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RISK ASSESSMENT FRAMEWORK FOR BALLAST WATER INTRODUCTIONS

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ABSTRACT

This report describes a quantitative risk assessment framework for ballast water introductions. The framework has been developed to help meet the objectives of the national Ballast Water Management Strategy, established by the Australian Quarantine and Inspection Service (AQIS) in 1995.

The risk assessment framework is modelled on the internationally endorsed, import risk assessment framework, and the Quantitative Risk Assessment (QRA) paradigm. The risk analysis component of the framework consists of five modules that deal with discrete elements of the ballast water introduction cycle, up to the point of introduction and survival of a non-native species in a new port (the assessment endpoint).

The framework is species and vessel specific. In the first instance it will be applied to a target list of marine pests, whose introduction or spread in Australian waters is to be avoided. Species-specific assessments of this kind are appropriate for quarantine purposes, and are the only effective way to approach ballast water risks.

The framework allows an assessment of ballast water risk to be made at several levels of complexity, depending on the availability of data. At its simplest level the framework provides a qualitative hazard ranking scheme that will allow AQIS to allocate its vessel sampling resources in the most cost effective manner.

At its most complex level the framework estimates the likelihood that a particular vessel is contaminated with a target species, and the probability that these organisms will survive if discharged into a port. The framework can therefore be used to assess the benefits of alternative ballast water management schemes.

The framework identifies the conditions under which a vessel's ballast water becomes contaminated with target species. This will allow a pro-active response to the marine pest hazard in individual ports in order to minimise the likelihood of vessel infection.

ACKNOWLEDGMENTS

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CONTENTS

1 INTRODUCTION

1.1 Project background

In 1995 the Australian Quarantine and Inspection Service (AQIS) established a national Ballast Water Management Strategy. The strategy's objectives are:

> '*to avoid the adverse economic and environmental impacts of unwanted aquatic marine organisms by minimising their risk of entry, establishment and spread in the Australian marine environment from ballast water and other shipping activities involving international and domestic shipping, whilst not unduly impeding trade*' (Paterson, 1995).

In the same year AQIS convened a non-statutory Australian Ballast Water Management Advisory Council to oversee the administration of the strategy (Bonny, 1995). The council is supported in its activities by a Research Advisory Group (RAG), whose role is to recommend research needs to meet the objectives of the management strategy. The RAG has recommended that AQIS support a number of research projects, including the development of a decision support system built around a quantitative risk assessment framework for ballast water introductions.

In September 1996, the CSIRO's Centre for Research on Introduced Marine Pests (CRIMP) successfully tendered for the risk assessment project, with two objectives: to undertake a literature review of ecological risk assessment methods, and to subsequently develop a framework for quantitative ballast water risk assessment.

Work on the literature review started in December. The review was completed in April 1997 and has been published as a CRIMP technical report (Hayes, 1997). Work on the risk assessment framework started in May, following the recommendations made in the review.

This report provides a blue-print of the risk assessment framework that has been developed, detailing its structure, approach and data requirements. This report, together with the review of ecological risk assessment methods, fulfils the requirements of the first year of the project contract.

1.2 The framework's objectives

The risk assessment framework aims to provide:

1. a vessel screening tool to scientifically prioritise AQIS sampling protocols;
2. a risk-benefit analysis tool for ballast water management strategies;
3. a predictive risk assessment tool that may allow the shipping industry to pro-actively alter its shipping and/or ballasting operations in order to minimise the risk of introducing, or spreading, non-indigenous marine organisms in Australian waters.

Without a formal risk assessment procedure, AQIS must view every vessel arriving and deballasting in Australian ports as being potentially contaminated with non-indigenous marine pests. AQIS does not have the resources to sample the ballast water of every vessel arriving in Australia. Therefore the framework's first objective is to provide a hazard identification procedure which will allow a qualitative hazard ranking of vessels in relation to targeted pest species. This is designed to assist in the allocation of vessel sampling resources, in particular identifying those vessels that are highly hazardous for a more thorough evaluation.

In order to meet the objectives of the ballast water management strategy, AQIS must identify the most cost effective option for individual vessels and target species, whilst at the same time minimising restrictions imposed on shipping. There are, however, at least thirty-two management options (detailed in Appendix A) available to prevent the introduction of marine organisms through ballast water discharges. Some of these options are mutually exclusive, but combinations of those that are not allow many more strategies to be applied in any given situation. No single strategy will be the most cost effective at killing or removing non-native organisms from the ballast water of all vessels, at all ports of arrival and departure.

The framework's second objective is to provide a quantified metric of introduction risk so that the efficacy of alternative management strategies can be compared, and the subsequent costs and benefits measured. The use of risk assessment to underpin quarantine policies and procedures in this manner, is in accordance with the recommendations made by the Australian Quarantine Review Secretariat (Nairn *et al*, 1996).

The framework's third objective is to identify the conditions under which a vessel's ballast water becomes contaminated with marine pests in specific (infected) ports. This will allow the shipping industry to review its operations, and modify its practises in these ports, in order to minimise the risk of vessel contamination. This objective recognises that the most cost effective ballast water management strategies will arise where the shipping industry is able to pro-actively respond to the marine pest hazard at individual ports.

1.3 Terms of reference

Transport vectors

Carlton *et al* (1995) identify nineteen separate transport vectors associated with shipping. Figure 1.1 summarises those that might be associated with a typical bulk carrier. The relative importance of these vectors has not been determined, but the two most significant are thought to be:

1. ballast water and ballast sediments - the transportation of organisms in the water and sediments of ballasted tanks and holds;

2. organisms on vessel exteriors, and in vessel interiors with exterior connections - the transportation of fouling and nestling organisms attached to vessel hulls, rudders, and propellers, and in sea chests and seawater pipe systems.

The risk assessment framework is concerned with ballast water and sediment discharges, and does not currently cater for fouling or nestling organisms, or any of the over transport vectors associated with commercial or recreational shipping.

Risk management standard

The risk assessment framework conforms to the joint Australian/New Zealand risk management standard 4360. This standard defines risk management as:

> '*the systematic application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, treating and monitoring risk*' (Standards Australia, 1995).

The risk management process, and the role of risk assessment within this, are illustrated in Figure 1.2. The terms of reference for this project include the following components of this process:

1. Decide the structure - define a logical framework for identification and analysis to ensure that significant risks are not overlooked;

2. Identify risks - identify what can happen, and how and why it happens;

3. Analyse risks - determine the likelihood of events occurring and the magnitude of their consequences.

The risk assessment framework does not develop acceptance criteria, assess risk against these criteria nor consider risk treatment plans (refer to Figure 1.2). Furthermore the framework does not identify the existing management and technical systems to control risk. A comprehensive list of ballast water management options, however, is provided in Appendix A. It is anticipated that the framework will identify procedures to control risk and indeed this forms part of the framework's objectives (refer to section 1.2).

Figure 1.1 Potential transport vectors associated with a typical bulk carrier

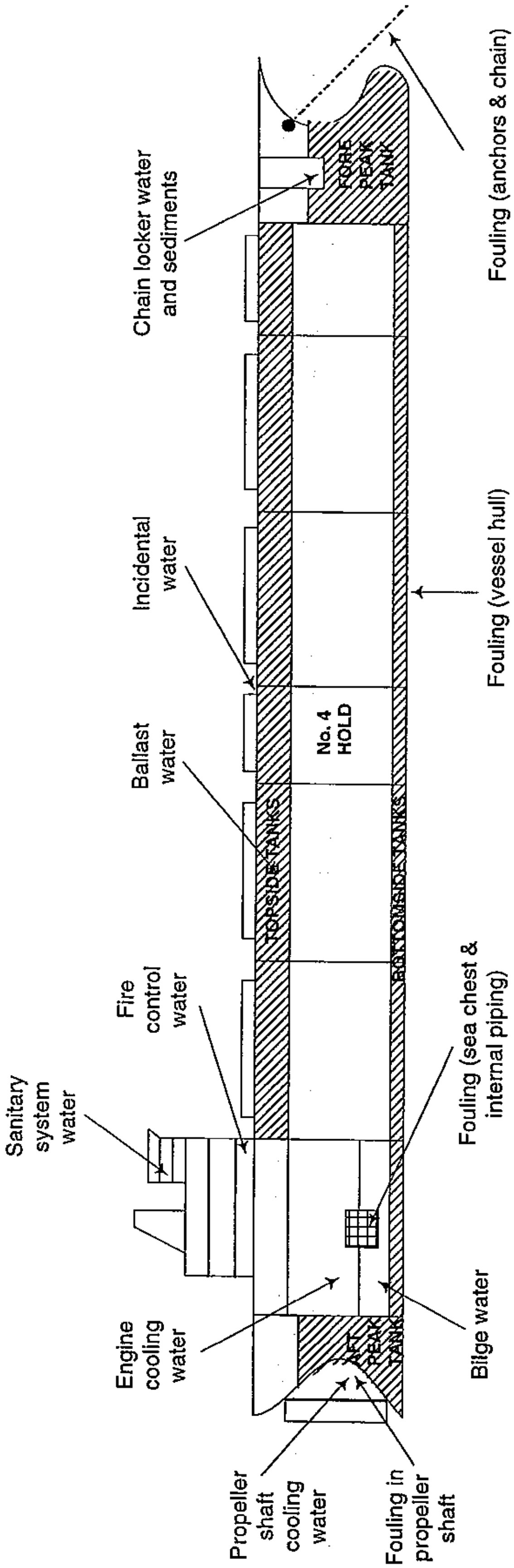
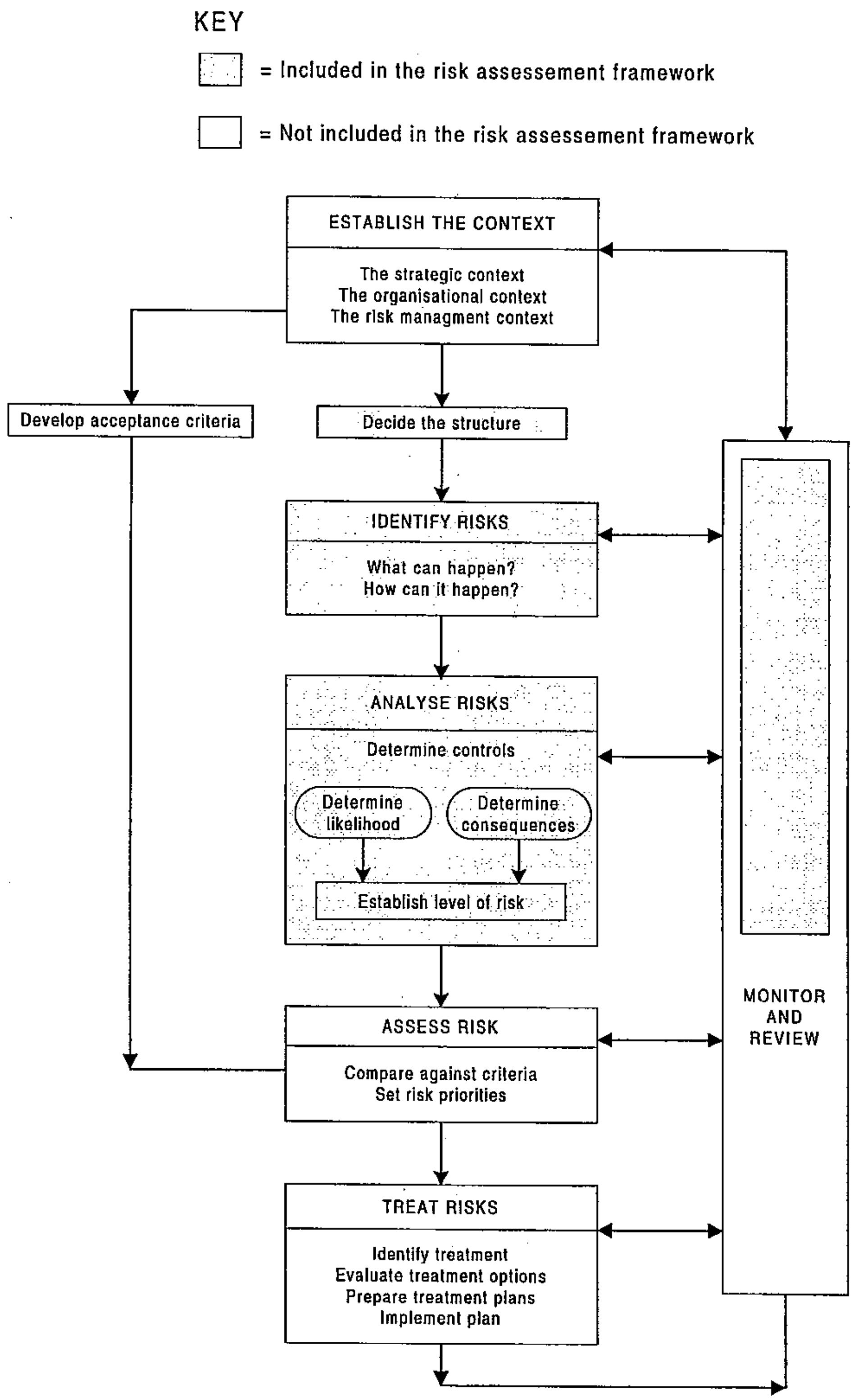


Figure 1.2 Risk assessment and the risk management process



(Source; adapted from Standards Australia, 1995)

Port infection scenarios

Once a non-indigenous marine pest has been introduced into a port environment, it can spread to uninfected ports in one of four ways (Hewitt & Martin, 1996):

1. directly from overseas ports by international shipping;

2. indirectly as a result of the translocation by shipping from the port of first entry;

3. indirectly as a result of translocation by some non-shipping activity from the port of first entry or secondarily infected area;

4. by natural range expansions from the port of first entry or secondarily infested area.

The risk assessment framework provides for the first two but the not the last two. The potential for non-shipping related infections emphasises the need to continually monitor ports. The implementation of the risk assessment framework will require that all Australian ports are regularly monitored to check their pest infection status.

1.4 The structure of the report

This report is divided into three volumes:

1. Volume I (this document) provides a summary description of the risk assessment framework, including its approach, the risk analysis modules and their data requirements;

2. Volume II provides a detailed account of the risk analysis modules and the inductive hazard identification procedure (HAZOP) introduced in Volume I;

3. Volume III contains a critical evaluation of Bayesian statistical inference and its potential application to ballast water risk assessment.

Chapter 2 of this document provides a definition of ballast water risk and outlines the risk assessment procedure. This chapter examines the problems associated with 'environmental match' risk assessments, and justifies the species-specific approach adopted for this assessment framework.

Chapter 3 uses fault trees to examine ballast water hazards. The objective of this chapter is to ensure that no significant introduction hazards are overlooked by the framework. Hazard identification is the most critical component of any risk assessment. Hazards that are not identified in the preliminary stages of an assessment will not be addressed, leading ultimately to an underestimate of risk.

Chapter 4 summarises the six levels of analysis that can be achieved by combining different components of the risk analysis modules. This chapter includes a brief description of the objectives, analysis and data needs at each level of assessment. Each of the chapter's sections concludes with an illustration of the benefits obtained by completing the assessment to each level (through the use of a hypothetical case study).

Chapter 5 characterises the types of uncertainty within the risk assessment framework, and includes a brief description of how this uncertainty will be dealt. This chapter also introduces the Bayesian statistical techniques which are discussed in a more detail in Volume III.

Chapter 6 provides some concluding remarks and recommendations. A brief discussion of some practical issues associated with the implementation of the framework is included here, most notably the extent to which the assessment must be progressed for individual ports and species, and at what point in a vessel's journey the assessment should be undertaken.

Five appendices (A to E) are included with this volume. The first describes ballast water and sediment management options, the second details the current target pest list, and the third describes the types of organisms that could be ballasted into a vessel. The fourth explains the event symbols used in the fault trees of Chapter 3, whilst the last provides a key to the data identifiers used through-out Chapter 4.

2 BALLAST WATER RISK ASSESSMENT

2.1 Defining ballast water risk

Risk is a difficult concept to define, particularly from an ecological perspective. In an engineering context, risk is understood in terms of the following relationship

$$Risk = \frac{Event}{Time} \times \frac{Consequences}{Event} = \frac{Consequences}{Time}$$

leading to risk functions that describe accidental events in terms of the frequency of consequences. The consequences in this approach usually refer to human injuries or fatalities (the risk assessment endpoints). The output of an engineering risk assessment would thus express the risk of some activity as 0.01 fatalities per annum, or a 1 in 100 chance of dying each year due to the activity in question.

This approach to risk is encapsulated in the five stage procedure of Quantitative Risk Assessment (QRA):

1. Hazard identification - what can go wrong (identify the events) and why;
2. Frequency analysis - how often do things go wrong (events/time);
3. Consequence analysis - how much harm is caused by the event (consequences/event);
4. Risk calculation - frequency x consequence;
5. Uncertainty and significance analysis - how sure are we of the risk estimate and how important is this level of risk.

Hayes (1997, 1998) suggests that QRA provides a useful approach to ballast water risk assessment but notes some difficulties with the interpretation of risk in this context. In particular the choice of assessment endpoint is critical. Ideally ballast water risks would be expressed as finite probabilities of environmental or economic harm, which occur because of the introduction and establishment of non-native species, through the discharge of contaminated ballast water or sediment. This approach, however, requires the analyst to predict the environmental or economic effects of establishment, and then to quantify the magnitude of these effects. This is too difficult given our current understanding of ballast mediated invasions.

Kaplan (1997) adopts a more flexible approach by emphasising that risk is defined not as a number, a curve, or a vector, but by three questions: What can happen? How likely is that to happen? If it does happen, what are the consequences? The answer to these questions constitutes a triplet $[S_i, L_i, X_i]$ where S_i denotes individual risk scenarios, L_i denotes the likelihood of the ith scenario and X_i the consequences of this scenario.

Uncertainty regarding the likelihood of risk scenarios, together with uncertainty regarding the type or magnitude of their consequences, means that these components should be expressed in probabilistic terms, denoted $[S_i, p(\varphi_i), p(X_i)]$. The definition of risk is completed by identifying the complete set of possible risk scenarios such that:

$$Risk = \{\langle S_i, p(\varphi_i), p(X_i)\rangle\}_c$$

This approach encourages a broader interpretation of risk and is therefore better suited to ecological risk assessment, where the events in question may not be 'accidental' in any sense, nor the endpoints restricted to human fatality or injury.

The endpoint selected for this risk assessment framework is:

> *The introduction of a non-native organism into (an uncontaminated) port whose environment satisfies the bio-requirements of the organism at the time of introduction.*

This endpoint has been chosen because it provides a simple, clear and (importantly) verifiable risk metric that avoids the more complex expression of the likelihood of establishment and adverse environmental or economic impact. For species which are *a priori* classified as marine pests, and therefore undesirable, this endpoint is also a suitable basis for risk-benefit analysis.

With this endpoint, ballast water risk assessment can be expressed by the following triplet:

1. pest entrainment scenarios S_i - the various processes by which a vessel's ballast water becomes contaminated with each of the life stages of a particular non-native species in a given donor port[2];

2. the likelihood or probability of contamination, $p(\varphi_i)$, for each of these scenarios, on any given ballasting event;

3. the probability that the species concerned will survive, $p(X_i)$, upon discharge in the receiving port environment.

Since pest entrainment scenarios are mutually exclusive, ballast water risk can now be defined:

$$Risk_{species} = \sum_{r=1}^{m}\sum_{i=1}^{n}\left[p(\varphi_i).p(X_i)\right]$$

for the life stages (r = 1 to m) of a particular species, under entrainment scenarios i = 1 to n .

To implement this approach the probability of survival must be expressed with reference to some time period. This should be chosen with care because the probability of vessel contamination in the donor port is dependant on this period[3]; the shorter the reference period the 'safer' the assessment. We recommend that this period be no greater than 24 hours.

[2] Donor port refers to the port from which the vessel draws its ballast water. Recipient port refers to the port in which this water is discharged.

[3] Refer to the third party infection scenario identified in Chapter 3.

2.2 The framework's structure

Hayes (1997) recommended that a ballast water risk assessment framework be based on the import risk assessment framework and the Quantitative Risk Assessment (QRA) paradigm. Import risk assessments view the risk of pest introduction as the culmination of a long chain of events, and have obvious parallels with the ballast water introduction cycle (Figure 2.1). QRA provides a logical and systematic framework for risk assessment, including structured hazard identification and assessment techniques.

The risk assessment framework that has been developed in response to these recommendations is illustrated in Figure 2.2. The risk analysis component of the framework consists of a series of modules that deal with discrete elements of the introduction cycle, up to the point of introduction and survival in the new environment (refer to Figure 2.1).

This approach assists with the management and implementation of the framework, provides the most effective manner for its further development, and also maintains flexibility, allowing different components to run at various resolutions depending on the availability of data. In this manner the assessment can be tailored to the available data for any given vessel/route combination. Figures 2.3 and 2.4 illustrate how different levels of assessment are achieved by combining different components of the individual modules.

The framework allows for a more accurate assessment of risk as requisite data needs are met. In practical terms this means that as the data available to the framework increases, fewer vessels will be targeted by the assessment as posing a risk.

In the first instance, with a minimal data requirement, the framework provides a set of simple decision criteria to allocate limited sampling resources. Further data allows a qualitative assessment of the relative hazards posed by vessels entering Australian ports. Importantly, however, a quantitative expression of introduction risk is not possible until a certain data threshold has been crossed (level 3).

The framework is species and vessel specific, and in the first instance will be applied to a target list of species (Appendix B). These species are marine pests whose introduction or translocation in Australian waters is to be avoided. The target list provides an important focus for the assessment during its initial development and implementation. The framework is not, however, restricted in its application to these species, but rather has been designed so that the ballast water introduction risk associated with any species can be assessed.

