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Manatū Ahu Matua

In-water cleaning of vessels:

Biosecurity and chemical contamination risks

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1 Executive summary

In-water cleaning of vessel hulls is a tool for both routine maintenance and emergency management of significant biosecurity risk. In-water cleaning supports the good hull husbandry essential for any effective "clean before you leave" initiative to reduce biosecurity risk associated with hull fouling. Any such initiative would also support the efforts of the International Maritime Organisation to reduce greenhouse gas emissions by increasing the fuel efficiency of vessels (IMO 2011).

In many jurisdictions, in-water cleaning is explicitly or effectively banned because it poses two types of environmental risk:

1. The release and accumulation in the marine environment of chemical contaminants from the vessel's hull coating(s); and,
2. The release of non-indigenous species (as adults, larvae or viable propagules) into new environments.

This project investigated the balance between the potential environmental costs and benefits of in-water cleaning as a biosecurity risk management tool. Relative risks of cleaning versus no action were assessed for a number of scenarios with the following prescribed set of parameters (MAF 2011a):

- Vessel origin (international/domestic);
- Vessel type (commercial/recreational);
- Vessel size (6 size classes of commercial vessel, 4 size classes of recreational vessel);
- Antifouling coating type (biocidal/biocide-free);
- Fouling type (slime layer/spot fouling/soft fouling/hard fouling);
- Cleaning method (soft cloth/hand removal/brush);
- Number of vessels cleaned per day (0.00274 to 2);
- Ports and marinas in which cleaning occurs (realistic worst case and typical case); and,
- Whether or not waste-capture technology was used.

Chemical risks were assessed by predicting copper concentrations released during in-water cleaning and comparing these with water quality guidelines (USEPA 1995 and ANZECC 2000 values for acute (4.8 µg Cu/L) and chronic risk (3.1 µg Cu/L), respectively). Copper was chosen as it is the most commonly used biocide in antifouling systems in both commercial and recreational vessels. Copper concentrations were predicted using the Marine Antifoulant Model to Predict Environmental Concentrations (MAMPEC) model. The model parameters and assumptions were derived from an extensive review of relevant literature, industry advice and expert judgement. However, some parameters had a significant level of uncertainty that is carried through to the model outputs.

Biological risks were estimated using expert judgement informed by a review of relevant literature. The judgements of six subject matter experts were combined in a tiered approach using an Infection Modes and Effects Analysis (IMEA) with a *post hoc* consideration of vessel itinerary and the level of fouling (LOF). Individual assessments were combined through a Delphi process.

Modelling of the various cleaning scenarios using the MAMPEC model showed that environmental concentrations of copper could exceed acceptable levels under certain circumstances. The significant factors leading to unacceptable copper concentrations within ports and marinas included the vessel area being cleaned, the number of vessels cleaned per day, and the technique used and rate of flushing.

With respect to the biosecurity risks of in-water cleaning, a LOF ≤ 3 (i.e. ≤ 15% macrofouling cover) appears to be a biologically significant cut-off in terms of the successful application of currently available in-water cleaning technologies. That is, the efficacy of current in-water cleaning technologies decreases when LOF > 3.

In terms of deciding between the use of in-water cleaning versus the option of no action, "acceptable in-water cleaning" was defined as meeting both the biosecurity and chemical acceptability criteria. A key assumption was that chemical and biosecurity risk associated with in-water cleaning are equal. This assumption had a critical influence on the conclusions made.

With respect to the scenarios analysed, the key conclusions of this study were:

- Acceptability of in-water cleaning risk is dependent on factors such as vessel type, level and type of fouling, location, and frequency;
- In-water cleaning is considered unacceptable, even when capture technologies are used, for all international vessel types with a LOF > 3;
- In-water cleaning is considered unacceptable, even when capture technologies are used, for all domestic vessel types with a LOF > 3 and carrying suspected non-indigenous species (NIS).

When in-water cleaning was poses an unacceptable risk, the following mitigation measures were deemed appropriate:

- Haul the vessel out for cleaning;
- Have the duration of the vessel visit reduced to < 48 h; or,
- Refusal of vessel entry.

Key findings for each vessel type were:

- **International commercial vessels**
  - In-water cleaning (with capture of waste) is preferable to not cleaning for vessels arriving with LOF ≤ 3 if their antifouling system is biocide-free.
  - If the antifouling system contains a biocide, in-water cleaning is acceptable when the fouling consists of slime and soft taxa (LOF ≤ 3), but the numbers of vessels cleaned per day should be restricted. Where the fouling consists of hard taxa, however, in-water cleaning is generally not recommended because of the risk of unacceptable chemical contamination. In this situation, it may be acceptable to clean only the sides or boot-tops of the vessel.
- **International recreational vessels**
  - In-water cleaning (with capture of waste) of international recreational vessels arriving with LOF ≤ 3 (i.e. spot fouling) is considered preferable to not cleaning for visits of > 48 h duration.
- **Domestic vessels with biocide-free paints, cleaned at their port of origin**
  - Vessels cleaned in their port of origin are of relatively low biosecurity risk. Consequently, recreational and commercial vessels with biocide-free antifouling systems should be encouraged to in-water clean with capture of waste. If there is a high level of confidence that the fouling is derived from the port where cleaning will take place, it is appropriate to allow in-water cleaning without capture of waste.
- **Domestic commercial vessels with biocidal paints, cleaned at their port of origin**
  - In-water cleaning of vessels with biocidal antifouling systems to remove hard fouling (i.e. aggressive cleaning) is generally not acceptable because of the risk of chemical contamination. In this situation, it may be acceptable to clean only the sides or boot-

    tops of the vessel depending upon specific risk factors, in which case in-water cleaning is deemed an unacceptable risk.
  - Cleaning soft fouling on vessels with biocidal antifouling systems is acceptable but with restrictions on the numbers and size of vessels cleaned per day.
- **Domestic vessels cleaned at the receiving port**
  - Domestic vessels cleaned at the receiving port represent a higher level of biosecurity risk than those cleaned at their port of origin, therefore restrictions on in-water cleaning are consequently greater.
  - For both commercial and recreational vessels with LOF > 3, in-water cleaning in the receiving port is considered unacceptable, even when capture technologies are used.
- **Domestic recreational vessels cleaned at the receiving port**
  - For recreational vessels, in-water cleaning (with capture) by hand removal of spot fouling (LOF ≤ 3) is considered acceptable and is preferred to not cleaning for visits of > 48 h duration.
- **Domestic commercial vessels cleaned at the receiving port**
  - Brush cleaning of hard fouling (LOF ≤ 3) from vessels with biocidal antifouling systems is generally not acceptable because of the risk of chemical contamination. In this situation, it may be acceptable to clean only the sides or boot-tops of the vessel. Otherwise, when the visit is of 2-10 d duration the vessel should not be cleaned. If specific risk factors are present, in-water cleaning is deemed an unacceptable risk. For visits of > 10 d duration, in-water cleaning is deemed an unacceptable risk.
  - Brush cleaning of soft fouling (LOF ≤ 3) from commercial vessels with biocidal antifouling systems is acceptable from the perspective of chemical contamination with some restrictions on numbers and size of vessels cleaned per day. In-water cleaning is not necessary (but is acceptable) for visits of 2-10 d duration depending upon specific risk factors. Where risk factors are present, in-water cleaning should be completed using capture technologies. For visits of > 10 d duration, cleaning (with capture) is preferred to not cleaning when the LOF is ≤ 3.
  - For vessels with biocide-free antifouling systems with either hard or soft fouling (LOF ≤ 3), in-water cleaning is not necessary (but is acceptable) for visit of 2-10 d duration depending upon specific risk factors. Where risk factors are present, in-water cleaning should be completed using capture technologies. For visits of > 10 d duration, cleaning (with capture) is preferred to not cleaning when the LOF is ≤ 3.

A relatively conservative approach was taken in these assessments given the large uncertainty associated with the biosecurity and chemical risks of in-water cleaning versus not cleaning. Current or future methods of cleaning or capture may prove to have better capabilities than indicated by available information, making in-water cleaning more acceptable, even when heavy fouling is present. Further, the adoption of a flexible approach may encourage phased or stepwise development of vessel biofouling cleaning and capture technologies in New Zealand, rather than relying on in-water cleaning offshore. The addition of specific research/evaluation systems to monitor the effects of in-water cleaning will aid in the mitigation/minimisation of impacts. Therefore, the assessments presented in this report need to be kept under review.

There is a shortage of detailed information for many aspects related to the risks of in-water cleaning, and much of the information that is available is subject to considerable uncertainty and to untested assumptions. This inevitably reduces the accuracy and precision of these assessments, from both the chemical and biosecurity perspectives. Consequently, there is a strong need to test the validity of the assumptions made and the risk assessments based on them through experimental studies of the effects of in-water cleaning. In particular, knowledge of copper content of the leached layer of paint and information on the cleaning and capture efficiencies of existing or future technologies will help to reduce uncertainty. Such experimental studies will allow the risk assessments to be updated where required and result in improved confidence.

These assessments provide the most up-to-date basis upon which authorities can determine the appropriateness of in-water cleaning as a biofouling management tool for their own jurisdictions. The benefits of in-water cleaning may be exploited provided that an adaptive management strategy is in place.

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List of abbreviations used in this report.

Abbreviation	Description
APVMA	Australian Pesticides and Veterinary Medicines Authority
ASTM	American Society for Testing Material
BCC	Basic copper carbonate
CDP	Controlled depletion polymer [antifouling coatings]
CEPE	European Council of the Paint, Printing Ink and Artists' Colour Industry
CRMS	Craft Risk Management Standard
DAFF	[Australian Government] Department of Agriculture, Fisheries and Forestry
DBTDL	Dibutyltin dilaurate
DFT	Dry film thickness
DOC	Dissolved organic carbon
EPA	Environmental Protection Authority [New Zealand] (previously ERMA)
EPS	Extracellular polymeric substances, or exopolysaccharide
ERMA	Environmental Risk Management Authority [New Zealand] (now EPA)
FPSO	Floating Production, Storage and Offloading Unit
FR	Foul(ing) release [coating]
FSU	Floating Storage Unit
HEP	Harbour exposed panels
HSE	Health and Safety Executive [UK]
IACS	International Association of Classification Societies
IAFS	International Anti-Fouling System [Certificate]
IMO	International Maritime Organization
ISO	International Organization for Standardization
MAF	[New Zealand] Ministry of Agriculture and Forestry (now MPI)
MAMPEC	Marine Antifoulant Model to Predict Environmental Concentrations
MPI	[New Zealand] Ministry for Primary Industries (previously MAF)
MSDS	Material Safety Data Sheet
NIS	Non-indigenous species
NIWA	National Institute of Water and Atmospheric Research Ltd. [New Zealand]

Abbreviation	Description
NSSC	[United States] Naval Sea Systems Command
OPRF	Ocean Policy Research Foundation [Japan]
PDMS	Polydimethylsiloxane
PEC	Predicted environmental concentration
PRMA	Pest Management Regulatory Agency [Canada]
PTFE	Polytetrafluoroethylene
REMA	Regulatory Environmental Modelling of Antifoulants
RFP	Request for Proposals
RMA	Resource Management Act
SCAMP	Submersible cleaning and maintenance platform
SPC	Self-polishing copolymer [antifouling coatings]
SPM	Suspended particulate matter
STC	Surface treated coating
TBT	Tributyltin [antifouling biocide]
TBTMA	Tributyltin methacrylate
TWSA	Total wetted surface area
UNDS	Uniform National Discharge Standards
USEPA	[United States] Environmental Protection Agency
USES	Uniform Systems for Evaluation of Substances
USN	United States Navy
WHOI	Woods Hole Oceanographic Institution

1. Introduction

1.1 PROJECT CONTEXT

Since the advent of seafaring, vessel biofouling has troubled mariners through its effects on speed, manoeuvrability, operability and durability (Schultz et al. 2010, IMO 2011). Today, in a world dependent on international shipping, biofouling is additionally recognised for its potential impact on the global environment by compounding CO_2 emissions from ships (IMO 2011) and facilitating the translocation of species (Bell et al. 2011). Addressing these risks has proven complex, due to the limitations of available preventive technology, and uncertainty regarding the environmental risks of management methods, such as the use of biocidal antifouling paints or uncontrolled in-water hull cleaning.

To reduce the biosecurity risk of vessel biofouling, the New Zealand government is considering a range of management options including how to support best practice hull maintenance for vessels that ply New Zealand waters.

In-water cleaning of vessel hulls is a tool for both routine hull maintenance and emergency management of significant biosecurity risk. In-water cleaning supports the good hull husbandry essential for any effective “clean before you leave” initiative to reduce the accumulation of biofouling. Any such initiative would also support the efforts of the International Maritime Organisation (IMO) to reduce green house gas emissions by increasing the fuel efficiency of vessels (IMO 2011).

In-water cleaning has been identified as an ongoing hull maintenance tool to manage biofouling risk in international guidance provided by the IMO (Annex 26 of Resolution MEPC.207(62)). The guidelines suggest, however, that it may be appropriate for Member States to conduct an assessment of the risks of in-water cleaning in the form of:

- Biosecurity risk from organisms removed from the hull (including viability of the material and the ability to capture it);
- The geographical source of the biofouling; and,
- Toxic effects related to the release of antifouling compounds during cleaning.

In response to the preparation and release of the IMO guidelines, Australia and New Zealand have updated the Code of Practice for Anti-fouling and In-water Hull Cleaning and Maintenance (ANZECC 1997; MAF 2011b). Similar to the IMO guidance, the Anti-fouling and In-water Cleaning Guidelines recommend that, where the removal of the vessel from the water is not practicable, in-water cleaning may be permitted if the risks are deemed acceptable (MAF 2011b).

The shipping industry seeks certainty with respect to the appropriateness of in-water cleaning tools. Therefore, regulators need to be able to provide guidance such as when the activity could be discretionary, permitted or prohibited under New Zealand’s Resource Management Act (RMA) legislation. This advice would also be relevant to decision-making in emergency situations. However, delivery of regulatory advice on the utility of in-water cleaning tools requires a solid evidence base.

1.2 PROJECT OBJECTIVES

The primary objective of this project was to determine *When do the environmental costs of releasing non-indigenous species and chemical contaminants during in-water cleaning outweigh the risk of no action?* In exploring this question, an evidence base for the chemical and biological risks will be created and allow authorities to refine the assessment of risk to best fit their needs.

1.3 PROJECT SCOPE

The scope of this study was limited to assessing the risks of in-water cleaning relative to the option of no action in the context of currently available technology.

A literature review was undertaken with the solicitation of expert advice regarding the release of contaminants of chemical and biosecurity risk as a result of in-water cleaning. This information was used to answer the following questions (MAF 2011a):

1. What are the (chemical) contaminant levels in the water column following in-water cleaning?
2. What are the (chemical) contaminant levels in the previous question equivalent to in terms of vessel numbers at typical leaching rate?
3. Is there a difference between the (chemical) emissions released from an in-water cleaned vessel, a vessel that has been hauled out and cleaned, and a newly anti-fouled vessel?
4. What is the likelihood of tributyltin (TBT) release from vessels following in-water cleaning? What would be the likely emission rate and environmental concentrations of TBT following in-water cleaning?
5. What types and levels of fouling organisms are likely to be released as a result of in-water cleaning? What is the viability of this contamination?
6. Is there a significant difference in risk between the outcome of the previous question and the management option of taking no action?
7. What conditions applied to in-water cleaning methods would ensure the management of contaminant release (chemical/biological) to acceptable levels into the surrounding environment?
8. When do the environmental costs of non-indigenous species and chemical contaminants released following in-water cleaning outweigh the risk of no action?

Within the above questions, specific cleaning scenarios were prescribed for consideration (Table 1.1, MAF 2011a). These specified:

- Vessel origin (international/domestic);
- Vessel type (commercial/recreational);
- Vessel size (6 size classes of commercial vessel, 4 size classes of recreational vessel);
- Antifouling coating type (biocidal/biocide-free);
- Fouling type (slime layer/spot fouling/soft fouling/hard fouling);
- Cleaning method (soft cloth/hand removal/brush);
- Number of vessels cleaned per day (0.00274 to 2, i.e. 1 to 730 vessels per year);
- Ports and marinas in which cleaning occurs (realistic worst case and typical case); and,
- Whether or not waste-capture technology was used.

Table 1.1 Summary of the cleaning scenarios prescribed for consideration by this project. Scenario codes were allocated for ease of reference.

Scenario Code	Vessel origin	Type of vessel	Paint type	Cleaning	Capture?
1	International	Recreational	Biocide	Spot fouling, no action*	Not applicable
2				Spot fouling, hand removal	Yes
3				Spot fouling, hand removal	No
4				Slime layer, no action	Not applicable
5				Slime layer, soft cloth	Yes
6				Slime layer, soft cloth	No
7			Biocide-free	Spot fouling, no action	Not applicable
8				Spot fouling, hand removal	Yes
9				Spot fouling, hand removal	No
10				Slime layer, no action	Not applicable
11				Slime layer, soft cloth	Yes
12				Slime layer, soft cloth	No
13		Commercial	Biocide	Slime layer/soft fouling, no action	Not applicable
14				Slime layer/soft fouling, brush cleaning	Yes
15				Slime layer/soft fouling, brush cleaning	No
16				Hard fouling, no action	Not applicable
17				Hard fouling, brush cleaning	Yes
18				Hard fouling, brush cleaning	No
19			Biocide-free	Slime layer/soft fouling, no action	Not applicable
20				Slime layer/soft fouling, brush cleaning	Yes
21				Slime layer/soft fouling, brush cleaning	No
22				Hard fouling, no action	Not applicable
23				Hard fouling, brush cleaning	Yes
24				Hard fouling, brush cleaning	No
25	Domestic	Recreational	Biocide	Spot fouling, no action	Not applicable
26				Spot fouling, hand removal	Yes
27				Spot fouling, hand removal	No
28				Slime layer, no action	Not applicable
29				Slime layer, soft cloth	Yes
30				Slime layer, soft cloth	No
31			Biocide-free	Spot fouling, no action	Not applicable
32				Spot fouling, hand removal	Yes
33				Spot fouling, hand removal	No
34				Slime layer, no action	Not applicable
35				Slime layer, soft cloth	Yes
36				Slime layer, soft cloth	No
37		Commercial	Biocide	Slime layer/soft fouling, no action	Not applicable
38				Slime layer/soft fouling, brush cleaning	Yes
39				Slime layer/soft fouling, brush cleaning	No
40				Hard fouling, no action	Not applicable
41				Hard fouling, brush cleaning	Yes
42				Hard fouling, brush cleaning	No
43			Biocide-free	Slime layer/soft fouling, no action	Not applicable
44				Slime layer/soft fouling, brush cleaning	Yes
45				Slime layer/soft fouling, brush cleaning	No
46				Hard fouling, no action	Not applicable
47				Hard fouling, brush cleaning	Yes
48				Hard fouling, brush cleaning	No

* Levels of fouling above spot fouling on recreational vessels was not originally included in this assessment based on cost of in-water cleaning, the biosecurity risk and availability of haul out facilities in New Zealand (Inglis et al. 2011). However, this scenario is assessed later in the document due to considerations based on the levels of fouling.

1.4 STRUCTURE OF THIS REPORT

To emphasise the main objective of the study, the structure of this report differs from the sequence of questions listed above. It begins (Section 0) by addressing the question *When do the environmental costs of releasing non-indigenous species and chemical contaminants during in-water cleaning outweigh the risk of no action?* This is done with reference to the literature reviews (Sections 3 and 4), and Questions 1-7 (Sections 5 and 6).

An analysis of knowledge gaps and an outline of further research to address those gaps forms an important part of this research project. These are discussed in Section 2.5. All references are included at the end of the report (Section 9).

2 When do the environmental costs of releasing non-indigenous species and chemical contaminants during in-water cleaning outweigh the risk of no action?

2.1 SUMMARY OF THE CHEMICAL CONTAMINATION RISKS OF IN-WATER CLEANING

Literature of the chemical contamination risks of in-water cleaning is reviewed in Section 3.

Copper is the most common active ingredient in antifouling paints, as it is toxic to many marine organisms at low concentrations (e.g. µg/L; Arnold 2005). Copper is therefore the primary contaminant of interest with respect to in-water cleaning of vessel hulls, and as such it provides a good proxy for estimates of chemical contamination risk.

The process of in-water cleaning is known to the release a pulse of biocide into the environment (Floerl et al. 2010a). The magnitude of this pulse is dependent on a range of factors therefore, estimation of the chemical contaminant levels in the water column following in-water cleaning was determined in relation to six different scenarios (Table 1.1, MAF 2011a):

- Hand removal (spot fouling – recreational vessels);
- Soft cloth (slime layer fouling – recreational vessels);
- Brush system (slime layer/soft fouling, full hull-commercial vessels);
- Brush system (slime layer/soft fouling, niche areas-commercial vessels);
- Brush system (hard fouling, full hull – commercial vessels); and,
- Brush system (hard fouling, niche areas – commercial vessels).

In-water cleaning can release biocides from three sources during in-water cleaning: biofilms, the leached paint layer, and the sound paint layer. Using values derived from the literature review and discussion with experts, copper emission rates were estimated for in-water cleaning of commercial and recreational vessels for a range of paint types (self-polishing copolymer [SPC], ablative and hard) and cleaning methods (soft and aggressive).

Estimated emission rates indicate that in-water cleaning may result in the release of large amounts of total copper. On recreational vessels this could be up to 1 kg, and on commercial vessels, up to 68 kg for soft cleaning methods and 300 kg for aggressive cleaning methods (Section 5.2.1). The potential impacts of copper are based on its form (total versus dissolved), and discharges/emissions are rapidly reduced by dilution and binding to dissolved organic carbon (Arnold 2005; Arnold et al. 2005; Gadd et al. 2011). As a result, these estimates may not have the environmental impact that could be expected based on mass alone.

The estimated copper emission rates for five of the scenarios were input into the Marine Antifoulant Model to Predict Environmental Concentrations (MAMPEC) model to estimate environmental concentrations (http://www.deltares.nl/en/software/1039844/mampec). The scenario "Hand removal (spot fouling – recreational vessels)" was not included as this would not be expected to cause significant copper emissions (Section 5.2.1).

Clearance of chemical inputs from in-water cleaning is influenced by the flushing environment in which they are released (Gadd et al. 2011). Therefore, low-flushing locations (Half Moon Bay Marina and Lyttelton Port) and high flushing locations (Westhaven Marina and Auckland Port) were modelled to take this factor into account (Gadd et al. 2011). Scenarios from Lyttelton Port and Half Moon Bay Marina are the most conservative estimates of risk because their enclosed natures lead to reduced flushing. Therefore, from the perspective of chemical contamination, cleaning scenarios acceptable in these locations are likely to be acceptable at all other ports and marinas, respectively (i.e. these locations represents realistic worst cases; Gadd et al. 2011). Within these four locations, different numbers of vessels, vessel sizes, areas cleaned and coating types were modelled. For each of the scenarios assessed, both a low and a high estimate of copper emission was modelled due to high uncertainty in the copper content of the leached surface of the paint coating and the significant contribution of this layer to copper emission (Section 5.2.2).

For the risk assessment, acute criteria (dissolved copper < 4.8 µg/L; USEPA 1995) and guidelines for protection of 90% of aquatic species (dissolved copper < 3 µg/L; ANZECC 2000) were applied to illustrate the relevant level of contamination for different scenarios within marinas and ports:

- Low risk: the average predicted environmental concentration (PEC) below the ANZECC 90% protection guideline;
- Medium risk: the average PEC above the ANZECC 90% protection guideline but below USEPA acute criteria; and,
- High risk: the average PEC above USEPA acute criteria.

Although the chronic criteria may seem a stringent use, the in-water cleaning scenarios assume a number of vessels are cleaned per day, rather than the in-water cleaning being a ‘one-off’ event. If the scenarios are based on a single vessel being cleaned followed by a period of no action, the application of chronic criteria would be too conservative. In this study, chronic criteria have been applied to scenarios where > 100 are vessels cleaned per year (i.e. > 0.274 vessels cleaned per day).

PECs in an area immediately surrounding a vessel being cleaned are well in excess of the USEPA acute criterion for copper. For commercial vessels being cleaned by soft cleaning, the criterion is expected to be exceeded within a zone up to 140 m away. For commercial vessels being aggressively cleaned, the criterion is expected to be exceeded within a zone extending more than 350 m from the vessel.

Even when based on the upper copper release estimate, the in-water cleaning of recreational vessels generally present a low risk of chemical contamination (Section 5.2.9; Table 2.1). Low-flow environments however, had less capacity for in-water cleaning with larger vessel numbers and/or size of vessels resulting in increased risk. When PECs were based on the low copper release estimate, a low risk was indicated for all scenarios in both marinas (Section 5.2.9).

Table 2.1 Summary of the risks for in-water cleaning of recreational vessels with soft cleaning, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
HMB [1]	25	5-11	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	76	11-20	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	148	21-30	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	269	31-40	Low risk	Low risk	Low risk	Low risk	High risk	High risk
WHN [2]	25	5-11	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	76	11-20	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	148	21-30	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	269	31-40	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Note: [1] HMB = Half Moon Bay Marina; [2] WHN = Westhaven Marina.

For in-water cleaning of commercial vessels using soft cleaning methods, most scenarios indicate a low risk based on mixing within the Port of Auckland (Table 2.2). There is a greater likelihood of guideline exceedance for in-water cleaning within Lyttelton Port, particularly for > 0.137 vessels per day or for vessels larger than 100 m (Table 2.2). This can be attributed to the low flushing associated with this port (Gadd et al. 2011).

The likelihood of exceedance is increased for in-water cleaning using aggressive cleaning methods and the upper copper release estimate (Table 2.3). A medium or high risk exists for the majority of aggressive cleaning scenarios within Lyttelton Port.

Table 2.2 Summary of the risks for in-water cleaning of commercial vessels with soft cleaning, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Medium risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	High risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk

Table 2.3 Summary of the risks for in-water cleaning of commercial vessels with aggressive cleaning, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	3,231	100-150	Low risk	Low risk	Medium risk	High risk	High risk	High risk
	6,333	150-200	Low risk	Low risk	High risk	High risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	High risk	High risk	High risk	High risk
	15,640	250-300	Low risk	Medium risk	High risk	High risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	Medium risk	High risk	High risk

The number of medium and high-risk scenarios in each port is reduced if the modelling is based on lower copper release estimates. For soft cleaning, all scenarios indicate a low risk in Port of Auckland. In Lyttelton Port, cleaning > 0.137 vessels per day that are > 200 m in length or > 0.274 vessels per day that are > 100 m in length indicate a medium or high risk. However, for aggressive cleaning, many combinations of vessel numbers and sizes indicate a high risk in both ports (Section 5.2.9).

The volume of copper released in the above scenarios is related to total wetted area of the vessel hull. However, for operational reasons it is likely that in-water cleaning carried out as routine maintenance will focus on the sides or boot-top, as these locations are difficult to prevent fouling on and are easily accessible. As expected, the cleaning of only vessel sides or boot-tops reduced the number of medium and high risk scenarios. For example, all scenarios for cleaning only boot-tops indicate a low risk in the Port of Auckland while for Lyttelton Port, only higher cleaning frequencies of larger vessels indicate medium or high risks (Table 2.4).

Table 2.4 Summary of the risks for in-water cleaning of commercial vessels boot-tops with aggressive cleaning, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Whilst in-water cleaning of recreational vessels is only expected to exceed the acute criterion for a limited number of scenarios, background concentrations within marinas require consideration (Table 2.1). Aggressive cleaning of commercial vessels is expected to exceed the acute criterion for many scenarios and should therefore be discouraged. The number of vessels undergoing in-water cleaning should be restricted and in some cases, the cleaning could be limited to niche areas such as the sides and boot-tops only. However, even cleaning of niche areas (boot tops or vertical sides) may exceed the acute criterion under some scenarios.

2.2 SUMMARY OF THE BIOSECURITY RISKS OF IN-WATER CLEANING

In-water cleaning poses a biosecurity risk due to its potential to facilitate the release of non-indigenous species. There is a paucity of information on the cleaning and/or recapture efficacy of current in-water cleaning technologies. This creates significant uncertainty regarding the potential propagule pressure.

Soft-cloth removal of slime layer fouling is likely to release significant amounts of microbial material into the marine environment (including bacteria, fungi, microalgae, protists and microscopic stages of macrofouling species).

Without capture, hand removal of spot fouling is likely to release significant amounts of soft (including ascidians, bryozoans, hydroids, macroalgae), motile (such as crustaceans, gastropods, errant polychaetes) and hard (including barnacles, bivalves, sedentary polychaetes) fouling.

Brush-based removal of slime layer/soft fouling without capture is likely to release significant amounts of slime, soft and motile fouling. Without capture, brush-based removal of hard fouling is likely to release significant amounts of slime and hard fouling. Motile organisms living among the sessile fouling may also be released. The proportion of material removed will be much smaller than for the cleaning of soft fouling and may be very low for taxa such as barnacles and polychaetes living in calcareous tubes.

Although diver-assisted cleaning methods may overlook some patches, automated brush-based systems may clean less thoroughly than diver-operated systems (Davidson et al. 2008). Surface micro-topography may affect successful removal of microscopic organisms, including microscopic stages of macrofouling species.

Much or all of the material removed via in-water cleaning may remain viable and capable of establishing in the receiving environment (Woods et al. 2007). Clonal organisms (such as colonial ascidians, bryozoans and sponges); organisms capable of regeneration from fragments (such as some macroalgae and polychaetes); and mobile organisms are most likely to establish. However, microscopic stages of macrofouling species may no longer be competent to resettle.

Biosecurity risks associated with in-water cleaning may be mitigated by capturing the waste released, but the technology currently available in New Zealand is limited. During soft-cloth cleaning of slime layer, the entire hull will be cleaned and the likelihood of the diver collecting all the material released while cleaning such a large area is small. Material is also likely to fragment, float and/or pass through a mesh bag.

Information on the recapture efficacy for material released by hand cleaning of spot fouling is scarce. The amount of material (hard/soft fouling) released is likely to be small and, assuming the diver uses (for example) a net bag around the area being cleaned, it is likely that most of it can be captured as it is scraped off. Some loss of material around the edges of the bag may occur, particularly in strong currents (Floerl et al. pers. comm.).

Cleaning systems using hand-operated brushes captured on average ~ 95% (minimum 90%, maximum 99%) of material removed from the hull, but less when the level of fouling was high or on curved surfaces. Material not captured represented about 1% of total material removed in an experimental study (Hopkins & Forrest 2008). However, it is difficult to quantify how much small material (e.g. gametes) was released, further the 1% lost could equate to a significant volume of material presenting a biosecurity risk.

While general information relevant to assessing the biosecurity risks from in-water cleaning exists, these risks are dependent on a large number of confounding factors (such as effects of local environmental conditions at the time of cleaning, the detailed composition of fouling assemblages and the reproductive status of their components; Floerl et al. 2010a)). There is currently insufficient information available to allow a quantitative assessment and ranking of risks from the various prescribed in-water cleaning scenarios or the option of no action.

Because of this lack of quantitative information, any attempt to address the question “is there a significant difference in risk between in-water cleaning and the option of no action?” was reliant on expert judgement, informed by the results of the literature review. A three-tiered approach was used to address this question:

1. An Infection Modes and Effects Analysis (IMEA) allowed the assessments of the relative biosecurity risks of each cleaning scenario by six subject matter experts to be combined in a transparent way. This provided a first-cut assessment of relative risk and identified that the duration of vessel visits needed to be included in the analysis (Section 6.2.2);
2. Those scenarios not clearly identified as posing an acceptable or unacceptable biosecurity risk in Tier 1 were assessed in more detail, taking duration of visit into account (i.e. increased opportunity for gamete release) (Section 6.2.3); and,
3. The same suite of scenarios was then assessed, taking level of fouling (LOF; i.e. greater potential propagule load and diversity) into account (Section 6.2.4).

As tier 1 of the IMEA process did not take duration of vessel visit into account, it was deemed to be applicable for vessel visits of short duration only (< 48 h in the context of this study). The tier 1 IMEA assessment of risk resulted in a preference to avoid unnecessary disturbance of biofouling for vessel stays of less than 48 h.

Taking duration of visit into account resulted in a variety of different decisions based on the potential biosecurity risk associated with the different types of fouling and vessel origin. For example, in the case of international commercial vessels:

- For visits of 2-10 d duration:
  - in-water cleaning of hard fouling was preferred to the option of no action because of the risk of "natural" propagule release from this type of fouling; and,
  - the option of no action was preferred with respect to a vessel with slime layer/soft fouling because of the risk of "natural" propagule release from this type of fouling was considered to be less than propagule release from cleaning.
- For visits of 10-21 d duration:
  - cleaning of international commercial vessels was preferred for both types of fouling because of the increasing risk of "natural" propagule release from an uncleaned hull over time.

Hand-cleaning of spot fouling on international recreational vessels was considered to be of lower biosecurity risk than that of commercial vessels because of the smaller amount of material that could potentially be released.

Release of propagules from uncleaned hulls of domestic vessels was considered less of a biosecurity risk than that from international vessels (Inglis et al. 2010).

LOF was taken into account as a further refinement of the IMEA process (Floerl et al. 2005a and Section 6.2.4), where:

- LOF < 2: clean hull or slime layer only;
- LOF 2: 1-5% cover of macrofouling;
- LOF 3: 6-15% cover, still patchy; and,
- LOF 4 and 5: 16-100% cover, extensive fouling.

This assessment also considered the location of domestic vessel in-water cleaning (i.e. at the vessel's port of origin or at the receiving port).

Taking LOF into account had a considerable influence on assessments of biosecurity risk. The risk of propagule release from vessels with heavy fouling (LOF > 3) was deemed to be high and increasing with visit duration. The use of cleaning with capture was also considered to present an unacceptable risk for heavily fouled vessels due to less efficient capture and the reduced efficiency of cleaning.

The biosecurity risk from in-water cleaning was considered to be acceptable where the LOF ≤ 3 and the vessel's duration of visit was greater than 48 h. Where possible, out-of-water cleaning was considered preferable due to the significant uncertainty with regard to the capture efficacy of current cleaning technologies.

Pragmatically, the risk of slime layer cleaning is acceptable, as it is currently not possible to manage biofouling below this level and in-water cleaning is unlikely to significantly raise the risk posed (Bell et al. 2011). Similarly, the risk of in-water cleaning may be low, where the origin of fouling can be established with some reliability. For example, vessels that have arrived clean and spent an extended period in local waters are not likely to have species of internationally based biosecurity concern. These vessels can be cleaned in support of the "clean before you leave" strategy that support global risk reduction efforts.

2.3 SUMMARY OF THE RELATIVE BIOSECURITY AND CHEMICAL CONTAMINATION RISKS OF IN-WATER CLEANING VERSUS NO ACTION

In their review of biosecurity and contaminant risks associated with in-water cleaning, Floerl et al. (2010a) concluded that "…in-water cleaning of vessel hulls is not viable as a mitigation option when it causes a significant increase in the rate at which organisms, propagules or biocidal contaminants are released into the environment, relative to baseline". It is this tipping point, where the environmental costs of releasing non-indigenous organisms and chemical contaminants during in-water cleaning outweigh those of no action ("baseline") that is the focus of the present study.

The chemical and biosecurity risks of different cleaning scenarios were compared to taking no action. The higher relative risk (biosecurity or chemical) was taken as the overall environmental risk of the cleaning scenario. This approach assumes that biosecurity and chemical risks have the same weight, which is considered to be a conservative approach reflecting the high degree of uncertainty around the relative risk.

The combined risk assessment was done in two parts. To identify scenarios of unacceptable risk, results of the tier 1 biosecurity assessment (IMEA) were compared with the chemical assessment (Part 1). Those scenarios that required further consideration (i.e. taking duration of vessel visit and LOF into account) were compared with the chemical assessment to provide an overall risk decision for each of these scenarios (Part 2).

Biosecurity and chemical risks associated with in-water cleaning are influenced by many environmental and vessel-related factors, making it difficult to identify theoretical "tipping points" between the relative risks of in-water cleaning versus no action. However, there are some conditions where the current state of technology means that the risk of in-water cleaning is deemed unacceptable.

With respect to the scenarios analysed, the key conclusions of this study were:

- Acceptability of in-water cleaning risk is dependent on factors such as vessel type, level and type of fouling, location, and frequency;
- In-water cleaning is considered unacceptable, even when capture technologies are used, for all international vessel types with a LOF > 3;
- In-water cleaning is considered unacceptable, even when capture technologies are used, for all domestic vessel types with a LOF > 3 and carrying suspected NIS; and
- When in-water cleaning poses an unacceptable risk (chemical or biosecurity), appropriate mitigation measures are:
  - To haul the vessel out for cleaning;
  - Have the duration of the vessel visit reduced to < 48 h; or,
  - Refusal of vessel entry.

2.3.1 Assessment of relative risks of cleaning versus no action: Part 1

In-water cleaning without capture was judged to present an unacceptable risk of releasing NIS in almost all cases (Table 8.9 and 8.10). The exceptions are:

- recreational vessels (international and domestic) with slime layer fouling; and,
- domestic vessels that are cleaned in their port of origin and for which there are no specific risk factors present. Risk factors could include previous voyages to ports where NIS of concern are known to be present (Section 6.2.4).

International and domestic recreational vessels with only slime-layer fouling do not require cleaning to reduce biosecurity risk, however in-water cleaning would be an acceptable practice from this perspective (Tables 8.9 and 8.10). However, restrictions should apply if cleaning recreational vessels with biocidal antifouling systems. Based on the chronic copper guideline value and the upper estimate of biocide release, no more than 0.274 vessels ≥ 21 m long or no more than 1 vessel ≥ 11 m should be cleaned per day in a given marina.

2.3.2 Assessment of relative risks of cleaning versus no action: Part 2

Key findings for each vessel type were:

2.3.2.1 International commercial vessels

In-water cleaning was considered unacceptable for international commercial vessels with LOF > 3, even when capture technologies are used (Table 2.5). In-water cleaning is preferable to no action for international commercial vessels arriving with LOF ≤ 3 if their antifouling system is biocide-free. If the antifouling contains a biocide, in-water cleaning is acceptable, within the limits of allowable chemical discharge, when the fouling consists of slime and soft taxa and brush cleaning is used. For example, in Lyttelton Port the risk associated with daily chemical discharges would become unacceptable after cleaning a single 100 m vessel (Table 2.5, Note 2).

When hard fouling is present on a vessel with LOF ≤ 3, in-water cleaning is unlikely to be acceptable if a biocidal antifouling system is used due to the risk of chemical contamination. In this situation, it may be acceptable to clean only the sides or boot-tops of the vessel (Table 5.2 and detailed in Section 5.2.9).

Table 2.5 International commercial vessels - combined biosecurity and chemical assessments of in-water cleaning with capture versus no action (extracted from Table 8.11).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
International commercial vessels, brush cleaning of hard fouling, biocidal paint								
≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions.	See restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions. See Note 1.
> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions.	No	Haul out, reduce visit time or refuse entry.
International commercial vessels, brush cleaning of hard fouling, biocide-free paint								
≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.
International commercial vessels, brush cleaning of soft fouling, biocide-free paint								
≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.
International commercial vessels, brush cleaning of soft fouling, biocidal paint								
≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See restrictions.	Yes (with capture) but see restrictions	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See Note 2.
> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See restrictions.	No	Haul out, reduce visit time or refuse entry.

Note 1: See risk matrices in Section 5.2.9 for risks associated with cleaning whole vessels, sides and boot-tops.
Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

2.3.2.2 International recreational vessels

In-water cleaning of international recreational vessels poses an unacceptable risk when LOF > 3. However, for vessels arriving with LOF ≤ 3 and intending to stay for more than 48 hours, in-water cleaning is preferable to no action. This reflects the small amount of fouling likely to be removed and the relatively high capture efficiency for hand removal of spot fouling (Table 2.6).

Table 2.6 International recreational vessels - combined biosecurity and chemical assessments of in-water cleaning with capture versus no action (extracted from Table 8.11).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
International recreational vessels, hand cleaning of spot fouling, biocide-free paint								
≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.
International recreational vessels, hand cleaning of spot fouling, biocidal paint								
≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.

2.3.2.3 Domestic commercial vessels

The relative risk of domestic vessel in-water cleaning depends largely upon operating profile and the location of the cleaning site relative to where fouling is likely to have originated. Many commercial vessels have localised operating profiles with little opportunity to accumulate fouling outside of their home port or region. As a consequence, such vessels pose a low biosecurity risk and any restrictions on in-water cleaning will be derived from the risks associated with chemical contamination (Tables 2.7 and 2.8).

The in-water cleaning risk for domestic commercial vessels with operational profiles that may lead to the accumulation of fouling from other regions, for example ferries, dredges and barges, will need to be assessed on a case-by-case basis. In general, the risk of in-water cleaning may be acceptable where the LOF ≤ 3 and the vessel is expected to stay for an extended period. However, this is dependent upon the risk associated with chemical contamination. However, when the LOF > 3 alternative risk management options should be considered (Tables 2.9 to 2.11).

2.3.2.4 Domestic recreational vessels

Domestic recreational vessels are most likely to operate in a very localised area (McClary and Nelligan 2001). As a consequence, they present a very low biosecurity risk and chemical contamination risks are likely to determine the numbers of vessels cleaned per day. Some vessels will venture beyond their home region, and such voyage profiles should be carefully considered alongside the level of fouling before undertaking in-water cleaning in their home port (Table 2.7).

Table 2.7 Domestic commercial vessels with biocide-free paint cleaned in their home port and domestic recreational vessels - combined biosecurity and chemical assessments of in-water cleaning versus no action (extracted from Table 8.12).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
Domestic commercial vessels, brush cleaning of hard fouling, biocide-free paint								
≤ 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors. Need to consider voyage history.
> 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors. Need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.
Domestic commercial vessels, brush cleaning of soft fouling, biocide-free paint								
≤ 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors. Need to consider voyage history.
> 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors. Need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.
Domestic recreational vessels, hand cleaning of spot fouling, biocidal paint								
≤ 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors. Need to consider voyage history.
> 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors. Need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.
Domestic recreational vessels, hand cleaning of spot fouling, biocide-free paint								
≤ 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors. Need to consider voyage history.
> 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with capture depending upon specific risk factors. Need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.

Table 2.8 Domestic commercial vessels with biocidal paint, cleaned in their home port - combined biosecurity and chemical assessments of in-water cleaning versus no action (extracted from Table 8.12).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
Domestic commercial vessels, brush cleaning of hard fouling, biocidal paint								
≤ 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions. See Note 1.	See restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions. See Note 1. Otherwise do not clean depending upon specific risk factors (need to consider voyage history), in which case haul out to clean, reduce duration of visit or refuse entry.
> 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions. See Note 1.	See restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions. See Note 1. Otherwise do not clean depending upon specific risk factors (need to consider voyage history), in which case haul out to clean, reduce duration of visit or refuse entry.
Domestic commercial vessels, brush cleaning of soft fouling, biocidal paint								
≤ 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See restrictions.	Yes but see restrictions	Cleaning is acceptable except for 1 or more vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See Note 2. Clean with or without capture depending upon specific risk factors: need to consider voyage history.
> 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave". Need to consider voyage history).	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See restrictions.	Yes but see restrictions	Cleaning is acceptable except for 1 or more vessel of 200 m or longer in Lyttelton: Acceptable all sizes in Auckland. See Note 2. Clean with or without capture depending upon specific risk factors (need to consider voyage history), in which case haul out to clean, reduce duration of visit or refuse entry.

Note 1: See risk matrices in Section 5.2.9 for risks associated with cleaning whole vessels, sides and boot-tops.

Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

Table 2.9 Domestic recreational vessels cleaned in the receiving port - combined biosecurity and chemical assessments of in-water cleaning versus no action (extracted from Table 8.13).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
Domestic recreational vessels, hand cleaning of spot fouling, biocide-free paint								
≤ 3	Yes	In –water cleaning (with capture) is acceptable.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors (consider voyage history), haul out, reduce visit or refuse entry. For 10-21 day visit:: haul out, reduce visit or refuse entry.
Domestic recreational vessels, hand cleaning of spot fouling, biocidal paint								
≤ 3	Yes	In –water cleaning (with capture) is acceptable.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors (consider voyage history), haul out, reduce visit or refuse entry. For 10-21 day visit:: haul out, reduce visit or refuse entry.

Table 2.10 Domestic commercial vessels with biocidal paint cleaned in the receiving port (hard fouling) - combined biosecurity and chemical assessments of in-water cleaning versus no action (extracted from Table 8.13).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
Domestic commercial vessels, brush cleaning of hard fouling, biocidal paint								
≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions. See Note 1.	See restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions. See Note 1. Otherwise for 2-10 days visit: do not clean and if specific risk factors are present (consider voyage history haul out, reduce visit or refuse entry. For 10-21 days visit; Haul out, reduce visit or refuse entry.
> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions. See Note 1.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors haul out (consider voyage history), reduce visit or refuse entry. For 10-21 day visit:: Haul out, reduce visit or refuse entry.

Note 1: See risk matrices in Section 5.2.9 for risks associated with cleaning whole vessels, sides and boot-tops.
Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

Table 2.11 Domestic commercial vessels with biocidal paint cleaned in the receiving port (soft fouling) - combined biosecurity and chemical assessments of in-water cleaning versus no action (extracted from Table 8.13).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
Domestic commercial vessels, brush cleaning of soft fouling, biocidal paint								
≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	Yes but see Note 2	No cleaning required but cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See restrictions.	See restrictions	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland. See Note 2. Otherwise for 2-10 days visit: No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history), in which case clean (with capture), haul out, reduce visit or refuse entry. For 10-21 day visit: Clean (with capture) however, depending upon specific risk factors, consider haul out, reduce visit or refuse entry.
> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes but see Note 2	No cleaning required but cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton. Acceptable all sizes in Auckland. See restrictions.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors haul out (consider voyage history), reduce visit or refuse entry. For 10-21 day visit: Haul out, reduce visit or refuse entry.

Note 1: See risk matrices in Section 5.2.9 for risks associated with cleaning whole vessels, sides and boot-tops.
Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

Table 2.12 Domestic commercial vessels with biocide-free paint cleaned in the receiving port - combined biosecurity and chemical assessments of in-water cleaning versus no action (extracted from Table 8.13).

	Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
Domestic commercial vessels, brush cleaning of hard fouling, biocide-free paint								
≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	See restrictions	For 2-10 day visit: No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history), in which case clean (with capture), haul out, reduce visit or refuse entry. For 10-21 day visit: clean (with capture) however, depending upon specific risk factors, consider haul out, reduce visit or refuse entry.
> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors haul out (consider voyage history), reduce visit or refuse entry. For 10-21 day visit: haul out, reduce visit or refuse entry.
Domestic commercial vessels, brush cleaning of soft fouling, biocide-free paint								
≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	See restrictions	For 2-10 day visit: No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history), in which case clean (with capture), haul out, reduce visit or refuse entry. For 10-21 day visit: Clean (with capture) however, depending upon specific risk factors, consider haul out, reduce visit or refuse entry.
> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors haul out (consider voyage history), reduce visit or refuse entry. For 10-21 day visit: Haul out, reduce visit or refuse entry.

2.4 DISCUSSION

In-water cleaning is essential to maintaining vessel operational efficiency and minimising the likelihood of non-indigenous species transfer. In-water cleaning is of particular importance to larger vessels due to issues associated with dry-docking, such as cost and facility availability. However, in-water cleaning may pose significant risks in terms of both biological and chemical pollution.

This research project has established a framework from which a case-by-case assessment of in-water cleaning applications can be made by decision makers. The framework has been illustrated by assessments that should cover the range of acceptable risk in New Zealand ports and marinas. Consequently, authorities should be able to define broad policy, and potentially some more specific guidance, on the acceptability of in-water cleaning within their jurisdiction.

Despite the framework presented by this study, other factors need to be considered in the permitting of in-water cleaning activities. These include the nature of the receiving environment, the specifics of the cleaning technology proposed, local attitudes to risk and available risk mitigation actions. As significant uncertainty exists with respect to the risks of in-water cleaning, a precautionary approach is warranted. Some of these factors are discussed in the following sections.

2.4.1 Chemical considerations when applying the proposed assessments

The chemical contamination assessment evaluated ports and marinas that are conservative in terms of environmental concentrations likely to result from in-water cleaning. The Port of Lyttelton and the Half Moon Bay Marina are considered the most conservative estimates of risk because of their enclosed natures – if a cleaning scenario is acceptable in these locations, from the perspective of chemical contamination, it is likely to be acceptable at all other ports or marinas (i.e. it represents a realistic worst case, Gadd et al. 2011).

The background concentrations present at the cleaning location is an important factor to be taken into account in determining the local acceptability of chemical discharges from in-water cleaning (Gadd et al. 2011, Gadd & Cameron 2012). This has not been taken into account in this report.

2.4.2 Biosecurity considerations when applying the proposed assessments

In-water cleaning scenarios presenting a potentially high risk of propagule release were considered to be unacceptable. It is unlikely, however, that such an approach to risk will be practical and thus, more refined considerations of risk may be required.

Judgements of risk relative to no action saw a preference to avoid unnecessary disturbance of biofouling for vessel stays of less than 48 hours as it is assumed that the risks of propagule release from an uncleaned hull would be low during this period. The risk of not cleaning within 48 h is not, however, negligible. There is an inherent risk of allowing vessels to enter New Zealand's waters due to the spawning of fouling species caused by differences in salinity or temperature between the receiving port and the port of origin or the open ocean (Apte et al. 2000 and Section 4.7). Nevertheless, from a practical perspective, 48 h appears to be a reasonable compromise in that international vessels visiting only one port in New Zealand generally have a turnaround time of 1-3 days (Inglis et al. 2011).

Strictly, in the case of international vessels, this time period applies to vessels that only visit one port. If these vessels stay < 48 h at the port of first arrival but then move on to other ports within New Zealand, the likelihood of propagules being released will continue to increase (Inglis et al. 2011).

Ideally the IMO Guidelines aim to keep the vessel's submerged surfaces as free of biofouling as practical through biofouling management. Therefore, regular in-water cleaning to achieve this would be considered acceptable. To encourage vessel operators to clean regularly, it may be advantageous in the short-term to allow frequent in-water cleaning of all or parts of the hull, such as the propeller, boot-tops and other niche areas, without capture under certain circumstances (extent of fouling, voyage history). Cleaning of only part of the hull may also be an option where a vessel is coated with a biocidal paint and a full clean of the hull is not acceptable for chemical contamination reasons. This may also be an option to reduce drag on hulls with biocide-free paint. It is not uncommon for vessel operators to clean only the boot-tops and sides of the hull to improve efficiency or, alternatively, to use a higher performance coating on the sides than on the bottom of the hull, to reduce fouling at waterline. Regular cleaning to remove slime layer and other low-level fouling can be done using soft brushes or low-pressure water jets, minimising the risk of release of chemical contaminants. It would also be more feasible to develop a capture system for slime-layer cleaning in order to reduce chemical contamination to acceptable levels than to develop capture and filtering systems for hard biofouling that might develop in the absence of regular, preventive cleaning.

If cleaning without capture is to be permitted, there needs to be a high level of confidence that there are no specific biosecurity risks associated with the vessel, based on one or more of voyage history, cleaning history, pre-clean inspection, and whether the whole hull or specific areas (e.g. boot-tops) are cleaned.

When specific risk factors are suspected, for example a vessel with heavy fouling or a vessel arriving from a port with known NIS of concern, it would be wise to err on the side of caution and if in doubt, inspect and/or clean. Examples of such specific risks related to the voyage history of a vessel include the known transfer of the colonial ascidian *Didemnum vexillum* from the North Island to Picton on a barge (Coutts & Forrest 2007), and the probable transfer from Auckland Harbour to Whangarei Harbour of the solitary ascidian *Styela clava* on marina pontoons and the fanworm *Sabella spallanzanii* and alga *Undaria pinnatifida* on fishing vessels (MPI, NIWA and Northland Regional Council, unpublished data).

Domestic recreational vessels visiting for > 48 h should be in-water cleaned of spot fouling (i.e. LOF ≤ 3), to be consistent with the recommendation for international recreational vessels and on the basis of estimated biosecurity risk of the cleaning versus no action. This is likely to produce a relatively small amount of waste and for which capture should be effective.

As with commercial vessels with LOF > 3, the efficiency of cleaning and capture of waste for recreational vessels is likely to be relatively low, therefore it is recommended that these vessels should preferentially be hauled out for cleaning or, failing this, have their duration of visit reduced to < 48 h or be refused entry. LOF > 3 is likely to be indicative of failed antifouling treatment, making hauling out for cleaning and repainting even more appropriate. For recreational vessels, professional in-water cleaning of this level of fouling is likely to be more expensive than hauling out and cleaning (Section 4.11).

It is generally considered that in-water cleaning of commercial vessels with LOF > 3 is unacceptable on the basis of the large amount of waste to be captured, the increased chance that unwanted NIS will be present (Inglis et al. 2010), the reduced effectiveness (and therefore benefits) of cleaning and the reduced efficiency of waste capture (Sections 2.2 and 4.3). These last two factors are based largely on experimental studies of relatively small-scale, proof-of-concept equipment. Although there have apparently been tests of the effectiveness of systems for capturing waste from larger-scale, commercial cleaning equipment, (Sections 4.2.1 and 6.3.2) the results do not appear to be publicly available.

In-water cleaning may become more acceptable if current or future methods of cleaning or capture prove to have better capabilities. Capture systems for in-water cleaning should be capable of capturing all particles larger than 60 µm and discharging the waste stream to a liquid effluent treatment system or passing it through filters to remove all solids larger than 60 µm for land disposal. This is consistent with the New Zealand guidelines for capture systems for on-shore treatment of biofouling from vessels that have arrived in New Zealand from overseas[1]. Some propagules may be smaller than this size (for example, the spores of *Undaria pinnatifida* are 10 µm), but were assessed as being unlikely to survive on-shore

[1] Guidance Document to the Standards for General Transitional Facilities for Uncleared Goods, as amended and reissued 1 September 2011, available at www.biosecurity.govt.nz/border/transitional-facilities/bnz-std-tfgen

cleaning (McClary & Nelligan 2001). Propagules may, however, be more likely to survive in-water cleaning because, for example, they are released into seawater rather than into a wash-down area where temperature, salinity and other variables are likely to be more variable and mechanical shock more likely (Woods et al. 2007). Consequently, a smaller maximum size (2 µm) is proposed for filtering effluent from in-water cleaning. A system of pre-filters with decreasing pore sizes and in-line pumps would be necessary to achieve this level of filtration. Waste retained on the filters should be disposed of to land where there is no possibility that leachate will flow to the sea. This proposal is based on a system currently under development in Western Australia (Section 6.3.3).

Setting this standard for capture of waste effectively prevents in-water cleaning of heavily fouled vessels with the technology currently available in New Zealand (and possibly overseas). However, it provides an indication to the hull-cleaning industry of what is required and may stimulate the development and demonstration of the effectiveness of appropriate technology.

Setting a less demanding standard for capture of waste from domestic vessels when cleaned at the receiving port may encourage phased or stepwise development of technology, leading eventually to the ability to capture waste from international vessels. The standard can be made less demanding by increasing either the size of organisms to be removed (for example, 60 µm as in the guidance for transitional facilities) and/or the proportion of waste to be captured. Assessment of relative risk is probably more feasible when the filter pore size is increased than when the proportion of waste captured is reduced. It is therefore suggested that a filtration system able to remove all particles larger than 60 µm would be appropriate for in-water cleaning of domestic vessels.

Although the assessments in Tables 8.11-8.13 apply to visits up to 21 d, the recommendations for 10-21 d visits by domestic vessels should also be taken to apply to visits > 21 d (Tables 8.12 and 8.13). According to the proposed CRMS, international vessels wishing to remain in New Zealand for > 21 d must have no more than a slime layer, with allowance for goose barnacles, on any part of the hull (E. Georgiades, MPI, pers. comm.).

Where in-water cleaning is not considered acceptable, the alternatives are to haul the vessel out to clean it, to reduce the duration of its visit to < 48 h or to refuse entry. It should be noted that there are still risks with shore-based cleaning since not all facilities in New Zealand are of adequate standard to capture all waste, including material as small as 60 µm (McClary & Nelligan 2001, Floerl et al. 2005c).

The assessments of this study have assumed that slime has an inherently low biosecurity risk and that in-water cleaning is therefore acceptable. However, this may neglect the risks posed by microscopic stages (well-known in the case of *Undaria* gametophytes, as evidenced by steam-cleaning of the hull of a sunken trawler in the Chatham Islands: Wotton et al. 2004). Removal of spores and other microscopic stages of macrofouling would probably require removal of slime at very frequent intervals which is logistically unfeasible and also would rapidly deplete the antifouling coating. The intrinsic biosecurity risks of microscopic organisms in fouling assemblages, such as toxic microalgae and pathogens, are poorly known (Bell et al. 2011).

2.4.3 General considerations when applying the proposed assessments

All maintenance of vessels and movable structures that occurs within the coastal marine area (i.e. the Territorial Sea) must comply with the Resource Management Act 1991 and plans prepared under that act (Pattle Delamore Partners Ltd 2003, MAF 2011b). Requirements for in-water cleaning can be found in regional or district plans produced by the relevant authority (the authority that has responsibility for environmental management in the area of water where the cleaning takes place). However, the ability of relevant authorities (regional or local councils, MPI, Department of Conservation) to impose recommended cleaning practices for domestic vessels appears to be unclear at present. Nevertheless, such controls are important to prevent the spread of NIS once they have arrived in New Zealand (recent examples of domestic transfer include *Sabella spallanzanii*, *Styela clava* and *Undaria pinnatifida*: Section 2.4.2). The feasibility/practicality of different cleaning methods, costs of delay, compliance with national and local regulations, and consistency with MPI strategy are discussed in Inglis et al. (2011).

It is uncertain whether domestic regulations are able to drive development of technology for in-water cleaning (including capture). It may be that only international (IMO) regulation is likely to achieve this. In the case of ballast water control, Australia's national regulations did not promote technological development, but the IMO convention did. Development of TBT-free paint, in contrast, was driven by domestic regulation in Japan, including international vessels built in Japan, but international uptake did not occur until the IMO convention came into force. The convention was accepted only because the technology had already been developed in Japan. European regulations on (chemical) waste from in-water cleaning seem to be driving development of capture technology in Europe (see examples from Norway and Spain, Section 4.2.1).

A broad and inflexible prohibition of in-water cleaning of vessels within New Zealand will inevitably encourage cleaning offshore (either the previous port before arrival or a convenient location where cleaning can be done most cheaply). Like many other environmentally hazardous vessel maintenance and ship-breaking activities, cleaning is likely to be done in countries with relatively weak environmental regulation and low costs. Cleaning of vessels bound for Western Australia is often completed in Peru or Indonesia. This is commonly done in-water without capture when removal from the water is not a practical or economical option (John Lewis, pers. obs.). Not only does this raise ethical issues but it also provides no stimulus for the development of methods of environmentally acceptable in-water cleaning. Therefore, in-water cleaning needs to consider marine stewardship at both domestic and international levels.

2.5 KNOWLEDGE GAPS

The risk assessments presented in Section 2.3 are based on best available information and expert judgement. We stress that there is a lack of information for many aspects of these assessments, and much of the information that is available is subject to considerable uncertainty and to untested assumptions. To improve the accuracy and precision of the assessments, further research in the following areas is required.

2.5.1 Chemical contamination

The significant uncertainties influencing the modelling results were:

- The copper content of biofilms on the vessels;
- The copper content of the leached layer of paint;
- The depth of coating removal during light and aggressive cleaning;
- Partitioning of copper from the removed biofilm and paint into the water (i.e. the dissolved fraction);
- The size of a mixing zone around a vessel being cleaned; and,
- Validation measurements during in-water cleaning of representative commercial and recreational vessels.

The greatest uncertainty was around the copper content of the leached layer and for this reason, a lower and upper release rate were calculated and modelled for the risk assessment. In terms of the project outcome, this represents a significant information gap that needs to be resolved before realistic informed decisions can be made by the end-user. In the meantime, the lower release rate has been primarily used in this risk assessment, with reference to the upper release rate at times. This information gap can only be resolved by studies to specifically measure the copper content within the leached layer. Whilst it is possible that the lower release rate may under-estimate the actual release, there is conservatism built into the risk assessment through the use of conservative water quality guidelines.

A further area of uncertainty relates to the partitioning of copper from the biofilms and abraded paint removed during in-water cleaning. This study conservatively assumed that all of this copper becomes dissolved and a smaller proportion partitions onto suspended sediment, some of which settles to the sea floor (Section 5.2.2). It is likely that not all of the copper is immediately dissolved. However, some field and laboratory studies could provide further information on this process. For example, wash-down water from vessel cleaning could be collected and the partitioning in seawater assessed immediately and at different time intervals.

Water samples collected near recreational and commercial vessels undergoing in-water cleaning would also provide validation of the modelled results. Samples could be collected at varying distances from a vessel undergoing in-water cleaning to provide information on the dilution, settling and dispersion. Samples would ideally be analysed for both total and dissolved forms of copper to provide some information on leaching from the removed paint and on subsequent partitioning to sediment. It should be noted that this sampling is difficult because of the highly variable nature of the abrasive cleaning process.

2.5.2 Contaminants of biosecurity concern

There is a considerable lack of information necessary for making informed assessments of the relative biosecurity risks of different cleaning scenarios, and considerable uncertainty around the information that is available (Section 4).

Specific information gaps include:

- The capture efficiencies of proprietary in-water cleaning equipment and for technology currently in development;
- Survival and establishment of organisms and propagules following in-water cleaning with different levels of capture;
- The release of propagules from the general fouling assemblage on an uncleaned hull, and how this risk changes over time;
- Propagule release rates for target pest species from uncleaned hulls and in response to light, temperature, salinity and mechanical disturbance;
- The viability of material released by proprietary in-water cleaning equipment;
- Effect(s) of environmental factors on the survival and establishment of propagules released during cleaning (and those released from an uncleaned hull);
- Determination of a recommended cleaning interval and the influence of the environment on it, i.e. variation due to water temperatures;
- The influence of cleaning on recolonization rates; and,
- The biosecurity risk of slime layer fouling.

Information on the cleaning and capture efficiencies of existing or future technology is likely to be most relevant if obtained from trials on vessels with different types and levels of fouling, rather than from small-scale experimental studies, because of the practical constraints involved with cleaning a real hull. In the case of new technologies, assessment of efficiency should be an integral part of development.

Smaller-scale (settling plate), experimental studies in the field and laboratory can provide information on release rates of propagules from uncleaned hulls, how this changes as the assemblages matures, how release rates vary with environmental factors and with mechanical disturbance due to cleaning, and the viability of material released but not captured. Laboratory and field experimental studies are also suited to determining the effect of environmental variables on establishment of uncaptured material. These types of studies allow adequate spatial and temporal replication and incorporation of appropriate control treatments that are unlikely to be feasible using real vessels. Recolonisation of cleaned hull surfaces can be studied by a combination of small-scale (settling plate) and vessel-scale experiments.

3 Review of the release and accumulation of chemical contaminants in the marine environment following in-water cleaning

3.1 SCOPE OF REVIEW

Where available information allows, this review addresses the following questions:

- What is the concentration of biocide in the surface biofouling, the depleted or leached paint surface, and the underlying intact paint film?
- How does the biocide concentration within these layers vary according to paint type, the component biocides and the age of the paint?
- What is the likelihood of TBT presence and possible release during in-water cleaning?
- What is an appropriate method for the calculation of biocide emission during in-water cleaning?
- What are the input parameters for this calculation?
- What are the input parameters for the MAMPEC model?
- Why were these parameters chosen?

References for this review are provided in Section 9.

3.2 ANTIFOULING COATINGS

3.2.1 Overview

The management of biofouling on the underwater hulls and other immersed surfaces of vessels is primarily achieved by the application of coatings formulated to prevent or minimise the settlement and attachment of sedentary organisms (WHOI 1952, Lewis 1998, O'Hagan 2002, Yebra et al. 2004, Chambers et al. 2006, 2007, Almeida et al. 2007, Finnie & Williams 2010, Dafforn et al. 2011). These coatings are broadly termed "antifouling" coatings although, strictly, this term should only apply to those which actively prevent biofouling settlement and attachment through biocidal action. Fouling release coatings, which minimise the strength of biofouling adhesion, and mechanically resistant coatings, which are hard, durable coatings able to withstand regular abrasion and mechanical cleaning, are used as biofouling management coatings but do not have inherent, broad spectrum biofouling deterrent characteristics.

Using "antifouling coatings" in the broader sense, six types of coating are recognised:

1. Biocidal:
    a) Soluble matrix/ablative;
    b) Insoluble matrix/contact leaching/diffusion;
    c) Self-polishing copolymer (SPC); and,
    d) Metallic.
2. Biocide-free:
    a) Fouling release; and,
    b) Mechanically resistant.

Only a limited number of antifouling biocides, that are both effective against biofouling and environmentally acceptable, are available for use in biocidal coatings. Since the now almost complete banning of organotin biocides (IMO 2005), the most commonly used biocide in antifouling paints is copper, either in the form of cuprous oxide (predominantly), cuprous thiocyanate, or metallic copper or copper-nickel particles. Many copper coatings also contain a secondary, or booster, organic co-biocide to broaden the spectrum of antifouling effectiveness to more-copper tolerant organisms. In New Zealand, of 48 approved and commercially available antifouling paints for vessels, all contain copper (85% cuprous oxide, 15% cuprous thiocyanate), and there are 14 secondary biocides registered for use. 90% of approved antifouling paints contain a secondary biocide (EPA 2012).

To be effective, the biocide in a biocidal coating must be continuously released at the coating surface at a concentration that will kill or deter settling organisms. The process for this release is one of hydration, dissolution and diffusion. Maintenance of long term release can be facilitated by formulating the paint matrix to include soluble or hydrolysable chemical components. The mechanism of effect of copper-based antifouling coatings is the generation of free cupric (Cu^{2+}) ions which are considered to be the toxic copper species. In the dissolution reaction of cuprous oxide (Cu_2O), the Cu_2O reacts with H^+ and Cl^- ions at the pigment front to produce chloro-copper complexes. These then oxidise to Cu^{2+} in the leach layer to be released as ionic copper or labile copper complexes (Howell & Behrends 2006).

3.2.2 Biocidal coatings

3.2.2.1 Soluble matrix coatings

Soluble matrix coatings, now often referred to as ablative coatings, are those in which the biocide or biocides are dispersed through a sparingly soluble paint matrix. Hydration causes the surface to slowly dissolve to enable release of the freely associated biocide. Conventional soluble matrix coatings utilise rosin, a natural gum from pine trees, as the matrix (Finnie & Williams 2010). Rosin is principally abietic acid, which is insoluble in acidic or neutral aqueous solutions, but soluble in alkaline solutions (O'Hagan 2002). Rosin is also brittle and unstable to oxidation, and rosin-based antifoulings can physically degrade if they experience prolonged exposure to the atmosphere, such as during ship construction, dockings, or along the wind and water line of vessels (Lewis 1998). Insoluble cofilm forming materials have been added to improve film-forming properties, but these lead to the formation of a wide leached layer at the coating surface after the release of the soluble components, leading to an inefficient polishing action, problems in recoating and less controlled biocide release (Lewis 1998).

Controlled dissolution can be achieved by combining the rosin with plasticizers and other components. Controlled depletion polymer (CDP) coatings combine high performance polymeric ingredients with seawater soluble binders to better control the dissolution rate. However, the mechanism is still a hydration/dissolution process, making CDP coatings a modern type of soluble matrix paint.

3.2.2.2 Insoluble matrix coatings

Insoluble matrix coatings, also known as contact leaching or diffusion coatings, are those in which the binder is largely insoluble and biocide release depends on the biocide content being high enough to ensure all biocide particles are in contact through the dry film. This enables the biocide within the coating to diffuse to the surface though micro-channels created as the more surficial biocide is dissolved (Lewis 1998). Insoluble matrix coatings were usually based on vinyl or chlorinated rubber resins, and were harder and more durable than soluble matrix coatings. However, with time, the skeletal matrix of the paint film becomes clogged with insoluble rosin soaps and copper compounds and release rates drop below effective levels (O'Hagan 2002).

Insoluble matrix coatings are intrinsically wasteful of biocide and are thickness limited (O'Hagan 2002). Their potential life is dependent on the exponential rate of leaching, giving a lifetime approximately proportional to the logarithm of thickness; thus doubling thickness gives 30% greater life, tripling thickness a 47% increase, but beyond this the effect is minimal (O'Hagan 2002). In these paints the release rate is excessive in the early stages of the paint life, dropping exponentially with time. The build-up of the skeletal layer usually limits the useful lifetime of these paints to 12 months or so (Finnie & Williams 2010), and the use of these paints is now largely restricted to the recreational market.

3.2.2.3 Self-polishing copolymer coatings

The first "self-polishing" coatings were the organotin copolymer paints in which tributyltin (TBT) methacrylate copolymer provided both the paint matrix and biocide. In seawater, the copolymer hydrolysed and split off the TBT moiety, releasing biocide, to leave a soluble copolymer backbone, that is then also released. The controlled nature of this process, in which the non-hydrolysed polymer remained hydrophobic until exposed after hydrolysis and dissolution of the surface layer, resulted in a self-polishing or self-smoothing effect. Micro-roughness across the surface of the coating was polished by the hydrolysis/dissolution process and hull roughness diminished during service. The controlled nature of the self-polishing process also resulted in consistent biocide release rates through the life of the coating, and an effective life proportional to coating thickness. Some TBT SPC paints, particularly those for low activity vessels, contained cuprous oxide or other co-biocides to boost performance in static conditions.

Replicating the self-polishing process in tin-free coatings provided a challenge to the marine paint industry, but this has been achieved with copper, zinc and silyl acrylate coatings. Unlike TBT SPCs, the copolymer does not provide the effective biocide and cuprous oxide and/or other biocides are freely dispersed through the copolymer paint matrix. However, the polishing mechanism is similarly achieved through a hydrolysis/dissolution process, not by hydration/dissolution. On this basis, only coatings which ablate via a hydrolysis process are considered to be true self-polishing or self-smoothing systems. The full benefits of a pure SPC coating are compromised in hybrid CDP/SPC coatings, in which significant amounts of rosin are added to SPC copolymers to generate cost and performance differences between the two coating types. As such, these systems should be classified as hybrid CDP/SPC coatings accordingly.

3.2.2.4 Metals and metal-containing coatings

Sheathing wooden ships with copper sheet was the first authenticated antifouling treatments and dates back to the mid-1700s (Lewis 1998). The antifouling effect has commonly been attributed to a non-biocidal property of the copper (e.g. Candries 2009), but various studies have shown that the antifouling mechanism is the release of copper ions as the metal slowly corrodes. The use of copper sheathing was largely superseded by the introduction of antifouling paints, which were cheaper and easier to apply. Although sheathing with copper-nickel alloy, which is more durable than copper sheet, continues to be promoted, there is a continued issue of cost and practicality. The primary antifouling application for 70/30 and 90/10 Cu-Ni is for the fabrication of seawater pipe work.

A more recent variant of this method is to mix or spray copper or copper-nickel particles or flake into an epoxy or other polymer matrix; commercially available products of this type include Corrocoat Biofoul™ and Ecosea Cuprotect™. These coatings have extremely hard and impervious resin matrices and the antifouling effect is dependent on metal particles exposed at the surface. As with copper sheathing, the antifouling effect is due to the combination of release of toxic material and exfoliation of a loosely attached or slightly soluble oxide layer. A low level of macrofouling can occur on these coatings, but it does not persist due to the instability of the metal surface. Although not considered practical for widespread application to vessels, these coatings are being applied to offshore and fixed installations where long-term (up to 20 y) minimisation of biofouling growth is needed and renewal of antifouling paint systems is not possible (J.A. Lewis, personal observation).

3.2.2.5 Leached layer

In all biocidal antifouling coatings, the mechanism of release of biocide results in a surface layer that is depleted, or "spent" of biocide and other soluble compounds. In soluble matrix/ablative and SPC coatings this is due to the biocidal pigments dissolving at a faster rate than the paint matrix dissolves or hydrolyses (Howell & Behrends 2006). Two fronts result: the polymer front at the coating surface, and the pigment front which, in SPC coatings, is typically 10-30 µm below the polymer front (Howell & Behrends 2006). The layer between these two fronts is termed the "leach" or "leached" layer, and has a lower concentration of biocide than the underlying unhydrated paint.

The depth of the leached layer can be a function of water velocity over the coating, due to the increased turbulence over the polymer front increasing the rate of mass transport across the polymer-seawater boundary and thus reducing the copper concentration within the leached layer (Howell & Behrends 2006). As the dissolution of cuprous oxide from the pigment layer depends on copper saturation of the pore water within the leached layer, this change in copper concentration will increase cuprous oxide dissolution and the leached layer will widen. This was demonstrated in experiments with painted cylinders held static, or rotated at 0.51 m/s and 2.06 m/s, which formed leach layers 15, 20 and 25 µm thick, respectively (Howell & Behrends 2006).

The depth of the leached layer also varies between coating types, which relates to the solubility or hydrolysis mechanism of the paint components. In insoluble matrix coatings the dissolution of biocide through the surface layers of the coating, and progressive and increasing depletion of biocide in from the matrix front, leads to a concentration gradient through the leached layer below the surface. The leached layer of this type of coating can be up to 75 µm thick (Anderson, undated). The leached layer in ablative, CDP coatings can exceed this thickness, whereas in SPC coatings the thickness is generally less than 15 µm (Table 3.1, International Coatings 1998). The leached layer of a copper ablative antifouling coating after 4 months immersion, illustrated in Lewis (1998), is approximately 30 µm thick.

Table 3.1 Increasing thickness of leached layer with time on different coating types (µm).

Coating Type	100 days	200 days	300 days	400 days
TBT SPC	2	5	10	15
Tin-free ablative	25	40	60	80
Tin-fee SPC	2.5	5	7.5	10

Values approximated from graphs in Anderson (1993) and International Coatings (1998)

Yebra et al. (2004) comment variously on the thickness of the leached layer of the different coating types in their comprehensive review of antifouling technology. However, they simply refer to a "thick" leached layer for insoluble matrix paints, a "relatively thick (more than 50 µm)" leached layers in soluble matrix paint, and "low (10-20 µm)" thickness for TBT-SPC paints. The thickness of the leached layer in tin-free SPC coatings was only specified for one product (Hempel Globic™); thin layers (below 22 µm) in rotary experiments lasting 16-20 months, but higher values (below 35 µm) measured on ships (Yebra et al. 2004). However, these authors do refer to a Sigma Coatings ablative paint having a leached layer 2-3 fold thicker than this same company's tin-free SPC product. This differs from the International Coatings measurements where thicknesses are 8-10 fold greater in ablative than SPC coatings (Table 3.2).

The above reported values for the thickness of leached layers for different paint types are summarised in Table 3.2.

Table 3.2 Published leached layer thicknesses on different coating types.

