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Ecological Risk Assessment for Ballast Water Introductions

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Abstract

An ecological risk assessment methodology is suggested as a means to investigate the efficacy of ballast water management strategies, addressing any one of a number of potential endpoints linked to the transport, release and control of non-indigenous marine organisms associated with ballast water. The methodology represents a synthesis of the ecological risk assessment framework espoused by the United States Environmental Protection Agency and the quantitative risk assessment paradigm more commonly employed in the nuclear and chemical process industries. This paper highlights some of the difficulties associated with quantifying risks within multivariate biological systems, notably the problems of stochastity, complexity and causality. A number of mathematical and ecological techniques are identified as exhibiting some utility in this context. The paper does not purport to provide an "off the shelf" risk assessment for ballast water management, but rather offers some insights into how such an assessment might be undertaken.

1 INTRODUCTION

Risk is an often loosely defined term which expresses the chance of an undesirable event occurring as a result of some activity or action, (including "no action"). Crucial to our understanding of risk is that it is associated with undesirable, and often unforeseen, events. One does not generally consider the risk of winning the lottery, for example.

Quantitative Risk Assessment (QRA) has its origins in the nuclear and space industries, but in the last 20 years or so has gained a more widespread acceptance in the oil, petrochemical and chemical process industries, and indeed for many other applications where the consequences of an undesirable event are potentially disastrous. The QRA paradigm is a rigorous, logical and interative risk analysis procedure, which can be formally defined as:

> *the quantitative evaluation of the likelihood of undesired events, and the likelihood of harm or damage being caused, together with value judgments concerning the significance of these results*

The key points here are that it is a quantitative exercise and that risk is a function of two parameters; the probability of occurrence of an undesired event and the consequences of that event. The quantitative nature of the QRA paradigm is often confused with an "objective strength of character". In reality, however, the distinction between objective and subjective risk assessment is at best blurred and more often than not artificial. The strength of QRA lies not in its objective stance but rather in the manner that it treats subjective input.

Under the definition provided above, QRA can be viewed as a 5 stage procedure entailing:

(i) the identification of hazards or potential undesired events;
(ii) analysis of the frequency or likelihood of occurrence of the events;
(iii) assessment of the effects or impacts should the undesired event(s) be realized;
(iv) calculation of the risk, expressed as a product of the probability of the undesired event and its consequences; and,
(v) an examination of the significance of the results often in the wider context of other social, economic or political concerns.

Importantly, however, QRA does not specify acceptance criteria for risks - this is a separate political and socio-economic decision.

The success of the QRA paradigm in the industrial context has encouraged its extension to novel areas, particularly ecological risk assessment. Again the objective in ecological risk assessments is to estimate the likelihood that some undesired event will occur. Such events are termed "ecological endpoints" (Bartell *et al* 1992). These endpoints are the expression of consequence and an expression of the values to be protected - that is the effects that are to be estimated and prevented or minimized by the assessment exercise.

In traditional QRA the endpoints are clear - human death or injury. In ecological risk assessment, however, the endpoints are often not as easily defined or identified. In theory ecological endpoints can be anyone of numerous structural and functional ecosystem components, for example the elimination of a commercially valuable species or an overall reduction in primary production. In reality, however, the assessor may be unaware of what endpoints he is, or should, be working towards, and may have to distinguish between those endpoints he can measure (measurement endpoints) and those endpoints which he is seeking to assess (assessment endpoints), extrapolating from one to the other.

These problems are compounded by the difficulties of quantifying perturbations to complex, multivariate ecological systems. Natural systems exhibit close interdependence between component functions and structure, and considerable spatial and temporal variability. Ecosystem processes are stochastic, i.e. influenced by chance and timing, and more often than not non-linear in nature. Establishing causality in such a system is difficult. The way we perceive ecosystems is scale dependent. At larger scales we may witness a steady "equilibrium" state, but at smaller scales the system is often one of constant flux; ecosystems have often been termed "chaotic" exhibiting some of the popular and scientific implications that such a term entails.

The complexity of natural systems remains a considerable hurdle to quantified ecological risk assessment. While this hurdle may remain insurmountable for the foreseeable future, the QRA paradigm still provides a rigorous and logical mechanism with which to interrogate risks arising in environmental media. In the face of this complexity, and the need to make defensible and repeatable decisions, the United States Environmental Protection Agency (USEPA) has devoted considerable resources to the issues of ecological risk assessment. The QRA approach is clearly recognizable in the resulting framework for ecological risk assessment developed by the agency, (USEPA 1992).

The risks associated with the introduction of non-indigenous organisms through ships ballast, and the ballast water management strategies aimed at reducing or eliminating these, exhibit an interesting combination of industrial and ecological risk assessment characteristics. A synthesis of the USEPA framework for ecological risk assessment with the techniques of the quantified risk assessment paradigm would seem therefore to be an appropriate means by which to interrogate these risks.

The purpose of this paper is to investigate the means by which such a synthesis may be achieved, with a particular view to establishing the efficacy of ballast water management strategies in terms of quantifying the probability of strategy failure, and the consequences of such. The importance of such an approach is seen in terms of the need to identify cost efficient strategies for ballast water management.

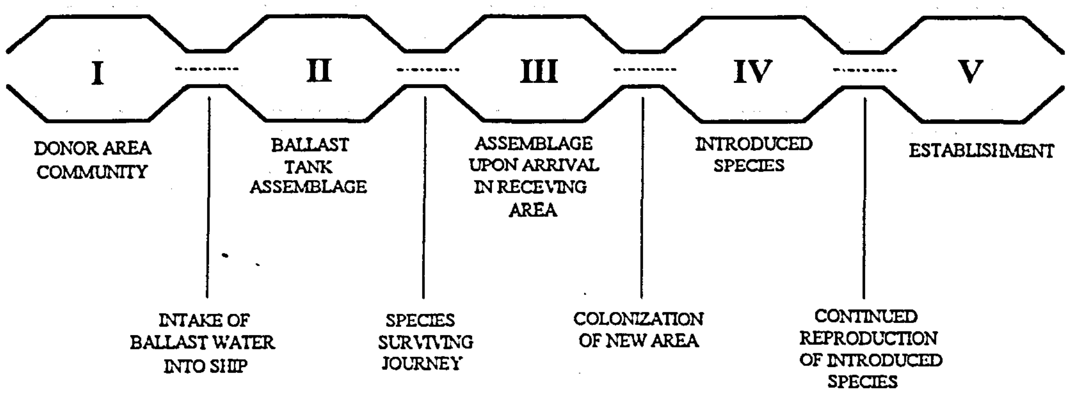
2 BALLAST WATER INTRODUCTIONS & MANAGEMENT STRATEGIES

Carlton (1986) has proposed a simple model representing the cycle of ballast water introductions, illustrated in Figure 2.1 Against this background it is possible to construct a simple, species specific, event tree for the introduction and establishment of a non-indigenous organism, as illustrated in Figure 2.2.