Ultimately the framework aims to determine the probability density function for the population of target organisms released into a recipient port. This provides a suitable platform from which to extend the risk assessment endpoint to the likelihood of environmental or economic harm, at some appropriate time in the future. This goal is ambitious, however, and the project does not anticipate meeting it until confidence has been established in the current framework.

Figure 2.1 The ballast water introduction cycle

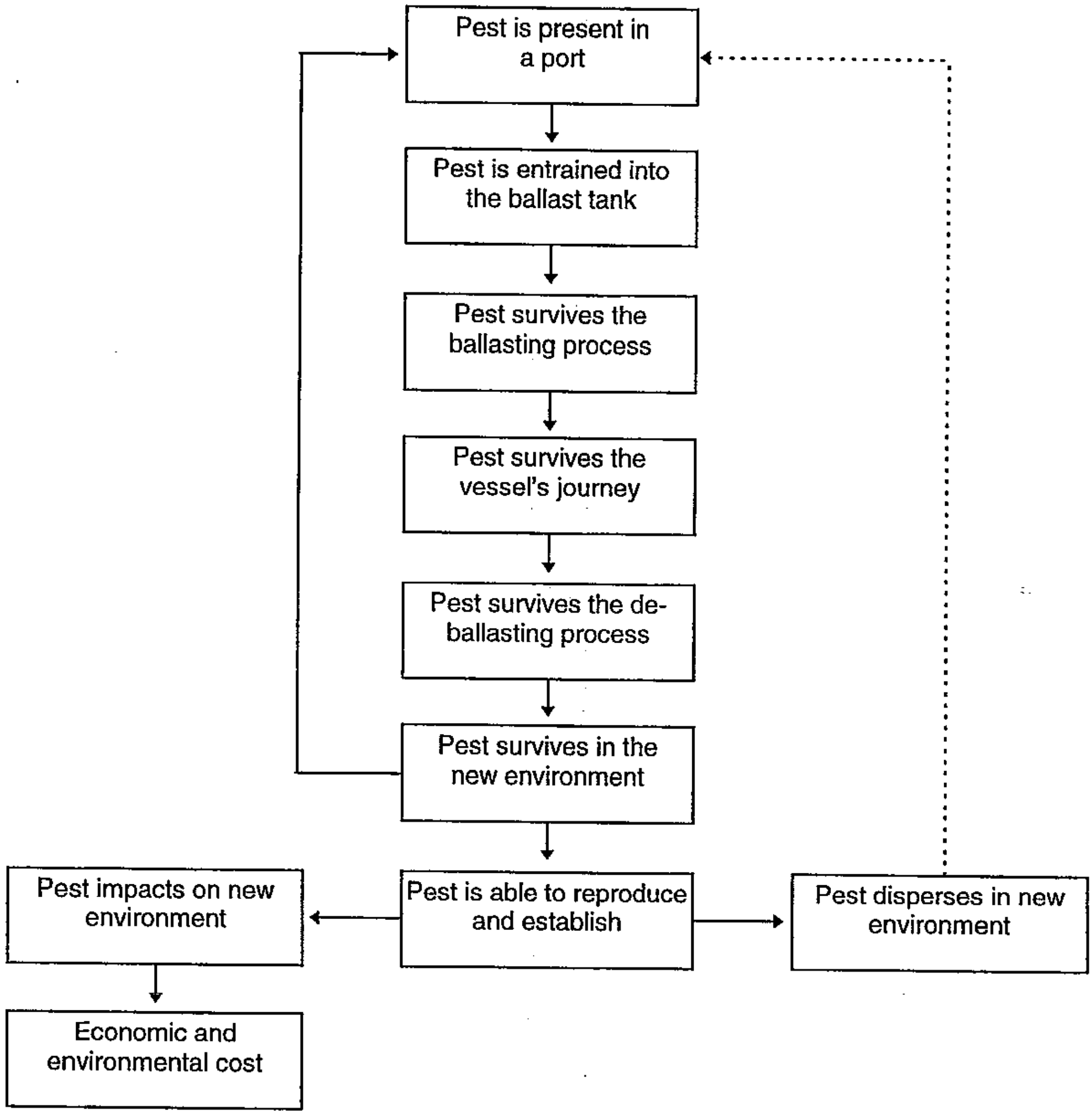
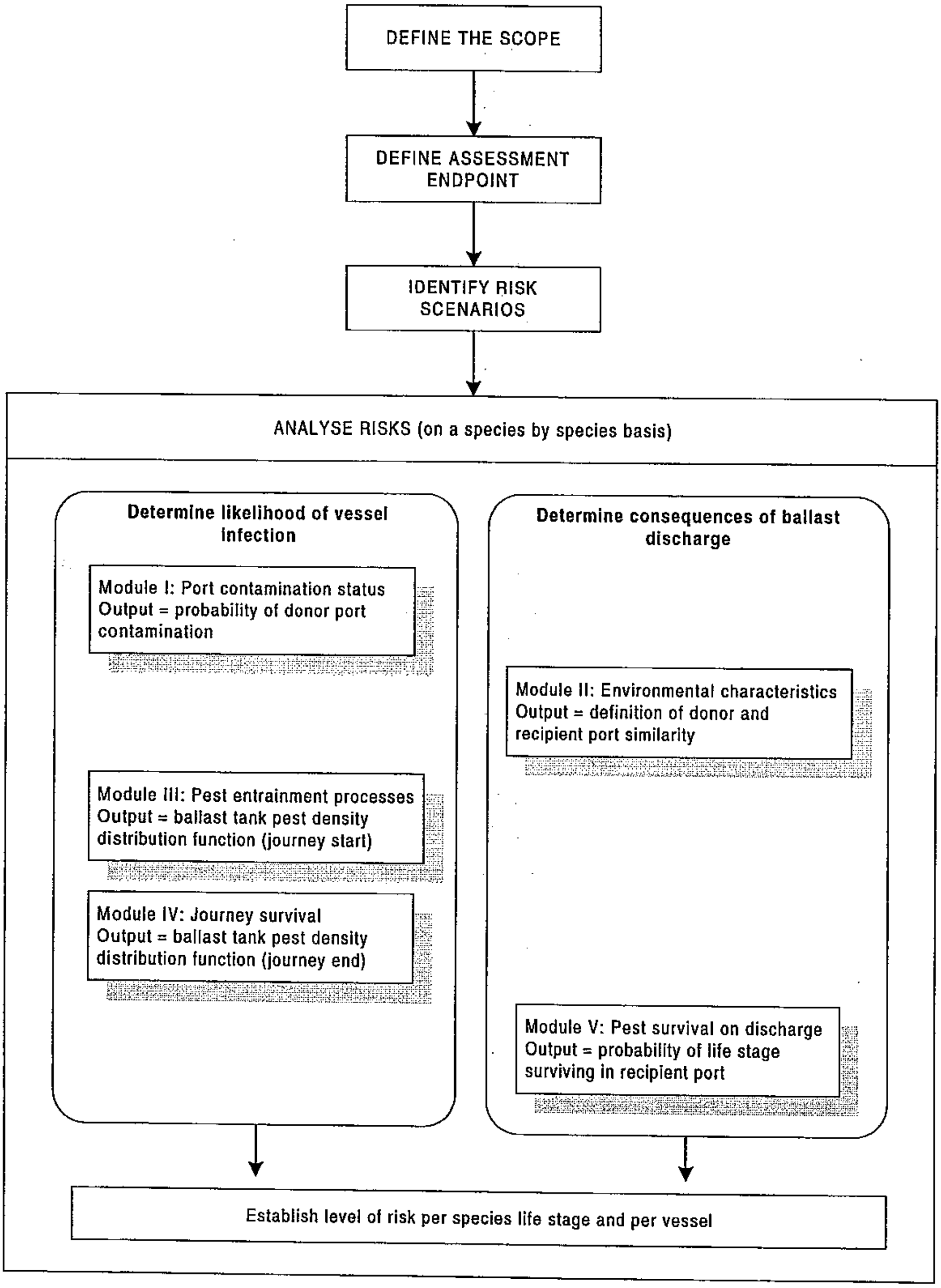


Figure 2.2 The ballast water risk assessment framework



As it currently stands the risk assessment framework includes:

1. an assessment of the donor port's infection status with respect to target species;

2. an evaluation of pest entrainment processes which considers the ways in which target species become entrained in ballast water, and seeks to determine the spatial and temporal determinants of the pest source;

3. an assessment of the journey survival rates which describes mortality (or growth) rates of ballast tank populations in order to establish the vessel infection period;

4. an environmental tolerance test to determine whether or not the specific species life-stage that is translocated can survive in the recipient port environment.

To extend the assessment endpoint to the likelihood of adverse economic or environmental impact would require additional analysis, including:

5. an investigation of pest discharge processes to determine the dilution and dispersal of pest species when discharged into the recipient port;

6. an estimate of the likelihood of establishment within a stochastically varying port environment;

7. an assessment of native community susceptibility, possibly linked to port management practices, and the extent to which these influence the likelihood of invasion success;

8. a quantitative impact assessment, expressed in terms of pre-selected economic and environmental endpoints.

Furthermore the extension of the assessment endpoint in this manner requires that the environmental tolerance test undertaken in module V is modified to test the reproductive suitability of the recipient port environment for the species concerned, together with the influence of phenological variables for the onset of spawning and development.[4]

The extension of the assessment to include an estimate of the likelihood of establishment and subsequent impact is unlikely to be successful unless the previous modules have been undertaken in the most complete manner specified within the framework (level 5).

[4] This is because the environmental conditions required for species survival are generally broader than the conditions required for successful reproduction (Gilchrist, 1995). Furthermore reproduction may require the (co)occurrence of one or more cues such as light or temperature.

Figure 2.3 Modular implementation for level Ø assessment

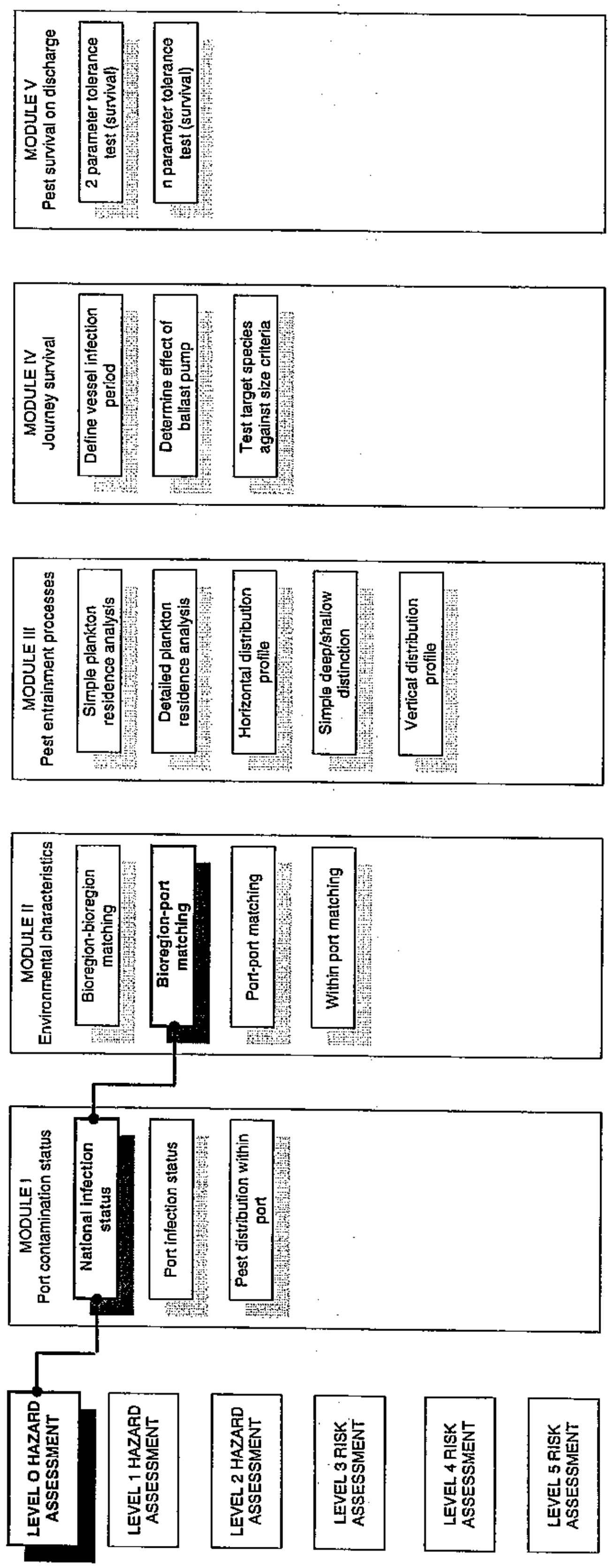
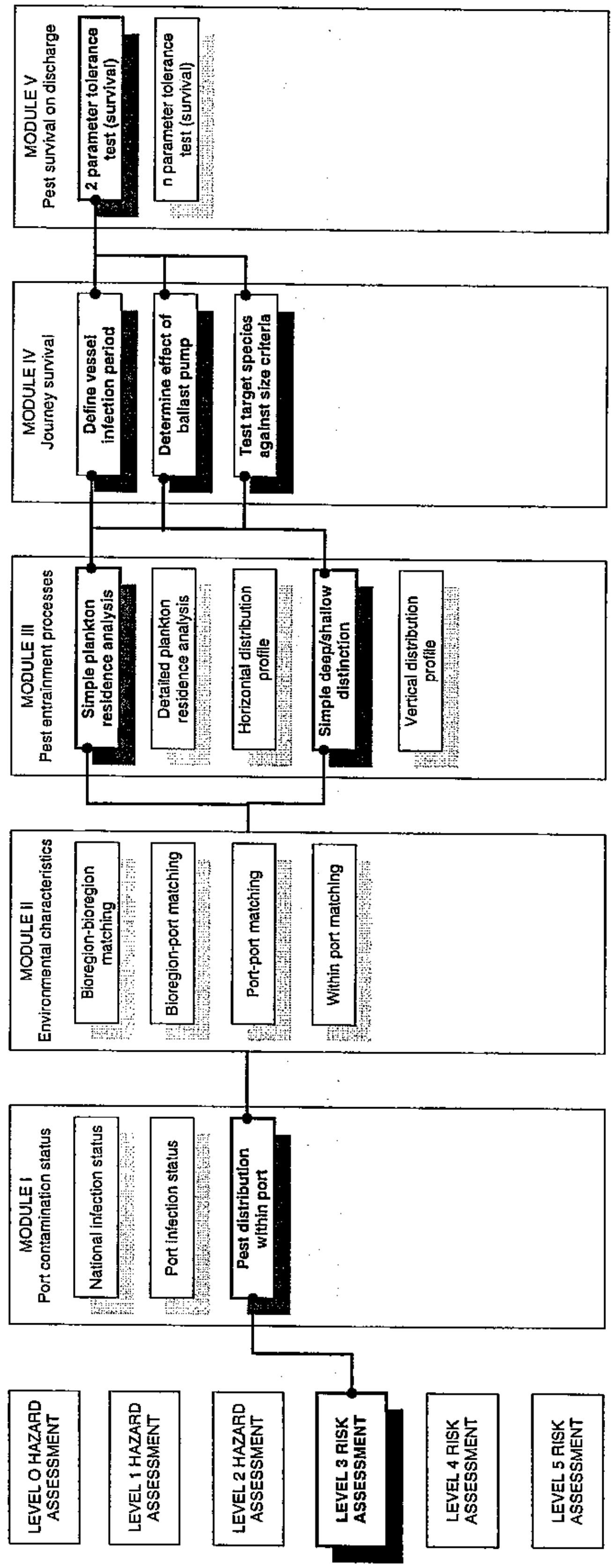


Figure 2.4 Modular implementation for level 3 assessment



2.3 Why a species-specific approach ?

Carlton *et al* (1995) suggest that ballast water and sediment management strategies should seek to emulate the basic philosophy of quarantine science and prevent the introduction of all non-native organisms. The definition of ballast water risk adopted for this framework, however, involves a species-specific assessment which does not protect against all non-native organisms.

Species-specific assessment have been criticised because it is impossible to predict which, if any, of the species resident in a donor port will establish pest-like populations if introduced into a new recipient port. This has led some agencies to recommend that ballast water risk assessment be based upon the environmental similarity between donor and recipient ports (see for example ICES, 1996 and Hilliard & Raaymakers, 1997). The assumption here is that if the donor and recipient ports have similar environmental characteristics, then species which inhabit one could inhabit the other.

In response we offer the following arguments:

1. ballast water risk assessments made solely on the basis of environmental matching are not effective management tools;

2. species-specific methods are appropriate for quarantine purposes, as evidenced by the import risk assessment framework used by AQIS and other equivalent quarantine agencies;

3. careful selection of the species assessed can protect for a wider set of organisms.

Ballast water risk assessment, as with any quarantine management system, acts only as a filter not as a barrier. Invasions will continue to occur no matter what type of ballast management system is put in place, now or in the future (Carlton *et al,* 1995). Environmental match risk assessments, however, are a far less effective filter for at least four reasons.

First any measure of environmental match is meaningless if a species' hypothetical distribution is wider than its realised distribution. In other words it is impossible to define whether an environment is suitable for a species in the absence of information regarding the species' environmental tolerances. However, as soon as the analyst selects a species for this purpose, he or she immediately adopts a species-specific approach.

Problems also arise in relation to the scale at which the match is made. Micro-environments within harbours are common. The discharge of power station cooling water for example may raise the water temperature in distinct areas of a port. These areas are then capable of supporting species which would not otherwise survive (Carlton, 1992).

More difficulties occur due to carry-over of ballast water between ports. In a study of American shipping patterns, Carlton *et al* (1995) note that the vessel's last port of call (LPOC) is a poor predictor of ballast source: 53% of all vessels surveyed in the study contained ballast water which did not originate from the LPOC. This figure rose to 66% for container vessels. It is difficulty to see how risk assessments based on environmental matching would address this problem without addressing the question of journey survivorship, which again is species dependant (see for example Murphy, 1997 or Wonham *et al*, 1996).

Finally the environmental match approach leaves no scope for improvement upon the inevitable discovery of a new introduction. Indeed it can only become more conservative with time, leading to a greater cost to the shipping industry as more vessels are targeted as posing a hazard (see Figure 2.5). By contrast the species-specific approach becomes more accurate if newly discovered introductions are added to the assessment list. In some cases this may lead to more vessels being identified as potentially hazardous but this is not necessarily so, as illustrated by Figure 2.6.

The internationally endorsed framework for quarantine or import risk assessment forms section 1.4 of the International Animal Health Code (Office International des Epizooties OIE, 1996)[5]. The purpose of the framework is to provide an objective and defensible method of assessing the disease risks associated with animal and animal product imports. The framework is generic (individual countries are required to design and adopt their own methodologies around it) but undeniably species-specific.

Quantitative import risk assessments (based on the quarantine framework) model the transmission of disease agents as the conclusion of a series of steps to which probabilities can be assigned (Kellar 1993, Morley 1993, MacDiarmid 1993, 1994). An assessment is normally instigated when a new transmission vector is identified, for example a request for a new import, or upon the identification of a new or more potent disease agent.

This model is analogous to the ballast water introduction cycle (Figure 2.1), suggesting that species-specific risk assessments are appropriate for ballast quarantine purposes. Ballast water risk assessments would also be instigated in the same manner: either upon identification of a new transmission vector, such as new trade route or newly infected donor port; or upon identification of a newly discovered non-native species.

Species-specific risk assessments could also protect against more organisms if the species selected for assessment was in some manner representative of a wider set. The philosophy behind this approach is illustrated by Orr R. L. (1993): As part of this study the analysis team compiled lists of insects and micro-organisms known to be associated with Monterey pines in Chile. From these lists, insects and pathogens having the greatest potential as pests in the United States were selected for subsequent inclusion in a pest risk assessment. Individual risk assessments could not be completed for each these potential pest species, however, because of a lack of basic biological data. Recognising this uncertainty, the assessment team focussed on those species for which good biological data was available in the hope that the mitigative measures developed as a result of the assessment would be equally effective for all other species that occupy the same niche on the imported logs.

In a similar way it seems likely that mitigative measures developed for target pests would be equally as effective for other species which exhibited identical entrainment scenarios or similar journey/environmental tolerances. The logical corollary is to include species on the target list that are representative of each of the entrainment scenarios, selecting those that are hardy, and consider these are indicator species for a much wider set. For example the cysts of a given dinoflagellate species could be considered as indicative of all cysts that have a similar or shorter dormancy period.

