It is also emphasized that the risk analysis process (as for EIA) needs to be related to management. The analysis is of limited practical use if there is no management framework suitable for addressing the most significant environmental risks associated with aquaculture development.

RISK ANALYSIS

Risk analysis is a tool for understanding where to focus management efforts to most effectively reduce the potential environmental effects of human activities. Risk assessment is considered part of the process of risk analysis, and is being widely used for human health and ecological assessments, varying widely in scope and application. Some assessments look at single hazards in a range of exposure scenarios such as many health risk analyses (e.g. Codex food safety-related risk analysis consideration of a chemical); others are more site-specific and look at the range of risks posed by an installation, while others are very broad and may consider multiple hazards posing multiple risks to ecosystems and human health.

There are some differences in terminology used in risk analysis and risk assessment, across a varied range of uses. In broad terms, risk assessments being carried out to examine the effects of hazards on humans (health risk assessment) (Fairman, 1999) and ecosystems (ecological risk assessment). Ecological risk assessment is the process of estimating likelihoods and consequences of the effects of human actions or natural events on plants, animals and ecosystems of ecological value, that is, the study of risks to the natural environment. Environmental risk assessment has been defined as the examination of risks resulting from technology that threaten ecosystems, animals and people, i.e. it is broader than health and ecological risk assessments. It includes human health risk assessments, ecological or ecotoxicological risk assessments, and also specific industrial applications of risk assessment that examine end-points in people, biota or ecosystems. The uses of risk assessments are likewise wide and varied. The risks examined in the assessment can be physical, such as radiation, biological, such as a genetically modified organism (GMO) or pathogen, or chemical, such as an immunotoxic substance.

The target/receptor to be examined in the risk assessment also varies. Human beings are the species most extensively considered in human health risk assessments – but other single species risk assessments are common in ecological risk assessments. Many ecological risk assessments have solely considered a single or a few species, since only ecologically representative organisms are selected as assessment end-point. Increasingly, ecological risk assessments are being applied to ecosystems or habitats, greatly increasing complexity. Environmental risk assessments as applied to aquaculture may therefore include the wide range of targets/receptors from humans to ecosystems.

Risk assessments also refer to "end-points". End-points are the environmental value that is to be protected, operationally defined by an ecological entity and its attributes. Ecological end-points should be ecologically, socially and politically relevant; sensitive to the potential stressors; amenable to measurement and relevant to the management goals (Suter, 1993). End-points can be mortality or morbidity in human health assessments or other single species assessments. For some ecological risk assessments, end-points may be those that indicate biodiversity or disturbance to ecological systems. These varied approaches are all relevant to aquaculture and are associated with a wide range of potential environmental hazards and a wide range of end-points. The term end-point is closely related those of impact, management objective and indicators used in EIA terminology.

Risk analysis and assessment approaches may seem overly complex and with varied terminology being applied, but the method also has considerable potential to simplify and focus the analysis and subsequent management recommendations on key environmental issues of concern. In practice, except for a few more advanced countries, it has been rarely used as a formal tool for addressing potential environmental hazards in aquaculture, within government or private business, and its potential as a tool for supporting better regulation and management of the aquaculture sector remains largely untested.

There are a number of unifying principles underlying all risk assessments. These underlying principles are developed from those laid down by Covello and Merkhofer (1993) as follows:

- Problem formulation – to formulate the problem being addressed, and the scope of the risk analysis;
- Hazard identification – to determine the nature of potential hazards (threat or stressor);
- Release assessment – to determine the likelihood of a "release" associated with the hazard[1];
- Exposure assessment – to determine the magnitude and extent the physical effects of an undesirable event (identified in the hazard identification and release assessment stages);
- Consequence assessment – attempts to quantify the possible damage caused by the exposure to the hazard; and
- Risk estimation – consists of integrating the estimation of the probability of release and exposure events with the results of the consequence assessment to produce an estimate of the overall risk or probability of the event occurring.

[1] The term "release", which is appropriate for single pathogen or contaminant risk analyses, is potentially confusing for some ecosystem-level risk analyses. Several ecological risk analysis protocols skip this phase and move from hazard identification to the exposure and consequence analysis.

International risk analysis protocols

Internationally recognized risk analysis protocols do exist, and the process is well established as a tool for health and ecological management and decision-making in various sectors. It is therefore important to look at the applicability of those protocols and pathways in applying risk analysis to aquaculture before considering creation of new protocols and pathways. It is also emphasised that in most countries, EIA is the main existing and legally required assessment tool, and many of the elements of risk analysis are already established within this framework.