Ballast water management strategies attempt to break the chain of events leading to a non-indigenous introduction, and this break can be made at any one of a number of points, or at a combination of points. There are therefore a large variety of different management strategies, indeed Carlton *et al* (1994) suggests there are at least 32 different management options, (these are reproduced in Appendix A). Whilst some of these options are mutually exclusive, combinations of those options that are not, allows many more strategies to be applied in any given situation.

Furthermore it seems reasonable to assume that any individual strategy is unlikely to be equally cost effective for all vessels at all ports of arrival and departure. It would seem unreasonable therefore to impose a blanket strategy across the shipping industry as a whole. If we accept this line of reasoning, we are naturally led to the conclusion that the implementation of ballast water management strategies should be done on a case by case basis. But on what basis should one strategy be chosen over a another?

Figure 2.1 The Ballast Water Introduction Cycle



(after Carlton 1986)

The purpose of this paper is to suggest that a quantified ecological risk assessment approach to determining the probability of management strategy failure, and the consequences of such, provides a defensible means by which to test cost efficiency, and thereby provide effective decision criteria for such a case by case evaluation.

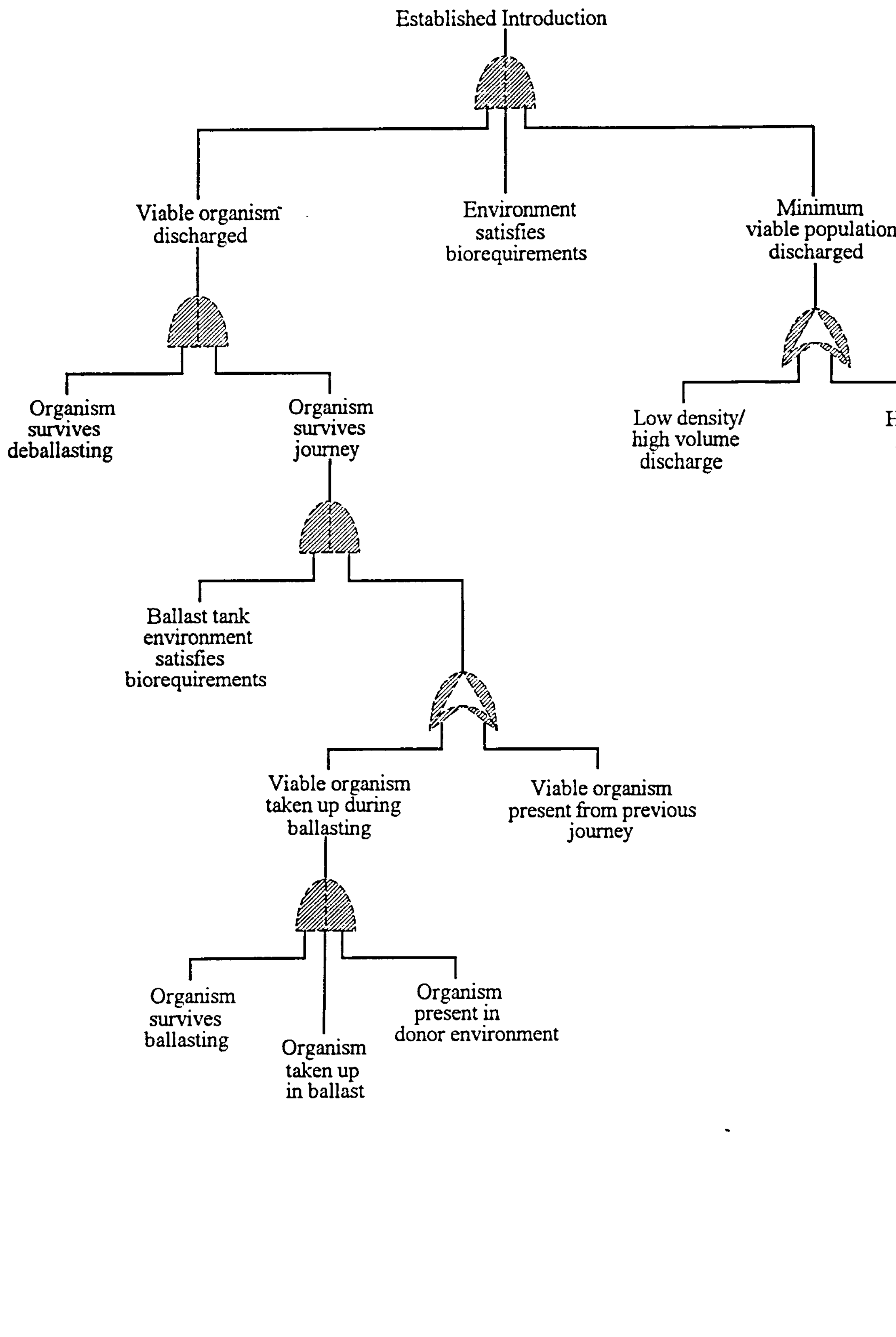
At this point it is worth pausing briefly to reflect on what has been suggested; the assumption made above is that cost efficiency is an appropriate means by which to differentiate between management strategies. This assumption must be made with care (as recent events surrounding the Brent Spar disposal have clearly demonstrated). It is not inconceivable that in certain circumstances the scientific and/or public community could adopt a zero-risk attitude. This is akin to a statement of environmental ethic; any probability of introduction and establishment of a given species, perhaps in a given location, is unacceptable. Under these circumstances applying the most cost efficient strategy may not be appropriate or desirable.