[5] Refer to Hayes (1997) for a more extensive review of the import risk assessment framework

Figure 2.5 Implementing an environmental match risk assessment

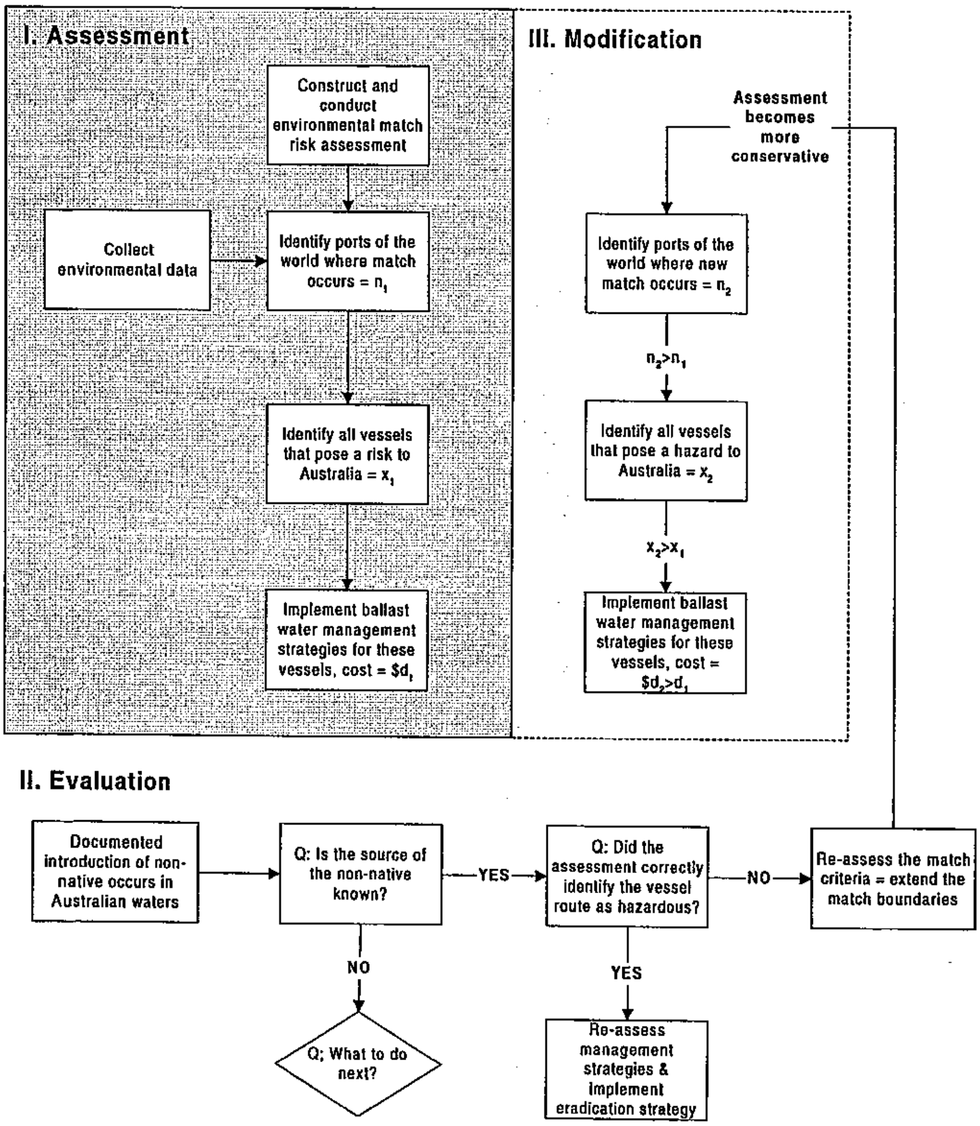
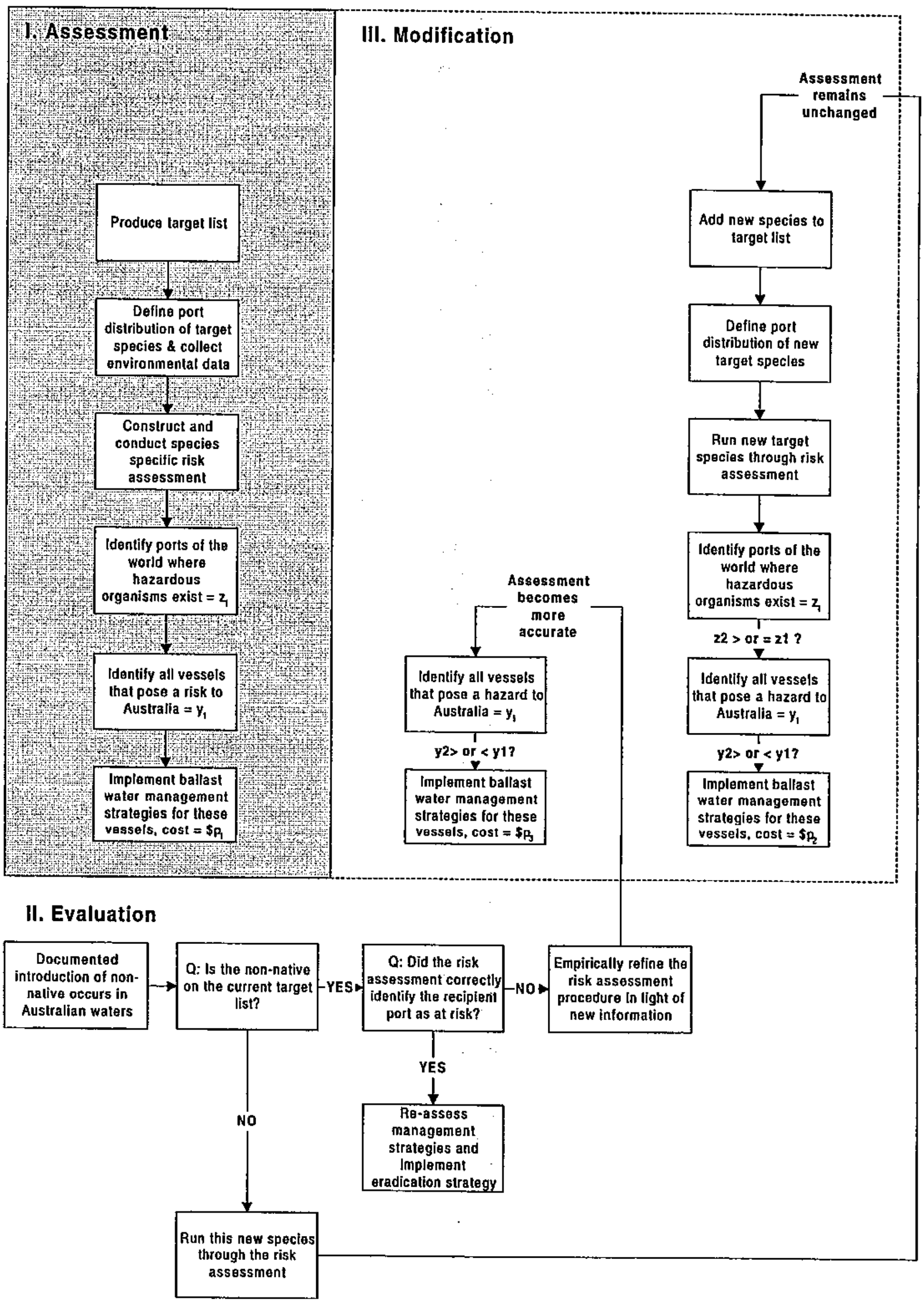


Figure 2.6 Implementing a species-specific risk assessment



3 IDENTIFYING RISK SCENARIOS

3.1 A profile of ballast water hazards

Vessels which take ballast water from contaminated ports[6] are not necessarily hazardous. A pest species may be present within a port but may remain unavailable to ballasting vessels, or may be available only at specific times of the year, or under specific environmental conditions. The organisms taken onboard may not survive the (de)ballast procedure or the journey. A ballast water hazard only exists when a vessel arrives at an uncontaminated port with viable target organisms in its ballast water. This manifests itself as risk if the vessel intends to deballast and the organisms in question are capable of surviving in this port.

With a multi-species approach, a ballast water hazard exists when the following conditions are satisfied:

1. a vessel draws ballast water from a port which is contaminated with any of the species on the target list;
2. the vessel's ballast water is contaminated with any-one of these species;
3. at least one of these species is capable of surviving the vessel journey;
4. the vessel intends to de-ballast into a port which does not contain any of the species that survived the journey.

The assessment must therefore be applied in an iterative fashion, to each of the species on the target list, in order to define the hazard status of a vessel/route combination.

By implication, a ballast water hazard does not exist if:

1. the donor and recipient ports are already contaminated with all of the species on the target list;
2. the recipient port is not contaminated with one or more of the species on the list, but these species are not capable of surviving the journey;
3. the donor and recipient ports do not contain any of the species on the target list.

The possible exception to this occurs under the third party hazard scenario (Figure 3.3) whereby a contaminated vessel visits an uncontaminated port, and infects shipping in that port, but does not alter the contamination status of the port itself. Furthermore a port may become infected with a target species through a number of mechanisms. This framework only specifically caters for those associated with shipping (refer to section 1.3).

[6] The terms 'contaminated' and 'infected' are used interchangeably in this report to mean that target species are present in ports or vessels.

These arguments are consistent with those developed in the review of ecological risk assessment methods (Hayes, 1997), and emphasise that hazard becomes risk only under very specific and finite conditions. The purpose of this risk assessment is to identify those conditions and quantify the introduction risk.

Ballast water hazards can be viewed from a number of different perspectives. The taxonomic hazard is that set of species which are available to vessels ballasting in a particular port, and are capable of survive the ballasting procedure and the vessel's journey. In this example the universal set is defined as the complete floral and faunal assemblage in the donor port. This set can be categorised according to the life stage characteristics of the species concerned (Appendix C).

Certain life-stage characteristics encourage membership of the taxonomic hazard set; species with long plankto-trophic larval periods for example. However, it is impossible to define the taxonomic hazards within a particular port without some reference to the vessel and its intended route. These components of the introduction cycle are the vector hazards, consisting of those vessels which harbour viable non-native species. The universal set in this instance consists of all vessels on a given route. There are certain characteristics, such as a short journey, that encourage inclusion in the vector hazard set, but again this cannot be defined without reference to a species. Taxonomic and vector hazards are two different perspectives of the same problem.

There is a third dimension to ballast water hazards; time. Taxonomic and vector hazards are a function of port locality, vessel operations and the distribution of target species at any moment in time. However, this is only a snap-shot of the risk assessment domain.

There are numerous examples of ballast water introductions that have occurred long after a dispersal corridor has been established by trading vessels. The reasons for this are thought to be associated with a change in the donor port, such as a range expansion by the species concerned, or a change in the recipient port, such as a change in the environmental conditions which facilitate the introduction (Carlton, 1996).

The framework must therefore incorporate regular port monitoring, and a hazard assessment methodology that allows for systematic and/or stochastic variation in the donor and recipient ports and vessel operations.

Any ballast water hazard assessment must therefore provide:

1. an examination of the vector hazard in relation to shipping activity;

2. an examination of the taxonomic hazard in relation to the distribution of target species, and their environmental tolerances;

3. an on-going assessment that tests for the inoculation of new ports, the changing environmental conditions at recipient ports, and the pest entrainment processes within contaminated donor ports.

3.2 Hazard assessment objectives

The objectives of the framework's hazard assessment stage are:

1. to evaluate the hazard status of routes and associated vessels on the basis of:

   a) the availability of data requirements for both donor and recipient ports;

   b) the relative contamination status of donor and recipient ports;

   c) the environmental conditions at the recipient port in relation to the bio-requirements of the target species concerned.

2. to provide a mechanism that continually re-evaluates route status on the basis of:

   a) the subsequent availability of data requirements;

   b) the continued presence or absence of target species;

   c) altered environmental conditions within recipient ports which were nominally identified as unavailable to the target species concerned.

3. to identify the circumstances under which vessels ballasting in contaminated ports are likely to entrain target species;

4. to provide a mechanism that identifies when these conditions are satisfied in contaminated ports which may otherwise be safe under 'normal' ballasting or environmental conditions.

3.3 Fault tree analysis

Fault trees are hazard analysis tools that are used in quantitative risk assessments to identify the chain of events leading to a hazardous occurrence (Kletz, 1986). They identify the logical combinations of events that are precursors of hazardous situations and, importantly, highlight the ways in which the event chain can be broken. Fault trees are a systematic way to ensure that all potential risk scenarios are identified, thereby mapping the risk domain.

If probability or frequency data can be generated for the basic events at the ends of each tree, then boolean algebra[7] can be used to estimate the overall frequency of the hazardous occurrence. This is not, however, the objective of the fault tree analysis developed in this document. Indeed some difficulty would be faced in this regards because many of the events within the trees are not mutually exclusive. Rather their purpose is to identify all the potential risk scenarios within the ballast water introduction cycle.

[7] Boolean algebra is an algebraic system comprising of only two kinds of elements, *true* or *false*, in which the basic operations are the logical AND and OR operations, which are normally symbolised as multiplication and addition respectively.

The first of the fault trees developed for the risk assessment framework is illustrated in Figure 3.1. This approach is developed further in Figures 3.2 to 3.6, which extend the analysis to address each of the potential sources of target species within a port environment.

The event symbols used within each of these diagrams are explained in Appendix D. The basic events at the ends of the trees provide a 'shopping list' of analysis and data needed to complete a quantitative ballast water risk assessment.

The endpoint selected for the framework requires that a viable target species is introduced into an uncontaminated port whose environment satisfies the bio-requirements of the species at the time of introduction. These conditions represent the first level within the fault tree. Figure 3.1 goes on to specify the necessary events for a viable introduction, namely that the vessel's ballast water is contaminated with a target species, a proportion of these individuals are alive, the vessel deballasts in the port, and so forth.

Figure 3.2 identifies three conditions that must be met for a viable target species to be entrained into a ballast tank. Two of these, the size above which the species is too large to pass through the ballast pump sieve, and the ability to survive the ballasting process, provide decision criteria against which the species life-stage can be tested.

Most (if not all) of the larval or spore stages of the species on the current target list will be small enough to pass through typical sea-chest and ballast pump sieves. We recommend that a separate project determine the age at which juvenile or adult stages of these species are too large, so that the temporal boundaries of the analysis can be defined for each cohort.

Empirical or experimental evidence should be used to establish survivability during the ballasting procedure. Records of live specimens within tanks would be sufficient to establish survivability. This issue, together with the question of viability under different ballasting procedures (for example gravity feed as opposed to pump), should be investigated as part of a separate project on the ability of target species to survive in ballast water.

The third condition requires that the target species is drawn into the vessel with the ballast water. This is extremely likely for crevicolous species which seek cavities such as sea chests or ballast water inlets. Species which exhibit this kind of behaviour within their life cycle warrant separate consideration. For most species, however, including all of those on the current target list, entrainment is assumed to be a passive process involving no specific avoidance or attraction behaviour.

Under these circumstances (Figure 3.3) individual organisms will be entrained into the ballast tank if their distribution within the port environment, in time and space, falls within the ballast withdrawal envelope (as defined in Volume II). The likelihood of pest entrainment therefore depends on the distribution of pest populations in a port, the sources that introduce organisms into a vessel's ballast withdrawal envelope, and the sinks that remove them from this envelope.

It is possible to identify three different risk scenarios associated with the source of the organism in question: soft-substrate sources (Figure 3.4), water-column sources (Figure 3.5) and hard-substrate sources (Figure 3.6). A fourth potential source occurs if the target species is a parasite of another organism. Under these circumstances, however, the entrainment analysis can be run with the host organism. Each of these entrainment scenarios are cross referenced to the categories of 'ballastable biota' detailed in Appendix C.

If a donor port does not contain any of the target species, vessel contamination can only occur if the port is inoculated by a third party vessel.[8] It is feasible, but perhaps unlikely, that an infected vessel de-ballasts in a port (which may or may not satisfy the bio-requirements of the species concerned) and infects another vessel which is ballasting at the same time.

This risk scenario cannot be ruled out without further analysis of dilution of target organisms when discharged from a ballast tank. This risk scenario is important because of its implications for the survival period used by the assessment endpoint (refer to section 2.1). It should therefore be investigated at an early stage in the assessment's development.

An alternative inoculation scenario arises if the third party vessel carries target species as fouling organisms. In this situation target species can be introduced into the waters of an uncontaminated port through dislodgment of individuals (accidentally or through active hull-cleaning activities), or via the spawning of adults. These scenarios are currently not catered for in the assessment framework.

[8] Third party vessel refers to any other vessel de-ballasting within the port environment.

Figure 3.1 Ballast water introduction fault tree analysis

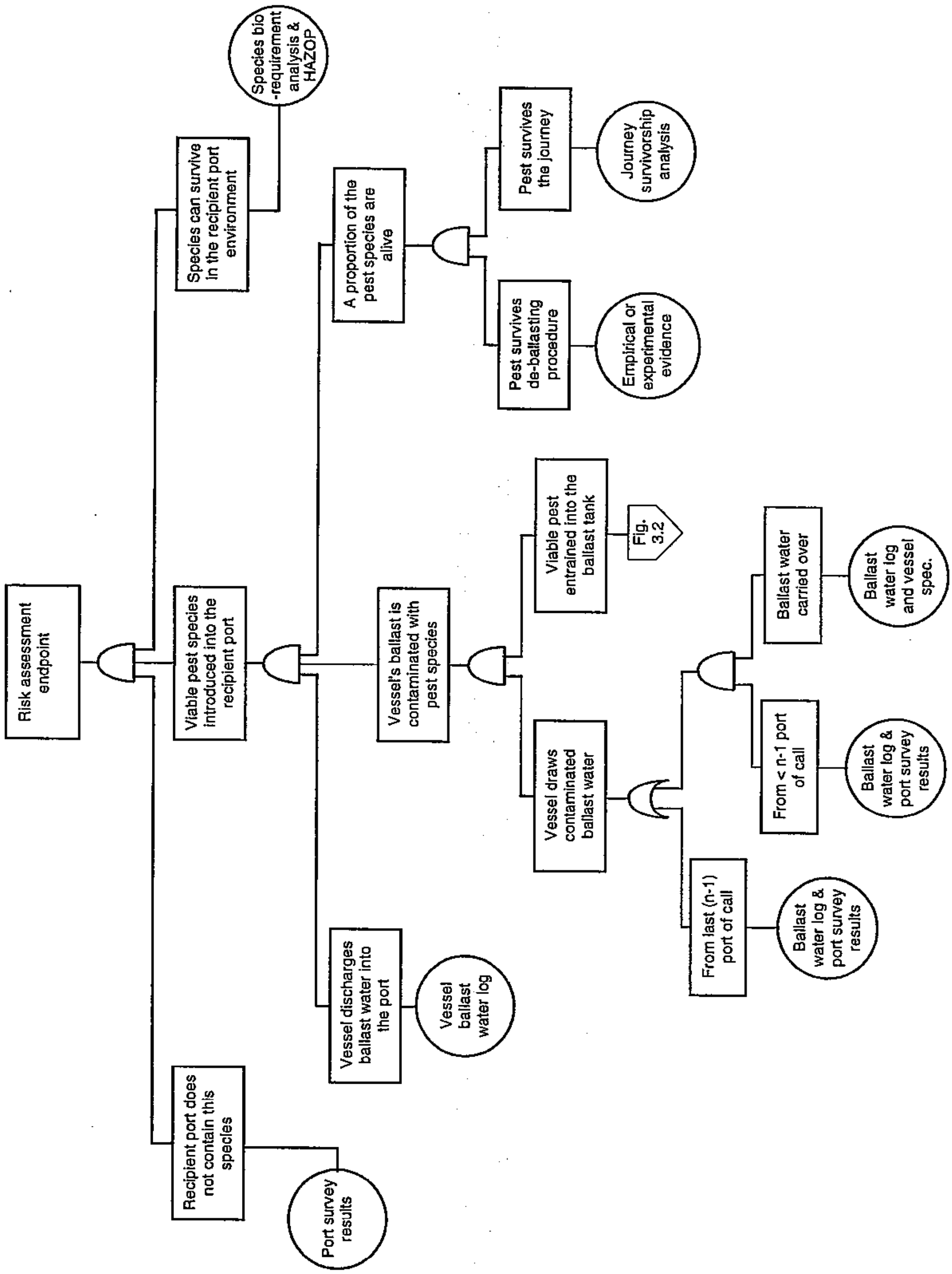


Figure 3.2 Pest entrainment process fault tree analysis

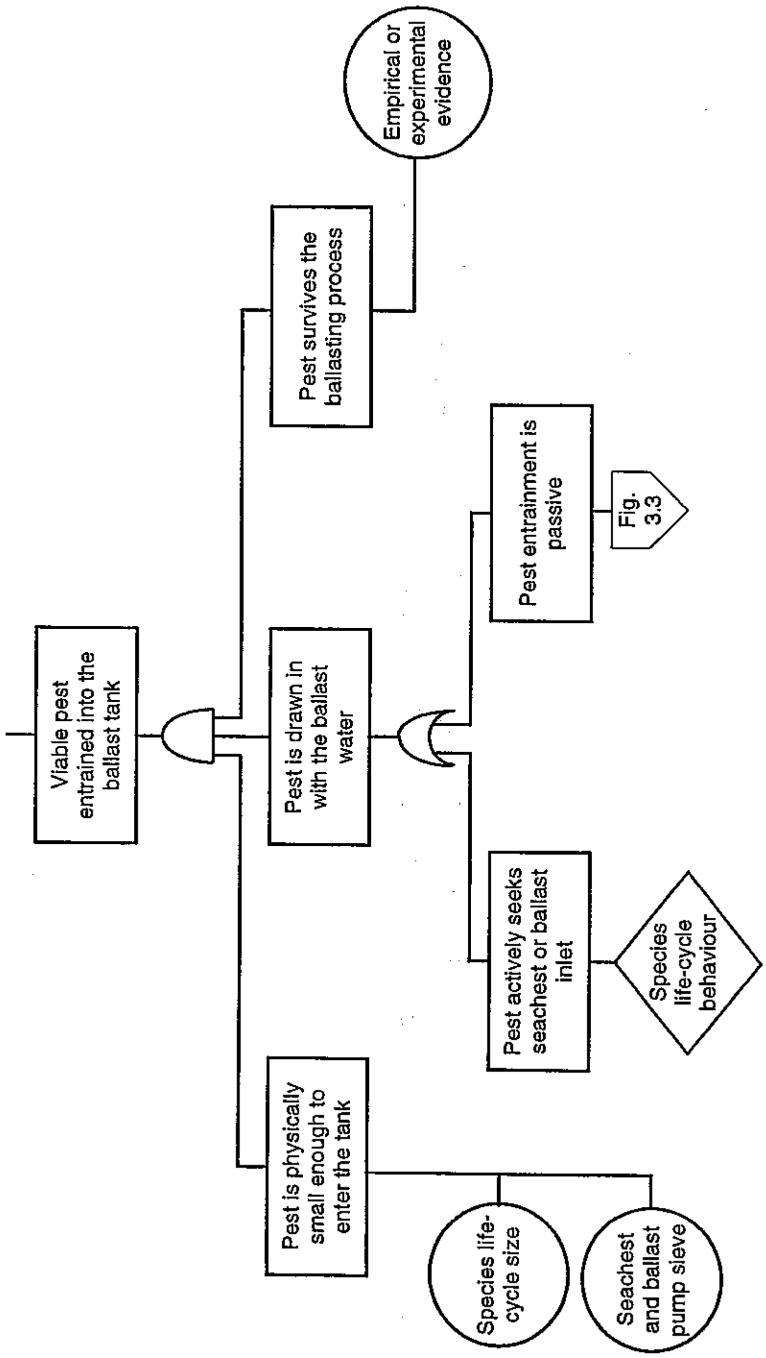


Figure 3.3 Pest entrainment fault tree analysis cont...