Coating Type	Thickness of leached layer (µm)	Source
Insoluble matrix	75	Anderson 1993, International Coatings 1998
Soluble matrix/ablative	40-80	Anderson 1993, International Coatings 1998
	30	Lewis 1998
	> 50	Yebra et al. 2004
TBT SPC	5-15	Anderson 1993, International Coatings 1998
	10-20	Yebra et al. 2004
Tin-free SPC	5-10	Anderson 1993, International Coatings 1998
	20-35	Yebra et al. 2004
	10-30	Howell & Behrends 2006

Additional leached layer thicknesses measured in cross sections of a range of TBT SPC, tin-free SPC and ablative coating was obtained from International Paints (C. Anderson, personal communication) (Tables 3.3-3.5). The trends in these measurements are an increase in leached layer thickness with immersion time, greatest thickness on ablative coatings, least on TBT SPC coatings, and tin-free SPC coatings in-between. The measurements agree generally with those listed in Table 3.2.

Table 3.3 Measured leached layer thicknesses on TBT SPC coatings.

Coating type	Time immersed (months)	Thickness (µm)	
		Min.	Max.
TBT SPC	15	6	10
TBT SPC	20	17	20
TBT SPC	20	10	15
TBT SPC	20	10	16
Mean $\pm$ SD		12 $\pm$ 4	17 $\pm$ 3

Table 3.4 Measured leached layer thicknesses on tin-free SPC coatings.

Coating type	Time immersed (months)	Thickness (µm) Min.	Thickness (µm) Max.
SPC-5	12	30	50
SPC-1	15	0	14
SPC-1	15	0	45
SPC-2	15	12	24
SPC-4	15	18	20
SPC-6	15	32	42
SPC-2	17	38	47
SPC-2	17	12	55
SPC-3	17	26	32
SPC-4	17	25	50
Mean ± SD	12-18	19 ± 13	37 ± 16
SPC-2	23	55	79
SPC-3	23	25	44
SPC-3	26	48	65
SPC-4	23	37	68
Mean ± SD	20-24	41 ± 13	64 ± 15

Table 3.5 Measured leached layer thicknesses on tin-free ablative coatings.

Coating type	Time immersed (months)	Thickness (µm) Min.	Thickness (µm) Max.
Ablative-2	7	10	20
Ablative-4	7	24	30
Ablative-1	15	52	64
Ablative-2	15	54	60
Ablative-2	15	50	60
Ablative-2	15	54	62
Ablative-5	15	23	40
Ablative-6	15	30	42
Ablative-7	15	60	80
Mean ± SD		46 ± 14	53 ± 25
Ablative-3	23	38	62
Ablative-2	42	78	90

3.2.2.6 Surface biofilms

Antifouling coatings in seawater become rapidly covered by microbial biofilms (Bishop et al. 1974, Jackson & Jones 1988, Yebra et al. 2006a, Molino et al. 2009a, 2009b, Dobretsov 2010). The first species to attach are often small, rod-shaped bacteria which begin to attach within hours and then assimilate nutrients and synthesize new cellular and extracellular material which accumulates in the surface deposit (Little & DePalma 1988, Wahl 1989, Lewis 1998). Attachment of secondary colonisers, including stalked or filamentous bacteria and diatoms, then proceeds quite rapidly. Diatoms contribute much of the biomass in biofilms on illuminated surfaces, including on antifouling paints due to the resistance of some species to copper and, when still in use, organotin compounds (Callow 1986a, 1986b). Stunted and prostrate filamentous brown algae can also establish within the biofilm (Woods et al. 1988). The biofilm surface is also highly adsorptive and, although microorganisms and their remains make up the most conspicuous components of the deposit, varying amounts of extracellular polymeric substances (EPS), trapped detritus, inorganic precipitates, and corrosion products compose the bulk of the layer (Lewis 1998).

The composition of the biofilm on antifouling coatings varies, not only with the duration of immersion of a substrate, but also with biocide, biocide concentration and shear stress (Howell 2010). Biofilms grown at low velocities exhibit low density and high effective diffusivity, whereas biofilms grown at higher flow velocities have high density and low effective diffusivity. External shear force can also influences biofilm detachment, which in turn influences biofilm formation.

The thickness of the biofilm can relate to the length of immersion and the specific biocide and its release rate, but seems inherently variable. Biofilm thicknesses on a range of soluble matrix, insoluble matrix and SPC antifouling coatings, containing organotin, organotin and copper, or copper biocide, range from 0-305 µm thick after six months immersion, and 0-572 µm thick after 12 months (Jackson & Jones 1988). The thicknesses of biofilms were found to be generally greater on soluble and insoluble matrix coatings than on SPCs. Fouling films consisting of bacteria alone did not exceed 5-10 µm thick, with thicker biofilms due to the growth of diatoms (Jackson & Jones 1988).

Antifouling paint samples, with TBT/Cu or TBT/Zn biocides, exposed on the bilge keel of an ocean going ship for 35 months accumulated biofilms averaging in thickness from 47-562 µm but, in contrast to the observations of Jackson & Jones (1988), the thinnest films were on insoluble matrix paints (47-261 µm), and the thickest on ablative paints (266-562 µm) (Woods et al. 1988). Thickest films, of around 550 µm, were found on ablative TBT/copper thiocyanate coatings. Fast erosion, lower biocide content ablative coatings developed thinner biofilms than slower eroding, high biocide content paints.

Lindner (1988) observed a continuous slime layer 10 µm thick after 14 days on the copper-based United States Navy (USN) vinyl antifouling F-121, increasing to 50 µm after 18 months. Much thicker films, 1,500-2,500 µm, were measured on a tanker coated with an insoluble matrix type vinyl antifouling paint (Doi 1982). Test panels coated with a USN approved copper ablative paint became rapidly fouled by biofilm after immersion and were 50% covered after 24 days (Tribou & Swain 2010).

The biofilm can modify biocide release and antifouling effectiveness in two ways: by the jelly EPS structure modifying concentration gradients along the diffusion zone and therefore the release rates, and by the EPS matrix trapping and binding copper ions (Brown et al. 1988, Yebra et al. 2006a). There is also evidence that microorganisms synthesise and excrete strong copper chelators in response to increases in copper concentrations (Voulvoulis et al. 2002). Biofilms could additionally affect paint performance by modifying localized chemistry such as by changing the pH.

3.2.2.7 Antifouling biocides

The non-copper biocides registered for use in New Zealand, and the percentage of registered and commercially available products for vessels each are used in, are provided in Table 8.1, Table 8.2 and Table 8.3 at the back of this report (EPA 2012):

- Chlorothalonil (4%);
- Copper pyrithione (13%);
- DCOIT (= Seanine 211™) (13%);
- Dichlofluanid (6%);
- Diuron (23%);
- Irgarol 1051™ (4%);
- Mancozeb (2%);
- Octhilinone (0%);
- Thiram (13%);
- Tolyfluanid (0%);
- Zinc pyrithione (10%);
- Zineb (4%); and,
- Ziram (2%).

Zinc oxide is also present in 40% of registered coatings, but the primary purpose of zinc oxide in antifouling paints is not as a biocide, but to control the solubility of the paint film, stabilise the wet paint, to modify dry film properties, and to pigment the system (CEPE 2011a, b). Copper pyrithione, DCOIT (Seanine 211™), dichlofluanid, and zinc pyrithione are "newer" biocides that are considered to be effective and environmentally safer biocides, primarily because of their rapid degradation rates (Harino & Langston 2009, Lewis 2010). Irgarol 1051™ is registered as an antifouling biocide in New Zealand, and is listed as occurring in several antifouling paints (EPA 2012). Although still in use in a number of other countries, concerns on the persistence and environmental impact of this herbicide has resulted in its registration as an antifouling biocide either declined (e.g. Australia) or revoked (e.g. UK). Other antifouling biocides are in use elsewhere in the world, including tolyfluanid, thiocyanomethyl thiobenzthiazole (TCMTB), tetrachloro-methylsulphonyl pyridine (TCMS pyridine), triphenylborane pyridine (TPBP) and ziram (Harino & Langston 2009, Mochida & Fujii 2009, Finnie & Williams 2010, Thomas 2010). Tralopyril is a new antifouling biocide approved for use in the US, but not yet in New Zealand, Australia or the UK (Lewis 2010).

3.2.2.8 Organotin biocides

In October 2001, the International Maritime Organization adopted the International Convention on the Control of Harmful Anti-Fouling Systems on Ships, 2001, known as "the AFS Convention" (IMO 2005). This convention mandated a global prohibition of the application of organotin compounds which acted as biocides in anti-fouling systems on ships by 1 January 2003, and a completed prohibition on the presence of organotin compounds which acted as biocides by 1 January 2008. Entry into force of the Convention was specified as 12 months after the date on which not less than 25 states, the combined merchant fleets of which constituted not less than 25% of the gross tonnage of the world's merchant shipping, had signed or ratified the Convention. These provisions were met in 2007, and the AFS Convention entered into force on 17 September 2008, and 56 States representing 78.8% of the gross tonnage of the world's merchant shipping are now signatories to the Convention (IMO 2011). The dates of 1 January 2003 and 1 January 2008 applied retrospectively, despite the later date of entry into force.

The specific controls on anti-fouling systems within the AFS Convention are that (IMO 2005):

1. From 1 January 2003, ships shall not apply or reapply organotin compounds which act as biocides in anti-fouling systems; and,
2. From 1 January 2008, ships either:
    a. Shall not bear such compounds on their hulls or external parts or surfaces; or,
    b. Shall bear a coating that forms a barrier to such compounds leaching from the underlying non-compliant anti-fouling system.

Further, a ship to which the Convention applies[2] can, in any port, shipyard, or offshore terminal of a Party, be inspected by officers authorized by that Party to determine if the ship is compliant with the Convention. Violations are prohibited and sanctions established under both the law of the administration of the ships concerned wherever the violation occurs and, where the violation occurs within the jurisdiction of a Party, under the law of that Party.

Under the AFS Convention the continued presence of antifouling coatings containing tributyltin, or other organotin biocides, on vessels hulls can only be in paint systems applied before 2003 that are now encapsulated beneath a sealer coat and the more recently applied tin-free antifouling systems. Anticorrosion coatings have been found to be effective as sealer coats. Under the AFS Convention, ships of Parties to the Convention are required to carry an "International Anti-Fouling System (IAFS)" certificate or, for ships of 24 metres or more in length but less than 400 gross tonnage, a "Declaration on Anti-Fouling System" to certify that the ship's antifouling system fully complies with the convention (IMO 2005). Ships of non-parties to AFS 2001 are not entitled to an IAFS Certificate but, as the convention applies equally to these vessels, the port state inspection for compliance requires looking for documentation that contains all the information in the IAFS Certificate.

The AFS Convention does not apply to "any warships, naval auxiliary, or other ships owned or operated by a Party and used, for the time being, only on government non-commercial service" (IMO 2005), and in Australia, "a ship that is being used on non-commercial service by the Commonwealth, a State, or a Territory, or the government of a foreign country" (Commonwealth of Australia 2006). Despite the exemption for navy and government vessels to the provisions in AFS Convention, as is also the case with other IMO conventions, it is known that the New Zealand (N. Rhodes, New Zealand Defence Force, pers. comm.), Australian, US and UK navies no longer apply TBT coatings.

In Australia the registrations of all antifouling products containing tributyltin were cancelled by the Australian Pesticides & Veterinary Medicines Authority (APVMA) on 31 March 2003. Subsequently in 2006, the Protection of the Sea (Harmful Anti-fouling Systems) Act 2006 (Commonwealth of Australia 2006) was passed as supportive legislation to enable ratification of the AFS Convention. Under this act it became an offence for either an Australian ship or a foreign ship to enter or remain in an Australian shipping facility[3] on or after the 1 January 2008 if it is not compliant with the anti-fouling requirements.

Many countries had introduced restrictions on the use of TBT antifouling paints prior to 2003, including a total ban in Japan, and bans on their use on vessels less than 25 m in length in Canada, the United States, the EU (Directive 2002/62/EC), most western European states

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[2] Defined as: a vessel of any type whatsoever operating in the marine environment and including hydrofoil boats, air-cushion vehicle, submersibles, floating craft, fixed or floating platforms, floating storage units (FSUs) and floating production storage and off-loading units (FPSOs).

[3] Port, shipyard or offshore terminal

outside the EU, Hong Kong, South Africa and Australia, although the US allowed exemptions for aluminium hulls and fittings (Courtaulds Coatings 1994). On vessels greater than 25 m, a maximum permissible TBT release rate was widely applied to restrict use to TBT SPC coatings, including in Canada, the US, Sweden and Australia.

New Zealand announced a partial ban on TBT in 1988 (coming into force in July 1989), banning its use on small vessels (< 25 m in length), with the exception of those with an aluminium hull or outdrive. The sale or application of antifouling paints containing organotin as an active biocide became an offence in New Zealand from 1 December 1993 under the Pesticides (Organotin Antifouling Paints) Regulations 1993 (SR 1993/326).

Although the AFS Convention has been signed by New Zealand, it has not yet been ratified. This means that foreign ships using organotins in their antifouling paints may enter New Zealand and New Zealand authorities would not have the powers to inspect international vessels for compliance or initiate actions against non-compliant vessels.

The major global paint manufacturers ceased manufacture of TBT antifouling coatings in 2003. In 2007 there were still some small paint companies in Asian countries, including India, China and Sri Lanka, making TBT based paints for sale primarily to local coastal fishing fleets and some military vessels (J. Millett, Akzo Nobel Pty Ltd, New South Wales, pers. comm.). Information suggests that tin-based paints continue to be used in some Caribbean countries, where they are favoured for their efficacy in tropical waters. Sea Hawk Paints in Florida continues to advertise tin-based antifouling paints on their web-site under the category "Antifouling Paints: Export – (non-US)" (Sea Hawk Paints 2012a). Three TBT SPC paints are currently advertised: Islands 44 Plus™ (17.2% TBTMA, 47.5% Cu_2O), Biotin Plus™ (15.6% TBTMA), and Clear Gear™ (15.6% TBTMA). Sea Hawk Paints also advertise a TBT additive, Tin Booster™ (45% TBTMA), for adding to antifouling paints to "add extra kick to any tin-based antifouling", including their Islands 44 Plus and Biotin Plus products. The recommendation by the company is to add up to one bottle (8 oz (230 ml)) to one gallon (~3.8 l) of paint (Sea Hawk Paints 2012b). The Sea Hawk Paints web-site provides a link to Caribbean based web-sites where these TBT products can be purchased on-line.

For merchant vessels, over the past 10 years, Classification Societies have insisted on the provision of TBT-free antifouling certificates at dockings they have overseen, and it is considered unlikely that any commercial vessels visiting Australia or New Zealand would have exposed TBT on the hull (J. Millett, Akzo Nobel Pty Ltd, Australia, pers. comm.). Petroleum industry FPSOs and FSUs, which may not have docked for 15 to 25 years, may still have exposed, although depleted, TBT antifouling on their hulls, but such vessels are unlikely to enter ports or harbours in New Zealand or Australia.

With respect to old TBT paints sealed under tin-free antifouling systems, an industry estimate is that probably less than 5% of vessels have residual TBT-coatings sealed on their hulls, and most would be on the flat bottom (J. Millett, pers. comm.). Vessels on 60 month docking cycles would now have at least three applications of tin-free antifouling paint over the TBT and sealer. The high build-up of paint layers on many of these vessels has resulted in detachment or cracking of the paint system at the 2nd or 3rd docking and, in these instances, the system has been fully removed and replaced by a full tin-free system.

Despite the widespread bans on TBT usage, some recent studies in Europe have continued to detect the compound in environmental samples. For example, seawater and mussel samples collected from ports and marinas along the Croatian Adriatic Coast in 2009 and 2010 indicate recent inputs of TBT; more so in marinas than ports (Furdek et al. 2012). The conclusion reached from these observations was that the ban on TBT-based antifouling was not efficient and these paints were still in use in Croatia. In contrast, sediment samples collected from fishing harbours and a marina on the West Iberian coast in Portugal in 2006 indicated no recent inputs (Sousa et al. 2012). Mussel contamination at one of these harbours, which indicated recent input of TBT, was attributed to desorption of organotins from the sediments.

Prior to adoption of the AFS Convention by IMO in 2001, industry were concerned that alternative tin-free systems do not match the performance of TBT SPC systems, particularly on ships with docking cycles greater than 36 months. Tin-free copolymer systems, with cuprous oxide as the primary biocide, subsequently did provide this performance (Finnie & Williams 2010, Thomason 2010), although at a greater material cost. Vessels with aluminium hulls could not, however, use cuprous oxide based coatings, because of the risk of galvanic corrosion to the hull material from the copper. These vessels could use coatings containing cuprous thiocyanate, which is less corrosive than cuprous oxide, but the effective life of cuprous-oxide free antifouling coatings rarely exceeded 24 months. Where vessels require longer docking cycles, non-toxic foul release coatings are now widely applied to aluminium hulled ships, particularly high speed catamaran and naval vessels.

3.2.3 Biocide-free coatings

3.2.3.1 Fouling release

Foul release (FR) coatings have low surface energy, minimally adhesive surface characteristics that reduce the strength of biofouling adhesion that ideally results in any macrofouling sloughing off as the vessel moves through the water, as water moves over the painted structure, or the organism detaches under its own weight (Lewis 1998). The first FR coatings were based on poly(tetrafluoroethylene) (PTFE) and were quite tough coatings. However, PTFE surfaces were found to foul quite rapidly because irregularities in the surface enabled adhesives to invade and cure in microcavities and create a secure mechanical interlock (Lewis 1998).

Successful FR coatings were subsequently formulated using silicone elastomers, and most major marine coating manufacturers now have a silicone FR coating in their product inventory (Lewis 2004, Williams & Finnie 2010). The foul release properties of silicone elastomeric coatings has been determined to not just relate to surface chemistry, but also to the elastic modulus and thickness of the coating (Townsin & Anderson 2010). FR coatings do foul on stationary and low activity vessels, and the ideal platform is therefore a high speed, high activity vessels which facilitate fouling release. For other vessels, fouling can be easily removed, but the soft nature of the silicone elastomer surface makes it highly susceptible to abrasion damage and scratching, and care must be taken to ensure cleaning methods do not cause surface damage (Lewis 2001). Biofilms also develop on silicone FR coatings (Molino et al. 2009a, 2009b), and persist on vessels with speeds up to 50 knots (Townsin & Anderson 2010). This is due to the biofilm lying within the boundary layer against the surface and therefore protected from turbulent flow. Low profile macrofouling organisms, such as encrusting bryozoans, have been observed to persist on high speed vessels for the same reason (Lewis, personal observation).

With no antifouling biocides purposely added to FR coating formulations, these coating are generally referred to as non-toxic. Dibutyltin compounds (e.g. dibutyltin dilaurate) are commonly used as catalysts in silicone manufacture, but this is assumed to be locked in the rubber matrix after curing (Watermann et al. 2005). Technical grade dibutyltin compounds uses as catalysts can contain tributyltin impurities. However, leach rates are low, and have been measured to be less than 0.0004 µg TBT/cm^2/day and 0.007 µg TBT/cm^2/day, which was less than, or in the same range, as from organotin-catalysed Formica tubes (Watermann et al. 1997). In this study no pre-leaching of test coatings is mentioned, which suggest the leach rates are for newly immersed coatings.

Lack of toxicity has been supported by studies that found leakage water from a commercial silicone paint (Intersleek 700™) did not show any toxic response in C*eramium* growth inhibition tests (Karlsson & Ecklund 2004) or in luminescent bacteria and cypris larvae settlement tests on ten different silicone coatings (Watermann et al. 2005). In the latter study, on one coating that exuded silicone oil, all cypris larvae became stuck in the oil and died, but the cause of death was considered to be immobilisation rather than a toxic effect of the silicone oil.

Sea urchin and fish assays have found commercial silicone coatings to have an effect on embryonic development (Feng et al. 2012). Freshly immersed coatings inhibited urchin development, delayed fish hatching, and reduced hatching success. Immersing coatings in running seawater for one month before testing reduced the impact on the early life stages of both test organisms. Possible sources of the toxicity from unleached coatings was considered to potentially originate from catalysts, unreacted components that migrate to the surface of the polymer, trapped solvents, and low levels of toxic compounds in pigments and other additives. The reduced toxicity of leached coatings is considered possibly due to biologically active molecules leaching rapidly out of the coatings, being modified to less toxic molecules by exposure to seawater, or the inhibition of release by biofilms.

Silicone coatings cured with dibutyltin dilaurate (DBTDL) have been found to promote, not inhibit, the settlement of *Ulva* (=*Enteromorpha*) spores, with similar attraction to both unleached coatings and coatings leached for up to 10 days (Callow & Callow 1998). Similar effects did not occur with silicones cured with dibutyltin diacetate, which led to the conclusion that lauric acid functioned as a chemo-attractant to the spores. Field observations of heavy slime films and macroalgal sporelings on DBTDL-cured foul release coatings within the first few weeks of immersion (Callow et al. 1987) was consequently considered to be possible due to the attraction of motile spores to these surfaces (Callow & Callow 1998).

Silicone FR coatings that contain and exude unbound silicone oils, although not toxic, are considered to have potential environmental impact (Nendza 2007). PDMS are persistent, adsorb to suspended particulate matter and may settle into sediments, where a build-up may inhibit pore water exchange. For organisms, they are not bioaccumulated and soluble fractions have low toxicity, but high exposure to undissolved oil films or droplets can cause physical-mechanic effects through trapping and suffocation.

3.2.3.2 Mechanically-resistant coatings

Mechanically resistant coatings are hard, smooth, abrasion resistant coatings able to withstand mechanical cleaning, ice scour and other abrasive forces. Commercially available products include coatings based on epoxy, ceramic/epoxy or polyester resins. The manufacturer of one of these products, a polyester resin containing glass flake, has termed it a surface treated coating (STC) to describe the regular in-water cleaning and polishing required to keep the coating fouling free (Wijga et al. 2007, Candries 2009).

3.3 MECHANISMS OF ANTIFOULING FAILURE

3.3.1 Biocidal coatings

The mechanism of prevention of biofouling settlement and attachment on to biocidal antifouling coatings is the continuous release of biocide at the coating surface at a concentration toxic or inhibitory to the settling organisms. Settlement and attachment can occur when the biocide release rate drops below the critical inhibitory concentration. This can occur through:

- Sub-optimal biocide release rate;
- Biocide depletion; and/or,
- Biocide release obstruction.

3.3.1.1 Sub-optimal biocide release rates

To be effective, the release of biocide at the surface of the antifouling coating needs to be continuous and at a rate that produces a toxic or deterrent environment to settling spores or larvae of potential fouling organisms. The tolerance of organisms to different biocides varies, and many common fouling species have a higher tolerance to biocides, and particularly copper (Allen 1953, Wisely 1963, Dafforn et al. 2008, Piola et al. 2009). These species include macroalgal species (notably species of the green *Ulva* and brown filamentous ectocarps), hydroids (e.g. *Ectopleura* spp.), bryozoans (e.g. *Watersipora* spp., *Bugula* spp.), tubeworms (*Hydroides* spp.) and barnacles (*Amphibalanus* spp.). For some of these species, including *Hydroides* tubeworms and some hydroids, low copper concentrations can actually stimulate settlement and recruitment - an effect known as hormesis. On copper-based antifouling coatings, the first signs of fouling usually appear on a ship's vertical sides, where copper-resistant green macroalgae such as *Ulva* (*Enteromorpha* form) grow quickly (Anderson 2004).

Due to their copper tolerance, and the predominance of copper-based antifouling coatings since their first application in the late 19th century, many of these copper tolerant organisms have been spread around the globe and are particularly prevalent in ports and harbours where they have a competitive advantage over more sensitive native species. Antifouling coatings therefore need to release biocide at the rate critical to prevent attachment of these organisms to ensure a biofouling-free surface. For animal fouling, the critical rate of release of copper is generally considered to be 10 µg/cm^2/day, although rates as high as 20 µg/cm^2/day may be necessary to prevent macroalgal fouling (Section 3.6.3.1). Microbial species, including bacteria and benthic diatoms, can have even higher biocide tolerance and a microbial biofilm, or slime, will develop on most antifouling coatings after immersion in natural seawater within days of immersion (Molino et al. 2009a, 2009b).

If a coating formulation contains insufficient biocide or a matrix that inhibits release of sufficient biocide, then the coating will foul if exposed to spores and larvae of species tolerant of the realised release rate. In ablative and SPC coatings, failure can occur if the speed and operational profile of the vessel are such that the water movement over the coating surface is insufficient to polish the coating at a rate to allow dissolution of biocide at the critical release rate. Some SPC coatings are specifically formulated to suit vessel activity; for example, "harder" coatings with are designed for high activity and/or high speed vessels, and "softer" coatings for low activity and/or slow vessels.

3.3.1.2 Biocide depletion

The effective life of a biocidal antifouling paint relates to the biocide content of the paint. When the biocide reservoir in the coating is exhausted, the coating will foul. In practice, in soluble and insoluble matrix coatings, the biocide reservoir in a coating is not completely exhausted, but the diffusion of the biocide to the paint surface drops to a level below that enabling the critical release rate, which leads to antifouling failure. In rosin-based soluble matrix coatings, the rate of dissolution of rosin in seawater is not constant, and gradually decreases due to the formation of insoluble calcium and magnesium soaps at the surface (O'Hagan 2002).

In SPC paints, the progressive hydrolysis of the coating and associated biocide release enables effective antifouling performance until the coating is fully polished, or eroded away, to expose the underlying anti-corrosive coating. The dry film thickness of SPC systems is generally specified to prevent widespread polish-through in the planned inter-docking cycle of the vessel, but polish-through can occur in localised areas of high water turbulence, such as on rudders or the extremities of hull protrusions.

3.3.1.3 Obstruction of biocide release

3.3.1.3.1 Chemical

A side reaction of the dissolution of cuprous oxide and release of copper ions at the antifouling paint surface is the formation of insoluble compounds, including basic cupric carbonate (BCC) and chloride, which can adhere to the paint surface and inhibit further copper release (Ferry & Ketchum 1952, O'Hagan 2002). This precipitate is often visible as a green patina on the coating surface. This has been considered the limiting factor to life of insoluble matrix paints (Cologer et al. 1977, Cologer 1984, Cologer & Preiser 1984). BCC is considered to have no biological activity (Yebra et al. 2004). The strength of adherence of the precipitate, and therefore difficulty of removal, has been observed to increase through cycles of cleaning to a point where it could not be removed using a Submersible Cleaning and Maintenance Platform (SCAMP) unit with standard brushes (Cologer 1983, 1984).

Within insoluble matrix paints, the formation of insoluble copper products within the dissolution channels can also plug these channels and obstruct further cuprous oxide release (Saroyan 1968b). To slow this process, rosin was added to some vinyl paints to internally dissolve along with the cuprous oxide to open dissolution channels (Saroyan 1968b). However, while such formulations could extend the time to obstruction, ultimately the antifouling would still fail through this mechanism with substantial residual biocide left within the coating.

Lindner (1984, 1988) investigated the mechanism of failure of the copper-based USN antifouling coating F-121. In that paper, the author refers to F-121 as a soluble matrix coating, but Saroyan (1968a, 1968b) describes F-121 as a hard, insoluble vinyl matrix containing rosin. By microscopy, Lindner observed a bluish-green layer containing copper under the yellowish-green slime layer. Analysis of the green layer determined the predominant copper compound to be copper (II) trihydroxy chloride in the form of the double salt $CuCl_2.3Cu(OH)_2$ which is insoluble in water. In contrast to the accepted theory of basic copper carbonate (BCC) forming the green patina (Ferry & Ketchum 1952), there was no evidence of carbonates present. The diatom biofilm was proposed as the facilitator of the insoluble oxychloride formation. The slime was considered to create an oxidative environment which oxidized copper(I) to copper(II), trapped and accumulated the copper(II) which reacts to form copper chloride and copper hydroxide (also trapped in the slime), which then combined to form less soluble hydroxychloride complexes on the coating surface (Lindner 1984, 1988). Alkaline conditions generated under the slime by photosynthetic removal of CO_2 favours hydroxide formation, ultimately leading to the formation of the very insoluble double salt and a dense, insoluble layer that causes the antifouling to fail despite its residually high cuprous oxide content.

The USN has reported that ablative and self-polishing paints do not generate a green chemical layer of cuprous oxide [*sic.*], unlike the non-ablative vinyl antifouling paint specified through until 2005 (NSSC 2006).

Chemical pollution in the water can also cause insoluble copper products to form on the coating surface. High sulphur levels can cause the releasing ionic copper to form copper sulphide which, like BCC, is insoluble.

3.3.1.3.2 Biological

In addition to facilitating the formation of insoluble copper precipitates, microbial films that form on the coating surface can more directly modify or obstruct biocide release from the underlying coating. For coatings containing cuprous oxide, mechanisms that could contribute to reduced copper release rates listed by Yebra et al. (2006b) are:

- Chelation by the EPS matrix;
- Diffusion resistance;
- Pore blocking by bacteria; and,
- Elimination of the polishing process by mechanically stabilising the paint surface.

3.3.2 Biocide-free coatings

Biofouling management using biocide-free antifouling coatings is achieved by either minimisation of adhesion strength, resulting in deterrence, detachment or dislodgement of settling or settled organisms, or no active deterrence mechanism but a physically durable surface that can be regularly scrubbed to remove attached biofouling growth. Persistent attachment on foul release coatings can occur when:

- Critical surface characteristics are sub-optimal;
- Chemical or microbiological fouling modifies the coating surface;
- Vessel speed or activity is insufficient to generate “self-cleaning”;
- Periods of inactivity enable biofouling attachment;
- Low profile organisms persist within the non-turbulent boundary layer; and/or,
- The coating suffers physical or mechanical damage that scratches or abrades the coating surface.

3.4 IN-WATER CLEANING

3.4.1 Requirement for in-water cleaning

In-water cleaning of coatings has primarily been undertaken for two purposes:

1. To remove biofouling growth, to improve the vessel’s hydrodynamic performance; and/or,
2. To regenerate the antifouling coating through removal of insoluble surface salts or surface layers of leached or otherwise inactive paint.

More recently, an added purpose is the application of in-water cleaning to minimise or address biosecurity risks, by preventing the colonisation and maturation of potentially invasive marine species on vessel hulls, or removing an identified potentially invasive species established on a vessel.

The largest cost for the operator of a ship is generally the fuel cost, and this cost is strongly influenced by the hydrodynamic performance of the hull. Any deterioration of the underwater hull surface, either through corrosion, paint roughness, or biofouling, can cause a significant increase in fuel consumption and consequently increased costs and the environmental penalty of increased greenhouse gas emissions (Anderson 2004). The underwater surfaces of ships roughen with age, increasing on average by approximately 10 µm per year over the first 10 years for ships painted with SPC coatings, primarily due to mechanical damage to the coating system by anchor chains, fenders, tugs etc. (Anderson 2004). For older soluble matrix coatings, the increase in roughness was approximately 40 µm per year over the first ten years. Such increases in hull roughness require either an increase in power to keep speed constant or a loss of speed if power is kept constant. Both result in increased fuel, through either increased fuel consumption to maintain speed, or increased voyage time from slower speed at constant power.

Biological growth on underwater hulls can also significantly increase hull friction and fuel consumption (Townsin 2003). Algal and bacterial slimes on antifouling paints have been measured in laboratory experiments to increase drag by up to 17% (Haslbeck et al. 1990), and removal of slime on a US Navy (USN) frigate reduced the required shaft power by 9% at 16 knots (Haslbeck & Bohlander 1992). Based on results from laboratory-scale drag measurements and boundary layer similarity law analysis, the predicted change in shaft power for a USN frigate at a speed of 15 knots was an increase of 11% for a deteriorated coating or light slime, 21% for heavy slime, 35% for small calcareous fouling or weed, and up to 86% for heavy calcareous fouling (Schultz 2007). The predicted reduction in speed at fixed shaft power was 2.7%, 4.0%, 5.8% and 10.7% for these same levels of fouling, respectively. The growth of copper-tolerant green weed on the upper vertical sides of a container ship was found to impose a 4% increase in fuel consumption, measured by comparison of a vessel painted with a CDP antifouling coating with a vessel painted with a higher performance SPC antifouling coating (Anderson 2004). The economics of removing the slime layer by in-water cleaning, or to even remove weed and maintain a slime layer, are therefore quite clear.

Translating the impact of fouling on drag to fuel costs for USN frigates, heavy slime has been estimated to increase fuel consumption by 10.3% at a cost of approximately $1.2M USD per ship per year, and a mixed community of relatively small hard fouling can result in a cumulative cost over 15 years of $43.8M USD per ship (Schultz et al. 2011). Studies on USN ships during sea trials measured fuel penalties between 5 and 25% (Hundley et al. 1980). Bohlander (2009) suggests that commercial ships may have similar fuel penalties, but may have less fouling and therefore a lower overall fuel penalty over time due to commercial ships spending more time at sea than naval vessels.

The USN regularly undertake in-water hull cleaning to remove biofouling growth on their ships to increase the availability of the ship to the fleet, extend the life of the hull coating system while minimizing maintenance costs associated with dry-docking, and to recover performance or operating efficiency lost due to the fouling growth (NSSC 2006, Schultz et al. 2011). The advantages of in-water hull cleaning are considered by the USN to include (NSSC 2006):

- Fuel savings of up to 15% as a result of hull cleaning and propeller polishing;
- Restoration of sonar system effectiveness from cleaning of sonar domes;

- Reduced ship self-noise;
- Extension of the service life of a non-ablative vinyl antifouling paint system from 2 years to as much as 7 or more years, and extension of the life of an ablative system beyond the normal 5 to 7 years; and,
- Removal of calcareous fouling that can accelerate paint system failure.

The USN decision to clean is based on inspection (e.g. a full hull clean is undertaken if more the 20% of a hull coated with an ablative antifouling paint bears small calcareous fouling or weed), or indicators such as speed reduction, increased fuel use, or increased shaft power to maintain constant performance (NSSC 2006, Schultz et al. 2011). The level of cleaning performed can be full cleaning (the entire underwater hull, propeller, shafts, struts, rudders, and all openings), interim cleaning (propellers, shafts, struts, and rudders), or partial cleaning (particular sections of the hull).

Ablative antifouling coatings used by the USN were designed to meet 5, 7, or 10 year dry-docking periods (USEPA 1999). These coatings typically remained free of fouling for three years after application before they required cleaning then, after the first cleaning, required an annual clean. Over a three year period the average frequency of cleanings for USN Arleigh Burke-class destroyers were 0.21 /year for full hull cleanings and 2.4 /year for interim cleanings (Schultz et al. 2011).

FR coatings ideally slough biofouling organisms when the vessel is underway and silicone FR coatings significantly do reduce the stress required to remove fouling species (Swain et al. 1998, Holm et al. 2000). However, the forces necessary to remove organisms from what were considered the best of existing systems were found to be still too great for complete hydrodynamic removal of fouling (Swain 1999), and cleaning may be required. Due to the susceptibility of silicone coatings to abrasion damage, methods deployed for copper-based paints utilising stiff rotating brushes are unsuitable, and less aggressive brush designs or cleaning unit configurations are needed (Holm et al. 2003).

3.4.2 Methods for in-water cleaning

In their review of biosecurity and contaminant risks associated with in-water cleaning, Floerl et al. (2010a) identify two different categories of currently available in-water hull maintenance technologies: those that remove biofouling organisms from targeted areas, and those that prevent or kill biofouling organisms, but do not actively remove them. Of the former, which is the focus of this review, Floerl et al. identified manual scrubbing or brushing, diver-operated rotating brush systems, underwater suction devices, and underwater pressure (water jet) cleaning. Manual scrubbing or brushing can include the use of cloths, brushes or plastic/metal scrapers used by diver, snorkeler or surface-based person (Floerl et al. 2010a). Diver-operated brush systems range in size from hand-held systems approximately 30 cm in diameter, to large self-propelled multi-brush systems such as the SCAMP. The type of brush used, both in small and large brushing systems, can be varied for the type of fouling to be removed: nylon brushes to remove slime, algae and soft-bodied organisms; steel brushes or abrasive discs for hard, calcareous organisms (Floerl et al. 2010a).

Bohlander (2009) sought and reviewed potential technologies that showed promise for waste containment in-water during hull cleaning. From this worldwide survey, four systems that had been built were identified, but none were commercially available. A general response was that there was currently insufficient customer demand for capture technologies to justify the investment in further developing the technologies.

Underwater hull cleaning for the USN is presently accomplished by divers operating hand-held rotary brush units, self-propelled multi-brush cleaning vehicles, water jets (guns and hydro-lances), and hand tools (abrasive pads and scrapers) (USEPA 1999, NSSC 2006, Bohlander 2009). A wide range of brushes and discs are available for both single and multi-brush units. Guidelines within the USN specify that divers inspect the surfaces requiring cleaning and determine which equipment is needed to effectively remove the fouling with the least aggressive force (NSSC 2006, Bohlander 2009).

FR coatings, which are highly susceptible to abrasion damage, can only be cleaned safely with soft materials or non-contact methods (Holm et al. 2003). For example, for their FR coating Intersleek™, Akzo Nobel (2005) recommend cleaning the water line by high volume, low pressure fire hose, and underwater with high pressure freshwater fan-jet lance, or hand cleaning with a rubber squeegee or high porosity sponge. Few mechanical systems are considered suitable for cleaning silicone FR coatings. Two exceptions are the UMC International PLC “Mini-Pamper™”, which uses special brushes developed specifically for FR coatings, and the Cleanhull AS “Clean ROV™”, which uses water jet cleaning, not brushes (Bohlander 2009).

The feasibility of applying light cleaning on a more regular basis to maintain the performance of antifouling coatings fouling-free has been investigated for both FR and copper ablative coatings (Tribou & Swain 2010). Over a 120 day test period, light grooming with a foam windscreen cleaning tool at intervals of up to 12 days was successful at reducing biofilm build up. However, at a cleaning frequency of 24 days, the biofilm did gradually build up and became increasingly difficult to remove.

3.4.3 Effects of in-water cleaning on coatings

The aggressiveness of the cleaning procedure can result in removal of:

- Only biofouling;
- Biofouling and hydrated superficial (leached) coating layers; or,
- Biofouling, hydrated surface (leached) layer, and sound antifouling paint.

Studies have indicated that hull cleaning brushes can remove between 12.5 and 75 µm (0.5-3 ml) of coating (Ingle 2006) and, for an ablative paint, between 25 and 50 µm (1-2 ml) (Forbes 1996). The amount removed is a function of not only the type of paint (insoluble, soluble, SPC), but also the age of the paint, the severity of the fouling, the type of brush and cleaning machine used, and the skill of the operator (Bohlander 2009). Advice from International Paints (C. Anderson, pers. comm.) is that highly aggressive techniques, such as steel bristle brushes on a rotating head, can easily remove 50-100 µm, whereas nylon brushes kept at a controlled height above the surface on a harder antifouling will remove less than 25 µm. The latter technique, when used to remove biofouling from silicone FR coating, has been found to cause little scratching of the elastomer surface. If the antifouling/anticorrosion coating is not physically intact with good adhesion, cleaning can accelerate the rate of damage at defective sites in the paint system (Cologer & Preiser 1984). The surfaces most vulnerable to damage are edges, corners, welds and seams. If there is paint blistering or delamination, either at internal coating interfaces such as between the antifouling and anticorrosive systems, or between the anticorrosive system and the hull plate, then paint flakes may be dislodged during the cleaning process. Cleaning can also aggravate the spread of corrosion by rupturing blisters at the coating-steel interface (Cologer & Preiser 1984). However, cleaning does no apparent damage to intact antifouling/anticorrosive paint systems on relatively flat and slightly contoured surfaces.

3.4.4 Contamination from in-water cleaning

In-water cleaning can increase the release of copper and other antifouling biocides by both the direct release of biocide-contaminated material from the coating surface and by elevating the rate of passive biocide leaching. The former occurs during the process of cleaning, while the latter continues until the release rate returns to steady state. Contamination released during cleaning can be either in the form of dissolved copper, paint particles, or paint flakes if the coating system is degraded and unsound. Although copper released passively may quickly bind to organic matter, reducing toxicity to aquatic and benthic organisms to a variable extent, it could be assumed to be dissolved at the time of release from the coating.

Dissolved copper concentrations increase dramatically in nearby water during in-water cleaning. As an example, during the cleaning of a 30' power boat the dissolved copper concentrations near the boat increased from a mean of 12 µg/L to 56 µg/L (McPherson & Peters 1995). This copper dissipated rapidly, dropping to 17 µg/L five minutes after the cleaning finished, and returned to 12 µg/L after ten minutes.

The waste generated by hull cleaning operations consists primarily of seawater, slime, marine growth and antifouling particles (Forbes 1996). In most in-water cleaning, this waste is released directly into the harbour or other local water body. For copper antifouling coatings, the three primary by-products of hull cleaning are considered to be dissolved copper, particulate copper, and organic fouling debris (Valkirs et al. 1994, Forbes 1996). Dissolved copper is defined as copper that will pass through a 0.45 µm filter.

As noted by Valkirs et al. (1994), although in many studies "total copper" is measured and assumed to be responsible for any toxic effects, considerable differences exist between the bioavailability and toxicity of various copper species (Section 9.1). As previously mentioned, copper toxicity to marine organisms is attributed to free cupric ions, and the release of these is considered to be the antifouling mechanism for cuprous oxide based paints (Howell & Behrends 2006). Ionic copper does, however, rapidly form organic and inorganic complexes and becomes less toxic to sensitive single cell and larval planktonic organisms (Allen & Hansen 1996, Zirino & Seligman 2002, Valkirs et al. 2003). A comparison of dissolved and particulate composition of copper in hull cleaning waste found 50-80% of the total copper to be particulate, and therefore not bioavailable to organisms in the water column (Valkirs et al. 1994). Particulate matter can settle to the sea floor where, although chemically bound to organic or inorganic substances, it can be ingested and mobilised by infaunal organisms (Jones & Turner 2010).

Paint particles suspended in wastewater from shore-based water-blasting operations, which could be considered comparable to the waste from in-water cleaning, have been found to be typically about 5-30 µm in size, with a copper content of 2-30% and average about 10% (Williamson et al. 1995). The disintegration of paints by both sanding and water-blasting resulted in a large number of small particles and a large increase in surface area, which was predicted to effectively increase leaching (Williamson et al. 1995). Paint particles were therefore predicted to lose their copper rapidly, within less than a day to a few weeks.

In-water cleaning has also been reported to cause a spike in biocide release rates immediately after cleaning, but passive release rates have been observed to return to baseline after approximately 3 days (Brown & Schottle 2006).

Brush cleaning is reported to dislodge paint chips along with biofouling organisms (Cross 1974, Preiser & Laster 1981), and it is considered possible that paint chips are also removed with hand scrubbing as well, particularly if the biofouling includes calcareous organisms such as barnacles (Conway & Locke 1994). Dislodged paint flakes that fall to the sea floor to become incorporated into the sediment can directly contaminate the sediment as paint flakes or particles and also through indirect contamination via metal dissolution and subsequent adsorption (Takahashi et al. 2012). Solubilisation of metals from within the paint will be greater from smaller and discrete particles of antifouling paint due to the greater mass-normalised surface areas of finer particles.

3.5 BIOCIDE CONTENT OF COATINGS

3.5.1 Paint Films

3.5.1.1 Dried paint

The amount of copper used within any antifouling paint varies widely from 20-76% of the total (Brooks & Waldock 2010). After application, the paint dries through the release and evaporation of solvents, leaving the residual solids as a dry film. For protective coatings, such as anti-corrosion coatings, adequate dry film thickness (DFT) is needed to prevent seawater ingress to the metallic substrate; for antifouling coatings, the dry film thickness needs to be adequate to hold sufficient biocide to be released at or above the critical rate for the planned period until the next docking or slipping of the vessel for paint repair or renewal. Marine paint manufacturers provide specifications for the DFT or volume of paint required per unit surface area to meet the required paint life.

The concentration of copper in the dried film can be calculated from the per cent volume of biocide in the wet paint, and parameters such as the per cent solids in the wet paint, the dry film thickness/wet film thickness ratio, the specific gravity of the wet paint, and the weight fraction of active ingredient in the biocide (CEPE 2005, Haslbeck & Ellor 2005).

For antifouling paints registered for use in New Zealand, the biocide content of the wet paint for some is available on the EPA web-site (EPA 2012). For those that the biocide content is not listed, if the products are registered in Australia, then the biocide content is available on the APVMA web-site (APVMA 2012) (Table 8.3). Other parameters required for calculation are generally reported in the product technical data sheets or material safety data sheets (MSDS) available from the manufacturer for each individual product.

3.5.1.2 Paint flakes

A number of studies have investigated contamination and its effects in the environment due to paint flakes and other wastes in the vicinity of vessel repair facilities (Williamson et al. 1995, Turner et al. 2008, Gammon et al. 2009, Singh & Turner 2009, Turner et al. 2009, Parkes et al. 2010, Turner 2010, Takahashi et al. 2012).

The analysis of fragments of antifouling paint collected from the hardstand of a leisure boat yard in southern England found the copper concentration in fractionated (< 1 mm) paint particle composites to be close to 300 mg Cu/g (30%) on a dry weight basis (Gammon et al. 2009). Of this, 0.13% was solvent extractable and attributed to organometallic secondary biocides. Singh and Turner (2009) reported a similar result of 311 mg Cu/g in samples collected form a large leisure boat maintenance facility in Plymouth, UK. A more extensive survey of nine locations in south-west England found copper concentrations in discarded paint particles from boatyards, marinas and near abandoned boats to range from about 24 mg/g to 375 mg/g (Parks et al. 2010). The copper content in a sample of fresh paint was 365 mg Cu/g. Ground, composite samples of paint fragments collected more widely from recreational boat maintenance facilities within the EU indicated dry weight copper concentrations of up to about 35%, estimated to be equivalent to 40% cuprous oxide content (Turner 2010), and samples from boatyards and hardstands in Malta ranged between 2.6-147 mg/g dry weight, with an arithmetic mean across all locations of 54.4 mg/g (Turner et al. 2009). The mean copper content of paint residues collected from the sanding and scraping of hard paints on recreational vessels hulls in Auckland repair facilities was about 33% (Williamson et al. 1995).

Paint flakes generated during hull maintenance activities would be representative of the full coating system, so could include primer, anticorrosive, sealer and tie coats in addition to the antifouling paint. As the overall concentration of copper in a paint flake is an average over all paint layers, the measured value would often be less than the concentration in the antifouling paint alone. Paint residues from sanding would also include removal of the copper-depleted leached layer. These factors would explain measured values below, and often much below, that present in dry antifouling paint films. For some other metals, including zinc and aluminium, the concentration may actually be elevated in a coating system sample because of the use of these metals in some anticorrosion coatings.

3.5.1.3 Leached layer

No published information has been found on the concentration of copper of other antifouling biocides in the leached layer. In Lewis (1998), the scanning electron micrograph (SEM) of a section through the leached layer and underlying unhydrated ablative coating includes an energy dispersive x-ray analysis (EDX) trace for copper. This shows high peaks and troughs of copper abundance through the sound paint as the trace passed through cuprous oxide particles. Within the leached layer the trace suggests elevated copper compared to the area above the paint, but the amplitude of fluctuations in the trace is about 1/5 of that in the underlying paint, with a marginally elevated copper concentration just above the pigment front. SEM/EDX scans through leached layers illustrated in Howell & Behrends (2006) indicate a drop in copper concentration to close to the background level.

The mean copper content of spent paint washed off recreational boats in Auckland vessel repair facilities was found to be 9.4%, compared with 33% in paint scrapings (Williamson et al. 1995). Wash down water may include residual biofilm, leached layers and, particularly for ablative coatings, sound paint. A common practice when vessels are being docked, slipped or lifted from the water is to give the hulls a preliminary wash down with high volume, low pressure water to remove sediment and slime. In doing this, the slime and its accumulated copper (see next section) could be removed, reducing the copper load of the waste later generated by high pressure washing. The lower copper content of spent paint washed off, compared with paint scrapings, may therefore provide an indication of the reduced copper content in the leached layer.

3.5.2 Surface biofilms

The microbial slime film on a paint surface accumulates biocide released from the paint and can contain “as much as 1,000 times the toxic concentration found in a saturated seawater solution” (Ketchum 1952a). This slime may potentially increase the antifouling effect by concentrating biocide on the coating surface, or reduce effectiveness if the biocide is bound in a biologically unavailable form and/or if the high concentration inhibits further biocide release. For effective copper-based paints with cuprous oxide content of between 12 and 40%, the copper content of slimes after two weeks immersion was between 0.98 and 2.40 $\mu g/cm^2$ (Ketchum 1952a).

Biofilms have been more recently reported to contain high copper concentrations (1.3-3.5 µg/mg dry wt) (French et al. 1984).

The study of copper emissions from in-water cleaning in San Diego Bay (Brown & Schottle 2006) can be used to make some assumptions about the copper content of biofilms. In their experiments that simulated different in-water cleaning methods, a 'light' cleaning was simulated by wiping the surface with carpet. It seems reasonable to assume that this would remove little more than the biofilm, so the measures of particulate copper associated with this test could provide a guide to the copper content of the biofilm. 'Light' cleaning of the two insoluble matrix coatings they tested generated around 9 and 190 µg/cm^2/event of particulate copper from 1 month fouling on the epoxy and vinyl coatings respectively, and 13 and 240 µg/cm^2/event from 3 month fouling. The authors attributed the greater release from the vinyl coating to this coating being a softer coating with the implication that some surface coating could have been removed. However, in the data logs for each vessel appended to the report, light green and brown algae are reported on the vinyl coatings at both 1 and 3 month events, whereas the epoxy-coated hulls had, at most, scattered tubeworm (Brown & Schottle 2006). These observations suggest that there may have been more substantial algal slime on the vinyl-coated hulls which, if copper is bound within the slime, could also contribute to higher copper release from this coating.

Williamson et al. (1995) measured the copper in wash down water collected from recreational vessels slipped for maintenance in the Auckland region. The mean copper content of the spent paint washed off the boats was 9.4%. The mean copper content of paint residues collected from sanding and scraping hard paints was about 33%. A more detailed analyses of paint washed off boats demonstrated a wide range in the amount of copper per unit areas removed from boats (Table 3.6).

Table 3.6 Copper release per unit surface areas calculated from copper and particulate content of wash down water (Williamson et al. 1995).

Boat ID	Area washed	Paint	Paint type	Area (m^2)	Cu ($\mu g/cm^2$)
AC1	Hull	*Interspeed*	Hard[1]	23	0.240
IV1	Keel & Hull	*War Paint*	Hard[2]	14	0.015
WF1	Hull	*War Paint*	Hard[2]	1	0.142
TN1	Hull	*Altex*	?	25	2.482
AM1	Hull	*Altex*	?	20	0.214
GM1	Keel & Hull	?	Ablative	23	2.157
OS1	Keel & Hull	*ABC-5*	Ablative	14	0.070
MC2	Keel & Hull	*Micron*	Ablative	14	0.260
MD1	Hull	*AwlCraft*	Ablative	20	70.463
MD2	Hull	*AwlCraft*	Ablative	20	5.664

[1]*Interspeed* variants can be hard or ablative; on recreational craft it is considered more likely to be the hard Interspeed 2000.
[2]*War Paint* is described their product as moderately ablative, ablating slower than most ablative paints but softer than traditional "hard vinyls" (Wet&Forget 2012).

More recently, Boxall et al. (2000) quote a Netherlands study in which emissions of copper from high pressure water blasting of recreational boats out of the water were demonstrated to be between 90 and 2800 mg/vessel. Using the authors' assumption that an average leisure vessel has an underwater surface area of 30.7 m^2, this emission would equate to between about 0.3 and 9 µg/cm^2/event.

3.6 BIOCIDE RELEASE RATES

3.6.1 Release rates

As previously mentioned, for biocidal antifouling coatings to be effective, the biocide must be continuously released at the surface of the coating at a concentration that will prevent the settlement and/or survival of fouling organisms. The rate at which antifouling biocide passes through the antifouling coating/seawater interface is termed the biocide leaching or release rate and is generally expressed as the mass of biocide, in micrograms, released from a square centimetre of antifouling coating in one day (µg biocide/cm^2/day). "Leaching rate" was commonly used for this parameter, as the mechanism of biocide release from conventional coatings with freely associated biocides was passive leaching. However, as the process of biocide release from TBT SPC coatings was through chemical hydrolysis, not hydration, "release rate" was considered to more correctly represent the process. With the return to coatings with freely associated biocide that has followed the banning of organotin antifouling paints, including tin-free SPCs," leaching rate" and "release rate" can be considered equally correct.

Controlling the release rate is considered one of the most difficult problems faced by the antifouling paint technologist (O'Hagan 2002). It must be neither too fast, resulting in biocide wastage and short effectiveness, nor too slow, when the biocides are locked in the film and surface concentrations are ineffective.

Biocide release rates from antifouling coatings can vary with the pH, temperature, salinity, water movement over the surface and copper concentration in the water (de la Court & de Vries 1973a). Copper release rates increase with increasing temperature and salinity, and decrease with increasing pH (Ferry 1952, de la Court & de Vries 1973b, Finnie 2006). For one ablative coating, a 2.5-fold increase in copper release rate, from 11 to 28 µg/cm^2/day, was observed over a 20^{o}C change in temperature, from 7 to 27^{o}C (Seligman et al. 2001, Valkirs et al. 2003). In addition to water parameters, copper release rates of antifouling paints in service can vary over the life of the coating system, depending on the formulation and the environment, and on differences in berthing locations, operating schedules, vessel speed, length of service, and condition of paint film surface, (ASTM 2005, OECD 2005). Other factors such as biofilm, static versus dynamic operation, and wet and dry cycling may also influence release rates (Valkirs et al. 2003, Howell 2010).

3.6.2 Release rate measurement

3.6.2.1 Bubbling method

Similar methods for the laboratory determination of copper leaching rates from antifouling paints on panels exposed in the sea were developed in the mid-20th century in Britain and at the Woods Hole Oceanographic Institution (WHOI) in the United States (Ketchum 1952b). Differences in the methods were only in the size and method of holding the panels in the measurement apparatus. In the WHOI method described by Ketchum (1952b), panels exposed in the sea by attachment to racks or rafts were returned to the laboratory at monthly intervals and immersed in a container of clean aerated seawater with a paint surface area (cm^2) to leaching solution volume (cm^3) ratio of 1:5. The leaching container was stirred by a vigorous stream of air bubbles, and sampling for analysis undertaken after one, two or four hours depending on leach rates. Ketchum noted that the copper concentration in the solution should not exceed 0.5 µg/ml, as above this the rate of release from the paint decreases and insoluble copper compounds precipitate. Although well below the solubility of cuprous oxide (5.4

µg/ml), a “pseudosaturation effect” is observed that causes dissolution rates to slow at concentrations greater than 1 µg/ml (Ferry 1952).

This method, also termed the “Ketchum Method” (Takahashi 2009), has been applied more recently to determine copper, organotin and DCOIT release rates from antifouling paints, but with painted panels immersed in laboratory holding tanks rather than in the field (Takahashi & Ohyagi 1988, Takahashi & Ikuta 1989, Takahashi 1990, 1991, Takahashi et al. 2002).

3.6.2.2 Paint analysis

Ketchum (1952b) also describes a method for determination of copper leaching rates by destructive analysis of paint samples after immersion. The procedure, of rinsing, air-drying, digesting the paint from the panel, then measuring copper concentration in the digest, was considered by Ketchum to be more laborious and less accurate than the leaching method.

3.6.2.3 ASTM/ISO rotating cylinder

In the ASTM and ISO methods for determining copper release rates (ISO 2000a, 2000b, ASTM 2003) the candidate paints are applied to cylindrical test specimens. The coated specimens are placed in a tank of substitute ocean water, where the copper levels are kept below 100 µg/L by circulating the substitute ocean water through a suitable filtration system. At specified intervals, each specimen is placed in a test container holding 1500 mL of substitute ocean water, and rotated at 60 revolutions per minute (rpm) for 1 h or less. The rate of copper release from the paint is determined by measuring copper concentrations of the substitute ocean water in the individual measuring containers.

This rotating cylinder method for determining biocide release rates was initially developed by ASTM to measure release rates of organotin compounds (ASTM 1990). The method was initially applied in a draft form (USEPA 1986) for US Congressional legislation to restrict the use of free-association TBT antifouling paints by imposing a maximum permissible release rate of 4 µg TBT/cm^2/day. Apart from some variation in release rate values which related to sampling timing and frequency (see Lewis & Baran 1993), the method could generate consistent results and was an effective means for comparing the relative release rates of different antifouling formulations. Copeland & Burns (1989), by extending the length of the test to eight weeks, found that they could estimate steady state release rates for a given cylinder to within 20% with 90% confidence.

However, it was recognised quite early that the method appeared to over-estimate the actual release rate of TBT from field immersed panels and in-service vessel hulls (Lewis & Baran 1993, Finnie 2006, Howell 2010). Compared to the 4-5 µg TBT/cm^2/day determined by the ASTM method for TBT SPC coatings, other methods yielded rates of 1-3 µg TBT/cm^2/day (Takahashi & Ikuta 1989), 0.1-0.2 µg TBT/cm^2/day (Anderson & Dalley 1986) and 0.1-0.9 µg TBT/cm^2/day (Grovhoug et al. 1989). These latter values relate closely to the minimum effective TBT release rate to prevent biofouling attachment, determined by perfusing a known flux of biocide through a membrane filter, of 0.22 µg TBT/cm^2/day for barnacles, and 0.83 µg TBT/cm^2/day for hydrozoans (Mihm et al. 1990).

The inconsistent relationship between the rotating cylinder results and environmental release was acknowledged by the USEPA in 1987, thus:

> “As designed, the ASTM method… was intended only to compare the relative release rate of organotin compounds of various paint formulations. Results from the ASTM

method were not intended to reflect actual environmental loading for any particular formulation since this would be impractical to accomplish in a standard laboratory setting, nor was it designed to predict actual release into the environment" (USEPA 1987).

The subsequently approved ASTM standard test method for measuring organotin release rates (ASTM 1990) included similar sentiments in the preamble:

"This test method serves only as a guide for organotin release rates in service. Organotin release rates of antifouling (AF) paint systems in service can vary over the life of the coating systems depending on the coating system, the formulation and the environment. Differences in berthing locations, operating schedules, length of service, condition of paint-film surface, temperature, pH, and salinity can affect results. Results obtained may not necessarily reflect actual tributyltin release rates that will occur in service, but provide reliable comparisons of the release rate characteristics of different antifouling formulations".

The progressive banning of organotin antifouling paints, and their replacement by antifouling coatings mostly with copper or copper compounds as the primary biocide, led to concerns on the input of copper into the marine environment from antifouling systems and a call for standard methods for copper release rate measurement. For example, in 1994, Canada included a maximum copper release rate value of 40 µg/cm^2/day for antifouling coatings containing copper within the regulatory requirements for the registration of antifouling coatings (PMRA 1994). The suggested method of determining the copper release rate was the ASTM method for determination of organotin release rate from antifouling coatings "adapted/modified for the determination of copper".

The rotating cylinder method was adopted as the basis for both ASTM and ISO standards for measuring copper release from antifouling paints (ISO 2000a, 2000b, ASTM 2003). However, modifications were needed to address the "pseudosaturation effect" in holding tanks, which required circulation of water through a filtration system (Berg 1995). Copper concentrations in test containers have also been observed to suppress copper release (Lewis & Baran 1993) and, in this study, the behaviour of the TBT/Cu SPC coatings differed to behaviour in-service in that the colour did not change (J. Lewis, pers. obs.). In-service, this colour change (for example, from plum to grey, or pink to white) was due to the dissolution of red-pigmented cuprous oxide from surface layers of the coating.

The specified testing time of up to 45 days in the ASTM method for TBT paints (ASTM 1990, 2002) has been considered likely to result in release data that is too high if applied to environmental release over the lifetime of the paints, due to the release rate of copper from both soluble and insoluble matrix coatings decreasing exponentially through the life of the paint (OECD 2005, Takahashi 2009, Howell 2010). Takahashi (2009) adds that these coatings may also not reach steady state for 4-6 month, well beyond the sampling schedule specified in ASTM/ISO. Testing extended to one year resulted in a measured release rate 3-4 fold less than the short term 21-45 day average (IMO 2009).

Round robin testing of the ASTM method has found considerable inter-laboratory variability in measured copper release rates from the same copper ablative or SPC antifouling coating, with coefficients of variation in results as high as 62% (Table 3.7; Haslbeck & Ellor 2005, Haslbeck & Holm 2005, Finnie 2006). Follow up studies with repeat measurements in a single laboratory produced less variation (CV = 13%), but this still translated to high variability in predicted release rates; for example a range of 17.9 to 30.5 µg/cm^2/day around an average of 24.2 µg/cm^2/day. Repeat measurements from a second ablative coating resulted in even higher variability of 24% and 47% for days 21 to 45, and 55 to 90, respectively (Haslbeck & Ellor 2005). A conclusion from the round robin study was that, without improvements to the method, interpretation and prediction of release rate results would not allow the accurate estimation of how reformulation of coatings, or limits placed on release rates, would impact on the environment (Haslbeck & Holm 2005).

Table 3.7 Release rates measured by 5 laboratories in round robin testing of ASTM D6442 (Haslbeck & Holm 2005).

Coating	Cumulative release to 14 d (µg Cu/cm²)	Cumulative release to 45 d (µg Cu/cm²)	Average release rate Days 21-45 (µg Cu/cm²/day)
Coating 1 – SPC	1,019 ± 125	2,174 ± 399	37 ± 10
Coating 2 - Ablative	916 ± 150	2,470 ± 630	49 ± 16
Coating 3 – SPC	111 ± 35	676 ± 174	18 ± 5
Coating 4 – SPC	1,384 ± 277	2,946 ± 726	50 ± 15
Coating 5 - Ablative	776 ± 155	1,691 ± 351	29 ± 7

As with TBT release rates determined using the rotating cylinder method, copper release rates generated by this method are also considered to significantly over-estimate actual release from ship hulls. Haslbeck and Ellor (2005) performed stoichiometric calculations using average release rates generated by the ASTM method and this predicted a coating life of only 3.6 years for a coating known to provide antifouling protection on commercial and naval ships for 5 or more years. Finnie (2006) proposed that, to account for the over-estimation, copper release rates measured for any paints by the ASTM/ISO method should be divided by a correction factor of 5.4 to more closely approximate environmental release.

The current ASTM method for measuring copper release rates (ASTM 2006) includes provisos on application of results, similar to those for TBT release rates, as follows:

> "The results of this test method do not reflect environmental copper release rates for antifouling products, and are not suitable for direct use in the process of generating environmental risk assessments, environmental loading estimates, or for establishing release rate limits for regulatory purposes"

and

> "By comparison with copper release rate measurements obtained either by direct measurements of copper release rate from AF coating systems on ship hulls, or copper release rate measurements from AF coating systems from harbour exposed panels, all available data indicate that the results of this test method (Test Method D 6442) significantly overestimate the release rate of copper when compared to release rates under in-service conditions. Published results demonstrate that this test method produces higher measurements of copper release rate than from direct in-situ measurements for the same coating on in-service ship hulls and harbour-exposed panels. The difference between the results of this test method and the panel and ship studies was up to a factor of about 30 based on data for several commercial antifouling coatings. Realistic estimates of the copper release from a ship's hull under in-service conditions can only be obtained from this test method where the difference between the results obtained by this test method and the release rate from an AF coating in-service is taken into account.
>
> Where the results of this test method are used in the process of generating environmental risk assessments, for environmental loading estimates, or for regulatory purposes, it is most strongly recommended that the relationship between laboratory release rates and actual environment inputs is taken into account to allow a more

> accurate approximation of the copper release rate from antifouling coatings under real-life conditions. This can be accomplished through the application of appropriate correction factors."

Howell (2010) observed that ASTM results for SPC coatings are much closer to the peak results shown by Howell & Behrends (2006) than to stable release rates. He considered this to be due to the coatings not being maintained under constant dynamic immersion in the ASTM methodology, as rotary step changes cause "burst" effects, where a pulse of biocide is released when rotation starts or rotation speed changes, up to an order of magnitude higher than the stable release rates that take up to six hours to develop. The ASTM method of immersion for 1 hour, the result of which is extrapolated to a daily release rate, is therefore considered to greatly over-estimate the stable release rate because of the influence of the burst effect on copper concentration in the test container (Howell 2010). Lewis & Baran (1993) reported a similar result from rotating cylinder measurements, with an initial pulse of biocide on immersion of cylinders in test containers influencing, and causing over-estimation, of release rates in standard calculations.

3.6.2.4 Flume and rotary tank

In a study funded by the UK Health & Safety Executive, and in response to observations that the rotating cylinder method provided results significantly higher than those that occur in the environment, methods were developed that aimed to derive environmentally representative TBT and copper release rates for a TBT-based, copper containing SPC paint and to investigate the short-term changes in environmental parameters on release rates (Thomas et al. 1999, Thomas & Waldock 2000). Two test systems were developed: a flume tank in which a painted panel was held under conditions of constant near-laminar flow, and a custom-designed rotary device by which the painted panels was moved through the water at constant velocity. Lower release rates were measured using both of these systems than from the ASTM method (Table 3.8).

Table 3.8 Comparison of TBT (µg TBT/cm^2/day) and copper (µg Cu/cm^2/day) release rates from the same TBT-based, copper containing, SPC coating from measurements with different test systems (Thomas et al. 1999).

Biocide	ASTM	Flume	Rotary
TBT	1.5-4	1.6	1.7
Cu	25-40	18.6 $\pm$ 6.5	21.6

3.6.2.5 Harbour exposed panel (HEP)

The harbour exposed panel (HEP) method is similar to the bubbling method but, rather than using vigorous air bubbling to agitate water in the test container, panels returned to the laboratory are mechanically moved gently up and down in the measurement container to simulate tidal flow past a ship hull (Lindner 1993, Haslbeck & Ellor 2005). Tests have been conducted on panels subjected to only static field immersion, and to panels dynamically aged by rotation on an immersed drum to simulate ships underway. Release rates measured by this method were approximately ½ to ¼ of those generated by the ASTM method.

Stoichiometric determinations of release rates, based on measured reductions in coating thickness of ablative antifouling systems on US Navy ships, resulted in release rates of 7.6 to 10 µg/cm^2/day (Haslbeck & Ellor 2005). This correlated far more closely with HEP calculations (8.9 static, 17.0 static/dynamic) than ASTM values, and also to the

10 µg/cm^2/day found to be the minimum level of copper release to control barnacle fouling (Ketchum 1952a).

Static/dynamic panel exposures are considered to provide some realism in release rate behaviour as they simulate in-port and underway periods of a ship's duty cycle (Valkirs et al. 2003). Higher copper release rates have been measured after dynamic exposure, which decreased within a week of the dynamic cycle ending. However, test panels are likely to erode and polish faster on the drum during dynamic exposure than on ships, due to the small panel size and drum diameter producing more turbulent flow across the panels. The dynamic cycle was observed to typically remove all traces of biofilm, and to erode outer layers of the paint, resulting in higher release rates. This differs to ships that typically retain a biofilm even after travelling at high speeds (Valkirs et al. 2003). Static exposure panels mimic pier-side conditions, and also accumulate an increasing biofilm over time.

As the method involves field immersion, applying this method for classification and regulation of release rates would be difficult because it would not be possible to standardise and replicate across locations and laboratories, due to variability in factors such as biofilm formation, temperature, pH and salinity.

3.6.2.6 US Navy dome

The US Navy dome for measuring biocide release rates was developed as a field method for directly measuring biocide release rates from ship hulls (Seligman & Neumeister 1983). A polycarbonate dome, 30.5 cm in diameter, is attached to an immersed painted surface by light suction and seawater circulated through the dome in a way that assures the coating is exposed to a circulating flow of water. A portion of the circulated water is passed through a cupric ion sensor that enables measurement of the dissolved copper in the water over time, or samples collected from the circulated water for laboratory analysis of dissolved copper from which the copper release rate of the coating is calculated (Seligman & Neumeister 1983, Lieberman et al. 1985, Grovhoug et al. 1989, Seligman et al. 1996, Valkirs et al. 2003). The dome method has also been used to measure copper release rates from large, field immersed test panels (Valkirs et al. 2003).

The US Navy dome method has been considered as the most reliable indicator of environmental release rates, but use has been largely restricted to the US Navy and its associated agencies (Finnie 2006). Measurements on vessel hulls are believed to provide realistic estimates of actual environmental loading under the existing physical-chemical and biological conditions present during the measurement process and, for large static immersion panels, release rates through biofilms (Valkirs et al. 2003).

However, Howell (2010) observes that the hydrodynamics of the dome method have never been quantified and it is assumed that is gives a measure of static flow. He adds that it has never been proven that the hydrodynamic conditions inside the dome actually reflect environmental conditions and results, although potentially close to reality, are only so for the given environmental scenario of static flow in San Diego Bay. The reported release rate values determined by the dome method on vessels are likely to underestimate the steady state copper release coatings on vessels with effective antifoulings, as evidence suggests the coatings measured were not providing effective fouling protection. For example, the recreational vessels studied used insoluble matrix coatings subject to regular in-water cleaning to remove fouling growth (Valkirs et al. 2003).

3.6.2.7 Mass-balance calculations

3.6.2.7.1 CEPE

A method for the calculation of biocide release rates from details of the antifouling paint formulation and application was developed by the European Council of the Paint, Printing Ink and Artists' Colour Industry (CEPE 2005, Finnie 2006), and has since been published as an international standard method (ISO 2010). The method is based on a simplified generic empirical model of biocide release and the inputs to the model are the specified service lifetime of the paint (months), the amount of biocide in the coating formulation (% by weight), the weight fraction of the active ingredient in the biocide, the volume solids of the wet paint (%), the specific gravity of the wet paint, the dry film thickness of the specified paint applied for the specified lifetime (µm), and the fraction of active ingredient in the dry film released during the specified lifetime of the paint (Finnie 2006). CEPE recommended that 0.7 be the value used as the fraction of active ingredient in the dry film released during the lifetime of the paint, but some regulatory authorities, including the United Kingdom, specified that a factor of 1.0 be used which represents the complete release of all biocide in the paint (Finnie 2006). More recently the position of European regulatory authorities has been to apply a factor of 0.9 (IMO 2009).

The calculation of the total amount of biocide released during the lifetime of the paint, in µg/cm^2, is calculated from the following equations (CEPE 2005, Takahashi 2009):

$$X + ((t - ½) \times 30 \times Y) = L_a \times a \times W_a \times 100/SVR \times SPG \times DFT$$
$$X/Y = 30$$

Where:

X	=	the amount of biocide released during the first 14 days (µg/cm^2);
Y	=	the average release rate during the rest of the lifetime (µg/cm^2/day);
t	=	the specified lifetime of the paint (months);
30	=	1 month = 30 days;
½	=	half a month (14 days);
La	=	the fraction of the active ingredient in the dry film released during the lifetime t (from practical experience, CEPE recommends 0.7);
a	=	the mass fraction of active ingredient in the biocide (organic biocide a=1; copper in copper thiocyanate a=0.522; copper in cuprous oxide a=0.86);
Wa	=	the concentration of biocide in the wet paint in weight %;
SPG	=	the specific gravity of wet paint (g/cm^3);
SVR	=	the solid volume ratio (volume of dry paint versus volume of wet paint) (in %);
DFT	=	the dry film thickness specified for the lifetime t (µm); and,
100		is included to secure the units of measurement in the equation.

3.6.2.7.2 ISO Method

The CEPE Method was adopted as the basis for the ISO standard method for the mass-balance calculation of biocide release rates from antifouling paints (ISO 2010). The formulae, although the same, are expressed slightly differently as:

$$M = \frac{L_a \times a \times W_a \times SPG \times DFT}{SVR}$$

Where:

M	=	the estimated total mass of biocide released per unit area of paint film over the lifetime of the paint, in micrograms per square centimetre (µg/cm^2);
L_a	=	the percentage of biocide that is released from the paint film during the lifetime of the paint;
a	=	the mass fraction of biocide in the biocidal ingredient;
W_a	=	the content of biocidal ingredient in the paint formulation as manufactured, in % by mass;
SPG	=	the density of the paint as manufactured, in kg/dm^3 (g/cm^3);
DFT	=	the dry-film thickness specified for the lifetime of the paint, in µm; and,
SVR	=	the non-volatile-matter content (volume solids content) of the paint, in % by volume.

A value of L_a = 90%, as distinct from 70% in the CEPE Method, is recommended as representing a realistic worst-cased maximum amount of biocide released over the lifetime based on experience of antifouling paints.

$$Y = \frac{M}{\left(\frac{365 \text{ x } t}{12}\right)} = 0.0329 \text{ x } \frac{M}{t}$$

Where:

Y	=	the mean biocide release rate over the lifetime of the paint, in micrograms per square centimetre per day (µg/cm^2/day);
t	=	the lifetime of the antifouling paint in months;
12	=	the number of months in a year;
365	=	the number of days in a year; and,
0.0329	=	a factor to convert months to days.

To enable calculation of the cumulative total release of biocide over the first 14 days of the specified paint lifetime, the following equation is given:

$$X = Y \times f$$

Where:

X	=	the 14-day cumulative release of biocide, in µg/cm^2; and,
f	=	an empirical factor that reflects the relationship between the cumulative release of biocide over the first 14 days following entry to service and the estimated average release rate over the lifetime of the paint (f = 30).

The given default value of f = 30 is based on the typical behaviour observed for a range of biocides and antifouling biocides and paint types and is the same value applied in the CEPE Method. The standard suggests the use of alternative values if the paint does not exhibit this typical behaviour.

ISO 10890:2010 is introduced with the preamble (ISO 2010):

> "The actual release rate of biocides from antifouling paints on ships' hulls into the environment will depend on many factors, such as ship operating schedules, length of

service, berthing conditions, paint condition, as well as the temperature, salinity, pH, pollutants, and biological community in a particular area…[but] an estimate of the mean biocide release rate from an antifouling paint over its specified lifetime can be obtained by the mass-balance calculation method described in this International Standard."

With respect to the use of the estimates in environmental risk assessments, the Introduction (ISO 2010) further adds:

> "Biocide release rate data is a key input to the environmental risk assessment process for antifouling products, and so it is vital that the estimated biocide release rate that is used be both accurate and representative of the release rate to the environment in the relevant scenario and risk assessment case… Published results demonstrate that the results of this calculation method are generally higher than direct *in situ* measurements of copper release rate from the hulls of harboured ships by a factor of about 4 or more for several commercial antifouling coatings… When the results of this calculation method are used in the process of generating environmental risk assessments, producing environmental loading estimates or for regulatory purposes, it is most strongly recommended that the relationship between calculated release rates and actual environmental inputs be taken into account to allow the most accurate and representative estimate of the biocide release rate from antifouling coatings under real-life conditions to be obtained. This can be accomplished through the application of appropriate correction factors [Finnie 2006]."