It is clear, however, that implementing ballast water management strategies will incur cost, and in certain circumstances these costs may be considerable. These costs will inevitably pass on to the public or sections thereof, and given that the public's willingness to pay for environmental protection or improvement is finite, establishing the most cost efficient management strategy is a justifiable objective. It is on this presumption that the paper proceeds.

The most cost efficient management strategy (or combination of strategies) can be defined as that option(s) which exhibits the highest risk reduction per unit cost. The endpoints towards which the risk assessment is directed becomes failure of any given management strategy. In this context we can distinguish between operational failure (or simple inefficiency) and accidental failure. For the mainpart this discussion will focus on the operational efficiency of control options, but the techniques discussed are equally applicable to an accidental event analysis.

The risk of control failure has two components; the frequency with which failure occurs and the consequences of such. Consider for example strategies designed to prevent organisms taken onboard with ballast. Failure is defined as organisms taken on board. The frequency with which this event occurs (either operationally or accidentally) and the consequences of failure - expressed as the number of organisms taken on board - defines the risk of failure.

Figure 2.2 Simple fault tree for ballast water introduction



It is possible therefore to envisage a series of "nested" risk assessment endpoints (nested in the sense of Russian dolls), applying to the various control strategies within the ballast water introduction cycle, as illustrated in Figure 2.3.

Again the objective of the risk assessment process is to quantify the risk of management strategy failure, allowing a comparative cost utility function to be determined on a case by case basis. Importantly, however, this approach also allows a quantitative assessment of the efficacy of combined option strategies. Applying Boolean logic, for example, to the probability of failure of any single strategy allows a determination of the probability of failure of two (or more) options in a serial or parallel fashion.

3 BIOCIDE TREATMENT RISK ASSESSMENT

In theory then quantitative risk assessment techniques would allow the determination of the most cost efficient combination of control options under any given circumstances. In practice, however, the assessor will be faced with many of the difficulties associated with quantitative ecological risk assessment outlined above.

The hurdles that such an assessment is likely to encounter, and some of the techniques currently available to tackle them, are perhaps best illustrated by a hypothetical example. Let us consider the use of a chemical biocide as a ballast treatment option, and subject it to a hypothetical risk assessment.

3.1 Hazard identification

The first stage of the quantitative risk assessment paradigm is hazard identification. The hazards identification stage should therefore elicit those events or sequences of events that contribute to a biocide's failure to eliminate organisms within the ballast tank environment.

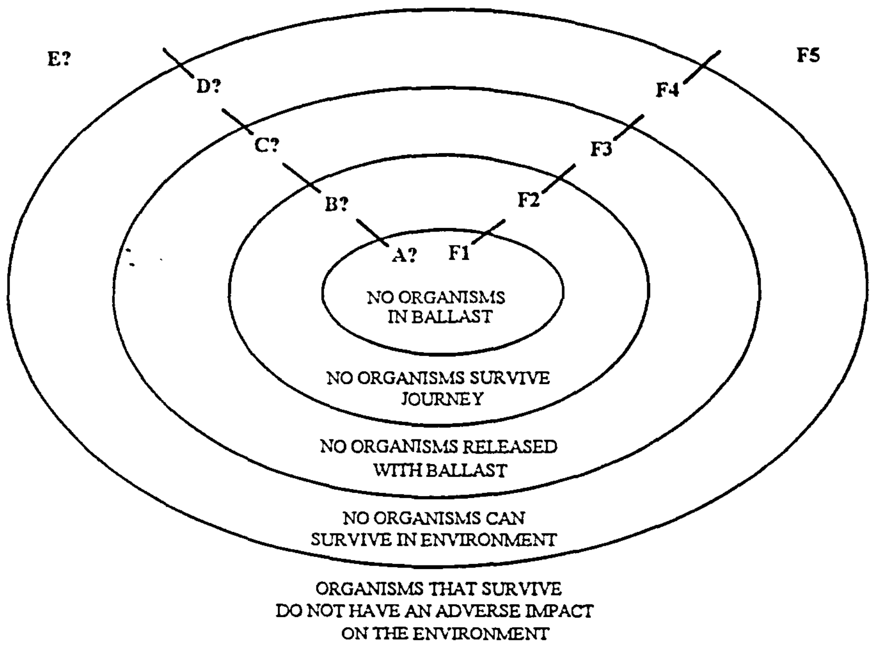
There are a number of techniques employed within an industrial context to identify hazards. Many of these techniques have been developed to provide structured ways of eliciting the identification of hazards by prompting those familiar with the system in question to apply their expertise in a rigorous and logical manner. Fault tree analysis forces the assessor(s) to consider the necessary events which contribute to the endpoint in question. A supplementary approach is HAZOP (Hazard and Operability) analysis which uses guide words to prompt "what if" type questions for each component of the system. In this manner the assessor(s) is encouraged to apply foresight and an inductive approach to determine potential hazards. Simple examples of both of these techniques are illustrated in Figure 3.1 for the hypothetical biocide treatment option.

3.2 Frequency Analysis

The purpose of the frequency analysis is to estimate the probability or frequency of the undesired events identified in the first stages of the risk assessment process. In the context of this assessment the frequency analysis would aim to quantify the probability of failure of any given control strategy. The frequency of failure is then determined on number of vessel trips, ballasting events, etc. In a traditional industrial QRA process, frequency analysis is undertaken in one of two alternative ways:

a) quantify the extent to which the system in question has failed in the past, deriving an empirically based frequency failure rate; or

Figure 2.3 Nested risk assessment endpoints for ballast water management strategies



Notes

F1	Endpoint #1	Failure of control option(s) designed to prevent organisms taken up during ballasting
F2	Endpoint #2	Failure of control option(s) designed to eliminate organisms within ballast tank environment
F3	Endpoint #3	Failure of control option(s) designed to prevent the release of organisms during deballasting
F4	Endpoint #4	Failure of control option designed to prevent the release of organisms into environments in which they can survive
F5	Endpoint #5	Failure of option that aims only to release organisms that will not have a detrimental impact on the receiving environment
A?	Question(s)	e.g. what organisms and how many?
B?	Question(s)	e.g. what survival strategies, which life stages, how many?
C?	Question(s)	e.g. which organisms, how many, how viable?
D?	Question(s)	e.g. organisms bio-requirements, environment characteristics?
E?	Question(s)	e.g. what impacts, what is adverse impact, what is acceptable?