Examples of existing risk analysis protocols in related disciplines are the World Organisation for Animal Health's (OIE) import risk analysis protocol, which focuses on aquatic animal diseases and health (Murray *et al.,* 2004,), and the international principles and guidelines for the conduct of microbiological and other food safety associated risk assessments, as developed by the Food and Agriculture Organization of the United Nations/World Health Organization (FAO/WHO) Codex Alimentarius Commission. Ecological risk analysis protocols are also being used for analysing impacts associated with introduction of exotic species, genetically modified organisms, residue contamination and increasingly, ecosystems. These approaches are clearly applicable in aquaculture, depending on the hazards and risks being analyzed.

Application of risk analysis in aquaculture

Risk assessment and management approaches to addressing environmental issues are increasingly being used at all levels of policy and regulation, with a wide range of applications (Fairman *et al.*, 1998), including:

- designing of regulation, for instance in determining societally "acceptable" risk levels that may form the basis of environmental standards;
- providing a basis for site-specific decisions, for instance in land-use planning or identifying a suitable site of an hazardous installation;
- prioritizing environmental risks, for instance in the determination of which chemicals to regulate first; and
- comparing risks, for instance to enable comparisons to be made between the resources being allocated to the control of different types of risk or to allow risk substitution decisions to be made.

Risk analysis has traditionally been a function of policy and regulatory agencies and most development has taken place in these fields. Environmental risk analysis is now becoming more common in industry in many industrialized countries, partly as a result of the use of risk analysis in regulation. The scope of risk analysis in industry for example includes:

- compliance with legislation,
- product safety,
- financial planning,
- site-specific decision-making, and
- prioritization and evaluation of risk reduction measures.

Although risk assessment and management have and will continue to become increasingly important environmental management tools, it is important to look at what the techniques can actually achieve and equally as importantly, what they cannot. Some of the good points, as identified by DEFRA (2002) include:

- a technique that can weigh-up information that is basically in different "languages";
- a mechanism to aid decision-making;
- a basis for effective risk communication; and
- a method for highlighting and prioritizing research needs.

There are a number of disadvantages and pitfalls:

- The techniques have been criticized for a number of reasons, some of which are

not real criticisms of the techniques but are related to the philosophical basis of carrying out such assessments in the first place (e.g. some stakeholders in ecological risk assessments conducted in Australia objected to the use of a risk assessment approach to single "end-points", arguing that the environment was too complex to simplify).
- Criticisms focusing on the use of the techniques include possible over-reliance and over confidence in results; a narrow focus on parts of a problem rather than the whole and awkward relationship between risk assessment and the precautionary principle.

Risk analysis has been less used to date in aquaculture, except for human food safety hazards (Codex) and hazards associated with movement of live aquatic animals (OIE and some ecological risk analyses concerning introduction of exotic species or genetically modified organisms). In Australia, risk analysis is becoming extensively used for policy development in aquaculture (DPIF, 2004, 2005) for:
- identifying appropriate monitoring methods for offshore aquaculture (risk analysis used to prioritize environmental issues, and the monitoring methods were part of the controls);
- developing translocation protocols used in risk assessments to determine relative risk of various translocations (level of risk associated with geography – local, interstate, international) and species (endemic, introduced, exotic);
- developing Codes of Practice to minimize risk of disease transfer (e.g. abalone viral ganglioneuritis);
- developing best practice environmental guidelines (e.g. for salmonids and recirculating aquaculture systems); and
- developing protocols for monitoring trout farms based on the size of the farm relative to a variety of environmental criteria.

GESAMP (Anon., 2007) has explored the application of risk analysis and identified various "objectives" for both the application of the risk assessment and risk communication protocols in coastal aquaculture as follows: [2]
- **Integration into sustainable use paradigms**: Risk assessment as a science-based assessment that 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 explicit levels of acceptable protection that are dictated by social processes and a consistent and explicit mechanism for transparent application of the precautionary principle.
- **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. In other words, "risk communication" and involvement of "stakeholders" are essential for effective application of risk analysis.
- **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.
- **Transparency**: To optimize 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 utilize.
- **Consistency**: Measures should be comparable in nature and scope with measures already taken in equivalent areas in which scientific data are available.

[2] Although GESAMP refers to these "objectives", they are more like statements and do not effectively convey the objectives of using risk analysis in the context of aquaculture and aquaculture management.

- **Proportionality**: Risk management measures must not be disproportionate to the marginal change in risk and to the desired level of protection. It also must not aim for zero risk. Where no hazard can be identified, the risk assessment risk assessment should be concluded and the risk evaluated as non-significant.
- **Monitoring of predicted effects**: Where ongoing monitoring is identified as a necessary component of risk management, the initial assessment must be considered as of a provisional nature. Availability of more reliable scientific data may lead to changes in understanding of the mechanisms leading to environmental change and the level of risk (increased or decreased) associated with aquaculture . A requirement to monitor must be tied to a requirement of regulators to regularly report on the outcome and implications of monitoring.