In this latter respect, Finnie (2006) proposes that, for the CEPE (=ISO) calculation method, a correction factor of 2.9 can be applied for all antifouling coating types when performing a generic environmental risk assessment for an antifouling paint where direct measurements of the environmental release rate are absent. This correction factor is derived from the ratio of the release rate predicted by this method to the upper 95% confidence limit for the estimated environmental release rate based on dome data.

Finnie (2006) adds that, as the proposed correction factor represents a realistic worst case and based on conservative 95% confidence limits, their application to copper release rate data generated by the CEPE (ISO) calculation method will still probably overestimate the environmental release rate for the majority of antifouling coatings. This was considered to be particularly likely for tin-free self-polishing antifouling coatings where available data suggests the calculation method to typically overestimate environmental release rate by a factor of 10. The overestimation was expected to further increase in cooler waters in, for example, much of Europe.

3.6.2.7.3 Haslbeck & Ellor

A second method of calculation is the stoichiometric method of Haslbeck & Ellor (2005) mentioned above in relation to the HEP method. This calculates release rate from the in-service polishing rate of the antifouling paint. As such, this method can only be used with ablative and self-polishing paints that erode during service (Finnie 2006). Inputs to the calculation are the polishing rate of the paint, the weight fraction of biocide in the coating formulation, the weight fraction of active ingredient in the biocide, the volume solids of the wet paint (%), and the specific gravity of the wet paint. The resulting release rate is the average release rate for the biocide over the period of service resulting in the coating thickness reduction.

3.6.2.7.4 REMA

The Regulatory Environmental Modelling of Antifoulants (REMA) software based on a model to predict environmental concentrations of antifouling chemicals in marinas and estuaries has been developed for the UK Health and Safety Executive (HSE) (Boxall et al. 2000, Comber et al. 2001). This model uses only leaching rates and physicochemical property data to predict environmental concentrations. Further, the biocide release rates used were estimated worst case leaching rates for leisure vessels calculated by assuming all biocide within an antifouling paint was leached out in a 9 month period. The formula used was:

$$\text{Leaching rate } (\mu g/cm^2/day) = \frac{C \times N}{275 \times A}$$

Where:

C	=	concentration of biocide in the product;
N	=	number of coats applied;
A	=	areas of paint covered by 1 L of paint (cm^2/L); and,
275	=	arbitrary time period in days assumed for total leaching.

The major assumptions in this model, that all biocide in antifouling coating are leached out during its life, and that the antifouling life is only 9 months, both seem to differ to practical knowledge and experience. Significant residual biocide is known to remain in a coating when it loses its antifouling effectiveness, and most antifouling coatings have an effective life longer than 9 months unless the biocide content of the paint is too low, or biocide release becomes obstructed.

3.6.2.8 Karlsson & Eklund method

Karlsson & Eklund (2004) measured release rates in the laboratory by painting 10 cm^2 of paint onto sterile plastic petri dishes, and after allowing 24 h for the paint to dry and immersing the dishes in artificial seawater for 1 h to allow contingent paint flakes to be removed, the dishes were immersed in beakers containing 1 L of seawater (Karlsson & Eklund 2004, Ytrberg et al. 2010). Beakers were then covered with aluminium foil to prevent evaporation and algal growth and placed on a shaker table. Tests were run for 14 days, or water replaced every 14 days for longer tests, with water samples for analysis and determination of release rates at various intervals within the 14 day period(s).

3.6.2.9 Comparison among methods

A comparison of release rates from the same coatings measured by HEP (static/dynamic and static) and dome (on panels and vessels) found that the static dynamic exposure generally resulted in higher release rates relative to the other methods (Valkirs et al. 2003). The effect of the dynamic rotation period was more pronounced in one SPC paint, which showed spikes 2-4 fold greater than the post-static measurement, than an ablative coating where rotation had little effect. This was attributed to removal of the biofilm and coating ablation during dynamic exposure.

A comparison between the above panel measurements and the ASTM method for the same paints showed ASTM copper release rates to be 5-25 times higher than the steady state levels observed in the panel treatments (Valkirs et al. 2003). A similar difference was previously observed for organotin release rates (Schatzberg 1996). When compared to in situ measurements of copper release from the paint BRA 640 on Navy vessels, the difference between this and the ASTM result was an order of magnitude (Table 3.9). Valkirs et al. (2003) reinforce the observation that the ASTM method, while providing some inter-comparability between coatings, does not provide a realistic estimate of environmental loading because it overestimates long-term release rates. The overestimation was considered likely due to the 45 day testing period being too short to measure steady state release rates, and the laboratory conditions precluding the development of biofilms.

All laboratory, field and calculation methods for copper release rate measurement, with the exception of a modified dome method for panels and the Karlsson-Eklund method, have been considered to significantly overestimate the environmental release rate (Table 3.9; Finnie 2006). The difference has been found to be greatest for SPC coatings and smallest for certain erodible/ablative coatings. The release rates of copper from two commercial ship ablative systems measured using the Karlsson-Eklund method to be 3.2 and 3.6 µg/cm^2/day in natural seawater, and 13 and 14 µg/cm^2/day in artificial seawater, were closer to dome results than other laboratory methods (Ytreberg et al. 2010).

Finnie (2006) has proposed that, if copper release rates calculated by ASTM/ISO or mass-balance methods are to be used for environmental risk assessment or regulatory purposes, the values should be divided by a correction factor. From available data, and taking a conservative approach based on realistic worst case and experimental uncertainty, the default correction factor proposed for all paint types for the ASTM/ISO method is 5.4 and, for the CEPE mass-balance method, 2.9 when 1.0 is used as the fraction of biocide released from the coating.

Table 3.9 Mean copper release rates (µg Cu/cm^2/day) calculated using different methods (Finnie 2006).

Method	BRA640[1]	BRA540[1]	Ablative A[1]	Formula 121[2]	SPC A[3]	SPC B[4]
ASTM/ISO	48.6	58.8	87.0	131.2	100.0	66.1
CEPE calc^n	18.4	18.3	15.5	30.4	30.7	30.2
HEP (static/dynamic)	16.3	n/d	n/d	n/d	n/d	n/d
Polish rate calc^n	12.8	n/d	n/d	n/d	n/d	n/d
HEP (static)	8.9	n/d	n/d	n/d	n/d	n/d
Dome (ship)	4.7	4.6	3.9	5.7	n/d	n/d
Dome (raft)	2.2	n/d	n/d	n/d	1.6	1.3

[1]Ablative soluble matrix, [2]Insoluble matrix, [3]TBT-free SPC for coastal vessels (faster polishing), [4]TBT-free SPC for deep sea vessels (slower polishing), n/d = not determined.

Ytreberg et al. (2010) used the Karlsson-Eklund method to compare the release rates of copper and zinc from five commercial antifouling paints in natural and artificial seawater and found copper release rates in natural seawater to be 4-6 times lower than in artificial seawater. This difference was attributed to the higher total organic carbon (TOC) content of the natural seawater (4.7 mg/l vs. 0.8 mg/l) and the possible formation of organic films on the coating surface or, alternatively, pH shift from 8 to 7 in the artificial seawater over the course of the test. The difference was, however, considered to suggest that release rate experiments using artificial seawater are likely to overestimate rates in the field.

Howell (2010) cautioned that, for building an environmental risk model, or assessing environmental conditions, it is important to understand that factors affecting biocide release rates from hydrolysing antifouling coating systems are much more complex than a simple measurement of biocide release rates in artificial seawater. He observed that the coatings are designed to interact with the surrounding dynamics and seawater chemistry, and therefore could behave very differently in harbours with differing tidal flow. Howell (2010) further proposed that current environmental risk models, such as REMA, MAMPEC and USES, do not give reliable estimates as they use the CEPE method as an input for leaching calculations, and this is flawed because it assumes that, beyond the first 14 days, release rates do not change over the life of the coating, and over-simplify actual release rates in harbours.

3.6.3 Copper release rates

3.6.3.1 Critical release rate

The minimal rate of copper release to prevent biofouling has long been considered to be 10 µg/cm^2/day, which was determined by comparing the antifouling performance of field immersed paints of differing cuprous oxide content to copper leach rates of these same paints measured using the WHOI or similar method (Ketchum 1952a). Of 73 paints tested that had a release rate greater than 10 µg/cm^2/day, only one was badly fouled and most were completely free of fouling. In contrast, none of the paints with release rates of less than 10 µg/cm^2/day gave 100% fouling resistance for 6 months. Additional support for this critical leach rate was provided by Miller (1946) who found that *Bugula neritina* larvae freely attached and developed on paints with leach rates less than 10 µg/cm^2/day, but any larvae that settled on paints with leaching rates between 10-15 µg/cm^2/day did not develop into colonies. In other studies, a release rate of 10 µg/cm^2/day was found adequate to prevent attachment of all animal forms, but some algae ("brown mats") could attach at rates of up to 20 µg/cm^2/day (Barnes 1948). de la Court (1989) presents critical release rates of 16 µg/cm^2/day to prevent barnacle fouling and 22 µg/cm^2/day to prevent algal fouling.

The relationship between copper release rates, as measured using the US Navy dome method, and fouling levels adds further support to the critical release rate of 10 µg/cm^2/day (Seligman & Neumeister, 1983). Prior to cleaning, when the release rate was measured to be less than 10 µg/cm^2/day, fouling on the ship hull was assessed as between 30 and 60; a 30 rating corresponds to macroalgae or soft non-calcareous animal fouling, 50 to either calcareous tubeworms or barnacles, and 60 to a combination of tubeworms and barnacles (NSSC 2006). In-water cleaning reduced fouling levels to less than 20 (slime only) and increased the release rate to close to 25 µg/cm^2/day, but after two months, when the release rate was remeasured at less than 5 µg/cm^2/day, the fouling rating had returned to greater than 30 (Seligman & Neumeister 1983).

The release rate of biocides from a freshly exposed antifouling coating is generally higher during the first weeks of immersion than later in its life (Ferry & Ketchum 1952, CEPE 2005). This is attributed to an excess of biocide within the surface layer of the dried paint. However, some coatings were also observed to have a low initial release rate, which increased within the first hours, days or weeks of immersion (Ferry & Ketchum 1952). This effect was attributed to the formation of a thin skin of paint matrix or other ingredient over biocide particles at the surface. More recently, OECD (2005) makes reference to "a new coating type on the market" that displays an initial low release rate which slowly increases to possible steady state.

For the development of the MAMPEC model, a set of default leaching rates was proposed "based on expertise available within the CEPE Antifouling Working Group" (van Hattum et al. 2006). The default release rate for copper is given as 50 µg/cm^2/day, which seems inordinately high in relation to both measured and practical critical release rates. This rate was chosen as the default on the basis of early measurements of copper release using the rotating cylinder method, and the adoption of corresponding high release rates in regulations by some countries (e.g. Canada, 40 µg Cu/cm^2/day) (M. Perreira, Hempel Denmark, ex-Chair CEPE Antifouling Working Group, pers. comm.). The current recommendation is to input values derived by the CEPE/ISO mass balance method.

OPRF (2010) also used a high release rate, 40 µg/cm^2/day, for estimating the passive release of copper from antifouling paints in the MAMPEC model. This study focussed on worst case scenarios so, "if two or more sets of existing data on leaching rate were available, the highest values were adopted as the inputs for the MAMPEC model". The reported ASTM test system results of 25-40 µg/cm^2/day (van Hattum et al. 2006), although higher than rates measured by other systems, are therefore the likely source of the OPRF input value.

For input to REMA software developed for the UK HSE, release rates were calculated for cuprous oxide and cuprous thiocyanate (Comber et al. 2001). These release rates are provided in Table 3.10. The input values for these calculations were that two coats of paint were applied, with the assumption that 1 L of paint would cover 94,000 cm^2. The biocide content for cuprous oxide containing paints was given as ranging from 2.5-100% w/w, but no similar values are given for paints containing cuprous thiocyanate. It is not clear in this report what the overarching maximum and minimum leaching rates represent or how they are calculated, nor the maximum – minimum ranges provided for each value. It is also not clear whether the values are as µg Cu, or µg Cu_2O/µg CuSCN, although the latter seems inferred.

Table 3.10 Calculated leaching rates for copper biocides in antifouling paints applied to small vessels (Comber et al. 2001).

Biocide	Minimum leaching rate (µg/cm^2/day)	Maximum leaching rate (µg/cm^2/day)
Cuprous oxide	16.12 (1.74-34.82)	25.33 (6.96-69.63)
Cuprous thiocyanate	5.13 (4.1-6.15)	9.23 (8.20-10.25)

Mean values with range in parentheses.

3.6.3.2 Environmental variation in release rates

Howell's (2010) caution regarding the relevance of measurements of biocide release rates in artificial seawater to actual rates in the field were referred to in Section 3.6.2.9. Because the coatings are designed to interact with the surrounding hydrodynamics and seawater chemistry, they may behave very differently in harbours with differing tidal flows. Furthermore, current environmental risk models, such as REMA, MAMPEC and USES, use the CEPE method as an input for leaching calculations. This method is flawed because it assumes that, beyond the first 14 days, release rates do not change over the life of the coating, and over-simplify actual release rates in harbours. Consequently, risk models that incorporate outputs from this method do not give reliable estimates of biocide release rates in the field.

The ASTM method for determining release rates specifies standard conditions for tests (substitute ocean water, pH 7.9-8.1, salinity 33-34 ppt, temperature $25^oC \pm 1^oC$). When tested using insoluble matrix, soluble matrix and SPC paints containing copper and/or tin, slight changes in conditions were found to have a significant effect on the release rates (Fisher et al. 1997). pH was found to have the greatest effect, with a 2-3 fold change in leach rate per 0.5 pH unit change, whilst salinity and temperature changes also had measurable effects (Thomas et al. 1999). However, using a flume and rotary test system, a wide range of environmentally relevant environmental conditions had no effect on copper release from a copper-containing TBT-based SPC coating (Thomas et al. 1999). Speed of motion was the only parameter to significantly change TBT release rates.

The latter observation was counter to earlier research that release rates increase at higher speeds, due to greater erosion of the paint surface at higher speeds (Thomas et al. 1999). The cause of the reduction in release at higher speeds was postulated to be due to the formation of a boundary layer which slows TBT release from the coating surface. Differences in response of copper and TBT release to differing conditions were attributed to the differing mode of release of the two biocides: TBT by reaction-controlled dissolution and copper by diffusion-controlled dissolution.

3.6.3.3 Soluble matrix/ablative coatings

In ablative coatings, after the initial weeks after immersion when high biocide release rates result from the release of surface concentrations of biocide in the dried film, the release rate should approach a steady state that corresponds to the biocide loading of the paint and the dissolution rate of the soluble paint matrix. However, over the duration of paint life, an exponential reduction in release rate is considered due to the mechanism of seawater penetrating the paint film to release biocides by a diffusion process (Bressy et al. 2010).

In HEP static immersion testing of one ablative coating, the release rate on immersion was about 10 µg/cm^2/day, increasing to 27 µg/cm^2/day by day 7, and then declining with time (Valkirs et al. 2003). The initial low release rate is attributed to acrylic resin ablative systems requiring hydration before significant copper is released.

In situ (dome) measurements of copper release rates from two ablative coatings, BRA 640 and ABC3, of varying ages and in different seasons on four US Navy ships found variation between 1 and 8 µg/cm^2/day, with an overall mean of 3.8 µg/cm^2/day (Valkirs et al. 2003). Results for BRA 640 were comparable with earlier studies on the similar BRA 540, in which measured copper release rates ranged from 1.2 to 6.0 µg/cm^2/day (Valkirs et al. 1994). Age of paint appeared to influence release rates of BRA 640, with rates on the ship coated about 1 year before the measurements 1.5-2.0 higher than the ship coated for 2 years (Valkirs et al. 2003). No similar trend was evident for the ABC3.

The mean release rates of two ablative commercial ship antifouling paints, Hempel Olympic 86951™ (39% CuO content) and International Interspeed 617™ (56% CuO content), were measured using the Karlsson-Eklund method and determined to be 13 and 14 µg/cm^2/day respectively in artificial seawater, and 3.6 and 3.2 µg/cm^2/day in natural seawater. Comparative rates from a lower copper antifouling permitted for use on small craft in the Baltic Sea (International Fabi 3959™ (6% CuO)) were 7.1 and 1.1 µg/cm^2/day. Due to apparent pseudo-saturation effects in the test containers, the rates in artificial seawater were determined from only the first 4 days of immersion for the Interspeed and Olympic, and 7 days for the Fabi. Rates in natural seawater were calculated from the full 14 days of testing as saturation concentrations did not appear to be reached.

Takahashi (2009) observed that the copper release curves for TBT-SPC antifouling paints with cuprous oxide as a co-biocide show a far more consistent pattern of copper release than tin-free, ablative antifouling paints. The former reached steady state at about 40 days, whereas the release rate from ablative paints had not reached steady state by 70 days.

3.6.3.4 Insoluble matrix coatings

In insoluble matrix antifouling coatings, no steady state biocide release rate is achieved, with the release rate falling gradually as extraction proceeds into the paint interior and the chains of contact between biocide particles are increasingly broken (Ferry & Ketchum 1952). The higher the initial biocide content of the paint, the higher the release rate through the life of the paint, and therefore the longer the paint effectiveness before the release rate drops below the critical value of 10 µg/cm^2/day. Increasing biocide loading or coating thickness will increase antifouling longevity, but with high environmental input of biocide (O’Hagan 2002). One paint with a 90% cuprous oxide loading was measured to have an initial release rate of 250 µg/cm^2/day, 25 times that required to prevent fouling attachment, and utilisation efficiency of the biocide as little as 20% (Ferry & Ketchum 1952). The USN antifouling F-

121 is reported to have an initial release rate of approximately 100 µg/cm^2/day, which is moderated by surface deposits to 10-20 µg/cm^2/day during most of the service life (Lindner 1984, 1988). In insoluble matrix paints, effective life is also not proportional to coating thickness, but to the depth of paint from which the critical release rate can be achieved. In-water scrubbing to regenerate these coatings requires the removal of the depleted surface layers of coating that impede biocide release.

Higher release rates from insoluble matrix than SPC coatings was reflected in measurements using the US Navy dome method on USN ships coated with TBT containing paints (Grovhoug et al. 1989, Seligman et al. 1996). The TBT release rate measured from a TBT SPC coating on one ship appeared to reach steady state 44 days after undocking at around 0.3 µg/cm^2/day, whereas the release rate from an insoluble matrix coating was still 2.8 µg/cm^2/day more than five years after paint application.

Dome measurements on the hulls of recreational vessels measured copper release rates of 2-14 µg/cm^2/day with the average 8.2 $\pm$ 2.7 µg/cm^2/day (Valkirs et al. 2003). The release rates from two different insoluble matrix coatings, Interlux Ultra-Kote and Proline 1088 Y, were measured on seven boats. For the Interlux, an epoxy ester coating, the results suggested an association between release rates and paint age. A newly painted vessel exhibited an average release rate of 11 µg/cm^2/day, while a vessel with the same paint after a year exhibited an average release rate of only 3 µg/cm^2/day. No similar trend was seen for the Proline, a vinyl coating, of ages between 75 and 712 days. The average release rates from this coating were between 7.5-11.0 µg/cm^2/day. Regular hull cleaning and subsequent re-establishment of biofilms were considered as possible reasons any changes in release rates with paint age to be obscured (Valkirs et al. 2003).

Schiff et al. (2004) utilised the US Navy dome method to measure copper release from two commercially available insoluble matrix antifouling coatings applied to fibreglass panels. The aim of the study was to simulate a typical cleaning regime utilised by recreational vessels in southern California to estimate copper emissions from recreational vessels. The coatings were a modified epoxy and a hard vinyl enhanced with Teflon™, both with cuprous oxide as the primary biocide, and these were tested along with a biocide-free two-pack epoxy with Teflon™. The two biocidal coatings were noted to not prevent fouling, but to slow the process, with coatings requiring monthly in-water cleaning to remove accumulated biofouling and improve copper release. Such ineffective management practices are attributed to clean air standards, as insoluble matrix coatings have lower volatile organic compound (VOC) content than more effective ablative antifouling coatings.

Passive release rates were reported as 4.32 µg/cm^2/day for the modified epoxy, and 3.71 µg/cm^2/day for the hard vinyl coating. It is not clear in this report how long after initial immersion this rate was measured, with the authors only stating that measurement was 14 days after a cleaning event and cleaning events were undertaken monthly after an initial 60 day immersion. From data presented in the paper, and the given method of calculation, it seems the release rate reported for the hard vinyl is too high as extrapolating the one hour concentration of 0.12 µg/cm^2 to a day should result in 2.8 µg/cm^2/day. The two release rates are also not corrected for the measured background copper concentration given as 0.01 µg/cm^2, which brings release rates down to 4.08 µg/cm^2/day and 2.64 µg/cm^2/day for the modified epoxy and hard vinyl coatings respectively. However, the corrected rates would still be below the accepted critical release rate for copper of 10 µg/cm^2/day, which is consistent with the observation that the paints do not prevent fouling.

3.6.3.5 SPC coatings

A study of release rates of copper and either copper or zinc pyrithione from 4 mixed biocide tin-free SPC coatings for 1 year, found no discernible difference between the release rate behaviours of the biocides (IMO 2009). This was despite cuprous oxide being several orders of magnitude less soluble than copper or zinc pyrithione. The results were interpreted to demonstrate that the paint film functions as a controlled release medium for the biocides that are present, and it is the properties of the paint film that control biocide release rather than the properties of the biocides themselves.

The average release rate of dissolved copper measured using in situ measurements from SPC coatings on US Navy ships was determined to be 3.8 $\mu g/cm^2/day$ (Valkirs et al. 2003). Using HEP static/dynamic methods, the initial copper release rate for these coatings varied from 16 to 56 $\mu g/cm^2/day$. Over the 780 day exposure there was a general trend of decreasing release rates, to a rate of 7-9 $\mu g/cm^2/day$. Periods of dynamic exposure, which removed the biofilm, often increased release rates to 15 to 20 $\mu g/cm^2/day$. After a further 80 days of static immersion after the completion of regular dynamic/static cycling, rates dropped further to between 3 and 6 $\mu g/cm^2/day$. This was attributed to the establishment of a biofilm.

High release rates were similarly measured in HEP static exposures immediately after immersion which then declined from 25-65 $\mu g/cm^2/day$, during the first few days, to 5-20 $\mu g/cm^2/day$ after the first three months of testing (Valkirs et al. 2003). In situ dome measurements of release rates from the same coatings on large, static immersion panels were consistent with the measurements from small static immersion panels with rates determined in the laboratory. The release rates for most of the paints tested were below 3 $\mu g/cm^2/day$ after 120 days of exposure, and then remained at that level over the entire 761 day study.

3.6.3.6 Biofilms

A laboratory study on the effect of biofilms on the release rate of tributyltin from an ablative coating found that bacterial films decreased the release rate, but algal films increased it (Mihm & Loeb 1988). The films were produced by inoculating test containers with organisms cultured from samples taken from a ship hull painted with organotin paint. The alga was a blue-green alga identified as *Anacystis montana.* Bacterial films reduced release rates by 60%, from an average of 0.135 $\mu g\ TBT/cm^2/day$ down to 0.07 $\mu g\ TBT/cm^2/day$. In contrast, the algal film increased the release rate to an average of 0.46 $\mu g\ TBT/cm^2/day$. Removal of the films lead to increased release rates approximately 2-5 times the stable rate before biofilm formation. The effect of bacterial films was considered to be possibly due to an interaction between released biocide and bacterial extracellular material, restriction of diffusion through the film, or inhibition of biocide release from the coating surface. The action of the alga is more difficult to understand, with the authors postulating that algal metabolites may modify chemical conditions within the film, for example pH, that catalyses the release reaction (Mihm & Loeb 1988).

In their comparative study of release rates from different SPC coatings by dynamic/static and wholly static immersion, Valkirs et al. (2003) found the results to suggest that biofilms were influencing release rates. In particular, rates after dynamic exposure that removed the biofilm had higher release rates, and long periods of static immersion that allowed increased biofilm development had reduced release rates. Consequently, some additional experiments were undertaken to specifically try and elucidate this possible effect (Valkirs et al. 2003). Gently removing the biofilm with a soft plastic brush increased release rates 2-3 fold for four of the six paints tested, but there was little or no increase on the other two. While the brushing was performed with care, the authors acknowledge that it was difficult to determine what proportion of the release was attributable to removal of the biofilm and what proportion to disturbance of the coating surface. An additional study in which a panel was more vigorously “brushed” with a coarse scouring pad led to release rates increasing 10-30 fold.

From modelling of bacterial biofilms, it was concluded that these did not appear to exert a significant influence on the net biocide leaching rate and paint polishing processes (Yebra et al. 2006b). Reported decreases in release rates were considered by these authors to most likely to result from biocide trapping within the EPS, which could act both as a permanent biocide capacitors at the surface, and to reduce environmental risk by chelation of labile ionic species. The shape of a biofilm also changes, not only through the growth cycle, but also with variation in fluid shear stress, and changes in biofilm shape will affect its porosity and density, and therefore the transfer of solutes into and through the biofilm (Howell 2010).

Subsequent laboratory research on biofilms and biocide release rates, on a cuprous oxide containing SPC coating under dynamic conditions, showed that biofilms can have an effect on biocide release rate by changing the conditions at the coating surface, and storing biocide in EPS (Howell 2010). Furthermore, the biofilm can increase release rate initially, due to a possible change in pH at the coating surface affecting cuprous oxide dissolution. Biofilms also have the ability to act as biocide capacitors, and to release high biocide concentrations after an increase in shear stress, although the majority of this is likely to be chelated and not biologically available (Howell 2010).

3.7 CONTAMINATION LEVELS

3.7.1 Copper release from cleaning

3.7.1.1 Soluble matrix/ablative coatings

The depth of an ablative coating removed by diver-operated brush systems from USN ships has been estimated to be between approximately 25-50 µm (1-2 mils[4]) from a 380 µm (15 mil) coating (Forbes 1996). More paint is estimated to be eroded from ablative coatings than insoluble matrix coatings because of their softer nature.

Forbes (1996) calculated the possible copper concentration and waste water volume during a cleaning operation by assuming the removal of 50 µm (2 mil) of paint and the paint containing 45% cuprous oxide. For one scenario, the predicted concentration was calculated to be 166 mg Cu/L, but the measured summed concentration of particulate and dissolved copper was only 28.4 mg Cu/L. This difference may be due to a reduced copper concentration in the leached layer not being considered or the removal of less paint than assumed.

Measurements of the dissolved and total copper concentrations in the discharge plume of a SCAMP unit during the cleaning of three USN ships enabled the copper release to be determined (USEPA 1999). The calculated value was 4.8 g Cu/m^2 of hull surface. The average concentration of dissolved copper in the discharge plume was 5.5% of total copper measured (Table 3.11).

[4] 1 mil = one thousandth of an inch.

Table 3.11 Dissolved and total copper concentrations (mean ± s.d.) measured in SCAMP discharge plumes during in-water cleaning of ablative antifouling coatings on USN ships (USEPA 1999).

Vessel	Cu (µg/L) (Filtered)	% Dissolved	Cu (µg/L) (Unfiltered)
Ship 1	66	4	1,668
Ship 2	136.8 ± 7.0	8.7	1,565 ± 58.3
Ship 3	116.8 ± 6.0	4.5	2,619 ± 338
Overall	106.5 ± 29.8	5.5	1,950 ± 474

The amount of copper in wash water from water-blasting of recreational vessels on land was found to be very similar in replicates from the same boat, but the amount of copper washed off different boats painted with ablative antifouling paints varied widely from 0.016 to 6.5 µg/cm^2 (Williamson et al. 1995).

The release rate of the ablative coating BRA540 was measured within hours before and after scrubbing using the dome method and release rates before scrubbing were 1.2-6.0 µg/cm^2/day and after scrubbing 2.8-5.7 µg/cm^2/day (Table 3.12) (Valkirs et al. 1994). The release rates measured here were all below the critical copper release rate of 10 µg/cm^2/day, and the authors noted that this was consistent with the hulls being heavily fouled. The age of the paints was considered likely to be responsible for the low release rates (Valkirs et al. 1994).

Table 3.12 Copper release rates from an ablative coating before and after cleaning (Valkirs et al. 1994).

Coating	Before brushing (µg/cm^2/day)	After brushing (µg/cm^2/day)
BRA540 – Ship 1	1.2	4.75 ± 1.34 (n=2)
BRA540 – Ship 2	2.85 ± 0.35 (n=2)	2.95 ± 0.07 (n=2)
BRA540 – Ship 3	5.8 ± 0.14 (n=2)	4.15 ± 1.91 (n=2)
ABC3 – Ship 3	1.15 ± 0.07 (n=2)	3.2
BRA540	4.73 ± 0.98 (n=4)	5.12 ± 0.33 (n=4)

The overall conclusion from these studies on copper release during commercial hull cleaning of USN ships in San Diego Bay was that, while total copper concentrations in bay waters were rapidly elevated near hull cleaning operations, the biologically active species of copper complexed rapidly, returning actual toxic copper potential to near ambient conditions within minutes to hours after hull cleaning ceased (Valkirs et al. 1994). Most of the copper released during the hull cleaning was determined to be in the particulate form, and rapidly incorporated into bottom sediments.

Lightly brushing static immersion test panels of the copper ablative coating BRA 640, a later version of BRA 540, increased release rates less than SPC paints tested under the same regime (Valkirs et al. 2003).

Brown and Schottle (2006) experimentally assessed the copper release from cleaning an ablative coating (Jotun Hydroclean Blue™) for comparison to insoluble matrix coatings. This was part of their study to determine the copper loading to a yacht basin in San Diego Bay, California, from in-water cleaning of leisure vessels in which insoluble matrix coatings were the primary focus. The ablative coating was only cleaned with the 'soft carpet' to simulate 'light' cleaning. Best management practices (BMP) in San Diego were to not clean ablative coatings, but these coatings were sometimes subject to light cleaning, thus the incorporation of this coating in the Brown and Schottle trials. The calculated emission from the ablative coating, which had approximately 4 months of natural fouling, was 2.7 µg dissolved

Cu/cm^2/event (Brown & Schottle 2006). The emission of particulate copper was not reported. The authors noted that this relatively low emission rate, compared to insoluble matrix coatings, was based on very limited results and further investigations on ablative coatings were warranted.

3.7.1.2 Insoluble matrix coatings

The effect of in-water cleaning on the copper release rate from an unspecified copper-based antifouling coating was illustrated in the patent for the US Navy dome method (Seligman & Neumeister 1983). The copper release rate increased from less than 10 µg/cm^2/day prior to the clean, to close to 25 µg/cm^2/day immediately after the clean. Two months later, the release rate had dropped to less than 5 µg/cm^2/day, with a corresponding increase in macrofouling levels. The release rate of US Navy Formula 121 (insoluble matrix) measured by dome method after scrubbing was 5.7 µg/cm^2/day (Valkirs et al. 1994). No information was given on the age of this coating or vessel activity.

Schiff et al. (2004) compared copper release from the panels coated with modified epoxy, hard vinyl and biocide free coatings using two hand cleaning methods: one considered best management practice using soft cleaning materials (shag carpet with minimal applied pressure), the second using more abrasive cleaning materials (nylon 3M scouring pad with greater applied pressure). Dissolved copper release from the modified epoxy coating was 8.57 and 17.45 µg Cu/cm^2/cleaning event for the less and more abrasive methods respectively. For the hard vinyl coating, the dissolved copper release was 3.84 and 4.18 µg Cu/cm^2/event. The authors noted that, although both coatings were classified by the manufacturers as hard, insoluble matrix systems, the modified epoxy was softer and coating particles discoloured the water during cleaning operations.

After cleaning, biocide release rates reduced quickly and approached the passive release rate within several days of cleaning. This was attributed to development of biofilms and biofouling on the coatings. However, it is possible that the reduction could relate to the exponential decline in biocide release known for insoluble matrix coatings, and the biofouling redevelopment a result, rather than the cause, of release rates dropping below critical levels.

Copper release from cleaning reported by Schiff et al. (2004) may have underestimated total copper release from cleaning because, firstly, released particulate matter was allowed to settle in the test containers before the bulk water was sampled for copper analysis. Secondly, water samples were filtered prior to analysis. Only dissolved copper, and not particle bound copper, was therefore measured. From their results, these authors concluded that roughly 95% of copper emitted over a month was from passive leaching and only the residual 5% was attributed to in-water cleaning.

More detailed experimental studies were subsequently undertaken on similar insoluble matrix paints on leisure vessels in San Diego (Brown & Schottle 2006). Three different cleaning methods were employed:

- Carpet to simulate light cleaning;
- Scouring pad to simulate a moderately aggressive and common cleaning practice; and,
- A nylon bristle brush to simulate the more aggressive cleaning of a mechanical brushing system.

The two coatings were a modified epoxy, Proline 1088™, and a vinyl-based coating, Interlux Ultra Kote™. These were measured at a 1 and 3 month fouling condition. The results of these experiments are presented in Table 3.13.

Table 3.13 Estimated mean and confidence intervals for emission rates of dissolved and particulate copper from experimental cleaning events (Brown & Schottle 2006).

Coating/Treatment	1-month fouling (µg/cm²/event)	3-month fouling (µg/cm²/event)
Modified Epoxy		
Light (carpet)	3.8 ± 0.8 (dissolved)	3.9 ± 1.1 (dissolved)
	8.9 ± 2.4 (particulate)	13.4 ± 2.7 (particulate)
Moderately aggressive (scouring pad)	8.1 ± 1.4 (dissolved)	10.5 ± 2.4 (dissolved)
	47.2 ± 18.6 (particulate)	62.1 ± 21.1 (particulate)
Aggressive (nylon brush)	2.3 ± 0.8 (dissolved)	4.3 ± 0.3 (dissolved)
	11.6 ± 1.8 (particulate)	44.4 ± 11.2 (particulate)
Hard Vinyl		
Light (carpet)	11.4 ± 3.8 (dissolved)	10.1 ± 2.4 (dissolved)
	190 ± 38.5 (particulate)	241 ± 98.4 (particulate)
Moderately aggressive (scouring pad)	16.7 ± 4.6 (dissolved)	14.4 ± 1.6 (dissolved)
	468 ± 190 (particulate)	645 ± 126 (particulate)
Aggressive (nylon brush)	8.9 ± 3.2 (dissolved)	8.7 ± 4.7 (dissolved)
	234 ± 116 (particulate)	425 ± 493 (particulate)
Ablative		
Light (carpet)		2.7* (dissolved)

* 4 month fouling

Although actual values were not reported by Brown and Schottle (2006), a comparison was made between powerboats and sailing craft. The overall concentrations of dissolved copper for all three cleaning methods were approximately 2.5 times lower on two powerboats than on three sailing craft. More directly comparing results for the same epoxy paint on one sailboat with two powerboats, the emissions of dissolved and particulate copper were respectively 50% and 300% higher from the sailboat than the power boat.

The general outcomes of these experiments were (Brown & Schottle 2006):

- Similar release of dissolved copper per event for each treatment on both 1 month and 3 month fouling levels;
- Increase in release of particulate copper per event , irrespective of treatment, between 1 month and 3 month fouling levels;
- Higher release of particulate copper from the vinyl coating than the epoxy coating;
- Higher release of both dissolved and particulate copper from the simulated moderately aggressive cleaning than the treatment designed to represent more aggressive cleaning; and,
- Less fouling was observed, and lower emissions measured, on powerboats than sailing craft.

The two to three fold higher release of copper from the vinyl coating than the epoxy coating was attributed by Brown & Schottle (2006) to the epoxy being a harder coating. Schiff et al. (2004) found the opposite result for dissolved copper from vinyl and epoxy coatings, but did note that the modified epoxy they tested was a softer coating. Brown & Schottle (2006) attributed the difference to factors such as lower cuprous oxide content of the paint brands tested and/or a difference in hardness of the two epoxy coatings. The epoxy and vinyl paints in Schiff et al. (2004) had cuprous oxide contents of 57.7% and 37.25% respectively, compared to 66.5% and 67.6% in Brown & Schottle (2006).

The lower release from the 'aggressive' brushing technique compared to the 'moderately aggressive' scouring pad technique was attributed to the brush cleaning a smaller surface area than the carpet and scouring pad. The small size of the brush and spacing of bristles may have also generated less abrasion of the surface than the scouring pad.

The difference between fouling levels and emissions on powerboats and sailing craft was attributed by Brown & Schottle (2006) to the higher speeds and consequently turbulent water flow over powerboat hulls than sailing craft. This could both reduce the development or persistence of biofilms, and also remove surface deposits and friable surface layers or the paint. If a powerboat has been recently active, then release rates of copper from the coating could conceivably be lower when stationary due to the extraction of dissolved copper from close to the paint surface during boat motion. If this happens, then release rates would be expected to increase with increasing time of inactivity.

Brown & Schottle (2006) found no significant increase in dissolved copper emissions with increased time of immersion, which they assumed would reflect increased fouling levels. They interpreted their results as suggesting that there had been no significant increase in fouling levels during the time span of the study. However, the biofouling appeared thicker, and higher levels of particulate copper were measured. An alternative interpretation is that the dissolved copper is representative of the continuous copper release from the underlying coating, the rate of which is likely to be, if not at steady state, then similar within the time frame of the two samplings. The sequestering and accumulation of copper within the biofilm, which would contribute to the particulate copper when removed, could be expected to increase in copper content as the organisms forming the biofilm multiply, produce more EPS, and entrap more organic matter from the water column.

Brown & Schottle (2006) identified the following gaps and uncertainties arising from their study:

- Although the epoxy paint yielded lower copper emission, results from other studies report a large range of emissions based on paint type and other variables, and lower release from all epoxy coatings in comparison to vinyl coatings should not be assumed; and,
- The indication that paint hardness plays a significant role in the quantity of particulate copper released warrants a more comprehensive study to specifically address paint matrix, as only two brands of paint were tested in their study.

3.7.1.3 SPC coatings

No specific information was found on tin-free SPC coatings.

3.7.1.4 Biofilms

High pressure washing of coatings on the underwater hull of vessels is routinely undertaken in drydock to prepare the hull for repainting by removing biofouling growth and the unstable leached layer of paint to ensure a sound base for recoating. High levels of biocide contamination can occur in this wash down water (Fletcher & Lewis 1999), and this contamination would be representative of the contamination from in-water cleaning.

In reviewing their suite of both release rate measurement trials and cleaning experiments, Valkirs et al. (2003) concluded that the relationship between cleaning/brushing and biofilm properties remained poorly understood and, more generally, the relationships between coating chemistry and cleaning also remained poorly understood.

3.7.1.5 Environmental loading

The global input of copper into the marine environment from antifouling paints has been estimated to be approximately 3,000 tonnes/yr, which is small compared to the input from natural weathering on land, estimated at 250,000 tonnes/yr (Brooks & Waldock 2010). However, input of copper from boats is often localised, and can potentially lead to elevated concentrations in enclosed water bodies such as marinas and harbours. In coastal waters, with high levels of boating, the contribution of copper from antifouling is still considered to be a small proportion of copper input, with urban run-off the main contributor, and, for example, estimates of input of copper from antifouling paints to the New York/New Jersey harbour area amount to 2% of total copper load and, in the UK, 10% of the overall anthropogenic inputs (Brooks & Waldock 2010).

3.7.1.5.1 New Zealand

The environmental loading of copper to the New Zealand marine environment from leaching of antifouling coatings has been estimated for 11 ports and 11 marinas for the Environmental Protection Authority (EPA) using OECD guidance and the MAMPEC model (Gadd et al. 2010). This suggested that based on a leaching rate of 8.2 µg/cm^2/day, taken from Valkirs et al. (2003), the total emissions from ports and marinas is approximately 20,000 kg/yr, of which approximately half is from ports and half from marinas (Gadd et al. 2010). The estimate for marinas is somewhat lower than the 16,000 kg/yr calculated by Williamson et al. (1995) for the Auckland Region, assuming 8,000 boats (similar to that for the 11 marinas in the EPA study). For their calculations Williamson et al. (1995) applied a higher release rate 22 µg/cm^2/day based on that deemed necessary to control algal fouling (de la Court 1988).

Environmental loadings of diuron were based on a leaching rate of 3.3 µg/cm^2/day (van Hattum et al. 2006). The total emissions from ports and marinas was estimated at ~8,000 kg/yr, of which (like copper), approximately half was from ports and half from marinas (Gadd et al. 2010). These estimated concentrations for diuron are based on a high use of diuron as co-biocides (90% of vessels) and represent a worst-case estimate, rather than a realistic estimate of the current loading. The estimates of both copper and diuron are heavily dependent on the leaching rates used in the calculations, which are based on new paints. These estimates may therefore be significant over-estimates, and validation of this work is needed.

Diuron has been measured in marinas, ports and estuarine waters around New Zealand at concentrations of < 10-830 ng/L (Stewart 2003, 2006), well below the concentrations predicted based on the emission estimates above. This suggests that either the leaching rates or usage rates (or both) for diuron are over-estimates. To date, there has been no national survey of copper in marina or port waters and therefore it is not possible to evaluate the accuracy of the copper loading estimates.

Additional copper and co-biocides including diuron are expected to be released to the marine environment during maintenance and repair of vessels, such as high-pressure washing and re-painting but this is more difficult to quantify. Estimates suggest this is a more minor source, with copper at approximately 240 kg/yr for marinas with hard stand areas used for boat maintenance and repair (Gadd et al. 2010), compared to ~2,000 kg/yr from antifouling leaching within a single marina. For ports, the copper release from maintenance and repair was estimated at ~2,000 kg/yr (Gadd et al. 2010). Diuron release from marinas was estimated at ~6.2 kg/yr and release from ports was estimated at ~70 kg/yr. Williamson et al. (1995) estimated a loss of 7,300 kg/yr of copper on hard stands in the Auckland Region from sanding, scraping and water blasting. This estimate assumed that there was no treatment or removal of paint flakes and that all paint removed was discharged into the marine environment. As many marinas now employ treatment systems, or divert their washwater from hard stand areas to the sewage system, the actual loading is likely to be substantially lower.

Stormwater runoff is a major source of copper to the New Zealand environment, due to the presence of copper at high concentrations in vehicle brake pads. Copper loading to the Waitemata Harbour, Auckland, has been estimated at ~1,500 kg/yr from stormwater (Timperley & Reed 2008). This compares with ~6,000 kg/yr for the ports and marinas. Furthermore, the majority of the copper released from stormwater is in particulate form with around 60% bound to particles 40 µm or larger (Green 2008), whereas the copper leached from antifouling paints is expected to be in dissolved form, at least initially.

3.7.1.5.2 San Diego Bay

The environmental loading of copper to a harbour or other water body is the sum of all inputs from all sources, which can include stormwater run-off, industrial, municipal and other discharges, atmospheric deposition, and leachates from the antifouling coatings and in-water hull cleaning of vessels (Johnson et al. 1998, Valkirs et al. 2003). For San Diego Bay, copper loading from all sources has been estimated to be 23,000 kg/year (Zirino & Seligman, 2002). This estimate was based on measurement data for vessels and calculated estimates from watersheds, stormwater and discharges (Valkirs et al. 2003). Release rates from antifouling coatings extrapolated to over 8,000 pleasure craft, 60 Navy ships, and other vessels. This represented approximately 48% of the total loading, with 37% from pleasure and commercial vessels, and 11% from naval vessels. In-water cleaning of vessel hulls was estimated to represent about 24% of the total dissolved copper, with 23% attributed to pleasure craft and 1% Navy, and collectively contributing approximately 72% of the copper loading from antifouling coating emissions (Valkirs et al. 1994, Johnson et al. 1998, Seligman & Zirino 1998, Zirino & Seligman, 2002, Valkirs et al. 2003).

More recent modelling of the mass balance and fate of copper in San Diego Bay estimated a similar copper loading from all sources of 20,000-22,000 kg/yr (Chadwick et al. 2004). The copper release rates used for this modelling copper release rates were 3.9 $\mu g/cm^2$/day for naval ships and 8.1 $\mu g/cm^2$/day for pleasure boats, based on the results of Valkirs et al. (2003). The rate of release of dissolved copper from in-water cleaning was estimated at 26 $\mu g/cm^2$/cleaning for naval ships and 6 $\mu g/cm^2$/cleaning for civilian vessels. The value 6 $\mu g/cm^2$/cleaning for civilian vessels was attributed by Chadwick et al. (2004) to “K. Schiff pers. comm.” and is presumably drawn from the latter’s study on copper emissions from antifouling paints on recreational vessels (Schiff et al. 2004). As noted in Section 3.7.1.2, this study may have underestimated the total copper emission during in-water cleaning. Naval and civilian hull cleaning inputs for particulate copper were calculated from the dissolved estimates by applying the particulate: dissolved ratio reported in USEPA (1999). The total contribution of copper from antifouling coatings and in-water cleaning was estimated to account for approximately 70% of copper input to the bay (Table 3.14).

Table 3.14 Estimated emission of dissolved and particulate copper from passive leaching and in-water hull cleaning (Chadwick et al. 2004).

Antifouling paint source	Dissolved copper (kg/yr)	Particulate copper (kg/yr)	Total copper (kg/yr)
Hull release (Navy)	2,405	0	2,405
Hull release (civilian)	8,336	0	8,336
Hull release (commercial)	356	0	356
Hull cleaning (Navy)	30	510	539
Hull cleaning (civilian)	169	2,914	3,083
Total (vessels)	11,296	3,424	14,720
Total (all sources)	14,839-16,096	5,552-5,860	20,391-21,956

3.7.1.5.3 Other Studies

Boxall et al. (2000) estimated that inputs of copper from high pressure washing of leisure vessels in the UK is about 0.1% of that released by leaching, although it was acknowledged that this input is within a short period and could lead to pulses of copper and other biocides entering the environment.

3.8 BIOCIDE FATE

3.8.1 Copper speciation and fate

The impact of copper on a marine ecosystem relates not just to the total copper input to the system, but also loss rates from hydrodynamic flushing, copper complexation and speciation, adsorption to particles and loss to sediments or through bioaccumulation (Valkirs et al. 2003). The primary form of copper in antifouling paints is cuprous oxide (Cu_2O), with a lesser amount in the form of cuprous thiocyanate (CuSCN). Although cuprous oxide is weakly soluble in freshwater with a pH of 8.1 (equal to seawater), it is readily soluble in seawater as the excess chloride ions in the solution form complexes with Cu^+. This drives the equilibrium of the equation below to the right.

$$Cu_2O + H_3O^+ + Cl^- \rightarrow CuCl, CuCl_2^-, CuCl_3^{2-}$$

The cuprous form is rapidly oxidised in the presence of oxygen to the cupric form, Cu(II). This is found in the dissolved (ionic) form Cu^{2+}, but the majority is found as inorganic or organic complexes and compounds and associated with particulates. The inorganic complexes include chlorides (e.g. $CuCl_3^-$), carbonates and bicarbonates ($CuCO_3$, $CuHCO_3$), and copper sulphates ($CuSO_4$). Organic complexes (e.g. with humic and fulvic acids, algal exudates) tend to dominate where dissolved organic carbon (DOC) is present.

Dissolved copper readily adsorbs to suspended particulates which may then settle out of the water column. Within aerobic benthic sediments, copper is typically bound to iron and manganese oxides and hydroxides, or attached to high molecular weight organic matter. In anaerobic sediments, any copper that is not tightly bound to organic complexes can be reduced back to the cuprous form Cu(I) (Williamson et al. 1995). This can also be adsorbed to organic matter or may form precipitates with sulphide. The majority of the copper in benthic sediments will therefore be in relatively stable complexes and have low bioavailability (more on this below). However, further transformations can occur if there are changes in the redox state, for example, within pore waters.

These processes result in rapid inactivation of the copper oxide and dissolved copper from the antifouling paints. Brooks & Waldock (2009) suggest that biofilms that exist on the surface of most vessels will result in organic-ligand complexes forming very close to the vessel.

Furthermore, most coastal waters contain appreciable levels of dissolved organic carbon (DOC) and suspended particulate matter (SPM) resulting in further complexation and adsorption within the water column. Modelling of the process of copper binding to organic matter and SPM suggests this is very rapid, reaching equilibrium within 5 hours (Orlob et al. cited by Knezovich 1994). Ultimately most of the copper leaching from antifouling paints will be deposited in benthic sediments (Williamson et al. 1995, Chadwick et al. 2004), particularly within the depositional environments of ports and marinas. These processes of copper leaching, oxidation, complexation and accumulation in sediment are summarised in Figure 3.1.

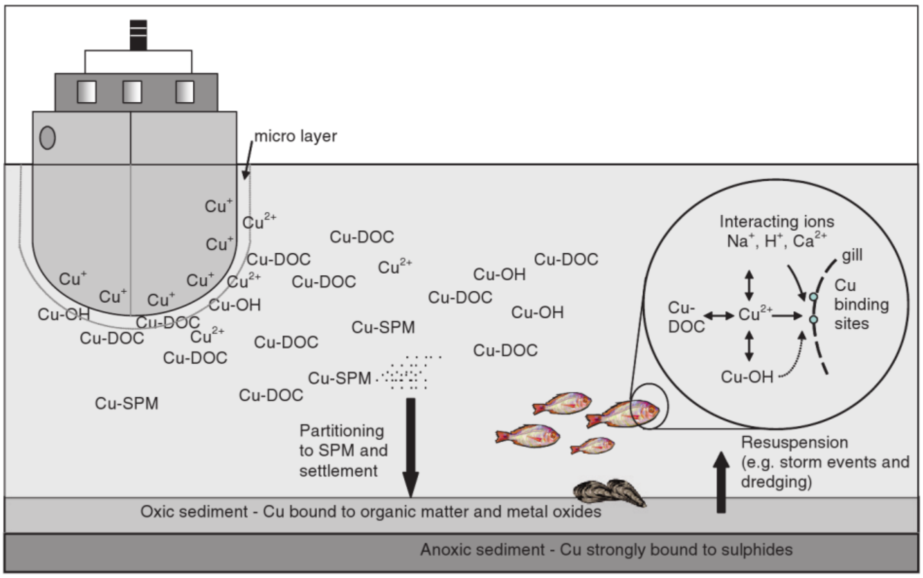

Figure 3.1 Schematic of copper leaching from a vessel painted with copper antifouling paint (Brooks & Waldock 2009).

Several studies internationally have assessed the speciation of copper sourced from antifouling paints in marinas and harbours. In San Diego Bay, ‘free’ and inorganically complexed copper, calculated from activity, was determined to be approximately two orders of magnitude less than the concentrations of the dissolved organic bound, and colloidally bound (Zirino & Bolam 1998). In UK marinas, labile copper (freely dissolved + inorganically complexed) comprised a greater fraction of the total dissolved concentration (which includes the organically-bound fraction), generally being between 10 and 30% of the total dissolved copper (Jones et al. 2007).

The speciation of copper directly affects its toxicity to aquatic organisms as different copper species differ in their bioavailability. Although copper is an essential nutrient at low concentrations, it is toxic to aquatic biota at concentrations only slightly higher than essential (Williamson et al. 1995). In laboratory experiments copper toxicity has been shown to not relate directly to total copper concentration, but to the dissolved concentration and more specifically, the freely dissolved (Cu^{2+}) concentration (Sunda et al. 1990, Seligman & Zirino 1998, Zirino et al. 1998), although inorganic complexes such as $CuOH^{+}$ may also contribute some toxicity (Arnold et al. 2005). The organically-bound ligands reduce copper toxicity, as shown by numerous studies that relate laboratory derived EC_{50}s/LC_{50}s for various aquatic organisms to DOC concentrations in water (Brooks & Waldock 2009). In water affected by copper from antifouling paints, the presence of SPM and DOC in the water will result in particulate-bound and metal-organic complexes reducing toxicity.

Copper in benthic sediments also poses a toxicity risk for aquatic biota, more specifically, those that dwell in and/or feed on the benthic sediments. Again the toxicity depends on the speciation of copper. For organisms living within the sediment, dissolved copper contained in sediment pore waters and the overlying water are the most bioavailable and toxic forms (Power & Chapman 1992). For organisms feeding on sediment, weakly-bound copper can also be considered bioavailable (Power & Chapman 1992). Additionally, experiments that digested estuarine sediment amended with antifouling paint particles using biologically relevant reagents predicted that infaunal deposit-feeding invertebrates would greatly accelerate the rate of mobilisation and local dispersal of metals in sediments contaminated by antifouling paint particles (Jones & Turner 2010).

Turner (2010) presents a comprehensive review of the contamination and fate of antifouling paint particles in the benthic environment, including a conceptual model of the biogeochemical pathways and fate in the coastal environment of inorganic, non-degrading biocides, such as copper, derived from boat maintenance activities. He concludes his review by observing that an extensive knowledge of biocide behaviour on painted surfaces is not sufficient for predicting the fate and effects of biocides in antifouling paint particles because of the different and, in some cases, poorly defined properties and pathways of biocides in particulate form. Differences relate to transportation in the aqueous medium, leaching rate, transfer to additional substrates, persistence, and interactions with and processing by invertebrates. Turner (2010) consequently calls for further research into physical or chemical means of identifying and quantifying fine paint particles in the benthic zone, and the biogeochemical behaviour of leached metals once in the interstitial environment.

More generally, in relation to knowledge of the chemistry, toxicity and bioavailability of copper in the marine environment, a USN workshop was held in 1997 with the aims of improving scientific understanding of copper in the marine environment and attempting to develop a solid scientific basis for future approaches to copper regulation (Seligman & Zirino 1998). The workshop identified a number of areas where specific research was considered necessary to improve understanding of the relationship between the input of low levels of copper into an estuarine environment and its ultimate ecological consequences. These were:

- Integration of bio-geochemical aspects of copper into hydrodynamic models, with special attention to the role of sediments as microbially active sources and sinks of copper;
- Standardisation of analytical protocols for copper species and copper complexation; and,
- Study of the role of organic matter in ameliorating the environment, including identification and characterisation of products of microalgal and microbial activity that are able to strongly bind copper and control its partitioning between the dissolve, colloidal, and particulate phases.

3.8.2 Fate of co-biocides

The fate of organic co-biocides is more complex than for copper as in addition to their state (e.g. freely dissolved, attached to colloids, or associated with particulate matter) they can also undergo a variety of degradation and removal processes, such as volatilisation, photolysis, hydrolysis and biological degradation. The fate of co-biocides used extensively in New Zealand is very briefly reviewed in this section. The reader is directed to Thomas and Brooks (2009) for a comprehensive review.

Diuron is relatively persistent in seawater and is frequently detected in surveys of marinas and harbours (Thomas and Brooks 2009) including in New Zealand (Stewart 2003, 2006). Diuron is relatively water soluble and only weakly bound to sediments. This is supported by data for

New Zealand, where diuron was frequently found in water, but infrequently in sediment, except at sites near slipways where paint flakes were thought to affect the results (Stewart 2003). Irgarol is also persistent with an estimated half-life of around 100 days in seawater. It is also relatively water soluble and partitioning coefficients suggest it is mainly associated with the dissolved phase rather than sediment. In New Zealand studies, Irgarol has been detected only rarely in either water or sediment (Stewart 2003, 2006). This is most likely due to its lower use than diuron. Both co-biocides have similar K_{ow} and these indicate a low likelihood for bioaccumulation. The persistence of both compounds is substantially higher when associated with paint particles (Thomas and Brooks 2009).

3.9 SYNTHESIS AND DERIVATION OF INPUT VALUES FOR MODELLING COPPER RELEASE FROM IN-WATER CLEANING

3.9.1 Assessment of copper contamination from in-water cleaning

In the absence of detailed and repeated measurements of copper concentrations in the water around vessels before, during and after in-water cleaning, the use of models such as MAMPEC can enable the estimation of contamination under different scenarios. However, the accuracy and reliability of modelling is dependent on the accuracy and reliability of the input values. The estimation of copper contamination of the marine environment as a consequence of the in-water cleaning of vessel hulls requires values for:

1. Copper released during the cleaning process (active release) which require values for the copper content of:
    a. Surface growth and biofilms;
    b. The leached layer;
    c. Unhydrated or unhydrolysed paint; and,
    d. Paint flakes;
2. Proportions of particulate and dissolved copper released during cleaning (active release);
3. Increase in copper release rate following in-water cleaning (passive release); and,
4. Copper speciation and bioavailability on and after release.

Additionally, the thickness of material removed from the surface, including surface biofilm and deposits and the depth of coating removed needs to be known or estimated, and the area of surface cleaned.

3.9.2 Copper released by the cleaning process

3.9.2.1 Surface biofilms

An assumption can be made that all methods of cleaning will remove the surface biofilm. However, although all antifouling coatings become rapidly colonised by biofilms after immersion (Section 3.2.2.6) little quantitative information is available on either the thickness or rate of development of biofilms on antifouling paints, or on the copper content of biofilms (Section 3.5.2). The few reported measures of biofilm thickness indicate a high range and variability in thicknesses against period of immersion, conditions of immersion, and coating type. Biofilm thicknesses from 0 to 2,500 µm have been measured, and generally films were thicker on ablative and hard coatings compared to SPC (Jackson & Jones 1988). Most reported biofilm thickness measurements are from TBT coatings which accumulated very thick diatom slimes due to TBT-tolerant diatom species secreting large volumes of extracellular polysaccharide to bind and ameliorate the toxicity of the TBT.

For tin-free coatings, the report of Lindner (1988) of a slime layer 50 µm thick on a copper-based insoluble matrix coating after 18 months is considered the best, or only, available guidance on biofilm thickness for modelling studies. Wood et al. (1988) found biofilms to be thicker on ablative than insoluble matrix coatings, and SPC coatings form the thinnest biofilms. It could be further assumed that thicker films develop on recreational vessel hulls compared to commercial vessel hulls, due to their lower activity.

However, the thickness of a biofilm is only useful in predicting copper release from in-water cleaning if the copper content per unit thickness or volume of wet biofilm is known or can be estimated. This is not the case.

The few published indicators of the biocide content of biofilms come from Ketchum (1952a), who reports the copper content of 2 week old biofilms as between 0.98 and 2.40 $\mu g/cm^2$, and Brown & Schottle (2006) who analysed copper content in waste streams from "light" in-water cleaning. The latter measured between 13 ($\pm$ 2.7) and 240 ($\pm$ 98) $\mu g/cm^2$/event of particulate copper from vessels with 3 months of biofilm accumulation.

Analysis of wash down water from vessels on land also gives guidance on the copper content of slime and leached layer removed. Williamson et al. (1995) calculated copper release per unit surface area to be mostly below 1 $\mu g\ Cu/cm^2$ (6 samples), but with two calculations between 2 and 2.5, one of 5.7, and one of 70.5 $\mu g/cm^2$/event. The estimation from Boxall et al. (2000) is between 0.3 and 9 $\mu g/cm^2$/event.

3.9.2.2 Leached layer thickness and copper content

In-water cleaning that removes the surface layers of an antifouling coating will remove all or part of the leached layer that is depleted of copper. Estimation of the amount of copper released from such cleaning requires knowledge of the thickness of the layer and its copper content.

Relatively few measurements of leached layer thickness were found and the reported thicknesses range from 5 to 90 µm (Section 3.2.2.5). General trends are for the thickness to increase with increased immersion time, and for thickest leach layers to develop in insoluble matrix coatings, thinnest in SPC coatings, and intermediate in ablative coatings.

No actual measures of the copper content of leached layers were found (Section 3.5.1.3). One paper (Howell & Behrends 2006) suggests that the copper content in the leached layer is low and close to the background level and the EDAX scan in Lewis (1998) seems to indicate a copper content of about 5% of the copper content of the underlying unleached paint.

3.9.2.3 Unleached/unhydrolysed paint

Should brushing remove more than the biofilm and leached layer, then unleached paint will also be removed. The copper content of this paint can be calculated with some certainty from available information on the % cuprous oxide or cuprous thiocyanate content of products registered by the APVMA in Australia (Table 8.3) and volume solids and specific gravity of the wet paint (sourced from product data sheets and MSDSs). Average copper content values can then be calculated for each category of antifouling (insoluble matrix, ablative, SPC), biocide (Cu_2O, CuSCN) and sector (recreational, commercial).

3.9.2.4 Particulate and dissolved copper

The release of biocide during cleaning would include both dissolved and particulate forms. Most of the copper released would be expected to be particulate from the biofilm, insoluble surface deposits, unleached cuprous oxide in the leached layer, and any unleached paint dislodged. The dissolved component would largely be from the leached layer where copper is in flux between the pigment and polymer front. Additional copper may dissolve from cuprous oxide in small paint particles generated by aggressive cleaning techniques.

Brown & Schottle (2006), in the one detailed study that measured dissolved and particulate copper release during in-water cleaning of actual vessel hulls using different methods, found the particulate copper release per event to be between 3 and 50 times the dissolved copper release.

3.9.2.5 TBT release

With the entry into force of the AFS Convention, no TBT or other organotin biocides should be present in the surface layers of antifouling systems and any such paint on a vessel would be encapsulated under a hard, impervious sealer coat. Extremely aggressive cleaning that would remove the full overlying antifouling systems would be needed to expose even the sealer coat. Exposure and release would only occur if the full paint system is breaking down and blistering or delamination happening within the inner paint layers or between the coating system and the hull steel or other structural material, or if mechanical damage has severely damaged the paint system. In either of these circumstances the release of TBT would be extremely low, due to either the small area of exposed TBT paint or the encapsulation of the TBT between other paint layers in detached flakes.

3.9.2.6 Paint thickness removed

The only published reports of the coating thickness removed by brushing give depths of 12.5 to 75 µm (Ingle 2006) and 25 to 50 µm (Forbes 1996). Industry advice is that the most aggressive brushing methods, using rotating steel bristle brushes, can remove 50-100 µm, whereas less aggressive techniques using nylon bristle brushes can remove less than 25 µm or just the biofouling. More paint would be expected to be removed from an ablative than hard insoluble matrix coating.

From the above, it seems reasonable in modelling studies to apply removal depths of 12.5-25 µm for light brushing and hard brushing of an insoluble matrix coating, respectively. For an ablative coating, 25-75 µm is suggested, and 25-50 µm for an SPC coating.

In the OPRF study of compounds released from hull coatings by in-water cleaning (OPRF 2010), it was assumed that the thickness of “painted pieces” scraped off was 100 µm using a soft brush over 95% of the cleaned area and 500 µm using a hard brush for the worst areas of biofouling, representing 5% of the area cleaned. The only justification given for these values was that in-water cleaning is undertaken at 2-year intervals that macrofouling would be severe on some ship components after this time, and that divers select brushes corresponding to the severity of macrofouling.

The OPRF logic is questionable for a number of reasons:

- Published and industry advice is that soft brushes will remove less than 25 µm and aggressive cleaning only 75-100 µm;
- Where there is severe macrofouling, there is unlikely to be any active coating;

- The dry film thickness of a newly applied antifouling is generally less than 400 µm for a 60 month system, and around 250 µm for a 24-36 month system, so removing 500 µm would take off more than the full thickness of antifouling coating and cut into the anticorrosive coating; and,
- The reduction of thickness in ablative and SPC coatings over the life of the paint does not seem to have been taken into account.

Furthermore, OPRF assume there to be only 10% of biocide left in the surface 100 µm of coating, because "the compounds in that layer…were considered to have almost completely leached out" (OPRF 2010). Although it is reasonable to assume 10% residual biocide in the leached layer, our evidence suggests that the leached layer is rarely this thick, and more often 75 µm or less.

The OPRF assumption that 82% of active substance would remain in a 500 µm paint chip would be an overestimate as this would include the underlying anticorrosive system. Immediately after application of, for example, a 350 µm DFT antifouling coating, the active content would only be 70%, and this would decrease further with polishing/ablation and development of leached layers.

3.9.3 Paint flakes

The copper concentration within detached paint flakes can be assumed to be the same as that of dried, unleached paint. Although the flakes may have the outer surface coated with slime and copper precipitates, and have a leached layer, the copper in these is likely to be insignificant compared to that in the bulk film. The total copper in the flake would represent the instantaneous release of copper into the environment, but the release of bioavailable copper from a detached paint flakes would be by passive release from the exposed surface of the paint. This would be from only the upper surface if the flake has disbonded between the coating system and the vessel hull, or both upper and lower surfaces if disbondment happened at the antifouling/anticorrosion coating juncture, or within the antifouling coating. A small release would also happen around the edges of the flake where various paint layers are exposed. These assumptions would equally apply to other biocides, including organotins if they have been encapsulated within a coating system.

No information is available on the quantity of paint flakes likely to be dislodged during in-water cleaning. If the in-water cleaning is part of hull husbandry to remove slime and light macrofouling to improve hull efficiency, or to reactivate a paint coating by removing the leached layer, then the extent of paint breakdown and delamination is expected to be low. If breakdown is extensive, there is also likely to be well developed biofouling, as the system would be at or close to its service life. In this latter situation slipping or dry-docking for antifouling renewal should be the recommended treatment, rather than in-water cleaning.

3.9.4 Copper from passive release

Despite what appears to be a substantial amount of work on copper release rates from antifouling paints, there are few published release rate values for different antifouling coatings and there is considerable variability in the rates that are published. The rates not only vary with the method of measurement and calculation, but there is clearly variability in the release rate of biocide from vessels as a consequence of the influence of environmental and operational factors. Laboratory methods for the measurement of copper release rates from antifouling coatings are accepted as generally over-estimating actual release rates on vessels. Conversely, the few measurements directly on ship hulls using the USN dome method, which has been considered the most reliable indicator of environmental release (e.g. Finnie 2006), may underestimate effective release rates because the coatings tested all show evidence that they are not fully effective, possibly due to sub-optimum release rates. Copper release rates in other modelling studies (e.g. MAMPEC (van Hattum et al. 2006), OPRF 2010) are not well justified and also appear to overestimate actual release.

As discussed in Section 3.6.3.1, the use copper release rates of 40 or 50 µg/cm^2/day in MAMPEC modelling were default values, and the current recommendation from CEPE is to use values derived by the CEPE/ISO method.

From studies extending over more than half a century, there is consistent evidence that the critical copper release rate to prevent macrofouling settlement and growth is 10 µg/cm^2/day. It is also well understood that all biocidal coatings have an elevated release rate on immersion, and steady state release rates are not reached for days (SPC coatings), months (ablative coatings), or not at all (insoluble matrix coatings).

Table 3.15 summarises the published copper release rates derived by the methods described in Section 3.6. The dome (ship) values are those considered the most reliable indicators of environmental release (Finnie 2006). The value derived by this method is 8.2 µg/cm^2/day, and this is justifiable (Section 3.6.3).

Table 3.15 Summary of release rates of copper (µg/cm^2/day) from antifouling coatings from different methods.

Coating Type	USN (stoich)	HEP static	HEP stat/dyn	CEPE	Dome (ship)	Dome (Raft)	Karlsson Eklund (NSW)	Karlsson Eklund (ASW)
SPC		5-20	7-9	30.2-30.7	3.8	1.3-1.5		
Ablative	7.6-12.8	8.90	17.00	15.5-18.4	1-8	2.20	3.2-3.6	13-14
Hard		10-20		30.4	5.7			
Average					8.2 ± 2.7			

Mass-balance calculations of release rates using the, and variants of the CEPE/ISO method (Table 3.16 and Table 3.17). Variations are mostly due to the use of different percentages for biocide release over the life of the paint (100, 90 or 70%) in the estimation, or the use of correction factors (Finnie). The results of the Finnie method are consistent with the use of 8.2 µg/cm^2/day.

Table 3.16 Summary of estimated release rates (µg Cu/cm^2/day) for merchant shipping/navy coatings by variants of the CEPE/ISO method.

Biocide	Coating type	ISO	Finnie	CEPE	$ISO_{Mod\ 1}$
Cu_2O	SPC	15.40	5.90	11.98	15.40
	Ablative	15.45	5.92	12.02	13.74
	Hard	23.19	8.88	18.04	18.04

Table 3.17 Summary of estimated release rates (µg Cu/cm²/day) for recreational/non-trading/fishing vessel by variants of the CEPE/ISO method.

Biocide	Coating type	ISO	Finnie	CEPE	$ISO_{Mod\ 1}$
Cu_2O	SPC	17.49	6.70	13.61	17.49
	Ablative	13.94	5.34	10.84	12.51
	Hard	17.20	6.59	13.38	13.38
CuSCN	Ablative	5.50	2.11	4.28	4.89
	Hard	4.38	1.68	3.40	3.40

3.9.4.1 Elevated release rates

In-water cleaning of an antifouling coating is undertaken either to remove the biofilm/slime layer to reduce drag and improve hull and energy efficiency, or to rejuvenate a coating in which the biocide release rate has dropped below that necessary to prevent biofouling attachment and growth. This could be due to the formation of a layer of insoluble copper salts on the coating surface, or a build of the leached layer that obstructs copper release. Removal of the insoluble copper or leached layers can expose a fresh layer of antifouling coating and restore antifouling effectiveness.

The removal of only the biofilm may increase the release rate into the water marginally, due to the known reduction of release rates caused by biofilms but, because the paint film would be undisturbed, not significantly above the steady state value. However, more aggressive cleaning to reactivate antifouling paint would expose a fresh layer of paint that could be considered similar to a newly painted and immersed surface and the release rate could significantly increase as freely-associated surface biocide dissolves. Studies of release rates before and after cleaning have shown this to happen, and data exists to enable estimates of this biocide pulse.

For passive release, it can be assumed that all of the copper released is in the dissolved form, as the release is a consequence of cuprous oxide dissolution and bioactivity is considered to be due to the free cupric ions.

3.9.5 Vessel surface area

The estimation and modelling of contamination from antifouling coatings on vessels requires the area of immersed surface relevant to the study to be calculated or estimated.
Van Hattum et al. (2006) provide simple formulae used by paint companies to estimate the underwater surface and required paint volume of recreational vessels. These are:

Motor launch (low draught)

$$A = L_{WL} (W + D)$$

Sailing yacht (intermediate draught)

$$A = 0.75\, L_{WL} (W + D)$$

Sailing yacht (deep keel)

$$A = 0.5\, L_{WL} (W + D)$$

Motor boat (generic)

$$A = 0.85\, L_{WL} (W + D)$$

Where:

A	=	wetted surface area (m^2);
L_{WL}	=	length at the waterline (m);
W	=	width (m); and,
D	=	depth (m).

Studies in California have adopted a stylized boat for estimation of contaminant inputs from recreational boats or the costs of their antifouling maintenance. The stylized boat has a length of 40 feet (12.2 m), a beam of 11 feet (3.4 m), resulting in a calculated wet hull surface area of 375 square feet (35 m^2; Carlson et al. 2002). Carlson et al. (2002) note that, as the length of a boat increases, the hull area increases more than proportionally. Schiff et al. (2004) used a 9.1 m powerboat as a typical recreational vessel in their estimations of dissolved copper release from passive leaching and in-water hull cleaning.

The derivation of average underwater areas of vessels for input to the MAMPEC included a review of various formulae and provides good guidance for the calculations of antifouled surfaces (van Hattum et al. 2006). Default values are also recommended by OECD (2005) and estimates based on these have been previously applied in the detailed study on the relevance to New Zealand of the OECD emission scenario document for antifouling products (Gadd et al. 2011).

In several studies related to vessel biofouling (Davidson et al. 2006, 2009, Lo et al. 2012), wetted surface area was calculated using a formula attributed to van Manen and van Oossanen (1988), thus:

$$WSA = L(2T + B)C_M 0.5(0.4530 + 0.4425C_B - 0.2862C_M - 0.003467B/T + 0.3696C_{WP}) + 2.38A_{BT}/C_B$$

Where:

L	=	length (m);
T	=	draft (m);
B	=	breadth (m);
C_M	=	midship coefficient;
C_B	=	blocking coefficient;
C_{WP}	=	waterplane coefficient; and.
A_{BT}	=	cross-sectional areas of bulbous bow (m^2) (calculated as a percentage of the immersed area of midship).

Hempel provide several more simple formulae for estimating underwater surface areas of commercial vessels (Hempel 2007):

Bottom (including boot-top):

A = ((2 x d) + B) x Lpp x P

Where:

d	=	draft maximum (m);
B	=	breadth extreme (m);
Lpp	=	length between perpendiculars (m);
P	=	0.90 for “big tankers”;
	=	0.85 for bulk carriers; and,
	=	0.70 for dry cargo liners.

Or

A	=	Lpp x (Bm + 2 x D) x (V/(Bm x Lpp x D)

Where:

D	=	mean draft at paint line (m);
Bm	=	breadth moulded (m);
Lpp	=	length between perpendiculars (m); and,
V	=	displacement (m^3) corresponding to the draft.

Boot-top

A	=	2 x h x (Lpp + 0.5 x B)

Where:

h	=	width of boot-top (m);
Lpp	=	length between perpendiculars (m); and,
B	=	breadth extreme (m).

In the OPRF (2010):
"The percentage of in-water cleaned area to the hull bottom area was set at 26.6%, based on the following information and settings:

- The ratio of the vertical part of the hull to the hull bottom area = 62:38 (based on the results of an interview survey of domestic shipbuilders); and,
- The percentage of in-water cleaned area to the vertical part of the hull = 70% (the biofouling conditions are confirmed by divers during visual inspection and the amounts of biofouling organisms present are expected to be less in deep water)."

The justifications given for these figures are not strong. The estimate of the area of vertical sides to be cleaned for the present study considered the area between the low load line and the turn of the bilge. The OPRF ratio of vertical part of the hull of ~62% may relate to full vertical sides, not just the antifouled area. For a vessel ~ 220 m long, dry-dock photos of similarly sized vessels were checked and, with a draft of 12 m (high load), the low load was at ~9 m, and turn of bilge between 2 and 4 m, from which 8.5 m was considered to be a reasonable estimate. If you consider that the beam of a vessel this size is ~35 m, the area of flat bottom exceeds the combined vertical sides even including to the high load line (24 m maximum).

3.9.5.1 Surface areas of niches

For the estimation of copper contamination from in-water cleaning, the surface area of most biofouling niches is not relevant because these are either unpainted (e.g. propellers, CP anodes, etc.) or inaccessible for brush cleaning (e.g. sea chests, rudder hinge recesses, bow thrusters etc.). Niches with outer surfaces flush with the hull, such as the outer surface of sea chest intake grates would be cleaned as, and their surface area included within, the total wetted surface area.

However, in addition to the total wetted surface of underwater hull, the area of vertical sides and the boot-top is of interest because these areas can be of importance for the removal of micro- and macroalgal growth which can be extensive on sunlit surfaces. The boot-top, or wind and water line, is commonly fouled by the green alga *Ulva*, whereas below the boot-top the algal growth is more commonly a short "fur" of brown and/or red filamentous algae and diatom biofilms.

We propose that the important niche areas for in-water cleaning of commercial vessels are the boot-tops and the ships sides. Boot-tops are the area between the water lines of a vessel when fully loaded and when loaded. Cleaning of just these areas is commonly undertaken to remove the algal slime to improve vessel performance. Cleaning of just the ships' sides to remove hard fouling is less likely, but we consider this to be worth modelling. For recreational vessels we suggest that spot cleaning of niche areas would be mostly removing growth from unpainted areas, so no there would be no biocide release.