Figure 3.1 Fault tree for biocide control failure

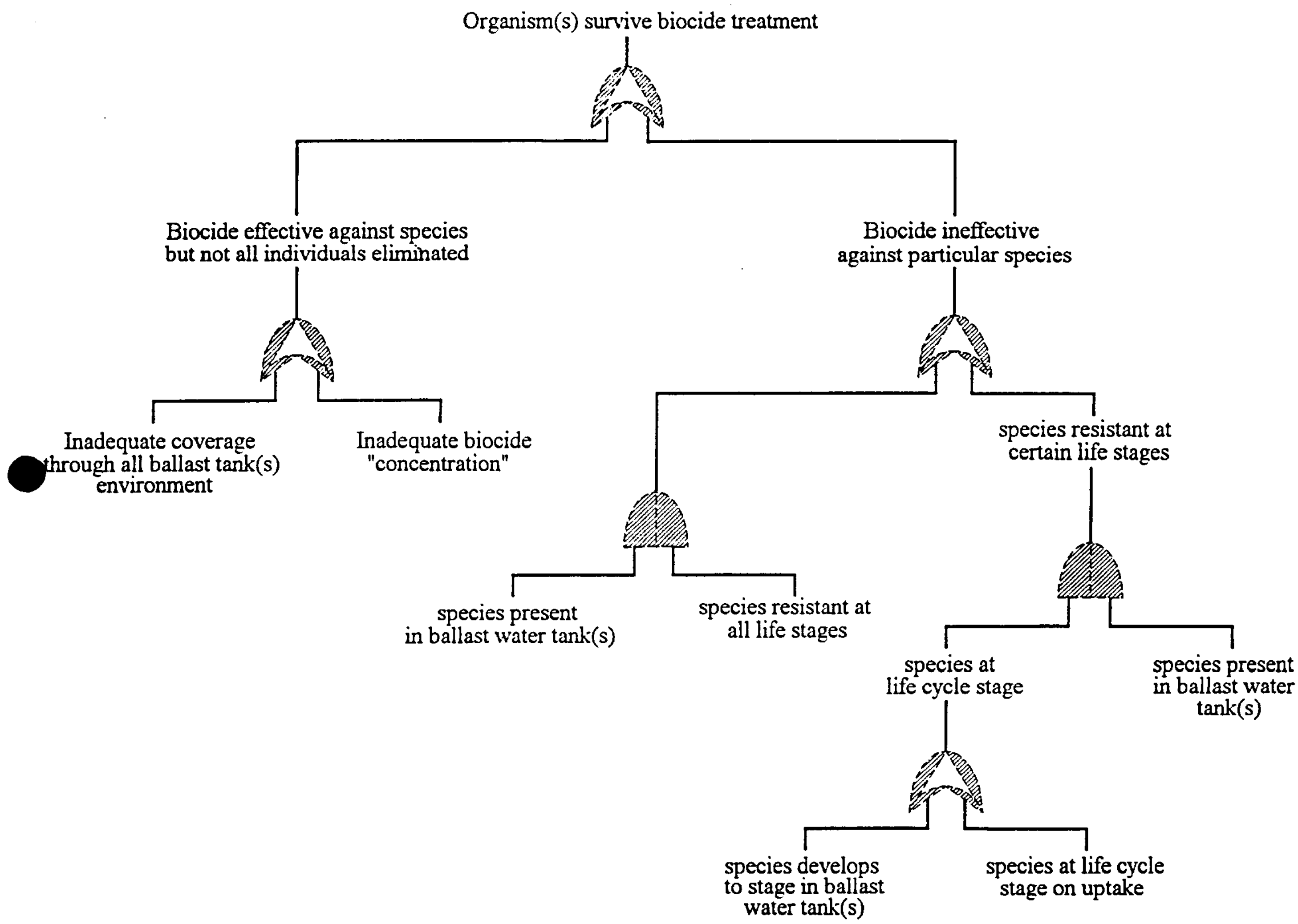


Figure 3.2 Simple HAZOP analysis for biocide treatment option

Control mechanism	**Guide word**	**Event**
Chemical biocide	Too much	Effective, but expensive, and may entail environmental damage upon deballasting, and/or damage to ballast tanks
	Too little	Probability failure increases, not all organisms eliminated
	Too slow	Inadequate coverage through all ballast water tanks over journey time
	Too quick	Inadequate treatment through all ballast water tanks over journey time

b) (in event that such data is unavailable) break down the failure event to its contributing components for which data is available and use Boolean logic to determine the overall probability of the failure scenario.

Frequency analysis within an ecological risk assessment, however, is considerably more difficult than its industrial counterpart. In the first instance it is very unlikely that a database of historical failure incidence will exist; clearly for ballast water management strategies no such database has been gathered. Furthermore establishing probability functions for the contributing events of a failure scenario are likely to be complicated by the complexity and stochastic behavior of the system being modeled.

For the biocide control option considered above for example, the failure endpoint is survival of organisms within the treated ballast water. This endpoint, however, would be poorly represented by a single parameter, and should properly be expressed as a size/probability function of numbers of organisms (of a given species) surviving. There are two components to this endpoint:

a) the birth-death processes which occur within the ballast tank population; and,
b) the effect of the control strategy (biocide) on these processes.

In effect the aim of the control strategy is to push the ballast tank population to extinction. (This is an important analogy and one that shall be referred to further). It is worth noting at this stage that the population of the ballast tank environment properly satisfies the ecological definition of a "closed population" (McArdle 1993), in so much as once the ballast operation is completed, there is no further immigration/emigration to or from the population over the duration of the vessel journey. In theory this simplifies the subsequent risk assessment; the ballast tank environment is more akin to a mesocosm than a ecosystem, and as such is more amenable to quantitative analysis.