Risk analyses have been applied to a limited extent in aquaculture and mostly for assessing hazards and risks associated with a single species or pathogen and most commonly in the context of human health, pathogens and species introductions (Table 1). Less common is the use of risk analysis to address other environmental issues associated with aquaculture development. There are also considerable gaps in knowledge and experience, particularly in the context of aquaculture and environmental interactions in developing countries. The need for new tools for environmental management of aquaculture is emphasized by various authors (e.g. Focardi, Corsi and Franchi, 2005).

Capacity for risk analysis

It must be recognized that many forms of risk analysis are a significant undertaking, requiring considerable capacity, both in terms of human skills and access to suitable information and tools, which may limit their application in some developing countries. For example, Hart *et al.* (2001) recommend that ecological risk assessments in wetlands involve a multidisciplinary team comprising a social scientist and experts with skills that may include ecology, biology, hydrology, water quality, environmental chemistry, ecotoxicolgy, statistics and modeling.

TABLE 1
Brief summary of some uses of risk analysis in addressing environmental issues in aquaculture

Hazard categories	Risk analysis approach	Examples in aquaculture	Key references
Human health: • Food safety hazards associated contaminants (residues, pathogens, chemicals) • Health and safety	FAO/WHO Codex and other health risk analysis protocols	Risks of *Vibrio* in seafood	Codex Alimentarius Commission (www.codexalimentarius.net)
Aquatic animal health: Release of pathogens	As outlined in the OIE Aquatic Animal Health Code	Many examples – e.g. import risk analysis associated with white spot syndrome virus in shrimp (Australia, Pacific islands)	OIE (www.oie.int) OIE (2007)
Ecological: • Release of genetically modified organisms (GMOs), exotic species, escapes	Ecological risk analysis used with single issue/ species	Impacts of salmon escapes Introduction of exotic *Penaeus* species to Pacific islands	Naylor *et al.* (2005) Arthur *et al.* (2004a)
• Release of wastes and other contaminants	Widely applied in industry, but limited application to aquaculture	Application to monitoring protocols for aquaculture wastes in salmonid culture (Australia) Organic contaminants in farmed salmon Use of antibiotics in aquaculture	DPIF (2004) Hites *et al.* (2004) Christensen, Ingerslev & Baun (2006)
• Disturbance/loss of ecosystem/biodiversity	Ecological risk analysis, but complex because of multiple hazards and multiple stresses that may effect many components of ecosystems	Very limited application to aquaculture to date. Some work on salinity impacts of shrimp farming Collection of wild pearls for aquaculture	Visuthismajarn *et al.* (2005) Wells and Jernakoff (2006)

On the other hand, risk analysis might offer some scope to contribute to capacity building and more efficient use of resources. One of the benefits of undertaking a risk analysis is to map out relationships and critical areas of uncertainty and ignorance. If this uncertainty is associated with potential severe impacts, then either the precautionary approach is invoked (according to local priorities!) or more research is required. However, the initial analysis is valid at all states of knowledge/capacity for research – indeed it contributes to building that capacity (J. Hambrey, pers. comm.).

ENVIRONMENTAL CONCERNS IN AQUACULTURE

On a global scale, the major areas of environmental concerns for aquaculture are now well identified, and include the following:

- wetland and habitat utilization and damage to ecosystem functions;
- abstraction of water;
- sediment deposition and benthic impacts;
- effluent discharge, hypernutrification and eutrophication;
- environmental contamination and human health risks associated with veterinary drugs;
- human health concerns related to chemical, biological and physical food safety hazards;
- ground water contamination;
- exotic species introduction;
- genetic impacts on wild populations;
- introduction of aquatic animal pathogens and pests;
- other wildlife and biodiversity impacts; and
- social issues related to resource utilization and access.

These issues have been discussed and reviewed in numerous papers and books (GESAMP, 1991, 2001; Barg, 1992; Naylor *et al.*, 1998; Phillips, 1998; Asche, Bremnes and Wessells, 1999; Black, 2001; Hindar, 2001; Crawford, 2003). Although the concerns are highly diverse and are farming species/system and site specific, there are some common characteristics to be taken into account if improved environmental management is to be achieved:

- Many of the impacts are subtle and cumulative – often insignificant in relation to a single farm but potentially highly significant for a large number of farms producing over a long period of time, particularly if crowded in relation to limited resources.
- Some of the impacts may be highly dispersed through space and time, depending on such factors such as seasonality, farm management, stocking practices and others.
- There is a high level of uncertainty and ignorance associated with many potential impacts of aquaculture. This argues for more extensive use of the precautionary approach to aquaculture but makes gathering and analysis of risk analysis data problematic.