The surface area of the sides of the vessel has been calculated based on dimensions of two model vessels. One of these was a shuttle tanker (244 m long x 41 m wide x 14 m deep) and the second a bulker (219 m x 35 m x 12 m). Both have a light load draft of 9 m and a heavy load line at 12 m. With an average load the draft is assumed to be 11.5 m. The turn of bilge (where the sides meet the bottom) is between 2 and 4 m draft. Assuming a mid-point of 3 m for the turn of bilge, the height of the vessel sides from the turn of bilge to the water-line is 8.5 m. For the bulker 219 m long, this equates to a total surface area for the two sides of 2 x 219 x 8.5 = 3,723 m^2. When compared to the TWSA of 10,469 m^2, it can be seen that this is approximately a third of the full hull surface area. Therefore for each vessel size class, a surface area for the sides has been calculated as a third of the full hull surface area (Table 3.18).

For the boot-tops the Hempel formula sums the areas of elongated rectangles along each side of the ship and across the stern. The required inputs to calculate this are therefore: ship length, ship width, and the height of the boot-top. For vessels less than 150 m, we have used a boot-top height of 1 m. For vessels longer than 200 m, we have used a boot-top height of 2 m. The breadth of the vessels is as follows 7, 13, 19, 28, 32 and 33 m. The boot-top surface area for each vessel length is tabulated in Table 3.18.

Table 3.18 Surface areas for full hulls, sides and boot-tops only for commercial vessels.

Vessel length category (m)	Full hull surface area (m^2)	Sides surface area (m^2)	Boot-top surface area (m^2)
< 50	412	137	73
50-100	1,163	388	163
100-150	3,231	1,077	270
150-200	6,333	2,111	728
200-250	10,469	3,490	932
250-300	15,640	5,213	1,140

3.9.6 Inputs for copper release calculations and uncertainty levels

The input values used in the copper release calculations as derived in the previous sections are summarised in Table 3.19, along with an estimate of the uncertainty.

There is considerable uncertainty in most of the values needed as inputs to modelling of copper contamination from the in-water cleaning of antifouling paints. This is due to the few reported measurements or studies into these values. High uncertainty is present in:

- The copper concentration within biofilms;
- The thickness of biofilms;
- The copper concentration within the leached layer;
- The thickness of the layer;
- The depth of coating removed by different cleaning method; and,

- The copper release rate of antifouling coatings both before and after cleaning.

Of all the inputs relating to copper concentrations and release, the only one of reasonable certainty is the copper content of unleached/unhydrated paint.

Despite the uncertainty in each of the values as identified in Table 3.19, these are considered the best available estimates at this time. The values were chosen on the basis of "best professional judgment" and they are considered appropriate for a pragmatic assessment. More certain estimates could be made for a "worst case" assessment, which would assume a fresh paint biocide content for each paint layer removed. However, this is clearly not a realistic or useful modeling scenario.

The possible ranges in the model values to be used were discussed in the preceding sections. For most parameters, these vary by a factor of two. The most uncertain parameter is that for the copper concentration in the leached layer, which may vary by up to ten-fold; and for the copper removed in the biofilm which may vary by up to 20-fold. For the leached layer, two estimates have been used in the modeling assessment. For the copper removed in biofilm, an upper value has been used to be conservative.

Table 3.19 Summary of inputs into copper release calculations and relative uncertainty of these estimates.

	Commercial		Recreational			
	SPC	Ablative	SPC	Ablative	Hard	Uncertainty estimate
Copper concentrations in paint µg/cm^2 /1 µm thickness						
Sound paint	120	120	120	120	120	fairly certain
Leached layer – Low estimate	2.4	2.4	2.4	2.4	2.4	very uncertain
Leached layer – High estimate	24	24	24	24	24	very uncertain
Paint Removal Depth (µm)						
Light cleaning	25	25	25	25	25	fairly uncertain
Aggressive cleaning	75	75	75	75	75	fairly uncertain
Thicknesses (µm)						
Leached layer	50	60	50	60	75	fairly uncertain
Coating Removed (µm)						
Light Cleaning						
Sound paint	0	0	0	0	0	
Leached layer	25	25	25	25	25	fairly uncertain
Biofilm	100%	100%	100%	100%	100%	fairly uncertain
Aggressive Cleaning						
Sound paint	25	15	25	15	0	fairly uncertain
Leached layer	50	60	50	60	75	fairly uncertain
Biofilm	100%	100%	100%	100%	100%	fairly uncertain
Copper removed in biofilm (µg/cm^2/cleaning event)	25	50	50	100	75	very uncertain

4 Review of the release of contaminants of biosecurity risk in the marine environment following in-water cleaning.

4.1 SCOPE OF REVIEW

Where available information allows, this review addresses the following questions:

- What is removed from the hull by each prescribed method of cleaning and what is left behind?
- Of the material removed, how much is captured and how much is lost to the surrounding environment?
- Of the material lost, how much is viable, able to reattach (in the case of sessile species) and able to reproduce (by fragmentation, external fertilisation, brooding etc.)?
- What are the rates of release of propagules from an untreated hull?
- Is the release of propagules stimulated by the cleaning process, including propagules released by organisms left on the hull after cleaning?
- How do these risks relate to and vary with environmental conditions, seasonality (relative to reproductive season)?
- What are natural propagule release rates (under the no action scenario)?
- What are the characteristics of fouling assemblages?
- What proportion of a recreational vessel surface would require spot cleaning?
- For recreational vessels, when do the costs of professional spot cleaning exceed the costs of haul out?
- What proportion of a commercial vessel surface would constitute the niche areas?

The following combinations of cleaning method, type of fouling and type of vessel were specified for answering Questions 5-8 (Section 5) and guided the scope of this review (MAF 2011a):

- Hand removal of spot fouling on recreational vessels;
- Soft-cloth removal of slime layer fouling on recreational vessels;
- Brush-cleaning of slime layer and soft fouling on commercial vessels;
- Brush-cleaning of hard fouling on commercial vessels; and,
- Available recapture technology for use in conjunction with the above methods of cleaning.

References for this review are provided in Section 9.

4.2 WHAT IS REMOVED FROM THE HULL BY EACH PRESCRIBED METHOD OF CLEANING AND WHAT IS LEFT BEHIND?

4.2.1 Relevant, currently available cleaning technology

Hand cleaning using paint scrapers is an effective and commonly-used method for removing organisms in isolated patches or niche areas. In a survey of owners of private vessels in marinas in Queensland, Floerl (2005b) found that in 53% of respondents cleaned their vessel hulls in-water between antifouling paint treatments, using paint scrapers or stiff brushes. Squeegees can be used for fouling-release coatings to avoid damage to the coating surface and subsequent re-fouling (Inglis et al. 2010). In-water cleaning of recreational boats is generally done using the aforementioned methods, most commonly without any method of capturing the material removed (Floerl et al. 2005c). Scraped material can be retained in mesh bags (Woods et al. 2007) but how effectively is not known. Some material is usually carried away by water currents before it settles into the bag (O. Floerl, NIWA, pers. comm.). Use of a suction device is likely to improve the effectiveness of capture (Coutts 2002). Removal by hand is the only method currently available in New Zealand when biofouling growth is dense or widespread because no commercially-available alternatives are able to remove thick fouling growth. For example, recent in-water cleaning of heavy fouling from the steel-hulled, sail-training vessel *Spirit of New Zealand* was done using shovels and the material collected in sacks (Matt Conmee, Northern Underwater Technical Services, pers. comm.).

Single-brush machines are used by divers to clean areas/hulls of higher radius e.g. yacht hulls and niche areas that are not amenable to cleaning by larger machines. They are commonly used for propeller cleaning and polishing. Examples include a hydraulic hand tool used and sold by UMC International in the UK (www.umc-int.com). Different grades of abrasive brushes are used to optimize organism removal and ensure minimal loss of antifoulant. These include various grades of polyester, stainless-steel and twisted wire bristles and, for heavy, hard fouling, discs with coach bolts attached to the brush surface (www.umc-int.com). Some in-water cleaning contractors overseas are apparently able to provide propeller cleaning with capture of waste. For example, according to their website, Underwater Contractors Spain (UCS: www.ucspain.com) offers diamond-disc and hydraulic brush cleaning of propellers and seals, incorporating "the ECO Propeller Cleaning Solution, which captures all debris in a filter system". No further information is provided on the website. Two diver-operated brush machines developed for trial in New Zealand (Hopkins & Forrest 2008, Hopkins et al. 2010) are discussed below.

Several large, multi-brush machines are currently in commercial use for cleaning vessel hulls (see reviews by Bohlander (2009) and Floerl et al. (2010a)) but few of these (and none available in New Zealand) captures material removed from the hull. Brush-based methods with actual or potential capture capability are in use or in development, including:

1. The AHCS (Advanced Hull Cleaning System – US Navy);
2. The modified SCAMP (Seaward Marine Services, USA);
3. UCS's ECO Crawler Hull Cleaner; and,
4. Subsea Solutions (USA, Canada, Malta).

The material removed from the hull by the AHCS is pumped ashore for the suspended waste to be settled and filtered out before the effluent is disposed of in the sewer. However, this system is not yet commercially available and may only be available for use by the US Navy (Daniel Kane, Propulsion Dynamics, pers. comm.). Seaward Marine Services, a hull-cleaning contractor for the US Navy, has developed a shroud system for SCAMP and a containment system for their diver-held brush system to capture waste. However, development of the capture system has been discontinued because of development of AHCS (Bohlander 2009). UCS's hull cleaning service uses a hydraulic multi-brush or water jet and "captures all debris in a filter waste system, the UCS DUTS (Direct Underwater Treatment System)" (no further information is given on the UCS website). UMC has a capture system for propeller cleaning and is developing one for their Mini-Pamper multi-brush, hull-cleaning vehicle (Bohlander 2009). Subsea Solutions has apparently developed a method of hull cleaning for use in the Port of Vancouver, where in-water cleaning has been prohibited[5]. The system captures and disposes of the waste through a process approved by the regulatory body but no information on the method is available on the Subsea Solutions website (www.subseasolutions.com). No response has been received following efforts to contact UCS and UMC directly.

There are also non-brush cleaning systems available that capture waste. For example, CleanROV (CleanHull, Norway: www.cleanhull.no) uses high-pressure seawater to clean the

[5] www.marinelink.com/news/solutions-cleaning-subsea342225.aspx

hull without damaging the antifouling and a waste-capture system has been incorporated for cleaning vessels in Algiceras Harbour, Spain.

A recent USEPA report (USEPA 2011) on underwater ship husbandry reviewed existing options for cleaning with waste capture and identified only two systems; the US Navy's AHCS and CleanROV. Much of the information in the USEPA report was, however, drawn from the reviews by Bohlander (2009) and Floerl et al. (2010a) and may have overlooked the more recent developments described above.

4.2.2 Effectiveness of currently-available cleaning methods

The efficacy of two shrouded, rotating bush systems for removing fouling has been tested on experimental plates and a vessel hull (Hopkins & Forrest 2008, Hopkins et al. 2010). Both systems, a commercially available brush (manufactured by Phosmarine, France) and a purpose-built brush system, were fitted with suction devices to capture material from the hull. These two systems were developed for proof-of-concept, and are not currently in use by commercial diving companies in New Zealand (Sol Fergus, New Zealand Diving and Salvage, Gaileen Thew, Diver Services Ltd, pers. comm.).

Up to 100% removal of biomass of soft/erect fouling, such as erect bryozoans, hydroids and other soft bodied taxa, was achieved on a fouled vessel, but brushes were less effective at removing calcareous taxa such as bivalves, barnacles and tube-dwelling worms on experimental plates (Hopkins et al. 2008). The performance of these rotating bush systems on experimental plates (on which fouling had been allowed to develop naturally over various periods of time) ranged from 88-93% reduction of mean percentage cover of fouling organisms on curved and flat surfaces. Defouling efficacy decreased as overall fouling became more advanced, with up to 61% of hard encrusting taxa remaining on flat plates after cleaning. Soft-bodied taxa growing adjacent to resistant species were also protected from the brushes. Effectiveness of treatment is therefore dependent on the composition of the fouling assemblage and its age. Treatments were, consequently, less effective against plates with mature taxa that mimicked commercial vessels that have been idle for an extensive period. Such high-risk biofouling vectors, often with long lay-up times, slow speed and generally low hull maintenance, can have very dense and extensive fouling assemblages.

Removal of heavy biofouling from a heavily-fouled, decommissioned vessel using SCAMP was moderately effective, reducing the extent of the cover from 89% to 37% (Davidson et al. 2008a). Effectiveness of cleaning with circular brushes (Table 4.1) is correlated with composition and age of the fouling community for both relatively recently settled surfaces (3-12 months) (Hopkins et al. 2010), and extensively fouled vessels (Davidson et al. 2008b). Filamentous algae and soft-bodied organisms are easily removed whereas calcareous species remained viable on plates and hull surfaces (Woods et al. 2007). Encrusting clonal organisms such as bryozoans can survive cleaning on heavily fouled surfaces to regrow and reproduce sexually or by fragmentation (Davidson et al. 2008b). Furthermore, the baseplates and shells of calcareous taxa that remain can provide substrate for chemo-induction of recruitment (Anil et al. 2010).

Moss & Marsland (1976) found that scrubbing of the hulls of tankers by diver-held brush or by SCAMP removed most of the algal biomass present, but that colonies of unicellular algae and the basal parts of larger algae, such as *Enteromorpha* and *Ectocarpus*, were left on the hull. The amount of algal material left on the hull was greater on rougher hull surfaces, where crevices and pits protected the algae from the action of the brushes. The effectiveness of cleaning was not related to the actual cleaning technique. Other macroalgal taxa that have regenerative basal structures likely to survive cleaning are *Grateloupia* and *Codium*.

Furthermore, taxa with encrusting alternate microscopic stages, such as *Undaria*, Scytosiphonales and Dictyosiphonales, or filamentous morphologies (*Polysiphonia, Ceramium, Womersleyella*), can also survive scrubbing.

Table 4.1 Summary of the effectiveness of different methods for in-water cleaning (J. Lewis, unpublished data).

		Uncoated	Biocidal	Foul release	Scrubbable
Hand removal (scraping)	Slime	Partial	Partial	Partial	Partial
	Macroalgae	Partial	Partial	Yes	Partial
	Soft Animal	Partial	Yes	Yes	Partial
	Hard Animal	Partial	Yes	Yes	Partial
Soft cloth	Slime	Yes	Yes	Yes	Yes
	Macroalgae	Partial	Partial	Yes	Partial
	Soft Animal	Partial	Partial	Yes	Partial
	Hard Animal	No	No	Partial	No
Brush systems	Slime	Yes	Yes	Yes	Yes
	Macroalgae	Partial	Partial	Yes	Partial
	Soft Animal	Yes	Yes	Yes	Yes
	Hard Animal	Partial	Yes	Yes	Partial

4.3 OF THE MATERIAL REMOVED, HOW MUCH IS CAPTURED AND HOW MUCH IS LOST TO THE SURROUNDING ENVIRONMENT?

Material hand-cleaned from a hull using cloths or scrapers can be captured by enclosing the area to be cleaned in a mesh bag, as done by Woods et al. (2007) in their experimental study (using a 200 µm mesh). In theory, a large proportion of the material should be capturable because the amount and rate of material released is likely to be small and, assuming the diver uses (for example) a net bag around the area being cleaned, it is likely that most of it can be captured as it is scraped off. Woods et al. (2007) did not estimate the proportion captured, but some relatively buoyant material, such as fragments of macroalgae and hydroids, was carried away by water currents (O. Floerl, NIWA, pers. comm.). Loss of material is likely to be much greater in fast currents. Use of a suction device is likely to improve the effectiveness of capture (Coutts 2002). At present, however, although this type of cleaning is commonplace in New Zealand, it is unlikely that any effort is made to capture material removed.

Coutts (2002) described a device to suck heavy fouling, composed predominantly of the soft-bodied colonial ascidian *Didemnum vexillum*, from the hull of a barge. The device consisted of a nozzle attached to a flexible hose, with suction provided by a water pump that passed the effluent through a 200-µm pre-filter and into a second pre-filter chamber where 100-µm and 200-µm filters were tested for effectiveness. A second in-line pump then passed the water through a filter bag in which mesh sizes of 1-200 µm were tested for retention of suspended solids. Successful filtering down to 50 µm was achieved at the third stage, but filters with smaller mesh all failed (i.e. particles larger than the mesh size were found in the filtered effluent). Mature larvae present in the adult colonies examined during the study had a body width of 300 µm. The suction nozzle was considered an effective method for removing colonies of *D. vexillum* from the hull, but other, harder-bodied fouling, such as mussels, occasionally blocked the equipment and required back-flushing to clear the blockage. Material expelled during back-flushing was not captured and fell to the seabed.

The only published empirical study quantifying the effectiveness of rotating brushes at removing and retaining material showed loss to the environment for biofouling removed from test plates and a ship hull of up to 9.0% (mean 3.8 ± 0.8% SE; Hopkins 2010, Hopkins et al. 2010). Losses were higher from curved than flat plates, and from plates with more advanced fouling. More material was lost in winter, when small barnacles were a larger proportion of the fouling assemblage, presumably because their settling speed exceeded the speed of advection by the suction system. There was no difference between the two brush systems tested but there is potential to minimize loss by improving shroud design.

No published data exist on capture efficiency of those brush-based hull-cleaning systems with capture technology suitable for large vessels, such as the AHCS, Seaward Marine Services' modified SCAMP, UCS's ECO Crawler Hull Cleaner or the Subsea Solutions system. Most such systems are designed to remove material without the ability to capture biofouling waste (Sections 4.2.1 and 6.3 of this report and Table 3.1 in Floerl et al. (2009)).

The size of the filter aperture also determines the effectiveness of the capture system. An aperture diameter of 60 µm was recommended by McClary & Nelligan (2001) to contain all mature and the majority of propagules for 43 target species identified in their study. Filtration with screens down to 50 µm will remove zooplankton and smaller screens (down to 20 µm) will remove hypnocysts of toxic dinoflagellates (Woods et al. 2007). The filter aperture sizes used in the brush systems tested by Hopkins et al. (2010) ranged from 1-30 µm. Woods et al. (2007) concluded that zoospores and propagules were found in final shore-based effluent facilities and should not be discharged back into the marine environment. Diatoms and algal spores require specialized techniques such as sand filters or cyclonic separators.

4.4 OF THE MATERIAL LOST, HOW MUCH IS VIABLE, ABLE TO REATTACH (IN THE CASE OF SESSILE SPECIES) AND ABLE TO REPRODUCE (BY FRAGMENTATION, EXTERNAL FERTILISATION, BROODING ETC.)?

4.4.1 Viability of lost material

The loss of viable biomass in the experimental cleaning by Hopkins et al. (2010) was low relative to the total amount removed (< 1%) and represented 8% of the material removed but not captured by the cleaning system. Organisms were considered viable when undamaged and a precautionary approach was taken for fragments of clonal species (i.e. they were recorded as viable). The composition of viable taxa was dominated by mussels, barnacles, polychaetes, erect bryozoan fragments, hydroids, colonial ascidians, nematodes and flatworms. Juvenile algae were also lost to the environment from both cleaning systems and the different surfaces tested (Hopkins et al. 2010). A total of 27 benthic fouling taxa were represented among the viable material lost.

Woods et al. (2007) found that tubiculous polychaetes comprised 71% of all organisms removed during in-water cleaning operations but were not viable after removal. If tubiculous polychaetes are removed from the analysis, large proportions (72.3 ± 8.0% SE in the winter experiment, 66.2 ± 5.1% in the summer) of the biota removed (predominantly bivalves, ascidians, errant polychaetes and sponges) remained viable after in-water hull cleaning.

Coutts (2002) did not find any larvae of the colonial ascidian *Didemnum vexillum* in water samples collected around the hull of a barge heavily fouled with this species either before or during removal of the material by suction. Nor were any larvae found in water in which adult colonies had been experimentally mechanically disrupted. However, examination of the adult colonies indicated that most larvae present were undeveloped, with only occasional mature larvae present. Consequently, the tests probably did not provide a realistic assessment of the potential release of mature larvae from adult colonies in response to mechanical disturbance.

Loss of mobile fauna to the receiving environment can be significant. In their comparison of the efficacy of hull cleaning operations, Woods et al. (2007) found that errant polychaetes, motile crustaceans, flatworms and nemerteans were a significant proportion of viable fouling organisms. Mobile organisms (errant polychaetes, crustaceans, platyhelminths, nemerteans, fishes and gastropods) are also dislodged in viable condition from vessels removed from the water for cleaning (Coutts et al. 2010). Greater numbers of mobile fauna remained viable after in-water cleaning than in dry-dock and haul-out operations. Furthermore, these mobile organisms may avoid capture and recolonize the hull in niche areas (Woods et al. 2007). Survival of mobile crustaceans is less affected than other taxa by haul-out cleaning (Fig. 12 in Woods et al. 2007). The seasonal variation in viability for most taxa removed by in-water cleaning was small with the exception of barnacles, which had significantly lower survival in summer (Woods et al. 2007).

4.4.2 Reattachment and reproduction of lost material

Fragmentation is a common dispersal strategy used by clonal organisms such as sponges, colonial ascidians and algae (Edlund & Koehl 1998, Bullard et al. 2007, Hopkins et al. 2011), and for some species of bryozoans such as cupuladriid bryozoans that are able to reproduce asexually by autofragmentation (O'Dea 2006). Sponges produce larvae and three types of external buds asexually (Bergquist 1978), and these are important mechanisms for survival of many sponge taxa (Battershill & Bergquist 1985). Anecdotal evidence of the ability of sponge fragments to heal and reattach is supported by the success in using clones in sponge aquaculture (Duckworth 2003) and field experiments (e.g. Johnston & Clark (2007)).

The importance of fragmentation in the life history of mobile fauna should not be underestimated in assessing the potential for survival and re-establishment of mobile fauna fouling ship hulls. Errant polychaetes are abundant organisms in the fauna captured after in-water hull cleaning (Woods et al. 2007) and the potential for survival and recolonization of suitable substrata is high for polychaetes. Bely (2006) concluded that annelids (the phylum to which polychaetes belong) in general exhibit qualitative and quantitative variation in regeneration ability, including among closely related species, and their segmental body organization makes comparing results among species relatively straightforward. The ability to regenerate posteriorly appears to be nearly universal in the annelids.

Annelids have the potential to regenerate from fragments by two processes. Architomy-fragmentation of the worm into two parts, followed by anterior regeneration at the caudal end and posterior regeneration at the cephalic end - is the only method of asexual reproduction in Lumbriculidae, Haplotaxidae, Lumbricidae, Naididae and Branchiobdellidae. Paratomy - regeneration of parts before separation resulting in complex chains of individuals or zooids some of which eventually separate into single individuals is found in the Families Aeolosomatidae and Naididae. In general, sexually reproduction in most Naididae families that show paratomy is rare or sporadic. Of the two methods, paratomy is evolutionarily more advanced (Bely & Wray 2004).

Epitoky, the formation of a free-swimming sexual form in polychaetes, involves tissue transdifferentiation and conversion of metabolism, locomotory and sensory capacities, is a one-way developmental process. The members of epitokous species are synchronized by meteorological parameters and by pheromones, and are adapted to spawn under pelagic conditions. The metameric (segmented) construction of the body predisposes for asexual reproduction by fission into fragments that are capable of regenerating into complete worms. This mode of reproduction is frequent among polychaetes and oligochaetes (Bely & Wray 2004).

Fission has been modified in many polychaetes: posterior fragments ('stolons') are formed, which take over the function of pelagic, epitokous sexual individuals and leave behind a 'stock' that lacks somatic sexual differentiation and can bud further stolons (Fischer 1999). Fragmentation during in-water cleaning may not, therefore, kill annelids living in fouling assemblages and has clear potential to stimulate sexual or asexual reproduction and increase the risk of infection of the receiving environment. Tubiculous polychaetes also have the potential to regenerate and reattach forming new mineral skeletons (Berrill 1931, Neff 1969).

Few studies have directly addressed the question of reattachment or recolonization of fragments lost during in-water hull cleaning (an exception is the study by Hopkins (2010) and Hopkins et al.(2011)). In Hopkins (2010), scrapers produced significantly larger fragments of colonial ascidians and bryozoans than rotating brushes. Reattachment success was dependent on species, fragment size and features of the receiving environment, including sedimentation rates, turbidity and predation. In clonal organisms such as sponges and ascidians, energy is generally directed towards somatic growth to heal damaged tissue, and then to reproduction and chemical defence (Cronin 2001). Therefore, larger fragments are likely to have higher survival rates and reproductive output than small ones that need to direct relatively more energy towards repair of damaged tissue. The colonial ascidians *Didemnum vexillum* and *Botrylloides leachii* form three-dimensional colonies and had the greatest survival and reattachment success among ascidians removed during cleaning (Hopkins 2010, Hopkins et al. 2011). Large fragments (> 20 mm) had the greatest (24-44%) reattachment success. *Didemnum vexillum* increases in size rapidly by zooid asexual budding. Large fragments and high fecundity have contributed to its spread throughout the Marlborough Sounds (Coutts & Forrest 2007). Encrusting and erect bryozoan taxa (*Watersipora subtorquata* and *Bugula neritina*) had no or low (< 1%) reattachment, respectively in field trials (Hopkins 2010). No research was done on the reproductive capability of reattached fragments. Other workers (Keough & Chernoff 1987) have, however, suggested that the erect bryozoan *Bugula neritina* may recruit to new habitats by rafting of fragments.

Hopkins et al. (2010, 2011) results are supported by those of (Bullard et al. 2007), demonstrating species-specific variation in reattachment ability among colonial ascidians, and by Paetzold & Davidson (2010) who demonstrated survival of *Botryllus schlosseri* following high-pressure water treatment. Differences in reattachment ability are most likely related to the life-history strategies of different species and the strength of the glue holding the colony to the substratum (Edlund & Koehl 1998). Some species with thick, fleshy colonies may only rarely become fragmented in the natural environment, whereas others may commonly use fragmentation as a strategy for asexual reproduction and dispersal (Bullard et al. 2007). This strategy is common in other clonal organisms such as sponges (Battershill & Bergquist 1985), where there is a positive relationship between clone size and survival (Duckworth 2003). Fragmentation may lead to greater rates of increase in biomass as the growth rate of fragments is higher than large undisturbed colonies. For example, Stoner (1989) concluded that fragmentation stimulated growth rates in the colonial ascidian *Diplosoma similis*.

Dislodged mussels (*Mytilus* spp., *Dreissena polymorpha*) are able to reattach byssal threads to available hard substratum over the course of 1-3 days (Crisp et al. 1985, Kavouras & Maki 2003, Vekhova 2006).

Detached and drifting plants of *Sargassum, Codium* and *Undaria* are all known to have facilitated dispersal, and many other algae can establish free-floating populations (*Ulva, Gracilaria*, *Cladophora*). Furthermore, spore release by most algae would also not be constrained after detachment. The green, ship-fouling alga *Enteromorpha*, for example, reproduces through production of motile zoospores and drifting plants are, therefore, capable of releasing large numbers of motile spores that may be chemically attracted to and adhere to ship hulls coated with foul-release silicone elastomers (Callow & Callow 1998).

Microbial organisms (slime) cleaned from a hull are highly likely to remain viable if not captured during cleaning. Capture of this material is also more difficult because it fragments, is carried easily by water currents, and cannot effectively be captured in mesh containers. The biosecurity risk of microbial slimes is generally considered to be low but this assessment is at least partly based on lack of information (Bell et al. 2011), and it is feasible that pathogenic or toxic organisms could be transported and released through in-water cleaning.

4.4.3 Summary

Viable material represents a small but potentially significant proportion of the material cleaned but not captured during in-water cleaning. Mobile organisms are more likely to survive cleaning and escape capture. Several other taxa, particularly those that exhibit colonial growth forms, asexual reproduction by fragmentation, or release spores from drifting plants, are also capable of surviving and reattaching or colonising the receiving environment. How much material is viable and able to reattach and reproduce cannot, however, be predicted quantitatively because it depends on the amount and type of fouling present and the reproductive states of the organisms. These, in turn, are dependent on numerous temporally and spatially variable factors including the voyage and hull-maintenance histories of the vessel, temperature and salinity regime of the receiving environment, availability of suitable substratum, and season.

4.5 WHAT ARE THE RATES OF RELEASE OF PROPAGULES FROM AN UNTREATED HULL?

To our knowledge there have been no studies conducted on the rates of release of propagules directly from ship and boat hulls. For the purposes of this review we have assumed that propagule release for assemblages living on untreated hulls is the same as for fouling taxa in similar environments, such as wharf pilings and aquaculture structures. We have, therefore, reviewed research relevant to the dominant taxa occurring in these fouling assemblages.

The definition of propagules for the purpose of this review includes all biological contamination; fragments, larvae, spores and gametes.

4.5.1 Algae

Zoospore production in *Undaria pinnatifida* is spatially variable in southern Australia. Release competency varies from 12.1 x 10^5 spores cm^{-2} h^{-1} in Port Phillip Bay to 0.6 x 10^5

spores cm^{-2} h^{-1} in Tasmania (Primo et al. 2010). Zoospore release is seasonal, the lowest numbers are released at the start of the sporophyte growth season (July – August) with a progressive increase towards the end of the season (Schaffelke et al. 2005). Higher zoospore release of 1 x 10^8 to 7 x 10^8 was reported by Brown (1999) for New Zealand populations.

Species of the red algal genus *Grateloupia* have been reported as one of the major invasive algal genera (García-Jiménez et al. 2008). *Grateloupia turuturu* can produce up to 10^4 spores that can differentiate into discoid crusts or filaments. The filaments can further produce 10^3 greater numbers of filaments than do discoid crusts (Shao et al. 2004), demonstrating the potential for this species to spread.

Further values for propagule output by algae include:

- A single plant of *Gelidium robustum* releases between 34,000 and 300,000 carpospores or 11,000 to 27,000 tetraspores per month (Guzman del Proo et al. 1972, cited in Kain & Norton 1990);
- *Botryocladia pseudodichotoma* produces 3.88 x 10^6 tetraspores per day (Neushul 1981, cited in Kain & Norton 1990);
- A single plant of *Rhodymenia pertusa* can produce 83 x 10^6 spores (Boney 1978, cited in Kain & Norton 1990);
- Each of the cystocarpic papillae that cover the surface of *Mastocarpus papillatus* can emit 3.6 x 10^6 spores (West & Crump 1975, cited in Kain & Norton 1990);
- The mean release per month from each m^2 of a stand of *Chondrus crispus* was estimated at 961 x 10^6 carpospores and 204 x 10^6 tetraspores (Bhattacharya 1985, cited in Kain & Norton 1990); and,
- In *Enteromorpha*, every cell except those in the rhizoids has the capacity to produce gametes (Maggs & Callow 2002, cited in Goldberg & Kendrick 2007).

4.5.2 Ascidians

Yund (2007) estimated that a population of the colonial, free-spawning ascidian *Botryllus schlosseri*, with a mixture of pre-reproductive and mature colonies at different stages in the reproductive cycle, produces several hundred cm^3 of sperm d^{-1}. *B. schlosseri* has large fertilization distances (10s to 100s of metres) compared to other free-spawning invertebrates. Sperm dilution is influenced by local flow and vertical mixing. The sperm are long-lived and brooding females have efficient sperm capture mechanisms, enabling successful fertilization to occur over large distances. The sperm of *B. schlosseri* have a significantly longer half-life than those of many other marine invertebrate taxa and are able to fertilize eggs at extremely low concentrations (10 sperm ml^{-1}: Johnson & Yund 2004). Botryllids are common introduced/cryptogenic taxa on artificial structures and boat hulls in New Zealand, so potential for successful fertilization of any fragments by a low concentration of incidentally released sperm is relatively high.

The larvae of colonial aplousobranch ascidians are brooded internally and didemnids, for example, release large competent larvae. Van Duyl et al. (1981) recorded release rates of up to 200 larvae per colony over a 4-hour period for the tropical species *Trididemnum solidum* (> 45 cm mean diameter). Hurlbut (1992) recorded similarly high numbers of larvae (up to average of 80 larvae per colony hour^{-1}) released into traps by *Didemnum candidum.* At the peak of the reproductive season, colonies of *Didemnum vexillum* as small as 100 g can spawn up to 500 larvae in 5 hours (Fletcher & Forrest 2011). The number of larvae produced by the whole colony is maintained by large numbers of zooids producing few embryos, rather than few zooids producing a large number. *Didemnum perlucidum* was also found to be highly fecund, with an average production of 21 ± 2.3 larvae cm^{-2} (Kremer et al. 2010).

Generally, solitary species are broadcast spawners and fertilization and embryogenesis are external events. Sperm and eggs are liberated into the water column where fertilization and development occurs. *Styela clava* larval concentrations can reach 0.24-0.56 larvae L^{-1} (Bourque et al. 2007). Larvae generally spend less than 24 hours as plankton before settling. *Ciona intestinalis* can release around 2,000-3,000 eggs per spawning and can spawn alternate nights or at three-night intervals, refilling their gonoducts within 24 hours in summer. The total fecundity was therefore estimated by Yamaguchi (1975) to be 10^5 per individual.

Fragmentation is very common in colonial ascidians and *Cystodytes dellalechajei* colonies attached to overhanging substrata produce protruding lobes which detach from the colony (Turon 2005). A similar process has been described for colonies of *Botryllus schlosseri* (Brunetti 1974) and is common in didemnids (Kott 2002). *Didemnum vexillum* produces fragments from spectacular, drooping tendrils exceeding 2 m long (Coutts & Forrest 2007). Fragments appear to have limited dispersal capability. For example, fragments detached from an infected barge in Shakespeare Bay, Picton were limited to an area of seabed immediately below the source vessel. While there has been no direct study on rate of fragment release, Coutts & Forrest (2007) estimated that the biomass of fragments on the seafloor comprised 460 kg, 33% of the 1,397 kg (~330 g fragment per kg of attached colony) biomass on the hull above. The vessel had been moored on the site for approximately ten months prior to the survey (B. Forrest, Cawthron Institute, pers. comm.).

Species in the genus *Clavelina* are capable of stolonic budding producing star-shaped, planktonic buds capable of greater distances of dispersal than are ordinary buds produced by other species (Turon 2005). The species studied, *C. gemmae*, is closely related to *C. lepadiformis*, a species recently introduced to New Zealand.

4.5.3 Bivalves

Female fecundity in *Crassostrea gigas* ranges from 12.2-146 million eggs $female^{-1}$ (Royer et al. 2008). Hatching rates of *Mytilus edulis* vary from 5.5 x 10^6 to 1.0 x 10^7 for females of average size (Pronker et al. 2008). A single female *Musculista senhousia* can release as many as 1.37 x 10^5 eggs (Sgro et al. 2002). Yields of *Pecten maximus* in commercial flow-through systems can reach 1.4 larvae μl^{-1}.

4.5.4 Barnacles

Amphibalanus improvisus (bay barnacle) is facultative self-fertilising barnacle (NIMPIS 2011). The ability to self-fertilise is especially advantageous for individuals of a species such as *A. improvisus*, which often has sparse and isolated populations. *A. improvisus* may produce 1,000 to 10,000 eggs per season and can produce several generations in a year. Embryos are brooded in an ovisac inside the mantle cavity. Development to hatching takes about 21 days at 18°C.

The reproductive pattern of the temperate barnacle *Balanus glandula* can vary significantly over a spatial scale of kilometres along an estuarine gradient, resulting in site-specific contributions to offspring to the larval pool (Berger 2009). Fecundity per individual can vary from 1,000 to 1,500 mass specific fecundity per individual (embryos mg^{-1}) for riverine to oceanic sites, respectively. The average brood size of *Balanus perforatus* in the eastern English Channel varies from 3,270-6,730 embryos per individual (Herbert et al. 2003). Under experimental conditions, the brood size of: *B. amphitrite* varies from 1,000-10,000 eggs brood^{-1}; *B. eburneus*, 1,000-5,000 eggs and *B. trigonus* 1,000-10,000 eggs (El-Komi & Kajihara 1991).

4.5.5 Decapods

The following summaries are drawn from the CABI Invasives Species Compendium (CABI 2011) and the National Sytem for the Prevention and Management of Marine Pest Incursions (NIMPIS 2011), and references are given therein.

Plaemon elegans (rock shrimp) is a euryhaline species that is native to the Atlantic and Mediterranean (including the Black Sea) coasts of Europe, ranging from Norway to South Africa. It breeds from April to September in the northern hemisphere and in favourable conditions females may produce two broods per year. As in all palaemonids, the eggs are protected by females and remain attached to her pleopods until the planctonic larva hatches. Then it undergoes typical development with variable number of zoeal stages recorded (from six to nine). The larva changes lifestyle to benthic in megalope (post-larval) stage.

Carcinus maenas (European shore crab) starts its life as part of the zooplankton community. It is a highly fecund species that reaches maturity quickly, and females are reproductively mature after one to three years. *C. maenas* is an iteroparous species and female crabs can mate multiple times during a breeding season but probably only produce one clutch of eggs per year. Maximum clutch size ranges from 185,000-200,000 fertilized eggs. The exact timing of the breeding season varies between geographic regions but usually occurs between April to November in the northern hemisphere (spring-autumn). The female carries the eggs in an egg sac (plug) under her abdominal flap (NIMPIS 2011). It is thought that females live in deeper water while gravid, to take advantage of more stable conditions of salinity and temperature. Eggs hatch into free swimming planktonic larvae that live in the water column for 17-80 days, depending on temperature (NIMPIS 2011).

Charybdis hellerii matures at a size smaller than that of most other *Charybdis* species. Females can reach maturity at a carapace size of 77 mm in 12 months. *C. hellerii* is thought to be capable of storing sperm for at least five months and it can produce at least six broods per year. Fecundity in *C. hellerii* is high and ranges from 22,550 to 3,200,000 eggs per brood depending on the size of the female. Total larval development is completed in 44 days.

Charybdis japonica (Japanese lady crab) releases larvae in late summer in its native Japan, and a bimodal reproductive season has been described in China, with spawning occurring in spring and autumn when sea temperatures are 20-28°C. Females may produce multiple broods each year with an average of 85,000 eggs per brood. Some species of *Charybdis* are able to store sperm and produce several broods from a single mating.

Eriocheir sinensis (Chinese mitten crab) ovigerous females can carry 250,000 to 1 million eggs. Larvae hatch in spring and early summer, mostly in the lower parts of estuaries.

Percnon gibbesi (Sally lightfoot crab) females reach sexual maturity at a carapace length of 15.0-16.0 mm. In the northern hemisphere, ovigerous females occur between the end of May and September and most mature females collected from July to October carried eggs. Brood size ranges from 254 eggs to nearly 32,000 eggs in largest egg mass and brood size is correlated with carapace size. Juveniles (< 15 mm) were first observed at the end of September and throughout the winter until March. In West Africa, ovigerous females have been collected in February, March, April and August.

4.5.6 Polychaetes

The sabellid *Sabella spallanzanii* has distinct reproductive seasonal periodicity. Spawning is synchronous between sexes, coinciding with reduced day length. The reproductive output is very high: large females shed > 5.0 x 10^4 eggs during an annual spawning season (Currie et al. 2000).

The average fecundity of *Hydroides elegans* ranges from 1,100-9,050 oocytes released per female (Qiu & Qian 1998).

High rates of fertilization in *Galeolaria caespitosa* requires high concentrations of sperm, and concentrations of 10^{7}-10^{8} sperm ml^{-1} were required to achieve fertilization rates of 60-80% (Kupriyanova 2006). These researchers did not, however, quantify sperm release and concentration in the wild.

4.5.7 Age to reproductive maturity

Age to reproductive maturity for organisms on an untreated hull will influence propagule release and abundance (Table 4.2). Time to reach reproductive maturity is variable and dependent on the voyage history, environmental conditions, and residence time at the receiving environment (e.g. Apte (2000)).

Table 4.2 Age at reproductive maturity for common introduced taxa.

Phylum	Class/ Order	Genus/species	Age at sexual maturity (days)	Reference
Annelida	Polychaeta	*Sabella spallanzanii*	100	(NIMPIS 2012c)
Annelida	Polychaeta	*Hydroides elegans*	16-21	(Hadfield 1998, Qiu & Qian 1998)
Arthropoda	Decapoda	*Carcinus maenas*	120-180	(Crothers 2001)
Chordata	Ascidiacea	*Eudistoma elongatum*	94	(Morrisey et al. 2008)
Chordata	Ascidiacea	*Styela clava*	270-300	(Clarke & Therriault 2007)
Chordata	Ascidiacea	*Diplosoma listerianum*	30-60	(Brunetti et al. 1988)
Chordata	Ascidiacea	*Botryllus schlosseri*	56-70	(Chadwick-Furman & Weissman 2003)
Chordata	Ascidiacea	*Botrylloides violaceus*	90	(Redfield & Deevy 1952)
Chordata	Ascidiacea	*Ciona intestinalis*	84	(Kanary et al. 2011)
Echinodermata	Asteroidea	*Asterias amurensis*	365	(Nojima et al. 1969)
Ectoprocta	Cheilostomata	*Bugula neritina*	40	(Redfield & Deevy 1952)
Ectoprocta	Cheilostomata	*Bugula flabellata*	30	(Redfield & Deevy 1952)
Mollusca	Bivalvia	*Crassostrea gigas*	365	(Pauley et al. 1988)
Mollusca	Bivalvia	*Musculista senhousia*	180-240	(Sgro et al. 2002)
Mollusca	Bivalvia	*Perna viridis*	60	(Hicks et al. 2001)
Mollusca	Bivalvia	*Perna perna*	1,096	(NIMPIS 2012a)
Mollusca	Bivalvia	*Potamocorbula amurensis*	60	(NIMPIS 2012b)
Phycophyta	Phaeophyceae	*Undaria pinnatifida*	30-50 (sporophyte) 24 (gametophyte)	(Schaffelke et al. 2005)

4.5.8 Summary

The preceding information indicates that there is considerable potential for the release of propagules from an untreated hull while the vessel is in port. Whether, and to what extent, this occurs will be temporally and spatially variable depending on features of the fouling assemblage and the receiving environment. The rates of release described above might occur for a vessel that resides in a port environment with the right combination of environmental conditions and at a time corresponding with the fouling organisms' lunar or seasonal reproductive cycles. The likelihood of this combination of conditions occurring during the residence time of the vessel in the port (which is often only one or two days for commercial vessels) is very variable, ranging from visits when there may be no release of propagules to those were large numbers may be released. Probability of release may increase with increasing residence time in port and, therefore, for recreational vessels and commercial vessels such as barges that spend longer in port. Probability and rates of release are likely to be influenced by environmental conditions (temperature, salinity, etc.) in the receiving environment.

4.6 IS THE RELEASE OF PROPAGULES STIMULATED BY THE CLEANING PROCESS, INCLUDING PROPAGULES RELEASED BY ORGANISMS LEFT ON THE HULL AFTER CLEANING?

Stimulation of propagule release may be in the form of the creation and release of viable fragments of colonial or other organisms capable of asexual reproduction. Alternatively, it may involve the release of gametes or larvae by organisms either left on the hull after cleaning or removed from it during cleaning, in response to mechanical shock or other stimulus.

Moss & Marsland (1976) found that colonies of unicellular algae and the basal parts of larger algae, such as *Enteromorpha* and *Ectocarpus*, left on the hulls of tankers after scrubbing were able to give rise to new thalli, with several vegetative branches arising where there had previously only been one. Furthermore, settlement of algal spores, probably released during the scrubbing process, coincided with, or immediately followed, in-water scrubbing. Small fragments of *Enteromorpha* also became entangled among remaining algae and each cell of such fragments was capable of giving rise to a new plant. These new plants were of "bottle-brush" form, resulting in numerous young plants being produced from a single piece of thallus. The process was stimulated by a temperature increase from 10 to 20°C.

Ceccherelli & Cinelli (1999) determined experimentally that fragmentation has a significant role in dispersal of *Caulerpa taxifolia*. They recorded high rates of reattachment of this species on natural substrata. Fragmentation is also a major reproductive strategy for the invasive algae *Sargassum muticum* (Klein & Verlaque 2008, Baer & Stengel 2010). West et al. (2009) demonstrated that boating and other in-water recreational activities significantly increase the biomass of fragments of *C. taxifolia* and the same potential for dispersal and attachment is likely to apply to *C. racemosa* (Klein & Verlaque 2008).

Moving vessels into areas of high productivity for in-water cleaning may induce spawning in some invertebrate taxa (Starr et al. 1990). Physical disturbance may trigger the release of gametes in *Styela clava*, as suggested by McClary et al. (2008). Similarly, the effect of removing colonies of a *Eudistoma* species from their substratum and transportation in buckets caused the colonies to release all their larvae (E. Vazquez pers. comm.). Gametes released as a result of mechanical shock or by release from the gonad may not, however, be capable of successful fertilisation. Oocytes of all animals enter periods of meiotic arrest at various stages of their development, the last of which may persist until fertilisation (Whitaker 2006). The environment into which gametes are released by cleaning must therefore be suitable to allow fertilisation to occur if cleaning is to stimulate propagule release in this manner.

Furthermore, the presence of gametes released from damaged or disturbed ascidians may induce congeners to spawn synchronously. Bolton & Havenhand (1996) found that sperm activity of *Ciona intestinalis* and *Ascidia aspersa* increased in response to compounds originating from eggs released into the water column. Evidence for the role of pheromones in spawning induction in polychaetes is unclear (Watson et al. 2003).

Changes in salinity and temperature can induce spawning in bivalves. For example, *Mytilus galloprovincialis* on the hull of the *USS Missouri* were able tolerate immersion in brackish (2-10 psu) water for nine days and weeks of travel across the Pacific, and spawned two hours after arrival in sub-tropical waters (Apte et al. 2000). They continued to spawn for five weeks after the vessel's arrival. Juvenile mussels successfully recruited to ballast tanks of another vessel located about 1 km away.

Colonial ascidians release larvae in response to light stimulation, often spawning at dawn under natural conditions (Hurlbut 1992). 'Light shocking' after a dark adaptation period is a technique used to stimulate larval release *in vitro* (Fletcher & Forrest 2011). Therefore, the timing of cleaning and potential release of organisms into the water column may maximise release of larvae from colonial ascidians by exposure to increased light if removal is from shaded areas of the hull in the early morning.

Physical damage to bryozoans from cleaning brushes may induce early maturation and spawning. Harvell (1988) found that experimentally-simulated grazing on the cheilostome bryozoan *Membranipora membrancacea* colonies caused early maturation. Similarly, laboratory studies on the polychaete *Hydroides elegans* suggest that gamete release may occur if tubes are broken by the cleaning process (Bryan et al. 1998, Pechenik et al. 2007).

In addition to stimulating release of propagules, in-water cleaning may also enhance the risk of subsequent recruitment by some fouling organisms. Floerl et al. (2005b) found that up to six times more individuals and colonies of fouling organisms recruited to manually defouled boat surfaces in Queensland marinas than to surfaces that had been sterilised (by soaking in 5% hydrochloric acid followed by freshwater) or that contained intact fouling assemblages. The taxa showing enhanced recruitment to the manually-cleaned surfaces included bivalves, colonial and solitary ascidians, encrusting bryozoans, hydroids, serpulid, sabellid and spirorbid polychaetes and sponges, and included non-indigenous species. Solitary ascidians (56 times more recruits on cleaned than uncleaned surfaces), encrusting bryozoans (34 times), serpulids (32 times), sabellids (10.4 times) and spirorbids (9.4 times) showed the greatest degree of enhancement. Traces of organic material such as barnacle base plates, oyster cement and sponge tissue remained on the surface after manual cleaning, Floerl et al. (2005b) suggested that cleaning may release chemical or physical cues for recruitment of taxa showing gregarious or associative behaviour, whereas established assemblages may provide resistance to further recruitment.

When cleaning is done prior to departure, this enhanced recruitment is likely to involve species already established in the original port. In this case, efforts to manage the biosecurity risks of hull fouling will only be compromised if the hull is colonised by pest species that were not previously present on it prior to departure. Similarly, when cleaning is done after arrival at a new port, it may increase the risk of establishment of species not yet present in the recipient port.

Removal of potential competitors by cleaning may also allow any individuals or colonies that survive cleaning to increase in size or abundance. For example, Switzer et al. (2011) reported that the removal of *Didemnum vexillum* created free space and allowed for other fouling organisms, such as *Botryllus schlosseri*, to increase in percentage cover.

4.6.1 Summary

The preceding discussion indicates that there is potential for the release of propagules as an indirect (stimulation of gamete or larval release by physical disturbance associated with cleaning) or direct (production of viable fragments or the release of gametes or larvae as a result of physical damage) result of in-water cleaning. The extent of these effects is dependent on the type of fouling organisms present, their reproductive status and environmental conditions at the time of cleaning. The effects of cleaning will, consequently, be very variable and difficult to predict.

4.7 HOW DO THESE RISKS RELATE TO AND VARY WITH ENVIRONMENTAL CONDITIONS, SEASONALITY (RELATIVE TO REPRODUCTIVE SEASON)?

4.7.1 Waves and currents

Environmental heterogeneity and seasonality affect survival and physiological performances of invasive (*Mytilus galloprovincialis*) and indigenous (*Perna perna*) intertidal mussels in South Africa (Nicastro et al. 2010). *P. perna* had significantly higher attachment strength than *M. galloprovincialis*. Attachment was strongly correlated with hydrodynamic stress and was lower for both species within coastal bays. Both species had a major spawning event when wave action was weakest. In bays, there was no correlation between gonad index (GI) and attachment strength for either species, but on the open coast GI was negatively correlated with attachment. In bays, maximum GI of *M. galloprovincialis* was 64% higher than for *P. perna*, while on the open coast values did not differ between the two. Thus, on the open coast, both species invest more energy in attachment but *P. perna* can accommodate energetic demands of increased byssal production without altering gonad production, while *M. galloprovincialis* cannot. Mortality was significantly correlated to sand stress, while the correlation with wave action was very weak in bays and non-significant on the open coast, probably because sand stress peaked during periods of low wave action. The success of the invader, and thus the outcomes of its interaction with the indigenous species, is governed by habitat-to-habitat variability. In this case the invasive species is likely to prove a weaker competitor on the more stressful and energetically-demanding open coast.

Local coexistence of *Perna perna* and *Mytilus galloprovincialis* may result from a combination of pre- and post-recruitment factors differing in importance for each species (Bownes & McQuaid 2009). *P. perna* is excluded from the high shore by recruitment failure (low settlement, high mortality). High survival and slow growth in juveniles may allow large densities of *M. galloprovincialis* to accumulate in the high shore, despite low settlement rates. With no differences between species in settlement or mortality on the low-shore, exclusion of *M. galloprovincialis* from that zone is likely to be by post-recruitment processes, possibly strengthened by periodic heavy recruitments of *P. perna*. At larger scales, larval retention and protracted recruitment may contribute to the success of *M. galloprovincialis*, while recruitment limitation may explain why *M. galloprovincialis* is less successful at other sites.

4.7.2 Temperature and salinity

Barnacle reproductive patterns are regulated by a complex interaction of multiple environmental variables; temperature, salinity, food availability and population pressure. Spawning of barnacles is coupled with phytoplankton productivity (Starr et al. 1991). The reproductive pattern of the temperate barnacle *Balanus glandula* can vary significantly over a spatial scale of kilometres along an estuarine gradient, resulting in site-specific contributions to offspring to the larval pool (Berger 2009).

Larval release in barnacles is affected by fluctuations in temperature and salinity (Cawthorne & Davenport 1980). Salinity and aerial exposure cause *Elminius modestus* and *Balanus balanoides* to release larvae on return to suitable environmental conditions, liberation ceases at 21 psu and 27 psu respectively. Reproductive output of *Balanus amphitrite* is positively correlated with temperature and chlorophyll *a* concentration (Desai et al. 2006).

There is interspecific variation in barnacle reproductive strategies; some breed over a wide range of temperatures (eurythermy), whereas others breed until a certain critical temperature is reached (stenothermy). *B. amphitrite* will breed continuously in tropical waters (Satheesh & Wesley 2009). High temperatures can delay the timing of reproduction in barnacles with temperate distributions. Berger (2009) found that an increase in water temperature was correlated with a reduction in the proportion of brooding individuals.

Adults of the European shore crab, *Carcinus maenas,* have reproductive temperature and salinity ranges of 3-26°C and 13-54 psu, respectively. Larvae are less tolerant of a wide range of abiotic conditions than adults, and survive in temperatures of 9-22°C and salinities of > 20 psu (NIMPIS 2011). Therefore, the environmental tolerances of larvae may be more limiting, and thus more important, for determining suitable habitats and understanding the ability of the species to spread and establish.

Rhithropanopeus harrisii is tolerant of a wide range of salinities and is typically associated with sheltered estuarine habitats. Adult crabs migrate into freshwater, but low salinity is believed to be the most important factor limiting the distribution of *R. harrisii* larvae which typically have reduced survival rates below 5 ppt. However, reproducing populations have recently been found in water bodies with salinities as low as 0.4 ppt (NIMPIS 2011).

Polychaete reproductive output is correlated to water temperature and salinity. Water temperature affects sperm swimming efficiency and fertilization in the serpulid polychaete *Galeolaria caespitosa.* Fertilization efficiency is reduced at both low and high sub-optimal temperatures (Kupriyanova & Havenhand 2005). Low salinity has been demonstrated in laboratory studies to interrupt the early development of *Hydroides elegans* eggs (Pechenik et al. 2007).

4.7.3 Seasonality and time of day

Early studies of fouling graphically demonstrated seasonality of fouling settlement. Examples of seasonality of common fouling species are given in (Skerman 1958, Skerman 1959, OECD 1966, Russ 1977). For example, in a study incorporating locations in Europe, north America and Africa (OECD 1966), settlement of one or more fouling species (including algae, barnacles, hydroids, bryozoans, polychaetes and molluscs) occurred throughout the year at stations below latitude 44°, whereas at higher latitudes there were distinct periods of between one and five months when settlement was absent. In the south of the United Kingdom, settlement of the barnacle *Balanus balanoides* occurred from March to May and that of *Elminius modestus* from June to October (OECD 1966). Skerman (1958) reported sparse recruitment of fouling organisms across a range of taxa in winter in Lyttelton Port, in contrast to heavy recruitment in summer. He suggested that development of dense populations of the bryozoan *Bugula* sp., following summer recruitment, may have suppressed recruitment of other taxa. Some taxa recruited throughout the year, including the barnacle *Elminius modestus* (contrasting with the pattern observed in the United Kingdom: OECD 1966). Similar results were obtained from the Port of Auckland (Skerman 1959). In Skerman's two studies (1958, 1959) recruitment was only recorded over the period of just over one year, so that inter-annual variation in seasonality could not be determined. The OECD (1966) study, however, measured recruitment over three years, and patterns of seasonality were generally consistent.

Floerl et al. (2010b) reviewed information on the short-term (≤ 4 weeks) development of fouling assemblages in temperate and tropical marine environments and highlighted the seasonality of reproduction and recruitment in temperate regions, particularly at higher latitudes. Recruitment in tropical regions, in contrast, occurred throughout the year, with the exception of monsoonal periods. Time to reproductive maturity was more rapid in tropical than in temperate regions for the same or related species. This seasonality in the lifecycles of fouling organisms translated into seasonally variable biofouling risk to vessels resident for short periods, particularly in higher-latitude regions.

Crassostrea gigas reproduces during summer, with highest recruitment occurring January to March (Jenkins 1979). This species has a long spawning season, from mid-spring to the end of summer, and the pattern of spat settlement reflects the extended spawning activity. Solar and lunar cycles drive activity rhythms of *Crassostrea gigas* (Tran et al. 2011), but it was not determined if these were primary drivers for gamete release.

Spore release in *Undaria pinnatifida* is geographically variable. High spore release occurred for three months from November to January in Tasmania (Schaffelke et al. 2005) and Primo et al. (2010) found a similar pattern occurred in Port Phillip Bay, Victoria. However, low rates of spore release occurred throughout most of the growing season when all size classes of sporophytes were combined (May – February). In New Zealand, the highest rates of release were recorded during August and September (Brown 1999).

Reproduction of *Styela clava* in New Zealand occurs when water temperatures rise above 15^{o}C, above which the potential for spawning and recruitment is high. At least some members of the population are reproductive at different times of the year, but there appears to be a lull in reproductive potential in mid-winter and in mid spring (McClary & Nelligan 2001). Peaks in larval abundance appear limited to a three-hour interval in the early afternoon (Bourque et al. 2007), but this timing has not been confirmed for New Zealand populations. *Styela plicata* has seasonal reproduction, breeding from late spring to early summer in Japan (Yamaguchi 1975).

Spawning in *Ciona intestinalis* is seasonal, with maximal larval abundance and subsequent recruitment occurring at between 12-16°C (Ramsay 2008). However, in warm climates the species breeds continuously throughout the year (Yamaguchi 1975).

High temperatures and intermediate salinities stimulate the maturation of gonads in the colonial ascidian *Botryllus schlosseri*, whereas low temperatures and extreme salinities stimulate colonial growth (Brunetti et al. 1984). Sexual reproduction commences as colonies approach terminal size (growth is determinate and fragmentation does not occur, unlike many other colonial ascidians). Release of brooded larvae is seasonal, occurring during summer and correlated with increasing temperature and phytoplankton productivity. In areas of higher productivity colonies may complete two reproductive cycles (Yund & Stires 2002).

The colonial ascidian *Eudistoma elongatum* broods larvae seasonally from late spring to late summer (November – May). Anecdotal evidence suggests that dislodged fragments may remain viable and reattach (Morrisey et al. 2008). The risk of re-establishment and subsequent propagule release is higher in summer than winter, when colonies are senescent.

Shorter time scales may also influence biofouling risk. For example, peak spawning in many species of ascidians occurs during the early morning (Yamaguchi 1975, Hurlbut 1992). Consequently, the timing of cleaning operations may be an important factor in minimizing release and fertilization of propagules.

4.7.4 Other considerations

The composition of a fouling assemblage is influenced by complex and highly variable interactions of physical and biological factors. Many of the physical factors are well documented from laboratory and in-situ studies. However, consideration should be given to biological interactions when predicting recruitment success and composition of non-indigenous species (NIS) on a ship hull. The species composition of the fouling assemblage may also enhance larval settlement of introduced species via chemically-mediated interactions. For example, settlement of the polychaete *Hydroides elegans* is positively correlated with the presence of the bryozoan *Bugula neritina*. *H. elegans* may gain refuge from predation from both structural and chemical attributes of *B. neritina* (Bryan et al. 1998).

4.7.5 Summary

As identified in preceding sections of this review, the risks related to the release of propagules by fouling organisms on uncleaned hulls or during in-water cleaning, and the survival and re-establishment of whole organisms or fragments dislodged during cleaning, are highly variable over time. Some of this variation derives from intrinsic processes of growth and reproduction of the fouling organisms, so that those arriving in New Zealand in a reproductively mature condition (ready to release gametes, larvae or other propagules) will present a higher risk of infection at the receiving locality. This risk may be further increased by in-water cleaning, for example through stimulation of larval release by physical disturbance. Environmental seasonality may interact with the reproductive seasonality of the fouling organisms to increase or decrease risk of propagule release and subsequent infection. For example, water temperature and salinity in the receiving environment may stimulate or inhibit release during the period that an infected vessel is in port. Temporally-variable environmental factors may affect the risk of infection from fragments or whole organisms released during cleaning by increasing or decreasing their probability of survival and establishment. A further level of interaction between temporal variability in the fouling organisms and the receiving environment may be present in the form of interactions between the fouling organisms or their propagules and native species that may alter the probability or pattern of establishment. This is illustrated by the example of native and exotic mussels in South Africa and by the preferential settlement of *Hydroides elegans* in association with *Bugula neritina*, described above.

4.8 WHAT ARE NATURAL PROPAGULE RELEASE RATES (UNDER THE NO ACTION SCENARIO)?

This information is presented above (*What are the rates of release of propagules from an untreated hull?*), as to our knowledge there are no published data on the rates of release of propagules from untreated vessels. Available information is derived from relevant taxa on experimental or other artificial substrata.

4.9 WHAT ARE THE CHARACTERISTICS OF FOULING ASSEMBLAGES?

Development of fouling assemblages begins with the adsorption of organic matter to the surface of an object as soon as it is submerged. The consequent modification of the surface facilitates the development of a microfouling assemblage, including microscopic stages (larvae or spores) of species that may subsequently grow to form macroscopic fouling (Richmond & Seed 1991). Wahl (1989) provided a generalised time-scale for the development of fouling assemblages, with bacterial and fungal colonisation occurring within hours of immersion, diatoms within days, protists within a week, and macrofauna and macroflora within weeks to months. The dominant macrofouling taxa are usually species of algae, sponges, cnidarians, polychaetes, molluscs, bryozoans, barnacles and amphipods.

The rate of accumulation of fouling material varies geographically with species composition, season, distance from shore and water depth (Richmond & Seed 1991). The relatively small seasonal environmental variation in the tropics generally reduces seasonality in the availability of propagules of fouling species. Consequently, the marked seasonality in recruitment and growth of fouling assemblages seen in temperate regions is less marked in the tropics. Rates of development of assemblages are higher in the tropics but the greatest production of biomass is often highest in high and mid-latitudes.

In the absence of antifouling treatment, the fouling assemblage continues to accumulate until most or all of the available space is occupied. Thereafter, ongoing recruitment and replacement of individuals and species occurs in response to intrinsic (e.g. patterns of individual and population growth, competition and predation within and among species) and extrinsic (e.g. water temperature, water movement, day length) factors. These post-recruitment changes are often seasonal, particularly in temperate regions. On vessels (as opposed to static objects), the development of fouling assemblages is also influenced by vessel activity and speed. Patterns of activity include the length of time spent stationary in port, which increases the likelihood of fouling development, and the geographical locations visited, which influences the type of species available to colonise and the likelihood of their survival when transported to other areas. The vessel’s speed also affects the ability of fouling to remain on the hull, and affects the distribution of fouling on the hull, with most fouling generally occurring in niche areas sheltered from the strongest hydrodynamic forces.

Inglis et al. (2010) provided a thorough overview of information from a MAF-funded study of fouling assemblages on different categories of vessels (commercial, recreational, passenger and fishing) entering New Zealand waters during the period 2004-2007. In summary:

- Systematic sampling of fouling organisms across all types of vessel produced 187 identifiable species, representing 17 phyla, and including 128 non-indigenous, 49 indigenous and 10 cryptogenic species;
- Crustacean represented 36% of all organisms collected and identified, polychaetes 15% and bryozoans 11%;
- Barnacles occurred on 63% of vessels, algae on 29%, bryozoans on 26%, bivalves on 24% and polychaetes on 21%;
- Frequency of occurrence of most major taxa varied among types of vessels. Ascidians and bryozoans were recorded almost exclusively from yachts and motor launches and polychaetes were recorded more frequently on yachts than other types of vessel. Amphipods, bivalves and hydroids were also more commonly found on yachts and passenger vessels than on most types of merchant vessel;

- Across all types of vessel, arthropods (72 species, of which 65% were barnacles), bryozoans (30 species) and polychaetes (14 species) represented 90% of non-indigenous species recorded. The remaining 10% consisted of hydroids (5 species), ascidians (4 species), anemones, red algae and bivalves (1 species each);
- Only 34 (26%) of the non-indigenous species recorded are known to have established populations in New Zealand and many of the remaining 94 species were recorded for the first time in New Zealand;
- At least one identifiable fouling species was found on 82% of yachts, 55% of bulk carriers and passenger vessels, 52% of container/cargo vessels and 38% of reefers. All three fishing vessels sampled had some biofouling;
- There was evidence that the density of species per vessel was greater on yachts than other types of vessel, and that species densities on passenger liners and merchant vessels were similar;
- Recreational, passenger and merchant vessels transport novel non-indigenous species into New Zealand at similar rates;
- The composition of the fouling assemblages on yachts and motor launches were most distinct from other types of vessels, largely due to the frequent occurrence (almost 50% of vessels) on the recreational vessels of the non-indigenous bryozoans *Bugula neritina* and *Watersipora subtorquata* and the large proportion of species that were only found on one type of vessel;
- Assemblages on merchant vessels were generally dominated by barnacles. These assemblages contained 78 non-indigenous, five cryptogenic and 25 indigenous species. Of the non-indigenous species, only 18 (23%) are known to be established in New Zealand, and only one of these (the barnacle *Amphibalanus amphitrite*) occurred among the 20 most frequently encountered non-indigenous species (17 of the 20 most-commonly encountered species were barnacles);
- Organisms collected from recreational vessels included 76 non-indigenous, eight cryptogenic and 30 indigenous species. Of the non-indigenous species, 27 (36%) are known to be established in New Zealand and, in contrast to merchant vessels, most novel species occurred relatively infrequently. Of the 20 most frequently encountered non-indigenous species, 12 (60%) are known to be established in New Zealand;
- Fouling assemblages on passenger vessels were similar to those on merchant vessels and were dominated by barnacles and serpulid polychaetes. They included 30 non-indigenous, three cryptogenic and 14 indigenous species. Of the non-indigenous species, 8 (27%) are known to be established in New Zealand. The assemblages were dominated by barnacles and serpulids;
- Yachts arriving in autumn and winter tended to have greater biomass and species richness than those arriving in spring or summer, but there were no such trends among passenger liners or container/cargo vessels; and,
- Species collected from niche areas of the hull contributed most to total species richness in all three vessel categories. Greatest contributions in each vessel class came from material collected around bow-thrusters, gratings, rudder and shaft, propeller and shaft and, where present, dry-docking support strips. Relatively large numbers of species also occurred on the keel in the case of yachts.

4.10 WHAT PROPORTION OF A RECREATIONAL VESSEL SURFACE WOULD REQUIRE SPOT CLEANING?

A working definition of ‘spot cleaning’ does not exist in the literature reviewed. Discussions with ship maintenance and commercial diving companies (Section 4.11) indicate that commercial in-water cleaning of recreational vessels is uncommon and that vessel owners are much more likely to clean the vessel themselves while it is in the water or have it hauled out for cleaning, depending on the level of fouling present. In Queensland, 53% of recreational boat owners clean their boats manually (either in or out of water) between applications of antifouling paint (Floerl et al. 2005b). More than two thirds of yachts arriving in New Zealand had cleaned their hull manually (either in or out of water) since the last application of antifouling paint (Inglis et al. 2010). However, timing of this cleaning did not appear to be influenced by the age of the antifouling, and there was no clear relationship between the date of manual cleaning and last date of painting.

Consequently, there does not seem to be a proportion of fouling cover at which owners of recreational vessels would switch from cleaning by commercial divers to having the vessel removed from the water for cleaning. There may, however, be a proportion of cover at which non-commercial in-water cleaning becomes too difficult and haul-out is necessary, although the type of fouling (and the associated difficulty of removing it by hand) and the time since antifouling paint was last applied are also likely to influence this decision.

The Level of Fouling (LOF) scale developed by Floerl et al. (2005a) includes the percentage cover of fouling on the hull surface in the definitions of each level. Level 2 fouling consists of "Light fouling. Hull covered in biofilm and 1-2 very small patches of macrofouling (only one taxon)" and the visual estimate of fouling cover is 1-5% of visible submerged surfaces. Level 3 fouling consists of "Considerable fouling. Presence of biofilm, and macrofouling still patchy but clearly visible and comprised of either one single or several different taxa" and the visual estimate of fouling cover is 6-15%[6]. The percentage cover predicted by the LOF was compared to the actual percentage cover observed on a sample of 189 yachts (Table 2 of (Floerl et al. 2005a)). All yachts with LOF 0 or 1 had < 6% cover while 79% of those with LOF 2 had < 6% and the remaining 21% had 6-15% cover. Among yachts with LOF 3, 76% had < 16% cover. Hard fouling, such as bivalves and tubiculous polychaetes, that may be relatively difficult to remove by hand scraping, were also only present on a small proportion of yachts with LOF 3 or less (Fig. 3 of Floerl et al. 2005a).

Based on these LOF data, we propose a working definition of the proportion of a vessel hull that would require spot cleaning as up to 15% cover of the general hull surface. Above this percentage of cover, we suggest that the amount and type (i.e. resistant to hand scraping) of fouling would prompt the owner to have the vessel hauled out for cleaning. LOF > 3 may also indicate that the antifouling coating has failed and that haul out and repainting is required. Where cover is less than 6% of the hull surface, in-water spot cleaning will probably be considered unnecessary because the fouling is likely to consist of slime with only 1-2 patches of macrofouling (i.e. LOF 2). Exceptions will occur when this limited fouling occurs on areas of the hull that compromise the vessel's performance, such as the propeller or water intakes, in cases where damage to the antifouling coat allows a small patch of heavy fouling to develop, or in the case of racing vessels.

4.11 FOR RECREATIONAL VESSELS, WHEN DO THE COSTS OF PROFESSIONAL SPOT CLEANING EXCEED THE COSTS OF HAUL OUT?

Floerl et al. (2010a) estimated the cost of professional in-water cleaning of a 12 m recreational vessel (yacht or launch) in Australia to be about A$240 (NZ$300 excluding GST), including the hull and all niche areas. Equivalent cleaning in New Zealand may incur

[6] Level 0 fouling refers to a clean hull with no slime on any visible submerged parts of the hull; Level 1 indicates that the hull is partially or completely covered with slime but no macrofouling is present; Level 4 is extensive fouling, 16-40% of the visible hull surface with macrofouling , remainder usually covered in slime; Level 5 is very heavy fouling, 41-100% of visible hull surface covered by macrofouling, remaining area often covered in slime.

additional costs and delays associated with obtaining a coastal permit from a regional council (McClary & Nelligan 2001).

Inglis et al. (2011) provided estimated costs for haul out, water-blasting to remove fouling, and hardstand storage for recreational vessels in New Zealand. Assuming that the vessel can be hauled out, scraped clean of fouling and returned to the water within one day (Floerl et al. 2010a), costs for haul out and storage on a hardstand for a small (12 m) vessel ranged from NZ$175-345, depending on the facility. Equivalent costs for a 22 m vessel ranged from NZ$620-1,480 (assuming one day of storage). The cost of water-blasting for a 12 m vessel ranged from NZ$80-85 and from NZ$180-315 for a 22 m vessel. Floerl et al. (2010a) estimated the cost of removal and return to the water for a 12 m yacht in Australia to be A$475 and the cost of biofouling removal by water-blasting to be A$100.

Based on the above sources, the cost of professional in-water cleaning is unlikely to be less than NZ$300 (plus the cost of a coastal permit where required) regardless of the level of fouling, because of mobilisation and occupational health and safety costs for the divers. The cost of haul-out and cleaning for an equivalent-sized vessel is NZ$255-430, depending on the facility. The financial advantage of professional in-water cleaning is, therefore, marginal even for low levels of fouling. In fact, some boat-maintenance companies offer special rates for haul-out and cleaning of low levels of fouling on, for example, racing yachts, further reducing any incentive to have vessels professionally cleaned in the water (Basil Hart, Dickson Marine, pers. comm.).

The commercial diving companies contacted indicated that while they do occasionally receive requests for quotes to in-water clean recreational vessels, the vessel owners generally do not take up the quote because of the cost and the need to obtain a coastal permit for the work (with associated financial costs and delays) (Sol Fergus, New Zealand Diving and Salvage Ltd, Matt Conmee, Northern Underwater Technical Services Ltd pers. comm.). It is apparently much more common for vessel owners to carry out in-water cleaning themselves, at minimal cost. In a survey of vessels arriving in New Zealand, Inglis et al. (2010) reported that manual cleaning was undertaken mostly by operators of private yachts and launches (ca 70% of vessels reporting this type of cleaning). In-water cleaning was also more likely to be carried out on yachts (and passenger liners) than other types of vessel.

More than two-thirds of the international yachts entering New Zealand surveyed by Inglis et al. (2010) reported having the hull cleaned manually at some time since their last application of antifouling paint. Almost half of arriving yachts had cleaned their hull within the month prior to arrival. This observation contrasts with a comment by the manager of a Nelson boatyard that most cleaning of recreational vessels is done when the vessel is hauled out to renew the antifouling paint, rather than between repaintings (Basil Hart, Dickson Marine Ltd, pers. comm.). This difference may reflect different practices between domestic and international recreational vessels because although Nelson is an approved port of arrival, it receives < 5% of all yachts entering New Zealand annually (Floerl et al. 2008). Dickson Marine Ltd typically receive 1-2 requests per year to haul out just for cleaning, usually for vessels that have been moored for a long time and are heavily fouled.

4.12 WHAT PROPORTION OF A COMMERCIAL VESSEL SURFACE WOULD CONSTITUTE THE NICHE AREAS?

Most commercial vessels have an “appendage factor” (i.e. ratio of the surface area of all hull appendages to total wetted surface area, TWSA) of 1.03-1.07, indicating that niche areas can be expected to represent between 3 and 7% of the TWSA (Jan Verdaasdonk, Raytheon

Australia, pers. comm.). This figure compares with a value of 6.1-7.1% of TWSA for recreational yachts estimated by Floerl et al. (2008). Coutts (1999), however, suggested that niche areas may comprise ≥ 20% of the submerged surface area of merchant vessel hulls. This figure, however, included dry-docking support strips, which would not be included in the appendage factor.

Floerl et al. (2008) estimated the percentage of the TWSA of recreational yachts represented by different niche areas, for the purpose of calculating fouling density. These were: bow thrusters 0.65%; gratings 1.22×10^{-4}%; keel 1.76%; propeller and shaft 0.66%; rudder and shaft 4.06%; hull areas devoid of antifouling (dry-docking support strips) 0.3%.

Approximate estimates of area as a percentage of TWSA can be made for some individual niches on commercial vessels, based on formulae used in vessel management (the information below is from Jan Verdaasdonk, Raytheon Australia, pers. comm.):

- **Bulbous bows** represent 6-13% of the TWSA, with higher values applying to faster vessels, although this niche would usually be included as part of the general hull area.
- The area of **propeller blades** is between 0.35-0.75 (normally ca 0.5) of the area (A_O) of the disk of the propeller diameter. The diameter of the propeller varies among different types of vessel and is also a function of the vessel's draft (T), being larger on faster vessels and those with smaller drafts:
  - General cargo ships, diameter = 0.65-0.75 T;
  - Container, LPG and other fast ships, diameter = 0.7-0.75 T;
  - Coastal trading vessels, diameter = 0.6-0.65 T; and,
  - Bulk carriers and ultra-large crude carriers, diameter = 0.4-0.45 T.
- **Bilge keel** area can be estimated from the keel length and width which, in turn, can be estimated as:
  - Length = 0.6 C_B x L;
  - Width = 0.18/(C_B – 0.2) where Cb is the block coefficient (the ratio of the volume of the hull below the water line to the volume of a rectangle equivalent to the length at the water line x beam at water line x draft) and L is the length between the perpendiculars; and,
  - C_B values vary with vessel type and hull shape and values for cargo ships are ca 0.43, for bulk carriers 0.45 and for coasters 0.76 (Watson & Gilfillan 1977).
- **Rudder** area can be estimated as K x L x T, where K is a coefficient that varies among types of vessel (Table 4.3):
  - General cargo ships, K = 1.5%;
  - Container, LPG and other fast ships, K = 1.2-1.7%;
  - Coastal trading vessels, K = 2.0-3.3%; and,
  - Bulk carriers and ultra-large crude carriers, K = 1.7%.
- There are no useful estimators for the area of **exposed propeller shafts**, but for commercial vessels the length of exposed shaft is generally very small (in contrast to military ships, where the exposed shaft length can be up to 15 m).
- There are no useful, general estimators of the area of **sea chests**.