The simple hazard identification exercise undertaken for the biocide example suggests that the following events could potentially contribute to the failure endpoint:

1. Inadequate biocide concentration
2. Species resistant to the biocide either generally or at a specific lifecycle stage
3. Inadequate coverage of all parts of the ballast water environment
4. Inadequate "treatment" time.

In this context there are clear parallels with ecotoxicological risk assessment, however, the control strategy is analogous to the reciprocal of the traditional ecotoxicological risk assessment which aims to ensure little or no impact upon components of an environment receiving a chemical contaminant; here we are attempting to ensure complete impact on the receiving environment.

The Ballast Tank Environment
The frequency analysis must first define the abiotic and biotic components of the ballast tank environment. These are the "ecosystem characteristics" which provide the context for the assessment. In effect the assessor is building a mesocosm model of the ballast water environment. As noted above the clearly defined spatial and temporal limits to this environment, and the closed population dynamics within it, suggest that this analysis should be considerably simpler than that for a "real world" ecosystem. The abiotic components of this environment are readily defined. The biotic components, however, are little more intractable.

In a simple deterministic analysis the population dynamics of any given species within this environment, assuming instantaneous rates of change in the initial inoculum, can be expressed:

$$\frac{\delta P}{\delta t} = (b-d)P \qquad [1]$$

which has the solution:

$$P = P_0 \exp[(b-d)t] \qquad [2]$$

where P_0 = inoculum, i.e. number of individuals taken onboard during ballasting
t = journey time
b = instantaneous fractional birth rate
d = instantaneous fractional death rate

Equation 1 above provides a very simple model that assumes constant birth and death rates and ignores such factors as food supply, density dependence, predation, etc. There are numerous techniques to incorporate predator prey interactions (see for example Yodzis 1994, Pimm 1982), trophic interactions (see for example Christensen 1992, Ulanowicz 1992) and to explicitly acknowledge the influence of dependent, independent and intervening variables (Buncher CR *et al* 1991).

In all such approaches, from the simplest to the most complex, however, the veracity of the analysis is dictated by the parameter values incorporated into the modeling. What makes ballast water strategy risk assessment amenable to such analysis is the mesocosm characteristic of the environment. In theory therefore the assessor should be able to empirically establish intrinsic birth and death rates, inoculum sizes, predator functional responses, etc. by reproducing the ballasting environment in the laboratory and measuring the population dynamics; the ballast tank environment is a real life mesocosm.

At this stage it is worth noting that the techniques outlined above are deterministic in nature. In reality stochastic influences would produce a distribution of possible population size at the end of the ballast journey, as illustrated in Figure 3.3. Again there are a variety of statistical techniques available to reflect the influence of chance and timing on population dynamics. In a stochastic model, parameter distributions represent the actual frequency distributions of the processes in question. Where these actual frequency distributions are unknown, as is more usually the case, a deterministic model (such as that represented by equation 1) can be made to mimic stochastic behavior by Monte Carlo sampling of the parameter values from suspected distributions. The incorporation of a priori information regarding the realistic limits to the system in question can improve the simulations considerably, (O'Neill *et al* 1982).

The Control Strategy Characteristics

A ballast water control strategy can be likened to an environmental stressor whose objective is to drive non-indigenous populations to extinction. With this analogy in mind the assessor can draw upon host of risk assessment techniques.

The efficacy of a chemical biocide, for example, can be investigated with ecotoxicological risk assessment methodologies. A simple deterministic analysis may define effectiveness as the LC_{100}/PEC quotient, representing the laboratory established concentration that is lethal to all of the test individuals, over the Predicted Environmental Concentration (PEC). A more realistic analysis, however, would consider the effects and exposure profile (USEPA 1992) of the stressor, which in this example could include:

a) LC_{100} effects profile: species sensitivity variation
concentration versus dose (biological uptake variation)
persistence, bio-degradation, environmental partitioning
laboratory-environment extrapolation error
time to LC_{100}

b) PEC exposure profile: fate and transport of biocide through ballast tank environment

A simple consideration of stochastic influences on both the effects and exposure profile, as illustrated in Figure 3.4, allows the determination of the probability of effect of the control option, which in turn defines the probability of failure.

The synthesis of these considerations with the results of the hazard identification stage provide the assessor with a toolkit with which to investigate potential control failure scenarios and the frequency with which they could be expected to occur. The simple analysis undertaken above for the biocide treatment option provides a clear example of some of the difficulties that may be encountered in establishing the efficacy of ballast water management strategies, as diagrammatically idealized for a biocide treatment in Figure 3.5.

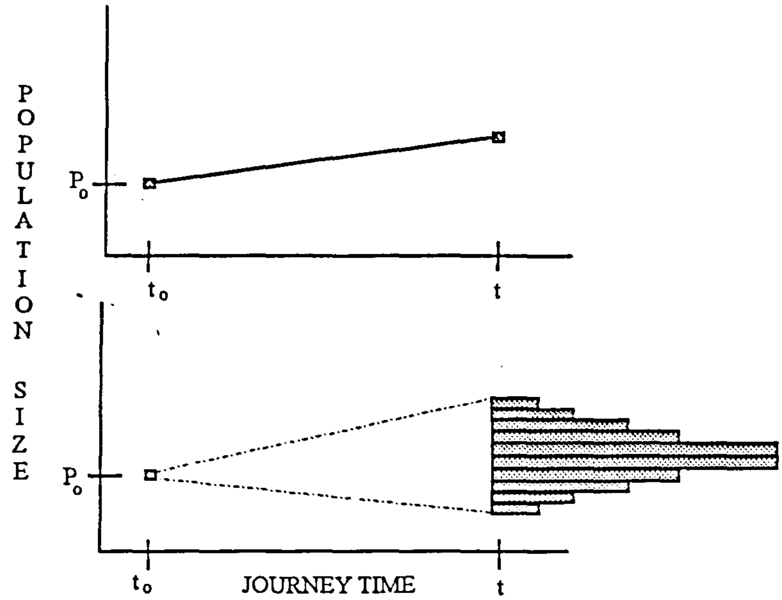
3.3 Consequence analysis

The consequences of control strategy failure are expressed in terms of the number of species, and number of individuals surviving to the next stage of the ballast introduction cycle. The significance of failure is also clearly a function of where in the ballast water cycle the survivors progress to.