Relevant treaties, agreements and guidelines

There are a number of international, regional and national standards; guiding principles; codes of practice or protocols available that relate to environmental issues and management in aquaculture, some of which can be useful for guidance in problem formulation and hazard identification, and in scoping the environmental risk analysis and risk management measures. Key international documents that encourage improved environmental management of aquaculture and provide relevant guidance or standards include:

- the Code of Conduct for Responsible Fisheries (CCRF), which provides principles and criteria for responsible fisheries, including (Article 9) on aquaculture (FAO, 1995);

- International Principles for Responsible Shrimp Farming (FAO/NACA/UNEP/WB/WWF, 2006);
- Convention on Biological Diversity (CBD, 2003),
- Codex Alimentarius food safety standards, Codes of Practice and guidelines; and
- World Organisation for Animal Health (OIE) Aquatic Animal Health Code (OIE, 2007)

However, international agreements by no means cover all aspects related to environmental risks associated with aquaculture production. For example, the Convention on Biological Diversity (CBD) recognizes that there are gaps and inconsistencies in the requirements for risk analysis associated with alien aquatic species and specifically mentions that movement of alien species associated with aquaculture is still not covered by any binding international instrument, despite the acknowledged vulnerability of aquatic biodiversity to biological invasion (CBD, 2003).

Environmental hazards

DEFRA (2002) defines "hazard" as a property or situation that in particular circumstances could lead to harm. "Hazard" is defined by the European Union (EU) more broadly as an agent, medium, process, procedure or site with the potential to cause an adverse effect (EU Commission, 2000).

Applied to aquaculture, such definitions could encompass, for example, the release of solid waste or nutrients, habitat disturbance or damage due to building of ponds in a wetland, abstraction of water leading to low river flows or the introduction of an exotic species. Where risk analysis is to be applied at the policy level, the hazard could be as broad as the adverse impacts of aquaculture on the environment.

Environmental interactions of aquaculture are extremely varied, and therefore a wide range of hazards can be identified, encompassing those affecting ecology as well as human health. While much attention is given to environmental hazards arising from aquaculture, there are also hazards arising from other sectors that may lead to harm for aquaculture. Environmental hazards can therefore arise from both within and outside the aquaculture sector and may cause harm to aquaculture or to the environment. It is important to understand that the nature of the hazards and the process of hazard identification should characterize those aspects that might facilitate the expression of undesirable effects. As a priority step before hazard identification, problem formulation, or what the risk analysis is trying to achieve and why, is also important in focusing efforts and resources. Recognizing such issues and to prevent expending unproductive effort, analysis should be terminated if hazard identification fails to identify evidence of an increased probability of the occurrence of an undesirable effect.

Environmental hazards and risk associated with aquaculture relate primarily to the siting, design and operations of aquaculture enterprises and their varied interactions with the surrounding environment, principally water, land, biodiversity and other natural resources required by aquaculture, as well as in some cases human food safety and health aspects. Many of the natural resources used by aquaculture are commonly shared with other aquaculturists or other user groups in coastal and inland areas (e.g. water), and therefore environmental hazards associated with aquaculture are of common concern to society in many countries.

There is no easy classification of the diversity of environmental hazards in aquaculture, but in general these may be classified broadly, with some overlap, as given below.

1) Disturbance or damage to ecosystems and biodiversity, including:
   - Hazards associated with the siting and operation of aquaculture facilities and damage to natural or man-made ecosystems and biodiversity, such as land clearing or ecosystem disturbance in mangroves, coral reefs and other sensitive habitats.

- Hazards associated with the release through escape or deliberate stocking of aquatic animals, including genetic impacts on native stocks, GMOs and disease. The escape of inbred or genetically modified aquaculture stocks also represents a concern for genetic diversity of wild stocks related to inappropriate breeding measures. Deliberate stocking of fish in culture-based fisheries may raise similar concerns over impacts on wild populations.
- Demand for fishmeal and fish oil is of concern in relation to damage to fish stocks and marine ecosystems associated with the use of fishmeal and fish oil in aquaculture diets.
- Collection of wild fry, fingerlings and broodstock from natural marine and freshwater ecosystems.

2) Water quality and supply
- Discharge of various solid and dissolved material from aquaculture farms leading to water quality changes in receiving waters. The discharge of solid and dissolved pollutants in intensive aquaculture effluent is a major environmental hazard leading to risks of water and sediment pollution, but more subtle changes, such as that caused by the filtering of organic material and plankton by mollusks, should also be considered. The seepage and discharge of saline pond water is a further hazard that may cause salinity changes in of groundwater and surrounding agricultural land.
- Consumptive use of water by aquaculture operations is a hazard that may lead to reduced flows and hydrological changes in natural habitats, mainly concerned with aquaculture farms utilizing water from freshwater ecosystems.
- Release of environmental contaminants arising from improper use of veterinary drugs, chemicals and other materials and their discharge to the environment.

