MAMPEC Modelling of Key Australian Ports to predict environmental impacts of in-water cleaning discharge

Technical Report for the Department of Agriculture, Water and the Environment

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1. Executive summary

In-water cleaning of biofouling on vessels has the potential to pose contaminant and biosecurity risks to the marine environment. The Australian Department of Agriculture, Water and the Environment is currently revising its national policy on in-water cleaning. In early 2020, the Department engaged the Centre of Excellence for Biosecurity Risk Analysis (CEBRA) to provide information to inform policy and risk thresholds for contaminant risks, that could be associated with in-water cleaning of biocidal antifouling coatings.

This report explores the risk of copper pollution exceeding environmentally safe levels in Australian ports due to in-water cleaning without capture, containment and treatment of waste. The report applies the methodology of Morrisey *et al.* (2013) to the Australian context and models in-water cleaning without capture in three Australian ports representing high, medium and low flushing rates. The report also builds on previous work using the Marine Antifoulant Model to Predict Environmental Concentrations (MAMPEC) by Summerson *et al.* (2019) which assessed the potential for exceeding environmentally safe levels in Australian ports due to release of disinfection by-products used in some ballast water management systems.

The key outputs of this report include:

- Summarizing the inputs used by Morrisey *et al.* (2013) and highlighting key assumptions in the modelling;
- Comparing these inputs to data available for Australia, to determine if the modelling assumptions are appropriate for this context;
- Running the MAMPEC model for the Australian ports used in Summerson *et al.* (2019), and comparing outputs to the Australian and New Zealand Environment and Conservation Council (ANZECC) Water Quality Guidelines for levels of dissolved copper in the water column, and the National Assessment Guidelines for Dredging (2009) for the concentration in sediments; and
- Providing recommendations to the Department on how many in-water cleans could be approved each year in each of the listed ports, contingent on vessel characteristics and the above assumptions.

The modelling conducted by Morrisey *et al.* (2013) was highly sensitive to the assumption of the remaining amount of copper in the leached layer of a ships' antifoulant coating. Morrisey *et al.* (2013) assumed that only 2% of copper remained in the leached layer, compared to the original amount in unleached paint and that this parameter was highly uncertain, and therefore also tested a higher level of 20% of copper remaining. This higher assumption would increase the resulting environmental concentrations by ten times, and in this case very little in-water cleaning would be able to be conducted in order to maintain concentrations within ANZECC guideline values. This highlights that actual discharges from in-water cleaning could potentially be highly variable.

The weaknesses of the MAMPEC model were also noted. MAMPEC is a steady state model, and so it cannot capture the local maximum copper concentration in the harbor at the time of in-water cleaning as it assumes continuous discharge (Zipperle *et al.*, 2011). The models taken from Summerson *et al.* (2019) also used the sedimentation parameters from the Default Commercial harbour scenario developed by the Joint Group of Scientific Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). The sedimentation process is more important for the fate of copper than the compounds considered in their original report, as the binding of copper to suspended sediments and the rate at which these sediments settle plays a large role in removing copper from harbour waters, which adds additional uncertainty to the modelling of Morrisey *et al.* (2013) undertaken in this report.

However, this modelling as well as the review of the results of Morrisey *et al.* (2013) highlight a number of strategies that can be used to reduce the risks of elevated copper contamination from in-water cleaning. These included

- Restricting in-water cleaning to vessels with sound antifoulant coatings and only allowing "soft" systems which remove minimal amounts of paint.

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- Placing restrictions on the total surface area of a vessel that is permitted to be cleaned by a cleaning operator.

It is recommended that in-water cleaning is only conducted in a port if monitoring data is collected as a requirement of the activity. This could include measuring biocide concentrations in the water and sediment before, during or after the clean or take the form of a long-term monitoring plan. This combined with initially undertaking low risk cleans could allow an evidence base to be built for the practice to be expanded, or demonstrate the risk of copper levels in water and sediments exceeding their trigger values as a result of the activity.

The contaminant risk of cleans will vary based on the flushing rate of a particular port, amongst other factors. This variation may be highlighted by applying the following scenario to a number of ports, whereby daily cleans are undertaken on a self polishing copolymer antifoulant coating, with only 2% of copper remaining in the leached layer of the paint. If an increase in the copper concentration the port of $1\mu g/L$ is considered environmentally acceptable, then in Port Hedland, full cleans of vessels between 50-100 metres in length might be acceptable. If only a portion of the vessel is cleaned, cleaning on the sides of vessels up to 150-200 metres in length might be considered acceptable, as may cleaning only boot-tops of vessels up to 250-300 metres in length.

Within the Port of Brisbane cleaning under the above scenario would be more restricted, as it is a lower flushing port compared to Port Hedland. Full cleans would still potentially be permissible for vessels up to 50-100 metres in length, but cleaning of sides would be reduced to vessels between 100-150 metres in length and cleaning restricted to boot-tops for vessels between 250-300 metres in length. For Swanson Dock in the Port of Melbourne, no cleans would be acceptable. This dock was the 'worst-case' for the Port of Melbourne, but the results for the other docks were similar as they have a much smaller tidal range and are not directly flushed by the Yarra River. Decision makers should consider a port's desired level of protection under the ANZECC guidelines and pre-existing copper concentrations in the port when identifying if a clean will be low risk to the environment. In all of these cases, a higher or lower modelled copper concentration increase might be more applicable.

2. Introduction

Biofouling is the accumulation of organisms on surfaces immersed in water and is a particular concern to the shipping industry as fouling can increase fuel costs and create biosecurity risks (Scianni & Georgiades, 2019). Biofouling can be managed by using antifoulant coatings which are paints designed to prevent biofouling, most commonly by releasing compounds toxic to aquatic organisms (Chambers *et al.*, 2006). The performance of these coatings is highly variable in practice (Georgiades & Kluza, 2017), and in-water cleaning is emerging as an important tool in biofouling management, particularly when vessels are seeking to maintain very low levels of biofouling (i.e. slime) on laminar surfaces.

However, there are concerns with current in-water cleaning techniques, including the biosecurity risks of failing to capture biofouling organisms released during cleaning and pollution from antifoulant biocides, co-biocides and paint flecks (Morrisey *et al.*, 2013). While all three components are of concern to the environment if released during in-water cleaning, this study focusses on copper as a potential contaminant. This report applies the methodology of Morrisey *et al.* (2013) to the Australian context, building on previous work using MAMPEC (Summerson *et al.*, 2019) to explore the risk of copper pollution exceeding environmentally safe levels in Australian ports due to in-water cleaning without capture, containment and treatment of waste. Technologies for in-water cleaning with capture are still being developed (Scianni & Georgiades, 2019) and there is currently insufficient information to incorporate this aspect into the modelling. The key outputs include

- Summarizing the inputs used by Morrisey *et al.* (2013) and highlighting key assumptions in the modelling.
- Comparing these inputs to data available for Australia, to determine if the modelling assumptions are appropriate for this context.
- Running the MAMPEC model for the Australian ports used in Summerson *et al.* (2019), and comparing outputs to the ANZECC Water Quality Guidelines for levels of dissolved copper in the water column, and the National Assessment Guidelines for Dredging (2009) for the concentration in sediments.
- Providing recommendations to the Department on how many in-water cleans can be approved each year in each of the listed ports, contingent on vessel characteristics and the above assumptions.

2.1. Antifoulant Coatings

For commercial vessels Morrisey *et al.* (2013) considered two types of anti-foulant coatings — self-polishing copolymers (SPC) and ablative or soluble matrix coatings. Both types of coatings are designed to have a matrix that either slowly dissolves or hydrolyses to release the biocide, which is commonly copper. In the past, tributyltin compounds were used, but these have since been banned due to their toxicity (International Maritime Organization, 1999). This is in contrast to insoluble matrix coatings, where the matrix is insoluble and biocide particles diffuse through to the surface of the paint (Morrisey *et al.*, 2013; Chambers *et al.*, 2006).

To be effective at preventing biofouling, the rate of copper release needs to be greater than 10 μg/cm^2/day (Morrisey *et al.*, 2013). The concentration of copper in the paint, and the thickness of application needs to be sufficient to hold biocide release at or above this level for the planned lifetime of the coating. Morrisey *et al.* (2013) compiled data on a number of different coatings, and found that on average commercial SPC and ablative paints had a copper concentration of 125μg/cm^2 per 1μm depth (Table 8.4 in Morrisey *et al.* (2013)).

For SPC and ablative coatings, thicker coats provide a longer lifespan — the dry film thickness of an antifoulant coating is generally 400μm for five years of effectiveness, and around 250μm for 2-3 years (Morrisey *et al.*, 2013; Earley *et al.*, 2014). Insoluble matrix coatings require biocides to migrate to the surface, so there are diminishing returns for thicker coats. This limits their lifetime to only around 12 months, and they are now largely restricted to the recreational market (Morrisey *et al.*, 2013). In a recent voluntary survey by the Department of Agriculture, Water and the Environment (the department), most vessels were found to be using SPC coatings (Ramboll, 2018); though noting that this was a pilot study with less than 40 vessels surveyed.

As the surface layer of an antifoulant coating is depleted a leached layer develops, even with SPC and ablative coatings as the biocidal pigments dissolve at a faster rate than the paint matrix retreats. This layer has a lower concentration of biocide compared to the fresh layers beneath, and its depth varies with the coating type, age, and vessel activity, with older paints or faster moving vessels generally having deeper leached layers. Morrisey *et al.* (2013) was able to obtain the leached layer thickness of a range of tin-free SPC and ablative paints. The leached layer in SPC paints ranged from 19-37μm on average after 12-18 months, and 41-64μm after 20-24 months (Table 3.4 in Morrisey *et al.* (2013)). Ablative paints had a thicker leached layer, ranging from 46-53μm after 15 months (Table 3.5 in Morrisey *et al.* (2013)).