Determining the number of individuals surviving beyond a particular control option is critical to an estimation of the likely effects of control strategy failure because small populations are considered to be more vulnerable to extinction - a phenomena generally referred to as the "Allee" effect, (Williamson 1989). The Allee effect manifests itself because small populations face the risk of extinction from demographic accidents - the chance fluctuations of birth and death rates - and from extreme environmental events. The concept is closely linked to that of a minimum viable population and Population Viability Analysis (PVA). PVA is a process in which the likelihood that a population will become extinct is assessed within a specified time and under particular circumstances (Possingham *et al* 1993).

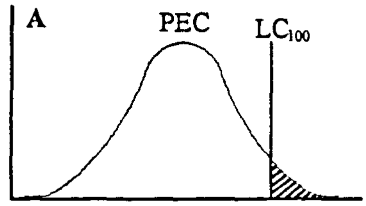
The importance of the extinction analogy drawn above is that conservation biology risk assessment techniques provide a clear means to establish the likelihood that a given population will become extinct, and that a control strategy may not have to eliminate all individuals to ensure eventual extinction, i.e. non establishment of an introduced species, (refer to Burgman *et al* 1993).

Figure 3.3 Stochastic influence on population dynamics

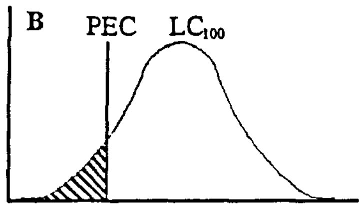


The difference between deterministic and stochastic models of population dynamics (adapted after Burgman *et al* 1993). The upper diagram represents the results of a deterministic model such as that illustrated in equation 1. The lower diagram represents the results of a model incorporating stochastic influences on population dynamics. P_0 represents the inoculum size (the population taken on board during ballasting), t represents the journey time.

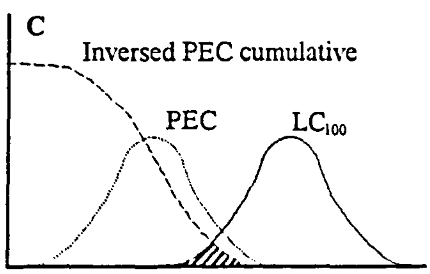
Figure 3.4 Stochastic influence on exposure/effects profile for chemical biocide



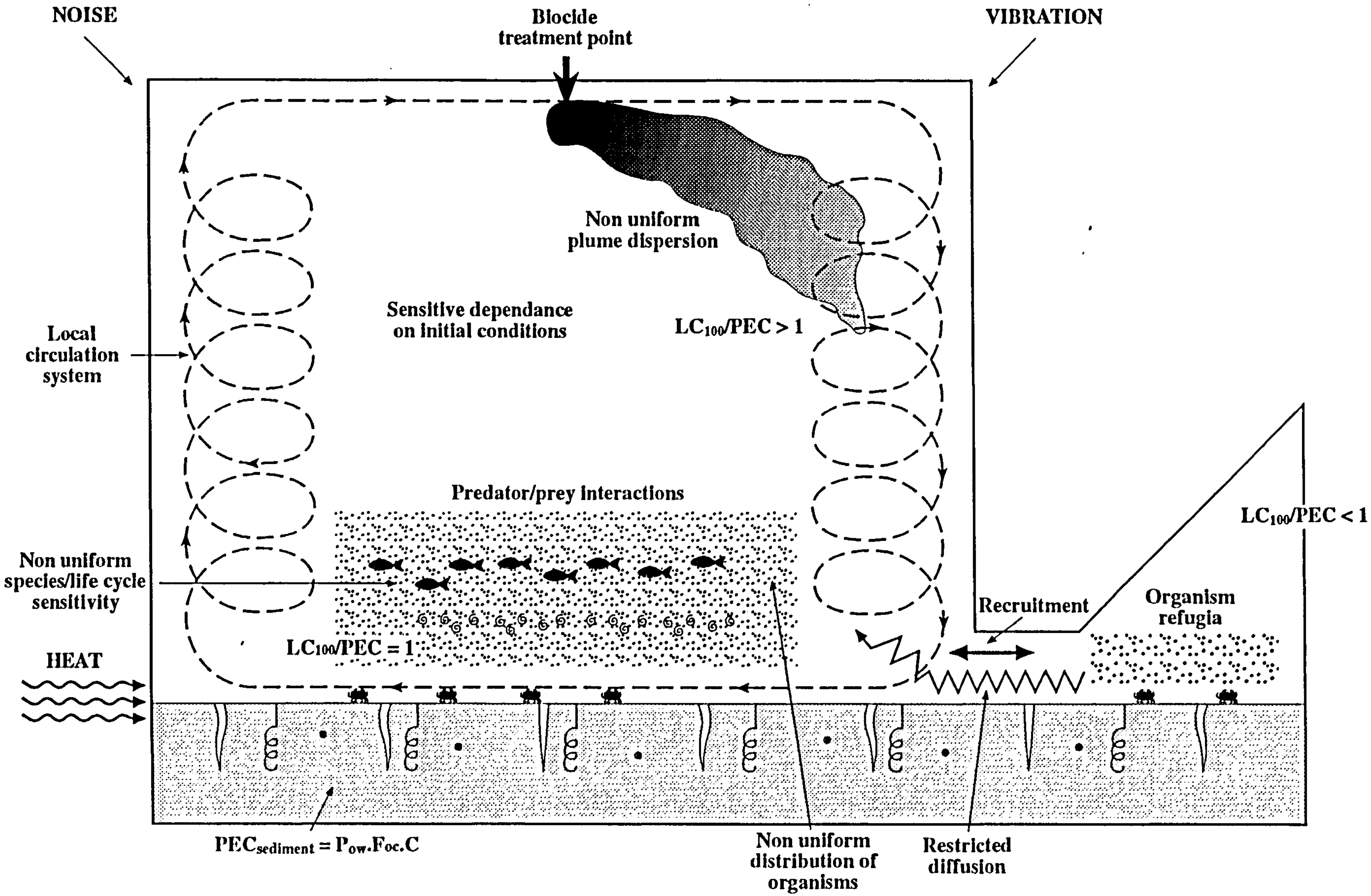
The probability of biocide effectiveness (adapted from Schobben & Scholten 1993). Figure A represents a distribution of potential Predicted Environmental Concentration (PEC) compared to a single LC_{100} for the species in question. The estimated efficacy of the control option (the shaded area) is expressed as the probability of $LC_{100} < PEC$.