3) Animal health and welfare
- Release of pathogens to the natural environment leading to aquatic animal and plant diseases and potential for impacts on both wild and cultured aquatic organisms.

4) Human health
- Food safety hazards associated with aquaculture, including chemical, biological and physical hazards associated with the farming, harvest and post-harvest treatment of farmed aquatic animals and plants.
- Occupational health hazards associated with the aquaculture working environment.

Examples of environmental hazards that may impact on aquaculture include the release of contaminants from other sectors, red tides, water abstraction and physical damage caused by natural hazards such as extreme weather, climate change or even catastrophic events such as the 2004 Indian Ocean tsunami.

Identification of hazards in aquaculture

The wide range of environmental hazards in aquaculture and sometimes, the costs of risk analysis, make it necessary at the outset to carefully determine the scope of the risk assessment. Decisions need to be made and clearly articulated on the specific objectives and scope of the risk assessment (e.g. qualitative or quantitative analysis of a single or multiple threats to a single or multiple environmental assets; determination of spatial and temporal scale). These decisions will guide the type of data and information that need to be gathered and help to identify knowledge gaps.

At this "problem formulation and hazard identification" stage, existing information typically needs to be compiled for the following:

- the environment of interest, particularly its most important assets (and their values), or at least those that need to be protected or are potentially at risk;
- the hazard(s) to which the environmental assets are, or may be, exposed; and
- the types of effects that the hazard(s) may have on the environmental assets.

The synthesis of such information should be done in consultation with stakeholders through an agreed-upon process. For example, the assigning of the "values" of ecological aspects in particular requires consultation to determine their significance for society and local communities.

End-points

End-points are the environmental values that are to be protected, operationally defined by an ecological entity and its attributes. For example, salmon are valued ecological entities; reproduction and age class structure are some of their important attributes. Together "salmon reproduction and age class structure" could form an assessment end-point. In other cases, ecological characteristics such as the abundance of some sensitive species could be considered. Ecological end-points should be ecologically, socially and politically relevant, sensitive to the potential stressors, amenable to measurement and relevant to the management goals (Suter, 1993).

The specific undesirable end-points that need to be managed may be identified in a variety of ways. Some of the end-points are the result of legislative mandates or international agreements. Others may be derived from special socio-economic concerns and may be identified through community consultations. Legislation and policies of the national or regional authority may identify some end-points that need to be managed. The IMO/FAO/UNESCO-IOC/WMO/WHO/IAEA/UN/UNEP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) notes five broad categories of environmental effects or end-points commonly raised as concerns by society in relation to temperate coastal marine aquaculture:

- changes in primary producers:
  –abundance (i.e. of macroalgae and marine angiosperms)
  –composition (i.e. harmful microalgae);
- changes in survival of wild populations due to genetic change, disease or competition from escaped aquatic animals and plants from aquaculture facilities;
- changes in composition and distribution of macrobenthic populations;
- changes in trophic resources; and
- changes in habitat (physical and chemical).

However, the actual end-points associated with the wide range of potential hazards in aquaculture will vary and will be site specific. Prior to initiating a risk analysis, it is important to identify the "end-point(s)".

Risk assessment[3]

Risk assessment is a process for evaluating the likelihood of adverse environmental effects arising from the hazard. This phase incorporates the release assessment, exposure (likelihood) assessment and consequences (effects) assessment. These are described separately below. The most pertinent information sources and techniques should be used, although these will vary depending on the assessment. Some types and sources of information include (Standards Australia 2004a, 2004b):

- past records, including relevant published literature;
- experiments and investigations;
- modeling;
- practice and relevant experience;
- results of public consultation; and
- specialist and expert judgements.

[3] Some ecological risk assessment guidelines refer to this step as "analysis".

Release assessment

Release assessment consists of describing the probability of release, as well as the quantity, timing and distribution of a hazard in an environment. If the release assessment demonstrates no significant probability of release, the risk assessment need not continue.

For example, a release assessment associated with a hazard such as discharge of nutrients from an intensive aquaculture farm would examine the probability of nutrient release, amounts of the nutrients of interest, timing and distribution into the receiving environment. The term release assessment is less relevant to some hazards associated with aquaculture, such as the siting of farms and habitat conversion. Some ecological assessments therefore do not consider this part of the risk assessment.

Exposure assessment

Exposure assessment determines the likelihood of the effects of an undesirable event (identified in the hazard identification and release assessment stages). Data on the effects of a hazard provide little useful information without knowledge on the actual level of exposure of the end-point to the hazard.