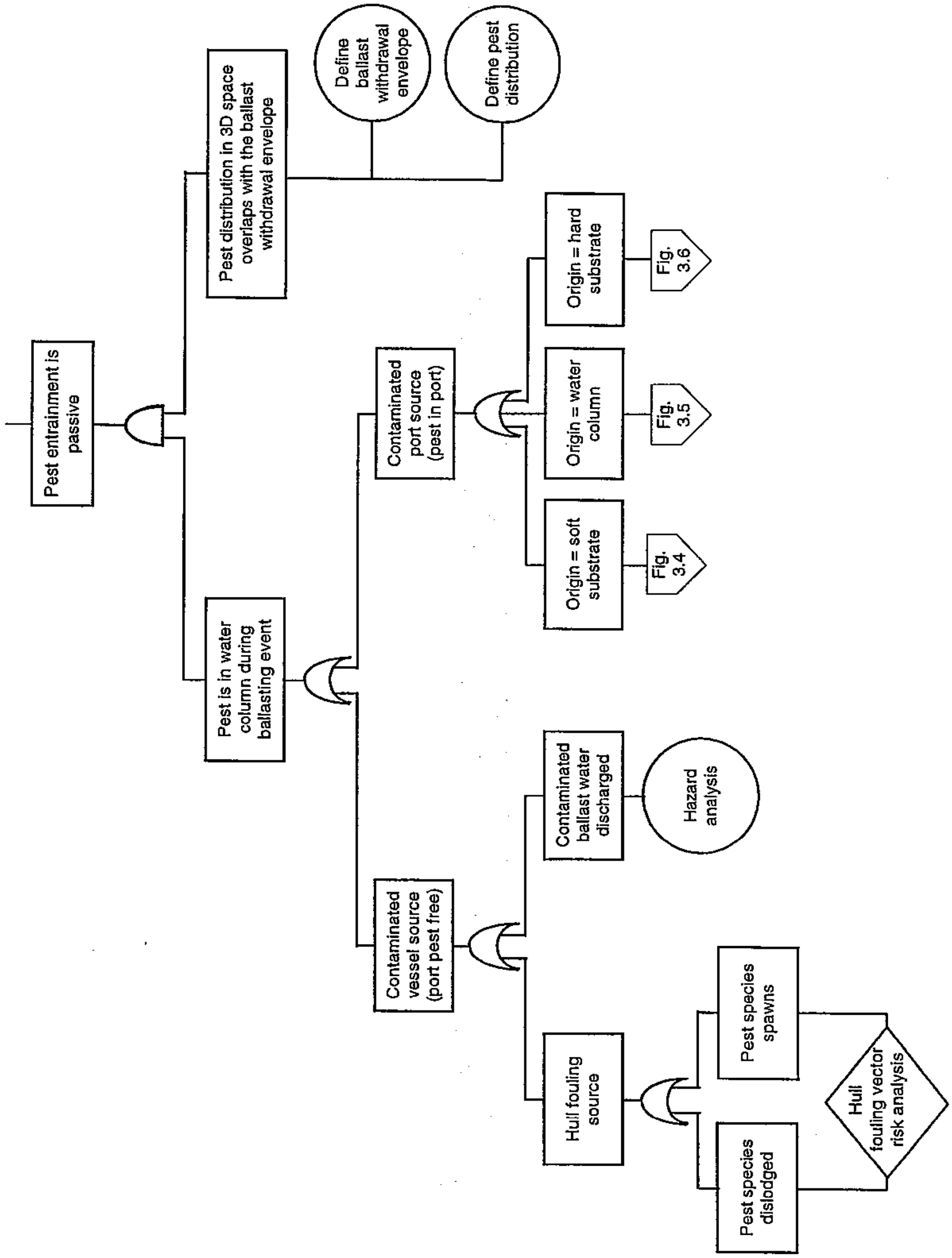


Figure 3.4 Soft-substrate source fault tree analysis

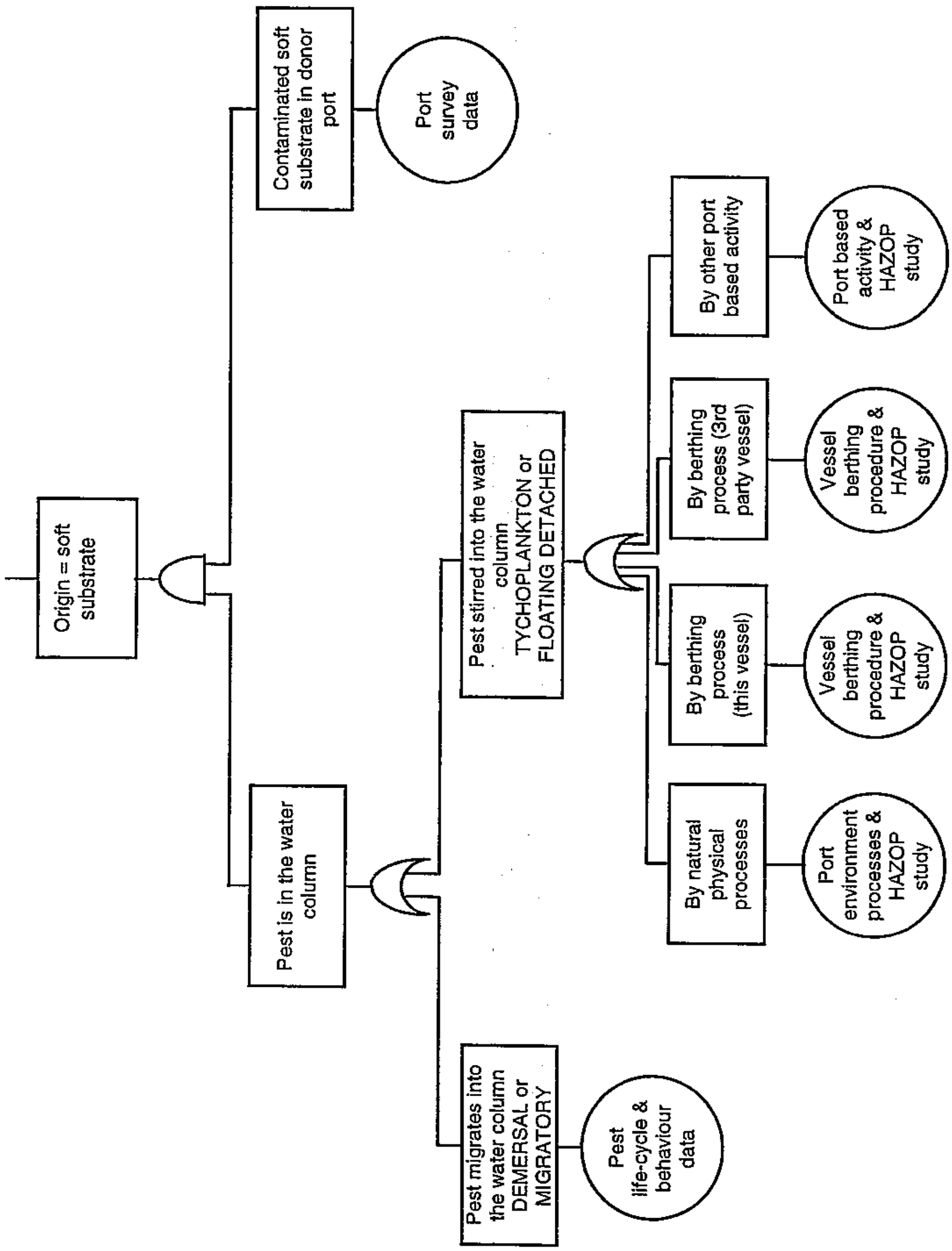


Figure 3.5 Water-column source fault tree analysis

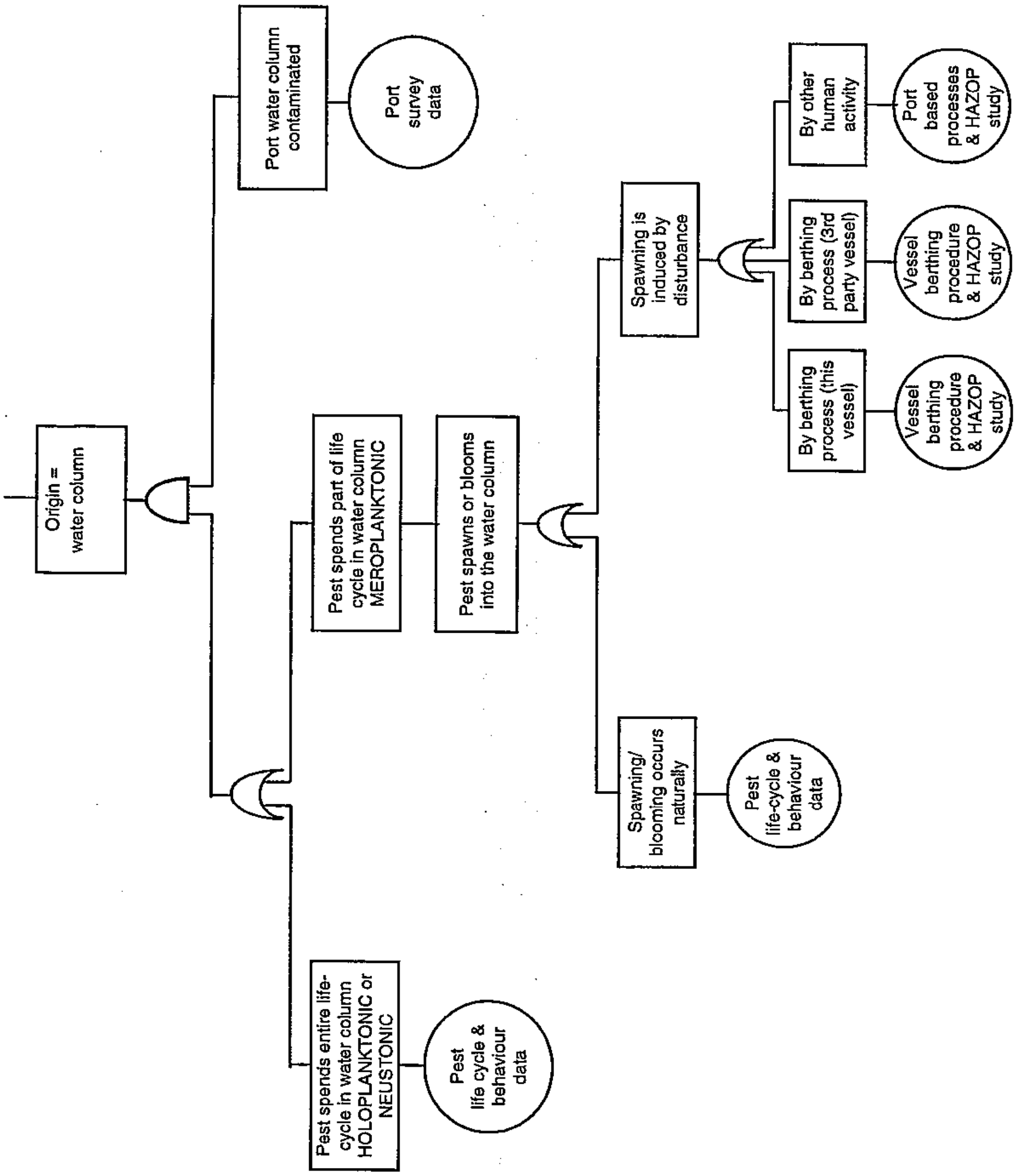
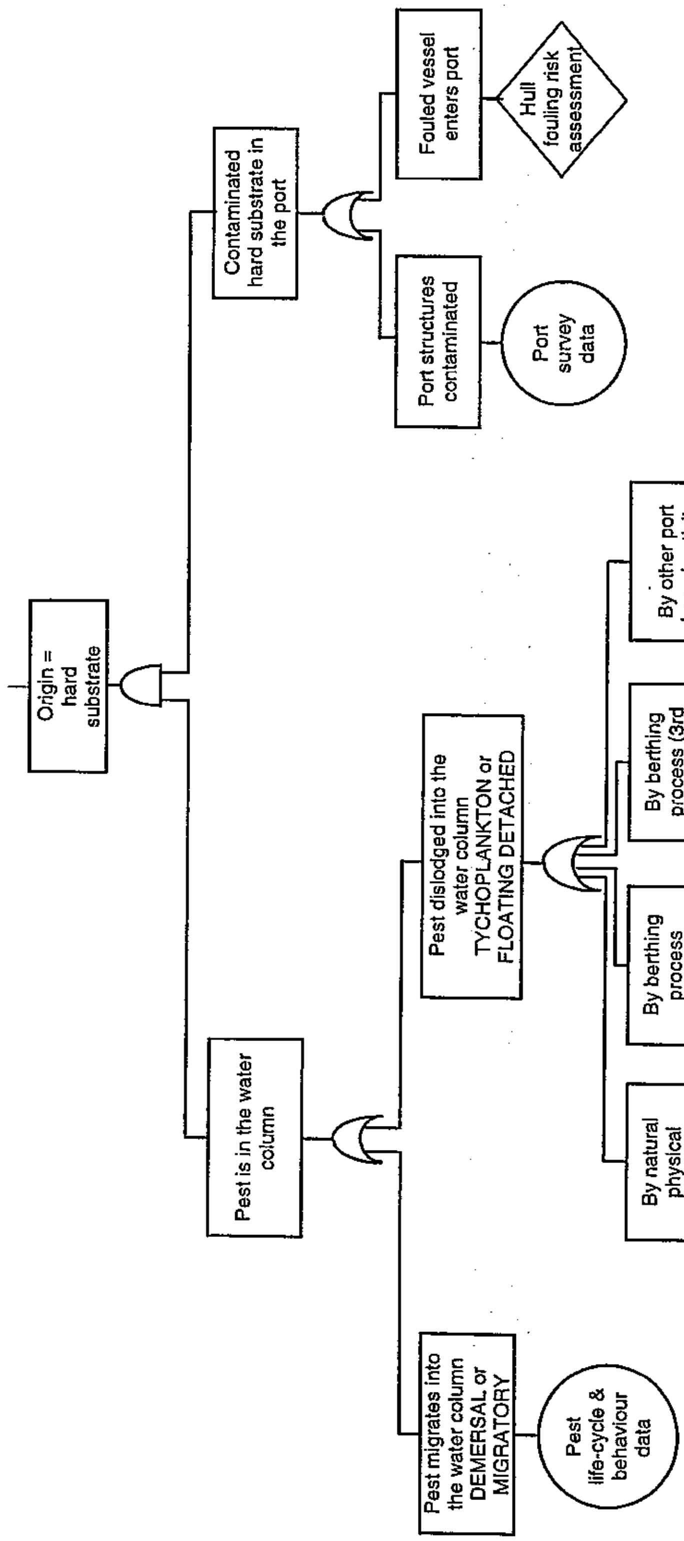


Figure 3.6 Hard-substrate source fault tree analysis



4 LEVELS OF RISK ASSESSMENT

4.1 Level ∅ assessment

Introduction & objectives

Level ∅ is the entry level of the analysis. It provides a basic assessment of vessel hazard using the minimum amount of data. It only requires the country of origin of the vessel's ballast water to be identified.

The objective of level ∅ is to provide decision criteria for vessel sampling protocols in the absence of any other information. A less conservative assessment can be conducted at this level if basic environmental data (temperature and salinity) is available for the donor and recipient ports (refer to Figure 4.2).

Assessment procedure & data requirements

The assessment procedure and data requirements for level ∅ are summarised in Table 4.1. The data identifiers are detailed in Appendix E, which includes a list of potential sources and suggested format.

The assessment can be implemented once bioregions have been allocated to all the nations in the study, their port and target species membership identified, and the rules for bioregion matching defined (refer to Volume II).

The assessment procedure consists of two stages: The first stage determines the infection status of donor and recipient ports with respect to target species. This can be done directly through port surveys, or indirectly through databases of national target-species distributions[9] (Figure 4.1). Port contamination status could be inferred indirectly for all levels of the assessment framework, but we recommend that it is determined directly from level 1 onwards.

Uncertainty regarding a donor port's infection status can be expressed as an 'infection probability'. For example where an unsurveyed port lies in close proximity to a target species that is expanding its range, such as *Carcinus maenas* along the west coast of North America (Grosholz and Ruiz, 1996)

The second stage of the assessment makes an environmental match between the donor and recipient bioregions for at least two seasons. If basic temperature and salinity data (maximum and minimum) is available for the donor or recipient ports, then the match can be made at a port specific scale, at a temporal resolution dictated by that of the available data. The assessment then allocates the vessel to one of seven qualitative hazard ranks (Figure 4.2) which can form the basis of sampling protocols.

These ranks are simple, qualitative indices of ballast hazard, on an ordinal scale. They are derived from self-evident principles; if neither the donor or recipient port are infected, or environmentally matched, then it is highly unlikely that a ballast water hazard exists (lowest

[9] Databases of this kind are currently maintained by the United Nation's Food and Agriculture Organisation (FAO), and the International Union for the Conservation of Nature (IUCN).

rating). By contrast if the donor port is infected, the recipient port uninfected, and both are environmental matched, then it is highly likely that a ballast water hazard exists (highest rating).

Table 4.1 Level ∅ hazard assessment procedure

DATA IDENTIFIERS							
A	B	C	D	E_D	E_R	$F_{D\&R}$	G
001	001	001		001	001	006	001
014	002	002		002	002	033	002
015	003	003		003	003	034	003
016	004	004		004	004		004
017		007		049	*039*		005
018		008		050	*040*		006
050		011		052	*048*		007
		015		053	049		008
		018			050		009
					052		010
					053		011
							012
							013
							014
							015
							016
							032
							033
							037
							038

ASSESSMENT PROCEDURE - LEVEL ∅
1. Identify the port(s) of origin of the vessel's ballast water
2. Select species from target list
3. Determine donor & recipient port contamination status with respect to this species
4. Conduct port and/or bioregion match
5. Assume that every vessel that ballasts in a contaminated port becomes infected
6. Determine vessel hazard ranking on the basis of port infection status and bioregion /port match (Figure 4.2)
7. Repeat step 6 if necessary for all bio-regions that donor port nation is a member of
8. Select next species and goto 3
9. Repeat steps 2 to 7 for all ports of origin for vessel's ballast water

E_D& F_D = donor port, E_R & F_R = recipient port. Data items in italics are optional

Expected benefits

The level ∅ analysis provides a hazard ranking scheme without any information other than the origin of a vessel's ballast water. Vessel sampling resources can be allocated on this basis, but benefits cannot be expressed in terms of risk reduction. It is also important to note that this level of assessment makes no allowance for ballast water carry-over.