There is significant uncertainty in the copper content of the leached layer. Morrisey *et al.* (2013) noted that Howell & Behrends (2006) found the copper content in the leached layer is low and close to the background level, while x-ray scans in Lewis (1998) indicate a copper content of about 5% of the underlying unleached paint. Further work by Marceaux *et al.* (2018) also found evidence of copper being present in the leached layer, using x-ray scans coupled with scanning electron microscopy. They did not quantify the proportion of copper in the leached and unleached layers, but it varied greatly between trials. This is a key parameter in the modelling, as a large portion of the copper released from in-water cleaning could come from the removal of the leached layer.

Even with an antifoulant coating, vessels will always develop a slime biofilm. It is unclear how this impacts the antifouling system. Morrisey *et al.* (2013) notes that slime accumulates biocides, but also can inhibit biocide release. Schottle & Brown (2007) is used by Morrisey *et al.* (2013) to make some assumptions about the copper content of biofilms. They simulated light cleaning by wiping a surface coated in antifouling paint with carpet, and found that insoluble matrix epoxy and vinyl coatings generated around 9 and 190μg/cm^2/event after one month, respectively, and 13 and 240μg/cm^2/event after three months. It was noted that the vinyl coatings had substantially more fouling compared to the epoxy, which could have contributed to the higher copper release. This highlights the variability that can be expected when considering the copper content of the biofilm layer. When initially painted, the release rate of a coating is significantly higher as a leached layer and biofilm is not present, but this decays until a constant release rate is reached. This also occurs when the paint is damaged or cleaned, as it exposes a fresh surface again with a higher concentration of copper (Earley *et al.*, 2014).

2.2. In-water cleaning

In-water cleaning involves removing the biofilm and fouling from the hull of a ship using mechanical methods, such as brushes or water jets. This can either be done pro-actively, as part of a biofouling management plan, or reactively, to remove biofouling on vessels in which preventative management has been ineffective or inadequately maintained (Scianni & Georgiades, 2019). Several factors influence the amount of paint removed in the process, including the type of paint, the severity of fouling and the type of cleaning method used. Morrisey *et al.* (2013) cite industry advice that aggressive cleaning, such as using rotating steel bristle brushes, removes around 50-100μm of antifouling paint, while soft or light cleaning using nylon bristle brushes can remove less than 25μm or just the biofouling. In practice this is also likely to be highly variable, as cleaning a paint that is in poor condition could dislodge paint flakes and accelerate the rate of damage (Morrisey *et al.*, 2013), decreasing its efficacy. Capturing and filtering the discharge from cleaning may go some way to reducing the pollution resulting from in-water cleaning. However, these technologies are still very much being developed (Scianni & Georgiades, 2019).

2.3. Copper as a pollutant

Copper is most toxic in its freely dissolved form, but when released into the ocean environment readily adsorbs to suspended particulate matter which can then settle out of the water column (Morrisey *et al.*, 2013). Within sediments copper complexes are relatively stable and copper has a low bioavailability but can still cause issues if dredging works need to be undertaken as there is a risk of re-release into the marine environment. Freely dissolved copper also readily forms complexes with organic and inorganic ligands, which can also reduce its toxicity. Morrisey *et al.* (2013) compares dissolved copper concentrations in their modelling to ANZECC and USEPA trigger values, as shown in Table 2.1, and these values appear to still be current.

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Table 2.1.: Marine water quality guidelines for copper.

Guideline Type	Guideline value (μg/L)	Reference
Acute (24 hour rolling 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)

The ANZECC water quality guidelines are designed to help determine if the quality of a water resource is adequate for its intended use. The trigger values in Table 2.1 are intended to be tailored to suit local requirements and conditions (ANZECC, 2000). For instance, in a high value conservation area a higher percentage species protection level would be desirable in comparison to a highly disturbed environment, such as a port. The US EPA guidelines are less flexible, and state that unless a locally important species is sensitive, saltwater organisms and their uses should not be affected unacceptably if the four-day average concentration does not exceed the chronic value or the 24-hour rolling average does not exceed the acute value more than once every three years on average (USEPA, 1995).

The National Assessment Guidelines for Dredging (NAGD) provide levels for sediment toxicants that trigger additional requirements when obtaining dredging approvals (DEWHA, 2009). The screening trigger value is 65mg/kg, which triggers additional requirements for obtaining permits. A second trigger value of 270mg/kg has also been used historically, but is no longer contained in the NAGD.

2.4. MAMPEC

Morrisey *et al.* (2013) uses the Marine Antifoulant Model for Predicted Environmental Concentration (MAMPEC) model to explore the potential of in-water cleaning to result in environmentally damaging concentrations of copper in the port environment. MAMPEC is a 2D steady-state hydrodynamic and chemical fate model and was initially designed to predict environmental concentrations of biocides as a result of leaching from antifoulant paints (van Hattum *et al.*, 2018). The model prioritizes ease of use and parameterization, and as a result the input parameters for a port are highly simplified. In validation studies, MAMPEC was found to be accurate to within an order of magnitude, and generally overestimated environmental concentrations (van Hattum *et al.*, 2018).

Being a steady-state model, MAMPEC assumes that chemicals are continually discharged into the port environment. This means it cannot predict the timescale over which the steady state concentration will be reached and neglects dynamic effects, such as short, irregular, and significant discharges, as is the likely case for in-water cleaning. In these scenarios, MAMPEC will under-predict the maximal concentration value (Zipperle *et al.*, 2011). However, the model is still useful as an exploratory tool to consider the risk continual that in-water cleaning in a port will elevate the environmental copper concentration above long-term environmentally damaging levels, as it has been used in Morrisey *et al.* (2013).

3. Methodology

3.1. MAMPEC Software

For this study the two latest versions of MAMPEC (v3.1 and v3.0) were used, obtained from Deltares (deltares.nl/en/software/mampec/). Version 3.1 has a different hydrodynamic model in comparison to the previous version, which was used for the Australian ballast water discharge study (van Hattum *et al.*, 2018; Summerson *et al.*, 2019). The older version has been available since 2011 (van Hattum *et al.*, 2014), so was likely also used by Morrisey *et al.* (2013). By considering both versions, the results from these previous studies can be reproduced and the impact of different hydrodynamic models on the results can be observed.

3.2. Port parameters

This study used the same ports modelled by Summerson *et al.* (2019), which included three locations representing high (Port Hedland), medium (Port of Brisbane) and low (Port of Melbourne) flushing rates. Ports with varied flushing rates were selected as clearance of chemical inputs from in-water cleaning is influenced by the flushing environment in which they are released (Gadd *et al.*, 2011). Parameters for these ports were taken from the appendix of Summerson *et al.* (2019) and included the dimensions of the port, tidal range, and flushing from rivers and other sources. The results of Morrisey *et al.* (2013) for New Zealand (NZ) ports was also reproduced, taking the port parameters from chapter 5.2.4.

3.3. Wetted surface area of vessels

The amount of copper discharged from a cleaning event depends on the total surface area cleaned. In the NZ study (Morrisey *et al.*, 2013), the surface area of a vessel was estimated based on formulas from Hempel (2007)

$$\mathrm{WSA} = LP(2D + B) \tag{3.1}$$

$$\mathrm{WSA}_{\text{boot-top}} = 2H(L + 0.5B) \tag{3.2}$$

where WSA is wetted surface area, and $WSA_{boot\text{-}top}$ is the wetted surface area of the boot-tops of the vessel, where boot-tops are defined as the area between the water lines of a ship when fully loaded and when unloaded. L is the length between perpendiculars, B is the breadth extreme, H is the boot top height, and D is the maximum draft. P is a scaling factor, with 0.7 recommended for dry cargo liners, 0.85 for bulk carriers and 0.9 for big tankers. The surface area of the vessel sides was estimated to be a third of the total wetted surface area.

We recalculated the values presented in Morrisey *et al.* (2013) with the above formula, as shown in Tables 3.1 and 3.2, and obtained slightly different results. However, it was not clear exactly what parameters they used for each vessel length class (the values for D and P in Table 3.1 were guessed based on the text), which likely result in the observed differences. Overall, the numbers are similar, especially for the boot-top surface area, and the NZ values were used in the rest of this report.

Table 3.1.: Inputs to WSA equations.

Vessel length category (m)	L (m)	H (m)	B (m)	D (m)	P
<50	25	1	7	11.5	0.85
50-100	75	1	13	11.5	0.85
100-150	125	1	19	11.5	0.85
150-200	175	2	28	11.5	0.85
200-250	225	2	32	11.5	0.85
250-300	275	2	33	11.5	0.85

Table 3.2.: Reproduction of NZ wetted surface area numbers (in m^2).

Vessel length category (m)	WSA	WSA (NZ)	WSA sides	WSA sides (NZ)	WSA boot-top	WSA boot-top (NZ)
<50	638	412	212	137	57	73
50-100	2295	1163	765	388	163	163
100-150	4462	3231	1488	1077	269	270
150-200	7586	6333	2529	2111	756	728
200-250	10519	10469	3506	3490	964	932
250-300	13090	15640	4363	5213	1166	1140

3.4. Cleaning methods and copper discharge

Morrisey *et al.* (2013) considered two different cleaning scenarios — soft and aggressive cleaning. The assumptions around the thickness of the leached layer, copper concentrations and paint removal depth are shown in Table 3.3, and are based on the information discussed in the introduction. Along with the wetted surface area estimates, these values were used to calculate the amount of copper released under different scenarios. These considered different frequencies of cleaning, different sized ships, and light versus aggressive cleaning. The copper release from these scenarios are shown in Table A.1 in the appendix. The grams of copper per day values were entered into MAMPEC as "Other Emissions".