Thus exposure assessment aims to determine the likelihood that the environmental asset(s) of concern will be exposed to the hazard and therefore, that an effect will be realized. For a biological hazard, such as an invasive species, exposure assessment might involve integrating information on the source of the species, the potential route of entry into the ecosystem of interest, rate of spread, habitat preferences and associated distribution. Existing information (e.g. remotely sensed imagery) or habitat suitability modelling can be used for such purposes. If the exposure assessment demonstrates no significant likelihood of significant exposure, the risk assessment may conclude at this step.

The outputs of the exposure assessment should involve and be crosschecked with stakeholders to ensure that data and information were used and interpreted appropriately. The assessment should also be iterative. Information that is obtained throughout the process should allow for reassessment of an earlier step. In particular, discoveries during the analysis stage may encourage a shift in emphasis. 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 study.

Consequence assessment

Consequence assessment aims to determine and characterize the impacts or consequences of the release on the measurement end-points selected during problem formulation. For example, reduced water quality (for whatever reason) might impact aquatic ecosystems as measured by reduced species diversity and abundance of macroinvertebrate and/or fish communities. It is desirable to quantify the magnitude of impact to the extent possible. The process of risk assessment associated with the theoretical release of solid organic material from a marine fish farm is summarized in Table 2.

Risk estimation[4]

This step integrates the outcomes of the effects (consequences) and exposure (likelihood) assessments in order to determine the level of risk (i.e. consequences × likelihood) to environmental values (end-points).

In general, there are three levels at which this analysis of risks can be undertaken: qualitative, semiquantitative and quantitative. Often, risk assessments are undertaken in a tiered manner, with initial screening-level qualitative or semiquantitative analyses

[4] Referred to as risk characterization in some ecological risk analysis documents.

TABLE 2
Risk assessment approach applied to solid organic material from an intensive marine fish farm

Risk analysis step	Description	Methods
Potential hazard	Discharge of organic fish farm waste	Consultation Analysis
End-point	Benthic macrofauna diversity and species retained	Scientific, legal review and public consultation
Release assessment	Assess amounts, patterns and types of organic wastes released from fish farm (uneaten food, faeces, displaced fouling organisms)	Review of scientific data, management information.
Exposure assessment	Assess organic material settling on the benthos (i.e. being exposed to solid organic waste)	Benthic models (relating current, depth and settling velocity of sold waste), site assessments
Consequence assessment	Assess how benthic macrofauna diversity and species are impacted by organic material accumulation rates	Review of scientific literature, site assessments
Risk estimation	Estimate consequences; the probability and extent that benthic macrofauna diversity and species will be impacted	Risk evaluation matrix method

being done prior to more detailed quantitative analyses. This approach can be used to first rank the threats and associated hazards so that more effort can be allocated to quantitative risk analyses for the most important (i.e. highest priority) hazards. Quantitative risk assessment methods are becoming more widely used. They include decision or logic trees, probabilistic methods, predictive models, dynamic simulation models and Bayesian networks (McDaniels, Keen and Dawlatabadi, 2006; GESAMP, 2007). An example of a qualitative risk estimation using a simple matrix approach is shown in Table 3.

GESAMP has attempted to develop a "logic model" to explore and illustrate the complex causal chain between hazard and ecological end-points. The "release-exposure" model is rather limited and difficult to apply to many aquaculture-associated hazards

TABLE 3
Risk evaluation matrix for determining level of risk

Probability of exposure[2]	N	L	M	H	C
H	Yes	No	No	No	No
M	Yes	No	No	No	No
L	Yes	Yes	No	No	No
VL	Yes	Yes	Yes	No	No
EL	Yes	Yes	Yes	Yes	No
N	Yes	Yes	Yes	Yes	Yes
	Significance of consequences[3]				

[1] Yes = the risk is acceptable and the activity can be permitted; No = the risk is unacceptable and the activity cannot be permitted without further risk management.
[2] Level of probability: H=high, M=moderate, L=low, VL=very low, EL=extremely low, N=negligible.
[3] Level of significance: C=catastrophic, H=high, M=moderate, L=low, N=negligible.

Source: Standards Australia, 2004a.

(it was developed originally in relation to simple toxic chemical release and exposure of organisms). GESAMP has therefore built up causal models with information on the probability of a causal effect, the uncertainty (lack of knowledge or unpredictability) associated with the relationship and the severity of the effect (intensity, extent, duration).

This approach may serve as a useful tool to: a) analyze the nature and overall significance of the risk, b) communicate and exchange knowledge and perspective on the various relationships and associated risks/uncertainties and c) focus further work on key areas where probability, severity and uncertainty are all high, and where research can significantly reduce uncertainty.