Figure 4.1 Defining donor and recipient port infection status

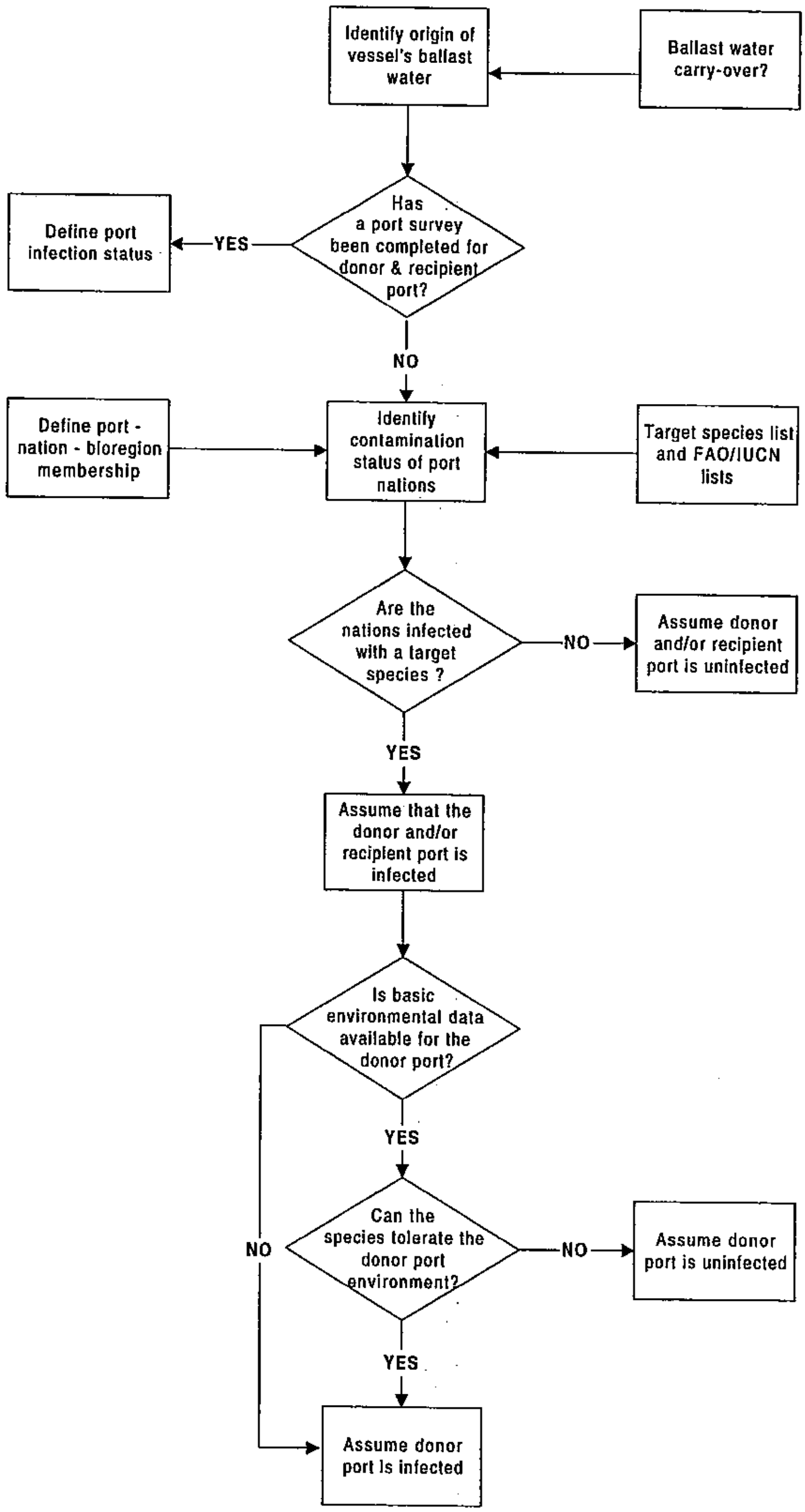
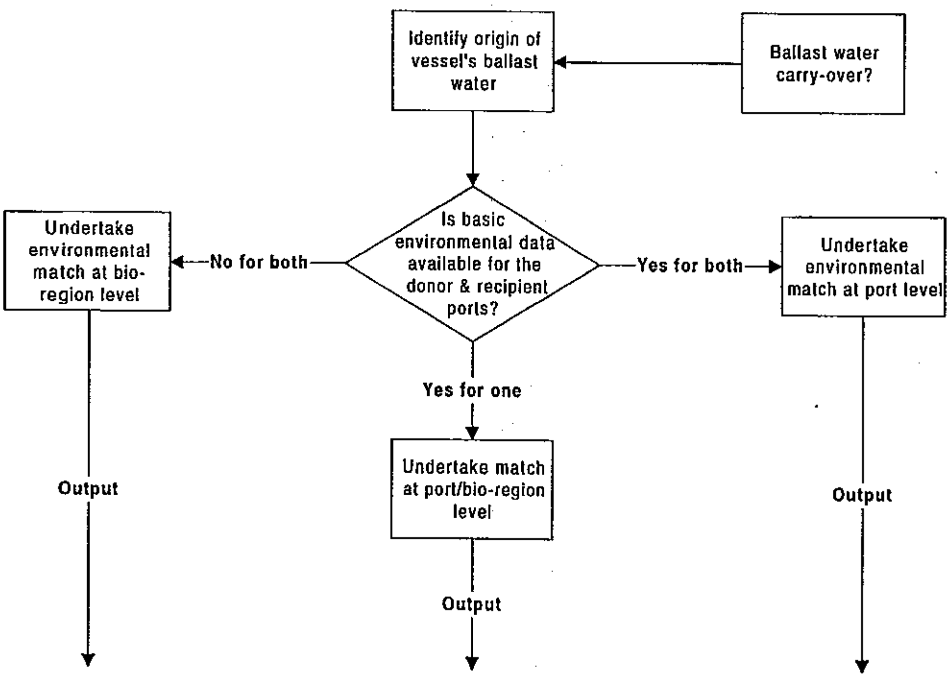


Figure 4.2 Environmental match output



	Recipient infected		Recipient uninfected	
	Match	No-match	Match	No-match
Donor infected	5	Error [a]	7 (high)	6
Donor uninfected	3	2	4	1 (low)

HAZARD RANKING SCHEME

[a] Error indicates that donor and recipient ports must match if both are infected

4.2 Level 1 assessment

Introduction & objectives

Level 1 builds on the hazard ranking scheme in level Ø by including information on the vessel infection period. The vessel infection period is defined as the number of days pest species are expected to survive in the vessel's ballast tanks.

The objective of level 1 is to provide a better assessment of vessel hazard, in particular to define those routes which are 'safe' because:

1. the donor and recipient ports are both infected with the same target species;

2. the donor and recipient port are both free of the target species;

3. the vessel infection period is less than the journey duration.

The best way to establishing 'safe routes' is to determine the vessel infection period. A vessel whose journey is significantly longer than this does not pose a ballast water hazard, irrespective of the infection status or environmental match of the donor and recipient ports.

For most species the ballast tank population is expected to decay exponentially following inoculation (Wonham *et al*, 1996, Murphy, 1997).

This may not be the case, however, for dinoflagellate cysts[10](and *Undaria* spores). Most toxic dinoflagellate species, such as *Alexandrium* spp. and *Gymnodinium catenatum*, produce resistant resting cysts that can remain fully viable under unfavourable environmental conditions for long periods of time (Hallegraef & Bolch, 1992).

Cysts which germinate whilst in a ballast tank are thought to perish. AQIS (1994) note that no viable *G. catenatum* cysts have been detected in ballast water samples, citing the short dormancy period (two weeks) as a possible cause. The authors also noted, however, that germination would be prevented if anoxic conditions existed within the ballast tank, thereby enhancing *G. catenatum* cyst survival.

It is much more difficult to establish safe routes if a vessel's journey is shorter than the infection period because of the problems with environmental matching (section 2.3), and the potential uncertainty over the infection status of the donor and recipient ports.

It is not possible to define a route as 'safe' just because the last port of call was not infected. This is because many vessels carry ballast water that originates from more than one port. In some cases this water is isolated within individual tanks (whose status can be tracked) but on other occasions mixing of ballast water may occur within the vessel itself. We recommend that vessels do not mix ballast water between tanks so that the infection status of individual tanks can be tracked.

[10] Survival rates for motile life-stages of dinoflagellates are thought to be very low, with massive mortality occurring within five days of entrainment into the ballast tank due to darkness, zooplankton grazing and changing temperature and nutrient conditions(*pers comm* G. Hallegraeff).

Similarly some residual water usually remains in a ballast tanks even when they are considered to be completely empty by the vessel's crew. This water is basically 'unpumpable ballast' (Carlton *et al*, 1995). For example, when the ballast tanks of the MV *Leon*[11] are pumped 'dry', 1-2 cm's of unpumpable water remains in the tanks, amounting to approximately 65,000 litres of water in the vessel as a whole (Wonham *et al*, 1996).

The volume of unpumpable ballast on a vessel could be expected to vary between vessel types, particularly between vessels whose cargo is less dense than seawater (and is therefore always accompanied by some ballast water), as compared to those whose cargo is more dense than seawater (who are commercially penalised by unpumpable ballast). In either case it may be sufficient to support pest species onto 'safe routes' defined solely on the basis of (an uncontaminated) last port of call.

These problems are exacerbated by the difficulty of obtaining representative samples from a vessel's ballast tank. In particular the analyst may be unable to distinguish between sampling zeros[12] and structural zeros (McArdle, 1993).

In conclusion safe routes can only be determined on the basis of port contamination status if the donor and recipients ports are already contaminated with all target species, or if the ports are free of all target pests, can be confidently and continually verified as such, and are serviced by vessels which trade exclusively between these ports and no others.

In both cases monitoring strategies should be developed to continually confirm the pest status of ports. Uncontaminated ports should be regularly monitored to ensure they remain uncontaminated. Contaminated ports should be continually monitored to document the progress of the target populations within them; they could to revert to an uncontaminated status if these populations become extinct, or if an eradication programme is successfully implemented.

An important analogy here is the designation of Pest Free Areas (PFA) under the International Plant Protection Convention (IPPC) 1951. There are three main components in establishing and maintaining a PFA (Food and Agricultural Organisation, 1996): systems to establish freedom; measures to maintain freedom; and checks to verify that freedom has been maintained.

The nature of these components vary according to the biology of the pest species concerned and the relevant characteristics of the PFA (such as size and degree of isolation). We recommend that similar systems are designed to ensure that ports remain free of target species.

Assessment procedure & data requirements

The assessment procedure and data requirements for a level 1 assessment are summarised in Table 4.2. The assessment can be implemented once the additional data and analysis requirements highlighted in Table 4.2 have been completed.

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[11] Cape class vessel with a total ballast tank capacity of 67, 815 m^3.

[12] Sampling zeros occur where target species are not detected within a vessel (which is therefore designated as pest free) but are in fact present, leading to a Type II error. Structural zeros occur when target species are not detected because they are not present.

Table 4.2 Level 1 hazard assessment procedure

DATA IDENTIFIERS							
A	B	C	D	E_D	E_R	$F_{D\&R}$	G
001	001	001		001	001	006	001
014	002	002		002	002	033	002
015	003	003		003	003	034	003
016	004	004		004	004		004
017	005	005		048	*039*		005
018	006	006		049	*040*		006
050	*014*	007		050	*048*		007
		008		052	049		008
		011		053	050		009
		015			052		010
		016			053		011
		017					012
		018					013
		019					014
							015
							016
							025
							028
							029
							032
							033
							037
							038
							055

ASSESSMENT PROCEDURE - LEVEL 1
1. Identify port(s) of origin of the vessel's ballast water
2. Select species from target list
3. Determine donor & recipient port contamination status with respect to this species
4. Conduct port and/or bioregion match
5. Assume that every vessel that ballasts in a contaminated port becomes infected
6. Define vessel infection period
7. Determine vessel hazard ranking on the basis of port infection status, vessel infection period and port/bioregion match
8. Repeat steps 4 and 7 for each port visited within infection period
9. Select next species and goto 3
10. Repeat steps 2 to 8 for each contaminated port from which vessel draws ballast water

The contamination status of ports in the study area can be achieved directly through port surveys, or indirectly on the basis of the national distribution of target species (Figure 4.1). The level 1 assessment can be run in either case but we recommend the use of port surveys.

In the first instance the contamination status of domestic Australian ports may be determined directly whilst that of international ports may have to be inferred indirectly. The assessment should also be supported by port monitoring strategies designed to continually verify the pest status of all the ports in the study area.

Expected benefits

A hypothetical risk-benefit analysis for two of the species on the current target list, *Alexandrium minutum* and *Asterias amurensis*, is illustrated in Figure 4.4. The benefits of the assessment are measured against a base reference (Figure 4.3) in which all vessels trading between 4 different ports pose a ballast water hazard. The base reference is intended to reflect AQIS's current position.

The benefits following completion of a level 1 assessment are expressed in terms of the expected proportion of vessels that are identified as non-hazardous. This occurs because the journey duration significantly exceeds the expected vessel infection period. For all other vessels the hazard status is determined on the basis of the recipient and donor port contamination status, and the environmental match (level ∅).

Figure 4.3 Hypothetical base reference

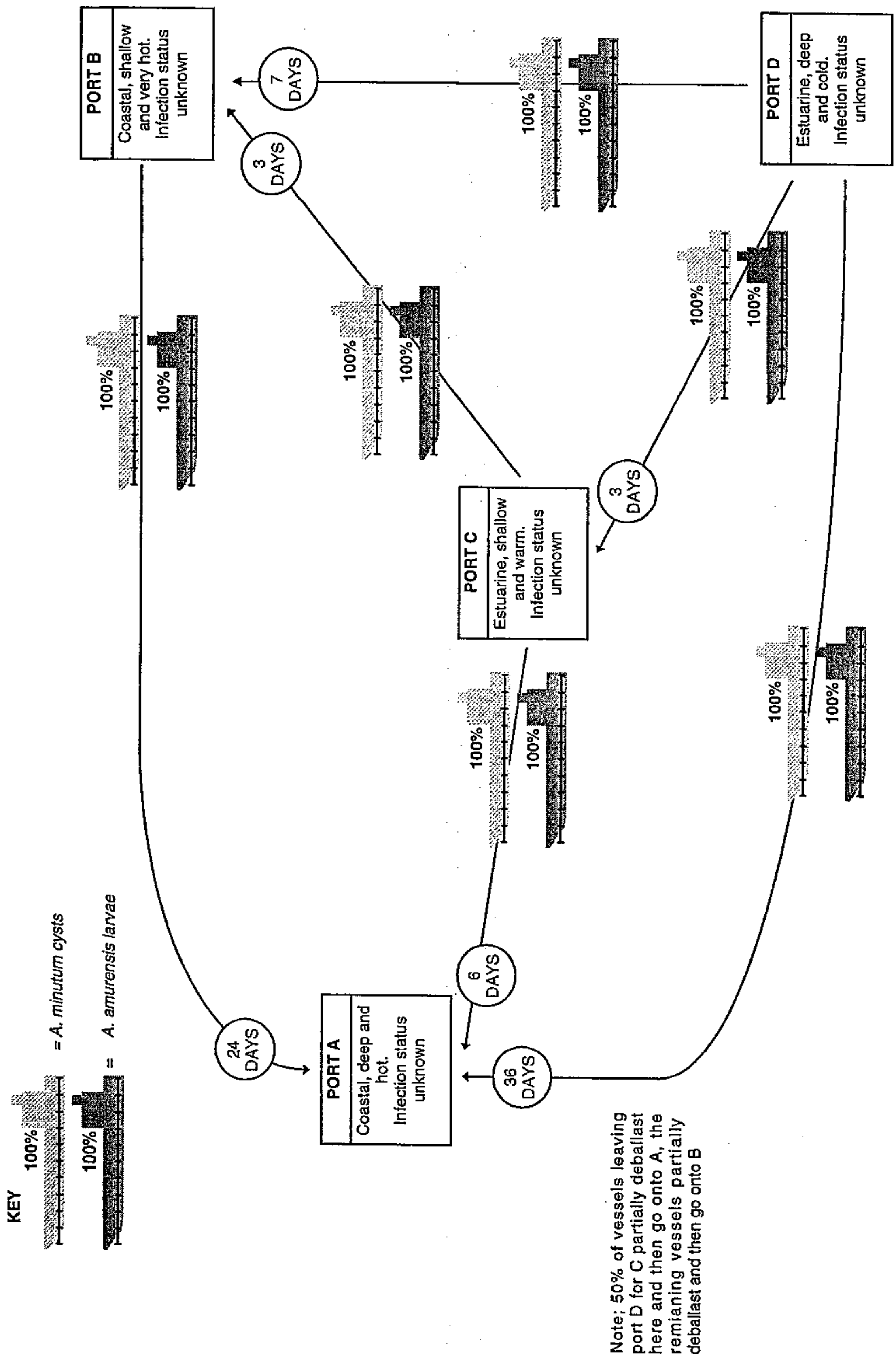
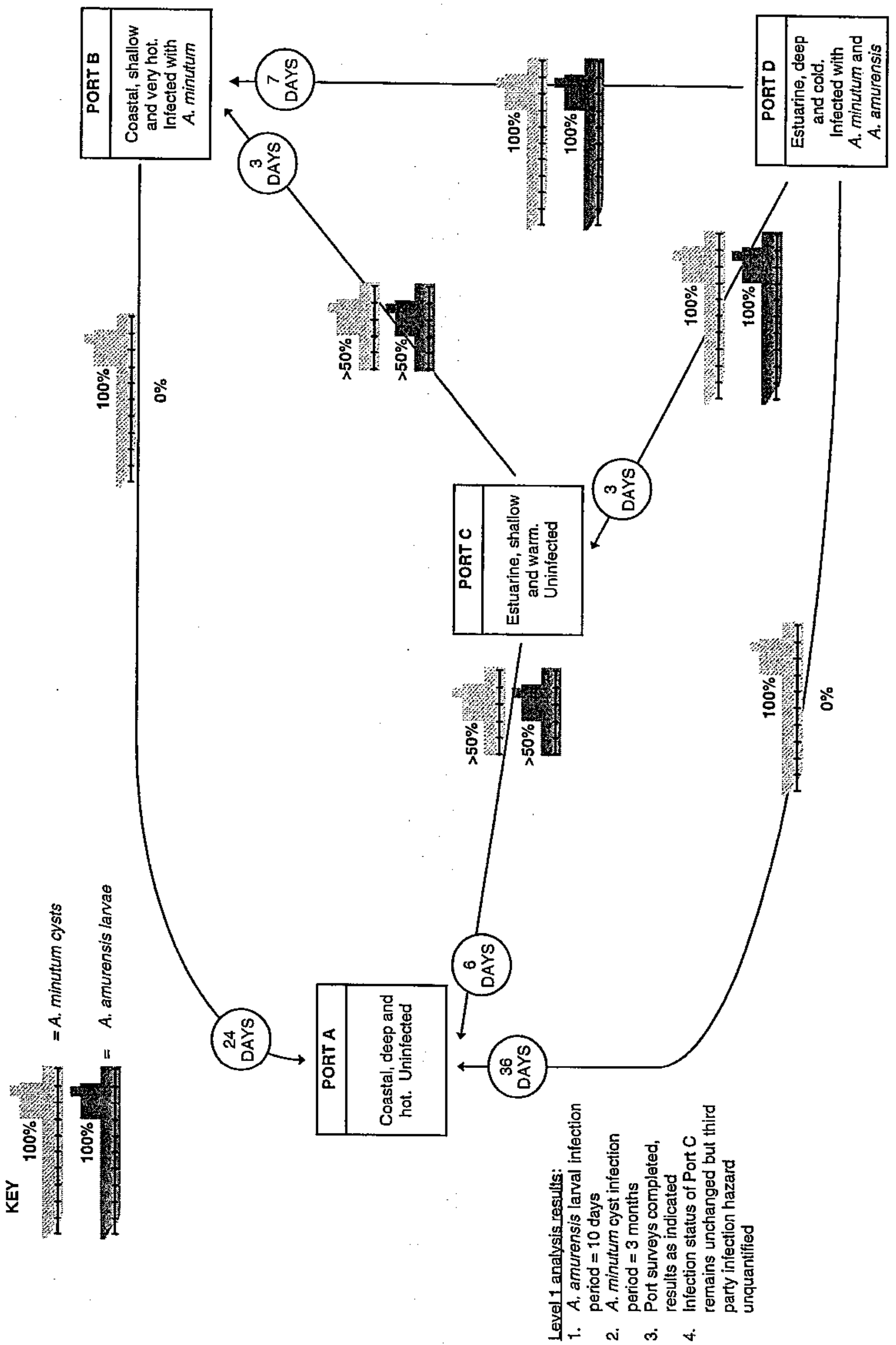


Figure 4.4 Hypothetical level 1 benefits



4.3 Level 2 assessment

Introduction & objectives

The objectives of the level 2 assessment are:

1. to distinguish different pest sources in contaminated ports;
2. to define cohort specific temporal boundaries;
3. to model organisms survivorship during the (de)ballast procedure and its influence on subsequent survivorship.

The second level assessment distinguishes between different pest sources in contaminated ports. This is particularly important in relation to diatom and dinoflagellate cyst infections Diatom and dinoflagellate cysts may originate from plankton blooms in the water column or from harbour sediments resuspended during the ship's ballasting procedures (Hallegraef & Bolch 1991, 1992).

These two sources present different hazards to ballasting vessels. Cyst re-suspension might give rise to consistent but low density infections. By contrast plankton blooms may occur infrequently but cause high density infections. Similar distinctions might be made for tychoplankton, and indeed for any target species that occupies different substrate within a port over the course of its life cycle.

The level 2 assessment also tests the species life-stage against pre-determined size criteria. The organisms must be small enough to pass through the vessel's sea chest grate and ballast pump sieve (typically 5 - 10 mm in diameter). Most, if not all, of the larval or spore stages of the species on the current target list are expected to be small enough. The age at which juvenile or adult stages of these species are too large to pass into the ballast tank should be determined because this provides a temporal boundary on the assessment.

Target species must also be capable of surviving the (de)ballast procedure, most notably the turbulent conditions associated with the ballast pump and any instream biocide treatment facilities[13]. Carlton *et al* (1995) suggest that ballast pump turbulence has little impact on most organisms. By contrast, Murphy (1997) suggests that this may actually be responsible for the immediate dramatic mortality often witnessed in ballast tank survival studies.

There is very little data to support either of these positions. It is unlikely, however, that all the various life-stages, of each of the target species, are equally tolerant of the turbulent conditions often associated with (de)ballasting. For example, Pearson *et al* (1989) recorded various mortality rates between different species of fish larvae and eggs when exposed to turbulent conditions within the laboratory. Similarly the motile life-stages of many toxic dinoflagellate species seem to be sensitive to turbulence (Rigby & Hallegraef, 1994). We recommend that this issue is investigated as part of a separate project on the ability of target organisms to survive in ballast water.

[13] The MV *Iron Sturt*, for example, feeds hypochlorite though its ballast water pipes and engine cooler to prevent the growth of fouling organisms.

Assessment procedure & data requirements

Table 4.3 summarises the level 2 assessment procedure and data requirements. The assessment can be implemented once the additional data and analysis requirements highlighted in Table 4.3 have been completed.

