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 endpoint)
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

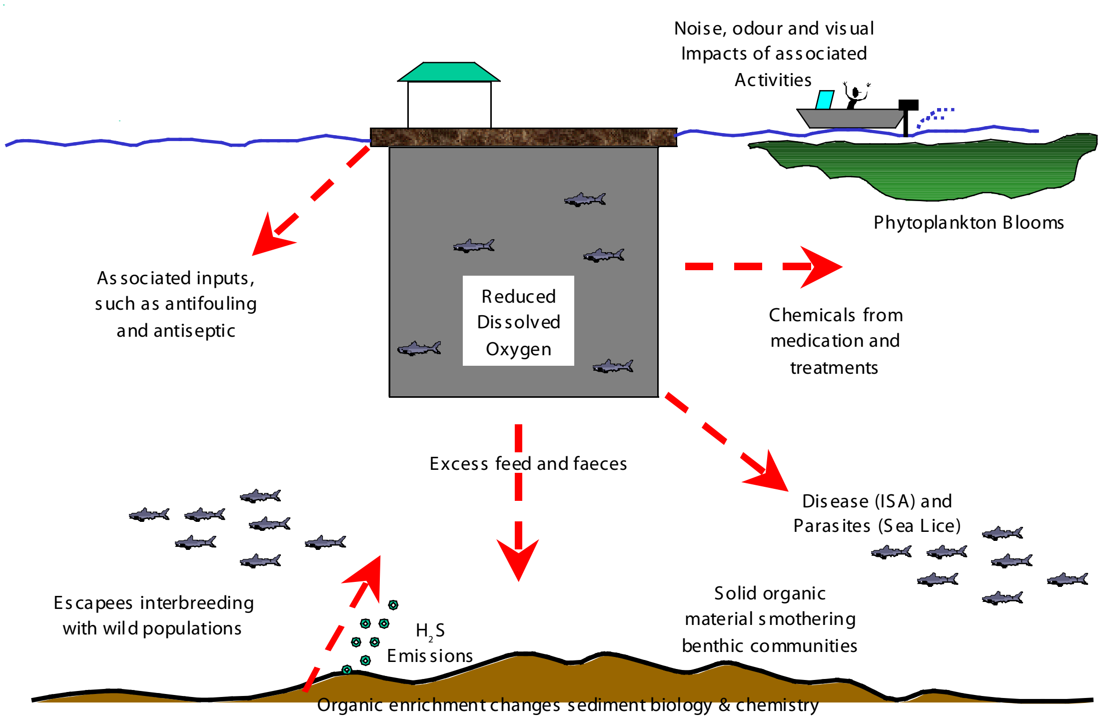
At this initial stage, when concerns are first raised in relation to a particular proposal, it is appropriate to start to adopt the formal approaches of risk analysis to structure the collation and organisation of information.

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).* **<u>Note:</u>** *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.