To estimate the above areas, we used data on the dimensions of commercial vessels visiting New Zealand between 2004 and 2007 (Table 8 in Inglis et al. 2010). Given the large approximations involved in these estimates, we considered it justified to use median values for simplicity, rather than ranges of values across the large number of vessels sampled for each vessel type. Areas of individual niches ranged from 0.1-1.13% of TWSA, depending on niche and vessel type (Table 4.3). In addition, dry-docking support strips may represent 5-10% of TWSA (Coutts 1999).

Table 4.3 Estimated areas of hull niches as a percentage of total hull wetted area, (TWSA). See text for methods of estimation and definition of C_B and K. Vessel dimensions are taken from Inglis et al. (2010). 'LBP' length between perpendiculars. The estimate for bilge keels assumes one each side of the hull.

	Vessel type			
	General cargo	Container, LPG, other fast vessels	Coastal trader	Bulk carrier, ultra-large crude carrier
Median TWSA (m^2)	6,264	6,264	6,264	5,836
Median draft (m)	11	11	11	9.8
Median LBP (m)	176	176	176	167
C_B	0.43	0.43	0.76	0.46
K (%)	1.5	1.2-1.7	2.0-3.3	1.7
Bilge keels (% TWSA)	1.13	1.13	0.82	1.09
Propeller (% TWSA)	0.27-0.32	0.37-0.43	0.27-0.32	0.10-0.13
Rudder (% TWSA)	0.46	0.37-0.53	0.62-1.02	0.48

5 Chemical contamination from in-water cleaning

5.1 WHAT ARE 'ACCEPTABLE LEVELS' OF BIOCIDES?

5.1.1 Available guidelines for biocides

Question 7 asks the following:
"What conditions applied to in-water cleaning methods would ensure the management of contaminant release (chemical/biological) to acceptable levels into the surrounding environment?"

This section of the report discusses what acceptable levels in the environment are, so that the predicted environmental concentrations (PECs) modelled in following sections can be compared to these levels. Conditions to manage contaminant release are discussed in Section 5.6.

Acute criteria are provided by USEPA (1995, 2004) for copper and for TBT (Table 5.1). ANZECC (2000) provides chronic guidelines based on various levels of protection (80 to 99% of species). The ANZECC guidelines include New Zealand species and are therefore the most applicable to New Zealand.

Table 5.1 Marine water quality guidelines for antifouling compounds.

Biocide	Guideline type	Guideline value (µg/L[1])	Reference
Copper	Acute (1 hour average)	4.8	USEPA (1995)
	Chronic (4 day average)	3.1	USEPA (1995)
	ANZECC 99% protection	0.3	ANZECC (2000)
	ANZECC 95% protection	1.3	ANZECC (2000)
	ANZECC 90% protection	3	ANZECC (2000)
	ANZECC 80% protection	8	ANZECC (2000)
TBT	Acute (1 hour average)	0.42	USEPA (2004)
	Chronic (4 day average)	0.0074	USEPA (2004)
	ANZECC 99% protection	0.0004	ANZECC (2000)
	ANZECC 95% protection	0.006	ANZECC (2000)
	ANZECC 90% protection	0.02	ANZECC (2000)
	ANZECC 80% protection	0.05	ANZECC (2000)

[1] Guideline values for copper represent the dissolved fraction.

The biocides released will include both particulate and dissolved contaminants from the antifouling coatings. The guidelines above are most applicable to the dissolved component of the total biocide concentration. Furthermore, copper speciation and bioavailability is known to greatly affect its toxicity for aquatic organisms. For freshwater, the biotic ligand model has been developed to incorporate the influence of copper speciation and bioavailability in the presence of competing ions. This model provides site-specific guidelines for different freshwater bodies. However, a marine-based biotic ligand model is not available, and the freshwater model is not considered appropriate due to the differences in the properties of freshwater and marine dissolved organic carbon (which is a primary constituent in this model).

Modifications to the marine copper criteria have been suggested based on complexation of copper to organic ligands which lowers bioavailability and toxicity. Arnold (2005) proposed equations for calculating site-specific criteria for copper based on the concentration of dissolved organic carbon (DOC) in the water body. These equations were derived from toxicity of copper to the mussel *Mytilus galloprovincialis*. These equations were:

$$\textit{Chronic criterion} = 3.71 * DOC^{0.54}$$
$$\textit{Acute criterion} = 5.843 * DOC^{0.54}$$

These values have not been adopted by any regulatory agencies but may be useful in risk assessment.

The European Copper Institute (2008) has recently undertaken a voluntary risk assessment for copper which included deriving a Predicted No Effect Concentration (PNEC) for copper in marine waters. This PNEC incorporated the influence of DOC by normalising toxicity data to a standard DOC concentration prior to PNEC calculation. The calculated PNEC for dissolved copper was 5.2 µg/L, for a water body with DOC of 2 mg/L. This is very similar to Arnold's chronic criterion of 5.4 µg/L for a DOC concentration of 2 mg/L. This risk assessment has been adopted by the European Commission (European Commission 2009).

Data for DOC in New Zealand coastal waters is limited in its extent and range (Gadd et al. 2011) but the available data suggest that DOC is generally lower than 2 mg/L and is more likely closer to 1.4 mg/L (this was used as the default for all scenarios in Gadd et al. 2011 and in the present study). A chronic criterion using Arnold's equation and based on this DOC would be 4.4 µg/L. This is slightly higher than the ANZECC 90% protection guideline which is for chronic effects. An acute criterion using Arnold's equation and based on DOC of 1.4 mg/L would be 7.0 µg/L.

Although use of DOC-adjusted guidelines would provide a closer assessment of true environmental risk, there is some work required before the internationally-derived guidelines should be used in New Zealand risk assessments. Although the equations developed by Arnold (2006) are in peer-reviewed literature, they have not been adopted by any government agency as guidelines and are based on a single species (*Mytilus galloprovincialis*). There is little information to establish whether such a guideline would be protective of New Zealand marine species. The PNEC developed by the European Copper Institute (2008) and adopted by the European Commission would be useful if New Zealand species are included in the development of this PNEC but needs to be adjusted for a DOC concentration appropriate to New Zealand waters.

5.1.2 Guidelines used in this risk assessment

If in-water cleaning is undertaken irregularly (i.e. < 1 vessel per day), acute criteria for water column exposure will be the most appropriate. Elevated concentrations are not expected to persist for more than a day as tidal currents will result in dispersion, settling and dilution. In this report, acute criterion from USEPA has been used for comparisons to short-term concentrations, such as the PECs immediately surrounding vessels undergoing in-water cleaning.

Chronic criteria are more appropriate for the average biocide concentrations in the marinas or ports if in-water cleaning is carried out on a daily basis, or if there is any reason to suggest that biocides are not rapidly flushed from the marinas or ports. This aspect cannot be assessed using the MAMPEC model, which predicts steady-state concentrations only.

In the figures for PECs in marinas and ports, the PECs are compared to both 90% and 95% protection guidelines from ANZECC (as marina habitats are typically slightly or moderately disturbed or modified) which are chronic guidelines. In addition, the USEPA acute criteria are included on figures where scale allows. These guidelines and criteria are used as an initial assessment to inform the reader of the relative level of contaminant for each scenario.

For the assessment of risk (Question 6, Section 2 and in Section 5.2) both the USEPA acute criteria and the ANZECC 90% protection guideline are used for comparison to PECs within the marinas and ports following in-water cleaning. This enables the risks to be established as low, medium and high. Low risk is defined as average PEC below the ANZECC 90% protection guideline. Medium risk is defined as average PEC above the ANZECC 90% protection guideline but below the USEPA acute criteria. High risk is defined as average PEC above the USEPA acute criteria.

Although the chronic criteria may seem a stringent use, the in-water cleaning scenarios reported in the following sections assume a number of vessels are cleaned per day, rather than the in-water cleaning being a ‘one-off’ event. If the scenarios are based on a single vessel being cleaned followed by a period of no action, this criteria would be too conservative. In this study, chronic criteria have been applied to scenarios where > 0.274 are vessels cleaned per day (i.e. 1 or 2 vessels cleaned per day).

5.1.3 Incorporation of background concentrations

Biocides released from in-water cleaning will be additional to the background concentration resulting from the “normal” marina or port activity. This includes any background concentrations in the water body, passive leaching from moored vessels, stormwater discharges during wet weather, and runoff from activities on the hard stand areas adjacent to marinas and ports.

Previous modelling of the copper release from passive leaching in marinas (Gadd et al. 2011) and recent sampling in Auckland marinas suggests that in many marinas the copper concentrations already exceed the 90% protection ANZECC guideline and in some cases, the European PNEC is also exceeded (Gadd & Cameron 2012).

These background concentrations have not been taken into account in this report, however, this is an aspect that must be considered by regulatory authorities managing in-water cleaning, particularly within marinas. This will need to be undertaken on a site-specific basis. Acceptability of in-water cleaning within a port or marina will depend on the levels of copper already contained in that port or marina, as well as expected releases from in-water cleaning.

5.1.4 Summary

New Zealand uses the ANZECC (2000) water quality guidelines, which provide guidance for copper concentrations in marine waters based on chronic (long-term) exposure. Trigger values are provided for four levels of protection: protection of 99%, 95%, 90% and 80% of species. ANZECC does not provide guidelines based on acute (short-term) exposure. Furthermore, the guidelines do not account for other aspects of water quality that affect bioavailability, such as DOC.

For this risk assessment, the 90% protection guideline from ANZECC is used for chronic exposures from in-water cleaning. The acute criterion derived by the USEPA is used to assess short-term effects from in-water cleaning. These guidelines/criteria are compared to the predicted environmental concentrations (PECs). Low risk is defined as average PEC below the ANZECC 90% protection guideline. Medium risk is defined as average PEC above the ANZECC 90% protection guideline but below the USEPA acute criteria. High risk is defined as average PEC above the USEPA acute criteria.

Background concentrations of copper are not be included in the risk assessment as this must be undertaken on a site-specific basis. However, it is recognised that this is an important aspect to be considered when cleaning within marinas or ports.

5.2 WHAT ARE THE CONTAMINANT LEVELS IN THE WATER COLUMN FOLLOWING IN-WATER CLEANING?

5.2.1 Introduction

This question is answered in relation to six different scenarios of in-water cleaning as specified in the RFP (MAF 2011a):

- Hand removal (spot fouling – recreational vessels);
- Soft cloth (slime layer fouling – recreational vessels);
- Brush system (slime layer/soft fouling, full hull - commercial vessels);
- Brush system (slime layer/soft fouling, niche areas - commercial vessels);
- Brush system (Hard fouling, full hull – commercial vessels); and,
- Brush system (hard fouling, niche areas – commercial vessels).

The primary contaminant of interest for in-water cleaning is copper as this is the most common active ingredient in antifouling paints.

The copper release rates during in-water cleaning using soft cloth, soft brush systems and aggressive brush systems have been estimated following literature review and discussion with experts (Section 5.2.2). For the modelling of PECs, the model inputs used and rationale for these are provided in the following sections. The results of the modelling to answer these questions are provided in Section 5.2.8.

Hand removal of spot fouling for recreational vessels was not included in the modelled scenarios as this was not expected to result in significant copper emissions, based on the evidence for soft cleaning of the entire hull surface for recreational vessels (see modelled results in following sections).

The modelling of PECs provides the concentrations after copper release into an entire marina or port and in the absence of other berthed or moving vessels leaching copper at typical rates. The copper concentrations immediately surrounding a vessel being cleaned is also an important factor. Therefore, modelling of PECs in an area immediately surrounding a vessel and at increasing distance from the vessel was undertaken (Section 5.2.6).

5.2.2 Copper release rates

Copper release rates have been developed for commercial and recreational vessels for a range of paint types (SPC, ablative and hard) and cleaning methods (soft and aggressive).
Copper is potentially released from three sources during in-water cleaning:

1. Biofilms;
2. Leached paint layer; and,

3. Sound paint layer.

These sources each have a different concentration of copper associated with them (Section 3.6).

Copper concentrations in sound paint are the most easily assessed. A review of different paint types (Table 8.4) indicates little variability in the copper content for commercial SPC and ablative paints, but substantial variability in the recreational paints. In particular, those containing copper thiocyanate have a much lower concentration of copper. Given the variation within each paint category (SPC, ablative, hard), for the purposes of modelling, all paints are considered to contain 120 $\mu g/cm^2$ of copper (Table 5.2).

Table 5.2 Copper content of different surfaces removed during in-water cleaning.

	Recreational vessels			Commercial vessels		
Layer	SPC	Ablative	Hard	SPC	Ablative	Comments
Sound paint ($\mu g/cm^2$)	120	120	120	120	120	Fairly certain; data too variable to distinguish between paint types
Leached layer ($\mu g/cm^2$)	2.4-24	2.4-24	2.4-24	2.4-24	2.4-24	Very uncertain; assumed to be 2-20% of sound paint content
Biofilm ($\mu g/cm^2$/event)	50	100	75	25	50	Fairly uncertain

There is very little information available on the copper content of the leached layer. Lewis (1998) suggests this could be up to 20% of that of the underlying paint, however, Howell & Behrends (2006) suggests the copper concentrations could be negligible (Section 3.5.1.3). For the purposes of modelling, two copper concentrations were selected within the leached layer. These are 2 and 20% of the sound paint copper content (Table 5.2).

There is also very little information available on the copper content of the biofilm layer. Some studies suggest that the copper concentration is similar to or less than that of the leached layer (Ketchum 1952, Yebra et al. 2006). Biofilm thickness ranges from 10-40 µm. Thicker films are expected on recreational vessels compared to commercial vessels, due to their lower activity. Thicker films are also expected on ablative and hard coatings compared to SPC (Jackson & Jones 1988). Brown & Schottle (2006) measured copper release during light cleaning, which is expected to remove only biofilms. This generated around 9 and 190 $\mu g/cm^2$/event of particulate copper from 1 month fouling on the epoxy and vinyl coatings respectively, and 13 and 240 $\mu g/cm^2$/event from 3 month fouling. These latter measurements are used in the modelling to estimate the release of copper from biofilms during in-water cleaning. The values (Table 5.2) also roughly equate to a copper concentration in biofilm of 2.5 $\mu g/cm^2$ for biofilm thicknesses of 10-40 µm. This provides some further certainty in this part of the total copper estimate.

The thickness of the leached layers have been estimated for each paint type based on data on leached layer thicknesses from a study by Anderson (1993 and pers. comm.), International Coatings (1998) and the US Navy (Forbes 1996, Ingle 2006). The data indicates that this thickness increases over time as the paint ages. Values for 24 months have been used in this assessment (Table 5.3). Although no data was available for the increase of leached layer thickness over time for hard paints, Anderson (1993) provided an estimate of 75 µm. This is slightly thicker than for SPC and ablative paints, which is consistent with their mode of action.

The total removal depths during in-water cleaning are not well known. For light cleaning using a soft cloth or soft brush, a depth of 25 µm was suggested by Anderson (1993). This would be expected to remove the biofilm or slime layer and soft fouling. For more aggressive cleaning using a hard brush to remove hard fouling, Anderson (1993), Forbes (1996) and Ingle (2006) provided values of 12.5-100 µm. An upper estimate of 75 µm has been used for this assessment to provide a realistic worst-case scenario (i.e. not the worst possible case, Table 5.3).

The removal depths of the different paint components (leached layer versus sound paint) are calculated from the total removal depth and the thickness of each layer (Table 5.3). For biofilms, the entire layer is expected to be removed with both light and aggressive cleaning.

Table 5.3 Layer thickness (µm) and removal depth (µm) during in-water cleaning.

	Recreational vessels			Commercial vessels		
Layer	SPC	Ablative	Hard	SPC	Ablative	Comments
Leached layer thickness	50	60	75	50	60	Fairly certain
Light cleaning total removal depth	25	25	25	25	25	Fairly uncertain
Light cleaning leached layer removal depth	25	25	25	25	25	Fairly uncertain
Light cleaning sound paint removal depth	0	0	0	0	0	Fairly certain
Aggressive cleaning total removal depth	75	75	75	75	75	Fairly uncertain
Aggressive cleaning leached layer removal depth	50	60	75	50	60	Fairly uncertain
Aggressive cleaning sound paint removal depth	25	15	0	25	15	Fairly uncertain

The copper release is then calculated for sound paint and the leached layer from the above data using the following formula for each type of cleaning and paint type:

Copper release = copper content x depth of layer removed

Copper release from biofilms is provided per cleaning event, regardless of the type of cleaning.

The total copper release is then calculated from the above data using the following formula:

Total copper release = copper release from sound paint + copper release from leached layer + copper release from biofilms

This results in the estimates for copper release during in-water cleaning (Table 5.4). Due to the uncertainty around the concentration of copper in the leached layer, two estimates are provided for light and aggressive cleaning. We have assumed for the basis of this risk assessment that all of the “released” copper is potentially available in a dissolved form once dispersed in the surrounding water. This is considered to be conservative, as much of the copper from leached and sound paint is likely to be in particulate form. However, the fine nature and therefore large surface area of the abraded antifouling will result in greater leaching from these particulates and contribute to the anticipated high release rate of dissolved copper. The MAMPEC model then partitions the dissolved copper into particulate and dissolved phases, based on factors such as the concentration of suspended solids in the water column. The results presented in Sections 5.2.6 to 5.2.8 are based on this partitioning within the model.

Table 5.4 Summary of copper release (μg/cm²) during in-water cleaning.

	Recreational vessels			Commercial vessels	
Layer	SPC	Ablative	Hard	SPC	Ablative
Light cleaning					
Lower estimate	110	160	135	85	110
Upper estimate	650	700	675	625	650
Aggressive cleaning					
Lower estimate	3,170	2,044	255	3,145	1,994
Upper estimate	4,250	3,340	1,875	4,225	3,290

5.2.3 Emission scenarios for in-water cleaning

The copper release rates calculated for in-water cleaning, as described above, were used for the MAMPEC modelling to predict environmental concentrations (summarised in Table 5.5).

Table 5.5 Copper release rates for recreational and commercial vessels.

	Recreational vessel	Commercial vessel
Copper release from light cleaning (μg/cm²)		
SPC	110-650	85-625
Ablative	160-700	110-650
Hard	135-675	N/A
Copper release from aggressive cleaning (μg/cm²)		
SPC	N/A	3,145-4,225
Ablative	N/A	1,994-3,290
Hard	N/A	N/A

MAMPEC also requires the number of vessels and the surface area of the hulls as inputs. A number of scenarios were modelled as per the project scope (Table 5.6).

Table 5.6 Vessel numbers and surface areas for recreational and commercial vessels.

	Recreational vessel	Commercial vessel
Number of vessels treated by in-water cleaning per day	0.00274, 0.0274, 0.137, 0.274, 1, 2	0.00274, 0.0274, 0.137, 0.274, 1, 2
Vessel Surface Area – Full hull (m^2)	25, 76, 148, 269	412, 1,163, 3,231, 6,333, 10,469, 15,640
Vessel Surface Area – Sides only (m^2)	N/A	137, 388, 1,077, 2,111, 3,490, 5,213
Vessel Surface Area – Boot-tops only (m^2)	N/A	73, 163, 270, 728, 932, 1,140

N/A = Not assessed

For recreational vessels it is suggested that spot cleaning of niche areas would be mostly removing growth from unpainted areas, so there would be little or no biocide release. Therefore, this cleaning scenario was not modelled. Furthermore, not all combinations of paint type, leaching estimate, number of vessels and surface areas were modelled, as this would have resulted in 1,152 different scenarios for commercial vessels and 288 scenarios for recreational vessels. Instead, a base case was constructed and each of the parameters varied and compared to this base case. The base case was:

- Lower release rate estimate for light cleaning of ablative paints for recreational vessels and SPC paints for commercial vessels;
- 1 vessel being treated by in-water cleaning per day; and,
- Surface area of 148 m^2 for recreational vessels and 10,469 m^2 for commercial vessels.

The above values were selected to provide a 'realistic worst-case' rather than a typical case or extreme worst case. Although the lower release rate was used for the base case, modelling was also undertaken using the upper release rate to assess the influence of this value on the PECs based on the base case of vessel number and surface area. For the risk matrices, on which the final risk assessment is based, the modelling used both the lower and upper release rates to ensure that the uncertainty associated with this release rate estimate was incorporated (Section 5.2.9).

Ablative paints are considered the most common paint type for recreational vessels, whereas SPC coatings are considered the most common for commercial vessels. One vessel being cleaned per day was considered a simple default.

The surface area of 148 m^2 for recreational vessels equates to a vessel of 21-30 m. This is not the most common length for a recreational vessel in New Zealand (which would be 11-20 m or 76 m) but is a common upper length in many marinas and therefore represents a 'realistic worst-case'. The upper length/size category of 31-40 m is rare in most marinas and would represent a more extreme worst-case scenario.

The surface area of 10,469 m^2 for commercial vessels equates to a vessel of 200-250 m. Again, this is not the most common length for a commercial vessel in New Zealand ports but this is a common upper length in many ports and therefore represents a 'realistic worst-case'. The upper length/size category of 250-300 m is rare in most ports and would represent a more extreme worst-case scenario.

Low flushing locations (Half Moon Bay Marina and Lyttelton Port) and high flushing locations (Westhaven Marina and Auckland Port) were modelled to take this factor into account with respect to clearance of chemical inputs from in-water cleaning (Gadd et al.

2011). Scenarios from Lyttelton Port and Half Moon Bay Marina are the most conservative estimates of risk because of their enclosed natures. Therefore, from the perspective of chemical contamination, cleaning scenarios acceptable in these locations are likely to be acceptable at all other ports and marinas, respectively (i.e. these locations represents realistic worst cases, Gadd et al. 2011).

The default emissions for Half Moon Bay and Westhaven marinas and for Lyttelton Port and Port of Auckland are shown in Table 5.7 and Table 5.8 . Vessel numbers were taken from Gadd et al. (2011). For the two ports, average numbers per day were estimated by summing the total number of days vessels of each size category were in the port during a year, then dividing this by the number of days in a year. Table 5.7 and Table 5.9 also indicate the vessel lengths associated with the surface areas required in Table 5.6.

Table 5.7 Vessel surface areas and numbers for Half Moon Bay and Westhaven marinas.

	5-11 m	11-20 m	21-30 m	31-40 m	Total vessels
Surface area (m^2)	25	76	148	269	
Half Moon Bay Marina	248	247	5	0	500
Westhaven Marina	596	862	31	3	1,491

Table 5.8 Vessel surface areas and numbers for Lyttelton Port and Port of Auckland[a].

	< 50 m	50-100 m	100-150 m	150-200 m	200-250 m	250-300 m
Surface area (m^2)	412[a,b]	1,163	3,231	6,333	10,469	15,640
Lyttelton						
In berth	5.5	4.9	1.7	2.4	0.9	0
Moving	0.1	0.2	0.2	0.3	0.2	0.1
Auckland						
In berth	4.6	3.8	3.9	4.3	1.5	0.2
Moving	0.2	0.2	0.3	0.4	0.2	0.1

Notes: [a] Vessel numbers are average numbers per day, derived from total number of vessels per year. [b] This is from OECD (2005) based on the Holtrop equation. For length classes greater than 50 m, the default values from the OECD (2005) Emission Scenario Document were used.

5.2.4 MAMPEC model set-up

The primary contaminant of concern with respect to in-water cleaning is copper. The characteristics of copper are shown in Table 5.9.

Table 5.9 Compound inputs for the MAMPEC model.

Compound name	Copper (total)
Metal/organic compound	Metal
Molecular mass	63.5
Saturated vapour pressure at 20°C	0.0 E + 00
Solubility at 20°C	1.0 E -03
Depth and 24 h averaged degradation rates (units d^{-1})	
In water – abiotic – at 20°C	N/A
In sediment – abiotic – at 20°C	N/A
In water – photolytic – at 20°C	N/A
In sediment – photolytic – at 20°C	N/A
In water – biological – at 20°C	N/A
In sediment – biological – at 20°C	N/A
Parameters describing partitioning	
Kd (for metals only)	30.0

The brief for this project (Section 2, MAF 2011a) required that release scenarios and predicted environmental concentrations were calculated for four scenarios: Lyttelton Port, Port of Auckland, Westhaven Marina and Half Moon Bay Marina. The release scenarios were outlined in the previous section and relate to commercial vessels for Auckland and Lyttelton ports, and recreational vessels for Westhaven and Half Moon Bay marinas.

The harbour and marina dimensions, flow velocities and water quality used in the modelling for this project are as used in the EPA project (Gadd et al. 2011, Table 5.10).

Table 5.10 Environment set-up for ports and marinas used in this study.

Condition	Half Moon Bay	Westhaven	Lyttelton	Auckland
x2: Nominal length (m)	310	1,050	870	2,030
x1: Distance from mouth (m)	470	1,575	1,305	3,045
y1: Nominal width (m)	250	540	410	520
y2: Width of estuary mouth (m)	250	540	410	520
Depth (m)	4	5.5	12.3	12
Mouth width (x3, m)	30	70	170	2,030
Flow velocity (m/s)	0.36	0.14	0.22	0.09
Tidal period (h)	12.41	12.41	12.41	12.41
Silt/SS conc. (mg/L)	9.7	6.6	17	6.6
POC conc. (mg/L)	1.4	0.9	2.38	0.94
DOC conc. (mg/L)	1.4	1.4	1.4	1.4
Chlorophyll (µg/L)	2.3	2.3	2.6	2.3
Salinity (ppt)	32	33	32.3	33
Temp. (ºC)	17	17	14	17
Latitude (degrees)	-37	-37	-44	-37

pH	8.1	8.1	8	8.1
Tidal difference (m)	2	3	1.8	2.3
Density difference of tide (kg/m^3)	0.1	0.1	0.4	0.4
Non tidal daily water level change (m)	0	0	0	0
Discharges into harbour (m^3/s)	0	0	0	0
Density diff. of discharges (kg/m^3)	N/A	N/A	0	0
Depth in harbour entrance (m)	4	5.5	13.7	10
Height of submerged dam (m)	0	0	0	0
Width of submerged dam (m)	0	0	0	0
Exchange volume (m^3/tide)	1.3×10^5	1.7×10^6		
Volume exchanged per tide (%)	38	55		

In addition to the environments described above which assumes mixing of the emissions from in-water cleaning in the entire marina or port, small box models were set up to predict concentrations immediately around the vessel being cleaned. The lengths and widths of these box models were approximately equal to the size of the actual vessel being cleaned (with some rounding up). The inputs for these models are shown in Table 5.11. For the recreational vessel scenario, the water quality characteristics required by the model were the same as for Westhaven Marina. For the commercial vessel scenario, the water quality characteristics required by the model were the same as for Port of Auckland. These two were selected as the water quality aspects were expected to result in the greatest proportion of copper in dissolved form.

Table 5.11 Environment set-up for modelling PECs immediately around recreational and commercial vessels during in-water cleaning.
Shaded rows are those changed from the Westhaven and Auckland scenarios (Gadd et al. 2011).

Condition	Recreational vessel	Commercial vessel
x2: Nominal length (m)	25	250
x1: Distance from mouth (m)	37.5	375
y1: Nominal width (m)	10	50
y2: Width of estuary mouth (m)	10	50
Depth (m)	5.5	12
Mouth width (x3, m)	25	250
Flow velocity (m/s)	0.01	0.01
Tidal period (h)	12.41	12.41
Silt/SS conc. (mg/L)	6.6	6.6
POC conc. (mg/L)	0.9	0.94
DOC conc. (mg/L)	1.4	1.4
Chlorophyll (µg/L)	2.3	2.3
Salinity (ppt)	33	33
Temp. (ºC)	17	17
Latitude (degrees)	-37	-37
pH	8.1	8.1
Tidal difference (m)	0	0
Density difference of tide (kg/m^3)	0	0
Non-tidal daily water level change (m)	0	0
Discharges into harbour (m^3/s)	0	0
Density diff. of discharges (kg/m^3)	N/A	0
Depth in harbour entrance (m)	5.5	10
Height of submerged dam (m)	0	0
Width of submerged dam (m)	0	0
Exchange volume (m^3/tide)	1.7 x 10^6	
Volume exchanged per tide (%)	55	

5.2.5 Total emissions

The total emission rates for recreational and commercial vessels undergoing in-water cleaning were compared to the emissions from the model marinas (Half Moon Bay and Westhaven) and ports (Lyttelton and Auckland) (Table 5.12 and Table 5.13, respectively). For recreational vessels the emission rates are substantially lower from in-water cleaning than for typical leaching.

The total copper emissions during in-water cleaning of recreational vessels are up to 1 kg based on an upper estimate of release from ablative paints. The total copper emissions for commercial vessels are up to 300 kg for aggressive in-water cleaning. Whilst this may appear to be unrealistic, a vessel may have over a tonne of copper in the paint on its hull.

Table 5.12 Comparison of total emission rates for recreational vessels from different in-water cleaning scenarios.

In-water cleaning scenario					Total emission rates (g/d)
Vessel size class (m)	Vessel surface area (m^2)	No. vessels being cleaned	Paint type	Cleaning type	
Different vessel sizes					
5-10	25	1	Ablative-low	Soft	40
11-20	76	1	Ablative-low	Soft	122
21-30	148	1	Ablative-low	Soft	237
31-40	269	1	Ablative-low	Soft	430
Different vessel numbers					
21-30	148	0.00274	Ablative-low	Soft	0.65
21-30	148	0.0274	Ablative-low	Soft	6.5
21-30	148	0.137	Ablative-low	Soft	32
21-30	148	0.274	Ablative-low	Soft	65
21-30	148	1	Ablative-low	Soft	237
21-30	148	2	Ablative-low	Soft	474
Different paint type					
21-30	148	1	SPC-low	Soft	163
21-30	148	1	Ablative-low	Soft	237
21-30	148	1	Hard-low	Soft	200
Upper release estimate					
21-30	148	1	SPC-high	Soft	962
21-30	148	1	Ablative-high	Soft	1,036
21-30	148	1	Hard-high	Soft	999
Half Moon Bay Marina					2,003
Westhaven Marina					6,684

Table 5.13 Comparison of total emission rates for commercial vessels from different in-water cleaning scenarios.

In-water cleaning scenario					Total emission rates (g/d)
Vessel size class (m)	Vessel surface area (m^2)	No. vessels being cleaned	Paint type	Cleaning type	
Different number of vessels					
200-250	10,469	0.00274	SPC-low	Soft	24
200-250	10,469	0.0274	SPC-low	Soft	244
200-250	10,469	0.137	SPC-low	Soft	1,219
200-250	10,469	0.274	SPC-low	Soft	2,438
200-250	10,469	1	SPC-low	Soft	8,899
200-250	10,469	2	SPC-low	Soft	17,797

In-water cleaning scenario					Total emission rates (g/d)
Vessel size class (m)	Vessel surface area (m^2)	No. vessels being cleaned	Paint type	Cleaning type	
Different vessel sizes					
< 50	412	1	SPC-low	Soft	350
50-100	1,163	1	SPC-low	Soft	989
100-150	3,231	1	SPC-low	Soft	2,746
150-200	6,333	1	SPC-low	Soft	5,383
200-250	10,469	1	SPC-low	Soft	8,899
250-300	15,640	1	SPC-low	Soft	13,294
Sides only					
< 50	137	1	SPC-low	Soft – sides	116
50-100	388	1	SPC-low	Soft – sides	330
100-150	1,077	1	SPC-low	Soft – sides	915
150-200	2,111	1	SPC-low	Soft – sides	1,794
200-250	3,490	1	SPC-low	Soft – sides	2,967
250-300	5,213	1	SPC-low	Soft – sides	4,431
Boot-tops only					
< 50	73	1	SPC-low	Soft – boot-tops	62
50-100	163	1	SPC-low	Soft – boot-tops	139
100-150	270	1	SPC-low	Soft – boot-tops	230
150-200	728	1	SPC-low	Soft – boot-tops	619
200-250	932	1	SPC-low	Soft – boot-tops	792
250-300	1,140	1	SPC-low	Soft – boot-tops	969
Different paint types					
200-250	10,469	1	SPC-low	Soft	8,899
200-250	10,469	1	Ablative-low	Soft	11,516
Upper release estimate					
200-250	10,469	1	SPC-high	Soft	65,431
200-250	10,469	1	Ablative-high	Soft	68,049
Different cleaning methods					
200-250	10,469	1	SPC-low	Aggressive	329,250
200-250	10,469	1	SPC-high	Aggressive	442,315
200-250	10,469	1	Ablative-low	Aggressive	208,752
200-250	10,469	1	Ablative-high	Aggressive	344,430
Lyttelton Port					2,966
Port of Auckland					5,062

5.2.6 PECs immediately surrounding vessels

5.2.6.1 Introduction

To provide an upper estimate of the concentrations that may be expected in the marine environment, PECs were calculated for the area immediately surrounding a vessel undergoing in-water cleaning. This region would be considered the “mixing zone” in relation to an assessment of a wastewater discharge to the receiving environment. In this section, all PECs are compared to acute guidelines as these concentrations are expected to rapidly decrease over time due to mixing from tidal currents and hydrodynamic exchange.

The scenarios modelled below are for the following base case:

- 1 vessel being treated by in-water cleaning per day;
- surface area of 10,469 m^2 for commercial vessels and 148 m^2 for recreational vessels;
- full hull being cleaned;
- lower release rate estimate for ablative paints for recreational vessels and SPC paints for commercial vessels;
- light cleaning methods; and,
- an area of 10 m wide by 25 m long by 4 m deep for a recreational vessel and 50 m wide by 250 m long by 12 m deep for a commercial vessel.

The plots shown in the following sections are for MAMPEC modelled concentrations that assume all of the copper in the removed biofilm and paint is initially dissolved, with subsequent partitioning of the copper to the particulate matter in marina or harbour resulting in the residual “dissolved” fraction. Total copper PECs are shown in each figure followed by dissolved PECs.

5.2.6.2 PECs

The PECs in areas immediately surrounding the vessels (Figures 5.1-5.3) are substantially higher than those from typical leaching and much higher than the acute criterion.

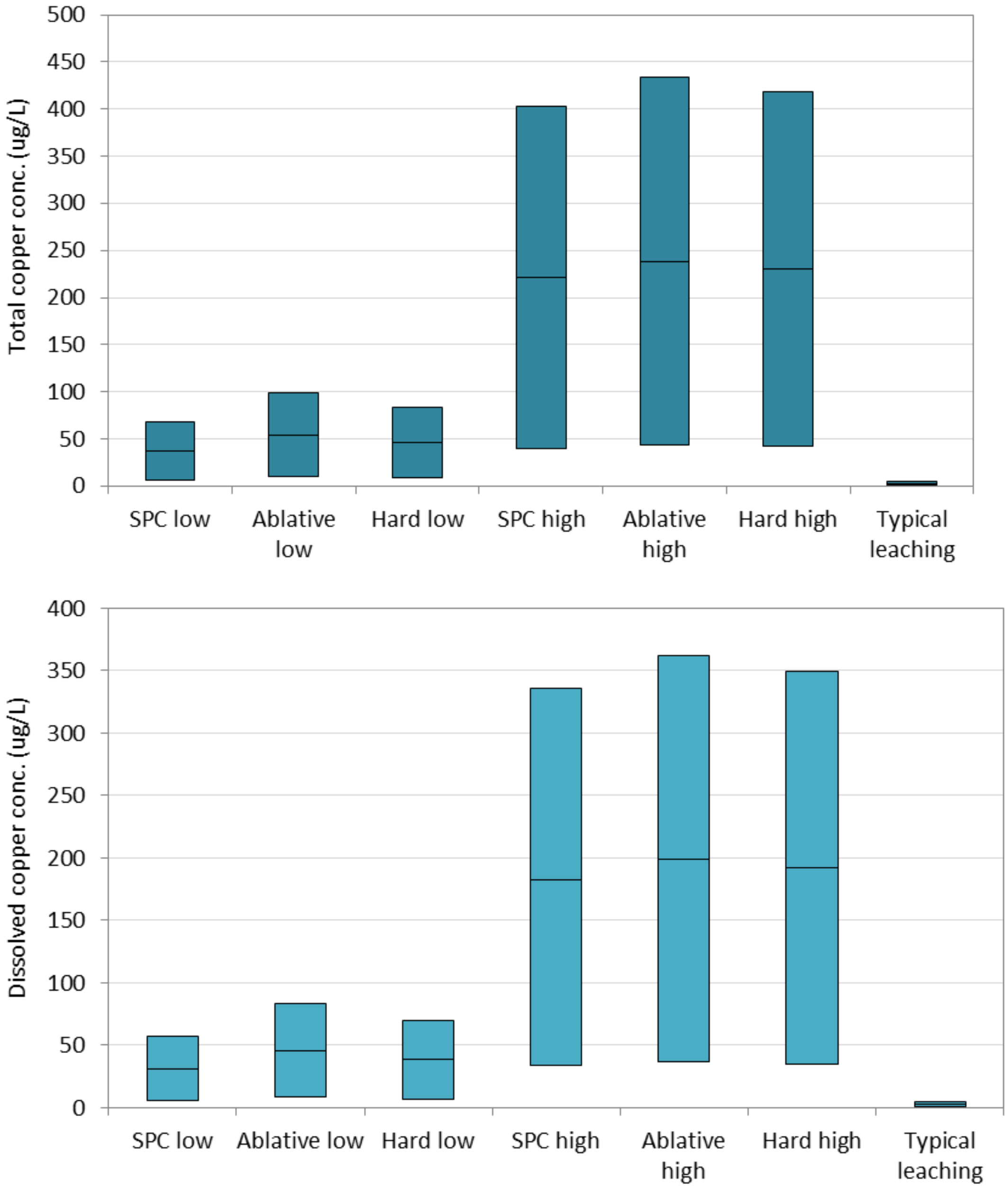

Figure 5.1 Total and dissolved copper PECs in an area directly around a recreational vessel during in-water cleaning with varying paint types and varying release estimates. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

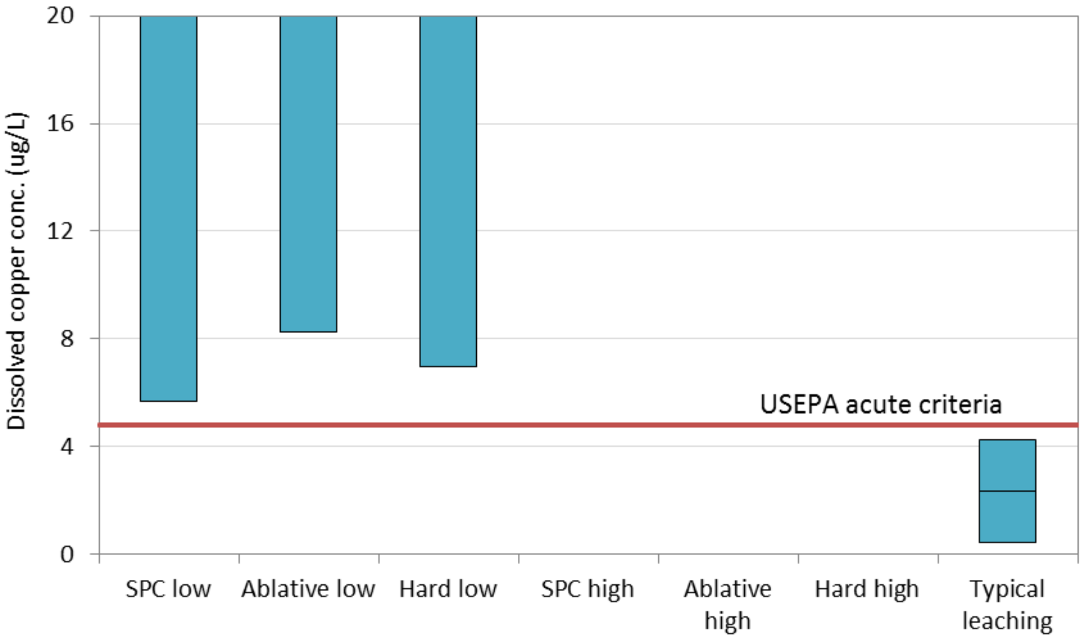

Figure 5.2 Comparison of USEPA acute criteria and dissolved copper PECs in an area directly around a recreational vessel during in-water cleaning with varying paint types and varying release estimates. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

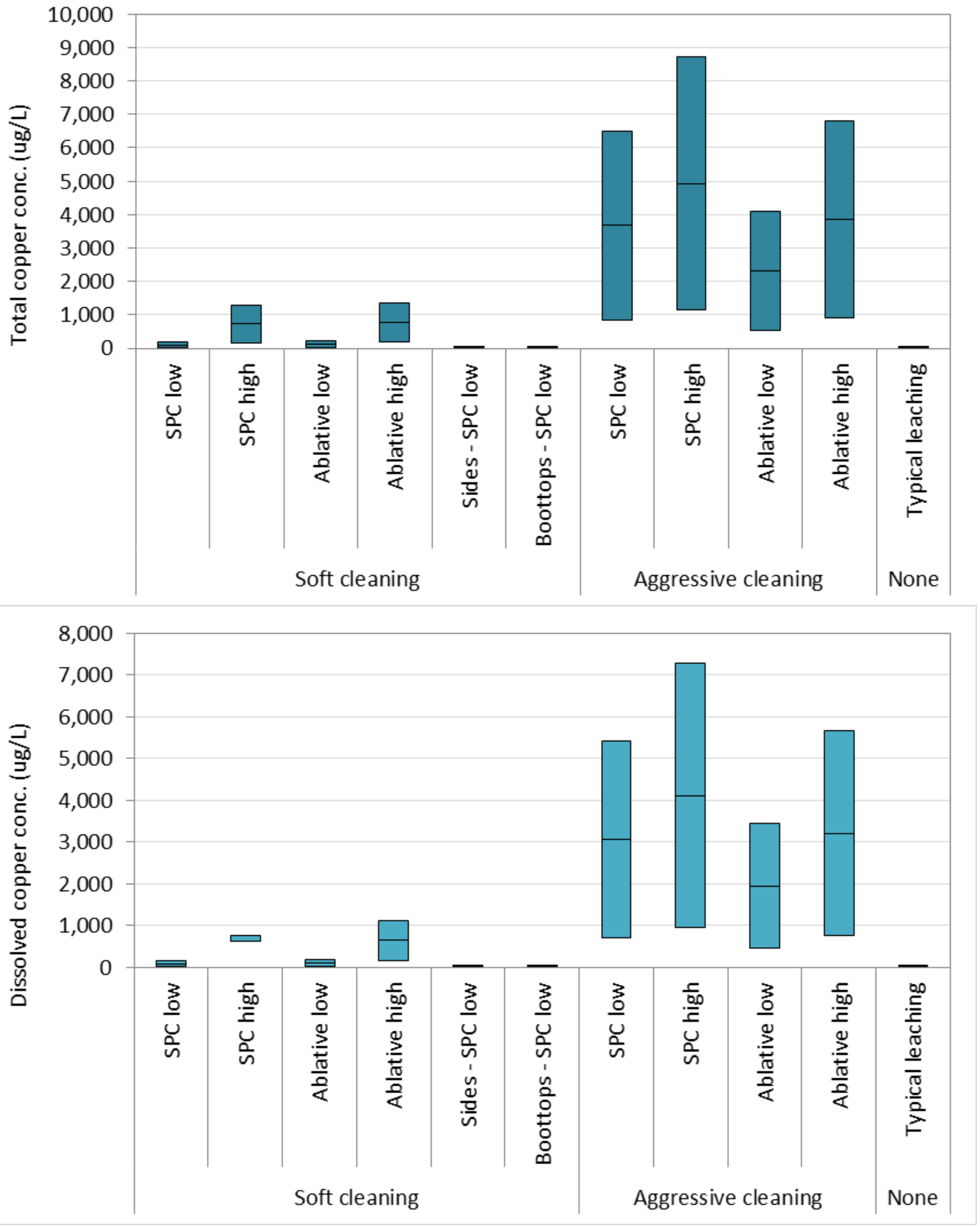

Figure 5.3 Total and dissolved copper PECs in an area directly around a commercial vessel during in-water cleaning with varying paint types and varying release estimates. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

5.2.7 Decrease in PECs with distance

For a subset of the scenarios above, the decrease in PECs with distance from the vessel was modelled (Figure 5.4, Figure 5.5). The results for recreational vessels are not presented here as the model predictions were approximately 100-fold lower for the surrounding area than for the lowest marina concentration. This is due to the different set-up for a marina (on the open coast) compared to a commercial harbour (within an estuary). For the purposes of this section, the decrease in PECs with distance from a vessels being cleaned in an enclosed body of water such as an estuary is considered more appropriate than the decrease if a vessel is cleaned on the open coast.

For soft cleaning of commercial vessels and a lower release estimate (SPC or ablative paints), the dissolved copper concentration exceeds the USEPA acute criteria for a distance of 50-140 m from the vessel being cleaned (Figure 5.4).

For a vessel 10,469 m^2, cleaning the sides only or the boot-tops only does not result in exceedance of the acute criteria outside the immediate zone of cleaning (SPC paint, lower release estimate, Figure 5.4).

For aggressive cleaning, copper concentrations more than 350 m from the vessel being cleaned remain well above the acute criteria (Figure 5.5).

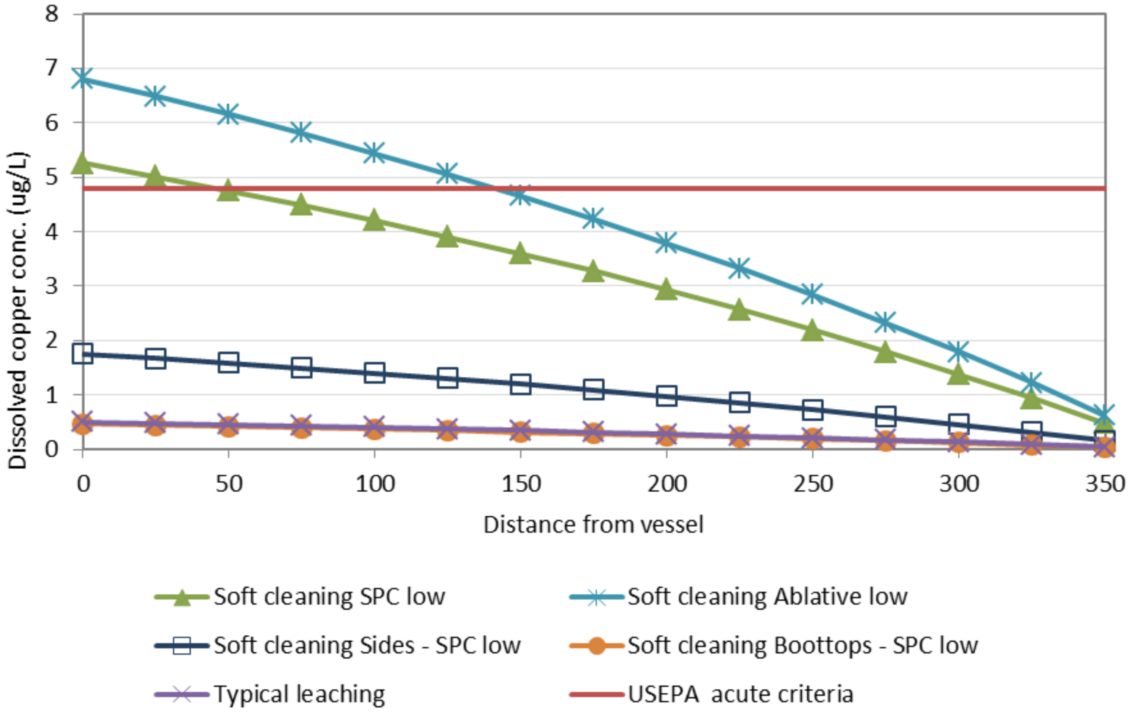

Figure 5.4 Decrease in total copper PECs with distance from a commercial vessel during soft in-water cleaning with varying paint types and different niche areas compared to typical leaching.

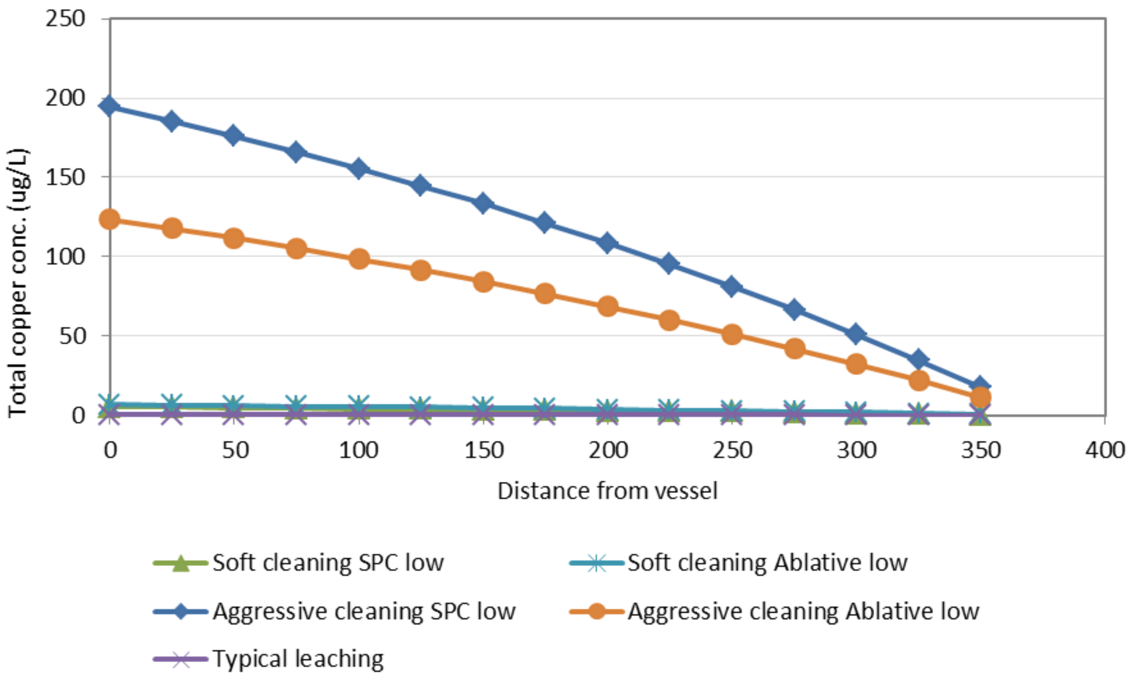

Figure 5.5 Decrease in total copper PECs with distance from a commercial vessel during aggressive in-water cleaning with varying paint types and varying cleaning methods compared to typical leaching.

5.2.8 PECs in marina and ports with in-water cleaning

5.2.8.1 Introduction

The results in this section are for a vessel being cleaned within a port or marina and in the absence of other vessels in that marina. The PECs are based on copper release over the course of a day and assume mixing within the marina due to tidal currents and hydrodynamic exchange. These results, therefore, do not represent the concentrations immediately around the vessel being cleaned.

The scenarios modelled below are for the following base case:

- 1 vessel being treated by in-water cleaning per day;
- surface area of 10,469 m^2 for commercial vessels and 148 m^2 for recreational vessels;
- full hull being cleaned;
- lower release rate estimate for ablative paints for recreational vessels and SPC paints for commercial vessels; and,
- light cleaning methods.

Factors such as vessel numbers, size (surface area), cleaning of niche areas, paint type and cleaning methods are varied in each section to see the effect on PECs.

The plots shown in the following sections are for MAM-PEC modelled concentrations assuming all of the copper in the removed biofilm and paint is initially dissolved, with subsequent partitioning of the copper to the particulate matter in marina or harbour resulting in the residual “dissolved” fraction. Total copper PECs are shown in each figure followed by dissolved PECs. Plots for dissolved PECs are compared to both acute criteria and chronic guidelines.

5.2.8.2 Number of vessels being cleaned

The average daily number of vessels being cleaned had a large influence on PECs, particularly in Half Moon Bay Marina (for recreational vessels) and in Lyttelton Port (for commercial vessels). In Half Moon Bay Marina up to one recreational vessel of 148 m^2 can be cleaned per day for the PECs to remain below all guideline values (Figure 5.6). Cleaning two vessels per day resulted in exceedance of the 95% guideline (for chronic exposure) but not the 90% guideline or acute criterion.

In Lyttelton Port less than one commercial vessel of 10,469 m^2 can be cleaned per day for the PECs to remain below all guideline values (Figure 5.7). The 95% guideline was exceeded when one vessel was cleaned per day. The 90% and 95% guidelines and the acute criterion were exceeded when two vessels were cleaned per day.

In Westhaven Marina and the Port of Auckland, the PECs will remain below all guideline values when up to, and including, two vessels are cleaned per day. It is noted that these scenarios are for vessels 148 and 10,469 m^2 and include the use of light cleaning methods and assumed a lower estimate for paint leaching.

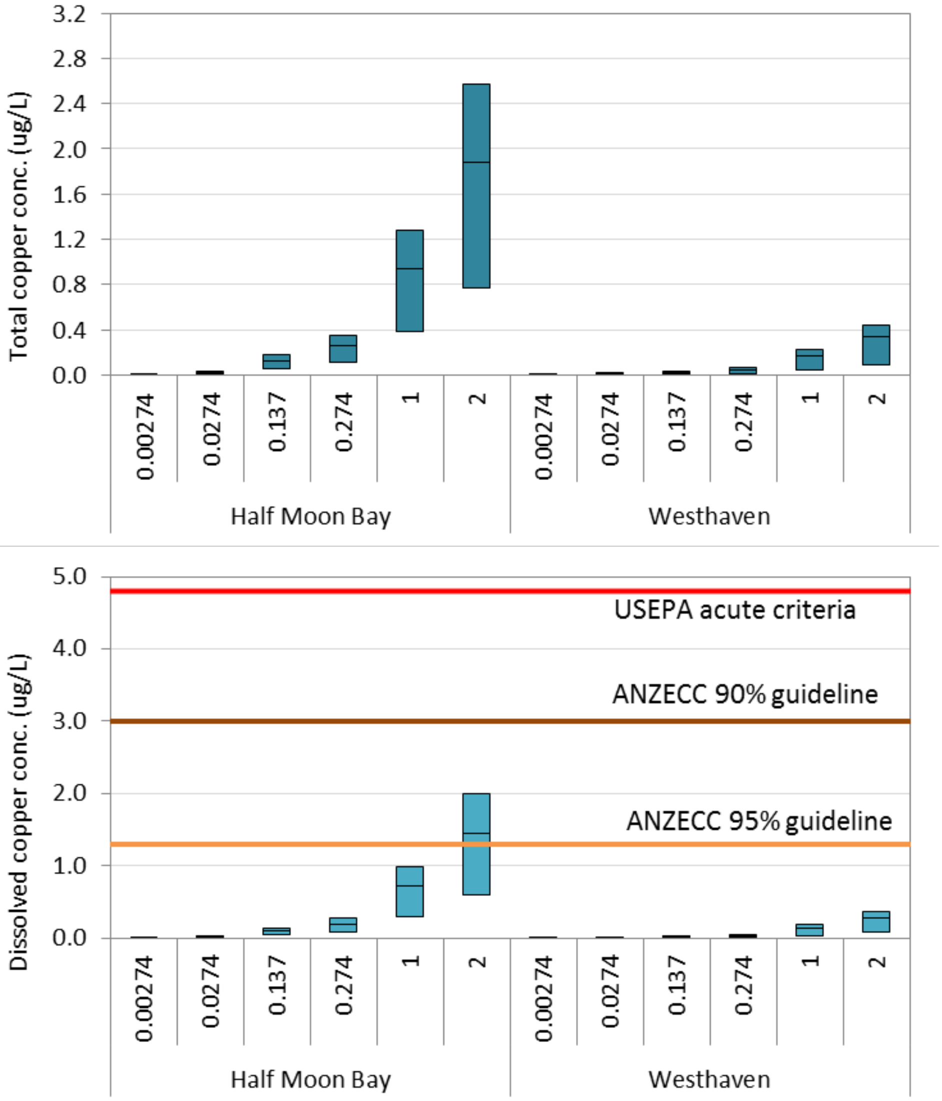

Figure 5.6 Total and dissolved copper PECs in Half Moon Bay and Westhaven marinas after in-water cleaning of varying numbers of vessels. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

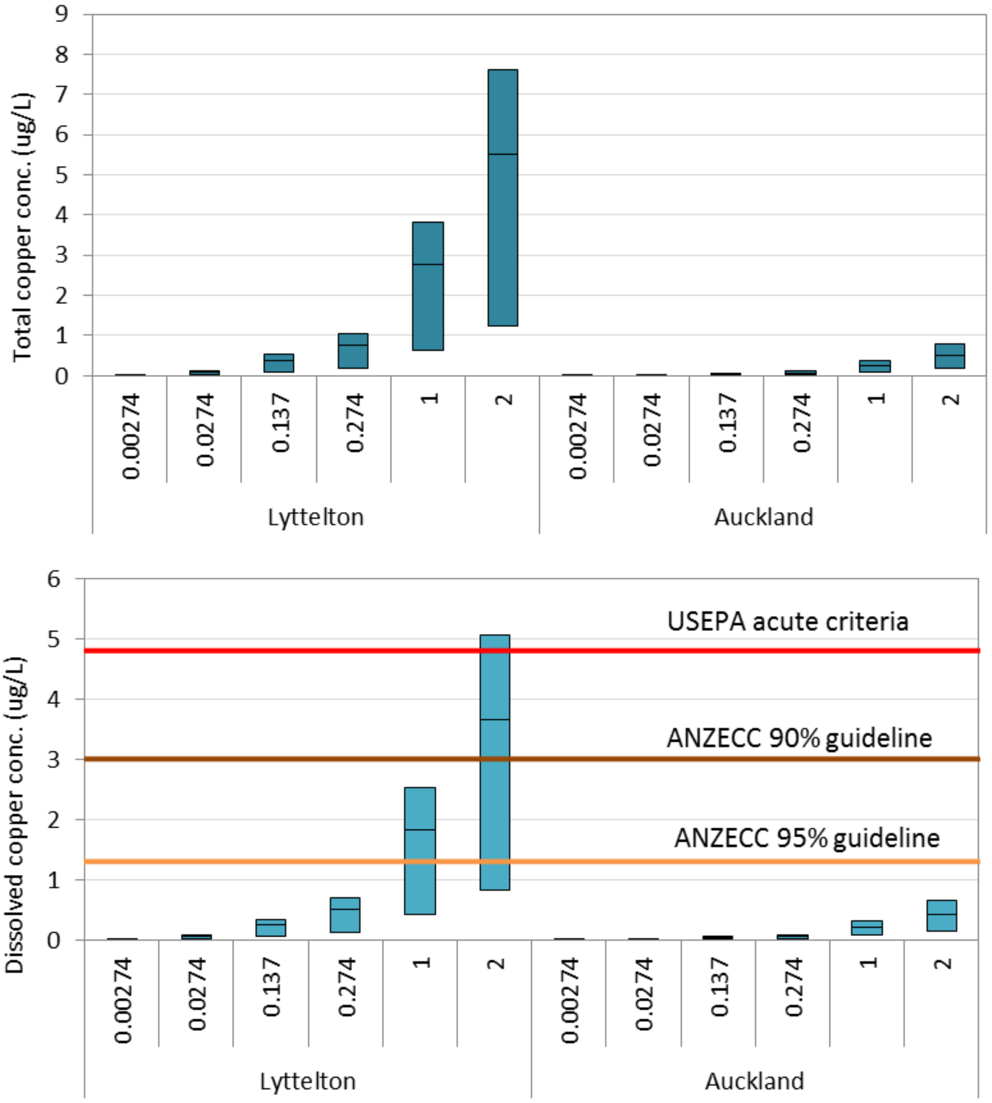

Figure 5.7 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning of varying numbers of vessels. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

5.2.8.3 Vessel size

The size of vessels being cleaned also has a large influence on the PECs, again particularly in Half Moon Bay Marina (for recreational vessels) and in Lyttelton Port (for commercial vessels). In Half Moon Bay Marina, cleaning one recreational vessel of 269 m^2 resulted in the PECs exceeding the 95% guideline but not the 90% guideline or acute criterion (Figure 5.8). In Westhaven Marina, the PECs remained below all guideline values regardless of the size of recreational vessel cleaned.

In Lyttelton Port, the cleaning of commercial vessels 6,333 m^2 resulted in the PECs exceeding the 90% and 95% guideline values (Figure 5.9). However, the acute criterion is not expected to be exceeded even when cleaning the largest vessels. In Port of Auckland, the PECs remained below all guideline values regardless of the size of commercial vessel cleaned.

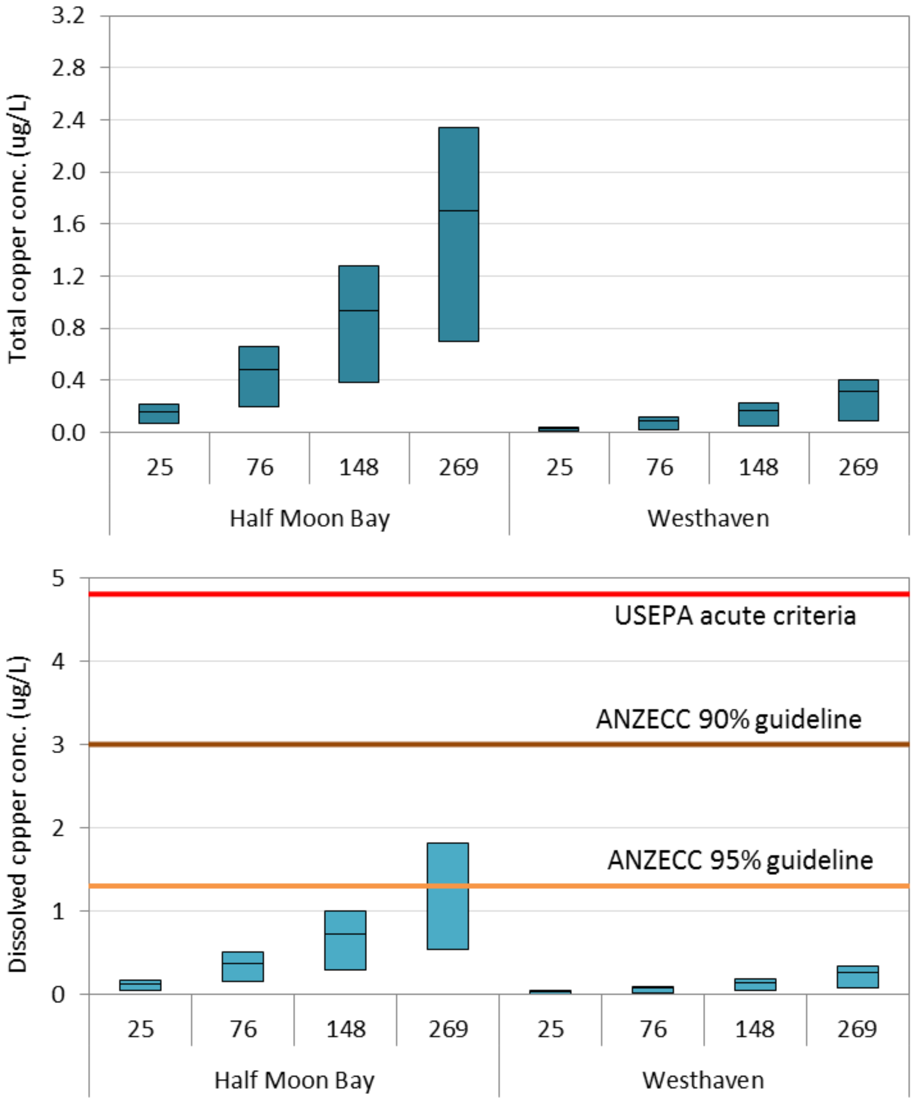

Figure 5.8 Total and dissolved copper PECs in Half Moon Bay and Westhaven marinas after in-water cleaning from a vessel of varying surface area. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC. See Table 5.7 for length and surface area summary.

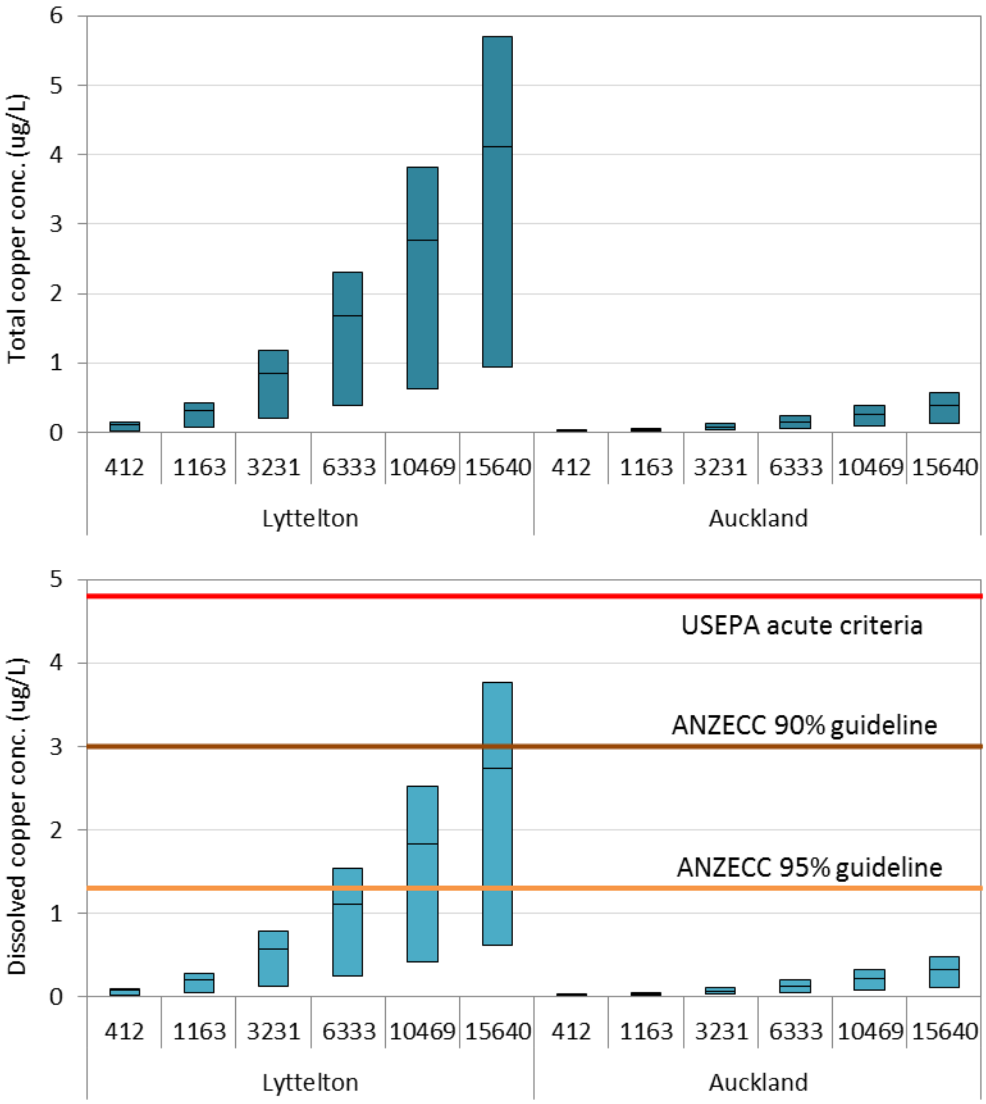

Figure 5.9 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning from vessels of varying surface area. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC. See Table 5.8 for length and surface area summary.

5.2.8.4 Niche areas

Cleaning of niche areas of recreational vessels was not modelled as niche areas do not often have antifouling paint applied and therefore little or no release of biocides would be emitted. Furthermore, hand removal of spot fouling from the hull is not expected to cause significant copper emissions, based on the evidence for soft cleaning of the entire hull surface for recreational vessels (see modelled results in previous sections).

For commercial vessels it is possible that only niche areas, such as the boot-tops or sides of the vessel, will be cleaned in-water. This has a large influence on the PECs, again particularly in Lyttelton Port. Whilst cleaning the full hull in Lyttelton Port would result in PECs exceeding the 95% guideline value (Figure 5.10), cleaning the sides only (Figure 5.11) or boot-tops only (Figure 5.12) will not. In Port of Auckland, the PECs remained below all guideline values regardless of the area of commercial vessel cleaned.

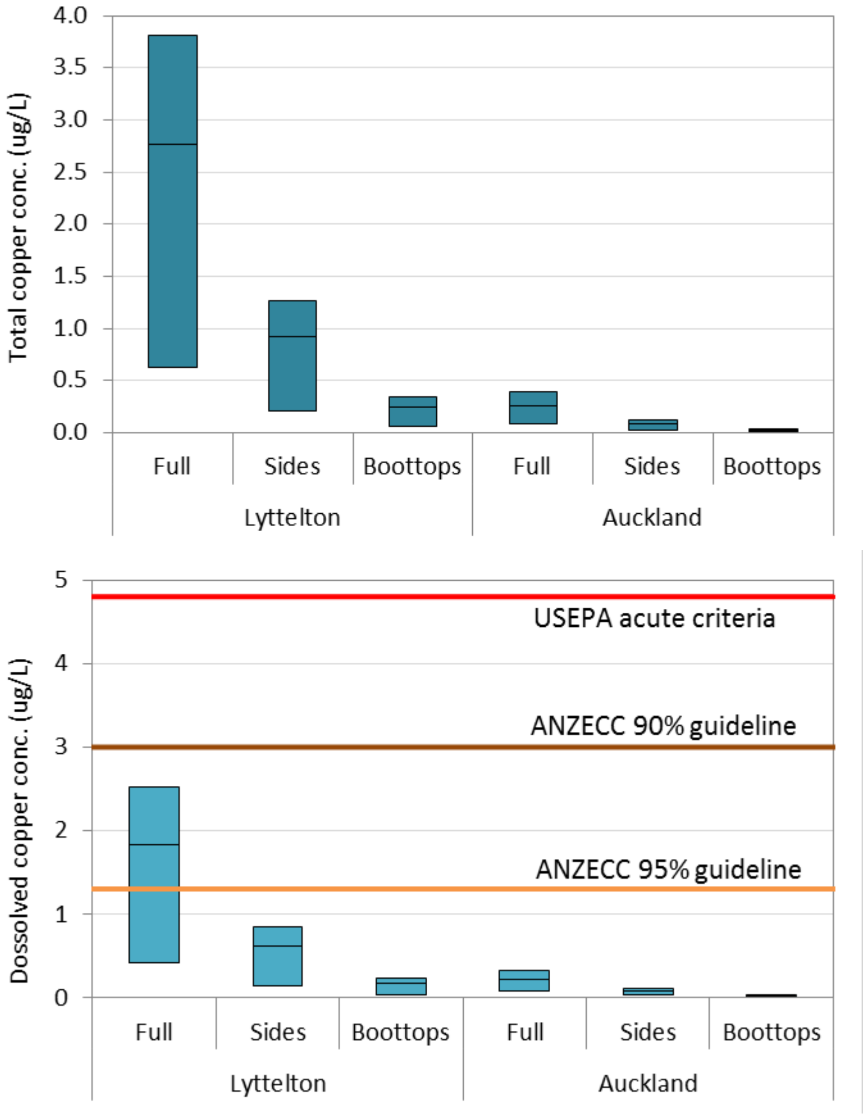

Figure 5.10 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning of various niche areas. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

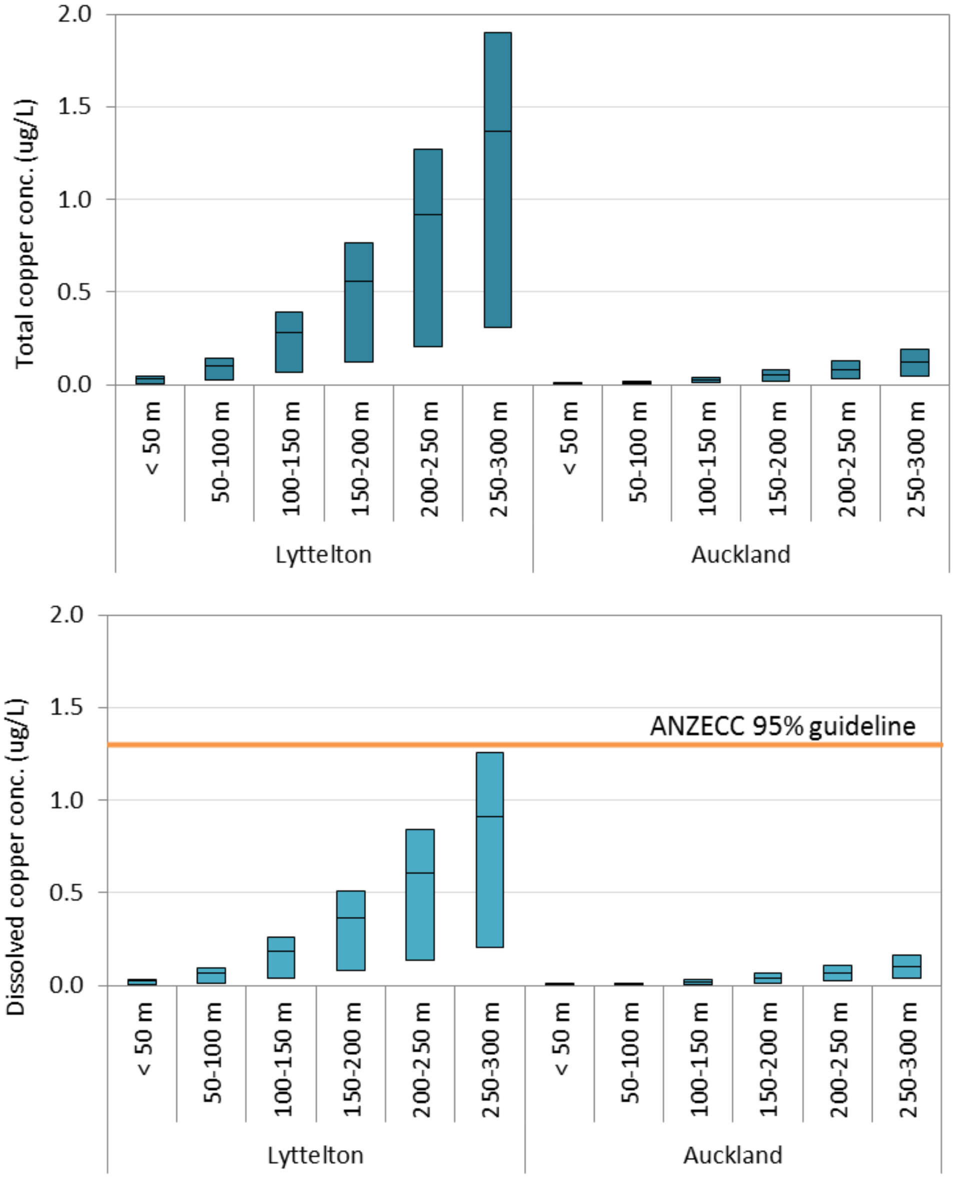

Figure 5.11 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning from vessel sides only. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC. USEPA acute criterion and ANZECC 90% guideline not shown at this scale.