Alternatively Figure B represents a distribution of single species LC_{100} compared to an assumed homogenous PEC in the ballast tank environment. The efficacy of the control option (the shaded area) is expressed as the probability of $PEC > LC_{100}$.



Combination of A and B above (Figure C), produces an integrated efficacy probability. This integral probability can be calculated by multiplying the inverse cumulative probabilities of PEC with the frequency distribution representing LC_{100}.


NOISE
Biocide treatment point
VIBRATION
Non uniform plume dispersion
Sensitive dependance on initial conditions
$LC_{100}/PEC > 1$
Local circulation system
Predator/prey interactions
$LC_{100}/PEC < 1$
Non uniform species/life cycle sensitivity
Recruitment
Organism refugia
$LC_{100}/PEC = 1$
HEAT
$PEC_{sediment} = P_{ow}.F_{oc}.C$
Non uniform distribution of organisms
Restricted diffusion

In theory then the assessor would be able to specify the frequency with which a given control strategy eliminated a particular ballast water population below its minimum viable population size. In practice the concept of population viability is unlikely to be sufficiently developed to control or predict establishment on a case by case basis. Were this to prove to be the case, the assessor could alternatively adopt the approach that the greater the population surviving to the next stage, the higher the probability that the species will progress through the ballast cycle and become established in the new receiving environment. In this approach the assessor seeks that control strategy, or combination of control options, which minimizes this size probability function in the most cost efficient manner.

4 RISK ESTIMATION & UNCERTAINTY ANALYSIS

Within the QRA paradigm risk is expressed as a function of the frequency (or probability) of undesired events and the consequence of these events. The result of the ballast water risk assessment would ideally be a cumulative probability density function expressing the probability that x% of the initial inoculum survives the control option. As intimated above this may allow some determination of the likelihood of subsequent growth and establishment of the non-indigenous species. Even where this cannot be established, however, the assessment exercise is a useful one if it is able to identify the most cost efficient means of minimizing this probability density function.

The estimation of risk in any risk assessment should properly be accompanied by an expression of the uncertainty in the results of the analysis, and the extent to which this uncertainty influences the subsequent conclusions of the assessment. Uncertainty analysis plays a critical role in providing a basis for selecting among alternative management options and deciding if and what additional information is needed (Reckhow 1994).

Uncertainty has been described as, "a measure of incompleteness of one's knowledge or information about a quantity whose true value could be established if a perfect measuring device were available", (Taylor 1993). It is important to recognize, however, that this is only applicable to empirical quantities, and that the risk assessor and decision maker may be faced with uncertainty regarding decision variables or value parameters which may not have a "true value", (Morgan & Henrion 1990).

Notwithstanding this last point, the major sources of uncertainty in a ballast water risk assessment are likely to be measurement error, stochastic variability and modeling approximation. The determination of sampling error, for example, is likely to be critical in ballast water management strategies to distinguishing between sampled structural zeros (the population is extinct), and sampling zeros that are due to sampling error when the population is really present, (McArdle 1993).

There are a range of techniques currently available to address these sources of uncertainty that can each be broadly defined as falling within one of three categories:

a) Sensitivity analysis - the effect of change in a model input parameter to the model output;

b) Uncertainty propagation - calculating the uncertainty in model outputs induced by the uncertainty in model parameter inputs; and,

c) Uncertainty analysis - methods for comparing the importance in input uncertainties in terms of their relative contribution to uncertainties in outputs.

Sensitivity analysis is most useful in the first instance by identifying those parameters/variables which contribute to the lion's share of uncertainty in the model result and therefore warrant further analysis. In this context it is important to be able to judge what is significant and what is negligible when dealing with uncertainty in risk assessment, since the blind pursuit of accuracy for its own sake may squander resources better spent in a more selective manner, (The Royal Society 1983).

Table 4.1 provides a summary of some types of uncertainty that may be encountered during a ballast water management risk assessment, together with some of the techniques available to address these.

The question of uncertainty is intimately linked to that of complexity. The cycle of introduction and establishment of non-indigenous organisms associated with ballast water discharges is undeniably complex. Addressing this issue (and the costs associated with controlling it) in a single analysis is therefore likely to result in potential variations in the analysis results, as uncertainty in individual elements are combined in the overall system. The results of a recent bio-economic risk assessment of ballast water introductions provides a good example of this phenomena; in attempting to quantify the risks associated with toxic dinoflagellate introductions across Australia, and the costs to the nation as a whole of treatment strategies (as opposed to no treatment), the analysis provides a point estimate for the cost of no treatment as $78 million although acknowledges that "a plausible range, taking into account sensitivities, would be from a negligible cost through to well over a hundred million dollars" (AQIS 1994) - a difficult basis from which to make a risk -benefit decision.

Complex problems, however, are often decomposable into subsystems with a hierarchical structure (Morgan & Henrion 1990). Careful ring fencing of an analysis, defining those interactions within a subsystem that are of interest to the objective and those that can be ignored for the purposes of the analysis, allows the decomposition of a complex system into more manageable parts. By minimizing the uncertainty within each of the individual parts the analyst may be able to avoid results which, due to massive uncertainty, are effectively useless as decision aids.

Assessing the risks associated with ballast water introductions and control strategies is therefore best tackled in a piecemeal, but strategic, fashion, minimizing uncertainty in individual studies that contribute to the overall view.

5 CONCLUSIONS

Environmental improvement strategies are often implemented under the auspices of cost benefit or risk benefit assessments. If we accept this approach for ballast water control strategies (as opposed to the zero risk tolerance approach) then quantified risk assessment provides a means of establishing the cost utility of individual or combined control options. This cost utility is expressed as the probability of strategy failure multiplied by the cost of implementing the control strategy.