Table 4.3 Level 2 hazard assessment procedure

DATA IDENTIFIERS							
A	B	C	D	E_D	E_R	$F_{D\&R}$	G
001	001	001	001	001	001	001	001
002	002	002	003	002	002	002	002
010	003	003	009	003	003	006	003
013	004	004	017	004	004	010	004
014	005	005	018	015	*039*	011	005
015	006	006	019	018	*040*	012	006
016	011	007	020	019	*048*	014	007
017	*014*	008	021	020	049	016	008
018		009	022	023	050	017	009
020		010	023	029	052	018	010
021		011	024	030	053	033	011
022		012	025	037		034	012
023		013		048			013
024		014		049			014
030		015		050			015
031		016		052			016
032		017		053			017
033		018		054			018
034		019					023
035							024
036							025
037							026
038							028
050							029
							032
							033
							037
							038
							047
							048
							055
							056
							057

ASSESSMENT PROCEDURE - LEVEL 2

1. Identify port(s) of origin of the vessel's ballast water
2. Select species from target list
3. Verify donor & recipient port infection status with respect to this species
4. Distinguish life-stage sources in contaminated donor ports over study period (one year)
5. Define life-stage distribution in time for donor ports with water-column hazard: postulate simple water column residence time.
6. Identify ports with soft-substrate hazard: identify donor ports with contaminated soft substrate as 'shallow' or 'deep' as a function of vessel, particle, oceanographic and bathymetric characteristics.
7. Identify donor ports with hard-substrate hazard
8. Conduct port and/or bioregion match
9. Assume all vessels that ballast during residence time of water-column sourced pest become infected
10. Assume all vessels that ballast within shallow port with soft-substrate hazard become infected
11. Assume all vessels that ballast in port with hard-substrate hazard become infected
12. Test life-stage size and survivability criteria
13. Define vessel infection period
14. Determine vessel hazard ranking on the basis of port infection status, infection period and port/bioregion match
15. Repeat steps 8 and 14 for all ports visited within vessel infection period
16. Select next pest and goto 3
17. Repeat steps 2 to 14 for each contaminated port from which vessel draws ballast water

Expected benefits

Figure 4.5 illustrates the expected benefits of the level 2 assessment. The second level allows a further reduction in the proportion of vessels visits identified as hazardous because:

1. ballast pump mortality reduces the initial inoculum[14] size and therefore shortens the vessel infection period;

2. vessels that ballast in contaminated ports, but outwith the water column residence time of target species, are not infected unless re-suspension occurs;

3. re-suspension events occur for a limited proportion of vessel visits to specific ports or berths.

The first result assumes that life stage mortality within the ballast tank is independent of pest density. This assumption does not hold if starvation is the main cause of mortality within the tank (Wonham *et al,* 1996).

Starvation, however, is unlikely to occur over relatively short international and domestic voyages. Furthermore some zooplankton larvae are known to be tolerate lengthy periods of food deprivation (Allison, 1994), leading some authors to conclude that starvation is not the main cause of zooplankton mortality within ballast tanks (Murphy, 1997).

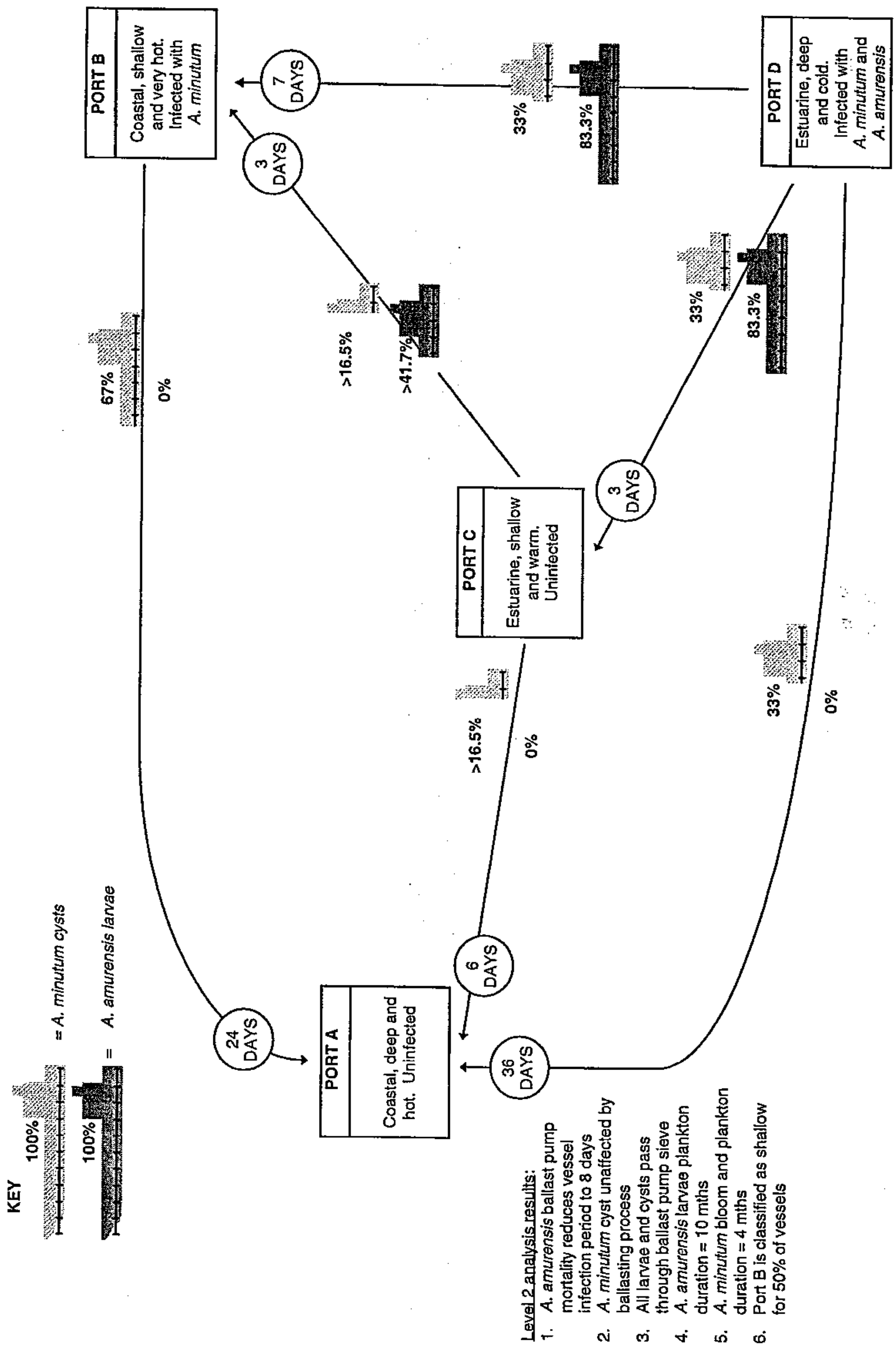
The risk-benefit analysis assumes that larval mortality upon ballasting (with a pump) reduces the vessel infection period. In Figure 4.5 the *A. amurensis* infection period is reduced from 10 days to 8 in this manner. As a result the overall journey duration between ports D and A, via C, exceeds the vessel infection period such that this route is no longer considered hazardous for *A. amurensis* larvae. This is not the case for the route between port D and B, via C. The initial reduction in infected vessels leaving port D, however, has a knock on effect, leading to a smaller proportion of potentially infected vessels departing port C. This also reduces the chance of the third party infection scenario occurring.

Dinoflagellate cysts are extremely tolerant of unfavourable environmental conditions, and can remain viable in ballast tanks for long periods of time. Hazard reductions for these species will not therefore cannot be gained through natural mortality in the ballast tank - these species could remain viable for periods well in excess of typical domestic or international voyages.

The most effective way to reduce hazard in relation to these species is to determine their availability to ballasting vessels. In Figure 4.5 it is assumed that conditions suitable for dinoflagellate blooms (which introduce cysts into the water column) occur during four months of the year. On this basis two thirds of the vessels departing from port D are identified as non-hazardous because blooms are not occurring, and the port is too deep for cysts to be re-suspended from contaminated, soft substrate. In port B, however, this is not the case - an additional 50% of vessels are identified as hazardous because shallow conditions at the berth allows re-suspension of cysts for these vessels.

[14] The inoculum is the number of individuals, or population of a species, that is taken on board the vessel with its ballast water.

Figure 4.5 Hypothetical level 2 benefits



4.4 Level 3 assessment

Introduction & objectives

The objectives of the level 3 assessment are:

1. to reduce the proportion of vessels identified as hazardous in level 2 by identifying periods of the year during which the recipient port is not suitable for target species;

2. to conduct a basic environmental HAZOP analysis.

The previous levels of the framework provide a quantitative assessment of hazard expressed as the expected proportion of vessels infected with viable target species on entry to the recipient port. The third level of the assessment framework translates this into a quantitative expression of risk by determining the likelihood that the port environment is suitable for survival of the species life-stage. At this level, port environment suitability is measured in relation to two environmental parameters: sea surface temperature and salinity.

Testing environmental suitability against a limited set of parameters will provide a reasonable risk estimate if the species response to these parameters is not correlated with other parameters such as dissolved oxygen levels. Sutton & Bruce (1996) note a complex interaction between salinity and the magnitude of temperature effects on the early larval development of *A. amurensis*. However, no such observation was made for bipinnaria subject to the same experimental regime.

These results underline the need for life-stage specific assessments but also suggest, for *A. amurensis* at least, that the strength of the correlative response is probably only significant at the margins of the species tolerance range. It seems possible therefore to select temperature and salinity values which are sufficiently beyond the tolerable range of a species, such that the assumption of independence from other environmental parameters holds[15].

An estimate of risk made on the basis of temperature or salinity tolerance should be accompanied by an assessment of local factors that may confound prediction. The presence of power station cooling effluent for example, may raise water temperatures within a port allowing the survival a species in an environment which is otherwise outwith its tolerable range. The establishment of *Diadumene lineata* (Orange-striped green anemone, native to Japan) in an Adelaide power station outfall (*pers comm* Karen Gowlett-Holmes) is a good example.

A formal inductive hazard identification procedure will be used to test for deviations from the expected sea temperature and salinity distributions in the recipient port. This procedure, termed environmental HAZOP, is discussed in detail in Volume II of this report.

[15] Drake (1994) warns against simple physiological tolerance testing in this context because of the potential for phenotypically plastic response. This and other related issues are discussed further in Volume II.

Assessment procedure & data requirements

The level 3 assessment procedure and data requirements are summarised in Table 4.4. The assessment can be implemented once the additional data and analysis requirements highlighted in Table 4.4 have been completed.

Expected benefits

Figure 4.6 illustrates the expected benefits of a level 3 risk assessment. Risk reductions are achieved on the grounds that the water temperature and salinity levels in the recipient ports will lie outside the tolerable limits of a species' life-stage for some proportion of the year.

In this example it is assumed that there is a 90% chance that sea temperature and/or salinity in Port B will be outside the tolerable range of *A. amurensis* larvae during the 10 months that the species is available to vessels ballasting in port D. Consequently there is 90% reduction in the *Asterias* introduction risk at B. Similar considerations apply to vessels trading between Ports D and C. Knock on effects also apply to vessels travelling to port B via C.

The level 3 assessment has no impact on the introduction risk for toxic dinoflagellate cysts. This is because of the extreme environmental tolerances exhibited by dinoflagellate cysts. In this example it is assumed that none of the recipient port environments experience temperatures or salinity levels outside the tolerance of *A. minutum* cysts during the year.

Table 4.4 Level 3 risk assessment procedure

DATA IDENTIFIERS

A	B	C	D	E_D	E_R	$F_{D\&R}$	G
001	001	001	001	001	001	001	001
002	002	002	003	002	002	002	002
010	003	003	009	003	003	006	003
013	004	004	017	004	004	010	004
014	005	005	018	005	005	011	005
015	006	006	019	014	014	012	006
016	011	007	020	015	023	014	007
017	*014*	008	021	018	024	016	008
018		009	022	019	025	017	009
020		010	023	020	026	018	010
021		011	024	023	027	029	011
022		012	025	029	041	030	012
023		013		030	042	031	013
024		014		037	049	032	014
030		015		048	050	033	015
031		016		049	051	034	016
032		017		050	052		017
033		018		051	053		018
034		019		052			023
035				053			024
036				054			025
037							026
038							028
050							029
							032
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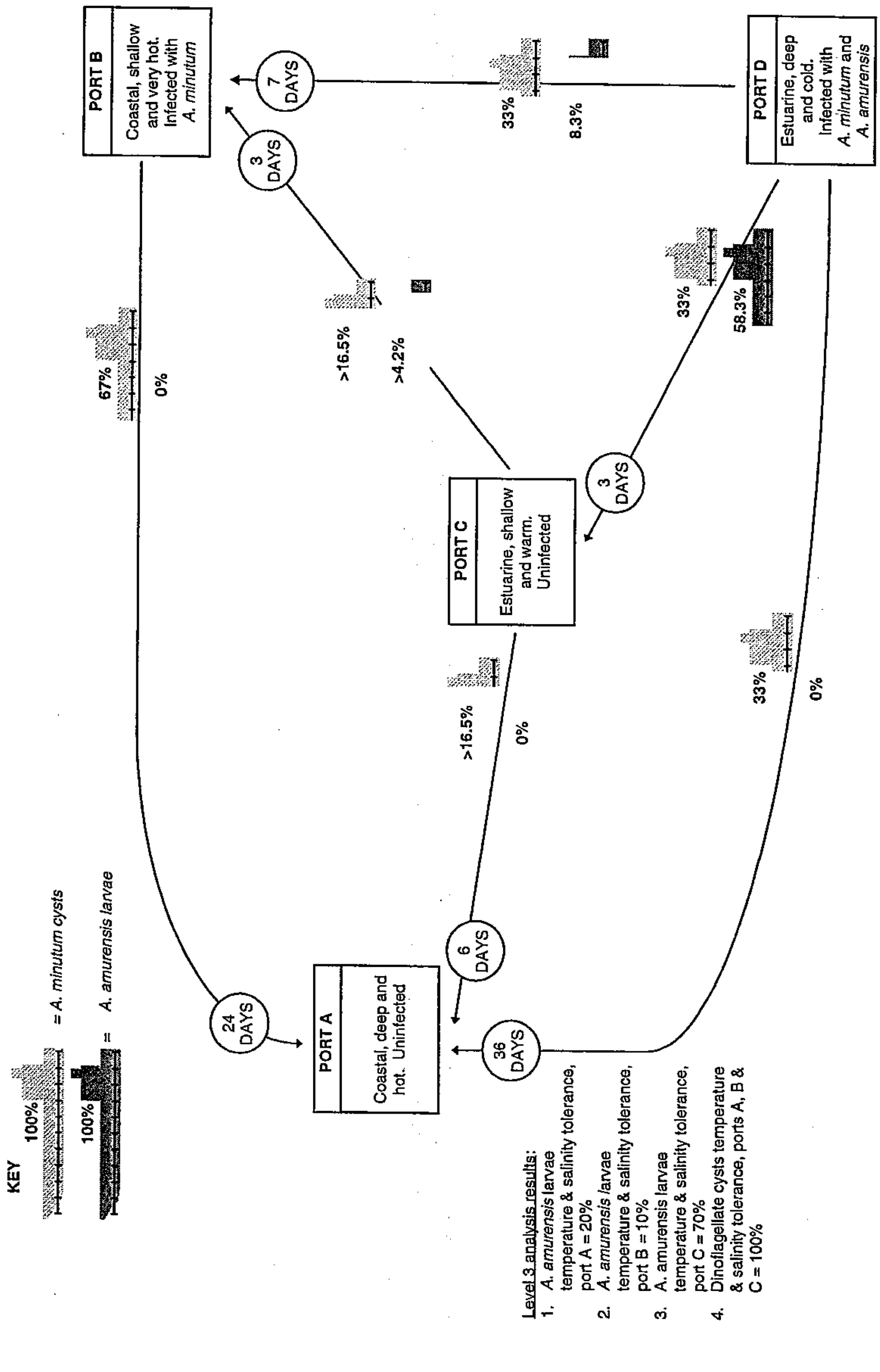
ASSESSMENT PROCEDURE - LEVEL 3

1. Identify port(s) of origin of the vessel's ballast water
2. Select species from target list
3. Verify donor & recipient port infection status with respect to this species
4. Distinguish life-stage sources in contaminated donor ports over study period (one year)
5. Define life-stage distribution in time for donor ports with water-column hazard: postulate simple water column residence time.
6. Identify ports with soft-substrate hazard: identify donor ports with contaminated soft substrate as 'shallow' or 'deep' as a function of vessel, particle, oceanographic and bathymetric characteristics.
7. Identify donor ports with hard-substrate hazard
8. Assume all vessels that ballast during residence time of water-column sourced pest become infected
9. Assume all vessels that ballast within shallow port with soft-substrate hazard become infected
10. Assume all vessels that ballast in port with hard-substrate hazard become infected
11. Test life-stage size & survivability criteria
12. Define vessel infection period
13. Define species life-stage temperature & salinity tolerance for a survival endpoint
14. Define monthly temperature & salinity distribution function for recipient port
15. Undertake temperature & salinity HAZOP for recipient port
16. Define probability of species survival within new port
17. Repeat steps 14 to 16 for each port visited within infection period in which vessel intends to deballast
18. For each port visited within infection period where species is not present, and can survive on the basis of temperature & salinity tolerance, deballasting = risk
19. Quantify risk
20. Select next species and goto 3
21. Repeat steps 2 to 19 for each contaminated port from which vessel draws ballast water

Figure 4.6 Hypothetical level 3 benefits



4.5 Level 4 assessment

Introduction & objectives

The objectives of the level 4 assessment are to:

1. identify those environmental parameters which target species are most sensitive to, and use these to conduct recipient port tolerance testing;

2. provide a better assessment of pest distributions in donor ports with a water-column source hazard, including an assessment of environmental cues for spawning and/or bloom events;

3. model the natural processes of erosion, suspension, transport and settlement, for donor ports with a soft-substrate source hazard;

4. consider the effect of human activity on these processes, and to model any subsequent deviations to the vertical concentration profile of soft-substrate sourced pests;

5. identify hazardous situations in otherwise 'safe' ports using an environmental HAZOP assessment.

The level 4 assessment tests the species tolerance against a larger set of environmental parameters. This must consider the correlation between environmental parameters, and the influence of any one parameter on the response of the species to any other.

The assessment seeks to identify that set of parameters that most completely describes the distribution of a target species, and undertake recipient port tolerance testing with this parameter set. This set will not be same for each species concerned. The tolerance test should therefore be preceded by a bio-geographic distribution analysis to determine those environmental parameters (including habitat) to which the target species is most sensitive. The determination of the species bioregion membership, conducted as part of level ∅, is expected to assist in this process.

The level 4 assessment also provides a better description of the vertical concentration profile of soft-substrate sourced species, and the temporal distribution of water-column sourced species. This will enable a move away from the 'all or nothing' approach advocated in level 2, to a more accurate estimate of vessel infection probability for sediment and plankton sourced organisms.

The vertical concentration profile of soft-substrate sourced species is determined by the natural processes that erode contaminated, soft substrate, and maintain negatively buoyant particles within the water column. Modelling these processes within a donor port environment is an important precursor to the more extensive characterisation of port environments required in the fifth level of the assessment framework.

HAZOP analysis will be used to investigate the effect of human activity on these processes, most notably the movement and berthing of vessels in restricted waterways.

All the elements of level 4 may not be necessary for all ports within the study area. For example those ports free of soft-substrate hazards, or those identified as 'deep' within the level 2 assessment, will not require a detailed examination of their vertical concentration profiles.

Assessment procedure & data requirements

The level 4 assessment procedure and data requirements are summarised in Table 4.5. The assessment can be implemented once the additional data and analysis requirements highlighted in Table 4.5 have been completed.

Expected benefits

The expected benefits of a level 4 assessment are summarised in Figure 4.7. Further risk reductions are achieved because:

1. the recipient port environment is assumed to be less suitable for target species when its suitability is evaluated against three or more parameters as opposed to two;

2. a more accurate (less conservative) assessment of the vertical concentration profile of soft-substrate sourced pests is competed, identifying less vessels as being infected;

3. the assessment quantifies the likelihood that the waters in the vicinity of commercial berths are sufficiently still to allow cyst settlement (this follows from the determination of the vertical concentration profile).

For the purposes of Figure 4.7 it has been assumed that Port C, when evaluated against the temperature, salinity and oxygen tolerances of *A. amurensis* larvae, is suitable for 60% of the year . Similarly Ports B and A are assumed to be available to *A. amurensis* larvae for 5% and 10% of the year respectively.

Ports A and B are assumed to be available to *A. minutum* (in terms of settlement probability) for 30% and 50% of the year respectively. Further reductions are also achieved in the number of vessels departing Port B that are contaminated with *A. minutum* cysts. This is because the vertical concentration profile of these cysts indicates that this port should be classified as 'shallow' for only 10% of vessels.