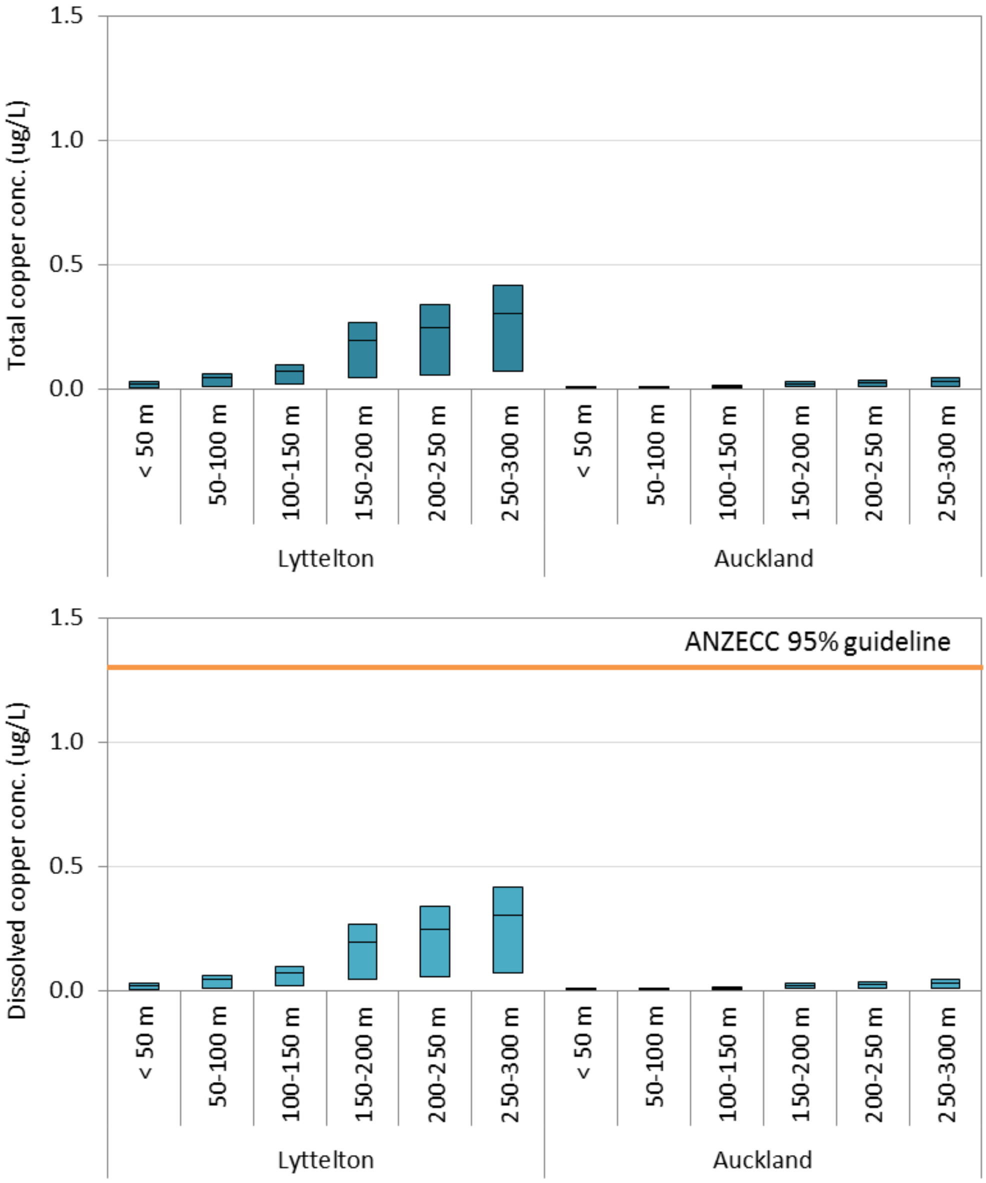

Figure 5.12 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning from vessel boot-tops only. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC. USEPA acute criterion and ANZECC 90% guideline not shown at this scale.

5.2.8.5 Paint type/Leached layer

The paint type has only a minor influence on the PECs for both recreational (Figure 5.13) and commercial vessels (Figure 5.14). However, as there is considerable uncertainty around the estimate of copper in the leached layer, an upper estimate for the total release rate was also modelled. This has a very significant influence on the range of PECs for a given paint scenario. In Half Moon Bay Marina cleaning a single recreational vessel 148 m^2 resulted in exceedance of both the 95% and 90% guideline values but not the acute criterion. In Westhaven Marina the PECs remained below the guideline values, however had increased 5-fold when based on the upper estimate.

In Lyttelton Port, based on the upper release estimate, cleaning one commercial vessel of 10,469 m^2 resulted in exceedance of the 90% guideline value by the minimum PEC (Figure 5.14). Exceedance of the acute criterion was also expected within the harbour. Significantly, at the Port of Auckland, where all previous modelling showed no guideline exceedance, use of the upper estimate resulted in exceedance of the 90% guideline value after cleaning a single commercial vessel.

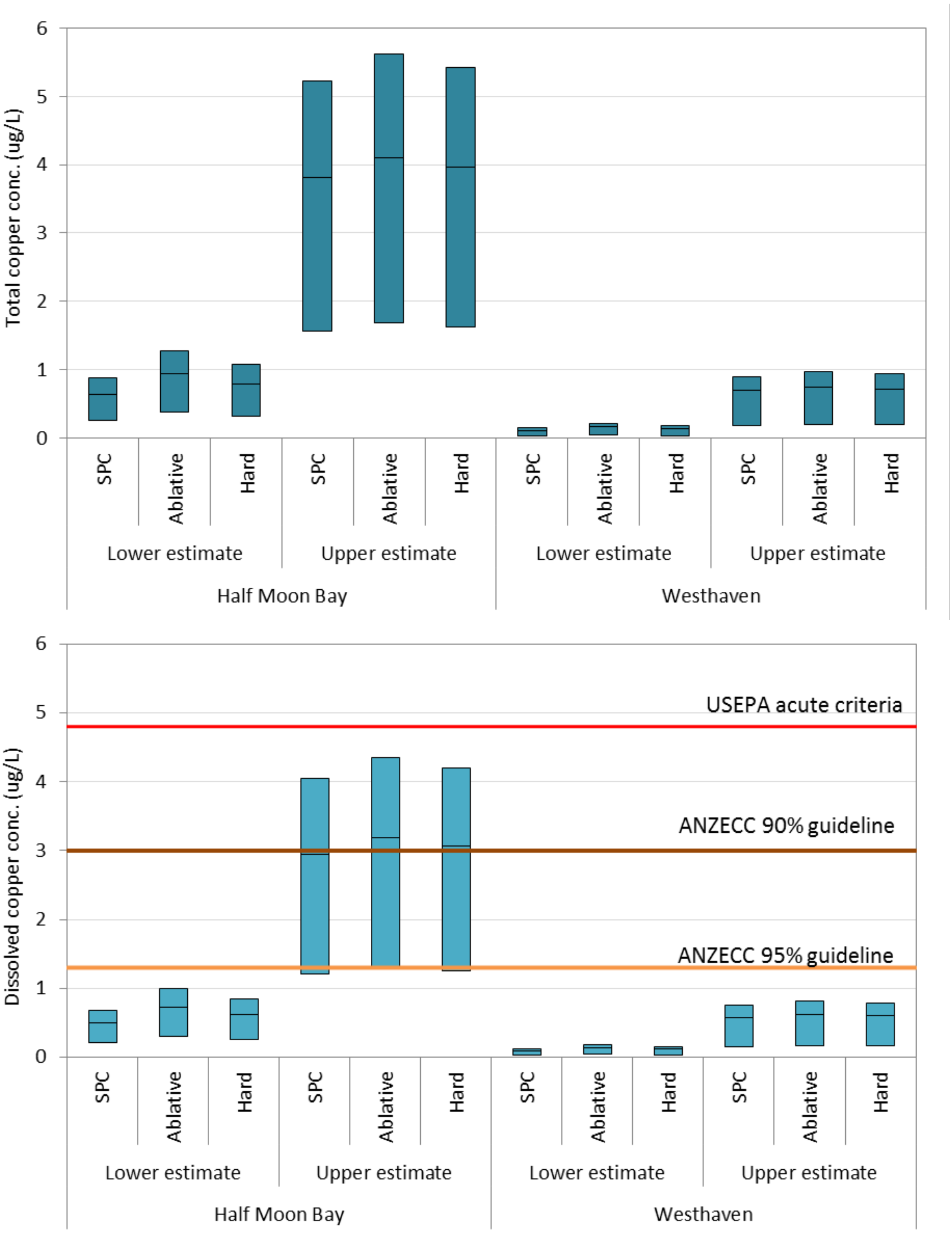

Figure 5.13 Total and dissolved copper PECs in Half Moon Bay and Westhaven marinas after in-water cleaning from a vessel of with varying paint types. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

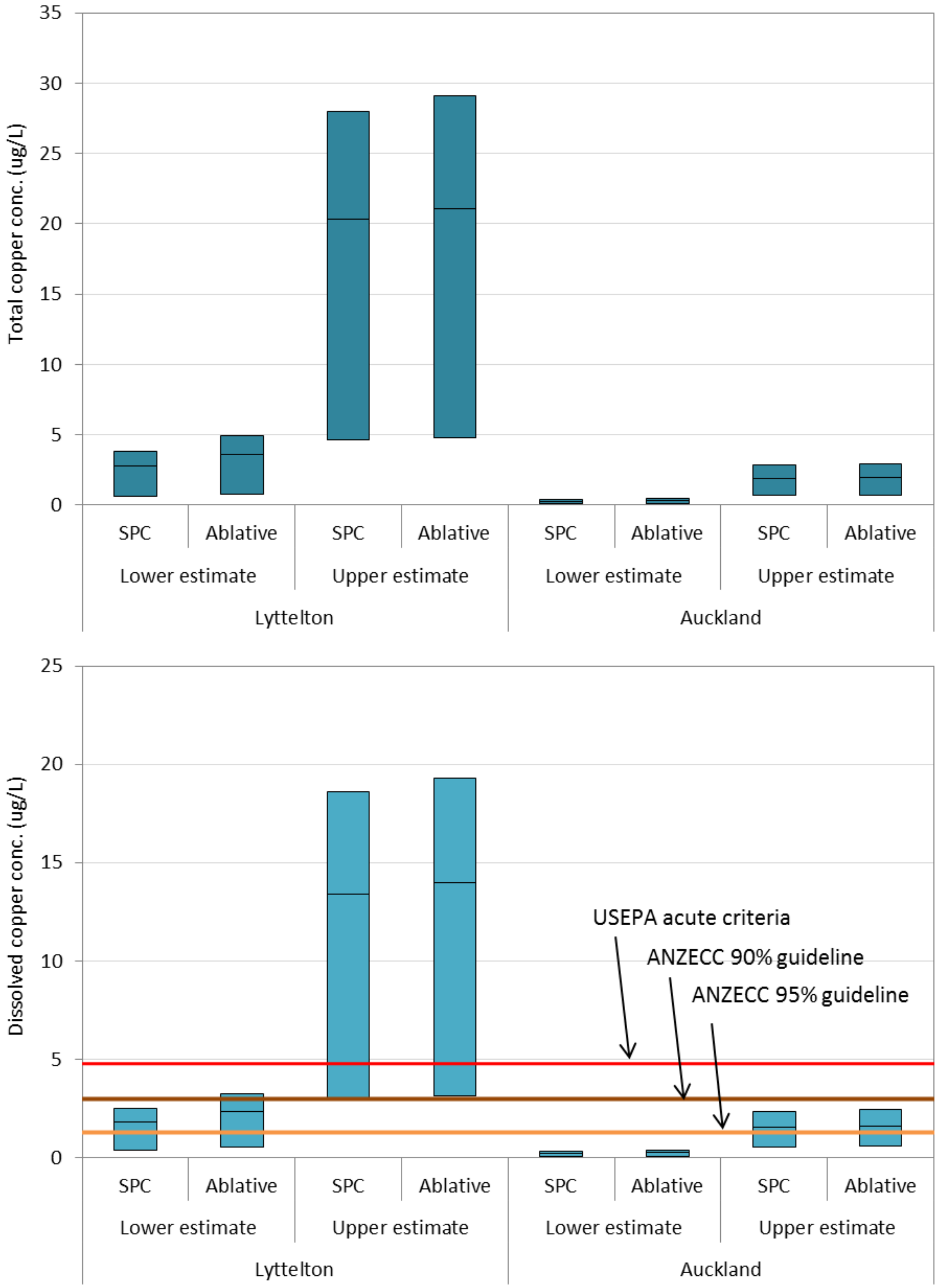

Figure 5.14 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning from a vessel with varying paint types. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

5.2.8.6 Cleaning type

For recreational vessels, soft cleaning was the only cleaning assessed. For commercial vessels, in-water cleaning may involve soft or aggressive cleaning. The type of cleaning undertaken has the largest influence on the PECs of all modelling undertaken. For commercial vessels, aggressive cleaning using a hard brush resulted in a very large increase in the release rate and consequently in the PECs in the ports when compared to soft cleaning (Figure 5.15).

For both ports, cleaning one commercial vessel of 10,469 m^2 using aggressive cleaning methods resulted in the minimum PEC exceeding the 95% guideline value and for all but ablative paints at Auckland, the minimum PEC also exceeded the 90% guideline value (by 5 - 7x in Lyttelton Port). Significantly, the acute criterion was exceeded in Lyttelton Port and in Port of Auckland, dependent on paint type.

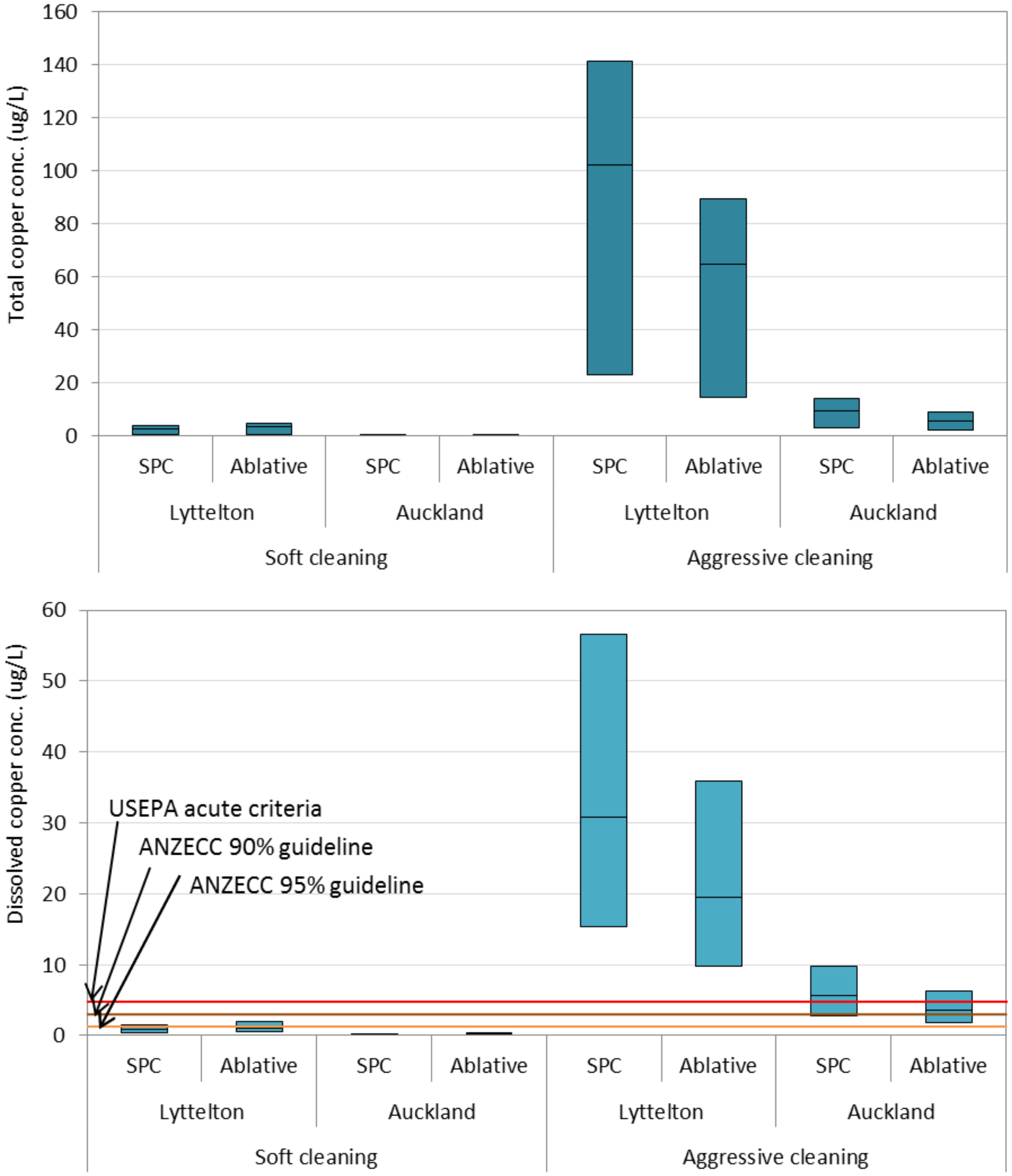

Figure 5.15 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning from a vessel with varying paint types. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

5.2.9 Risk matrices for in-water cleaning

The previous sections provided information on a limited set of scenarios, based on the base case. This section provides risk matrices for the full range of scenarios of vessel size and vessel number under-going in-water cleaning. Risks are assessed based on both lower and upper copper release estimates. All recreational vessel scenarios are based on cleaning a vessel with ablative coating and all commercial vessel scenarios are based on cleaning a vessel with SPC coating.

The risks in the tables in this section are based on the mean PECs modelled using MAMPEC. Risks are characterised as low, medium or high, based on the following criteria:

- Low risk: Mean PEC is less than the ANZECC guideline for 90% protection of 3.0 µg/L;
- Medium risk: Mean PEC exceeds the ANZECC guideline for 90% protection 3.0 µg/L but is below the USEPA acute guideline of 4.8 µg/L; and,
- High risk: Mean PEC exceeds the USEPA acute guideline of 4.8 µg/L.

The information from this risk assessment was used along with the biosecurity risk assessment in the final decision of when the environmental costs of releasing chemical contaminants during in-water cleaning outweigh the risk of no action (Section 2). Risk matrices are presented for recreational vessels (Tables 5.14 and 5.15) and commercial vessels (Tables 5.16 to 5.23), respectively.

Table 5.14 Summary of the risks for in-water cleaning of recreational vessels using soft cleaning methods, based on the lower copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
HMB [1]	25	5-11	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	76	11-20	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	148	21-30	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	269	31-40	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
WHN [2]	25	5-11	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	76	11-20	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	148	21-30	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	269	31-40	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Note: [1] HMB = Half Moon Bay Marina; [2] WHN = Westhaven Marina.

Table 5.15 Summary of the risks for in-water cleaning of recreational vessels using soft cleaning methods, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
HMB [1]	25	5-11	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	76	11-20	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	148	21-30	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	269	31-40	Low risk	Low risk	Low risk	Low risk	High risk	High risk
WHN [2]	25	5-11	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	76	11-20	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	148	21-30	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	269	31-40	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Note: [1] HMB = Half Moon Bay Marina; [2] WHN = Westhaven Marina.

Table 5.16 Summary of the risks for in-water cleaning of commercial vessels using soft cleaning methods, based on the lower copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Low risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Table 5.17 Summary of the risks for in-water cleaning of commercial vessels using soft cleaning methods, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Medium risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	High risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk

Table 5.18 Summary of the risks for in-water cleaning of commercial vessels using aggressive cleaning methods, based on the lower copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	High risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	3,231	100-150	Low risk	Low risk	Low risk	High risk	High risk	High risk
	6,333	150-200	Low risk	Low risk	High risk	High risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	High risk	High risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	High risk	High risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	High risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	Medium risk	High risk	High risk

Table 5.19 Summary of the risks for in-water cleaning of commercial vessels using aggressive cleaning methods, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	3,231	100-150	Low risk	Low risk	Medium risk	High risk	High risk	High risk
	6,333	150-200	Low risk	Low risk	High risk	High risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	High risk	High risk	High risk	High risk
	15,640	250-300	Low risk	Medium risk	High risk	High risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	Medium risk	High risk	High risk

Table 5.20 Summary of the risks for in-water cleaning of commercial vessels sides using aggressive cleaning methods, based on the lower copper release estimate.

Site	Surface area (m²)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	High risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	6,333	150-200	Low risk	Low risk	Low risk	Medium risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	Medium risk	High risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Medium risk	High risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk

Table 5.21 Summary of the risks for in-water cleaning of commercial vessels sides using aggressive cleaning methods, based on the upper copper release estimate.

Site	Surface area (m²)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	6,333	150-200	Low risk	Low risk	Low risk	High risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	Medium risk	High risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	High risk	High risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	High risk	High risk

Table 5.22 Summary of the risks for in-water cleaning of commercial vessels boot-tops using aggressive cleaning methods, based on the lower copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Medium risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

Table 5.23 Summary of the risks for in-water cleaning of commercial vessels boot-tops using aggressive cleaning methods, based on the upper copper release estimate.

Site	Surface area (m^2)	Length class (m)	No. vessels cleaned per day					
			0.00274	0.0274	0.137	0.274	1	2
Lyttelton	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Medium risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	High risk	High risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	High risk	High risk
Auckland	412	< 50	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	1,163	50-100	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	3,231	100-150	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	6,333	150-200	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	10,469	200-250	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk
	15,640	250-300	Low risk	Low risk	Low risk	Low risk	Low risk	Low risk

5.2.10 Summary

Copper release rates during in-water cleaning have been estimated based on literature information regarding the copper concentration in, and the thickness removed for biofilms, leached paint and sound paint, respectively. During light in-water cleaning of recreational vessels release rates range from 110-700 µg/cm^2 depending on the paint type and the estimate of copper in the leached layer. During light in-water cleaning of commercial vessels release rates range from 85-650 µg/cm^2. During aggressive in-water cleaning of commercial vessels release rates are expected to be substantially higher at 1,994-4,225 µg/cm^2. The estimate of copper concentration within the leached layer has the most uncertainty associated with it.

The MAMPEC model was set up for two marinas: Half Moon Bay and Westhaven; and for two ports: Auckland and Lyttelton, in accordance with the parameters identified by Gadd et al. (2011). In addition, 'marinas' the size of a recreational and commercial vessels, respectively were set-up to model the PECs immediately surrounding a vessel undergoing in-water cleaning.

The copper release rates were input into MAMPEC based on a range of scenarios including:

- The type of in-water cleaning (soft/aggressive);
- The vessel type (recreational/commercial);
- The vessel length;
- The number of vessels under-going in-water cleaning per day; and,
- The area of the vessel under-going in-water cleaning (full hull, sides only, boot-tops only).

In-water cleaning is expected to result in the release of large loads of copper. For recreational vessels this could be up to 1 kg. For commercial vessels, this could be up to 68 kg for soft cleaning methods and 300 kg for aggressive cleaning methods depending on the size of the vessel being cleaned.

Predicted environmental concentrations in an area immediately surrounding a vessel being cleaned are well in excess of the acute criterion for copper. For commercial vessels being cleaned by soft cleaning, the criterion is expected to be exceeded within a zone up to 140 m away. For commercial vessels being cleaned by aggressive cleaning, the criterion is expected to be exceeded within a zone more than 350 m away.

The PECs during in-water cleaning of recreational vessels exceeded the chronic guidelines (3.0 µg/L) in Half Moon Bay Marina in the following scenarios:

- Soft cleaning of > 1 vessels ≥ 11 m long per day based on the upper release estimate; and,
- Soft cleaning of > 0.274 vessels ≥ 21 m long per day based on the upper release estimate.

The PECs during in-water cleaning of commercial vessels exceeded the chronic guidelines (3.0 µg/L):

- Soft cleaning of > 1 vessel > 200 m long in Lyttelton Port per day based on the lower copper release estimate;
- Soft cleaning of 0.274 vessels > 100 m long or 0.137 vessels > 200 m long in Lyttelton Port per day based on the upper copper release estimate;
- Soft cleaning of > 1 vessels > 200 m long in Port of Auckland per day based on the upper copper release estimate;
- Aggressive cleaning of many vessel sizes and numbers in both Lyttelton Port and Port of Auckland per day based on both lower and upper copper release estimates;
- For aggressive cleaning of vessel sides only for many vessel sizes and numbers in Lyttelton Port and for large vessels in Port of Auckland per day based on both lower and upper copper release estimates;
- Aggressive cleaning of vessel boot-tops only for > 1 vessels > 100 m long or > 0.274 vessels > 150 m long per day in Lyttelton Port per day based on the lower copper release estimate; and,
- Aggressive cleaning of vessel boot-tops only for > 0.274 vessels > 100 m long or > 1 vessels > 50 m long in Lyttelton Port per day based on the upper copper release estimate.

The PECs during in-water cleaning of recreational vessels exceeded the acute criterion (4.8 µg/L) in the following scenarios:

- Soft cleaning of > 0.274 vessels ≥ 31 m long or > 1 vessels ≥ 21 m long are cleaned within Half Moon Bay Marina per day based on the upper copper release estimate.

The PECs during in-water cleaning of commercial vessels exceeded the acute criterion (4.8 µg/L) in the following scenarios:

- Soft cleaning of > 0.274 vessels > 250 m long in Lyttelton Port per day based on the lower copper release estimate;
- Soft cleaning of > 1 vessels > 100 m long, > 0.274 vessels > 150 m long, or 0.137 vessels > 250 m long in Lyttelton Port per day based on the upper copper release estimate;
- Aggressive cleaning of many vessel sizes and numbers in both Lyttelton Port and Port of Auckland based on both lower and upper copper release estimates;
- Aggressive cleaning of vessel sides only for many vessel sizes and numbers in Lyttelton Port and for large vessels only in Port of Auckland based on both lower and upper copper release estimates;
- Aggressive cleaning of vessel boot-tops only for > 1 vessels > 150 m or 0.274 vessels > 200 m long in Lyttelton Port per day based on the lower copper release estimate; and,
- Aggressive cleaning of vessel boot-tops only for > 0.274 vessels > 150 m long in Lyttelton Port per day based on the upper copper release estimate.

5.3 WHAT ARE THE CONTAMINANT LEVELS IN THE PREVIOUS QUESTION EQUIVALENT TO IN TERMS OF VESSEL NUMBERS AT TYPICAL LEACHING RATES?

5.3.1 Introduction

This question has been answered based on the emission rates, without modelling environmental concentrations, as this also provides the same information as modelling in the different environments. The typical leaching rate used is 8.2 µg/cm^2/day (Valkirs et al. 2003) for both recreational and commercial vessels, regardless of paint type.

A leaching rate of 8.2 µg/cm^2/day is considered the best estimate of release rates from in-service vessels. This leaching rate is also considered a suitable estimate for vessels about to undertake in-water cleaning for maintenance purposes. Synthesis of the literature suggests that 10 µg/cm^2/day is required to prevent biofouling, and 8.2 µg/cm^2/day would therefore be consistent with the growth of green weed and primary macro-invertebrate colonisers. There seems to be no strong argument to use another number. Much lower release rates (probably less than 5 µg/cm^2/day and potentially close to zero) would be expected on vessels on which the antifouling has “failed”, but these would require dry-docking for antifouling renewal, rather than in-water cleaning. Possibly acceptable in-water cleaning scenarios are proposed to be those vessels on which slime, leached layer and surface precipitates have reduced the release rate to allow colonisation by the more copper-tolerant species.

A leaching rate of 8.2 µg/cm^2/day was also used in the previous EPA modelling study (Gadd et al. 2011), which makes these two assessments consistent.

5.3.2 Comparison of emission rates

The total emission rates for commercial and recreational vessels from a number of in-water cleaning scenarios are shown in Table 5.24 and Table 5.25, along with the equivalent number of vessels at typical leaching rates. This information is also shown graphically in Figure 5.16 to Figure 5.18. For simplicity, the equivalent number of vessels has been calculated based on a single vessel size. For recreational vessels this was 11-20 m, which is the most common vessel size in most marinas, with a surface area of 76 m^2. For commercial vessels this was 150-200 m, which is relatively common, with a surface area of 6,333 m^2.

For recreational vessels, none of the in-water cleaning scenarios exceed the typical leaching rates from Half Moon Bay or Westhaven marinas.

This analysis indicates that the emission rates for cleaning large commercial vessels, and for aggressive cleaning are well in excess of the emissions within a port from typical vessel leaching. If selected areas of a vessel only are cleaned, the emission rates would be less than or similar to emissions from a port.

Table 5.24 Comparison of total emission rates for recreational vessels from in-water cleaning and typical leaching from a vessel 11-20 m in length.

In-water cleaning scenario					Total emission rates (g/d)	Equivalent no. vessels at typical leaching rates [1]
Vessel size class (m)	Surface area vessel (m^2)	No. vessels being cleaned	Paint type	Cleaning type		
Different vessel sizes						
5-10	25	1	Ablative-low	Soft	40	6
11-20	76	1	Ablative-low	Soft	122	20
21-30	148	1	Ablative-low	Soft	237	38
31-40	269	1	Ablative-low	Soft	430	69
Different vessel numbers						
21-30	148	0.00274	Ablative-low	Soft	0.65	0.1
21-30	148	0.0274	Ablative-low	Soft	6.5	1.0
21-30	148	0.137	Ablative-low	Soft	32	5
21-30	148	0.274	Ablative-low	Soft	65	10
21-30	148	1	Ablative-low	Soft	237	38
21-30	148	2	Ablative-low	Soft	474	76
Different paint type/Leached layer estimate						
21-30	148	1	SPC-low	Soft	163	26
21-30	148	1	SPC-high	Soft	962	154
21-30	148	1	Ablative-low	Soft	237	38
21-30	148	1	Ablative-high	Soft	1,036	166
21-30	148	1	Hard-low	Soft	200	32
21-30	148	1	Hard-high	Soft	999	160
Half Moon Bay Marina					2,003	321
Westhaven Marina					6,684	1,073

Notes: [1] Based on a single size class for all vessels in the marina of 11-20 m, 76 m^2.

Table 5.25 Comparison of total emission rates for commercial vessels from in-water cleaning and typical leaching from a vessel 150-200 m in length.

In-water cleaning scenario					Total emission rates (g/d)	Equivalent no. vessels at typical leaching rates[1]
Vessel size class (m)	Surface area vessel (m^2)	No. vessels being cleaned	Paint type	Cleaning type		
Different number of vessels						
200-250	10,469	0.00274	SPC-low	Soft	24	0.05
200-250	10,469	0.0274	SPC-low	Soft	244	0.5
200-250	10,469	0.137	SPC-low	Soft	1,219	2.4
200-250	10,469	0.274	SPC-low	Soft	2,438	5
200-250	10,469	1	SPC-low	Soft	8,899	17
200-250	10,469	2	SPC-low	Soft	17,797	34
Different vessel sizes						
< 50	412	1	SPC-low	Soft	350	0.7
50-100	1,163	1	SPC-low	Soft	989	1.9
100-150	3,231	1	SPC-low	Soft	2,746	5
150-200	6,333	1	SPC-low	Soft	5,383	10
200-250	10,469	1	SPC-low	Soft	8,899	17
250-300	15,640	1	SPC-low	Soft	13,294	26
Sides only						
< 50	137	1	SPC-low	Soft – sides	116	0.2
50-100	388	1	SPC-low	Soft – sides	330	0.6
100-150	1,077	1	SPC-low	Soft – sides	915	1.8
150-200	2,111	1	SPC-low	Soft – sides	1,794	3.5
200-250	3,490	1	SPC-low	Soft – sides	2,967	6
250-300	5,213	1	SPC-low	Soft – sides	4,431	9
Boot-tops only						
< 50	73	1	SPC-low	Soft – boot-tops	62	0.1
50-100	163	1	SPC-low	Soft – boot-tops	139	0.3
100-150	270	1	SPC-low	Soft – boot-tops	230	0.4
150-200	728	1	SPC-low	Soft – boot-tops	619	1.2
200-250	932	1	SPC-low	Soft – boot-tops	792	1.5
250-300	1,140	1	SPC-low	Soft – boot-tops	969	1.9
Different paint type/Leached layer estimate						
200-250	10,469	1	SPC-low	Soft	8,899	17
200-250	10,469	1	SPC-high	Soft	65,431	126
200-250	10,469	1	Ablative-low	Soft	11,516	22
200-250	10,469	1	Ablative-high	Soft	68,049	131
200-250	10,469	1	SPC-low	Aggressive	329,250	634
200-250	10,469	1	SPC-high	Aggressive	442,315	852
200-250	10,469	1	Ablative-low	Aggressive	208,752	402
200-250	10,469	1	Ablative-high	Aggressive	344,430	663
Port of Auckland					5,062	10
Lyttelton Port					2,966	6

Note: [1] Based on a single vessel size of 150-200 m, 6,333 m^2.

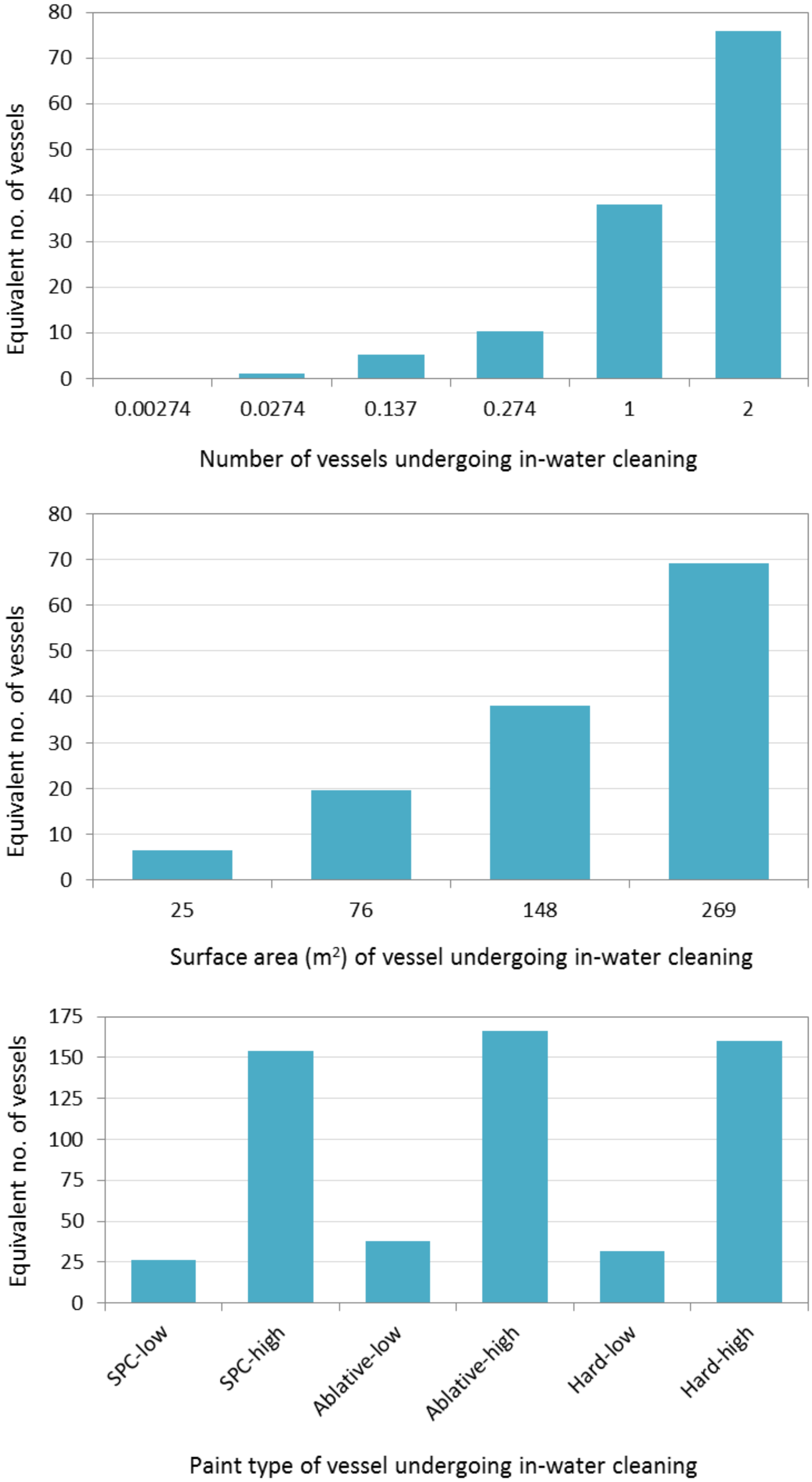

Figure 5.16 Comparison of in-water cleaning scenarios for recreational vessels and equivalent number of vessels at typical leaching rates.

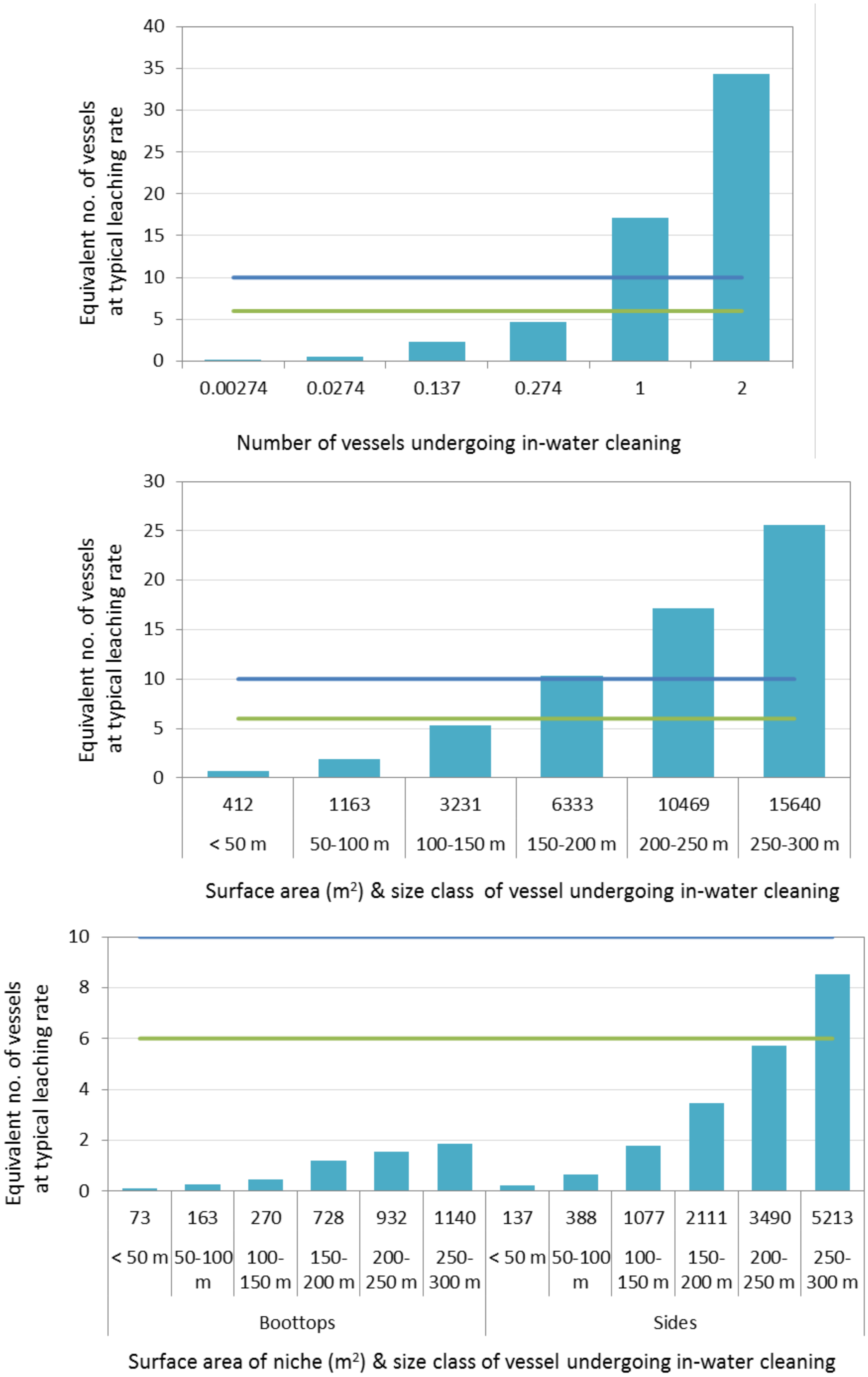

Figure 5.17 Comparison of in-water cleaning scenarios for commercial vessels and equivalent number of vessels at typical leaching rates and compared to total equivalent vessels in Port of Auckland (blue line) and Lyttelton Port (green line).

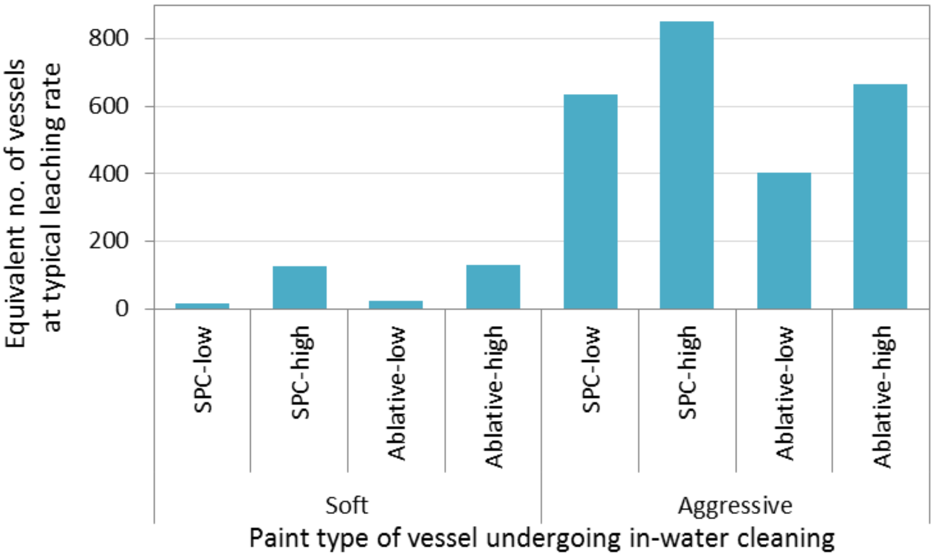

Figure 5.18 Comparison of in-water cleaning scenarios for commercial vessels and equivalent number of vessels at typical leaching rates.

5.3.3 Time-based comparison of emission rates

A further question that may be asked is: "How long would one additional vessel leaching at the typical rate take to release the same amount of copper as released during in-water cleaning?"

This yields the answers in Table 5.26 and Table 5.27. For recreational vessels, this ranges from a few days for vessels < 10 m to 2 months for a vessel ≥ 31 m. With the upper copper release rate estimate, the equivalent time may be over 5 months for a vessel ≥ 31 m. For soft cleaning of commercial vessels, the equivalent time is generally several days, but up to a month for cleaning 2 vessels of 200-250 m or a single vessel > 250 m. For cleaning of boot-tops only, the equivalent time is less than 2 days even for a vessel > 250 m. The upper estimate of leaching for soft cleaning suggests the emissions are similar to typical leaching over three months. For aggressive cleaning, the copper released is similar to that released in ~two years of typical leaching.

Table 5.26 Comparison of total emission rates for recreational vessels from in-water cleaning and typical leaching from a vessel 11-20 m long.

In-water cleaning scenario					Total emission rates (g/d)	Time for 1 vessel at typical leaching rates to emit equivalent copper (no. days)
Vessel size class (m)	Vessel surface area (m^2)	No. vessels being cleaned	Paint type	Cleaning type		
Different vessel numbers						
21-30	148	0.00274	Ablative-low	Soft	0.65	0.1
21-30	148	0.0274	Ablative-low	Soft	6.5	1.0
21-30	148	0.137	Ablative-low	Soft	32	5
21-30	148	0.274	Ablative-low	Soft	65	10
21-30	148	1	Ablative-low	Soft	237	38
21-30	148	2	Ablative-low	Soft	474	76
Different vessel sizes						
5-10	25	1	Ablative-low	Soft	40	6
11-20	76	1	Ablative-low	Soft	122	20
21-30	148	1	Ablative-low	Soft	237	38
31-40	269	1	Ablative-low	Soft	430	69
Different paint type/Leached layer estimate						
21-30	148	1	SPC-low	Soft	163	26
21-30	148	1	SPC-high	Soft	962	154
21-30	148	1	Ablative-low	Soft	237	38
21-30	148	1	Ablative-high	Soft	1,036	166
21-30	148	1	Hard-low	Soft	200	32
21-30	148	1	Hard-high	Soft	999	160

Table 5.27 Comparison of total emission rates for commercial vessels from in-water cleaning and typical leaching from a vessel 150-200 m long.

In-water cleaning scenario					Total emission rates (g/d)	Time for 1 vessel at typical leaching rates to emit equivalent copper (no. days)
Vessel size class (m)	Vessel surface area (m^2)	No. vessels being cleaned	Paint type	Cleaning type		
Different number of vessels						
200-250	10,469	0.00274	SPC-low	Soft	24	0.05
200-250	10,469	0.0274	SPC-low	Soft	244	0.5
200-250	10,469	0.137	SPC-low	Soft	1,219	2.4
200-250	10,469	0.274	SPC-low	Soft	2,438	5
200-250	10,469	1	SPC-low	Soft	8,899	17
200-250	10,469	2	SPC-low	Soft	17,797	34
Different vessel sizes						
< 50	412	1	SPC-low	Soft	350	0.7
50-100	1,163	1	SPC-low	Soft	989	1.9
100-150	3,231	1	SPC-low	Soft	2,746	5
150-200	6,333	1	SPC-low	Soft	5,383	10
200-250	10,469	1	SPC-low	Soft	8,899	17
250-300	15,640	1	SPC-low	Soft	13,294	26
Sides only						
< 50	137	1	SPC-low	Soft – sides	116	0.2
50-100	388	1	SPC-low	Soft – sides	330	0.6
100-150	1,077	1	SPC-low	Soft – sides	915	1.8
150-200	2,111	1	SPC-low	Soft – sides	1,794	3.5
200-250	3,490	1	SPC-low	Soft – sides	2,967	6
250-300	5,213	1	SPC-low	Soft – sides	4,431	9
Boot-tops only						
< 50	73	1	SPC-low	Soft – boot-tops	62	0.1
50-100	163	1	SPC-low	Soft – boot-tops	139	0.3
100-150	270	1	SPC-low	Soft – boot-tops	230	0.4
150-200	728	1	SPC-low	Soft – boot-tops	619	1.2
200-250	932	1	SPC-low	Soft – boot-tops	792	1.5
250-300	1,140	1	SPC-low	Soft – boot-tops	969	1.9
Different paint type/Leached layer estimate						
200-250	10,469	1	SPC-low	Soft	8,899	17
200-250	10,469	1	SPC-high	Soft	65,431	126
200-250	10,469	1	Ablative-low	Soft	11,516	22
200-250	10,469	1	Ablative-high	Soft	68,049	131
200-250	10,469	1	SPC-low	Aggressive	329,250	634
200-250	10,469	1	SPC-high	Aggressive	442,315	852
200-250	10,469	1	Ablative-low	Aggressive	208,752	402
200-250	10,469	1	Ablative-high	Aggressive	344,430	663

5.3.4 Individual vessel PECs

The total emissions and PECs for individual recreational and commercial vessels are provided in Table 5.28 and shown in Figures 5.19 and 5.20.

Table 5.28 Total emission rates and PECs for individual recreational and commercial vessels from typical leaching.

Vessel length category (m)	Full hull surface area	Total leaching (g/d)	Mean PEC total copper (µg/L)	
Recreational vessels			Half Moon Bay	Westhaven
5-11	25	2.1	0.0081	0.0015
11-20	76	6.2	0.025	0.0045
21-30	148	12	0.048	0.0088
31-40	269	22	0.087	0.016
Commercial vessels			Lyttelton	Auckland
< 50	412	34	0.011	0.0010
50-100	1,163	91	0.028	0.0026
100-150	3,231	252	0.078	0.0072
150-200	6,333	519	0.16	0.015
200-250	10,469	858	0.27	0.024
250-300	15,640	1,218	0.38	0.035

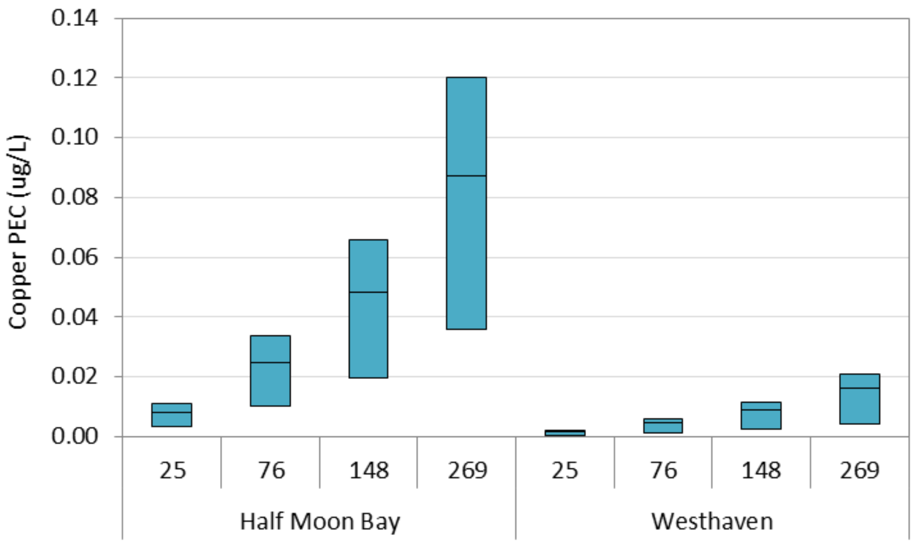

Figure 5.19 PECs of total copper in Half Moon Bay and Westhaven marinas from vessels of varying surface area (m^2) at typical leaching rates. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

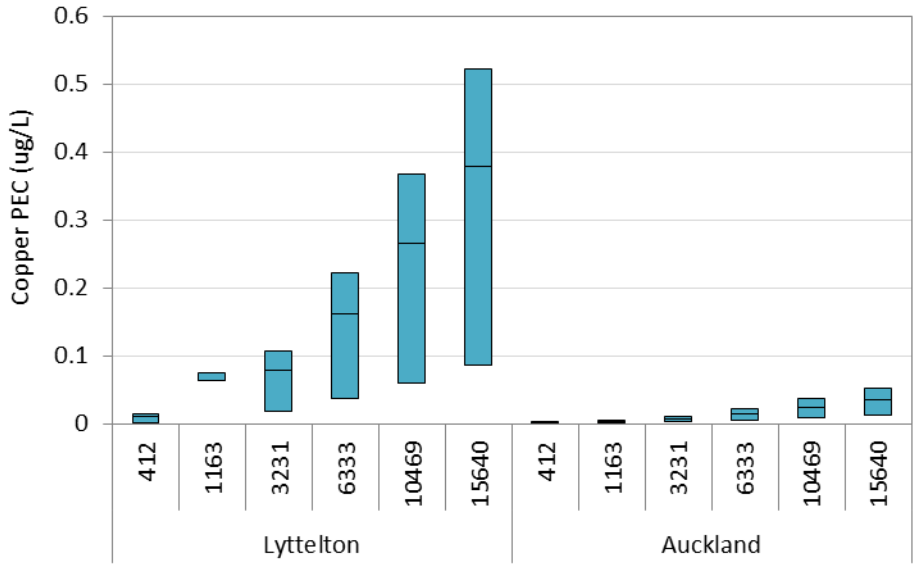

Figure 5.20 PECs of total copper in Lyttelton Port and Port of Auckland from vessels of varying surface area (m^2) at typical leaching rates. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

5.3.5 Summary

The emission rates for in-water cleaning of recreational vessels are equivalent to the leaching of 0.1 to 166 vessels at typical leaching rates of 8.2 µg/cm^2/day. Alternatively, the emission rates for in-water cleaning of recreational vessels are equivalent to that from a single vessel leaching over 0.1 to 166 days. However, the total emissions within a marina greatly exceed the emissions from in-water cleaning even based on upper release estimates.

The emission rates for soft in-water cleaning of commercial vessels are equivalent to the leaching of 0.05 to 131 vessels at typical leaching rates (or alternatively, the leaching over 0.05 to 131 days). The emission rates for aggressive in-water cleaning of commercial vessels are equivalent to the leaching of up to 663 vessels at typical leaching rates (or alternatively, the leaching over almost 2 years). Emission rates for in-water cleaning are in most cases far in excess of that released from normal leaching within either Lyttelton Port or Port of Auckland. If only the sides or boot-tops of a vessel are cleaned, the emission rates would be similar to or less than the emissions from a port.

5.4 IS THERE A DIFFERENCE BETWEEN THE EMISSIONS RELEASED FROM AN IN-WATER CLEANED VESSEL, A VESSEL THAT HAS BEEN HAULED OUT AND CLEANED, AND A NEWLY ANTI-FOULED VESSEL?

5.4.1 Introduction

This question is answered in relation to six different scenarios of in-water cleaning as specified (MAF 2011a):

- Hand removal (spot fouling – recreational vessels);
- Soft cloth (slime layer fouling – recreational vessels);
- Brush system (slime layer/soft fouling, full hull-commercial vessels);
- Brush system (slime layer/soft fouling, niche areas-commercial vessels);
- Brush system (Hard fouling, full hull – commercial vessels); and,
- Brush system (hard fouling, niche areas – commercial vessels).

5.4.2 Average leaching rates

The typical leaching rates prior to cleaning are assumed to be 8.2 µg/cm^2/day of copper for both commercial and recreational vessels, respectively. This value (from Valkirs et al. 2003) was the average from multiple measurements on 6 pleasure craft with paint of varying ages and its use was justified in Section 5.3.1.

For the purposes of assessing Question 3, the leaching rate for average paints is based on the CEPE mass-balance calculations. This has been undertaken for a range of paint types and brands (Table 8.5). The CEPE calculation assumes that 70% of the biocide is leached from the paint within the life specified (36 months for commercial vessels and 24 months for recreational vessels). The calculations suggest overall average leaching rates would be 12 µg/cm^2/day of copper for SPC and ablative paints and 10 µg/cm^2/day of copper for hard paints (Table 5.29).

5.4.3 Emission rates for new paint

The literature review (Section 3.6.3) discusses leaching rates for new paints based on field and laboratory studies. For ablative and SPC paints, the CEPE method gives the best indication for the first 14 days, which is close to 25 µg/cm^2/day. After this two factors will decrease release: the stabilisation of chemical release close to the surface, and the development of biofilm. In the period beyond 14 days, the average CEPE leaching rate is 12 µg/cm^2/day for SPC and ablative coatings. Hard coatings are likely to have a much higher release over the first 14 days (higher than CEPE calculations), and decrease more slowly. Leaching rates are difficult to predict and are best measured. It is likely that the initial leaching rate is somewhere around 50 µg/cm^2/day, decreasing slowly to be ~30 µg/cm^2/day at day 50 and ~20 µg/cm^2/day at day 100.

5.4.4 Leaching rates after in-water cleaning

Spot cleaning may result in minor increases in leaching rates from selected sections of a vessel but this is not expected to result in any change in overall leaching rates as the majority of the hull will not be cleaned. Therefore, the overall leaching rate before and after spot cleaning is expected to be ~8.2 µg/cm^2/day of copper.

Soft cleaning of recreational vessels is expected to remove the biofilm layer and some of the leached layer of paint. For SPC, half of the leached layer is expected to be removed, whilst for hard paints only a third of the leached layer is expected to be removed (Section 5.2.2). Ablative paints are somewhere in between. Removal of the biofilm layer and some of the leached layer is expected to result in a slight increase in the copper leaching rate. It is expected that this would result in a return to the average CEPE leaching rate of 12 µg/cm^2/day for SPC and ablative coatings. For hard coatings, much of the leached paint layer will remain (~50 µm) and therefore the increase in leaching rate is not expected to fully return to the average CEPE leaching rate. These values are summarised in Table 5.29.

Table 5.29 Biocide leaching rates before and after in-water cleaning (µg/cm²/day).

	Recreational vessels			Commercial vessels	
Scenario	SPC	Ablative	Hard	SPC	Ablative
Spot cleaning – recreational vessels					
Before cleaning	8.2	8.2	8.2	N/A	N/A
After cleaning	8.2	8.2	8.2	N/A	N/A
Soft cleaning– recreational vessels					
Before cleaning	8.2	8.2	8.2	N/A	N/A
After cleaning	12	12	10	N/A	N/A
Soft brush cleaning – commercial vessels					
Before cleaning	N/A	N/A	N/A	8.2	8.2
After cleaning	N/A	N/A	N/A	12	12
Aggressive brush cleaning – commercial vessels					
Before cleaning	N/A	N/A	N/A	8.2	8.2
After cleaning	N/A	N/A	N/A	25	25

N/A = Not assessed.

Soft brush cleaning of commercial vessels is expected to do the same. That is, the biofilm layer and about half of the leached layer of paint are expected to be removed, resulting in an increase in leaching rates to 12 µg/cm²/day.

Aggressive brush cleaning of commercial vessels is expected to remove all of the leached layer of paint as well as some of the sound paint below this. This is expected to result in a return to leaching rates equivalent to freshly painted vessels (25 µg/cm²/day based on CEPE calculation for initial 14 days leaching).

These higher rates of leaching are expected to last for approximately seven days. Although the CEPE calculations indicate that higher emission rates apply for 14 days, studies suggest that the actual emission rate rapidly decreases even within that period. This is because a newly applied paint releases unbound biocide from close to the surface in the first few days, which would not happen from exposed sub-layers of cured paint. The scant studies on release after cleaning also suggest a rapid return to pre-clean values as the biofilm quickly redevelops.

5.4.5 PECs after in-water cleaning

The PECs of total copper after spot cleaning of recreational vessels will be the same as those for a single vessel at typical leaching rates (Section 5.4.2). For soft cleaning, the PECs will be slightly higher, as will the PECs after aggressive cleaning of commercial vessels (Figure 5.21 and Figure 5.22).

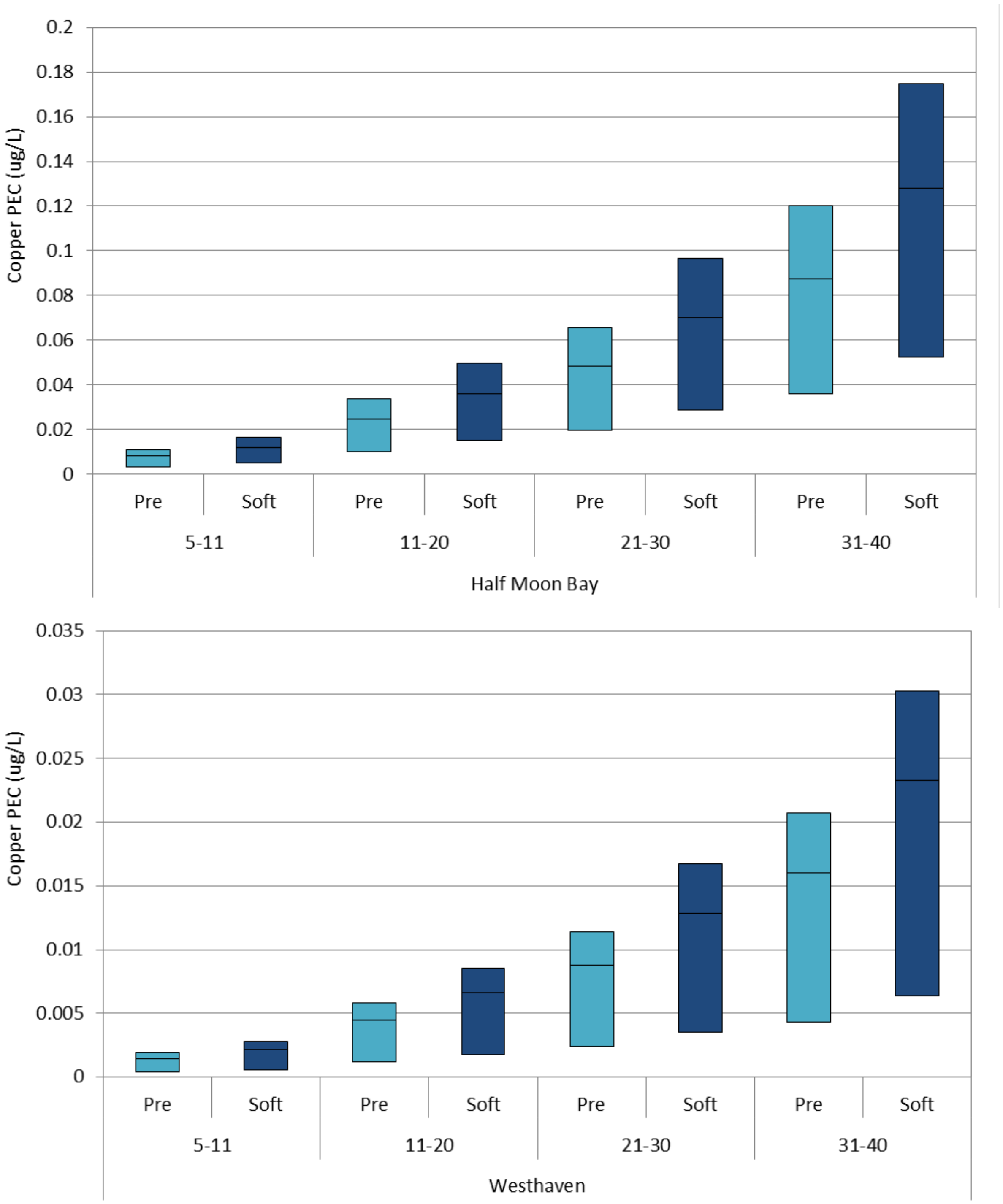

Figure 5.21 PECs of total copper in Half Moon Bay and Westhaven marinas for vessels of varying surface area before and after cleaning. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC. Pre = Prior to cleaning; Soft = soft cleaning.

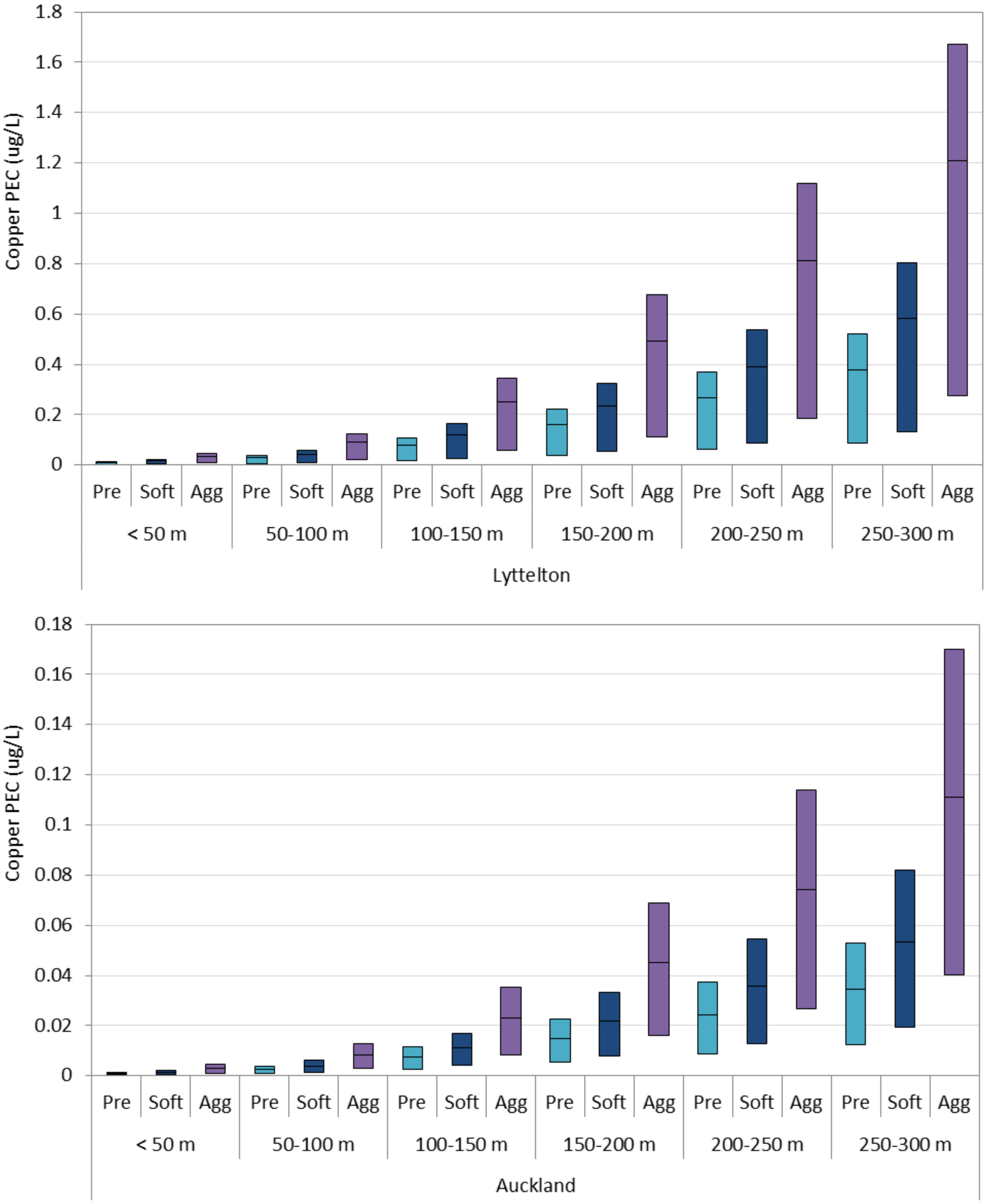

Figure 5.22 PECs of total copper in Lyttelton Port and Port of Auckland for vessels of varying surface area before and after cleaning. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC. Pre = Prior to cleaning; Soft = soft cleaning; Agg = Aggressive cleaning.

5.4.6 Difference in marina PECs after in-water cleaning

The leaching rates for vessels after in-water cleaning were input into model scenarios for a full marina or port to assess the difference in marina PECs after in-water cleaning compared to the usual PECs. This is shown in Figure 5.23 and Figure 5.24, below, for just the Half Moon Bay Marina and Lyttelton Port, which show the highest PECs of the two marina and port scenarios.

For recreational vessels (Figure 5.23), the increase in PECs with the addition of a vessel that has been newly cleaned is very slight and is unlikely to be measurable. The addition of a vessel with new SPC or ablative paint (with a leaching rate of 25 µg/cm^2/day) or with new hard paint (with a leaching rate of 50 µg/cm^2/day) is also very slight. The difference in PECs in Westhaven Marina is expected to be even less.

For commercial vessels (Figure 5.24), there is a discernible increase in PECs with the addition of a vessel that has been newly cleaned using soft cleaning. However, the range in PECs is greater than this difference. There is a more substantial increase in the PECs with the addition of a vessel that has been newly cleaned using aggressive cleaning, or with a newly painted vessel. This results in a maximum PEC that is almost 1 µg/L higher than the baseline PEC (without additional vessels) and a mean PEC that is ~0.7 µg/L higher than the baseline PEC (a 60% increase). The difference in PECs in Port of Auckland is expected to be less.

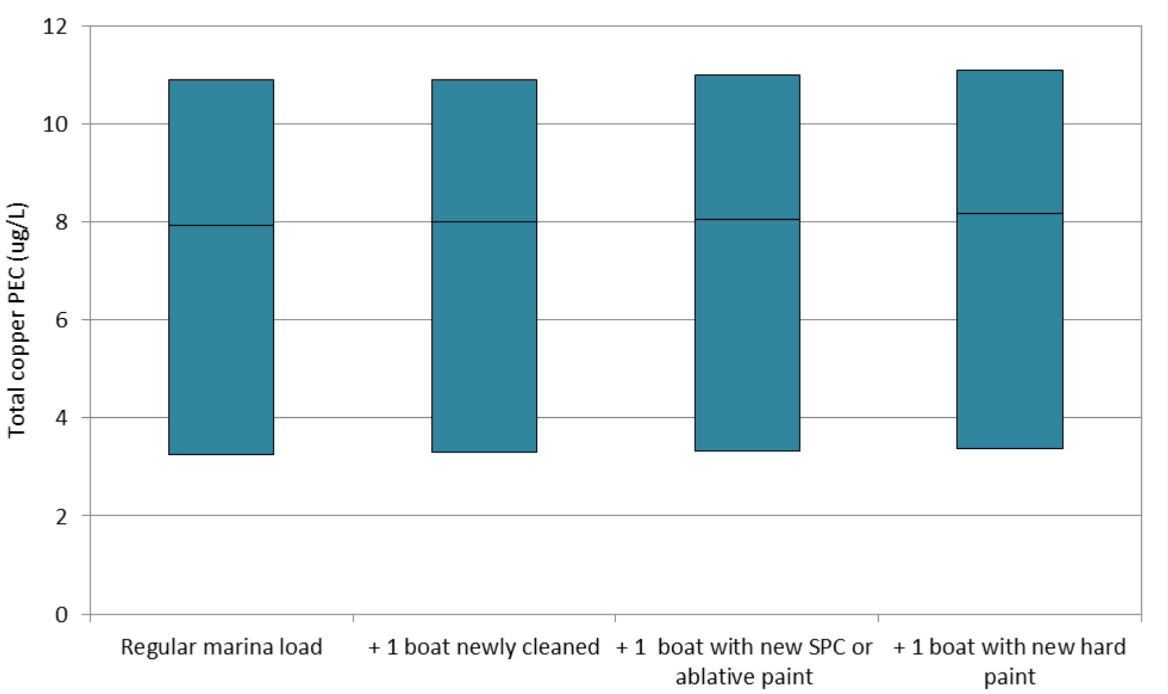

Figure 5.23 PECs of total copper in Half Moon Bay Marina for the usual marina emissions and with the addition of a single newly cleaned or newly painted vessel. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

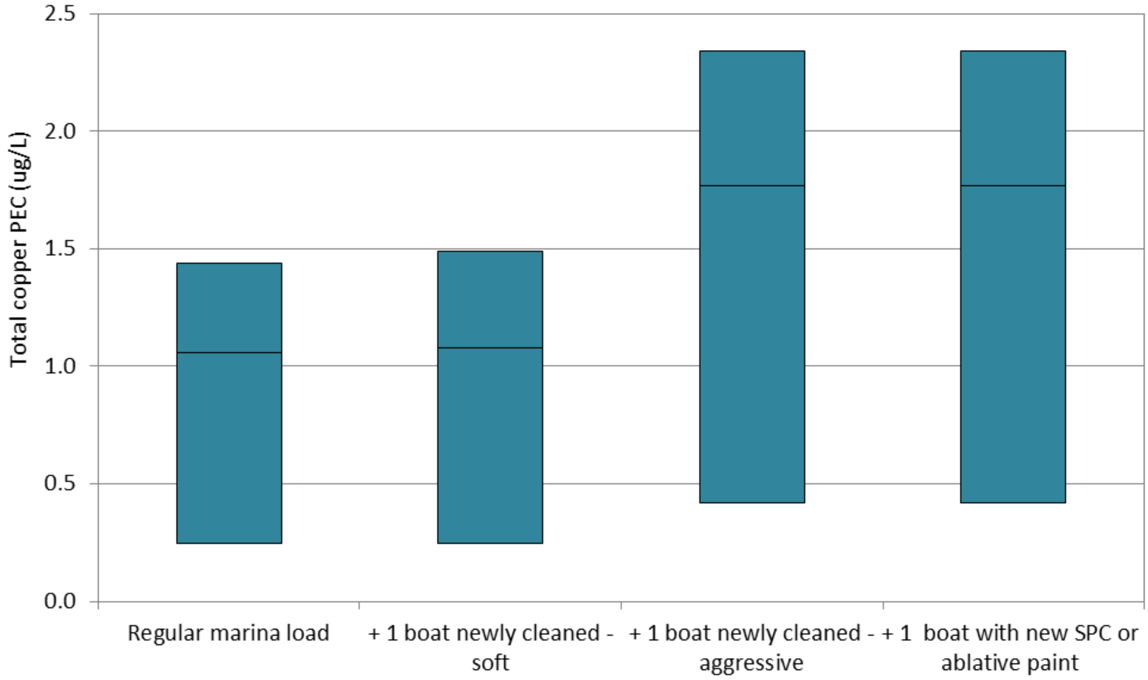

Figure 5.24 PECs of total copper in Lyttelton Port for the usual marina emissions and with the addition of a single newly cleaned vessel (with either soft or aggressive cleaning) or newly painted vessel. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

5.4.7 Summary

The leaching rates for vessels cleaned in-water using spot or soft cleaning methods are expected to be lower than the emission rates for vessels that have been hauled out and cleaned and for newly anti-fouled vessels.

The leaching rates for vessels cleaned in-water using aggressive brushing methods are expected to be the same as the emission rates for vessels that have been hauled out as both processes are expected to remove biofilm layers and leached paint layers.

The leaching rates for vessels cleaned in-water using aggressive brushing methods are expected to be the same as the emission rates for newly anti-fouled vessels as the aggressive in-water cleaning is expected to strip paint back to fresh layers, equivalent to new paint.

The addition of a single vessel to a port or marina after soft cleaning will have very little influence on the PECs of copper. Addition of a commercial vessel after aggressive cleaning will result in a 60% increase in the mean PEC.

5.5 WHAT IS THE LIKELIHOOD OF TRIBUTYLTIN (TBT) RELEASE FROM VESSELS FOLLOWING IN-WATER CLEANING? WHAT WOULD BE THE LIKELY EMISSION RATE AND ENVIRONMENTAL CONCENTRATION OF TBT FOLLOWING IN-WATER CLEANING?

5.5.1 Introduction

Information from the literature review, the methodology and the rationale used to answer this question are provided below.

5.5.2 Current TBT use

The application and use of antifouling paints containing organotin compounds as biocides has been progressively and increasingly banned in nations around the world since the mid-1980s (Section 3.2.2.8). The International Maritime Organisation, in 2001, adopted the International Convention on the Control of Harmful Anti-Fouling Systems on Ships, 2001 (the AFS Convention) that proposed a global ban on application to shipping from 2003. This convention entered into force in 2008. The supply of organotin-based antifouling paints by the major global marine paint companies ceased in 2003, and the registration of such paints was revoked in countries where there was a requirement for the registration of antifouling paints containing biocides (Section 3.2.2.8).

The AFS convention does allow vessels with tin coatings to apply a sealing coat then apply tin-free antifouling paint. Information from paint companies suggests that less than 5% of commercial vessels would have this type of coating.