Table 3.3.: Summary of inputs into copper release calculations, with uncertainty estimates originally given by Morrisey *et al.* (2013). Reproduced from Table 3.19 in Morrisey *et al.* (2013).

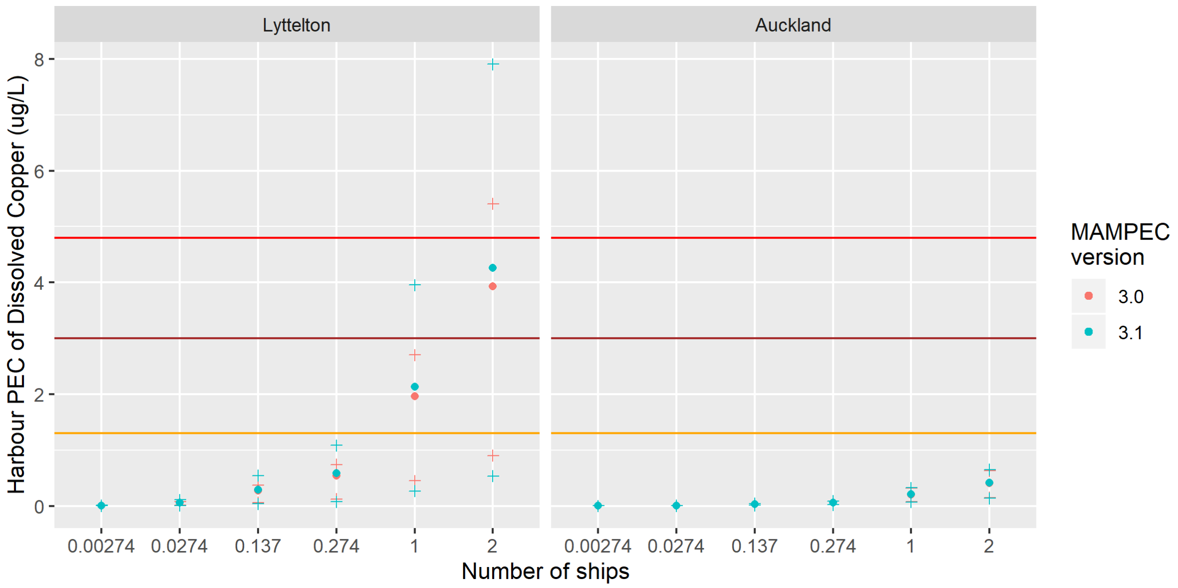
	SPC coating	Ablative coating	Uncertainty estimate
Copper concentrations in paint $\mu g/cm^2/1\mu m$ thickness			
Sound paint	120	120	fairly certain
Leached layer - low estimate	2.4	2.4	very uncertain
Leached layer - high estimate	24	24	very uncertain
Paint removal depth (μm)			
Light cleaning	25	25	fairly uncertain
Aggressive cleaning	75	75	fairly uncertain
Thickness (μm)			
Leached layer	50	60	fairly uncertain
Coating Removed (μm)			
Light cleaning			
Sound paint	0	0	
Leached layer	25	25	fairly uncertain
Biofilm	100%	100%	fairly uncertain
Aggressive cleaning			
Sound paint	25	15	fairly uncertain
Leached layer	50	60	fairly uncertain
Biofilm	100%	100%	fairly uncertain
Copper removed in biofilm $\mu g/cm^2$/cleaning event	25	50	very uncertain

4. Results

4.1. Reproducing previous studies

To ensure the methodology was consistent with the NZ approach outlined in Morrisey *et al.* (2013), their results for differing numbers of vessels were reproduced. Results were obtained that were very close, particularly using MAMPEC version 3.0, although version 3.1 also provided similar predictions. The results are shown in Figure 4.1 and A.1.

The methodology from Summerson *et al.* (2019) was also checked using dibromoacetonitrile as a test case, as it was a compound with a relatively high concentration in comparison to its predicted no effect concentration and reported for all ports. It was found that in the Australian port data, results could be reproduced in MAMPEC version 3.0 using the sedimentation parameters from the Default Commercial harbour scenario developed by the Joint Group of Scientific Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP). An abiotic half-life of 2 days for dibromoacetonitrile (GESAMP, 2020), and a tidal density difference of $0 kg/m^3$ was also used. The results are shown in Figure 4.2 and in this case MAMPEC version 3.1 gave very different predictions. This highlighted the importance of considering both MAMPEC versions, as it appears the different parameterisations of the hydrodynamic model can lead to substantially different results.



(a) Results using the input parameters from Morrisey *et al.* (2013).

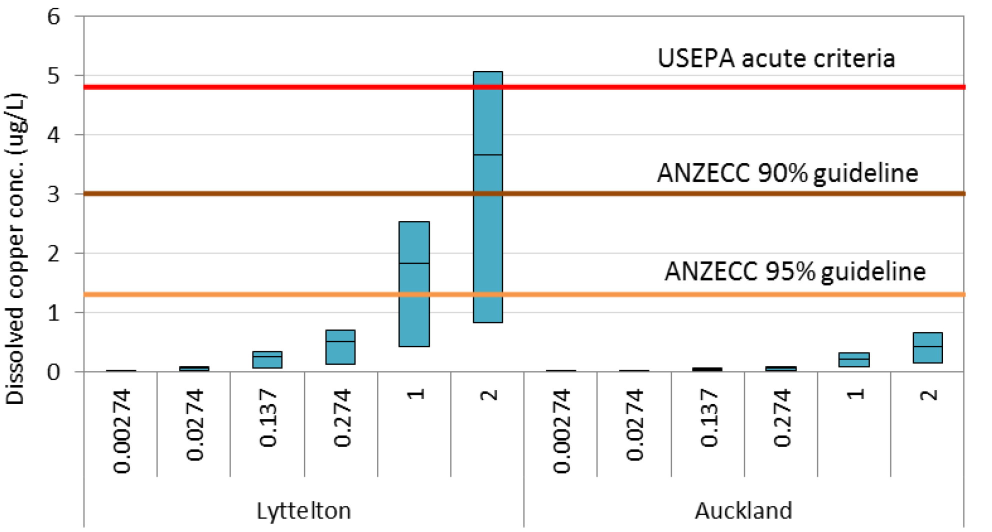


Figure 5.7 Total and dissolved copper PECs in Lyttelton Port and Port of Auckland after in-water cleaning of varying numbers of vessels. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

(b) Figure reproduced from Morrisey *et al.* (2013).

Figure 4.1.: Comparing results from Morrisey *et al.* (2013) for commercial vessels with our results using their input parameters.

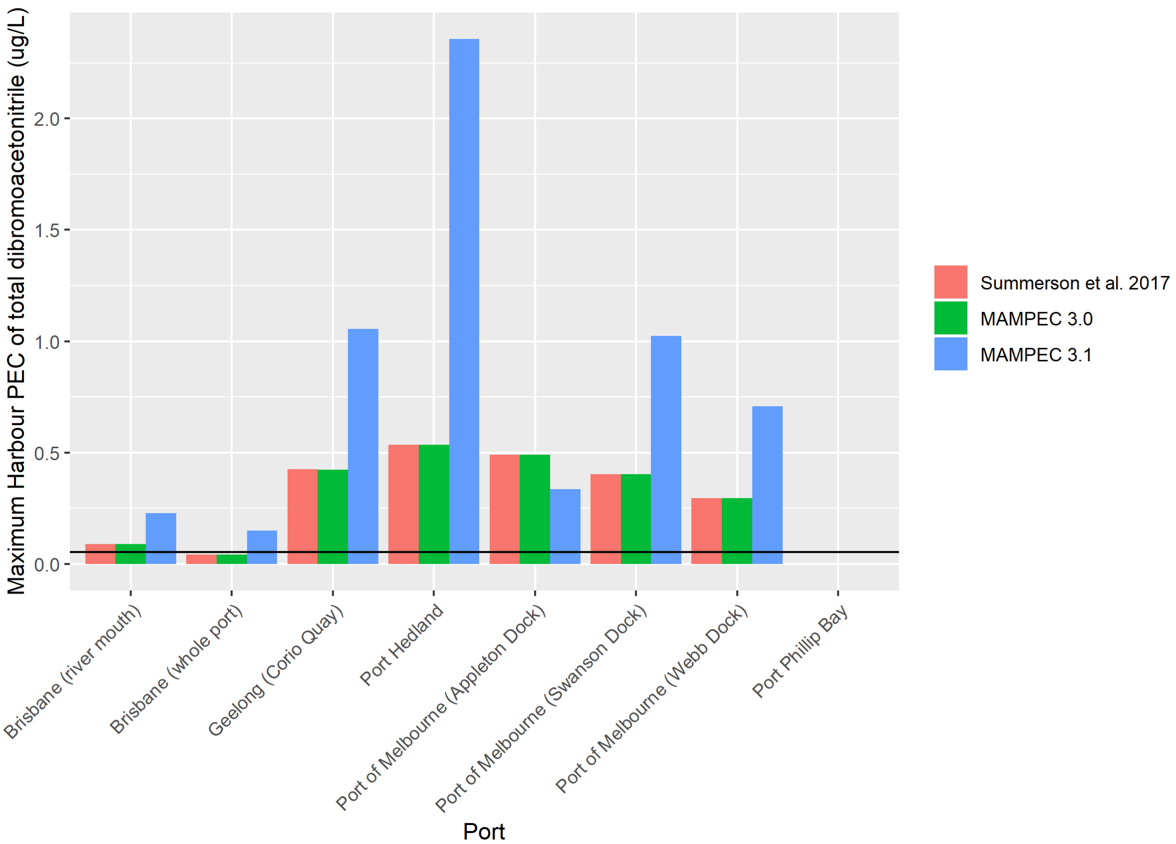


Figure 4.2.: Reproducing results from Summerson *et al.* (2019).