Table 4.5 Level 4 risk assessment procedure

DATA IDENTIFIERS

A	B	C	D	E_D	E_R	$F_{D\&R}$	G
001	001	001	001	001	001	001	001
002	002	002	003	002	002	002	002
010	003	003	007	003	003	005	003
011	004	004	008	004	004	006	004
012	005	005	009	005	005	010	005
013	006	006	017	014	014	011	006
014	007	007	018	015	023	012	007
015	008	008	019	018	024	013	008
016	009	009	020	019	025	014	009
017	010	010	021	020	026	016	010
018	011	011	022	023	027	017	011
020	013	012	023	028	028	018	012
021	*014*	013	024	029	029	019	013
022		014	025	030	030	020	014
023		015		031	031	022	015
024		016		032	032	023	016
030		017		033	033	024	017
031		018		035	036	025	018
032		019		036	038	026	023
033				037	041	027	024
034				041	042	028	025
035				042	043	029	026
036				047	044	030	027
037				048	045	031	028
038				049	046	032	029
050				050	048	033	030
				051	049	034	032
				052	050	035	033
				053	051		034
				054	052		035
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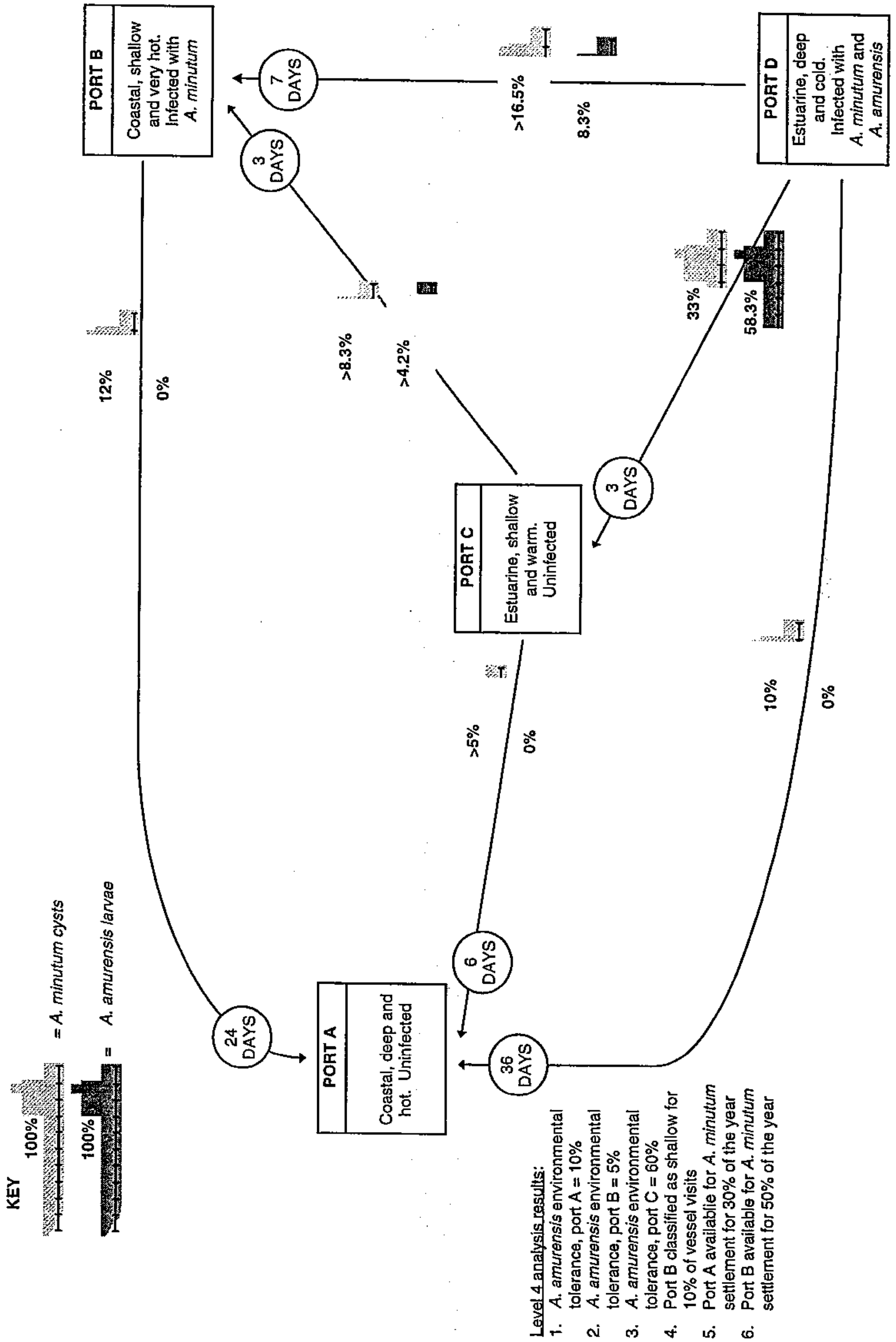
ASSESSMENT PROCEDURE - LEVEL 4

1. Identify port(s) of origin of the vessel's ballast water
2. Select species from target list
3. Verify donor & recipient port contamination status with respect to this species
4. Distinguish life-stage sources in contaminated ports over study period (one year)
5. Define life-stage distribution in time for donor ports with water-column hazard: identify spawning/bloom cues, postulate water column residence time.
6. Define species vertical concentration profile for donor ports in which a soft-substrate hazard exists: identify settling velocity, natural water column velocity vectors and bed shear stress, identify vessel flow field and induced shear stress, test for engineering or other anthropogenic activity in the port
7. Identify ports with hard-substrate hazard
8. Assume all vessels that ballast during residence time of water-column sourced pest become infected
9. Define probability density function for inoculation population for sediment sourced organisms.
10. Assume all vessels that ballast in port with hard-substrate hazard become infected
11. Test life-stage size & survivability criteria
12. Define vessel infection period
13. Define species life-stage n parameter tolerance range for a survival endpoint
14. Define monthly n variate density function for recipient port
15. Undertake port environment HAZOP for recipient port
16. Define probability of species survival in recipient port
17. Repeat steps 13 to 16 for each port visited within infection period in which vessel intends to deballast
18. For each port visited within infection period where species is not present, and can survive, deballasting = risk
19. Quantify risk
20. Select next species and goto 3
21. Repeat steps 2 to 19 for each contaminated port from which vessel draws ballast water

Figure 4.7 Hypothetical level 4 benefits



4.6 Level 5 assessment

Introduction & objectives

Level 5 is the last level in the ballast water risk assessment framework. The objectives of level 5 are to :

1. model the temporal and vertical/horizontal distributions of target species within contaminated ports;

2. define the ballast water withdrawal envelopes described by vessels in donor ports;

3. compare the extent to which the ballast withdrawal envelope overlaps with the pest distribution in the donor port.

At this level the assessment framework is completed by comparing the spatial and temporal distribution of the target species in donor ports, with the ballast water withdrawal envelope described by a ballasting vessel (as a function of the ballast pumping rate and duration, and the strength and direction of ambient currents). From this, the probability distribution function describing the inoculation population, for any ballasting event, can be determined.

Assessment procedure & data requirements

Table 4. 6 summarises the analysis procedure and data requirements of level 5. The assessment can be implemented once the additional data and analysis requirements highlighted in Table 4.6 have been completed.

Expected Benefits

The anticipated benefits of a level 5 assessment are illustrated in Figure 4.8. At this level of assessment benefits occur because the analysis is able to provide a more accurate (less conservative) estimate of the proportion of vessels that are infected whilst ballasting in contaminated ports. This will to lead to a reduction in the number of vessels initially identified as hazardous, which has a knock on effect through-out the analysis as a whole

For the purposes of Figure 4.8 it is assumed that 15% of vessel ballasting in Port B become infected with *A. minutum* cysts. The equivalent figure for port D is 10%. Similarly 60% of vessels ballasting in Port D are assumed to become infected with *A. amurensis* larvae. All other factors in the analysis have been held constant.

Table 4.6 Level 5 risk assessment procedure

DATA IDENTIFIERS

A	B	C	D	E_D	E_R	$F_{D\&R}$	G
001	001	001	001	001	001	001	001
002	002	002	003	002	002	002	002
010	003	003	007	003	003	005	003
011	004	004	008	004	004	006	004
012	005	005	009	005	005	010	005
013	006	006	012	014	014	011	006
014	007	007	013	015	023	012	007
015	008	008	017	018	024	013	008
016	009	009	018	019	025	014	009
017	010	010	019	020	026	016	010
018	011	011	020	021	027	017	011
019	012	012	021	022	028	018	012
020	013	013	022	023	029	019	013
021	*014*	014	023	024	030	020	014
022		015	024	025	031	022	015
023		016	025	026	032	023	016
024		017		027	033	024	017
030		018		028	035	025	018
031		019		029	036	026	023
032				030	037	027	024
033				031	038	028	025
034				032	041	029	026
035				033	042	030	027
036				034	043	031	028
037				035	044	032	029
038				036	045	033	030
050				037	046	034	032
				041	047	035	033
				042	048		034
				047	049		035
				048	050		036
				049	051		037
				050	052		038
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				052			040
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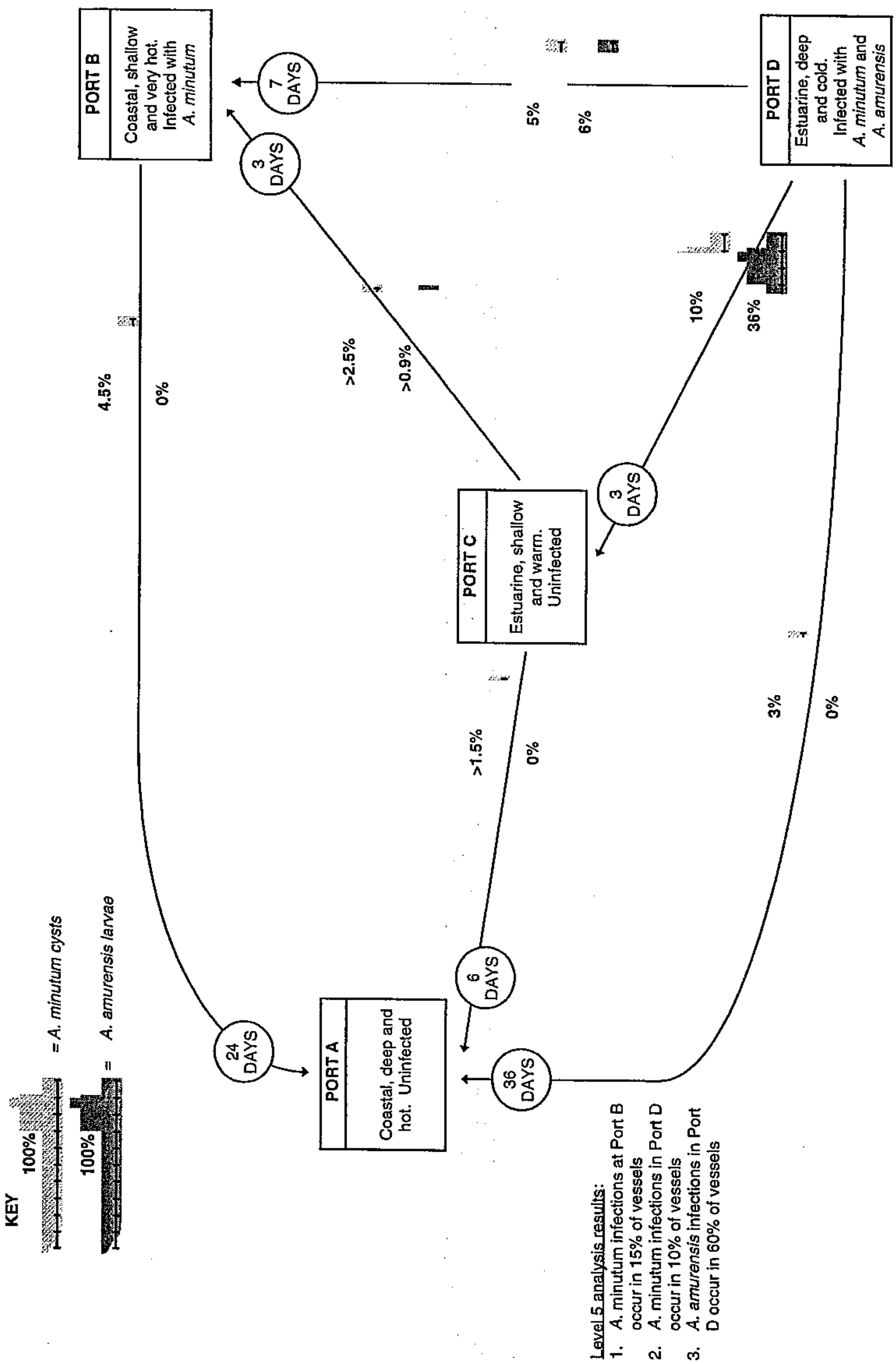
ASSESSMENT PROCEDURE - LEVEL 5

1. Identify port(s) of origin of the vessel's ballast water
2. Select species from target list
3. Map species distribution in contaminated donor ports (utilise GIS)
4. Define life-stage distribution in time and space for water-column source: identify spawning/bloom cues, postulate life-stage water column residence time, postulate water column dispersal patterns in donor port
5. Define species vertical concentration profile for donor ports in which a soft-substrate hazard exists: identify settling velocity, natural water column velocity vectors and bed shear stress, identify vessel flow field and induced shear stress, test for engineering or other anthropogenic activity in the port
6. Identify donor ports with a hard-substrate hazard.
7. Assume all vessels that ballast in port with hard-substrate hazard become infected
8. Define ballast water withdrawal envelope on a case by case basis
9. Test for overlap of life-stage distribution and ballast water withdrawal envelope
10. Undertake (refer to) port processes and berthing HAZOP
11. Test life-stage size & survivability criteria
12. Define probability distribution function for inoculation density for all soft-substrate and water-column sourced life-stages
13. Define vessel infection period
14. Define species life-stage n parameter tolerance range for a survival endpoint
15. Define monthly n variate density function for recipient port
16. Undertake (refer to) port environment HAZOP for recipient port
17. Define probability of species survival within recipient port
18. Repeat steps 14 to 17 for each port visited within infection period in which vessel intends to deballast
19. For each port visited within infection period where species is not present, and can survive, deballasting = risk
20. Quantify risk
21. Select next species and goto 3
22. Repeat steps 2 to 20 for each contaminated port from which vessel draws ballast water

Figure 4.8 Hypothetical level 5 benefits



5 UNCERTAINTY

5.1 Types of Uncertainty

Two types of uncertainty occur in the risk assessment framework[16]:

1. uncertainty caused by the natural or stochastic variation that occurs in the model variables used by the risk assessment framework;

2. uncertainty caused by our incomplete understanding of the biological, physical or anthropogenic systems that are being modelled.

The second of these has been termed 'knowledge uncertainty' (Hession *et al*, 1996). The first can be referred to as model variable uncertainty.

It is also possible to be uncertain about the domain and resolution of the analysis. The domain of the analysis (not to be confused with the risk domain - section 3.3) is determined by the ports which are included in the study area, and the vessels which trade between these ports. Uncertainty regarding the analysis domain is removed by being able to track fixed and unfixed vessels[17] which trade with the ports in the study area.

Note in this context that the management boundaries of a port may not be the most appropriate for the purposes of the risk assessment. In some instances individual ports may be distinguished on the basis of distinct environmental conditions (for example Fremantle inner and outer harbour), restricted circulation patterns (for example the Newcastle Basin), or for other similar reasons.

Uncertainty regarding the resolution of the analysis will be tackled as a compromise between data availability, computational costs and benefit. This will become apparent during the implementation of the risk assessment framework, and will be dealt with accordingly. In the first instance, however, we recommend that the analysis strive for a temporal resolution of one month.

Uncertainty occurs elsewhere in the risk management process (Figure 1.2), particularly in regard to acceptance criteria; what is an acceptable level of risk? This must be determined in relation to the social, economic and environmental goals of the national Ballast Water Management Strategy. The uncertainty associated the framework's estimates of risk is only one of many inputs to this process.

[16] Volume III of the framework documentation provides a more extensive discussion of the types of uncertainty within the framework and how these are addressed in probabilistic terms.
[17] Unfixed vessels are vessels whose next port of call is not fixed in advance but determined by the availability of commercially advantageous trade.

5.2 Uncertainty analysis

Model variable uncertainty

Model variable uncertainty is best tackled through the use of probability density functions[18]. A probability density function is a quantitative way of expressing uncertainty regarding the value taken by a variable within the risk assessment framework.

Geometrically the function describes a line on a graph whose abscissa (horizontal axis) plots the parameter value, and whose ordinate (vertical axis) plots the probability that the parameter takes this value. All probability density functions are indexed by their own parameters, most commonly a location parameter (typically a measure of the 'centre' of the distribution) and a spread parameter (describing the rate at which values of the variable diverge from the centre).

Key decisions that must be taken within the risk assessment concern:

1. the type or form of the probability density function used to represent variables within the model;

2. the values of the function's indexing parameters.

These decisions are usually taken using a mixture of evidence, precedence and classical statistical inference rules.

An alternative statistical approach is provided by Bayes' theorem[19] which proposes simple 'prior' distributions for these variables and then modifies these in light of subsequent data. This data is generated by monitoring procedures that should form an integral part of any risk assessment framework (refer to Figure 1.2). Bayesian techniques allow the accuracy of the assessment to improve with time, emphasising that the development of the framework is as an iterative and progressive process.

Model variable uncertainty will represent the bulk of the uncertainty in the assessment framework because there will be a large number of variables within the analysis. Under these circumstances the effect of this uncertainty is best explored through the use of Monte Carlo simulation.

Monte Carlo simulation involves running a model many times whilst randomly sampling from each probability distribution function specified for the model's variables. This produces a large number of scenarios known as iterations or trials (Vose, 1996). The results of these trials are then plotted as a frequency distribution showing the individual model result and the number of times this occurred within the simulation. Monte Carlo simulation enables the effect of model variable uncertainty to be quantified within a single metric, a cumulative frequency distribution of the model result, and because each distribution is sampled in a manner that reproduces its shape, this metric provides a good reflection of the influence of this uncertainty on the results of the assessment.

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[18] Probability density functions refer to the uncertainty associated with continuos variables, probability mass functions perform the equivalent roles for discrete variables.

[19] A detailed description of Bayesian statistical inference and its potential role in ballast water risk assessment is provided in Volume III of this report.

Knowledge uncertainty

Examples of knowledge uncertainty within the assessment framework include:

1. the potential for flocculation, entanglement or settlement of pest organisms on soft substrates which could alter the predicted vertical concentration profile (level 4);

2. the spawning time of possible sub-populations of pests within port environments which could alter their water column distribution and residence time (level 2 and 5);

3. the behaviour of personnel associated with shipping operations and that of the target species.

This type of uncertainty is the most intractable within the assessment. It can be tackled through a combination of HAZOP analysis and monitoring to test the predictions made by the risk assessment. HAZOP analysis aims to qualitatively identify, for example, the possible effects of extreme values taken by knowledge uncertain variables. The quantitative implications can be investigated through a sensitivity analysis by assigning realistic upper and lower bounds to these variables and investigating the effects on the results of the analysis.

The objective of monitoring and HAZOP analysis is to convert knowledge uncertainty into model variable uncertainty. Additional research and/or targeted sampling can then be implemented to reduce knowledge uncertainty where necessary.

6 DISCUSSION & RECOMMENDATIONS

Discussion

This report provides a blue-print for a quantitative ballast water risk assessment. It identifies the analysis and data needed to complete an assessment of ballast water risk at several levels of complexity.

A methodology for quantitative ballast water risk assessment does not currently exist (Hayes, 1997). The individual components required of such a methodology, however, do. These individual components have been developed in very separate disciplines and often applied to very different problems. The challenge is to draw these separate strands together; this is the purpose of the framework outlined above.

The framework is modular in structure. Individual modules address each of the stages in the ballast water introduction cycle (Figure 2.1), up to the point of survival of a non-native species in a new port environment (the assessment endpoint). The modules allow an assessment of risk to be made at various levels of accuracy, depending on the availability of data. If the data cannot be collected for an analysis at any-one of these levels, then it must be run at a lower level of accuracy. Note, however, that the risk assessment layers need not be those portrayed above. For example tolerance testing for a given species may run at a level 4 accuracy, whilst data gaps force a level 2 pest entrainment analysis, with donor port contamination status assessed at level Ø.

The framework is designed to provide an increasingly accurate assessment of risk progressing from level 0 to level 5. It is not necessary therefore to progress to higher levels of assessment, if an acceptable level of risk is reached at an earlier level. The framework does not, however, define acceptance criteria (refer to section 1.3). This is separate socio-economic decision that must acknowledge the uncertainty in the risk estimate, and the possible consequences of introducing a target species into an environment which is suited to its survival.

A number of other issues arise in relation to the implementation of the framework:

1. the framework need not be implemented through to level 5 for all ports and vessel routes. It is anticipated that level 5 will only be used for those ports (and routes) which are consistently identified as posing a high risk at all preceding levels of the analysis.

2. the amount of data available to the analysis will vary between individual ports, and therefore vessels on different routes will be subject to different levels of analysis. Note that donor ports which operate at lower levels may shift the focus of AQIS sampling activity disproportionately to vessels that operate out of these ports.

3. an assessment of vessel hazard or risk should be made at the earliest possible opportunity, preferably prior to departure from the donor port. If the data requirements are met, then an assessment of vessel hazard or risk can be made as soon as the vessel's departure date and next port of call are known. For fixed vessels this information should be available prior to departure from the donor port. For unfixed vessels, however, this information may be unavailable until the vessel signifies its intention to enter the recipient port.

The successful implementation of the framework also depends on a number of related but separate projects. Determining the infection status of ports and identifying vessel routes provides the initial conditions under which the framework operates. Other projects, such as the survivability of target organisms in ballast water, are aimed at reducing knowledge uncertainty within the framework. Additional projects of this nature may be required in the future. The assessment framework should be used as both a guide for prioritising future research needs, and a means to assess the potential benefits of additional research.

Some of the research required by the framework is being undertaken in various national and international institutions, for often very different problems. Developing collaborative links with these institutions is seen as an important step towards the completion of the framework.

Monitoring is as a critical component of the risk assessment framework. Monitoring requires vessel and port sampling protocols which are designed to:

1. test the predictions of the risk assessment, particularly the distribution and dispersal of target species in port environments, and ballast tank inoculation densities;

2. provide empirical information that will allow a better estimate of the functional form, and indexing parameters, of the probability distribution functions used by the framework.

Bayes theorem provides a unified statistical framework with which the accuracy of the risk assessment can be improved as more empirical information is gathered. The theorem allows the analyst to update his or her prior assumptions regarding key parameters within the framework in light of new information, and is well suited to the iterative development of quantitative risk assessment techniques. The potential application of Bayesian methods to ecological risk assessment, and its adoption as the preferred statistical paradigm of the ballast water risk assessment framework, is explored in Volume III of this report.

The framework is predicated on a target list of non-native species, which are considered marine pests. From a risk assessment perspective, however, each of the species on the current target list can be viewed as representative of a wider set of species. The cysts of *A. minutum*, for example, can be considered as representative of species that exhibit resistant cyst like stages within their life cycle. Similarly the larvae of *A. amurensis* might be considered representative of zooplankton species that become entrained in ballast tanks as planktonic larvae.