New Zealand announced a partial ban on TBT in 1988 (coming into force in July 1989), banning its use on small vessels (< 25 m in length), with the exception of those with an aluminium hull or outdrive. This was followed in 1993 by a total ban on the sale or use of antifouling paint containing organotins as active ingredients, under the Pesticides (Organotin Antifouling Paints) Regulations 1993 (SR 1993/326) (Section 3.2.2.8).

Although New Zealand has not ratified the AFS Convention, which would create an offence for vessels coated with TBT paint to enter New Zealand waters, most commercial vessels are covered by the International Association of Classification Societies (IACS), which requires tin-free coatings. Information from paint manufacturers suggests that there is a very low likelihood of any vessels visiting New Zealand with tin-based paints still exposed on the hull. No vessels with tin-based paints are allowed to enter Australian waters, which reduces the likelihood of vessels with tin-based paints visiting New Zealand.

However, there are still some small paint companies in some parts of the world producing tin-based antifouling paints for domestic and recreational vessels. Anecdotal information suggests that tin-based paints continue to be used in some Caribbean countries, where they are favoured for their efficacy in tropical waters.

5.5.3 Likelihood of TBT release from vessels undergoing in-water cleaning

No domestic commercial vessels will have tin-based antifouling coatings as these coatings have been fully banned in New Zealand since 1993. Documentation of the antifouling coating will be available for most visiting commercial vessels (although not required by law in New Zealand). It is considered that there is a very low likelihood of vessels using TBT coatings visiting New Zealand's waters. However, there may be some vessels that have TBT coatings underneath sealing coats. With regards to commercial vessels, there is virtually no likelihood of TBT being released from in-water cleaning. Even aggressive cleaning is unlikely to remove outer paint layers, the sealing coat and the underlying TBT-based paint. Such layers may however, be removed in a dry dock by heavy grit sweeping or reblasting.

Based on this, it is considered that there is negligible likelihood of TBT emissions from in-water cleaning and therefore no further investigation of emission rates or modelling of PECs has been undertaken.

5.5.4 Summary

There is negligible likelihood of TBT emissions from in-water cleaning of vessels entering, or resident in, New Zealand and therefore no further investigation of emission rates or modelling of PECs has been undertaken.

5.6 WHAT CONDITIONS APPLIED TO IN-WATER CLEANING METHODS WOULD ENSURE THE MANAGEMENT OF CONTAMINANT RELEASE (CHEMICAL/BIOLOGICAL) TO ACCEPTABLE LEVELS INTO THE SURROUNDING ENVIRONMENT?

5.6.1 Introduction

Acceptable environmental levels were discussed in Section 5.1. PECs during in-water cleaning were compared to these levels within Section 5.2.6 and 5.2.8. In many cases, the PECs exceeded the acute criterion and chronic guidelines. This section discusses considerations around acceptable environmental levels and possible management options to prevent the exceedance of such levels.

5.6.2 Additional issues around acceptable environmental levels

As discussed in Section 5.1, acute criteria are considered most suitable for in-water cleaning where this is a one-off event (i.e. < 1 vessel per day). However, if in-water cleaning is expected to be a daily event then chronic guidelines may be more appropriate.

When applying acute criteria there should be some consideration of the use of a mixing zone around the vessel, within which these criteria would not apply. This is a situation similar to a wastewater or stormwater discharge. There are no clear guidelines for the size of mixing zones in coastal waters and these may need to be assessed on a site-specific basis, depending on currents and tidal exchange. Although the PECs in the areas immediately surrounding vessels undergoing in-water cleaning were compared to acute criteria in this report, this was for assessing risks from the various scenarios and is considered appropriate for assessing environmental effects. The size of the mixing zone should be somewhere between this and the whole marina/harbour scenarios modelled.

When assessing the effects of in-water cleaning within a marina or port, the ‘background’ concentration within the marina or port from the leaching of berthed vessels should be considered. Only the in-water cleaning scenarios for recreational vessels based on the upper copper release estimate resulted in any exceedance of the acute copper criterion within a marina (Half Moon Bay only, and > 0.274 vessels ≥ 31 m long or > 1 vessel ≥ 21 m long), however these were modelled in the absence of other copper sources. Figure 5.25 shows that the acute criterion is expected to be exceeded in Half Moon Bay and Westhaven even in the absence of in-water cleaning. The additional load from in-water cleaning must be considered in conjunction with these existing loads.

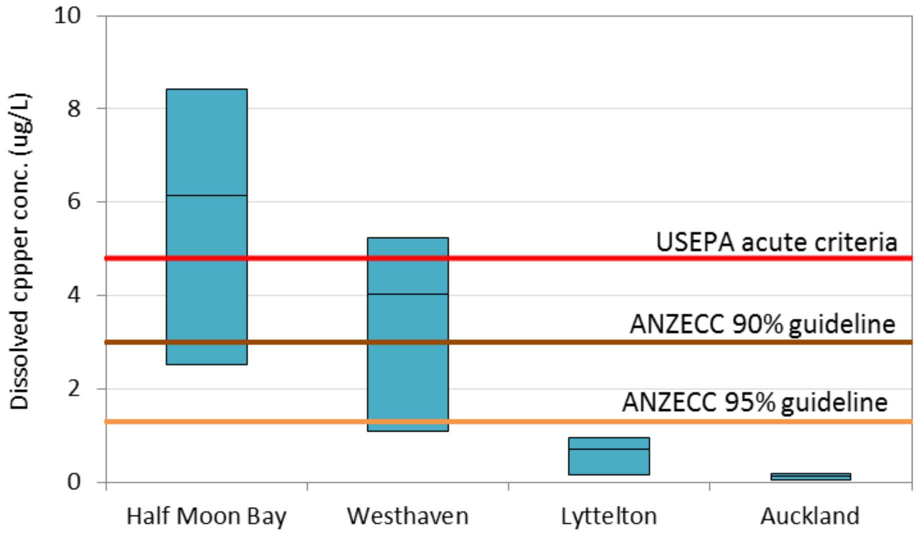

Figure 5.25 Mean predicted environmental concentrations of copper in Half Moon Bay and Westhaven marinas and ports of Lyttelton and Auckland for the typical marina scenarios (Gadd et al. 2011). Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

A further consideration in relation to acceptable environmental levels relates to sediment quality. An assessment of the effects of in-water cleaning on benthic sediment quality was outside the scope of this report. However, the high loads of copper released would undoubtedly result in increases in copper concentrations in the benthic sediment in the zone of in-water cleaning and to a lesser extent, in a wider area surrounding this. This may have further implications for copper concentrations in the water column if sediments are re-suspended. If in-water cleaning was carried out in a designated area (such as adjacent to a wharf) then a nominal mixing zone exists where environmental guidelines would not apply. However, the effects on the broader area should be considered.

5.6.3 Management conditions to control copper release

In-water cleaning of recreational vessels is expected to result in exceedance of acute criteria within a zone immediately surrounding the vessel being cleaned. However, when mixing within the volume of a whole marina is considered, the acute criteria will only be exceeded when the upper estimate of copper release from in-water cleaning is used. For the lower estimate, the criteria will not be exceeded under any of the scenarios assessed. This suggests that management of in-water cleaning of recreational vessels may not be required. However, as discussed above, the background concentrations within a marina should be taken into account.

Furthermore, if in-water cleaning is considered to be a regular event (i.e. > 1 vessel per day), for which chronic guidelines would apply, then there may need to be consideration of the size of the vessels allowed to undertaken in-water cleaning, as those greater than 31 m may result in exceedance of chronic guidelines.

For commercial vessels, in-water cleaning is expected to result in a major release of copper into the environment (up to 300 kg for aggressive cleaning). This will result in very elevated concentrations in the zone around a vessel being cleaned. Furthermore, even within a port, many of the in-water cleaning scenarios modelled resulted in exceedance of acute criteria. Several management conditions could be employed to minimise the discharges of copper and to ensure copper concentrations are at acceptable levels. These include:

- Do not permit aggressive cleaning of commercial vessels, for example using steel brushes. Only permit cleaning methods that remove biofilms but minimise coating removal;

- Limit the number of vessels to be cleaned in a single day to less than one on average, particularly in enclosed ports such as Lyttelton; and,
- Limit the surface area of the vessel to be cleaned, for example, only the sides or boot-tops of a vessel.

5.6.4 Management conditions to control TBT release

The release of TBT from in-water cleaning of vessels can be most easily controlled by:

- Only allowing commercial vessels with IACS paperwork to undergo in-water cleaning of any kind; and,
- Not permitting in-water cleaning of recreational vessels that do not have evidence of TBT-free coatings: e.g. a Declaration on Anti-Fouling System, as prescribed in the AFS Convention for vessels 24 m in length but less than 400 gross tonnes, or equivalent evidence such as receipts from last application of antifouling paint.

5.7 UNCERTAINTIES AND INFORMATION GAPS

There are several uncertainties that may significantly affect the modelling results presented in this report:

- The copper content of biofilms on the vessels;
- The copper content of the leached layer of paint;
- The depth of coating removal during light and aggressive cleaning;
- Partitioning of copper from the removed biofilm and paint;
- The size of a mixing zone around a vessel being cleaned; and,
- Validation measurements during in-water cleaning of representative commercial and recreational vessels.

The greatest uncertainty was around the copper content of the leached layer and for this reason, a lower and upper release rate were calculated and modelled. However, most of the model scenarios were based on the lower estimate. If the upper estimate is found to be more appropriate then much greater exceedance of guidelines can be expected. For recreational vessels, this may result in the exceedance of the acute criterion under some scenarios, such as cleaning of very large vessels or multiple vessels in one day. For commercial vessels, this would result in the exceedance of the acute criterion under more scenarios than currently, particularly in Lyttelton Port.

A further area of uncertainty relates to the partitioning of copper from the biofilms and abraded paint removed during in-water cleaning. It has been conservatively assumed that all of this copper becomes dissolved and then a smaller proportion of that partitions onto suspended sediment (some of which settles to the sea floor). It is likely that not all of the copper is immediately dissolved. However, some field and laboratory studies could provide further information on this process. For example, wash-down water from vessel cleaning could be collected and the partitioning in seawater assessed immediately and at different time intervals.

Water samples collected near recreational and commercial vessels undergoing in-water cleaning would also provide validation of the modelled results. Samples could be collected at varying distances from a vessel undergoing in-water cleaning to provide information on the dilution, settling and dispersion. Samples would ideally be analysed for both total and dissolved forms of copper to provide some information on leaching from the removed paint and on subsequent partitioning to sediment.

5.8 SUMMARY OF CHEMICAL CONTAMINATION FROM IN-WATER CLEANING

In-water cleaning is expected to result in the release of large loads of copper. For recreational vessels this could be up to 1 kg. For commercial vessels, this could be up to 68 kg for soft cleaning methods and 300 kg for aggressive cleaning methods.

Predicted environmental concentrations in an area immediately surrounding a vessel being cleaned are well in excess of the USEPA acute criterion for dissolved copper (4.8 µg/L). For commercial vessels being cleaned by soft methods, the criterion is expected to be exceeded within a zone up to 140 m away. For commercial vessels being cleaned by aggressive methods, the criterion is expected to be exceeded within a zone more than 350 m away.

Summary of dissolved copper PECs that exceeded the ANZECC 90% chronic guideline (3.0 µg/L)

For soft cleaning of recreational vessels in Half Moon Bay Marina and based on the upper copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel ≥ 11 m is cleaned per day; and,
- > 0.274 vessels ≥ 21 m are cleaned per day.

For soft cleaning of commercial vessels in Lyttelton Port, based on the lower copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 200 m is cleaned per day.

For soft cleaning of commercial vessels in Lyttelton Port, based on the upper copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 100 m is cleaned per day;
- > 0.274 vessels > 100 m are cleaned per day; and,
- > 0.137 vessels > 200 m are cleaned per day.

For soft cleaning of commercial vessels in Auckland Port, based on the upper copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 200 m is cleaned per day.

For aggressive cleaning of commercial vessels in Lyttelton Port, based on the lower copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel is cleaned per day;
- > 0.274 vessels > 50 m are cleaned per day;
- > 0.137 vessels > 100 m are cleaned per day; and,
- > 0.0274 vessels > 150 m are cleaned per day.

For aggressive cleaning of commercial vessels in Auckland Port, based on the lower copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 100 m is cleaned per day;
- > 0.274 vessels > 150 m is cleaned per day; and,
- > 0.137 vessels > 250 m are cleaned per day.

For aggressive cleaning of commercial vessels in Lyttelton Port, based on the upper copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel is cleaned per day;
- > 0.274 vessels are cleaned per day;
- > 0.137 vessels > 100 m are cleaned per day;
- > 0.0274 vessels > 100 m are cleaned per day; and,
- > 0.00274 vessels > 250 m are cleaned per day.

For aggressive cleaning of commercial vessels in Auckland Port, based on the upper copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 100 m is cleaned per day;
- > 0.274 vessels > 100 m is cleaned per day; and,
- > 0.137 vessels > 250 m are cleaned per day.

For aggressive cleaning of commercial vessel sides in Lyttelton Port, based on the lower copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 50 m is cleaned per day;
- > 0.274 vessels > 100 m are cleaned per day;
- > 0.137 vessels > 150 m are cleaned per day; and,

- > 0.0274 vessels > 200 m are cleaned per day.

For aggressive cleaning of commercial vessel sides in Lyttelton Port, based on the upper copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 50 m is cleaned per day;
- > 0.274 vessels > 50 m are cleaned per day;
- > 0.137 vessels > 150 m are cleaned per day; and,
- > 0.0274 vessels > 200 m are cleaned per day.

For aggressive cleaning of commercial vessel sides in Auckland Port, based on the lower copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 200 m is cleaned per day; and,
- > 0.274 vessels > 250 m are cleaned per day.

For aggressive cleaning of commercial vessel sides in Auckland Port, based on the upper copper release estimate, the chronic criterion was exceeded when:

- > 1 vessel > 150 m is cleaned per day; and,
- > 0.274 vessels > 200 m are cleaned per day.

For aggressive cleaning of commercial vessel boot-tops in Lyttelton Port, based on the lower copper release estimates, the chronic criterion was exceeded when:

- > 1 vessel > 100 m is cleaned per day; and,
- > 0.274 vessels > 150 m are cleaned per day.

For aggressive cleaning of commercial vessel boot-tops in Lyttelton Port, based on the upper copper release estimates, the chronic criterion was exceeded when:

- > 1 vessel > 100 m is cleaned per day; and,
- > 0.274 vessels > 150 m are cleaned per day.

Summary of dissolved copper PECs exceeding the USEPA acute criterion (4.8 µg/L)
For soft cleaning of recreational vessels in Half Moon Bay Marina, based on the upper copper release estimate, the acute criterion was exceeded when:

- > 1 vessel ≥ 21 m is cleaned per day; and,
- > 0.274 vessels ≥ 31 m are cleaned per day.

For soft cleaning of commercial vessels in Lyttelton Port, based on the lower copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 250 m is cleaned per day.

For soft cleaning of commercial vessels in Lyttelton Port, based on the upper copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 100 m is cleaned per day;
- > 0.274 vessels > 150 m are cleaned per day; and,
- > 0.137 vessels > 250 m are cleaned per day.

For aggressive cleaning of commercial vessels in Lyttelton Port, based on the both copper release estimates, the acute criterion was exceeded when:

- > 1 vessel is cleaned per day;
- > 0.274 vessels > 50 m are cleaned per day;
- > 0.137 vessels > 100 m are cleaned per day; and,
- > 0.0274 vessels > 150 m are cleaned per day.

For aggressive cleaning of commercial vessels in Auckland Port, based on the both copper release estimates, the acute criterion was exceeded when:

- > 1 vessel > 100 m is cleaned per day; and,
- > 0.274 vessels > 200 m are cleaned per day.

For aggressive cleaning of commercial vessel sides in Lyttelton Port, based on the lower copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 50 m is cleaned per day;
- > 0.274 vessels > 100 m are cleaned per day; and,
- > 0.137 vessels > 200 m are cleaned per day.

For aggressive cleaning of commercial vessel sides in Lyttelton Port, based on the upper copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 50 m is cleaned per day;
- > 0.274 vessels > 100 m are cleaned per day;
- > 0.137 vessels > 150 m are cleaned per day; and,
- > 0.0274 vessels > 250 m are cleaned per day.

For aggressive cleaning of commercial vessel sides in Auckland Port, based on the lower copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 250 m is cleaned per day.

For aggressive cleaning of commercial vessel sides in Auckland Port, based on the upper copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 200 m is cleaned per day; and,
- > 0.274 vessels > 250 m are cleaned per day.

For aggressive cleaning of commercial vessel boot-tops in Lyttelton Port, based on the lower copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 150 m is cleaned per day; and,
- > 0.274 vessels > 200 m are cleaned per day.

For aggressive cleaning of commercial vessel boot-tops in Lyttelton Port, based on the upper copper release estimate, the acute criterion was exceeded when:

- > 1 vessel > 150 m is cleaned per day; and,
- > 0.274 vessels > 150 m are cleaned per day.

The emission rates for in-water cleaning of recreational vessels are equivalent to the leaching of 0.1 to 166 vessels at typical leaching rates (or alternatively, the leaching of an 11-20 m recreational vessel over 0.1 to 166 days). However, the total emissions within a marina greatly exceed the emissions from in-water cleaning even based on upper release estimates.

The emission rates for soft in-water cleaning of commercial vessels are equivalent to the leaching of 0.05 to 131 vessels at typical leaching rates (or alternatively, the leaching over 0.05 to 131 days). The emission rates for aggressive in-water cleaning of commercial vessels are equivalent to the leaching of up to 663 vessels at typical leaching rates (or alternatively, the leaching of a 150-200 m vessel over almost two years). Emission rates for aggressive in-water cleaning are in most cases far in excess of that released from normal leaching within either Lyttelton Port and Port of Auckland. If selected areas of a vessel only are cleaned, the emission rates would be less than or similar to emissions from a port.

After in-water cleaning, the leaching rates for vessels cleaned in-water using spot or soft cleaning methods are expected to be lower than the emission rates for vessels that have been hauled out and cleaned and for newly anti-fouled vessels, whilst the leaching rates after aggressive cleaning methods are expected to be the same as those from newly painted vessels.

Vessels with TBT as the outer coating are unlikely to enter New Zealand waters. Some vessels may have TBT under a sealing coat and then non-TBT antifouling coatings on the surface. Based on this, there is therefore a very low likelihood of TBT being released during in-water cleaning even using aggressive cleaning.

Acute criteria should apply to in-water cleaning in an area greater than the immediate zone around a vessel. Whilst in-water cleaning of recreational vessels is only expected to result in exceedance of the acute criterion for a limited number of scenarios, background concentrations within marinas should also be considered. Aggressive cleaning of commercial vessels is expected to result in exceedance of the acute criterion for many scenarios and should therefore be discouraged. The number of vessels undergoing in-water cleaning should be restricted and in some cases, the cleaning could be limited to niche areas such as the sides and boot-tops only. Even cleaning of niche areas may result in exceedance of the acute criterion under many scenarios.

6 Biosecurity risk from in-water cleaning

6.1 WHAT TYPES AND LEVELS OF BIOLOGICAL CONTAMINATION ARE LIKELY TO BE RELEASED AS A RESULT OF IN-WATER CLEANING? WHAT IS THE VIABILITY OF THIS CONTAMINATION?

Some empirical information is available on the amounts of material removed (and potentially released into the environment) by some of the different methods of in-water cleaning (hand scraping and brush cleaning). Technology for capturing material removed is currently of very limited availability in New Zealand and consists of suction-based devices developed for a MAF-funded experimental study in 2007. The equipment still exists but has not been in general use since the study. Information is available on the performance of these systems in terms of capturing material removed from experimentally fouled plates or the hull of a fouled vessel. A related study in New Zealand produced information on the survival of fouling organisms after cleaning, including clonal ascidians and bryozoans, and information is also available in the literature.

This question is addressed by using the information obtained during the literature review (Section 4) to determine, to the extent possible:

1. the type, amount and viability of material that may be released during in-water cleaning of each type of vessel, type of fouling and method of cleaning;
2. the amount of material released that may be retained if waste-capture technology is used; and,
3. factors that modify the biosecurity risk from in-water cleaning. Relevant information is summarised in bulleted format for brevity and clarity.

6.1.1 Type and amount of material that may be released during in-water cleaning

6.1.1.1 Recreational vessels: soft cloth removal of slime layer fouling (without recapture)

Composition of the fouling assemblage

- Slime layers consist initially of bacteria and diatoms and are later colonised by fungi, protists and microscopic larvae and spores of macrofouling species;
- Bacterial biofilms can influence settlement and metamorphosis of larvae and spores of other organisms and increase their adhesion strength;
- There have been no studies of the taxonomic composition of the bacterial assemblage (Molino et al. 2009a);
- Diatoms arrive after the bacterial film has developed, and do not interact directly with the substratum surface itself but, rather, they adhere to and proliferate on a layer of bacteria and their associated mucus and other extracellular polymeric substances (Molino et al. 2009b);
- Diatom assemblages that developed on experimentally-deployed antifouling (biocidal) and fouling-release coatings deployed in Williamstown, Victoria and Cairns, Queensland, Australia (Molino et al. 2009b) consisted of up to six genera. Diversity was larger on FR than antifouling coatings; and,
- Slime layer fouling may also contain microscopic macroalgal filaments and newly settled spores and larvae of macrofouling organisms.

Amount of fouling released

- Soft-cloth cleaning is presumably capable of removing 100% of the slime layer fouling, but surface micro-topography may affect success of removal of microscopic organisms (c.f. its effect on settlement of microbial and other organisms, which tends to be enhanced when the size of surface micro-topographies is slightly larger than that of settling larvae of spores: Carl et al. 2012); and,
- As with spot cleaning, divers may miss patches while hand-cleaning recreational vessels.
- Micro- and macroalgal fragments left on the hull after cleaning can each give rise to several new thalli, and cleaning probably releases spores, which settle immediately after cleaning (Moss & Marsland 1976).

Viability of material removed

- Microbial material removed is likely to be viable but settled microscopic stages of macrofouling species may no longer be competent to resettle.

Summary

Soft-cloth removal of slime layer fouling is likely to release significant amounts of microbial material (including bacteria, fungi, microalgae, protists and microscopic stages of macrofouling species). The method is potentially capable of releasing all fouling present, including niche areas, though, in practice, divers may overlook some patches. Much or all of this material may remain viable and capable of establishing in the receiving environment, but settled microscopic stages of macrofouling species may no longer be competent to resettle.

6.1.1.2 Recreational vessels: hand removal of spot fouling (without recapture)

Composition of the fouling assemblage

Among recreational yachts and launches (Floerl et al. 2008):

- Fouling organisms collected from 182 recreational vessels entering New Zealand included representatives of 13 Phyla: Annelida, Arthropoda, Bryozoa, Chlorophyta, Chordata, Cnidaria, Echinodermata, Mollusca, Ochrophyta, Platyhelminthes, Porifera, Rhodophyta and Sipuncula;
- Polychaete worms, crustaceans and bryozoans accounted for 62% of all organisms collected;
- 82% of the vessels examined carried identifiable fouling organisms;
- The amount of fouling biomass per vessel ranged from 1 g to 19.55 kg (range of biomass density was ≤ 0.01-495 g/m^2. 78% of fouled yachts carried ≤ 1.0 kg while 4% carried ≥ 5 kg;
- Ca. 80% of vessels had an average fouling cover of ≤ 5% and 3% had ≥ 30% fouling cover; and,
- 68% of the species identified (75 out of 111) were NIS and 6% were cryptogenic.

Comparing international recreational and commercial vessels arriving in New Zealand (Inglis et al. 2010):

- The average number of all fouling species (including natives) was larger on recreational vessels than on commercial vessels;
- The average number of non-indigenous species (NIS) and cryptogenic species combined was also larger;
- The average number of NIS not yet established in New Zealand was not significantly different among yachts, passenger vessels and merchant vessels (though the authors

stressed that differences in methods used to sample the different types of vessels made direct comparisons unreliable);

- Fouling assemblages on recreational vessels were different from those on all types of commercial vessels, largely due to the frequent occurrence (ca 50% of vessels) of *Watersipora subtorquata* and *Bugula neritina* on recreational vessels;
- 60% of the NIS recorded are not yet established in New Zealand (but 60% of the 20 most commonly-occurring fouling species are already established - most of the new NIS occurred infrequently);
- The most frequently-occurring NIS fouling taxa were bryozoans, barnacles, calcareous polychaetes and oysters. Ascidian NIS were also found on recreational vessels;
- Ascidians and bryozoans were almost only found on recreational vessels, while polychaetes, amphipods, bivalves and hydroids occurred more frequently on recreational vessels than commercial vessels (excluding passenger ships);
- Average no. of NIS or cryptogenic species was 4.28/recreational vessel (range 0-14).
- Average no. of NIS already established in New Zealand was 2.94/ recreational vessel (range 0-9); and,
- Average no. of NIS not already established was 2.13/ recreational vessel (range 0-8).

Amount of fouling released

- Assume ≤ 15% of the hull is spot fouled (Section 4.10);
- 100% removal of small areas of macrofouling is presumably possible by hand cleaning of spot fouling, but no information is available on removal of microscopic organisms; and,
- Divers may miss patches while hand-cleaning recreational vessels (Floerl et al. 2008) - 80% of vessels cleaned 3 weeks previously had biofouling (1-15 species), including NIS.

Viability of material removed

Viability of organisms removed using soft cloth and scraper (Woods et al. 2007):

- The likelihood of survival was high for motile species, moderate for soft taxa (particularly colonial taxa), and low for calcareous, sessile taxa;
- Soft-bodied taxa: 69-89% (summer-winter) undamaged by cleaning;
- Soft-bodied taxa: 72-88% (summer-winter) survived cleaning;
- Hard-bodied taxa: 17-34% (summer-winter) undamaged by cleaning;
- Hard-bodied taxa: 25-35% (summer-winter) survived cleaning;
- Up to 55% of organisms removed were "viable" (if the dominant tubiculous polychaetes are removed from analysis, values were 72% in winter and 66% in summer);
- Viability varied among taxa, and was highest among: anemones, ascidians, bivalves, bryozoans, flatworms, motile crustaceans, motile molluscs, nemerteans, errant polychaetes and sponges;
- Most motile organisms collected, such as crustaceans, gastropods and errant polychaetes, were viable, and often occurred in protected microhabitats e.g. barnacle tests, sponges, etc;
- No information on viability of macroalgae removed, but *Enteromorpha*/*Ulva* (dominant taxa) are likely to be able to grow from fragments (Moss & Marsland 1976);
- Micro and macroalgal fragments left on the hull after cleaning can each give rise to several new thalli, and cleaning probably releases spores, which settle immediately after cleaning (Moss & Marsland 1976);
- Survival and viability was not generally correlated with amount of fouling present;
- Fragmentation or dislodgement of macroalgae, e.g. *Sargassum muticum*, plays a significant role in dispersal;

- Fragmentation is a common means of dispersal for many clonal organisms including sponges, bryozoans and ascidians;
- Many polychaetes have the ability to regenerate from fragments;
- Physical damage to bryozoans may cause early maturation and spawning;
- Physical disturbance may stimulate release of larvae by *Styela clava* and *Eudistoma* species; and,
- Release of gametes from damaged ascidians or serpulid tubeworms may induce congeners to spawn synchronously.

Summary

Hand removal of spot fouling is likely to release significant amounts of soft (including ascidians, bryozoans, hydroids, macroalgae), motile (such as crustaceans, gastropods, errant polychaetes) and hard (including barnacles, bivalves, sedentary polychaetes) fouling, and this may include NIS. The method is potentially capable of removing all fouling present, including niche areas, though, in practice, divers may overlook some patches. Much (up to 70% of soft fouling organisms and up to 55% of all fouling organisms) of this material will remain viable and some organisms may be capable of establishing in the receiving environment, particularly clonal organisms, such as colonial ascidians, bryozoans and sponges, organisms capable of regeneration from fragments, such as some macroalgae and polychaetes, and mobile organisms.

6.1.1.3 Commercial vessels: brush-system removal of slime layer/soft fouling (without recapture)

Composition of the fouling assemblage

Among merchant vessels (bulk carriers, container vessels, tankers, etc.) arriving in New Zealand (Inglis et al. 2010):

- 54% of 270 vessels inspected had identifiable fouling species;
- 78 NIS species were identified (c.f. 5 cryptogenic and 25 indigenous species);
- 77% of NIS are not established in New Zealand (19 of the 20 most commonly-occurring species are not already established);
- Total fouling assemblage, and the NIS component, were dominated by barnacles (17 out of the 20 most frequently occurring NIS), motile crustaceans (amphipods and isopods) and calcareous polychaetes. Soft fouling organisms were uncommon; and,
- Strong relationships were observed between the extent of biofouling (mean density of biomass per vessel) and the total number of fouling species and numbers of NIS.

Amount of fouling released

Diver-operated brush systems:

- Rotating brushes effective at removing erect and soft-bodied fouling organisms (up to 100% of biomass). Mean percentage cover was reduced by 88-93%, however, on average, 5% of removed material was not captured (Hopkins et al. 2008);
- Effectiveness of removal of soft-bodied taxa can be reduced in presence of hard-bodied fouling (Hopkins et al. 2008);
- Divers may miss patches while using rotating brushes, especially when cleaning irregular hull surfaces (e.g. bilge keels, stern tubes, stabiliser fins, thruster tunnels, etc.) (Hopkins et al. 2008);
- 40% of species remained on a very heavily fouled vessel cleaned with hand-held brushes (polypropylene bristles and polypropylene with steel inserts) (Davidson et al. 2008);

- Cover reduced from 89% to 37% (21.8% of entire hull area still biofouled by soft and hard encrusting species) (Davidson et al. 2008); and,
- Brushes may fail to remove microscopic life-stages e.g. gametophytes of *Undaria* (Blakemore & Forrest 2006).

Automated brush systems:

- With SCAMP brush system, percentage of species still present after cleaning ranged from 40 to 60%, depending on hull region and 30 out of 37 species (81%) were still present across the entire hull (Davidson et al. 2008).

General comments:

- Micro- and macroalgal fragments left on the hull after cleaning can each give rise to several new thalli, and cleaning probably releases spores, which settle immediately after cleaning (Moss & Marsland 1976).

Viability of material removed

Diver-operated brush systems (Hopkins et al. 2008):

- 8% of material not collected during cleaning was viable - amount of viable material lost from flat experimental plates was similar across all fouling ages, but amount from curved plates increased (up to 20%) with fouling age;
- There was little difference between the two diver-operated brush systems tested;
- Viable material lost included a wide range of intact organisms, including fragments of bryozoans, hydroids and colonial ascidians; and,
- For soft-bodied, clonal organisms (e.g. some algae, ascidians, bryozoans and sponges) and motile organisms, viability of material may be similar to that recorded for hand-removal with scrapers (up to 70%: Woods et al. 2007).

Automated brush systems (Davidson et al. 2008):

- No empirical information available;
- Viability likely to be similar to that with diver-operated systems; and,
- For soft-bodied, clonal organisms (e.g. some algae, ascidians, bryozoans and sponges) and motile organisms, viability of material may be similar to that recorded for hand-removal with scrapers (up to 70%: Woods et al. 2007).

General comments:

- Fragmentation and dislodgement of macroalgae, e.g. *Sargassum muticum*, plays a significant role in dispersal;
- Fragmentation is a common means of dispersal for many clonal organisms including sponges, bryozoans and ascidians;
- Many polychaetes have the ability to regenerate from fragments;
- Physical damage to bryozoans may cause early maturation and spawning;
- Physical disturbance may stimulate release of larvae by *Styela clava* and *Eudistoma* species; and,
- Release of gametes from damaged ascidians may induce congeners to spawn synchronously.

Summary

Brush-based removal of slime layer/soft fouling is likely to release significant amounts of slime (including spores and larval stages of macrofouling species), soft (including ascidians, bryozoans, hydroids, macroalgae) and motile (such as crustaceans, gastropods, errant polychaetes) fouling, including NIS. In the absence of capturing systems, the method is potentially capable of releasing up to 90% of fouling present, including niche areas in the case of diver-operated systems, though, in practice, divers may overlook some patches. Automated systems may clean less thoroughly, with up to 81% of fouling species still present across the whole hull surface. Surface micro-topography may affect success of removal of microscopic organisms, including microscopic stages of macrofouling species. Much (up to 90% of soft fouling organisms and up to 55% of all fouling organisms) of this material may remain viable and capable of establishing in the receiving environment, particularly microbial taxa and clonal organisms, (e.g. colonial ascidians, bryozoans and sponges), organisms capable of regeneration from fragments (e.g. some macroalgae and polychaetes), and mobile organisms. However, settled microscopic stages of macrofouling species may no longer be competent to resettle.

6.1.1.4 Commercial vessels: brush-system removal of hard fouling (without recapture)

Composition of the fouling assemblage

See *Commercial vessels: brush-system removal of slime layer/soft fouling*.

Amount of fouling released

See *Commercial vessels: brush-system removal of slime layer/soft fouling*.

- Rotating brushes are less effective at removing hard fouling organisms (up to 60% of calcareous tubeworms, bivalves, barnacles remaining) than soft fouling (Hopkins et al. 2008).

Viability of material removed

See *Commercial vessels: brush-system removal of slime layer/soft fouling*.
Diver-operated brush systems (Hopkins et al. 2008):

- 8% of material not collected during cleaning was viable - amount of viable material lost from flat experimental plates was similar across all fouling ages, but amount from curved plates increased (up to 20%) with fouling age;
- There was little difference between the two diver-operated brush systems tested; and,
- Viable material lost included wide range of intact organisms, including juvenile mussels, barnacles, calcareous and non-calcareous worms, fragments of bryozoans, hydroids and colonial ascidians (but note that Woods et al. 2007 reported that few tubeworms or barnacles survived cleaning with a scraper, except for those living epibiotically).

Summary

Brush-based removal of hard fouling is likely to release significant amounts of slime (including spores and larval stages of macrofouling species) and hard fouling, including NIS. Motile organisms living among the sessile fouling may also be released. The method is potentially capable of releasing up to 60% of hard fouling present, including niche areas in the case of diver-operated systems. Automated systems may clean less thoroughly, with up to 81% of fouling species still present across the whole hull surface. Surface microtopography may affect success of removal of microscopic organisms, including microscopic stages of macrofouling species. Some of this material may remain viable and capable of establishing in the receiving environment, though the proportion of the material removed will be much smaller than for soft fouling and may be very low for taxa such as barnacles and polychaetes living in calcareous tubes.

6.1.2 The amount of material that may be retained by recapture technology

6.1.2.1 Hand cleaning of spot fouling

- Hand cleaning of spot fouling – there is no information available on the effectiveness of capture of material released by hand cleaning of spot fouling. The amount of material released is likely to be small and, assuming the diver uses (for example) a net bag around the area being cleaned, it is likely that most of it can be captured as it is scraped off. Some loss of material around the edges of the bag may occur, particularly in strong currents; and,
- Soft-cloth cleaning of slime layer – the entire hull will be cleaned and the likelihood of the diver collecting material while cleaning such a large area is small. Material is also likely to fragment, float and/or pass through a mesh bag.

6.1.2.2 Diver-operated, brush-based systems

For the diver-operated, single-brush systems trialled by Hopkins & Forrest (2008):

- Hand-operated brush systems tested experimentally captured on average ca 95% (minimum 90%, maximum 99%) of material removed from the hull, but less when fouling level was high or on curved surfaces;
- Divers knocked material off with their fins and by dragging hoses and other gear across the hull while using the cleaning brushes - this material was not captured;
- The amount of material not captured was higher in winter, when large numbers of small barnacles were present in the fouling assemblage and were dislodged but not captured (due to faster sinking rate); and,
- Material not captured represents about 1% of total material removed in the experimental study.

6.1.3 Factors that modify the biosecurity risk from in-water cleaning

6.1.3.1 Type of paint

- Biocidal and biocide-free fouling-release paints are designed to deter settlement or reduce attachment strength that facilitates sloughing of macrofouling organisms;
- Biocide-free mechanically-resistant coatings are designed to be cleaned regularly;
- Biocidal paints may be generally more effective but both types fail eventually. Globally, biocide-free paints are less commonly used on recreational vessels (Floerl et al. 2010a), particularly the mechanically-resistant types. However, their use is very common on recreational vessels in the San Diego (California, USA) area;
- Both biocidal and biocide-free, fouling release (FR) coatings develop bacterial slime fouling within ~2 weeks (16 d on a biocidal antifouling paint in Victoria, Australia: Molino et al. 2009a) but FR coatings may be colonised slightly faster (e.g. major modification of the substratum surface within 2-4 d at the same site);
- Diatom fouling occurred more rapidly on FR coating than biocidal paints at sites in Victoria and Queensland, Australia (Molino et al. 2009b), and colonisation on both types of surface was generally slow during the 16-d study;
- FR paints are designed to reduce strength of attachment of fouling to the hull, so cleaning may be easier and less material is likely to remain after cleaning;
- Silicone FR coatings appeared resistant to fouling for up to 150 d, but were fouled by sponges and molluscs beyond that time in tests in Hawaii (Holm et al. 2000). The development of fouling after an initial, resistant lag phase may correspond to changes in the surface properties of the coating, such as absorption of proteins from the water

or the development of microbial films, or short term leaching of toxic components; and,

- Biocide-free paints may attract a different suite of fouling organisms to biocidal paints, with biocide-intolerant species more likely to be present on the former and biocide-tolerant species on the latter. For example, following the introduction of paints containing tributyltin, the previously dominant, copper-tolerant alga *Enteromorpha* spp. were replaced by *Ectocarpus* spp., as the dominant cosmopolitan fouling algae (Callow 1986a).

6.1.3.2 Fouling location (niche areas versus general hull)

Recreational vessels (Floerl et al. 2008):

- Overall, niche areas represented ca 6.8% of the total wetted surface area of the hull of international yachts, or ca 14 times less than the general hull areas;
- Despite the difference in relative area, niche areas contained nearly 75% of the total fouling biomass on each international yacht, with rudder (including the shaft) and keel contributing the most (43.4% and 38.4%, respectively) and the general hull areas the least (0.46-3.26%);
- 89% of total species richness on recreational vessels occurred in niche areas;
- Among niche areas, unpainted parts of the hull contained, on average, 30-50% of the total species pool of a yacht, while antifouled parts of the hull contributed 5-10%;
- Amphipods, ascidians, barnacles, bryozoans, bivalves and polychaete worms occurred 1.8-4.8 times more frequently in niche areas than on the general hull, while no taxa occurred more frequently on the general hull than in niche areas;
- 20% (22 out of 111) of all species were only collected from general hull areas, including barnacles, motile crustaceans, bryozoans, ascidians, macroalgae, polychaetes and bivalves and including 13 NIS or cryptogenic species;
- 35% (39 out of 111) of all species were recorded only from niche areas, including barnacles, motile crustaceans, bryozoans, hydroids, ascidians, macroalgae, polychaetes and bivalves and including 26 NIS or cryptogenic species;
- Average biomass density, average percentage cover and average number of species were higher in niche areas than on other (antifouled) parts of the hull by factors of 13.5, 9.5 and 5.3, respectively;
- Areas of the hulls that were not antifouled (dry-docking support strips) had fouling percentage cover similar to that of niche areas (ca 24%), 5.4 times larger average biomass and 15% larger average number of species, although only a few yachts had dry-docking support strips; and,
- Comparing different niche areas on international yachts, average biomass density, average percentage cover and average total number of species were highest on bow thrusters and decreased in the sequence: keel, propeller and propeller shaft, gratings, rudder and rudder shaft, although these differences were not statistically significant.

Commercial vessels (Inglis et al. 2010):

- Approximate estimates suggest that niche areas may comprise up to 20% of the submerged surface area of merchant vessel hulls (Section 3, Coutts 1999);
- 98% of total species richness on merchant vessels occurred in niche areas (and the percentage contribution was less variable among individual merchant vessels than among individual recreational vessels); and,
- Of the merchant vessels with some biofouling, the most commonly fouled niche areas were: gratings (67% of fouled vessels); bow thrusters (40%); stern (35%); rudder and shaft (32%); and propeller and shaft (29%).

6.1.3.3 Duration of vessel visit

The prescribed durations of visit for the present study are: < 48 h; 2-10 d; 10-21 d; > 21 d. Information on the duration of visits to ports in New Zealand by international vessels is provided by Inglis et al. (2011):

- Most (96.6%) international recreational vessels spend more than 14 d in each port, while the remaining 3.4% spend 1-14 d;
- The average duration of stay in each port visited by international recreational vessels in 2002-2003 was 24.2 d (range 1.8-357 d);
- 73% of passenger vessels spend < 1 d in port, and only 1% spend more than 14 d;
- Among other types of commercial vessels, 8-72% spent < 1 d, 39-87% spent 1-14 d and 3-36% spent > 14 d;
- The average time in port for container vessels ranges from < 1 d for smaller vessels to 2.4 d for the largest;
- Most visits by tankers are of 1-3 d duration but smaller tankers tend to make shorter visits (< 1 d);
- The likelihood that biofouling species will spawn or escape from a vessel will increase with increasing time spent in port; and,
- For vessels visiting a single port for < 1 d, this risk is small (but not negligible)

6.1.3.4 Seasonality of biofouling

Recreational vessels (Floerl et al. 2008):

- There were no clear patterns in the average fouling biomass, percentage cover, number of species and number of NIS recovered from yachts that arrived in New Zealand from different bioregions (Australia and the South Pacific) during winter and summer sampling periods; and,
- Mean biomass density was, however, ca 3 times higher on yachts arriving in winter (0.031 kg m^{-2}) than in summer (0.011 kg m^{-2}), and 3.3 times higher on yachts arriving from Australia (0.038 kg m^{-2}) than from the South Pacific (0.011 kg m^{-2}).

Commercial vessels (Inglis et al. 2010):

- There were no clear trends in the average species richness or biomass among container/cargo vessels arriving in New Zealand in summer, winter, autumn or spring.

6.1.4 Overall summary

While there is a body of general information relevant to assessing the biosecurity risks from in-water cleaning, we agree with the conclusion of Floerl et al. (2010a) that it is dependent on a large number of confounding factors (such as effects of local environmental conditions at the time of cleaning, the detailed composition of fouling assemblages and the reproductive status of their components). There is currently insufficient information available to allow a quantitative assessment and ranking of risks from the various prescribed in-water cleaning scenarios or the option of no action. How this lack of quantitative information was overcome is described in Section 6.2.

6.2 IS THERE A SIGNIFICANT DIFFERENCE IN RISK BETWEEN THE OUTCOME OF THE PREVIOUS QUESTION AND THE MANAGEMENT OPTION OF TAKING NO ACTION?

6.2.1 Approach to assessing the relative risk of in-water cleaning

A three-tiered approach was taken to answering this question. The first tier required each subject matter expert to make an assessment of the relative biosecurity risk of each of the combinations of:

- Vessel origin (international/domestic);
- Vessel type (commercial/recreational);
- Antifouling coating type (biocidal/biocide-free);
- Fouling type (slime layer/spot fouling/soft fouling/hard fouling);
- Cleaning method (soft cloth/hand removal/brush);
- Method of cleaning (no action/hand removal/soft cloth/brush cleaning); and,
- Whether or not waste-capture technology was used (Section 4.1, MAF 2011a).

These assessments were informed by the literature review and the assessor's expertise.

Individual assessments were then combined into a joint assessment using the Infection Modes and Effects Analysis (IMEA) method developed by Hayes (2002) (Section 6.2.2). This was a relatively coarse assessment, identifying those scenarios that clearly (in the collective opinion of the subject matter experts) posed negligible or unacceptable biosecurity risk.

The second tier analysed those scenarios requiring further consideration by taking into account the additional factor of the duration of vessel visit to the receiving port. Again, each subject matter expert made an individual assessment of whether the no action scenario was of less biosecurity risk than each of the alternative scenarios for each of three visit durations (< 48 h, 2-10 d, 10-21 d (Sections 6.1.3.3 and 6.2.3)). Individual assessments were then combined through a Delphi process, noting those that differed from the majority assessment and any assumptions made.

Several subject matter experts identified the level of fouling on a vessel (LOF) as an additional factor that needs to be taken into account in assessing relative biosecurity risk of different cleaning scenarios. A third-tier assessment was therefore made of the same set of scenarios as the second tier, with this factor included (Section 6.2.4).

Each of these tiers is described in more detail below.

6.2.2 Infection Modes and Effects Analysis

The qualitative risk ranking process used by Floerl et al. (2010a) was extended to compare the relative environmental risks from specified cleaning strategies for commercial and recreational vessels. The Infection Modes and Effects Analysis (IMEA) method (Hayes 2002) was used to investigate the spread of marine organisms by human vectors. This approach allows the qualitative risk assessments of several subject matter experts (Floerl, Georgiades, Lewis, Morrisey, Page and Woods) to be synthesised in a transparent manner into an single, overall assessment of the relative risk of each of the prescribed vessel types and cleaning scenarios.

The overall risk of non-indigenous species becoming established as a result of in-water cleaning was broken down into a series of components. These were:

1. The likelihood of arrival of a new species;
2. The amount of fouling removed by each of the prescribed cleaning scenarios;
3. The proportion of the material removed that is captured under each scenario;
4. The likelihood that material not captured is capable of establishing in the receiving environment;
5. The likelihood that release of propagules is stimulated by cleaning; and,
6. The residual risk of propagule release from fouling left on the hull (including the no action scenarios).

Each subject matter expert independently assessed the relative risk for each risk component under each of the prescribed vessel type versus cleaning scenarios, scoring each on a scale of 1-10 (1 being the lowest biosecurity risk). These assessments were made using the information collated in Sections 4 and 6.1 and as provided to the assessors in the spreadsheet used to conduct the IMEA (Appendix 10.1).

The overall risk ranking (the Risk Priority Number, RPN) for each scenario was calculated as the product of the scores (1-10) of the individual risk components for the scenario in question. These calculations were performed in an Excel spreadsheet. Each component was simultaneously scored for minimum, maximum and "average" risk to capture the uncertainty inherent in each assessment, and equivalent minimum, maximum and average RPN values calculated ($RPN_{minimum}$, $RPN_{maximum}$ and $RPN_{average}$).

$RPN_{minimum}$, $RPN_{maximum}$ and $RPN_{average}$ values were each then averaged across the six subject matter experts to provide an overall assessment of the relative biosecurity risk of each scenario (Table 8.6). The $RPN_{average}$ values were plotted against cleaning scenario to identify those scenarios considered by the project team to represent the highest biosecurity risk (Figure 6.1).

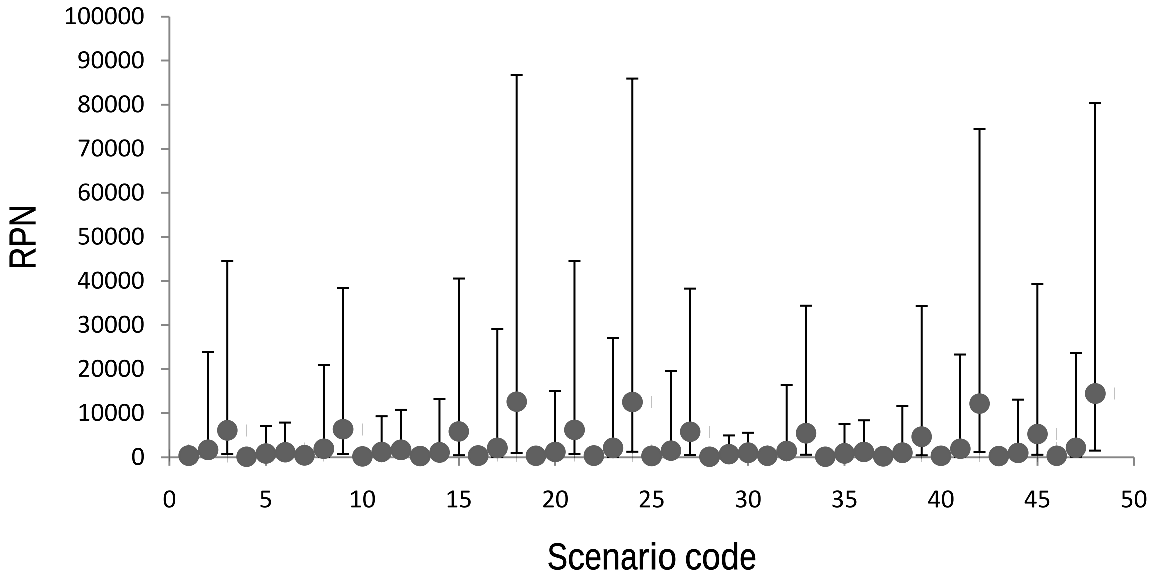

Figure 6.1 Risk Probability Numbers (error bars are averaged minimum and maximum estimates) averaged across the six subject matter experts. Values are shown for each of the prescribed vessel type/cleaning scenarios, identified by the code numbers (1-48) shown in Table 8.6. See text for details.

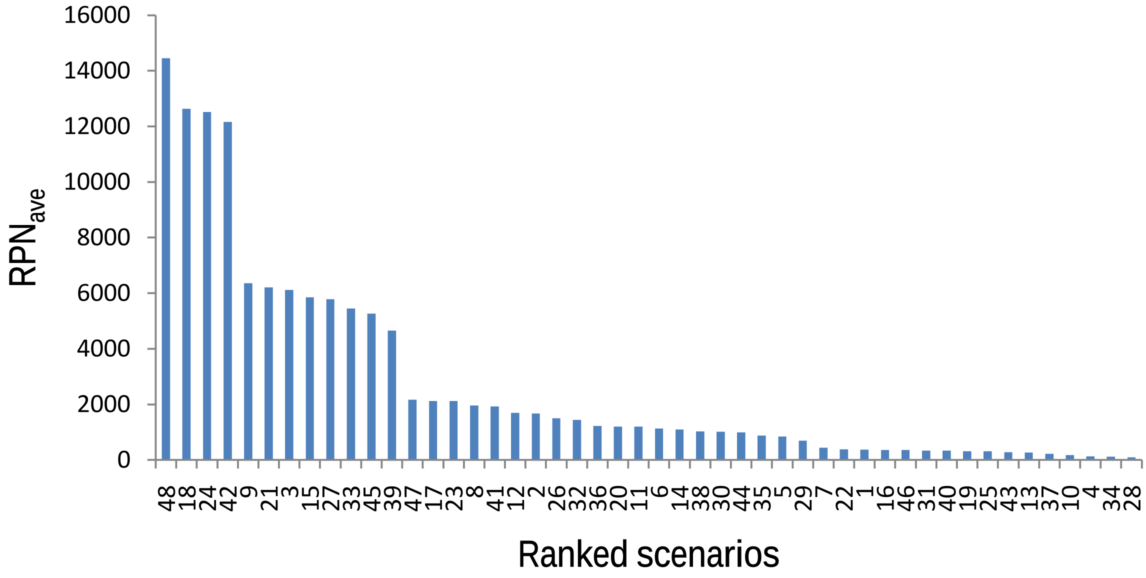

Figure 6.2 Prescribed vessel type/cleaning scenarios ranked by their average Risk Probability Numbers (RPN_{ave}) value (averaged across the six subject matter experts). Scenarios are identified by the code numbers (1-48) shown in Table 8.6. Highest risk scenarios are on the left. See text for details.

Ranking of the scenarios by their $RPN_{average}$ values shows that the collective estimates of relative risk decline in a series of steps (Figure 6.2). The group of four highest-risk scenarios (left-hand side of the plot in Figure 6.2) all involve brush cleaning of hard fouling on commercial vessels with no capture of waste. The eight scenarios in the next highest-risk group involve hand removal of spot fouling on recreational vessels or brush cleaning of slime layers and soft fouling on commercial vessels, again with no capture of waste. The next 12 scenarios were cleaning using recapture technology, followed by slime layer removal and the no action scenarios.

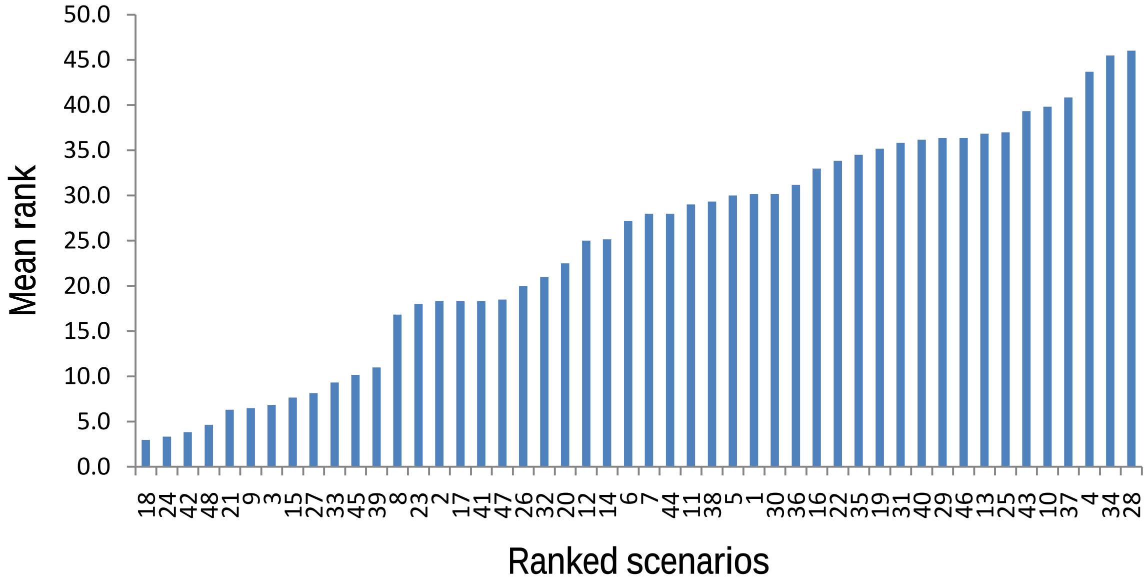

Figure 6.3 Prescribed vessel type/cleaning scenarios ordered by the average rank of their Risk Probability Numbers (RPN_{ave}) across the six subject matter experts. Scenarios are identified by the code numbers (1-48) shown in Table 8.6. Scenarios with the highest risk are on the left. See text for details.

When the rank of the RPN scores given to each scenario was averaged across the six subject matter experts and the scenarios ordered by their averaged rank (Figure 6.3), the same 12 scenarios came out as having the highest biosecurity risk, although the sequence of scenarios in the ranking was slightly different. This method of displaying the results of the IMEA smoothes out some of the variation seen in the average values in Figure 6.1 and Figure 6.2 because it downplays differences in the numerical scores (1-10) given to each scenario in each component of the analysis by the different team members.

Summary
The collective assessment of the subject matter experts is that in-water brush or spot cleaning of vessels without capture of waste represents the highest level of biosecurity risk and should not be permitted. This assessment applies to both international and domestic vessels because it considers the risk of release of propagules of risk species into the receiving port regardless of whether the risk species are already present at other ports in New Zealand. In the case of domestic vessels cleaned in their port of origin, however, this may be relaxed under certain circumstances (Section 6.2.4).

The IMEA does not explicitly address differences in relative risk due to the intended duration of stay of the vessel in the port or the level of fouling on its hull. The lowest ranked scenarios (right-hand side of the plot in Figure 6.3) are those involving no action. This ranking is, however, at least partly an artefact of the imbalance between the number of components of overall risk (components [1] to [6] of the IMEA) in which the no action scenarios can potentially score highly (3 components) versus the number in which the other scenarios can score highly (all 6 components). As a default, the no action scenarios scored “1” for each of the cleaning-related components, therefore their final RPN scores were constrained relative to other scenarios (because the RPN is the product of the scores of the individual components).

This artefact could be addressed in two ways:

1. The components of the overall biosecurity risk in the IMEA can be restructured in such a way that risks for the no action and cleaning scenarios are symmetrical and there is (theoretically) an equal chance that each could achieve a score anywhere in the range 1-10 for each component; and,
2. The artefact can be explicitly acknowledged and addressed *post hoc* in a separate assessment by the project team.

The second option was chosen because it allowed more flexibility in incorporating other relevant factors when considering individual scenarios for which the IMEA did not identify clear acceptability or unacceptability. In effect the IMEA was used as a first-cut analysis to eliminate cleaning scenarios that clearly posed negligible or unacceptable biosecurity risk. The remaining scenarios were then reassessed taking into account other relevant factors.

6.2.3 Incorporating duration of visit into assessments of biosecurity risk

One of the main factors influencing the risk associated with the no action scenarios is the length of time the vessel spends in port. Under the no action scenario, the biosecurity risk increases over time because of the cumulative probability of release of propagules. In reality, however, there may be a slight short-term decline in risk after an initially high risk because some species, such as mussels, may release propagules immediately on arrival, in response to temperature, salinity or other environmental shocks or mechanical damage during vessel docking. For example, Apte et al. (2000) describes the spawning and subsequent establishment of *Mytilus galloprovincialis* in Hawaii within 2 h of vessel arrival, apparently in response to the difference in water temperature between the vessel’s ports of origin and destination.

How quickly the biosecurity risk increases with time is a function of the instantaneous rate of propagule release. This is unknown and will be highly variable among species and over time, but is presumably higher for species that spawn frequently or over long periods rather than in one event. For example, *Ciona intestinalis* can release eggs every other night over summer and *Undaria pinnatifida* releases spores over a reproductive season of several months. Numbers of gametes or propagules released can be very large in some (r-selected) species but this does not necessarily mean greater risk of establishment since (k-selected) species producing fewer but more advanced or better-provisioned larvae may be equally or more successful at recruiting and establishing.

Probability of propagule release during the period a ship is in port is also dependent on the suitability of local environmental conditions for survival of biofouling species on a hull (particularly relevant for international arrivals), and the time to sexual maturity of the fouling organisms. The shorter this latter period, the more likely it is that individuals will reach sexual maturity before or after arrival in port. Examples of maturation times of some fouling organisms are given in Table 4.2.

The IMEA did not consider timing as a factor but this must now be taken into account in addressing the risks of no action versus cleaning scenarios. The durations of vessel stays in port examined in the present study were:

- < 48 h;
- 2-10 days;
- 10-21 days; and,
- > 21 days.

These durations can be considered in the context of the proposed thresholds for the vessel biofouling Craft Risk Management Standard (CRMS) (E. Georgiades, MPI, pers. comm.). These specify acceptable levels and types of fouling on different parts of a vessel (general hull, wind/water line, niche areas) arriving in New Zealand for different durations of visit (“short-stay” < 21 d, “long-stay” > 21 d). Any vessel intending to stay more than 21 d must have no more than slime-layer fouling on all parts of the hull, with allowances for goose barnacles. A number of points are relevant when relating the visit durations specified for the present study with those in the CRMS and the IMEA:

- The IMEA has implicitly considered the < 48 h timeframe because it assumes the risks of propagule release from an uncleaned hull to be low. The risk is not, however, negligible, as evidenced by the spawning of mussels within 2 h of arrival (Apte et al. 2000); Nevertheless, from a practical perspective, 48 h appears to be a reasonable compromise in that international vessels visiting only one port in New Zealand generally have a turnaround time of 1-3 days (Inglis et al. 2011);
- Strictly, in the case of international vessels, this interpretation of the < 48 h scenario applies to vessels that only visit one port. If they stay < 48 h at their port of arrival but then move on to other ports within New Zealand, the likelihood of propagules being released will continue to increase. Under the proposed CRMS thresholds (E. Georgiades, MPI, pers. comm.), however, short-stay vessels are only allowed to visit designated Places of First Arrival (designated under the Biosecurity Act 1993). If they wish to visit places that are not so designated, they will be bound by the long-stay thresholds of acceptable fouling (i.e. slime layer and goose barnacles only on all hull surfaces);

- In the case of visits of > 21 d duration ("long-stay") and/or vessels that intend to visit areas other than those designated as Places of First Arrival, the maximum acceptable amount of biofouling on any part of the hull is slime layer and goose barnacles;
- In-water cleaning techniques without recapture technology are not acceptable options for international vessels staying between 2 and 21 d; and,
- Recreational vessels staying between 2 and 21 d and with only a slime layer do not need to be assessed or cleaned because they fall within the acceptable level of fouling for long and short-stay visits.

Removing the above from the list of 48 vessel type/cleaning scenarios left 12 scenarios for assessment against the scenario of no action under the category of visits of > 2 d duration (Table 6.1).

Table 6.1 Vessel type/cleaning scenarios to be assessed against the option of no action for vessel visits of > 2 d duration.

Scenario number	Origin	Vessel	Paint	Fouling type	Recapture
2	International	Recreational	Biocide	Spot fouling, hand removal	Yes
8	International	Recreational	Biocide-free	Spot fouling, hand removal	Yes
14	International	Commercial	Biocide	Slime layer/soft fouling, brush cleaning	Yes
17	International	Commercial	Biocide	Hard fouling, brush cleaning	Yes
20	International	Commercial	Biocide-free	Slime layer/soft fouling, brush cleaning	Yes
23	International	Commercial	Biocide-free	Hard fouling, brush cleaning	Yes
26	Domestic	Recreational	Biocide	Spot fouling, hand removal	Yes
32	Domestic	Recreational	Biocide-free	Spot fouling, hand removal	Yes
38	Domestic	Commercial	Biocide	Slime layer/soft fouling, brush cleaning	Yes
41	Domestic	Commercial	Biocide	Hard fouling, brush cleaning	Yes
44	Domestic	Commercial	Biocide-free	Slime layer/soft fouling, brush cleaning	Yes
47	Domestic	Commercial	Biocide-free	Hard fouling, brush cleaning	Yes

The six subject matter experts assessed each of the cleaning scenarios in Table 6.1 against the no action scenario for vessel visits of both 2-10 d and 10-21 d. The following information and assumptions were taken into consideration:

- Among the cleaning scenarios to be considered, hand removal of spot fouling probably offers the best chance of removing all of the fouling and of capturing the material removed;
- Brush cleaning of hard fouling is less successful than for soft fouling and, when small barnacles are present, for example, a smaller proportion of the material removed is captured;

- Brush-cleaning of hard fouling is more likely to kill the organisms removed whereas fragmentation of clonal organisms with soft fouling assemblages presents a relatively high probability of establishment if the material is not captured;
- Hard fouling may harbour soft-fouling species and both soft and hard fouling are likely to harbour motile species, which have relatively high rates of viability after removal and are likely to be less easily captured; and,
- The likelihood of release of propagules from an uncleaned hull increases over time. Assuming that some fouling organisms may reach sexual maturity within four weeks after settlement (Table 4.2) and an average voyage time for international vessels to New Zealand of 11 d (Inglis et al. 2010), there is a chance that some fouling organisms present on the hull at the time of arrival will become sexually mature within 10-21 d of arrival.

The individual assessments were then combined in a Delphi process to identify the majority decision and to record variations among individual assessments (Table 8.7).

Summary

For visits of 2-10 d duration by international commercial vessels, the majority decision was that in-water cleaning was preferable to the option of no action. Cleaning is likely to minimise biosecurity risk where hard fouling was present because of the risk of propagule release from this level of fouling over the duration of visit. In the case of slime layer/soft fouling, there was a majority preference for the option of no action because the risk of propagule release from this level of fouling was considered to be less than that from cleaning. For visits of longer duration (10-21 d), however, cleaning was considered the better option than no action because of the increasing risk over time of propagule release from an uncleaned hull.

Hand-cleaning of spot fouling on recreational vessels was considered to be of relatively lower biosecurity risk than that of commercial vessels because of the smaller amount of material that could potentially be released during cleaning. Therefore, in-water cleaning was the preferred option for visits of 2-21 d.

Release of propagules from uncleaned hulls of domestic vessels was considered less of a biosecurity risk than that from international vessels. Consequently, for visits by both commercial and recreational vessels of 2-10 d and 10-21 d duration, the majority decision was that it was preferable to leave the vessels uncleaned. However, there was more variation among subject matter experts in their assessments of the relative risks of cleaning versus not cleaning for domestic vessels. In the case of domestic commercial vessels with hard fouling there was no clear majority decision.

In the case of spot fouling on recreational vessels, the relatively small amount of material to be removed and the relative ease of capture resulted in a decision in favour of cleaning vessels on visits of 10-21 d. For shorter visits, the biosecurity and financial costs of cleaning were not considered justified for the resulting, relatively small reduction in biosecurity risk provided by the reduced risk of propagule release from the cleaned hull.

In addition to their assessments of relative risk, the assessors also noted the following points:

- Domestic vessels were assumed not to travel or have travelled outside New Zealand;
- Hard fouling can be susceptible to vessel-to-vessel transfer;
- Irrespective of capture efficiency, the sooner fouling is removed, the better;
- Although voyage time to New Zealand from last international port of call may be short (e.g. 11 d); the origin, and therefore time of settlement and age, of fouling may be prior ports of call. A short time since last dry docking is the only surety of biofouling age; and,

- Cleaning of biocide-free paints should be done in such a way that damage to the paint surface, and consequent risk of increased recolonization, is minimised.

The initial assessment of the 12 scenarios (Table 8.7) identified the level of fouling as another factor that needs to be taken into account when assessing the relative biosecurity risk and acceptability of different cleaning scenarios. This factor, together with the bullet points above, was incorporated into the process of assessing the acceptability of the different cleaning scenarios through an additional stage.

6.2.4 Incorporating level of fouling into assessments of biosecurity risk

The relative biosecurity risk and the acceptability of each of the 12 scenarios was reassessed taking into account different levels of fouling (LOF: Floerl et al. 2005a), defined as follows:

- Level 2 – light fouling, 1-5% of hull covered by macrofouling or filamentous algae, remaining area usually covered in slime;
- Level 3 – considerable fouling, macrofouling clearly visible but still patchy, 6-15% of hull covered by macrofouling or filamentous algae, remaining area usually covered in slime;
- Level 4 – extensive fouling, 16-40% of hull covered by macrofouling or filamentous algae, remaining area usually covered in slime; and,
- Level 5 – very heavy fouling, 41-100% of hull covered by macrofouling or filamentous algae, remaining area usually covered in slime.

In the following assessments the in-water cleaning of heavily fouled (LOF > 3) commercial vessels was considered unacceptable even when capture technology is used because of the reduced cleaning and capture efficiency at high levels of fouling. This is based on the capabilities of currently-available cleaning and capture technology (Section 6.1) but it is feasible, and to be hoped, that future technology developments may improve the efficiency of cleaning and capture such that in-water cleaning of these vessels becomes acceptable from the biosecurity perspective.

Consistent with the treatment of international commercial vessels with fouling levels > 3, in-water cleaning is considered unacceptable for international recreational vessels, even when capture technologies are used, because of the biosecurity risk that results from the decreased efficiency of capture of biofouling removed from the hull and the reduced effectiveness of cleaning (which reduces the benefits of cleaning) at these fouling levels.

With respect to mitigation/management of heavily fouled vessels (LOF > 3) that either arrive in New Zealand or wish to transfer between domestic ports, the following actions should be considered:

- Haul out for cleaning;
- Reduction of visit duration to < 48 h; or,
- Refusal of entry.

The assessment also considered whether in-water cleaning of domestic vessels should be done at the vessel's port of origin or at the receiving port. The results are shown in Table 8.8.

Summary
In-water cleaning (with capture of waste) is considered an acceptable practice for international commercial and recreational vessels with low levels of fouling (LOF ≤ 3) for visits between 2-21 d. Although the initial risk of "natural" propagule release from the uncleaned hull (and the consequent biosecurity benefit of cleaning) is relatively low this will increase over time. Cleaning is also consistent with the "clean before you leave" philosophy".

For international vessels with LOF > 3, the risk of "natural" release of propagules from the uncleaned hull is relatively large, and will increase with duration of visit. However, the risk of release of viable propagules during cleaning is larger, due to less efficient capture, and the efficiency of cleaning is also reduced. Consequently, in-water cleaning is not recommended for international vessels with LOF > 3, therefore the vessel should be hauled out for cleaning, have the duration of visit reduced to < 48 h, or be refused entry.

In the case of cleaning of domestic vessels, cleaning at the port of origin ("clean before you leave") is acceptable and is the preferred to the option of no action. Cleaning at the port of origin poses less biosecurity risk than cleaning at the receiving port because most, if not all, of the fouling present will theoretically occur in that port. When a vessel has been present in a port long enough that there is certainty that all of its fouling was acquired there, in-water cleaning before moving to another port is the preferred option. From the perspective of biosecurity risk, this can be done without capture. However, particularly for LOF > 3, there must be certainty that the biosecurity risk is minimal, based on the voyage history and, if necessary, a pre-cleaning inspection.

For visits of < 10 d, domestic commercial vessels with LOF ≤ 3 are considered to present a small risk of "natural" propagule release and are better left uncleaned at the receiving port. An exception would be in cases where there are specific risk factors indicated by the vessel's voyage history, such as having recently visited a port known to contain a NIS not currently present in the receiving port. In this case, the vessel should be cleaned in the water (with capture of waste), hauled out to clean, have the duration of visit reduced to < 48 h or be refused entry to the port. A pre-arrival inspection of the hull may be appropriate to assess the level of risk. For longer visits (> 10 d), the low initial risk of "natural" propagule release will increase with time, therefore cleaning (with capture) as soon as possible after arrival is appropriate.

For domestic commercial vessels with LOF > 3, the efficiency of in-water cleaning and capture of waste will be reduced and the risk of release of viable NIS consequently greater. If the intended stay is < 10 d, cleaning is not recommended at the receiving port depending upon specific risk factors. In this case the vessel should be hauled out to clean as soon as possible after arrival, the duration of visit reduced to < 48 h, or be refused entry. In-water cleaning is not appropriate for intended stays of > 10 d.

Domestic recreational vessels intending to stay in the receiving port for less than 10 d, and with LOF ≤ 3 (i.e. spot fouling) pose a relatively small risk of "natural" propagule release from the uncleaned hull. However, in-water cleaning (with capture of waste) is encouraged because the small amount of fouling removed and the likely effectiveness of capture reduce the risk of propagule release during in-water cleaning. Cleaning is particularly important if there are specific risk factors associated with the vessel's voyage history. Where the intended length of stay is > 10 d, all domestic recreational vessels with LOF ≤ 3 should be in-water cleaned as soon as possible after arrival because the risk of "natural" propagule release from the uncleaned hull will increase over time. Alternatively, such a vessel may be required to haul out and clean, reduce the duration of its visit to < 48 h or be refused entry.

Domestic recreational vessels with LOF > 3 (i.e. greater than spot fouling) should not be cleaned in-water in the receiving port, even when capture technologies are used. For visits of 2-10 d duration, vessels with LOF > 3 should not be cleaned. If specific risk factors are present, the vessel should be hauled out and cleaned, have the duration of visit reduced to 48 h, or be refused entry. For visits of 10-21 d duration the vessel should be hauled out and cleaned, have the duration of visit reduced to 48 h, or be refused entry.

6.3 WHAT CONDITIONS APPLIED TO IN-WATER CLEANING METHODS WOULD ENSURE THE MANAGEMENT TO ACCEPTABLE LEVELS OF CONTAMINANT RELEASE INTO THE SURROUNDING ENVIRONMENT?

6.3.1 Soft-cloth removal of slime and hand-cleaning of spot fouling

Paint scrapers and stiff brushes are the most commonly-used tools for removing fouling from small vessels (Floerl et al. 2005b). Material hand-cleaned from a hull using cloths or scrapers can be captured by enclosing the area to be cleaned in a mesh bag, as done by Woods et al. (2007) in their experimental study (using a 200 µm mesh). However, this could be difficult to effect around some niche areas, and may require deformable mesh frame to mould to curved surfaces. Currently, some commercial dive companies attempt to capture material in bags when spot-cleaning in order to minimise the amount of material released (Sol Fergus, New Zealand Diving & Salvage Ltd, pers. comm.). In theory, a large proportion of the material should be capturable as it is scraped off. Woods et al. (2007) did not estimate the proportion captured, but some relatively buoyant material, such as fragments of macroalgae and hydroids, was carried away by water currents (O. Floerl, NIWA, pers. comm.). Loss of material is likely to be much greater in fast currents.

More effective capture may be achieved using a suction hose in combination with hand-cleaning, as used for the removal of *Didemnum* from a fouled barge (Coutts 2002), allowing waste to be actively captured. Such a hose and nozzle, with an easily-cleaned, coarse pre-filter to prevent clogging by hard fouling organisms, could be housed within a shroud surrounding the scraping tool. Back-flushing of material clogged on the pre-filter into a secondary collection bag may be required.

6.3.2 Brush cleaning of soft and hard fouling

Proprietary diver-held brush cleaning equipment capable of capturing the waste produced (for polishing propellers and cleaning other niche areas) are available overseas (Section 4.2.1). For example, Underwater Contractors Spain (UCS: www.ucspain.com) offers diamond-disc and hydraulic brush cleaning of propellers and seals, incorporating “the ECO Propeller Cleaning Solution, which captures all debris in a filter system”. UMC and Seaward Marine also offer diver-held brush cleaning with capture, using a shroud to surround the cleaning head and contain waste (Bohlander 2009). Presumably the waste is collected by suction and pumped through a filter, however no further information is publicly available.

Small-scale, diver-operated brush systems developed in New Zealand for specific projects or as proof-of-concept (Coutts 2002, Hopkins et al. 2008) indicate the potential for local development of technology in response to market demand. Commercial dive companies contacted during the present study indicated that they were very willing to develop the appropriate technology if there was a demand for it. The devices described by Hopkins et al. (2008) were effective at cleaning and capturing the waste from flat surfaces but less so for curved surfaces and, since they were fairly large (Fig. 1 of Hopkins et al. 2008) are not suitable for cleaning confined niche spaces. The suction required to collect waste material made the cleaning heads difficult to manoeuvre over the hull. The hoses taking the waste to the filter system were also unwieldy and tended to scrape against the hull, dislodging fouling organisms that were not subsequently captured. Access to confined areas will be constrained by the arrangement of the suction hose for removal of waste and hydraulic hoses to drive the brushes, which need to be either articulated or sufficiently flexible.

There are no brush-based systems currently available in New Zealand (or Australia) that can clean large vessels and capture the waste released, but at least three (UCS, UMC and Subsea Solutions) are reportedly in use or in development overseas and could presumably be brought to New Zealand if there was demand for their services (Section 4.2.1).

The Western Australian Department of Fisheries issued a request for proposals in 2011 for an in-water hull cleaning and filtration system, capable of cleaning fouling from larger commercial vessels, separating the solids via a first stage 50 µm filter, then removing particles > 2 µm via a cross-flow cartridge system before a final ultra-violet light treatment stage prior to return of the effluent to the sea. The contract was awarded to a local company and the system has been developed to the testing stage. However, testing is currently suspended for technical reasons, apparently related to the effects on chemical water quality (Justin MacDonald, WA Fisheries, pers. comm.).