4.2. Australian Ports

After reproducing predicted environmental concentrations from Morrisey *et al.* (2013) and Summerson *et al.* (2019), the NZ scenarios were then applied to the Australian ports. These scenarios included conducting cleans at different frequencies, on different sized vessels, different parts of a vessel, and for different paint types, cleaning methods and leached layer concentration. For illustrative purposes, the most conservative model for each port is presented here and only the most useful results in terms of making a decision on whether cleaning a vessel could pose a risk are plotted. The full set of results for all ports and scenarios is given in Appendix A.2.2. The total copper concentrations are compared to the ANZECC trigger values, rather than dissolved copper, as the sedimentation parameters used for the Australian ports were based on the default GESAMP model port inputs (Summerson *et al.*, 2019). In the next section summary results for each port are presented, and a rate of one in-water clean per day is focused on, given that MAMPEC is a steady state model and assumes continuous discharge of the modelled biocide.

4.2.1. Port of Brisbane

The Port of Brisbane is a major container port situated at the mouth of the Brisbane River, as shown by the high proportion of visiting container vessels (Fig 4.4). The port has a tidal rage of 1.8 metres, which along with a 25.6m^3/s flushing velocity provided by the Brisbane river (Summerson *et al.*, 2019) allow for 17-25% of water in the port to be exchanged with the surroundings each tidal cycle in the MAMPEC models.

In 2014 copper levels generally ranged from 1-3μg/L for the Port of Brisbane, but some samples were found to have concentrations up to 8μg/L (BMT, 2015). This is in line with the ANZECC 90% protection guideline, apart from these exceptions. The mean sediment concentrations were around 25-30mg/kg between 2013-2018, but in a number of years maximums reached up to 110mg/kg (Wilson, 2020).

The two different port areas considered for the MAMPEC models are shown in Figure 4.3. The results for the river mouth model is presented here, as it was slightly more conservative than the whole port model due to having a smaller volume. A summary of the MAMPEC results is shown in figure 4.5.

If cleans that were predicted to increase the copper concentration in the port by 1μg/L or less when conducted on a daily basis are considered to be low risk, then Figure 4.5b shows full cleans of vessels up to 50-100 metres in length could be considered unlikely to have a significant impact on water quality or marine sediment, or restricted cleans of larger vessels up to 100-150 metres for sides and 250-300 metres for boot-tops. When making a decision as to what level of increase in copper concentration is considered low risk, the background copper contamination levels in the locality where cleaning is proposed and the desired ANZECC species protection level need to be considered by the relevant authorities.

Figure 4.3.: Port of Brisbane overlayed with areas considered to be the port for constructing MAMPEC models. Reproduced from Summerson *et al.* (2019).

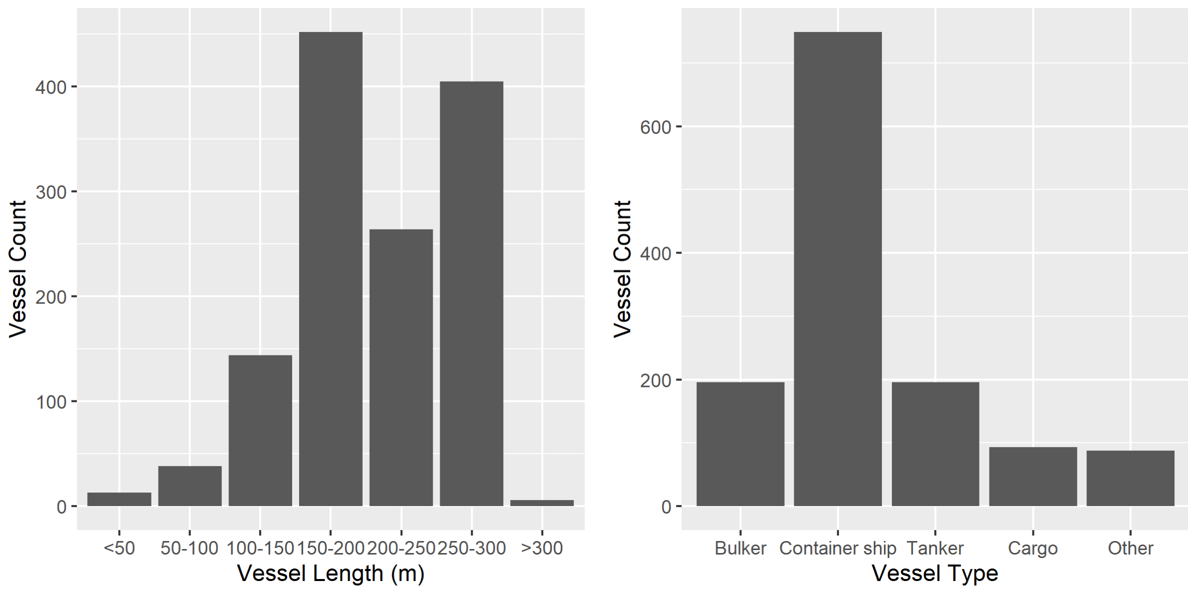
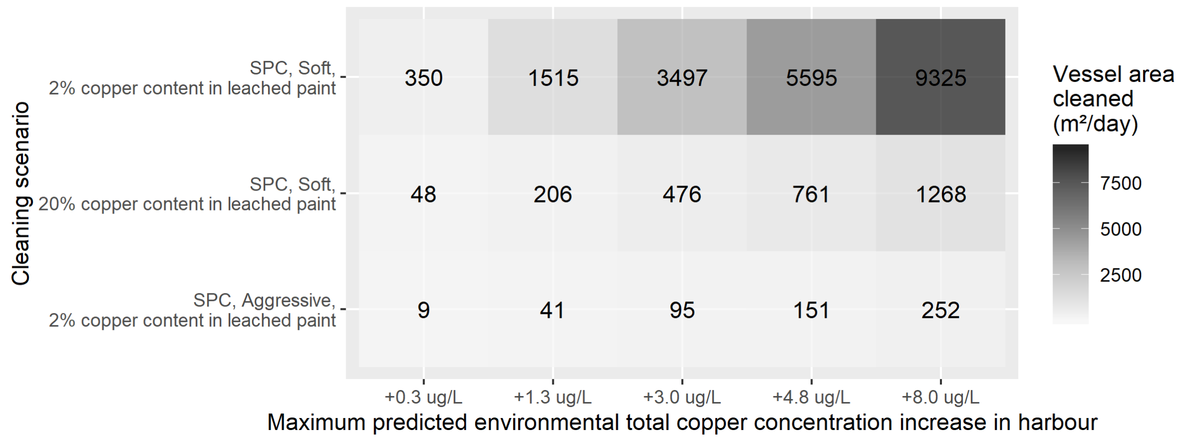
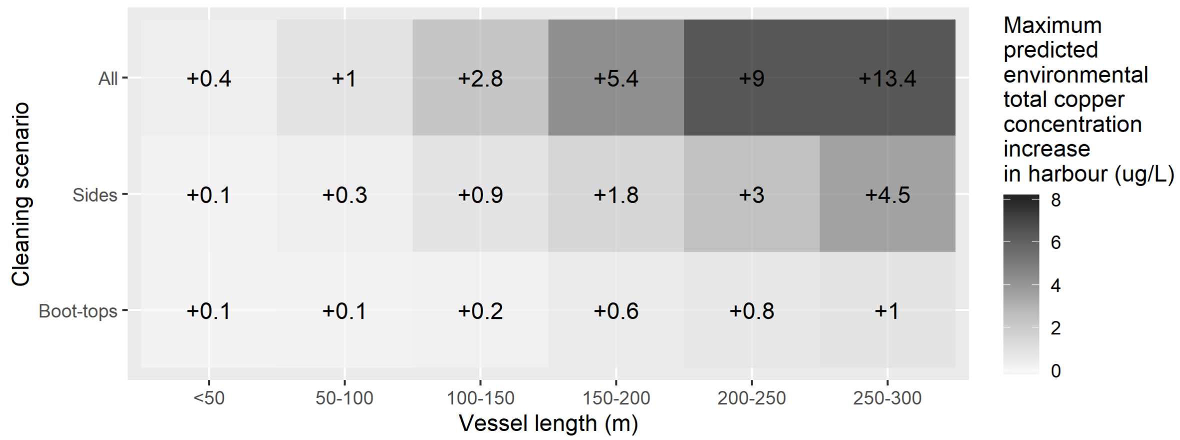


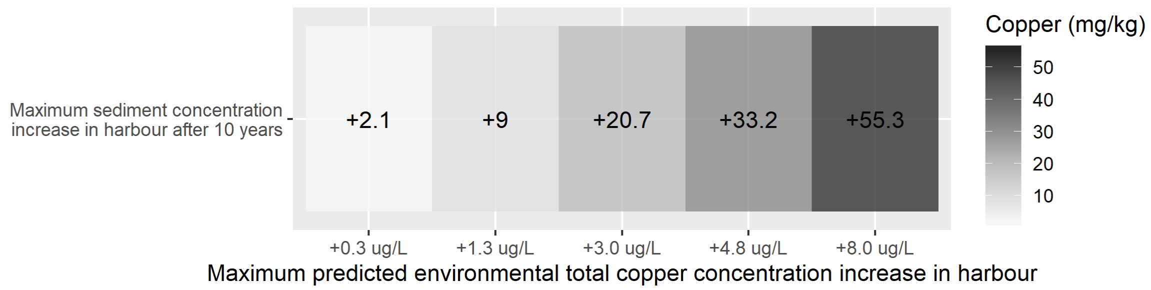
Figure 4.4.: Vessel visit statistics from 2019 for Port of Brisbane.