Ballast water management exhibits an important asymmetry in that the introduction of control strategies ensures higher shipping costs for a probable reduction in environmental risk (AQIS 1994). Determining cost utility within a probabilistic quantified risk assessment framework is therefore an appropriate approach.

Furthermore ballast water introduction risk assessment exhibits a curious mixture of ecological and more traditional risk analysis problems; the population dynamics and establishment of a non-indigenous species entails the stochastic complexity of biological modeling but within a mesocosm like environment whose variables are relatively well defined and uniform. The "mesocosm" nature

Table 4.1 Uncertainty analysis summary - Ballast water management strategy risk assessment

Assessment parameter	Characteristic	Biocide treatment risk assessment example	Methods for reducing uncertainty
Empirical quantity	Measurable (at least in principle) property of real world systems	Majority of the parameters in the biocide treatment risk assessment will be empirical. For example birth/death rates, predation coefficients, PEC's, LC_{100}, diffusivity coefficients, etc...	Simple analytical techniques where the number of variables is low. For example discrete probability distributions, scenario trees, first order Gaussian approximation. Where the number of variables is high; Monte Carlo simulation sampling from n dimensional space defined by ranges in n uncertain parameters.
Index variable (independent variable)	Identifies a location or cell in the spatial or temporal domain	Geographical extent of analysis, journey times, ports of ballast/deballast.	Careful ring fencing of analysis. It does not make sense to be uncertain about index variables.
Model domain parameter	Domain or scope of the system being modeled generally defined by the range and increments for index variables.	Discrete versus continuos population models, time increments within discrete models, granularity or resolution of spatial index, a priori limits to physical/biological parameters	Chosen as a balance between ensuring the model deals adequately with the full range of the system of interest and computational costs. No "true" value but can be uncertain about appropriate value. A prior truncation of biological parameters can be drawn from empirical evidence.
Value parameter	Aspects of the preferences of decision makers or the people they represent	Acceptability of failure probability, zero tolerance versus risk benefit assessment, BATNEEC decisions.	Again no "true" value. Switchover techniques allow explicit analysis of when and why decision change. ALARP principle for acceptable/unacceptable risk (assuming acceptance criteria defined). Catalogue of decisions currently made to create market value.

(adapted after Morgan & Henrion 1990).

of the ballast tank environment reduces uncertainty in a number of assessment parameters, making it more amenable to quantified analysis.

There are a number of points within the ballast/deballast procedure where the cycle of introduction can be interrupted. The significance of the probability of failure of control strategies at different stages in the cycle, however, are not equal when viewed in light of the overall objective of any management strategy; the prevention of the introduction of non-indigenous species. The cost utility function described above can only be compared across control option acting at the same point within the ballast cycle unless some allowance is subsequently made for the probability of organisms progressing through the chain becoming established as alien species.

In this context, conservation risk assessment techniques can further contribute to the evaluation that a given population size, surviving a particular control strategy, will progress to extinction or not. Two conclusions are evident from these considerations:

a) that a given control strategy need not necessarily eliminate all organisms to ensure that the surviving population does not establish itself; and,

b) the most cost effective control strategies may prove to be those which entail combinations of control options, working in harmony with the ballast/deballast cycle, to drive inoculum populations to extinction.

Quantified ecological risk assessment provides a means by which to investigate and quantify the extent of control strategy elimination, the likelihood of surviving population establishment and the efficacy of combined control options.

The ballast water introduction cycle is undoubtedly complex. Decomposing this cycle into its component parts, however, provides manageable risk assessment units. By focusing on the components parts of the cycle the assessor is able to reduce a complex procedure into clearly defined subsystems, as exemplified by the nested endpoint approach for a ballast water risk assessment. This encourages precision in assessment results and helps avoid very large uncertainties which may effectively render the assessment useless as a decision aid.

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Appendix A; Ballast Water & Sediment Management Options, (after Carlton *et al* 1994)

I ON OR BEFORE DEPARTURE FROM PORT-OF-BALLAST WATER ORIGIN

Water Supply Uptake

1. Specialized shore facility provides treated salt or fresh water
2. Port provides city fresh water

Prevention of Organism Intake: Ballasting Management

3. Site: Do not ballast in "global hot spots"
4. Site: Do not ballast with high sediment loads
5. Site: Do not ballast water in areas of sewerage discharge or known disease incidences
6. Site/time: Do not ballast at certain sites at certain times
7. Site/time: Do not ballast at night

Prevention of Organism Intake: Mechanical

8. Filtration

Extermination of Organisms Upon Ballasting (Ballast Treatment)

9. Mechanical agitation
   a) water velocity
   b) water agitation mechanism
10. Altering water salinity
    a) add fresh water to salt
    b) add salt water to fresh
11. Optical: ultraviolet treatment
12. Acoustics (sonic): ultrasonic treatment

II ON DEPARTURE AND/OR WHILE UNDERWAY (EN ROUTE)

Extermination of organisms after ballasting (while at port-of-origin or while underway, but before arrival at destination port).

Active Disinfection (Ballast Treatment)

13. Tank wall coatings
14. Chemical biocides
15. Ozonation
16. Thermal treatment
17. Electrical treatment (including microwave)
18. Oxygen deprivation
19. Filtration/ultraviolet/ultrasonic underway
20. Altering water salinity; partial exchange

Passive Disinfection

21. Increase length of voyage
22. Exchange (deballast/reballast)
23. Sediment removal and at sea disposal

Deballast only

24. Deballast/No reballasting

III BACK UP ZONES

25. Exchange or deballast

IV ON ARRIVAL AT BALLAST DISCHARGE PORT

Water Supply: Discharge

26. Shore facility receives treated and untreated water

Prevention of Discharge to Environment

27. Discharge to existing sewage treatment facilities
28. Discharge to reception vessel
29. Sediment removal and onshore disposal
30. *In situ* extermination of organisms upon arrival (options 8, 11, 14)

Non Discharge

31. Non discharge of ballast water

V RETURN TO SEA: EXCHANGE WATER

32. Vessel returns to sea and undertakes exchange