The point here is that the processes and determinants of successful translocation by ballast water may be common to a wide variety of species. The practical implementation of the framework will provide a better understanding of these processes, and thereby allow a more extensive assessment of inoculation risk than that based solely on the target list. Furthermore the ballast water management strategies that protect against the introduction of species on the target list are also likely to protect for a much wider range of species within the same set.

Recommendations

In developing the risk assessment framework we have made the following recommendations:

1. that species survival be evaluated against a reference period no greater than 24 hours;

2. that a separate project determine the age at which juvenile or adult stages of target species are too large to pass into ballast tanks;

3. that port contamination status is determined by a port survey for a level 1 assessment onwards.

4. that a separate project investigates the effects of the ballasting process on the subsequent ability of target organisms to survive in the ballast tank;

5. that vessels do not mix ballast water between tanks so that the contamination status of individual tanks can be tracked.

6. that port monitoring systems, similar to the systems used by the FAO to designate Pest Free Areas, are developed to monitor the infection status of ports

7. that the risk assessment strive for a temporal resolution of one month.

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APPENDIX A BALLAST WATER & SEDIMENT MANAGEMENT OPTIONS

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

Water Supply Uptake

1. Specialised 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

(Source: Carlton *et al*, 1995)

APPENDIX B ABWMAC TARGET PEST LIST[20]

Species	Common name	Life stage category[a]
Sabella (=Spirographis) spallanzanii	Sabellid fan worm, European fan worm	Larvae/gametes = meroplanktonic[b]; juvenile/adult = benthic (hard); possibly tychoplanktonic or floating detachable
Carcinus maenas	European shore crab, Green crab, N. Atlantic edible shoe crab	Larvae/gametes = meroplanktonic[b]; juvenile/adults = benthic (hard & soft); possibly tychoplanktonic as juveniles
Asterias amurensis	N. Pacific seastar, Japanese starfish	Larvae/gametes = meroplanktonic[b]; juvenile/adult = benthic (hard & soft); possibly tychoplanktonic as juveniles
Undaria pinnatifida	'wakame'	Gametophytes/sporophytes = benthic (primarily hard some soft associated with seagrasses and shells) and tychoplanktonic; some indication of gametophyte 'ball' formation which may become suspended in water column; possibly floating detachable due to settlement of other algae
Alexandrium catenella *Alexandrium minutum* *Alexandrium tamarense* *Gymnodinium catenatum*	Toxic cyst forming dinoflagellates	Adults = holoplanktonic[b]; cysts = tychoplankton
Musculista senhousia	Asian mussel, Bag or Senhouse's mussel	Larvae/gametes = meroplankton[b]; juvenile/adults = benthic (hard & soft); possibly floating detachable and tychoplanktonic due to settlement on seagrass and algae.
Corbula gibba		Larvae/gametes = meroplankton[b]; juvenile/adults = benthic (soft & some nestling); possibly tychoplanktonic
Crassostrea gigas	Japanese oyster, Pacific (king or rock) oyster	Larvae/gametes = meroplankton[b]; juvenile/adults = benthic (primarily hard but can settle on soft to form oyster beds); possibly tychoplankton as juveniles due to settlement on seagrass and algae
Potamocorbula amurensis	Chinese clam, Asian bivalve	Larvae/gametes = meroplankton[b]; juvenile/adults = benthic (soft and some nestling); possibly tychoplanktonic
Mnemiopsis leidyi	Comb jelly	Adults/larvae = holoplanktonic[b]

a = after Carlton *et al* (1995), b = possible vertical migrators

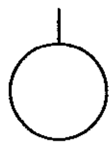
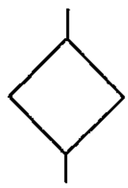
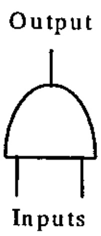
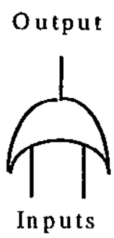
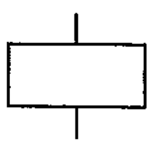
[20] In addition to these species, *Vibrio cholera* and 24 fish pathogens (which have been identified as the causative agents of serious fin and shellfish diseases) have also been earmarked for priority attention. The assessment framework may require minor modification to accommodate bacterial and viral agents of this type, but will remain essentially unchanged so long as the assessment data requirements are met are for each species in question.

APPENDIX C ORGANISMS THAT COULD BE BALLASTED INTO A VESSEL

Category	Member examples
HOLOPLANKTONIC organisms that spend most or all of their life cycle in the water	PHYTOPLANKTON: diatoms, dinoflagellates, blue-green algae, nanoplankton, autotrophic picoplankton and other groups, and ZOOPLANKTON: comb jellies, jellyfish, hydrozoans (siphonophores), polcheate worms, rotifers, gastrotrichs, planktonic gastropods (snails: the pteropods and heteropods), copepods, hyperiid amphipods, isopods, mysids, ostracods, cladocerans, pelagic shrimps, krill (euphausiids), arrow worms (chaetognaths), pelagic tunicates (including salps, doliolids and larvaceans), and FISH
NEUSTONIC organisms that occur at or near the air-sea interface (if carried to the depth of the ballast intake)	The larvae and juveniles of the by-the-wind-sailor Velella, the blue button Porpita, nauplii and cyprids of the barnacle Lepas, and the sea strider Halobates
MEROPLANKTONIC organisms that spend a portion (usually the shorter) of their life cycle in the water column	PHYTOPLANKTON: the dispersal propagules of benthic plants, and ZOOPLANKTON: the larvae of many benthic invertebrates including sponges, sea anemones, corals, hydroids, molluscs (snails including seaslugs or nudibranchs), chitons, mussels, clams, oysters, scallops, crustaceans (barnacles, shrimp, lobsters, crabs, hermit crabs), nemerteans (ribbon worms), sipunculans, polychaete worms, bryozoans, phoronids, echinoderms (seastars, brittle stars, sea urchins, sea cucumbers), hemichordates, tunicates (sea squirts), and the larvae of FISH
MIGRATORY organisms including DEMERSAL organisms that migrate vertically up into the water column at night	These organisms include a variety of small crustaceans (including gammarid amphipods, isopods, mysids, cumaceans, crangonid and other shrimp, and benthic harpacticoid copepods, some fish species and polychaete worms. Other examples include the wood boring gribble *Limnoria*, a tiny isopod crustacean which undergoes nocturnal excursions known as migrations by swimming between wood habitats
TYCHOPLANKTON organisms that get swept up into the water column by tidal currents, waves and ship's propellers, including benthic organisms that could be brought into the vessel with bottom sediment	Examples include forams, flatworms, polychaetes, crustaceans (copepods, amphipods, isopods and tanaids, hydroids, benthic copepods, insect larvae and adults, mites and nematodes, leeches, and oligochaete worms.
FLOATING DETACHED biota including EPIPHYTIC organisms on the blades of floating plants	Examples include seaweeds (algae), seagrasses (eelgrass, Sargassum, turtle grass), marsh plants, spirorbid tubeworms, bryozoans, seasquirts, and sponges, molluscs and crustaceans
DISEASES, PATHOGENS and PARASITES	Marine diseases, pathogens and parasites, including mariculture and aquaculture diseases are transportable by ballast water

(Source; adapted after Carlton *et al*, 1995)

APPENDIX D EVENT SYMBOLS USED IN THE FAULT TREE ANALYSIS

SYMBOL	MEANING OF SYMBOL
	Basic event with sufficient data - basic events indicate the limit of the resolution of the fault tree. These are the events or processes for which data is required in order to undertake the hazard assessment. It is unnecessary to develop fault tree branches beyond these events if data is available
	Undeveloped event - can be contrasted with basic events, indicating that the fault tree could be developed further at this point
	AND gate - output event occurs only if all input events occur simultaneously. For the purposes of the ballast water risk assessment simultaneous is taken to mean within the duration of the vessel's ballast/de-ballasting operation
	OR gate - output occurs if anyone of the input events occur
	Event within the fault tree, text within the rectangle describes the event in question.
	Off page connector

APPENDIX E DATA IDENTIFIERS

E1 Vessel data requirements

Identifier	Description	Type	Units	Notes
A001	vessel name	text		
A002	date built	date	YR	
A003	flag or port registry	text		
A004	call sign	text		
A005	IMO number	numeric		
A006	owner/manager	text		
A007	operator	text		
A008	communication media	text		VHF Channel, TELEX, etc...
A009	available deck voltage	numeric		
A010	type/class of vessel	text		
A011	vessel length	numeric	m	
A012	vessel beam	numeric	m	
A013	vessel draft	numeric	m	
A014	tonnage - GRT	numeric	tonnes	
A015	tonnage - DWT	numeric	tonnes	
A016	total ballast capacity	numeric	m3	
A017	list of ballast tanks and capacity	text/numeric	m3	
A018	dedicated ballast tanks and capacity	text/numeric	m3	number of
A019	number of ballast intakes	numeric		
A020	location of ballast intakes	text/numeric		
A021	ballast tank sieve diameter	numeric	mm	
A022	ballast tank sieve condition	text		
A023	pump make & type	text		
A024	pump rate (max, min, avg)	numeric	m3/s	
A025	number of sea chests	numeric		
A026	location of sea chests	text/numeric		
A027	sea chest size	numeric	m3	
A028	sea chest sieve diameter	numeric	mm	
A029	sea chest sieve condition	text		
A030	engine size	numeric	hp/kW	
A031	max shaft rpm	numeric	rps	max up to level 3 and speed table above
A032	propeller diameter	numeric	m	
A033	propeller type	text		
A034	propeller draft	numeric	m	
A035	number of thrusters	numeric		
A036	make & type of thrusters	text		
A037	location of thrusters	text/numeric		
A038	thrust force of thrusters	numeric	N	
A039	time since last dry docking	time	days	
A040	location of last dry docking	text/Lat/Long		
A041	type of antifouling paint	text		
A042	last in water cleaning (hull)	time	days	
A043	last in water cleaning (propeller)	time	days	
A044	last sea-chest cleaning(s)	time	days	
A045	periodicity of sea-chest cleaning(s)	time	days	
A046	sampling limitations	text		operational safety limitations
A047	ballast exchange limitations	text		operational safety limitations
A048	typical cargo(es)	text		
A049	ballast management plan	binary		presence/absence
A050	ballast log	binary		presence/absence
A051	compliance history	binary		

E2 Voyage data requirements

Identifier	Description	Type	Units	Notes
B001	route	text/numeric/map		account for all ballast on board to 3 to 6 months??
B002	date of departure from LPOC	date	DDMMYY	
B003	date of arrival	date	DDMMYY	
B004	ballast exchange at sea	binary	/tank	see ballast operations
B005	ballast tank temperature	numeric	°C	at sea but temporal scale?
B006	ballast tank salinity	numeric	‰	at sea but temporal scale?
B007	ballast tank DO	numeric	mg/l	at sea but temporal scale?
B008	ballast tank pH	numeric		at sea but temporal scale?
B009	ballast tank nutrients	numeric	ppm	at sea but temporal scale?
B010	ballast tank toxicants	numeric	ppm	at sea but temporal scale?
B011	tugs in attendance at donor ports	text		names/IMO #
B012	tugs in attendance at recipient ports	text		names/IMO #
B013	berths at ports (donor and recipient)			Berth/Port Identifiers
B014	max/min sea state	numeric		Beaufort Scale

E3 (De)Ballast operation data requirements

Identifier	Description	Type	Units	Notes
C001	vessel	text		
C002	ballast tank	text/numeric		
C003	uptake/discharge	binary		
C004	date	date	DDMMYY	of ballast operation
C005	start time of operation	time	24:00:00	
C006	end time of operation	time	24:00:00	
C007	start location of operation	numeric	lat/long	
C008	end location of operation	numeric	lat/long	
C009	vessel draught (start)	numeric	m	
C010	vessel draught (end)	numeric	m	
C011	total volume of uptake/discharge	numeric	m3	
C012	ballasting method	text		(gravity, pump)
C013	maximum pump rate	numeric	m3/s	
C014	ballast intake/outlet(s) used	text/numeric		
C015	salinity	numeric	‰	
C016	turbidity	numeric	??	
C017	bloom event in donor port	binary		bloom event during ballast uptake?
C018	name of port	text		
C019	location in port	text		lat/long or berth identifier

E4 Tug data requirements

Identifier	Description	Type	Units	Notes
D001	vessel name	text		
D002	date built	date	YY	
D003	IMO number	numeric		
D004	owner/manager	text		
D005	operator	text		
D006	communication media	numeric		VHF Channel, TELEX, etc...
D007	vessel length	numeric	m	
D008	vessel beam	numeric	m	
D009	vessel draft	numeric	m	
D010	tonnage - GRT	numeric	tonnes	
D011	tonnage - DWT	numeric	tonnes	
D012	number of sea chests	numeric		
D013	location of sea chests	text/numeric		
D014	sea chest size	numeric	m3	
D015	sea chest sieve diameter	numeric		
D016	sea chest sieve condition	text		
D017	engine size	numeric	hp/kW	
D018	max shaft rpm	numeric	rps	speed table from level 4 onwards
D019	propeller diameter	numeric	m	
D020	propeller type	text		
D021	propeller draft	numeric	m	
D022	number of thrusters	numeric		
D023	make & type of thrusters	text		
D024	location of thrusters	text/numeric		
D025	thrust force of thrusters	numeric	N	
D026	time since last dry docking	time	days	
D027	location of last dry docking	text, lat/long		
D028	type of antifouling paint	text		
D029	last in water cleaning (hull)	time	days	
D030	last in water cleaning (propeller)	time	days	
D031	last sea-chest cleaning	time	days	
D032	periodicity of sea-chest cleaning	time	days	

E5 Port data requirements

Identifier	Description	Type	Units	Notes
E001	name of port	text		
E002	country	text		
E003	latitude	numeric		
E004	longitude	numeric		
E005	charts	numeric		chart numbers
E006	contact officer and position	text		
E007	contact tel	numeric		
E008	contact fax	numeric		
E009	contact telex	alphanumeric		
E010	contact address	text		
E011	port control	text		corp, private, govt
E012	customs officer	text		
E013	quarantine officer	text		
E014	harbour limits	map/numeric		lat/long polygon
E015	commercial berths	numeric		number of
E016	commercial fishing berths	numeric		number of
E017	recreational berths	numeric		number of
E018	periodic engineering activity	text		
E019	planned engineering activity	text		
E020	dredging activity	text/time		
E021	disposal at sea permit	binary		
E022	at sea dumping sites	numeric		location - lat/long polygons
E023	port bathymetry	numeric		
E024	port morphology	text/numeric		
E025	coastal morphology	text		
E026	fluvial geomorphology	text/numeric		
E027	land use	text/map		
E028	tidal periodicity	text/time	hrs	diurnal, semi-diurnal etc...
E029	tidal HHW	numeric	m	monthly resolution
E030	tidal LLW	numeric	m	monthly resolution
E031	tidal diamonds	numeric	m/s	monthly resolution, real time at level 5 if possible
E032	flushing rate	numeric	m/s	monthly resolution
E033	precipitation	numeric	mm	monthly resolution, real time at level 5 if possible
E034	air temperature	numeric	degC	monthly resolution, real time at level 5 if possible
E035	wind	numeric	m/s	monthly wind rose, real time data if possible at level 5
E036	sunlight	numeric	??	monthly resolution, real time at level 5 if possible
E037	port sediment	numeric/text	mm	qualitative level 2, % size fractions descriptors level 4
E038	sediment toxicants	text/numeric	ppm	spatial resolution determined by environment sub-units
E039	water temperature	numeric	degC	max/min per month at level 0-2, at least week at level 3, spatial resolution determined by environment sub-units at level 3
E040	water salinity	numeric	ppt	max/min per month at level 0-2, at least week at level 3, spatial resolution determined by environment sub-units at level 3
E041	water temperature profiles	numeric	degC	temporal & spatial resolution as discussed in E039 (also see berth)
E042	water salinity profiles	numeric	ppt	temporal & spatial resolution as discussed in E039 (also see berth)
E043	water DO profiles	numeric	mg/l	monthly resolution, spatial resolution determined by environment sub-units

E044	water pH profiles	numeric		monthly resolution, spatial resolution determined by environment sub-units
E045	nutrient profiles	numeric	ppm	monthly resolution, spatial resolution determined by environment sub-units
E046	toxicant profiles	numeric	ppm	monthly resolution, spatial resolution determined by environment sub-units
E047	stratification	text/numeric		monthly resolution, spatial resolution determined by environment sub-units
E048	habitats	names		presence/absence at level 1-3, level 4-5 mapped distributions
E049	presence of target pests	text/map		presence/absence at level 0-3, level 4-5 mapped distributions
E050	presence of algal blooms	text/map		presence/absence at level 0-3, level 4-5 mapped distributions
E051	presence of dinoflagellate cysts	text/map		presence/absence at level 0-3, level 4-5 mapped distributions
E052	introduced species survey	last date	ddmmyy	
E053	monitoring for target pests	text/time	ddmmyy	periodicity and method
E054	names of tugs in port	text		
E055	tug SOP including radius of operation	text/numeric	m	dependant on vessel size/class and tidal level
E056	location of anchorages	text/map		
E057	pilotage compulsory?	binary		
E058	pilotage boarding location	text/map		
E059	harbour communications	text		
E060	import cargoes	text		
E061	export cargoes	text		

E6 Berth data requirement

Identifier	Description	Type	Units	Notes
F001	name of berth	text		
F002	berth identifier	code		
F003	date berth built	date	yy	
F004	dates of renovations	date	yy	list dates and renovations
F005	type of berth	text		facing, piles, etc...
F006	name of port	text		
F007	primary import cargo	text		
F008	primary export cargo	text		
F009	length	numeric	m	
F010	min depth	numeric	m	
F011	maximum draught	rel MLW		
F012	minimum draught	rel MLW		
F013	berth bathymetry	numeric	m	
F014	required vessel draught	numeric	m	
F015	loading capacity	numeric	tonnes/hr	
F016	periodic engineering activity	text/time		
F017	planned engineering activity	text/time		
F018	dredging activity	text/time		
F019	tidal diamonds	numeric	m/s	monthly resolution
F020	sediment toxicants	text/numeric	ppm	
F021	env data collection at berth	binary		
F022	water temperature profile	numeric	degC	resolution as per E041
F023	water salinity profile	numeric	ppt	resolution as per E042
F024	water DO profile	numeric	mg/l	resolution as per E043
F025	water pH profile	numeric		resolution as per E044
F026	nutrients profile	numeric	ppm	resolution as per E045
F027	toxicants profile	numeric	ppm	resolution as per E046
F028	stratification	numeric		resolution as per E047
F029	habitats	names		presence/absence at level 1-3, level 4-5 mapped distributions
F030	berth sediment profile	text/numeric	mm	qualitative level 2, % size fractions descriptors level 4
F031	presence of target pests	binary		presence/absence at level 0-3, level 4-5 mapped distributions
F032	presence of dinoflagellate cysts	binary		presence/absence at level 0-3, level 4-5 mapped distributions
F033	introduced species survey	date	ddmmyy	
F034	last monitoring for target pests	date	ddmmyy	
F035	berth occupancy	text/date		vessel name, date and time

E7 Species data requirement

Identifier	Description	Type	Units	Notes
G001	species identifier	alphanumeric		CAAB code
G002	phylum	text		
G003	class	text		
G004	order	text		
G005	family	text		
G006	genus	text		
G007	species	text		
G008	synonymy	text		
G009	common name	text		
G010	potential mis-identification(s)	text		
G011	distinctive characteristics	text		
G012	native distribution	text/map		lat/long, country
G013	introduced distribution worldwide	text/map		country, port
G014	introduced distribution in Australia	text/map		state, port
G015	date of first Australian discovery	date	YY	
G016	location of first Australian discovery	text/map		lat/long, state, port
G017	adult introduction mechanisms	text		
G018	larval introduction mechanisms	text		
G019	economic impacts	text		
G020	ecological impacts	text		
G021	economic benefits	text		
G022	ecological benefits	text		
G023	primary habit	text		epifaunal, infaunal, benthic, planktonic
G024	life cycle	text		benthic/planktonic, mero-, holo-, tycho
G025	diapause/resistance stage	binary		presence/absence
G026	reproductive season	time of year	mm-mm	
G027	spawning cues	text		
G028	developmental period	time	dd	per life stage
G029	settlement cues	text		
G030	progeny/per event	numeric		
G031	adult maturation period	time	dd	
G032	adult survivability index temperature	numeric	degC	
G033	adult survivability index salinity	numeric	ppt	
G034	adult survivability index DO	numeric	mg/l	
G035	adult survivability index pH	numeric		
G036	adult survivability index toxicants	numeric	ppm	
G037	larval survivability index temperature	numeric	degC	
G038	larval survivability index salinity	numeric	ppt	
G039	larval survivability index DO	numeric	mg/l	
G040	larval survivability index pH	numeric		
G041	larval survivability index toxicants	numeric	ppm	
G042	reproductive index temperature	numeric	degC	
G043	reproductive index salinity	numeric	ppt	
G044	reproductive index DO	numeric	mg/l	
G045	reproductive index pH	numeric		
G046	reproductive index toxicants	numeric	ppm	
G047	life stage size range	numeric	mm	range
G048	life stage growth rate	numeric	mm/d	
G049	life stage settling velocity	numeric	m/s	
G050	life stage vertical dispersal	text/numeric	m/s	
G051	life stage horizontal dispersal	text/numeric	m/s	
G052	life stage trophic status	text		consumer/predator
G053	life stage horizontal habitats	text		
G054	life stage vertical habitats	text		
G055	life stage habitat	text		
G056	life stage activity time	time		

G057	life stage activity cues	text
G058	life stage food/prey	text
G059	life stage consumers	text
G060	life stage competitors	text