(a) Area of vessel hull that may be cleaned per day under different assumptions, so that the maximum total copper concentration in harbour waters increases by the given amount.



(b) Increase in maximum total copper concentration in harbour waters due to daily cleans of different sized vessels and vessel regions. This assumes that soft cleaning is used, the vessel has an SPC antifoulant coating, and that there is only 2% of the original copper amount remaining in the leached layer (i.e. the most permissive cleaning scenario).



(c) Copper concentration increase in harbour sediments after ten years as a result of the maximum total copper concentration in the harbour increasing by the given amount.

Figure 4.5.: Modelled increase in copper concentration in the harbour and sediments under different in-water cleaning scenarios for the Port of Brisbane. The worst-case result between MAMPEC version 3.0 and 3.1 is presented here. When using these figures keep in mind that it is not guaranteed that total copper concentrations will remain below the corresponding threshold and resulting sediment copper concentrations may be higher, as noted in the discussion.

4.2.2. Port of Port Hedland

The Port of Port Hedland is a major bulk export port in Western Australia (Fig 4.6), with nearly all vessel visits are made by bulk carriers (Fig 4.7). The port has a large tidal range of 5.9 metres, (Summerson *et al.*, 2019) which allows for 41% of water in the port to be exchanged with the surroundings during each tidal cycle in the MAMPEC model.

A survey in 2006 of Port Hedland found copper levels of 0.4μg/L(Wenziker *et al.*, 2006), but more recent sampling from creek inlets found copper concentrations in the range of around 1-3μg/L. Concentrations of copper in sediments varied significantly depending on the location, with values between 30-50mg/kg for two berths, but from 50-130mg/kg at another (Kitchen, 2020). The variability of copper concentrations within the sediments at the port of Port Hedland can largely be attributed to the export of copper concentrate through selected berths. Improved handling practices over recent years has seen a decline in copper concentrations within these sediments at these locations (Kitchen, 2020).

A summary of the MAMPEC results is shown in Figure 4.8. As Port Hedland has more hydrodynamic exchange in the MAMPEC model compared to the Port of Brisbane, Figure 4.8b is more permissive in the size of vessels that could theoretically be cleaned in the model. If cleans that were predicted to increase the copper concentration in the port by 1µg/L or less when conducted on a daily basis were considered low risk, then it shows full cleans of vessels up to size class 50-100 metres could be considered unlikely to have a significant impact on water quality or marine sediment, or restricted cleans of larger vessels up to 150-200 metres for sides and 250-300 metres for boot-tops. However, again it needs to be kept in mind that these discharges would be additional to the current copper levels present in Port Hedland.

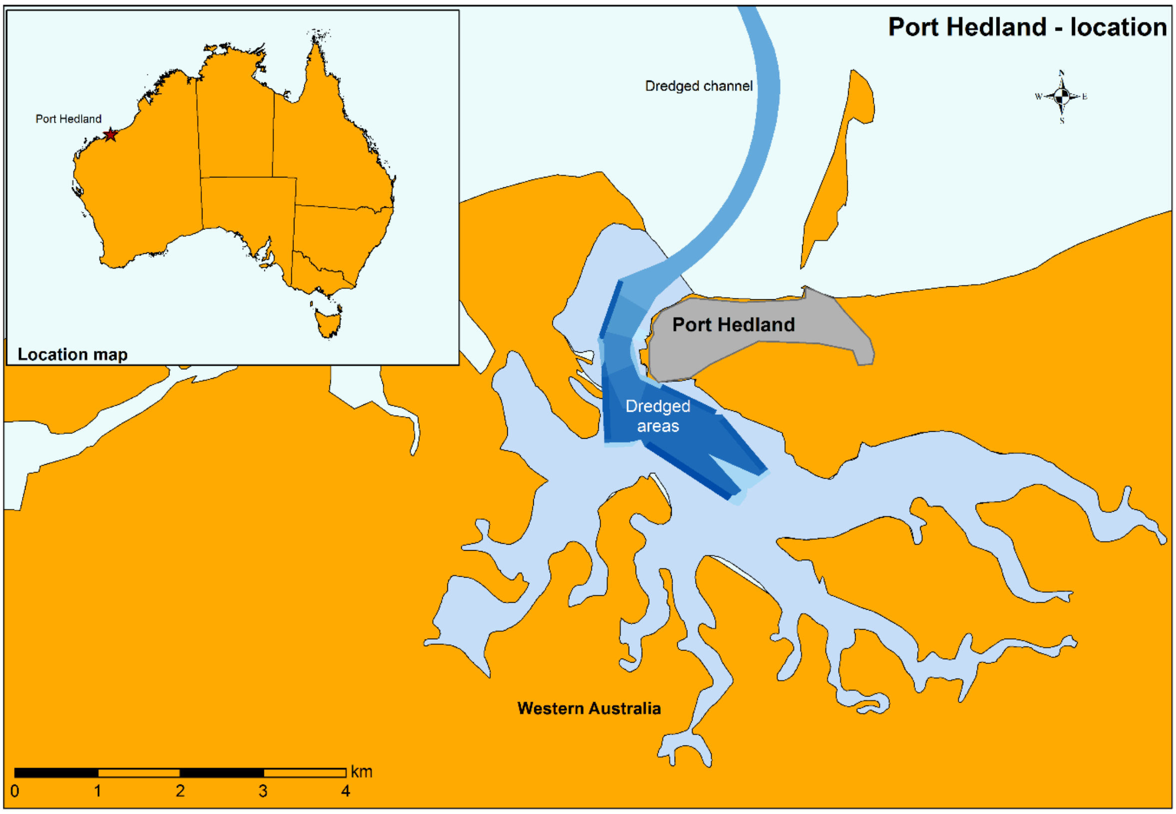


Figure 4.6.: Port Hedland overlayed with dredged area, which used to inform the dimensions of the MAMPEC model. Reproduced from Summerson *et al.* (2019).

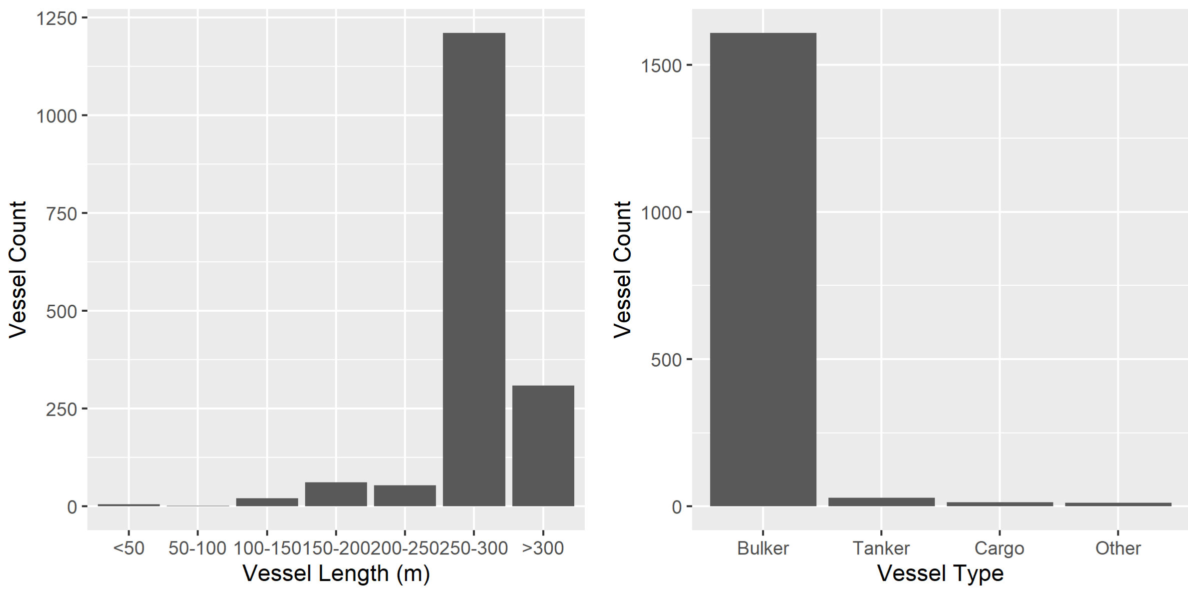
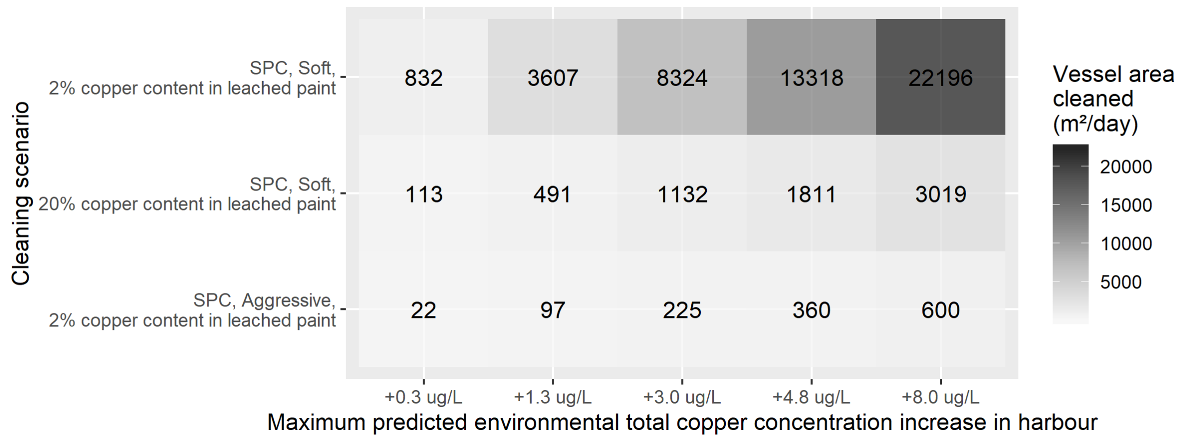
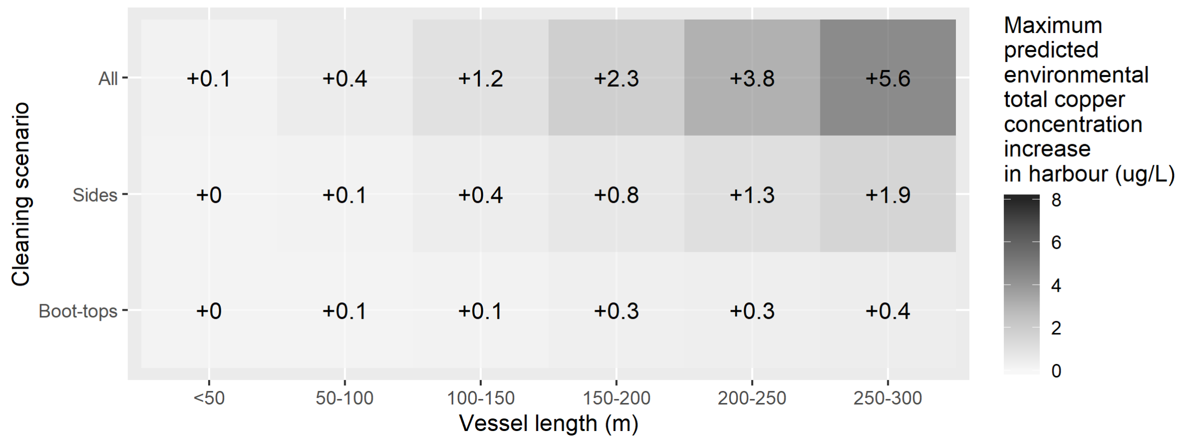