There are also many variations on this in the form of networks, trees, matrices and associated scoring systems that can be used to explore alternative outcomes and/or the likely benefit to be derived from specific management interventions.

The wide range of environmental issues in aquaculture therefore requires a wide range of tools and approaches. The complexities of environmental risk assessment in aquaculture will also be influenced by a complex interaction of different factors related to the sector, such as:

- the variability associated with technology, farming and management systems, and the capacity of farmers to manage technology;
- the variability associated with location (i.e. climatic, water, sediment and biological features), the suitability of the environment for the cultured animals and the environmental conditions under which animals and plants are cultured;
- the financial and economic feasibility and investment, such as the amount invested in proper farm infrastructure, short versus long-term economic viability of farming operations, investment and market incentives or disincentives, and the marketability of products;
- the socio-cultural aspects, such as the intensity of resource use, population pressures and social and cultural values and aptitudes in relation to aquaculture; social conflicts and increasingly, consumer perceptions, all play an important role; and
- institutional and political factors such as government policy and the legal framework, political interventions, plus the scale and quality of technical extension support and other institutional and non-institutional factors that are also influential in determining the risks, possibilities for management and the success with which the risk analysis approach can be applied.

The risk analysis approach however can also be used, as it has been in Australia, to explore the risks associated with different technologies and indeed, to use such information to develop industry codes of practice (DPIF, 2005).

The role of social aspects

The social aspects of environmental risk analysis for aquaculture deserve special attention. Economic, political, legal and social concerns play important roles throughout the assessment, evaluation and decision-making stages of risk management. Ensuring dialogue between interested parties at all stages requires an understanding of the social aspects of risk along with an appreciation of the mechanisms by which stakeholders can be actively engaged in the process.

The evaluation of risk entails a judgment about how significant the risk is to the receiving environment and to those concerned with, or affected by, the decision. In conjunction with formal scientific input, this requires the examination of public and political judgments about risks alongside the measurable costs and benefits of the activity in question. The precise knowledge required for an objective evaluation is often lacking for environmental risk assessment and an element of judgment is therefore usually needed. Furthermore, environmental quality involves both scientific elements and social elements. There is, therefore, a need to consider carefully the social dimensions of a risk as a part of the decision-making process. Indeed, the process of risk analysis has, perhaps unfairly, been criticized as being "too scientific" and ignoring social values.

Society is increasingly conscious of the harm that its activities can cause to the environment and the harm to people or the loss of quality of life that can result from environmental degradation. Decisions about environmental risks should, according to DEFRA (2002), take account of social issues because:

- General awareness of environmental risks has increased, and this is often associated with heightened levels of concern;
- Recent experience has shown how essential it is to have in place a framework that ensures transparency in decision-making and that forms a justifiable basis for policies on environmental protection;
- Calls have been made for a greater degree of public involvement in decision-making processes for environmental protection; and
- There is increasing pressure on those who create and regulate risk to inform the public about the risks to which they and their environment are exposed.

In conjunction with the assessment of a risk, it is important therefore to ensure the decision-maker asks whether the risk is likely to be acceptable to those concerned with, or affected by, the risk or consequent management decision. Evaluating the social significance of a risk can guide decision-making and help towards communicating about the risk to interested parties. It is, therefore, essential that the decision-maker considers social dimensions as part of the processes to identify, assess, evaluate and manage risks to the environment. A further detailed discussion of the social aspects of risk is provided in DEFRA (2002).

Risk management

Risk management is the design, selection and implementation of a programme of actions to minimize risk to an acceptable level. Risk management measures may also include monitoring, the outcomes of which should be used to re-assess risk as well as to determine or modify the success of risk management measures.

Risk management measures to address environmental issues in aquaculture are now being used in several countries following risk assessment. An example is in the State of South Australia, where the type and level of environmental management and reporting requirements for effluents from inland aquaculture farms are varied depending on the risk classification from the assessment phase. Higher risk farms require additional parameters and increased frequency of sampling (Government of South Australia, undated).

Risk communication

The purpose of risk communication is to supply planners, managers, industry experts, environmental agencies and laypeople with the information that they need to make informed, independent judgments about risks to their health, about the safety of the operation under consideration and about the potential environmental effects, as well as concerning the economic and social risks associated with the development (DEFRA, 2002).

Risk communication is widely recognized as a critical component of the risk analysis process. GESAMP has identified the following important aspects for risk communication as applied to coastal aquaculture:

- **Social buy-in is critical:** Offer stakeholders a sense of ownership of the process and built trust in those conducting the exercise.
- **Stakeholders needs are important:** Identify issues of concern and stakeholder priorities that need to be incorporated in hazard identification and risk assessment.