6.3.3 Filtration systems for effluent

Most capture systems involve pumping the waste through a filter or series of filters, with the filtered effluent often being returned to the sea. The filtration pore size determines the effectiveness of the capture system for marine NIS (and for particles of paint). A pore size of 60 µm was recommended by McClary & Nelligan (2001) to contain all mature organisms and the majority of propagules for 43 target species identified in their study. This standard has been adopted in Biosecurity New Zealand's (now the Ministry for Primary Industries) guidance document for standards for facilities for the removal of biofouling from vessels that have arrived in New Zealand from overseas.[7] Filtration with pore-sizes down to 50 µm will remove zooplankton and pore-sizes of 20 µm will remove hypnocysts of toxic dinoflagellates (Woods et al. 2007). Woods et al. (2007), however, concluded that zoospores and propagules were found in final shore-based effluent facilities and should not be discharged back into the marine environment. Removal of diatoms and algal spores requires specialized techniques such as sand filters, cyclonic separators or microsand ballasted clarification (as used in the US Navy's Advanced Hull Cleaning System (Bohlander 2009): see http://blog.hpthompson.com/wp-content/uploads/2011/09/ACTIFLO.pdf).

The suction collection system for waste described by Coutts (2002) passed the effluent through a 200 µm pre-filter and into a second pre-filter chamber where 100 µm and 200 µm filters were tested for effectiveness. A second in-line pump then passed the water through a filter bag in which mesh sizes of 1-200 µm were tested for retention of suspended solids. Successful filtering down to 50 µm was achieved at the third stage, but filters with smaller mesh all failed (i.e. particles larger than the mesh size were found in the filtered effluent).

The pore sizes of the series of filters used to treat effluent from one of the brush systems tested by Hopkins et al. (2008) ranged from 1-30 µm. The second system pumped straight into a collection bag, with subsequent filtration capability of 30-1,200 µm.

McClary & Nelligan's (2001) recommendation of a filter pore-size of 60 µm for treatment of waste from hull-cleaning facilities was based on the assumption that smaller propagules, notably spores of *Undaria pinnatifida* (10 µm diameter), were unlikely to survive typical shore-based hull cleaning practices. Survival of these propagules may be better during in-water cleaning, partly because they are released into seawater rather than onto a wash-down area where temperature, salinity and other variables are likely to be more variable and

[7] Guidance Document to the Standards for General Transitional Facilities for Uncleared Goods, as amended and reissued 1 September 2011, available at www.biosecurity.govt.nz/border/transitional-facilities/bnz-std-tfgen.

mechanical shock more likely. Consequently, and for consistency with the system under development in Western Australia described above, we propose a smaller minimum size for filtering of effluent from in-water cleaning of 2 µm. A system of pre-filters with decreasing pore sizes and in-line pumps will be necessary to achieve this level of filtration. Waste retained on the filters should be disposed of to land where there is no possibility that leachate will flow to the sea.

As an alternative to filtration on board the support vessel or on the wharf where the vessel is berthed, the waste stream may be coarse-filtered (1 mm, consistent with MPI's standards for facilities for the removal of biofouling from vessels). The solid waste should be disposed of to land. The liquid effluent should then be discharged to a system that kills all organisms larger than 2 µm (for example, by irradiation with ultra-violet light) or to a sewage system with secondary treatment, or processed through sand filters to remove particles larger than 2 µm, or directly to the ground if more than 100 m from the sea (or any waterway or drainage system to the sea) and on permeable ground that is able to absorb all discharged water and where there is no likelihood that it could flow back to the sea within two days (again, consistent with MPI's standards for facilities for the removal of biofouling from vessels).

Collection of defouled material by suction and lifting it into a filtration system on a barge or on the dockside requires adequate pump power and infrastructure. For example, the experimental systems developed for the study by Hopkins et al. (2008, their Fig. 41) used 12 or 40 hp pumps, which required a truck to transport them. The equipment used to clean the barge described by Coutts (2004) was housed on a second barge moored next to the fouled vessel.

Despite the need for large and heavy equipment for pumping and filtering, the above examples illustrate that this is logistically possible where suitable access to the fouled vessel is available via land or water. In-water cleaning will be most effective when the vessel is on a mooring rather than alongside a wharf, because of ease of access for divers and cleaning equipment (Hydrex Group 2012). However, calm conditions and good water clarity are required for effective and thorough cleaning. In this case pumping and filtering equipment will have to be mounted on a support vessel. If cleaning is done alongside a wharf it may be possible to discharge waste directly to a sewer or other waste-water treatment system. McClary & Nelligan (2001) and Floerl et al. (2005c) provide guidelines for treatment of waste from hull cleaning operations and identify New Zealand facilities with compliant treatment systems.

6.3.4 Summary

More effective capture of material removed by cleaning of slime-layer and spot fouling may be achieved using a suction hose in combination with hand-cleaning, allowing waste to be actively captured. Such a hose and nozzle, with an easily-cleaned, coarse pre-filter to prevent clogging by hard fouling organisms, could be housed within a shroud surrounding the scraping tool.

Proprietary diver-held brush cleaning equipment capable of capturing the waste produced (for polishing propellers and cleaning other niche areas) are available overseas. Experimental versions of diver-operated devices developed in New Zealand are not suitable for cleaning confined niche spaces. Further, the hoses that take the waste to the filter system were unwieldy and tended to scrape against the hull, dislodging fouling organisms that were not subsequently captured. However, commercial dive companies indicated that they were willing to develop the appropriate technology if there was a demand for it.

There are no brush-based systems currently available in New Zealand (or Australia) that can clean large vessels and capture the waste released. However, at least three systems are reportedly in use or in development overseas and could presumably be brought to New Zealand if required.

Most capture systems involve pumping the waste through a filter or series of filters, with the filtered effluent often being returned to the sea. The filtration pore size determines the effectiveness of the capture system for marine NIS (and for particles of paint). The maximum proposed size for filtering of effluent from in-water cleaning is 2 µm. A system of pre-filters with decreasing pore sizes and in-line pumps will be necessary to achieve this level of filtration. Waste retained on the filters should be disposed of to land where there is no possibility that leachate will flow to the sea. Alternatively, the waste stream could be passed through a coarse filter (e.g. 1 mm) and the liquid effluent discharged to:

- A system that kills all organisms larger than 2 µm; or,
- To a sewage system with secondary treatment; or,
- Processed through sand filters to remove particles larger than 2 µm; or,
- Directly to the ground if there is no likelihood that it could flow back to the sea.

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8 Tables

Table 8.1 New Zealand EPA approved and commercially available antifouling paints for vessels – January 2012.

Company Product Name	Cuprous oxide	Cuprous thiocyanate	Chlorothalonil	Copper pyrithione	Dichlofluanid	Diuron	DCOI	Irgaorol 1051	Mancozeb	Octhilinone	Thiram	Tolyfluanid	Zinc oxide	Zinc pyrithione	Zineb	Ziram
Akzo Nobel Coatings																
VC Offshore	+					+										
Trilux		+			+											
Trilux 33		+												+		
Cruiser Superior		+				+										
Ultra	+				+											
Ultra Dover White	+				+											
Longlife	+					+										
Longlife Extra	+					+										
Micron 66	+													+		
Interspeed 642 BQA407/412	+					+										
Micron Extra	+					+										
Interclene 165 BWA900	+					+										
Coppercoat Extra	+					+										
Micron Extra Dover White	+					+										
Interspeeed 642 BQA405	+					+										
Intersmooth Ecoloflex 360	+													+		
Intersmooth Ecoloflex 460	+													+		
Interspeed BRA240 [=Interclene 175]	+														+	
Altex Coatings																
Sea-Barrier 1000	+										+		+			
Sea-Barrier 3000	+										+		+			
Sea-Barrier 4000	+						+						+			
Sea-Barrier Alloy 100		+					+						+			
No 5 Antifouling	+										+		+			
No 10 Antifouling	+						+						+			
Pettit Vivid		+											+	+		
Awlcraft	+										+					
Benjamin Moore Pacific																
Seahorse Propulsion		+						+								
Seahorse Formula 1000	+							+								
GemCo NZ																
Gemcoat AB	+										+		+			
Hempel Australia																
Globic	+						+									
Globic NCT 8195M	+			+												

Company Product Name	Cuprous oxide	Cuprous thiocyanate	Chlorothalonil	Copper pyrithione	Dichlofluanid	Diuron	DCOI	Irgaorol 1051	Mancozeb	Octhilinone	Thiram	Tolyfluanid	Zinc oxide	Zinc pyrithione	Zineb	Ziram
Globic NCT 8190M	+			+												
Olympic 86901	+												+			
Olympic 86951	+												+			
Mille Dynamic 7170	+					+							+			
Jotun Australia																
SeaQuantum Ultra	+			+									+			
SeaQuantum Classic	+			+									+			
Jotun Paints NZ																
Seavictor 40	+												+			
Seavictor 50	+						+						+			
Seaguardian	+												+			
SeaSafe		+											+		+	
Polymer Group [Jotun]																
Seasafe Ultra	+						+									
SeaForce 60	+			+												
SeaForce 90	+			+												
PPG Industries NZ																
ABC #3	+										+		+			+
Protective Paints NZ																
271 Longlife	+		+													
AF 500 Cleanship	+		+						+							
Warpaint [Wet&Forget]																
Warpaint Marine Fouling Inhibitor	+												+			

Table 8.2 Copper content of wet paint for New Zealand EPA registered and commercially available antifouling paints for vessels – January 2012.

Paint Type	Company	Product Name	HSR Approval No.	Cuprous oxide (g/L)	Cuprous thiocyanate (g/L)	Commercial (C) Recreational (R)
Commercial - Ablative- Cu_2O						
	Akzo Nobel Coatings	Interspeed 642	924	450-849		C
	Altex Coatings	Sea-Barrier 1000	35	?		C
	Altex Coatings	Sea-Barrier 3000	35	?		C
	Hempel (Australia)	Olympic 86901	2484	?		C
	Hempel (Australia)	Olympic 86951	2598	?		C
	Jotun Paints NZ	SeaVictor 50	931	840		C
	Jotun Paints NZ	SeaVictor 40	930	780		C
	Polymer Group	SeaForce 60	100411	?		C
Recreational - Ablative- Cu_2O						
	Akzo Nobel Coatings	Coppercoat Extra	924	450-849		C/R
	Akzo Nobel Coatings	Micron Extra	924	450-849		R
	Akzo Nobel Coatings	Micron Extra Dover White	924	450-849		R
	Altex Coatings	No 5	35	?		R
	Altex Coatings	AwlCraft	35	?		R
	GemCo NZ	GemCoat AB	928	750		R
	Hempel (Australia)	Mille Dynamic 7170	925	580		C/R
	Jotun Paints NZ	Seaguardian	931	840		R
	PPG Industries NZ	ABC#3	7897	?		C/R
	Protective Paints NZ	AF500 Cleanship	914	518		C/R
Commercial - Ablative- CuSCN						
	Altex Coatings	Sea-Barrier Alloy 100	38		?	C
Recreational- Ablative- CuSCN						
	Akzo Nobel Coatings	Cruiser Superior	916		230	C/R
	Altex Coatings	Pettit Vivid	951		?	R
	Benjamin Moore Pacific	Seahorse Propulsion	917		220	R
	Jotun Paints NZ	Seasafe	918		290	R
Commercial - Hard- Cu_2O						
	Akzo Nobel Coatings	Interclene 165	924	450-849		C
	Akzo Nobel Coatings	Interclene 175	933	648		C
	Akzo Nobel Coatings	Longlife	924	450-849		R
	Akzo Nobel Coatings	Longlife Extra	924	450-849		R
	Akzo Nobel Coatings	Ultra	923	408-494		R
	Akzo Nobel Coatings	Ultra Dover White	923	408-494		R
	Altex Coatings	Sea-Barrier 4000	35	?		C
	Altex Coatings	No 10	40	?		R
	Benjamin Moore Pacific	Seahorse Formula 1000	927	570		R
	Protective Paints NZ	0271 Longlife	912	722		R
	Warpaint Marine Systems	Warpaint Marine Fouling Inhibitor	929	764		R
Insoluble Matrix- CuSCN						
	Akzo Nobel Coatings	Trilux	889		215	R

Paint Type	Company	Product Name	HSR Approval No.	Cuprous oxide (g/L)	Cuprous thiocyanate (g/L)	Commercial (C) Recreational (R)
	Akzo Nobel Coatings	Trilux 33	121		?	R
SPC – Cu_2O						
	Akzo Nobel Coatings	Intersmooth Ecoloflex 360	932	640		C
	Akzo Nobel Coatings	Intersmooth Ecoloflex 460	932	640		C
	Akzo Nobel Coatings	Micron 66	932	640		R
	Hempel Australia	Globic	112	?		C
	Hempel Australia	Globic NCT 8195M	36	?		C
	Hempel Australia	Globic NCT 8190M	36	?		C
	Jotun Coatings NZ	Seaquantum Ultra	36	?		C
	Jotun Coatings NZ	Seaquantum Classic	36	?		C
	Polymer Group	SeaForce 90	100412	?		C
SPC- CuSCN						
	Polymer Group	Seasafe Ultra	100427		?	C/R

Table 8.3 Copper content of wet paint for Australian (APVMA) registered and commercially available antifouling paints for vessels with the copper content (from manufacturers' MSDSs) of the wet paint.

Paint Type Company	Product Name	Cuprous oxide (g/L)	Copper as Cu_2O (g/L)	Cuprous thiocyanate (g/L)	Copper as CuSCN (g/L)	% Solids	Specific Density (g/cm^3)
Commercial – SPC – Cu_2O							
Hempel (Australia)	Globic	764				57	1.9
International (Akzo Nobel)	Intersmooth 360 SPC	626				40	1.56
International (Akzo Nobel)	Intersmooth 460 SPC	626				40	1.58
Jotun Paints (Australia)	Seaquantum Ultra		625			47	1.67
PPG Industries (Australia)	Ecofleet 290		590			55	1.8
Commercial – Ablative – Cu_2O							
Hempel (Australia)	Olympic 86951		666			52	1.7
Hempel (Australia)	Olympic 86901		654			50	1.6
International (Akzo Nobel)	Interspeed 642 Topcoat	745				60	1.8
Jotun Paints (Australia)	SeaVictor 50		610			50	1.8
Jotun Paints (Australia)	SeaVictor 40		695			50	1.8
Commercial – Hard – Cu_2O							
International (Akzo Nobel)	Interclene 165	525				60	1.65
Recreational – SPC – Cu_2O							
International (Akzo Nobel)	Biolux Micron 66	660				40	1.6
Recreational – Ablative – Cu_2O							
International (Akzo Nobel)	AWLCRAFT	610				48	1.64
International (Akzo Nobel)	Bottomkote	530				60	1.73
International (Akzo Nobel)	Coppercoat	555				48	1.64
International (Akzo Nobel)	Coppercoat Extra Trade	610				48	1.62
International (Akzo Nobel)	Biolux Micron Extra	900				60	2.0
International (Akzo Nobel)	Biolux Micron Extra HS		759			60	1.88
Jotun Paints (Australia)	Seaguardian		745			50	2.06
Jotun Paints (Australia)	Super Tropic		485			50	1.48
Norglass Laboratories	Soft Copper	560				58	1.7
PPG Industries (Australia)	ABC-3	839				52	1.93
Resene Paints (Australia)	Altex No 5		640			50	1.94
Resene Paints (Australia)	Boero Supernavi SA633		640			52	1.84
Resene Paints (Australia)	Sea-Barrier 1000		332			52	1.79
Resene Paints (Australia)	Sea-Barrier 3000		764			52	1.84
Sea Hawk Paints	Biocop TF	814				62	2.02
Wattyl Australia	Seapro CU120		559			50	1.65
Recreational – Ablative – CuSCN							
Hempel (Australia)	Mille Dynamic ALU 71600				138	54	1.5
International (Akzo Nobel)	Cruiser Superior			290		50	1.37
Jotun Paints (Australia)	Seasafe				390	50	1.33
Recreational – Hard – Cu_2O							
International (Akzo Nobel)	Ultra HS Hard		425			45	1.53
Norglass Laboratories	Topflight	1,030				48	2.04

Paint Type Company	Product Name	Cuprous oxide (g/L)	Copper as Cu_2O (g/L)	Cuprous thiocyanate (g/L)	Copper as CuSCN (g/L)	% Solids	Specific Density (g/cm^3)
Recreational – Hard – CuSCN							
International (Akzo Nobel)	Trilux Hard				250	46	1.31
International (Akzo Nobel)	Trilux 33 Hard				125	52	1.34
Wattyl Australia	Seapro Plus 100				172	50	1.52
Incomplete Data							
Recreational – Ablative – Cu_2O							
Resene Paints (Australia)	Altex AF3000		764			#	#
Resene Paints (Australia)	Altex No 5 Oyster White		332			50	#
Recreational – Ablative – CuSCN							
PPG Industries (Australia)	Ecofleet Alloy				172	50	#
Recreational – Hard – Cu_2O							
International (Akzo Nobel)	Longlife High Strength	460				#	1.49
International (Akzo Nobel)	VC Offshore Extra	*1				#	1.49
Topline Paint	Marine Systems Traditional	985				#	#
Recreational – Hard – CuSCN							
Wattyl Australia	Newport 88 Hard Racing		622			#	#

[1] VC Offshore is supplied as two packs: cuprous oxide powder and wet paint, and the two are mixed before application. As supplied, the wet paint component therefore has no copper content.

Table 8.4 Copper content of different antifouling paint types.

Paint Type	Manufacturer	Paint Name	Biocide	Biocide content g/L	Mass fraction Cu	Volume Solids %	[Cu2O] dry paint g/cm³	[Cu] dry paint g/cm³	Cu in 1 µm µg/cm²	Average
Commercial (Merchant Shipping/Navy)										
SPC	Hempel	Globic	Cu2O	764	0.86	57	1.3	1.2	115	
SPC	International	Intersmooth 360	Cu2O	626	0.86	40	1.6	1.3	135	
SPC	International	Intersmooth 460	Cu2O	626	0.86	40	1.6	1.3	135	
SPC	Jotun	Seaquantum Ultra	Cu2O	625	1	47	1.3	1.3	133	
SPC	PPG Industries	Ecofleet 290	Cu2O	590	1	55	1.1	1.1	107	125
Ablative	Hempel	Olympic 86951	Cu2O	666	1	52	1.3	1.3	128	
Ablative	Hempel	Olympic 86901	Cu2O	654	1	50	1.3	1.3	131	
Ablative	International	Interspeed 642	Cu2O	745	0.86	60	1.2	1.1	107	
Ablative	Jotun	SeaVictor 50	Cu2O	610	1	50	1.2	1.2	122	
Ablative	Jotun	SeaVictor 40	Cu2O	695	1	50	1.4	1.4	139	125
Hard	International	Interclene 165	Cu2O	525	0.86	53	1.0	0.85	85	85
Recreational/Non-Trading/Fishing										
SPC	International	Biolux Micron 66	Cu2O	660	0.86	40	1.7	1.4	142	142
Ablative	International	Awlcraft	Cu2O	610	0.86	48	1.3	1.1	109	
Ablative	International	Micron Extra	Cu2O	900	0.86	60	1.5	1.3	129	
Ablative	International	Micron Extra HS	Cu2O	759	1	60	1.3	1.3	127	
Ablative	International	Coppercoat	Cu2O	555	0.86	48	1.2	1.0	99	
Ablative	International	Coppercoat Extra	Cu2O	610	0.86	48	1.3	1.1	109	
Ablative	International	Bottomkote	Cu2O	530	0.86	60	0.9	0.8	76	

Paint Type	Manufacturer	Paint Name	Biocide	Biocide content	Mass fraction Cu	Volume Solids	[Cu2O] dry paint	[Cu] dry paint	Cu in 1 µm	Average
				g/L		%	g/cm³	g/cm³	µg/cm²	
Ablative	Jotun	SeaGuardian	Cu2O	745	1	50	1.5	1.5	149	
Ablative	Jotun	SuperTropic	Cu2O	485	1	55	0.9	0.9	88	
Ablative	Norglass Industries	Soft Copper	Cu2O	560	0.86	58	1.0	0.8	83	
Ablative	PPG Industries	ABC-3	Cu2O	839	0.86	52	1.6	1.4	139	
Ablative	Resene	Altex No 5	Cu2O	640	1	50	1.3	1.3	128	
Ablative	Resene	Altex No 5 Oyster White	Cu2O	332	1	50	0.7	0.7	66	
Ablative	Resene	Boero Supernavi SA633	Cu2O	640	1	52	1.2	1.2	123	
Ablative	Resene	SeaBarrier 1000	Cu2O	332	1	52	0.6	0.6	64	
Ablative	Resene	SeaBarrier 3000	Cu2O	764	1	52	1.5	1.5	147	
Ablative	Sea Hawk Paints	Biocop TF	Cu2O	814	0.86	62	1.3	1.1	113	
Ablative	Wattyl	SeaProCU120	Cu2O	559	1	50	1.1	1.1	112	109
Ablative	Hempel	Mille Dynamic ALU71600	CuSCN	142	1	54	0.26	0.26	26	
Ablative	International	Cruiser Superior	CuSCN	290	0.522	50	0.58	0.30	30	
Ablative	Jotun	SeaSafe	CuSCN	390	1	50	0.78	0.78	78	
Ablative	PPG Industries	Ecofleet Alloy	CuSCN	172	1	50	0.34	0.34	34	42
Hard	International	Ultra	Cu2O	425	1	45	0.94	0.94	94	
Hard	Norglass Laboratories	Topflight	Cu2O	1,030	0.86	48	2.1	1.8	185	139
Hard	International	Trilux 33	CuSCN	125	1	52	0.24	0.24	24	
Hard	International	Trilux	CuSCN	250	1	46	0.54	0.54	54	39
All										104
Cu2O										117
CuSCN										41

Table 8.5 Calculation of average leaching rate for different paints using the CEPE formula.

Paint Type	Manufacturer	Paint Name	Biocide	Biocide content	Density	Biocide content	Mass fraction Cu	Volume Solids	Typical DFT	Life	Cu	Release rate	Average release rate
				g/L	g/cm3	% mass		%	µm	months	µg/cm2	µg/cm2/day	µg/cm2/day
					ρ	wa	a	NVV	DFT	t	mrel	R	
Commercial (Merchant Shipping/Navy)													
SPC	Hempel	Globic	Cu2O	764	1.9	40.2	0.86	57	150	36	12,103	11.1	
SPC	International	Intersmooth 360	Cu2O	626	1.56	40.1	0.86	40	150	36	14,132	12.9	
SPC	International	Intersmooth 460	Cu2O	626	1.581	39.6	0.86	40	150	36	14,132	12.9	
SPC	Jotun	Seaquantum Ultra	Cu2O	625	1.67	37.4	1	47	150	36	13,963	12.8	
SPC	PPG Industries	Ecofleet 290	Cu2O	590	1.8	32.8	1	55	150	36	11,264	10.3	11.98
Ablative	Hempel	Olympic 86951	Cu2O	666	1.7	39.2	1	52	150	36	13,448	12.3	
Ablative	Hempel	Olympic 86901	Cu2O	654	1.6	40.9	1	50	150	36	13,734	12.5	
Ablative	International	Interspeed 642	Cu2O	745	1.799	41.4	0.86	60	150	36	11,212	10.2	
Ablative	Jotun	SeaVictor 50	Cu2O	610	1.8	33.9	1	50	150	36	12,810	11.7	
Ablative	Jotun	SeaVictor 40	Cu2O	695	1.8	38.6	1	50	150	36	14,595	13.3	12.02
Hard	International	Interclene 165	Cu2O	525	1.646	70.4	0.86	53	150	36	19,749	18.0	18.04
Recreational/Non-Trading/Fishing													
SPC	International	Biolux Micron 66	Cu2O	660	1.602	41.2	0.86	40	100	24	9,933	13.6	13.61
Ablative	International	Awlcraft	Cu2O	555	1.635	33.9	0.86	48	100	24	6,961	9.5	
Ablative	International	Micron Extra	Cu2O	900	1.996	45.1	0.86	60	100	24	9,030	12.4	
Ablative	International	Micron Extra HS	Cu2O	900	1.881	47.8	1	60	100	24	10,500	14.4	
Ablative	International	Coppercoat	Cu2O	555	1.635	33.9	0.86	48	100	24	6,961	9.5	

Paint Type	Manufacturer	Paint Name	Biocide	Biocide content	Density	Biocide content	Mass fraction Cu	Volume Solids	Typical DFT	Life	Cu	Release rate	Average release rate
				g/L	g/cm³	% mass		%	µm	months	µg/cm²	µg/cm²/day	µg/cm²/day
					ρ	wa	a	NVV	DFT	t	mrel	R	
Ablative	International	Coppercoat Extra	Cu2O	610	1.619	37.7	0.86	48	100	24	7,650	10.5	
Ablative	International	Bottomkote	Cu2O	530	1.733	30.6	0.86	60	100	24	5,318	7.3	
Ablative	Jotun	SeaGuardian	Cu2O	745	2.06	36.2	1	50	100	24	10,430	14.3	
Ablative	Jotun	SuperTropic	Cu2O	485	1.48	32.8	1	55	100	24	6,173	8.5	
Ablative	Norglass Industries	Soft Copper	Cu2O	560	1.7	32.9	0.86	58	100	24	5,812	8.0	
Ablative	PPG Industries	ABC-3	Cu2O	839	1.93	43.5	0.86	52	100	24	9,713	13.3	
Ablative	Resene	Altex No 5	Cu2O	640	1.94	33.0	1	50	100	24	8,960	12.3	
Ablative	Resene	Boero Supernavi SA633	Cu2O	640	1.84	34.8	1	52	100	24	8,615	11.8	
Ablative	Resene	SeaBarrier 1000	Cu2O	332	1.79	18.5	1	52	100	24	4,469	6.1	
Ablative	Resene	SeaBarrier 3000	Cu2O	764	1.84	41.5	1	52	100	24	10,285	14.1	
Ablative	Sea Hawk Paints	Biocop TF	Cu2O	814	2.02	40.3	0.86	62	100	24	7,904	10.8	
Ablative	Wattyl	SeaProCU120	Cu2O	559	1.65	33.9	1	50	100	24	7,826	10.7	10.84
Ablative	Hempel	Mille Dynamic ALU71600	CuSCN	138	1.5	9.2	1	54	100	24	1,789	2.5	
Ablative	International	Cruiser Superior	CuSCN	290	1.365	21.2	0.522	50	100	24	2,119	2.9	
Ablative	Jotun	SeaSafe	CuSCN	390	1.33	29.3	1	50	100	24	5,460	7.5	4.28
Hard	International	Ultra	Cu2O	425	1.528	27.8	1	45	100	24	6,611	9.1	
Hard	Norglass Laboratories	Topflight	Cu2O	1,030	2.04	50.5	0.86	48	100	24	12,918	17.7	13.38
Hard	International	Trilux 33	CuSCN	125	1.338	9.3	1	52	100	24	1,683	2.3	
Hard	International	Trilux	CuSCN	250	1.306	19.1	1	52	100	24	3,365	4.6	3.46

Table 8.6 Minimum, average and maximum Risk Probability Numbers (RPN_{min}, RPN_{ave}, RPN_{max}) averaged across the six subject matter experts. Values are shown for each of the prescribed vessel type/cleaning scenarios as identified by code numbers.

Code no.	Origin of vessel	Type of vessel	Paint type	Cleaning	Recapture?	RPN_{min}	RPN_{ave}	RPN_{max}
1	International	Recreational	Biocide	Spot fouling, no action	Not applicable	160	375	627
2				Spot fouling, hand removal	Yes	97	1,677	23,909
3				Spot fouling, hand removal	No	768	6,117	44,527
4				Slime layer, no action	Not applicable	78	135	275
5				Slime layer, soft cloth	Yes	160	840	7,136
6				Slime layer, soft cloth	No	230	1,137	7,888
7			Biocide-free	Spot fouling, no action	Not applicable	208	443	692
8				Spot fouling, hand removal	Yes	126	1,957	20,930
9				Spot fouling, hand removal	No	778	6,357	38,440
10				Slime layer, no action	Not applicable	85	180	285
11				Slime layer, soft cloth	Yes	166	1,201	9,311
12				Slime layer, soft cloth	No	247	1,692	10,798
13		Commercial	Biocide	Slime layer/soft fouling, no action	Not applicable	85	263	462
14				Slime layer/soft fouling, brush cleaning	Yes	54	1,096	13,230
15				Slime layer/soft fouling, brush cleaning	No	462	5,857	40,567
16				Hard fouling, no action	Not applicable	137	365	607
17				Hard fouling, brush cleaning	Yes	83	2,127	29,074
18				Hard fouling, brush cleaning	No	987	12,630	86,790
19			Biocide-free	Slime layer/soft fouling, no action	Not applicable	120	318	528
20				Slime layer/soft fouling, brush cleaning	Yes	81	1,201	15,033
21				Slime layer/soft fouling, brush cleaning	No	733	6,207	44,593
22				Hard fouling, no action	Not applicable	177	378	667
23				Hard fouling, brush cleaning	Yes	116	2,120	27,066
24				Hard fouling, brush cleaning	No	1,280	12,520	85,937
25	Domestic	Recreational	Biocide	Spot fouling, no action	Not applicable	147	312	500
26				Spot fouling, hand removal	Yes	92	1,505	19,633
27				Spot fouling, hand removal	No	555	5,783	38,283
28				Slime layer, no action	Not applicable	38	97	228
29				Slime layer, soft cloth	Yes	131	695	4,967
30				Slime layer, soft cloth	No	173	1,020	5,590
31			Biocide-free	Spot fouling, no action	Not applicable	162	333	545
32				Spot fouling, hand removal	Yes	89	1,445	16,362
33				Spot fouling, hand removal	No	602	5,447	34,410
34				Slime layer, no action	Not applicable	50	122	232
35				Slime layer, soft cloth	Yes	142	882	7,605
36				Slime layer, soft cloth	No	187	1,218	8,393
37		Commercial	Biocide	Slime layer/soft fouling, no action	Not applicable	67	225	428
38				Slime layer/soft fouling, brush cleaning	Yes	66	1,027	11,633
39				Slime layer/soft fouling, brush cleaning	No	450	4,650	34,287
40				Hard fouling, no action	Not applicable	137	332	523
41				Hard fouling, brush cleaning	Yes	109	1,923	23,327
42				Hard fouling, brush cleaning	No	1,210	12,155	74,483
43			Biocide-free	Slime layer/soft fouling, no action	Not applicable	97	277	478
44				Slime layer/soft fouling, brush cleaning	Yes	76	990	13,094
45				Slime layer/soft fouling, brush cleaning	No	597	5,267	39,283
46				Hard fouling, no action	Not applicable	170	355	573
47				Hard fouling, brush cleaning	Yes	153	2,170	23,640
48				Hard fouling, brush cleaning	No	1,530	14,450	80,333

Table 8.7 Results of assessments by six subject matter experts of vessel type/cleaning scenarios against the option of no action for visits of 2-10 d and 10-21 d duration. Majority score shown, with other scores shown in brackets. Scenarios involving international vessels are shown above the grey line, and domestic vessels below the line. Scenario codes are described in Table 8.6.

Scenario	Relative risk*	Better to clean? 2-10 days	Better to clean? 10-21 days	Reasons for ranking (comments from subject matter experts)
17	Highest	Yes (Yes if LOF< 4, otherwise haul out or refuse entry; No – reduce visit time or refuse entry)	Yes (Yes if LOF< 4, otherwise haul out or refuse entry; No – reduce visit time or refuse entry)	For this level of fouling of international origin there is a significant biosecurity risk from propagule release from the uncleaned hull, even for the shorter duration. (For 'considerable fouling' (LOF3) or more, risk of propagule release significant and effectiveness of cleaning reduced (reducing benefit of cleaning). Risk of continuous "ship jumping" of mobile species irrespective of accumulated risk of propagule pressure.)
23		Yes (Yes if LOF< 4, otherwise haul out or refuse entry; No – reduce visit time or refuse entry)	Yes (Yes if LOF< 4, otherwise haul out or refuse entry; No – reduce visit time or refuse entry)	For this level of fouling of international origin there is a significant biosecurity risk from propagule release from the uncleaned hull, even for the shorter duration. (For 'considerable fouling' (LOF3) or more, risk of propagule release significant and effectiveness of cleaning reduced, reducing benefit of cleaning)
20		3 No (2 Yes; 1 Yes if LOF< 5, otherwise haul out or refuse entry)	Y (Yes if LOF< 5, otherwise haul out or refuse entry)	For this lower level of fouling of international origin the biosecurity risk from propagule release from the uncleaned hull for the longer duration, but the risk of release of viable material during cleaning is considered to offset this for the short duration. (Removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible likelihood of being viable.)
14		3 No (2 Yes; 1 Yes if LOF< 5, otherwise haul out or refuse entry)	Yes (Yes if LOF< 5, otherwise haul out or refuse entry)	For this lower level of fouling of international origin the biosecurity risk from propagule release from the uncleaned hull for the longer duration, but the risk of release of viable material during cleaning is considered to offset this for the short duration. Removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible likelihood of being viable
8		Yes	Yes	Limited amount of fouling removed (small vessel, spot fouling) and relatively high capture feasible make cleaning relatively low risk.
2	Lowest	Yes	Yes	Limited amount of fouling removed (small vessel, spot fouling), relatively high capture feasible make cleaning relatively low risk.
47	Highest	No (No if LOF< 3 and acquired in another port, Yes if LOF=3, No if LOF> 3- haul out or refuse entry)	3 Yes, 2 No (No if LOF< 3 and acquired in another port, Yes if LOF=3, No if LOF> 3- haul out or refuse entry)	For this level of fouling of domestic origin there is a significant biosecurity risk from propagule release from the uncleaned hull over the shorter duration but for the shorter duration, this is exceeded by the risk of propagule release due to cleaning. ('Yes' conditional on no planned change of activity (low to high) which may release fouling w/o need to clean. The method must also ensure no damage to the coating and, if this cannot be assured, would say no to both due to damage increasing susceptibility to refouling. For 'considerable fouling' (LOF3) or more, risk of propagule release significant and effectiveness of cleaning reduced (reducing benefit of cleaning) No for short-term scenario from the perspective of the CRMS. There is merit in considering the risks to ONE port associated with cleaning a domestic vessel to the risk of this vessel potentially contaminating several other New Zealand ports. Any cleaning of fouling release coatings ONLY if they do not damage the coating. If domestic vessel is coming from an area where a NIS of concern has established (e.g. *Sabella spallanzanii*), then

Scenario	Relative risk*	Better to clean? 2-10 days	Better to clean? 10-21 days	Reasons for ranking (comments from subject matter experts)
				this may be a case for cleaning under both timeframes.)
41		No (No if LOF< 3 and acquired in another port, Yes if LOF=3, No if LOF> 3- haul out or refuse entry)	No (1 Yes; No if LOF< 3 and acquired in another port, Yes if LOF=3, No if LOF> 3- haul out or refuse entry)	For this level of fouling of domestic origin the biosecurity risk from propagule release from the uncleaned hull is exceeded by the risk of propagule release due to cleaning. (This would depend on the extent of fouling. I would accept a much higher tolerance than the proposed CRMS for a vessel of domestic origin, but if well developed (> LOF3), the sooner it is removed the better. The risks of cleaning in New Zealand port X as having to be balanced against the risk of the vessel contaminating New Zealand ports A, B and C following not being cleaned in port X. Not an easy one to decide on. For 'considerable fouling' (LOF3) or more, risk of propagule release significant and effectiveness of cleaning reduce, reducing the benefit of cleaning)
38		No (No unless LOF> 3; N if LOF< 3 and acquired in another port, Yes if LOF=3-4, No if LOF> 4- haul out or refuse entry)	No (No unless LOF> 3; No if LOF< 3 and acquired in another port, Yes if LOF=3-4, No if LOF> 4- haul out or refuse entry)	For this level of fouling of domestic origin the biosecurity risk from propagule release from the uncleaned hull is exceeded by the risk of propagule release due to cleaning. (Removal and capture efficiency likely to be reduced at very heavy levels of fouling and material released has non-negligible likelihood of being viable.)
44		No (No unless LOF> 3; N if LOF< 3 and acquired in another port, Yes if LOF=3-4, No if LOF> 4- haul out or refuse entry)	No(No unless LOF> 3; N if LOF< 3 and acquired in another port, Yes if LOF=3-4, No if LOF> 4- haul out or refuse entry)	For this level of fouling of domestic origin the biosecurity risk from propagule release from the uncleaned hull is exceeded by the risk of propagule release due to cleaning. (Removal and capture efficiency likely to be reduced at very heavy levels of fouling and material released has non-negligible likelihood of being viable.)
26		No (Yes if acquired in another port; No unless LOF> 3)	Yes (Yes if acquired in another port; No unless LOF> 3)	Limited amount of fouling removed (small vessel, spot fouling), relatively high capture feasible make cleaning relatively low risk.
32	Lowest	No (Yes if acquired in another port; No unless LOF> 3)	Yes (Yes if acquired in another port; No unless LOF> 3)	Limited amount of fouling removed (small vessel, spot fouling), relatively high capture feasible make cleaning relatively low risk.

Table 8.8 Results of assessment of vessel type/cleaning scenarios against the option of no action for visits of 2-10 d and 10-21 d duration and different levels of fouling.

					Visit duration 2-10 d		Visit duration 10-21 d		
Scenario number	Vessel type	Paint type	Cleaning scenario	LOF	Better to clean?	Specific Comments	Better to clean?	Specific Comments	General notes
International vessels with recapture technology									
17	Commercial	Biocide	Hard fouling, brush cleaning	≤ 3	Yes	In-water cleaning with capture acceptable	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	For 'considerable fouling' (LOF 3) or more risk of propagule release during cleaning is significant and effectiveness of cleaning reduced (reducing benefit of cleaning)
23	Commercial	Biocide-free	Hard fouling, brush cleaning	≤ 3	Yes	In-water cleaning with capture acceptable	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	For 'considerable fouling' (LOF 3) or more risk of propagule release during cleaning is significant and effectiveness of cleaning reduced (reducing benefit of cleaning)
20	Commercial	Biocide-free	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	In-water cleaning with capture acceptable	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	For 'considerable fouling' (LOF 3) or more risk of propagule release during cleaning is significant and effectiveness of cleaning reduced (reducing benefit of cleaning)
14	Commercial	Biocide	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	In-water cleaning with capture acceptable	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	For 'considerable fouling' (LOF 3) or more risk of propagule release during cleaning is significant and effectiveness of cleaning reduced (reducing benefit of cleaning)
8	Recreational	Biocide-free	Spot fouling (and worse), hand	≤ 3	Yes	In –water cleaning (with capture) is acceptable	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Limited amount of fouling removed (small vessel, limited amount of fouling), relatively high capture feasible

					Visit duration 2-10 d		Visit duration 10-21 d		
Scenario number	Vessel type	Paint type	Cleaning scenario	LOF	Better to clean?	Specific Comments	Better to clean?	Specific Comments	General notes
			removal						
				> 3	No	Haul out, reduce visit time or refuse entry	No	Haul out, reduce visit time or refuse entry	Low cleaning and capture efficiency
2	Recreational	Biocide	Spot fouling (and worse), hand removal	≤ 3	Yes	In –water cleaning (with capture) is acceptable	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Limited amount of fouling removed (small vessel, limited amount of fouling), relatively high capture feasible
				> 3	No	Haul out, reduce visit time or refuse entry	No	Haul out, reduce visit time or refuse entry	Low cleaning and capture efficiency
Domestic vessels with recapture technology: cleaning at port of origin									
47	Commercial	Biocide-free	Hard fouling, brush cleaning	≤ 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
				> 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
41	Commercial	Biocide	Hard fouling, brush cleaning	≤ 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
				> 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
38	Commercial	Biocide-free	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
				> 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
44	Commercial	Biocide	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
				> 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)

Scenario number	Vessel type	Paint type	Cleaning scenario	LOF	Visit duration 2-10 d Better to clean?	Visit duration 2-10 d Specific Comments	Visit duration 10-21 d Better to clean?	Visit duration 10-21 d Specific Comments	General notes
								history).	
26	Recreational	Biocide-free	Spot fouling, hand removal	≤ 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
				> 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
32	Recreational	Biocide	Spot fouling, hand removal	≤ 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
				> 3	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	Yes	Clean (without capture unless risk factors are present, to encourage "clean before you leave": need to consider voyage history)	If LOF 2 or 3, cleaning without capture is acceptable, if LOF 4 or 5, need to ensure that the risk is minimal by considering voyage history (and hull inspection)
Domestic vessels with recapture technology: cleaning at receiving port									
47	Commercial	Biocide-free	Hard fouling, brush cleaning	≤ 3	No	Low risk of propagule release from uncleaned hull but clean if risk factors present (e.g. comes from port with known NIS of concern) - or haul out or refuse entry	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Better left uncleaned because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable but haul out, reduce length of visit or refuse entry if risk factors present (e.g. comes from port with known NIS of concern)	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	Haul out, reduce visit time or refuse entry
41	Commercial	Biocide	Hard fouling, brush cleaning	≤ 3	No	Low risk of propagule release from uncleaned hull but clean if risk factors present (e.g. comes from port with known NIS of concern) - or haul out or refuse entry	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Better left uncleaned because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable but haul out, reduce length of visit or refuse entry if risk factors present (e.g. comes from port with known NIS of concern)	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	Haul out, reduce visit time or refuse entry
38	Commercial	Biocide-free	Slime/soft fouling, brush cleaning	≤ 3	No	Low risk of propagule release from uncleaned hull but clean if risk factors present (e.g. comes from port with known NIS of concern) - or haul out or refuse entry	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Better left uncleaned because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of	For 'considerable fouling' (LOF 3) or more that has been acquired in another port, risk of propagule release during cleaning is significant and

					Visit duration 2-10 d		Visit duration 10-21 d		
Scenario number	Vessel type	Paint type	Cleaning scenario	LOF	Better to clean?	Specific Comments	Better to clean?	Specific Comments	General notes
						has non-negligible risk of being viable but haul out, reduce length of visit or refuse entry if risk factors present (e.g. comes from port with known NIS of concern)		fouling, and material released has non-negligible risk of being viable	effectiveness of cleaning reduced (reducing benefit of cleaning)
44	Commercial	Biocide	Slime/soft fouling, brush cleaning	≤ 3	No	Low risk of propagule release from uncleaned hull but clean if risk factors present (e.g. comes from port with known NIS of concern) - or haul out or refuse entry	Yes	In-water cleaning with capture acceptable. Low initial risk of propagule release from uncleaned hull but will increase over time	Cleaning and capture effective at low LOF
				> 3	No	Better left uncleaned because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable but haul out, reduce length of visit or refuse entry if risk factors present (e.g. comes from port with known NIS of concern)	No	Haul out, reduce visit length or refuse entry because removal and capture efficiency likely to be reduced at very heavy levels of fouling, and material released has non-negligible risk of being viable	For 'considerable fouling' (LOF 3) or more that has been acquired in another port, risk of propagule release during cleaning is significant and effectiveness of cleaning reduced (reducing benefit of cleaning)
26	Recreational	Biocide-free	Spot fouling (and worse), hand removal	≤ 3	Yes	In –water cleaning (with capture) is acceptable	Yes	In-water cleaning with capture required. Low initial risk of propagule release from uncleaned hull but will increase over time	Limited amount of fouling removed (small vessel, limited amount of fouling), relatively high capture feasible
				> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry	No	Haul out, reduce visit time or refuse entry	Low cleaning and capture efficiency
32	Recreational	Biocide	Spot fouling (and worse), hand removal	≤ 3	Yes	In –water cleaning (with capture) is acceptable	Yes	In-water cleaning with capture required. Low initial risk of propagule release from uncleaned hull but will increase over time.	Limited amount of fouling removed (small vessel, limited amount of fouling), relatively high capture feasible
				> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry	No	Haul out, reduce visit time or refuse entry	Low cleaning and capture efficiency

Table 8.9 Combined biosecurity and chemical assessment of vessel type/cleaning scenarios against the option of no action: Part 1 – International vessels. Scenario codes refer to each combination of origin and type of vessel, type of paint and type of cleaning.

Type of vessel	Paint type	Cleaning scenario	Recapture capability?	Scenario code	Biosecurity decision	Chemistry decision	Overall decision
Recreational	Biocide	Spot fouling, no action	Not applicable	1	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	Yes	2	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	No	3	Not acceptable.	Cleaning acceptable.	Not acceptable.
		Slime layer, no action	Not applicable	4	No cleaning required.	Acceptable for all vessel sizes, but see Note 1.	No cleaning required but acceptable for all vessel sizes, but see Note 1.
		Slime layer, soft cloth	Yes	5	No cleaning required.	Acceptable for all vessel sizes, but see Note 1.	No cleaning required but acceptable for all vessel sizes, but see Note 1.
		Slime layer, soft cloth	No	6	No cleaning required.	Acceptable for all vessel sizes, but see Note 1.	No cleaning required but acceptable for all vessel sizes, but see Note 1.
	Biocide-free	Spot fouling, no action	Not applicable	7	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	Yes	8	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	No	9	Not acceptable.	Cleaning acceptable.	Not acceptable.
		Slime layer, no action	Not applicable	10	No cleaning required.	Cleaning acceptable.	No cleaning required but cleaning is acceptable.
		Slime layer, soft cloth	Yes	11	No cleaning required.	Cleaning acceptable.	No cleaning required but cleaning is acceptable.
		Slime layer, soft cloth	No	12	No cleaning required.	Cleaning acceptable.	No cleaning required but cleaning is acceptable.
Commercial	Biocide	Slime layer/soft fouling, no action	Not applicable	13	< 48 h - better not to clean. > 48 h. See "Part 2."	Acceptable, but not for 1 or more vessel of 200 m or longer in Lyttelton; acceptable all sizes in Auckland; see Note 2.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Slime layer/soft fouling, brush cleaning	Yes	14	< 48 h - better not to clean. > 48 h. See "Part 2."	Acceptable, but not for 1 or more vessel of 200 m or longer in Lyttelton; acceptable all sizes in Auckland; see Note 2.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Slime layer/soft fouling, brush cleaning	No	15	Not acceptable.	Acceptable, but not for 1 or more vessel of 200 m or longer in Lyttelton; acceptable all sizes in Auckland; see Note 2.	Not acceptable.
		Hard fouling, no action	Not applicable	16	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning generally not acceptable in Lyttelton, only acceptable for vessels < 100 m in Auckland. Can do sides or boot-tops, with restrictions; see Note 3.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Hard fouling, brush cleaning	Yes	17	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning generally not acceptable in Lyttelton, only acceptable for vessels < 100 m in Auckland. Can do sides or boot-tops, with restrictions; see Note 3.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Hard fouling, brush cleaning	No	18	Not acceptable.	Cleaning generally not acceptable in Lyttelton, only acceptable for vessels < 100 m in Auckland. Can do sides or boot-tops, with restrictions; see Note 3.	Not acceptable.
	Biocide-free	Slime layer/soft fouling, no action	Not applicable	19	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Slime layer/soft fouling, brush cleaning	Yes	20	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Slime layer/soft fouling, brush cleaning	No	21	Not acceptable.	Cleaning acceptable.	Not acceptable.
		Hard fouling, no action	Not applicable	22	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Hard fouling, brush cleaning	Yes	23	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Hard fouling, brush cleaning	No	24	Not acceptable.	Cleaning acceptable.	Not acceptable.

Note 1: If upper estimate of biocide release rate is used, > 0.274 vessel day^{-1} ≥ 21 m should not be cleaned per day; or > 1 vessel day^{-1} ≥ 11 m (based on chronic threshold being used at > 0.274 vessels being cleaned per day).

Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

Note 3: See risk matrices in Section 5.2.9 for whole vessels, sides & boot-tops.

Table 8.10 Combined biosecurity and chemical assessment of vessel type/cleaning scenarios against the option of no action: Part 1 – Domestic vessels. Scenario codes refer to each combination of origin and type of vessel, type of paint and type of cleaning. Lower release estimate assumed.

Type of vessel	Paint type	Cleaning scenario	Recapture capability?	Scenario code	Biosecurity decision	Chemistry decision	Overall decision
Recreational	Biocide	Spot fouling, no action	Not applicable	25	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	Yes	26	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	No	27	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Slime layer, no action	Not applicable	28	No cleaning required.	Acceptable for all vessel sizes, but see Note 1.	No cleaning required but acceptable for all vessel sizes, but see Note 1.
		Slime layer, soft cloth	Yes	29	No cleaning required.	Acceptable for all vessel sizes, but see Note 1.	No cleaning required but acceptable for all vessel sizes, but see Note 1.
		Slime layer, soft cloth	No	30	No cleaning required.	Acceptable for all vessel sizes, but see Note 1.	No cleaning required but acceptable for all vessel sizes, but see Note 1.
	Biocide-free	Spot fouling, no action	Not applicable	31	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	Yes	32	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Spot fouling, hand removal	No	33	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h. See "Part 2."
		Slime layer, no action	Not applicable	34	No cleaning required.	Cleaning acceptable.	No cleaning required but cleaning is acceptable.
		Slime layer, soft cloth	Yes	35	No cleaning required.	Cleaning acceptable.	No cleaning required but cleaning is acceptable.
		Slime layer, soft cloth	No	36	No cleaning required.	Cleaning acceptable.	No cleaning required but cleaning is acceptable.
Commercial	Biocide	Slime layer/soft fouling, no action	Not applicable	37	< 48 h - better not to clean. > 48 h. See "Part 2."	Acceptable, but not for 1 or more vessel of 200 m or longer in Lyttelton; acceptable all sizes in Auckland; see Note 2.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Slime layer/soft fouling, brush cleaning	Yes	38	< 48 h - better not to clean. > 48 h. See "Part 2."	Acceptable, but not for 1 or more vessel of 200 m or longer in Lyttelton; acceptable all sizes in Auckland; see Note 2.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Slime layer/soft fouling, brush cleaning	No	39	< 48 h - better not to clean. > 48 h. See "Part 2."	Acceptable, but not for 1 or more vessel of 200 m or longer in Lyttelton; acceptable all sizes in Auckland; see Note 2.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Hard fouling, no action	Not applicable	40	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning generally not acceptable in Lyttelton, only acceptable for vessels < 100 m in Auckland. Can do sides or boot-tops, with restrictions; see Note 3.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Hard fouling, brush cleaning	Yes	41	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning generally not acceptable in Lyttelton, only acceptable for vessels < 100 m in Auckland. Can do sides or boot-tops, with restrictions; see Note 3.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Hard fouling, brush cleaning	No	42	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning generally not acceptable in Lyttelton, only acceptable for vessels < 100 m in Auckland. Can do sides or boot-tops, with restrictions; see Note 3.	< 48 h - better not to clean. > 48 h: see "Part 2"
	Biocide-free	Slime layer/soft fouling, no action	Not applicable	43	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Slime layer/soft fouling, brush cleaning	Yes	44	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Slime layer/soft fouling, brush cleaning	No	45	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Hard fouling, no action	Not applicable	46	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Hard fouling, brush cleaning	Yes	47	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h: see "Part 2"
		Hard fouling, brush cleaning	No	48	< 48 h - better not to clean. > 48 h. See "Part 2."	Cleaning acceptable.	< 48 h - better not to clean. > 48 h: see "Part 2"

Note 1: If upper estimate of biocide release rate is used, > 0.274 vessel day^{-1} ≥ 21 m should not be cleaned per day; or > 1 vessel day^{-1} ≥ 11 m (based on chronic threshold being used at > 0.274 vessels being cleaned per day).

Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

Note 3: See risk matrices in Section 5.2.9 for whole vessels, sides & boot-tops.

Table 8.11 Combined biosecurity and chemical assessment of vessel type/cleaning scenarios against the option of no action: Part 2 – International vessels. Levels of fouling (LOF) are described in Section 6.2.4. Scenario codes are given in Table 8.6.

Scenario description					Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
Scenario code	Vessel type	Paint type	Fouling type	LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
17 vs 16	Commercial	Biocide	Hard fouling, brush cleaning	≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions.	Yes (with capture) but see restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions; see Note 1.
				> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions.	No	Haul out, reduce visit time or refuse entry.
23 vs 22	Commercial	Biocide-free	Hard fouling, brush cleaning	≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
				> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.
20 vs 19	Commercial	Biocide-free	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
				> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.
14 vs 13	Commercial	Biocide	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see Note 2.	Yes (with capture) but see restrictions	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see Note 2.
				> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see Note 2.	No	Haul out, reduce visit time or refuse entry.
8 vs 7	Recreational	Biocide-free	Spot fouling, hand removal	≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
			Greater than spot fouling, hand removal	> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.
2 vs 1	Recreational	Biocide	Spot fouling, hand removal	≤ 3	Yes	Clean (with capture).	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
			Greater than spot fouling, hand removal	> 3	No	Haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	Haul out, reduce visit time or refuse entry.

Note 1: See risk matrices in Section 5.2.9 for risks associated with cleaning whole vessels, sides and boot-tops.

Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

Table 8.12 Combined biosecurity and chemical assessment of vessel type/cleaning scenarios against the option of no action: Part 2 – Domestic vessel cleaning in port of origin. Levels of fouling (LOF) are described in Section 6.2.4. Scenario codes are given in Table 8.6.

Scenario Description					Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
Scenario code	Vessel type	Paint type	Fouling type	LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
47 and 48 vs 46	Commercial	Biocide-free	Hard fouling, brush cleaning	≤ 3	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history).	Yes	Clean (without capture depending upon specific risk factors, to encourage "clean before you leave": need to consider voyage history).	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history.
				> 3	Yes	As above.	Yes	As above.	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.
41 and 42 vs 40	Commercial	Biocide	Hard fouling, brush cleaning	≤ 3	Yes	As above.	Yes	As above.	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions.	See restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions; see Note 1. Otherwise do not clean depending upon specific risk factors (need to consider voyage history), in which case haul out to clean, reduce duration of visit or refuse entry.
				> 3	Yes	As above.	Yes	As above.	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions.	See restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions; see Note 1. Otherwise do not clean depending upon specific risk factors (need to consider voyage history), in which case haul out to clean, reduce duration of visit or refuse entry.
38 ad 39 vs 37	Commercial	Biocide	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	As above.	Yes	As above.	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see restrictions.	Yes but see restrictions	Cleaning is acceptable except for 1 or more vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see Note 2. Clean with or without capture depending upon specific risk factors: need to consider voyage history.
				> 3	Yes	As above.	Yes	As above.	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see restrictions.	Yes but see restrictions	Cleaning is acceptable except for 1 or more vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see Note 2. Clean with or without capture depending upon specific risk factors (need to consider voyage history), in which case, haul out to clean, reduce duration of visit or refuse entry.
44 and 45 vs 43	Commercial	Biocide-free	Slime layer/soft fouling, brush cleaning	≤ 3	Yes	As above.	Yes	As above.	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history.
				> 3	Yes	As above.	Yes	As above.	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.
26 and 27 vs 25	Recreational	Biocide	Spot fouling, hand removal	≤ 3	Yes	As above.	Yes	As above.	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history.
			Greater than spot fouling, hand removal	> 3	Yes	As above.	Yes	As above.	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.
32 and 33 vs 31	Recreational	Biocide-free	Spot fouling, hand removal	≤ 3	Yes	As above.	Yes	As above.	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history.
			Greater than spot fouling, hand removal	> 3	Yes	As above.	Yes	As above.	Yes	Cleaning acceptable.	Yes	Clean with or without capture depending upon specific risk factors: need to consider voyage history. If risk factors are present, in-water cleaning is not acceptable. Remove from the water, clean and renew antifouling system.

Note 1: See risk matrices in Section 5.2.9 for risks associated with cleaning whole vessels, sides and boot-tops.

Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

Table 8.13 Combined biosecurity and chemical assessment of vessel type/cleaning scenarios against the option of no action: Part 2 – Domestic vessel cleaning in recipient port. Levels of fouling (LOF) are described in Section 6.2.4. Scenario codes are given in Table 8.6.

Scenario Description					Biosecurity 2-10 d		Biosecurity 10-21 d		Chemical		Overall decision	
Scenario code	Vessel type	Paint type	Fouling type	LOF	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Decision	Better to clean?	Restrictions and alternative actions
47 vs 46	Commercial	Biocide -free	Hard fouling, brush cleaning	≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	See restrictions	2-10 day visit: No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history), in which case clean (with capture), haul out, reduce visit or refuse entry. 10-21 day visit: clean (with capture) however, depending upon specific risk factors, consider haul out, reduce visit or refuse entry.
				> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	2-10 day visit: Do not clean however, depending upon specific risk factors haul out (consider voyage history), reduce visit or refuse entry. 10-21 day visit: haul out, reduce visit or refuse entry.
41 vs 40	Commercial	Biocide	Hard fouling, brush cleaning	≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions (see Note 1).	See restrictions	Cleaning generally not acceptable but can do sides or boot-tops, with restrictions (see Note 1). Otherwise for 2-10 days visit: do not clean and if specific risk factors are present (consider voyage history haul out, reduce visit or refuse entry. For 10-21 days visit: haul out, reduce visit or refuse entry.
				> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	No	Cleaning generally not acceptable. Can do sides or boot-tops, with restrictions (see Note 1)	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors (consider voyage history), haul out, reduce visit or refuse entry. 10-21 day visit:: haul out, reduce visit or refuse entry.
38 vs 37	Commercial	Biocide	Slime layer/soft fouling, brush cleaning	≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see restrictions.	See restrictions	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see Note 2. Otherwise for 2-10 days visit: No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history), in which case clean (with capture), haul out, reduce visit or refuse entry. 10-21 day visit: clean (with capture) however, depending upon specific risk factors, consider haul out, reduce visit or refuse entry.
				> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes but see Note 2	Cleaning is acceptable except for > 1 vessel of 200 m or longer in Lyttelton: acceptable all sizes in Auckland: see restrictions.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors haul out (consider voyage history), reduce visit or refuse entry. 10-21 day visit: Haul out, reduce visit or refuse entry.
44 vs 43	Commercial	Biocide -free	Slime layer/soft fouling, brush cleaning	≤ 3	No	No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history): clean (with capture), haul out, reduce visit time or refuse entry.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	See restrictions	2-10 day visit: No action (but cleaning acceptable) depending upon specific risk factors (consider voyage history), in which case clean (with capture), haul out, reduce visit or refuse entry. 10-21 day visit: clean (with capture) however, depending upon specific risk factors, consider haul out, reduce visit or refuse entry.
				> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors haul out (consider voyage history), reduce visit or refuse entry. 10-21 day visit: Haul out, reduce visit or refuse entry.
26 vs 25	Recreational	Biocide	Spot fouling hand removal	≤ 3	Yes	In –water cleaning (with capture) is acceptable.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
			Greater than spot fouling, hand removal	> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors (consider voyage history), haul out, reduce visit or refuse entry. 10-21 day visit: haul out, reduce visit or refuse entry.
32 vs 31	Recreational	Biocide -free	Spot fouling hand removal	≤ 3	Yes	In –water cleaning (with capture) is acceptable.	Yes	Clean (with capture).	Yes	Cleaning acceptable.	Yes (with capture)	
			Greater than spot fouling, hand removal	> 3	No	Do not clean but if specific risk factors are present (consider voyage history) haul out, reduce visit time or refuse entry.	No	Haul out, reduce visit time or refuse entry.	Yes	Cleaning acceptable.	No	For 2-10 day visit: Do not clean however, depending upon specific risk factors (consider voyage history), haul out, reduce visit or refuse entry. 10-21 day visit: haul out, reduce visit or refuse entry.

Note 1: See risk matrices in Section 5.2.9 for risks associated with cleaning whole vessels, sides and boot-tops.

Note 2: If upper release estimate is used, then do not clean > 0.137 vessels day^{-1} > 250 m; or > 0.274 vessels day^{-1} > 100 m or > 1 vessels day^{-1} > 100 m in Lyttelton; or > 1 vessel day^{-1} > 200 m in Auckland (chronic threshold identified as > 0.274 vessels being cleaned per day).

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10 Appendices

10.1 TEMPLATE USED FOR IMEA ASSESSMENT OF RELATIVE RISK OF DIFFERENT CLEANING SCENARIOS

10.1.1 Assessment matrix

Origin of vessel	Type of vessel	Paint type	Cleaning scenario	Recapture capability?	Min. estimate (RPN_{min} 1-10)	Ave. estimate (RPN_{ave} 1-10)	Max. estimate (RPN_{max} 1-10)
International	Recreational	Biocide	Spot fouling, no action	n/a			
			Spot fouling, hand removal	Yes			
			Spot fouling, hand removal	No			
			Slime layer, no action	n/a			
			Slime layer, soft cloth	Yes			
			Slime layer, soft cloth	No			
		Biocide-free	Spot fouling, no action	n/a			
			Spot fouling, hand removal	Yes			
			Spot fouling, hand removal	No			
			Slime layer, no action	n/a			
			Slime layer, soft cloth	Yes			
			Slime layer, soft cloth	No			
	Commercial	Biocide	Slime layer/soft fouling, no action	n/a			
			Slime layer/soft fouling, brush cleaning	Yes			
			Slime layer/soft fouling, brush cleaning	No			
			Hard fouling, no action	n/a			
			Hard fouling, brush cleaning	Yes			
			Hard fouling, brush cleaning	No			
		Biocide-free	Slime layer/soft fouling, no action	n/a			
			Slime layer/soft fouling, brush cleaning	Yes			
			Slime layer/soft fouling, brush cleaning	No			
			Hard fouling, no action	n/a			
			Hard fouling, brush cleaning	Yes			
			Hard fouling, brush cleaning	No			
Domestic	Recreational	Biocide	Spot fouling, no action	n/a			
			Spot fouling, hand removal	Yes			
			Spot fouling, hand removal	No			
			Slime layer, no action	n/a			
			Slime layer, soft cloth	Yes			
			Slime layer, soft cloth	No			
		Biocide-free	Spot fouling, no action	n/a			
			Spot fouling, hand removal	Yes			
			Spot fouling, hand removal	No			
			Slime layer, no action	n/a			
			Slime layer, soft cloth	Yes			
			Slime layer, soft cloth	No			
	Commercial	Biocide	Slime layer/soft fouling, no action	n/a			

Origin of vessel	Type of vessel	Paint type	Cleaning scenario	Recapture capability?	Min. estimate (RPN_{min} 1-10)	Ave. estimate (RPN_{ave} 1-10)	Max. estimate (RPN_{max} 1-10)
			Slime layer/soft fouling, brush cleaning	Yes			
			Slime layer/soft fouling, brush cleaning	No			
			Hard fouling, no action	n/a			
			Hard fouling, brush cleaning	Yes			
			Hard fouling, brush cleaning	No			
		Biocide-free	Slime layer/soft fouling, no action	n/a			
			Slime layer/soft fouling, brush cleaning	Yes			
			Slime layer/soft fouling, brush cleaning	No			
			Hard fouling, no action	n/a			
			Hard fouling, brush cleaning	Yes			
			Hard fouling, brush cleaning	No			

10.1.2 IMEA Component 1: Likelihood of arrival

Risk scoring:

Score	Description	
1	Highly unlikely	Lowest risk
2	Unlikely	
3	Slight chance	
4	Small chance	
5	Occasional	
6	Moderate chance	
7	Frequent	
8	Highly likely	
9	Very likely	
10	Certain	Highest risk

Scores refer to the likelihood that a non-indigenous species novel to the port of arrival is present on the incoming vessel under this scenario relative to other scenarios.

Background information
Inglis et al. 2010:
Across different types of commercial vessels:

- 38-100% of those examined carried identifiable fouling organisms.
- Ave. no. of NIS or cryptogenic species ranged from 1.50-5.50/vessel (range of min-max 0-19).
- Ave. no. of NIS already established in New Zealand ranged from 0.0-1.63/vessel (range of min - max 0-5).
- Ave. no. of NIS not already established in New Zealand ranged from 1.50-4.75/vessel (range of min-max 0-17).
- 77% of NIS are not established in New Zealand (19 of the 20 most commonly-occurring species are not already established).

Among recreational yachts and launches:

- 82% of those examined carried identifiable fouling organisms.
- Ave. no. of NIS or cryptogenic species 4.28/vessel (range of min - max 0-14).
- Ave. no. of NIS already established in NZ2.94/vessel (range of min - max 0-9).
- Ave. no. of NIS not already established in New Zealand 2.13/vessel (range of min -max 0-8).

NB comparisons of the above values are confounded by differences in sampling design and intensity between commercial and recreational vessels.
Allowing for this confounding:

- The average number of all fouling species (including natives) was larger on recreational vessels, the average number of NIS plus cryptogenic species was also larger.
- But the average number of NIS not yet established in New Zealand was not significantly different.
- Fouling assemblages on recreational vessels were different from those on all types of commercial vessels.
- This difference was largely due to the frequent occurrence (ca 50% of vessels) of *Watersipora subtorquata* and *Bugula neritina* on recreational vessels.

Floerl et al. (2008):

- About 50% of the NIS found on yachts that are not yet established in New Zealand are capable of surviving in New Zealand conditions.
- 64% of NIS recorded on recreational vessels are not yet established in New Zealand (but 60% of the 20 most commonly-occurring fouling species are already established - most of the new NIS occurred infrequently).

Miscellaneous:

- Biocidal and biocide-free paints are both designed to deter settlement of fouling organisms, apart from mechanically-resistant non-toxic coatings designed to be cleaned regularly.
- Biocidal paints may be generally more effective but both types fail eventually. Biocide-free paints are less commonly used on recreational vessels (Floerl et al. 2009)
- Both biocidal and biocide-free (FR) coatings develop slime fouling within a couple of weeks (16d in study by Molino et al. 2009) but FR coatings may be colonised slightly faster.
- Approximately 50% of commercial vessels sampled yielded no identifiable fouling species.
- Approximately 80% of international yachts had at least 1 identifiable fouling species.

10.1.3 IMEA Component 2: Fouling left on hull after cleaning

Risk scoring:

Score	Description	
1	0-10%	Lowest risk
2	10-20%	
3	20-30%	
4	30-40%	
5	40-50%	
6	50-60%	
7	60-70%	
8	70-80%	
9	80-90%	
10	90-100%	Highest risk

Scores refer to the percentage of material originally present on the hull that remains after cleaning under this scenario relative to other scenarios (i.e. it is not a true percentage but is relative to other scenarios).

Score "no action" option as 10 (because the final RPN is the product of the individual components, if any score is left blank, the product will be zero)

Background information

- Soft-cloth cleaning of slime layer - presumably all visible fouling is removed, but no information available on microscopic organisms (e.g. *Undaria* gametophytes)
- Hand cleaning of spot fouling - presumably 100% is possible for small areas of macrofouling, but no information available on removal of microscopic organisms
- Fouling-release paints are designed to reduce strength of attachment of fouling to the hull, so less material likely to remain after cleaning.

Hopkins et al. (2008):

- Rotating brushes effective (up to 100% of biomass) at removing erect and soft-bodied fouling organisms. 88-93% reduction in mean percentage cover.
- Rotating brushes less effective at removing hard fouling organisms (up to 60% of calcareous tubeworms, bivalves, barnacles remaining).
- Removal of soft-bodied taxa can be reduced in presence of hard-bodied fouling

Inglis et al. (2010):

- 86% of total species richness on recreational vessels occurred in niche areas
- 98% of total species richness on commercial vessels occurred in niche areas

Davidson et al. (2008):

- 40% of species remained on a very heavily fouled vessel cleaned with hand-held brushes (polyprop bristles and polyprop with steel inserts).
- Cover reduced from 89% to 37% (21.8% of entire hull area still biofouled by encrusting species.).

- With SCAMP brush system, percentage of species still present after cleaning ranged 40-60%, depending on hull region and 30 out of 37 spp (81%) were still present across entire hull

Miscellaneous:
- Brushes may also fail to remove microscopic life-stages e.g. gametophytes of *Undaria* (Blakemore & Forrest 2006)
- Divers may miss patches while using rotating brushes (Hopkins & Forrest 2008)
- Divers may miss patches while hand-cleaning recreational vessels (Floerl 2008) - 80% of vessels cleaned 3 weeks previously had biofouling (1-15 species), including NIS.

10.1.4 IMEA Component 3: Fouling capture

Risk scoring:

Score	Description	
1	0-10%	Lowest risk
2	10-20%	
3	20-30%	
4	30-40%	
5	40-50%	
6	50-60%	
7	60-70%	
8	70-80%	
9	80-90%	
10	90-100%	Highest risk

Scores refer to the percentage of material removed during cleaning that is NOT captured under this scenario relative to other scenarios (i.e. it is not a true percentage but is relative to other scenarios).
Score the "no action" option as 1 (in effect, no loss of material) and the "no capture" option as 10.

Background information
- Hand cleaning of spot fouling - assuming diver uses net around area being cleaned - some loss around edges probable and very likely in strong currents
- Soft cloth cleaning of slime layer - entire hull will be cleaned and likelihood of diver collecting material while cleaning such a large area is small. Material also likely to fragment and pass through a mesh bag.

Hopkins et al. (2008):
- Hand-operated brush systems tested experimentally captured on average about 95% (minimum 90%, maximum 99%) of material removed from the hull, and was less when fouling level was high or on curved surfaces.
- Divers knocked material off while using the cleaning brushes and this material was not captured.

- The amount of material no captured was higher in winter, when large numbers of small barnacles were present in the fouling assemblage and were dislodged but not captured.
- Material not captured represents about 1% of total material removed in experimental study

10.1.5 IMEA Component 4: Establishment of escapees

Risk scoring:

Score	Description	
1	Highly unlikely	Lowest risk
2	Unlikely	
3	Slight chance	
4	Small chance	
5	Occasional	
6	Moderate chance	
7	Frequent	
8	Highly likely	
9	Very likely	
10	Certain	Highest risk

Scores refer to the likelihood that material not captured is viable and capable of establishing in the receiving environment under this scenario relative to other scenarios
For each vessel/cleaning scenario, the score should be the same with capture as without capture, since it is the likelihood of establishment of the material NOT captured that is being considered, independent of how much is captured.
Score "no action" scenario as 1 because no material released (propagules released from uncleaned hull or hull after cleaning are dealt with in another sheet)

Background information
See biological contamination review:

- Likelihood of survival and establishment high for motile species, moderate for soft taxa, particularly colonial taxa, and low for calcareous, sessile taxa.

Woods et al. (2007):
Cloth and scraper cleaning:

- Soft-bodied taxa: 69-89% (summer-winter) undamaged by cleaning
- Soft-bodied taxa: 72-88% survived cleaning
- Hard-bodied taxa: 17-34 % (summer-winter) undamaged by cleaning
- Hard-bodied taxa: 25-35 % (summer-winter) survived cleaning
- Up to 55% of organisms removed were "viable" (if the dominant tubiculous polychaetes are removed from analysis, values were 72% in winter and 66% in summer)
- Viability varied among taxa, highest were: anemones, ascidians, bivalves, bryozoans, flatworms, motile crustaceans, motile molluscs, nemerteans, errant polychaetes and sponges
- Most motile organisms collected were viable, and often occurred in protected microhabitats e.g. barnacle tests, sponges, etc..

- No information on viability of macroalgae removed, but *Enteromorpha/Ulva* (dominant taxa) are likely to be able to grow from fragments
- Survival and viability was not generally correlated with amount of fouling present

Hopkins et al. (2008):
Rotating brush cleaning:
- 8% of material not collected was viable - amount of viable material lost from flat plates similar across all fouling ages, but amount from curved plates increased (up to 20%) with fouling age.
- Viable material lost included wide range of intact organisms, including juvenile mussels, barnacles, calcareous and non-calcareous worms, fragments of bryozoans, hydroids and colonial ascidians (but note that Woods et al. 2007 reported that few tubeworms or barnacles survived cleaning with a scraper, except for those living epibiotically)
- Little difference between the 2 brush systems tested

10.1.6 IMEA Component 5: Stimulation of propagule release by cleaning

Risk scoring:

Score	Description	
1	Highly unlikely	Lowest risk
2	Unlikely	
3	Slight chance	
4	Small chance	
5	Occasional	
6	Moderate chance	
7	Frequent	
8	Highly likely	
9	Very likely	
10	Certain	Highest risk

Scores refer to the likelihood that cleaning will enhance the release of propagules from the hull under this scenario relative to other scenarios.
Score "no action" options as 1.
Score same for "capture" and "no-capture" since this material may be released after cleaning tool has passed, and will then not be captured.

Background information
See biological contamination review

Enhancement of dispersal by creation of fragments:
- Micro and macroalgal fragments left on the hull after cleaning can each give rise to several new thalli, and cleaning probably releases spores, which settle immediately after cleaning (Moss & Marsland 1976)
- Fragmentation of macroalgae, including *Caulerpa taxifolia* and *Sargassum muticum*, plays a significant role in dispersal.

- Fragmentation is a common means of dispersal for many clonal organisms including sponges, bryozoans and ascidians.
- Many polychaetes have the ability to regenerate from fragments.

Stimulation of propagule release

- Physical damage to bryozoans may cause early maturation and spawning.
- Physical disturbance may stimulate release of larvae by *Styela clava* and *Eudistoma* species.
- Release of gametes from damaged ascidians may induce congeners to spawn synchronously.

10.1.7 IMEA Component 6: Residual risk of propagule release after cleaning

Risk scoring:

Score	Description	
1	Highly unlikely	Lowest risk
2	Unlikely	
3	Slight chance	
4	Small chance	
5	Occasional	
6	Moderate chance	
7	Frequent	
8	Highly likely	
9	Very likely	
10	Certain	Highest risk

Scores refer to the likelihood of infection from residual material on the hull after cleaning (or from an uncleaned hull) under this scenario relative to other scenarios.
Score "capture" and "no-capture" options the same, since this sheet relates to material left on the hull.

Background information

See biological contamination review

- Botryllid colonial ascidians are common fouling organisms and are capable of fertilisation over relatively large distances (10s-100s m) and at low concentrations of sperm.
- Colonial aplousobranch ascidians (e.g. didemnids) brood and release large numbers of competent larvae.
- Solitary ascidians are generally broadcast spawners with external fertilisation and may be highly fecund. Larval life of *S. clava* 12-24hr.
- Some colonial ascidians, including botryllids and didemnids, reproduce asexually by producing protruding lobes that detach.
- Other colonial ascidians (e.g. *Clavelina* sp.) produce planktonic buds from the stolon that are capable of dispersal over longer distances than non-planktonic buds.
- Bivalves such as *Mytilus* and *Musculista*, can be extremely fecund.

- *Sabella spallanzanii* has high reproductive output, synchronous spawning and fertilisation within the female's tube. Fertilised eggs are released into the plankton, with a lifespan of 2d.
- Peak spawning in Lyttelton of *S. clava* in New Zealand December-Feb (Oct-March?), of *Ciona intestinalis* in October-Feb (early spring-late autumn), of *Undaria* in July-Sept , and *Sabella* in Sept-Oct (late autumn-late summer in Port Phillip) (Floerl et al. 2011)
- Brood sizes of barnacles range from 1,000-10,000 (within and among species of *Balanus*).
- *Carcinus maenas* highly fecund, one clutch/yr with up to 200,000 eggs. Breeding in N Hemisphere spring-early winter. Larvae planktonic for 17-80d, depending on temperature.