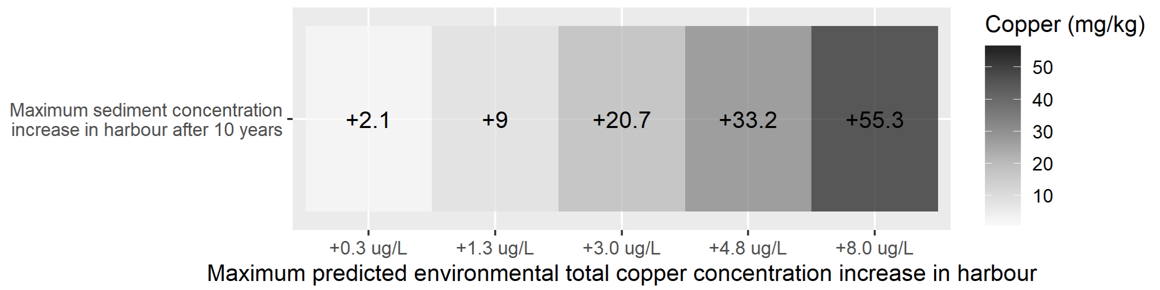
Figure 4.7.: Vessel visit statistics from 2019 for Port Hedland.



(a) Area of vessel hull that may be cleaned per day under different assumptions, so that the maximum total copper concentration in harbour waters increases by the given amount.



(b) Increase in maximum total copper concentration in harbour waters due to daily cleans of different sized vessels and vessel regions. This assumes that soft cleaning is used, the vessel has an SPC antifoulant coating, and that there is only 2% of the original copper amount remaining in the leached layer (i.e. the most permissive cleaning scenario).



(c) Copper concentration increase in harbour sediments after ten years as a result of the maximum total copper concentration in the harbour increasing by the given amount.

Figure 4.8.: Modelled increase in copper concentration in the harbour and sediments under different in-water cleaning scenarios for the Port Hedland. The worst-case result between MAMPEC version 3.0 and 3.1 is presented here. When using these figures keep in mind that it is not guaranteed that total copper concentrations will remain below the corresponding threshold and resulting sediment copper concentrations may be higher, as noted in the discussion.

4.2.3. Port of Melbourne

The Port of Melbourne is based along the Yarra River, with several different docks as the river flows through the city. Container ships and tankers are the most common (Figure 4.10) and these will berth at different locations depending on their vessel type. As the Port of Melbourne is situated in Port Phillip Bay, it only has a tidal range of 0.8 metres. In the MAMPEC models, it was estimated the amount of water exchanged each tide for the docks are around 5-8%.

Sampling from the Yarra River near Melbourne's ports and throughout Port Phillip Bay found negligible copper concentrations $< 1.3\mu g/L$ in 2010, although samples were not collected from within the primary docking areas (EPA Victoria, 2010). Sediment sampling has found copper concentrations of 17-28 mg/kg in Swanson Dock, <1 to 22.6 mg/kg in Webb Dock, and up to 40mg/kg at other locations that are part of the port (Storch, 2020).

The docks that were modelled in MAMPEC are shown in Figure 4.9. The results for just Swanson Dock is presented here, as it was more conservative than the other docks. A summary of the MAMPEC results is shown in Figure 4.11.

As Swanson Dock, and others within the Port of Melbourne have significantly less hydrodynamic exchange in the MAMPEC model compared the other ports, Figure 4.11b is significantly more restrictive in the size of vessels that could theoretically be cleaned in the model. If an acceptable increase in copper concentration was 1µg/L, then no cleans would be permissible, unlike the Port of Brisbane or Port Hedland. If this was increased to 3µg/L, then cleaning the sides of vessels less than 50 metres in length could be permissible, and the boot-tops of vessels up to 50-100 metres in length.

It is unknown which areas in the Port of Melbourne will be used for in-water cleaning, but using the larger docks (e.g. Webb Dock) or conducting cleans at anchorage may help reduce the localised impact of copper pollution from in-water cleaning and allow larger vessels to be cleaned. However, choosing a different site within Port Phillip Bay will change the background copper contamination levels and may also have implications for the desired ANZECC species protection level.

Figure 4.9.: Port of Melbourne with docks highlighted. Reproduced from Summerson *et al.* (2019).

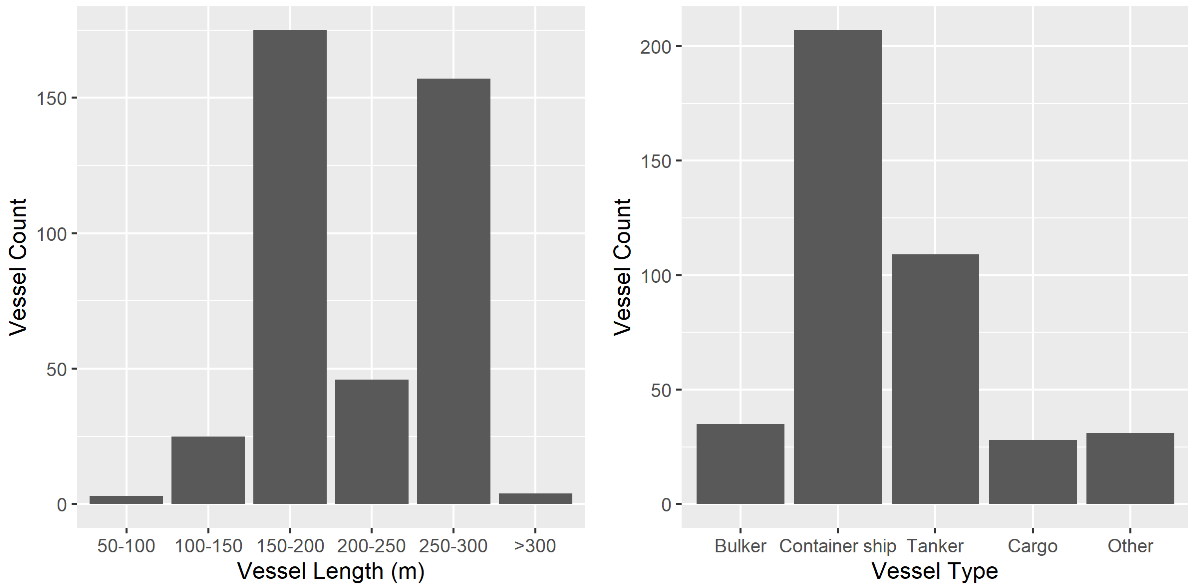
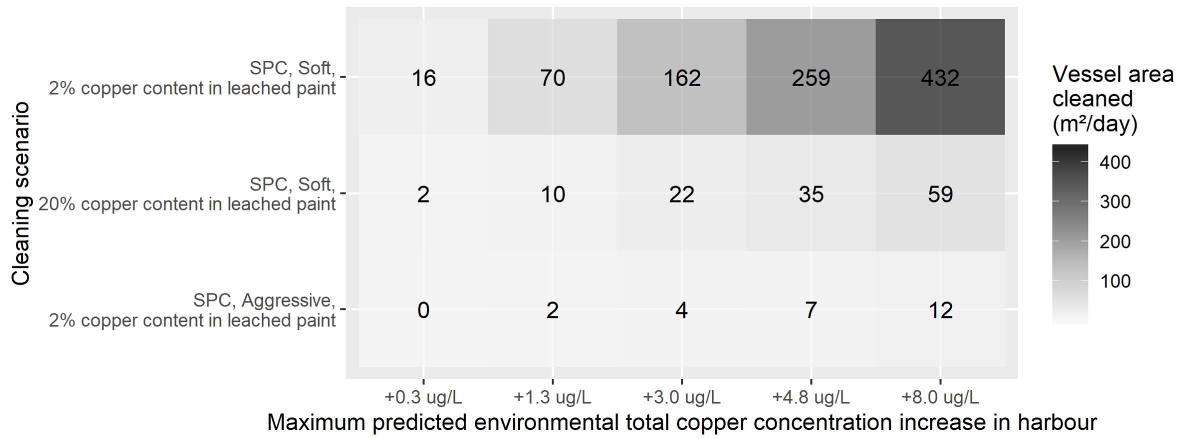
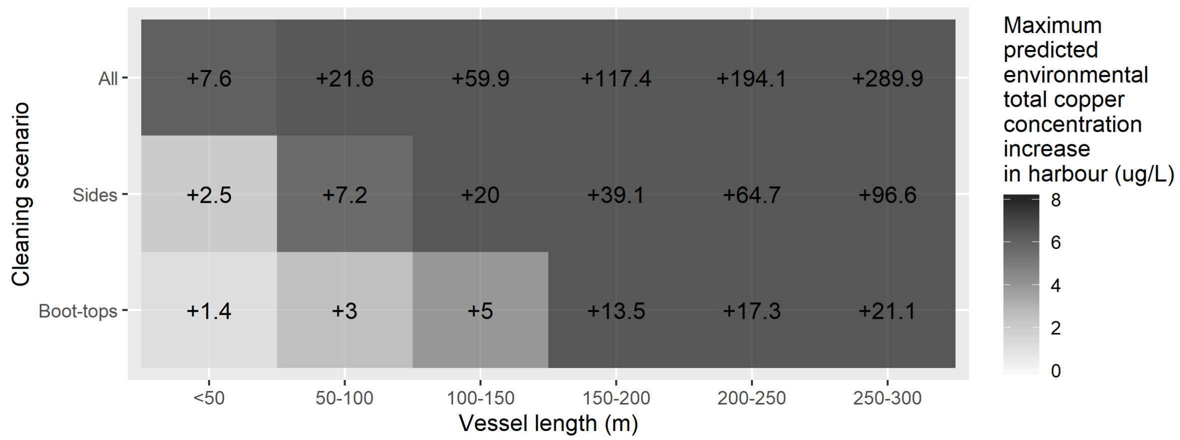