- **Show what science can and cannot say:** Provide a sound mechanism by which stakeholders are informed about the nature and strength of causal relationships and the probabilities and uncertainties associated with the predicted environmental risks of the aquaculture development.
- **Build trust:** Guarantee that transparency of the entire risk analysis process leading to decision-making is facilitated by effective exchange of information and deals with perceptions, facts and uncertainty
- **Value non-science sources of information:** Ensure that all pertinent and significant data required for the risk analysis are captured, not only from solid natural science disciplines that allow assessment environmental influence or change, but also incorporating stakeholder information on objectives, priorities and perceived risks.

Communication about environmental risks serves many important purposes. It can be used either as a tool to provide information, explain and warn, or to encourage collective partnership approaches to decision-making through greater public participation in the risk management process.

Risk communication, although difficult to achieve successfully, can be implemented in different ways. It should also aim to engage diverse stakeholder audiences. These audiences may hold different values and have different levels of understanding, and the interpretation of a message can be dependent on a variety of social factors. Provided these complexities are borne in mind and the objectives are clearly defined, communication can achieve its desired outcome.

Efforts simply aimed at the provision of quantitative risk estimates are likely to be of limited value because of the complex nature of risk judgements. Communication should be sensitive to a broad concept of risk, encompassing not only quantitative information, but also other dimensions such as individual attitudes and issues of trust and credibility. GESAMP has further highlighted various objectives for risk communication as essential to:

- offer stakeholders a sense of ownership of the process and build trust in those conducting the exercise;
- identify issues of concern and stakeholder priorities that need to be incorporated in risk identification and risk analysis;
- ensure that user knowledge is effectively incorporated into the decision process;
- provide sound mechanisms by which stakeholders are informed about the nature and strength of causal relationships and the probabilities and uncertainties associated with the development;
- guarantee that transparency of the entire risk analysis process leading to decision-making is facilitated by effective exchange of information and deals with perceptions, facts and uncertainty;
- ensure that all pertinent and significant data required for the risk analysis are captured, not only from solid natural science disciplines that allow assessment of environmental influence or change, but also incorporating stakeholder information on objectives, priorities and perceived risks;
- provide the means so that any information generated as a result of the implementation of recommendations (e.g. for mitigation or additional research) arising from the risk analysis is also captured; and
- guarantee that the results of the risk analysis are communicated in a format that is clear and useful to individuals and organizations who use the information in their decision-making processes.

Of these eight 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 its perceived and real risks. Therefore, a high degree of flexibility is required to facilitate communication between scientists, planners, managers, regulators, developers and the public at both the governmental and local levels. It is almost impossible, without empirical testing, to predict the effects that effective communication will have on 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).

CONCLUSIONS

Traditional risk analysis deals primarily with the human health concerns of various anthropogenic activities, but this approach has now been broadened to encompass a wide range of environmental concerns. Numerous protocols exist for estimating the human health risks associated with various hazards, and there are an increasing number for the analysis of environmental risks arising as a result of human activity.

There are a number of environmental hazards associated with aquaculture operations. The risk analysis framework is useful for identifying, evaluating and addressing environmental hazards associated with aquaculture, however, there are clearly a number of constraints and issues to consider:

- The potential hazards from aquaculture and their impacts depend upon the species, culture system and operations management practices, and other non-technical factors such as human capacity and institutional capacity.
- The likelihood of hazards becoming undesirable consequences is difficult to quantify given present knowledge and the lack of tools. The wide range of environmental hazards related to aquaculture requires a wide range of tools for risk assessment and skills among the people concerned.
- The effective use of risk analysis in aquaculture will also require effective communication and explanation of how risk analysis can be effectively applied to aquaculture issues, for government and industry stakeholders involved with aquaculture.

RECOMMENDATIONS

A number of recommendations arise from this overview of the use of risk analysis to address environmental issues in aquaculture:

- There are presently limited experiences and case studies associated with the more complex ecological risk analyses as applied to aquaculture. Promotion of case studies and sharing of experiences are needed.
- The information on risk analysis that could be applied to aquaculture is scattered across the literature, from peer review to grey literature. A practical manual would be useful to assist risk analysis practitioners in the sector and to raise awareness on useful applications.
- The understanding of some key issues (e.g. risks associated with aquaculture and ecosystem functions, use of trash fish) is still limited. As far as possible, simple tools should be developed for the different hazards concerned with aquaculture.
- The need for developing and demonstrating cost-effective risk management systems for small aquaculture operations is apparent.
- Capacity-building in all aspects of environmental risk analysis for aquaculture is needed.
- Risk analysis has a potentially important role in policy setting but to be successful needs the institutional roles and responsibilities should be carefully considered.
- A major challenge is to apply practical risk analysis methods to the small-scale aquaculture sector.

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