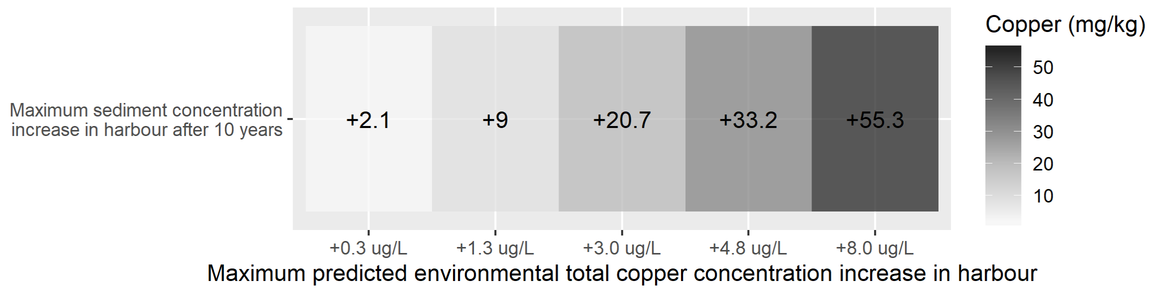
Figure 4.10.: Vessel visit statistics from 2019 for Port of Melbourne.



(a) Area of vessel hull that may be cleaned per day under different assumptions, so that the maximum total copper concentration in harbour waters increases by the given amount.



(b) Increase in maximum total copper concentration in harbour waters due to daily cleans of different sized vessels and vessel regions. This assumes that soft cleaning is used, the vessel has an SPC antifoulant coating, and that there is only 2% of the original copper amount remaining in the leached layer (i.e. the most permissive cleaning scenario).



(c) Copper concentration increase in harbour sediments after ten years as a result of the maximum total copper concentration in the harbour increasing by the given amount.

Figure 4.11.: Modelled increase in copper concentration in the harbour and sediments under different in-water cleaning scenarios for the Port of Melbourne (Swanson Dock). The worst-case result between MAMPEC version 3.0 and 3.1 is presented here. When using these figures keep in mind that it is not guaranteed that total copper concentrations will remain below the corresponding threshold and resulting sediment copper concentrations may be higher, as noted in the discussion.

5. Discussion

The actual amount of copper released into the environment from in-water cleaning will likely be highly variable depending on the copper load in the surface biofilm and leached layer of the paint. In the voluntary survey of ships visiting Australia, the maximum level of fouling and the age of the antifoulant coating varied considerably (Ramboll, 2018), and these are both factors which will impact the copper content of a ships biofilm and leached layer. Key to this analysis was the assumption that copper levels in the leached layer are around 2% of the levels in sound paint, and also that a 50-60μm thick leached layer was present. If copper levels are higher, say 20% instead of 2%, the results of this study show that the predicted environmental concentrations in the soft cleaning case also increases by ten times. If cleaning is conducted improperly and sound paint is also removed, this would also significantly increase the amount of copper released. Similar uncertainty is also present in the copper content of the ship's biofilm, with one of the few studies cited by Morrisey *et al.* (2013) finding discharge values ranging from 10-200μg/cm^2 per event.

It is also noted that the key process for removal of toxic, free copper ions from the water column is binding to suspended particulate matter and then sedimentation. This makes the build-up of copper in sediments a concern (DEWHA, 2009), but there is high uncertainty around the predicted copper levels in sediment presented here given that the Australian port models use the default sedimentation parameters from the GESAMP model port (Summerson *et al.*, 2019), and this is highlighted in that each port has the exact same sediment concentration as a result of each threshold in Figure 4.5c, 4.8c and 4.11c. This also adds to uncertainty to the total concentration of copper predicted in the harbor, as other than exchange with the surroundings, sedimentation is the primary pathway copper is removed from the harbor waters.

When interpreting the results, the expected accuracy of the MAMPEC model should also be kept in mind (to within an order of magnitude), and it should be noted that there were large differences in the results for Australian ports between the MAMPEC model versions. The model also uses a steady state assumption, which means it assumes continuous input of the discharged biocide. The maximum concentrations reported here will likely underestimate the true maximum concentration of biocide reached in local waters from an in-water cleaning event, particularly when modelling infrequent in-water cleans (Zipperle *et al.*, 2011).

These uncertainties mean that great care should be taken when using these results to advise how in-water cleans can be conducted in ports to keep biocide concentrations within safe levels. Given the variability expected in the copper content of the leached layer, the assumptions used and the accuracy of the MAMPEC model, resulting water and sediment copper concentrations may end up being higher or lower than these modelled results. Nevertheless, this study does highlight the strategies that could be used to reduce the risk of copper exceeding environmentally safe levels in Australian ports when cleaning is undertaken without capture and treatment of the effluent. These include

- Restricting in-water cleaning to vessels with sound antifoulant coatings and only allowing "soft" systems which remove minimal amounts of paint.

- Only conducting in-water cleaning in areas with high flushing rates and where sediments are unlikely to be disturbed

- Placing restrictions on the total surface area that is permitted to be cleaned by a vessel.

It is recommended that in-water cleaning is only conducted in a port if monitoring data is collected as a requirement of the activity. This could include measuring biocide concentrations in the water and sediment before, during or after the clean, or by having a long-term monitoring plan in place. Copper input to harbours can come from a range of sources, from passive release of ships hulls to urban or industrial run-off. Because of this, it may be difficult to measure the contribution of in-water cleaning specifically to copper in the water and sediments, and ports should decide what the most effective strategy for monitoring changes in copper pollution levels due to in-water cleaning activity would be.

Keeping in mind the caveats, this modelling could be used to identify cleans that will pose a low risk of increasing copper pollution levels above the ANZECC species protection level desired by a port. A highly simplified example of this would be a port with a measured copper concentration of 2μg/L and a desired ANZECC 90% protection level (3μg/L) allowing in-water cleaning for vessel-size and cleaning area combinations that would only raise the copper concentration in the port by 1μg/L when conducted on a daily basis, as shown in Figures 4.5b, 4.8b and 4.11b. Combined with sufficient monitoring this would allow an evidence base to be built for the practice to be expanded or demonstrate the risk of copper levels in water and sediments exceeding their trigger values as a result of this activity.

Acknowledgements

Bianca Brooks and Timothy Carew provided oversight of the project and along with Sonia Gorgula edited the report. The vessel visit data was provided by Rupert Summerson, and John Lewis provided an insightful review of the work.

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A. Appendix

A.1. Inputs

Table A.1.: Comparison of total emission rates for commercial vessels from different in-water cleaning scenarios. Reproduced from Table 5.13 in Morrisey *et al.* (2013).

Vessel size class (m)	Vessel surface area (m^2)	No. vessels being cleaned	Paint type	Cleaning type	Total emission rates (g/d)
Different number of vessels					
200-250	10469	0.00274	SPC-low	Soft	24
200-250	10469	0.0274	SPC-low	Soft	244
200-250	10469	0.137	SPC-low	Soft	1219
200-250	10469	0.274	SPC-low	Soft	2438
200-250	10469	1	SPC-low	Soft	8899
200-250	10469	2	SPC-low	Soft	17797
Different vessel sizes					
<50	412	1	SPC-low	Soft	350
50-100	1163	1	SPC-low	Soft	989
100-150	3231	1	SPC-low	Soft	2746
150-200	6333	1	SPC-low	Soft	5383
200-250	10469	1	SPC-low	Soft	8899
250-300	15640	1	SPC-low	Soft	13294
Sides only					
<50	137	1	SPC-low	Soft	116
50-100	388	1	SPC-low	Soft	330
100-150	1077	1	SPC-low	Soft	915
150-200	2111	1	SPC-low	Soft	1794
200-250	3490	1	SPC-low	Soft	2967
250-300	5213	1	SPC-low	Soft	4431
Boot-tops only					
<50	73	1	SPC-low	Soft	62
50-100	163	1	SPC-low	Soft	139
100-150	270	1	SPC-low	Soft	230
150-200	728	1	SPC-low	Soft	619

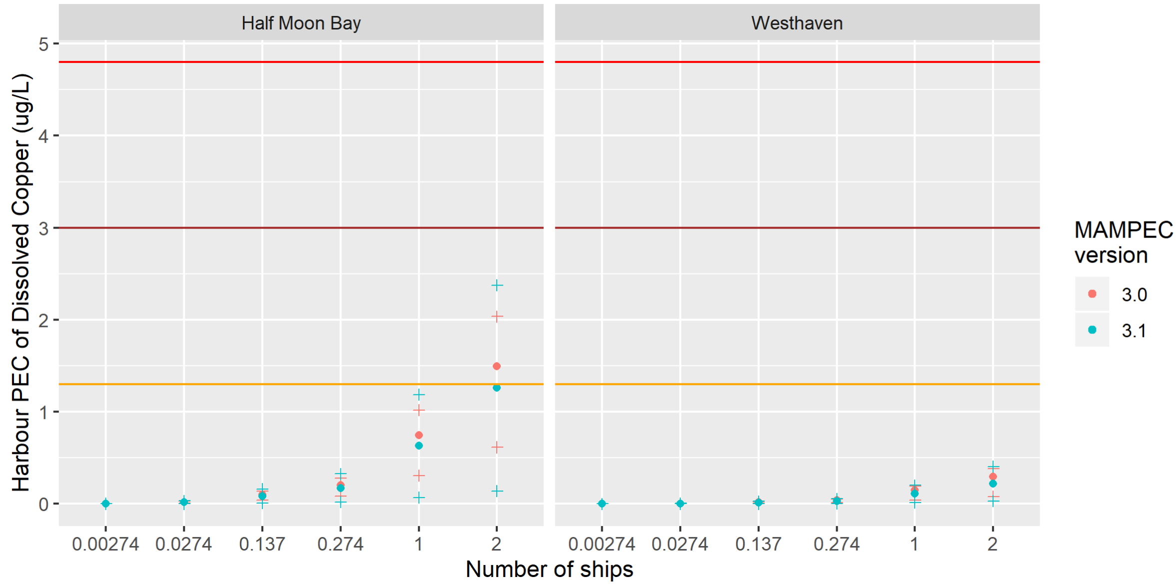
Continued on next page

Table A.1 – *Continued from previous page*

Vessel size class (m)	**Vessel surface area (m^2)**	**No. vessels being cleaned**	**Paint type**	**Cleaning type**	**Total emission rates (g/d)**
200-250	932	1	SPC-low	Soft	792
250-300	1140	1	SPC-low	Soft	969
Different paint types					
200-250	10469	1	SPC-low	Soft	8899
200-250	10469	1	Ablative-low	Soft	11516
Upper release estimate					
200-250	10469	1	SPC-high	Soft	65431
200-250	10469	1	Ablative-high	Soft	68049
Different cleaning methods					
200-250	10469	1	SPC-low	Aggressive	329250
200-250	10469	1	SPC-high	Aggressive	442315
200-250	10469	1	Ablative-low	Aggressive	208752
200-250	10469	1	Ablative-high	Aggressive	344430

A.2. Results

A.2.1. Reproducing Morrisey *et al.* (2013) results



(a) Results using the input parameters from Morrisey *et al.* (2013).

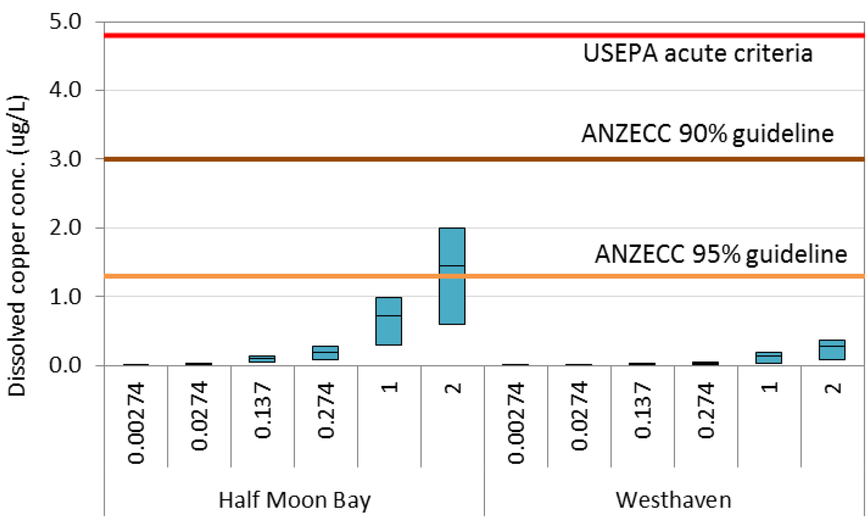


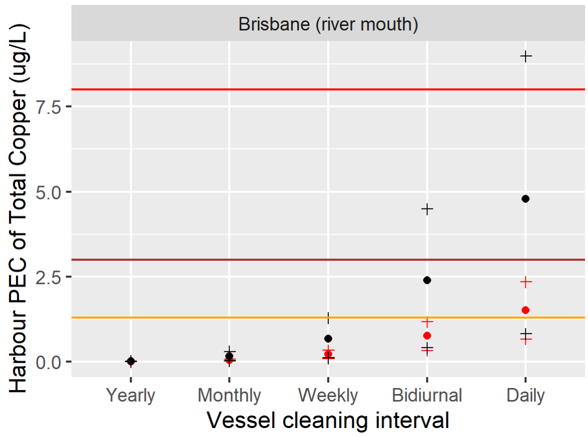
Figure 5.6 Total and dissolved copper PECs in Half Moon Bay and Westhaven marinas after in-water cleaning of varying numbers of vessels. Bottom of bar indicates minimum, middle line indicates mean and top of bar indicates maximum PEC.

(b) Figure reproduced from Morrisey *et al.* (2013).

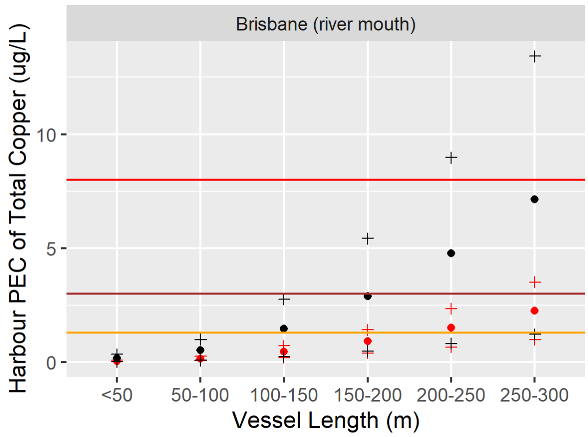
Figure A.1.: Comparing results from Morrisey *et al.* (2013) for recreational vessels with our results using their input parameters.

A.2.2. Applying Morrisey *et al.* (2013) (NZ) to all Summerson *et al.* (2019) (AUS) ports

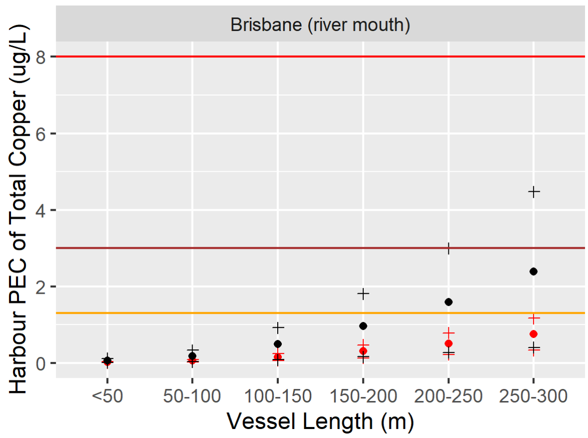
A.2.2.1. Total copper in harbour



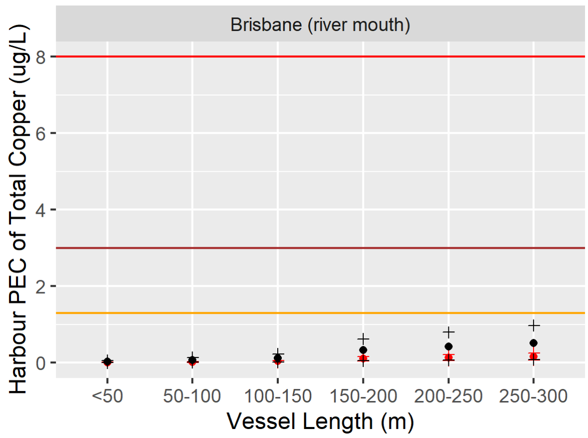
(a) Frequency of ship cleans.



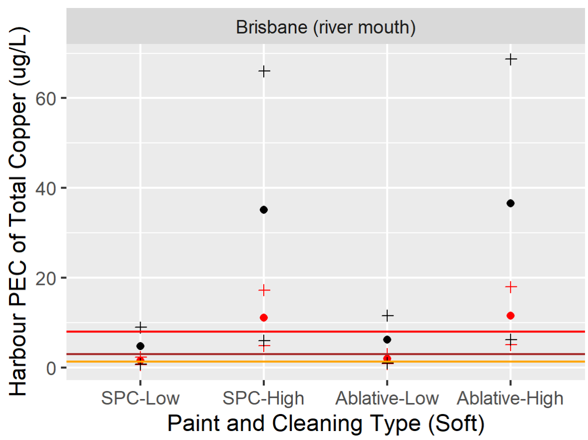
(b) Length of ship.



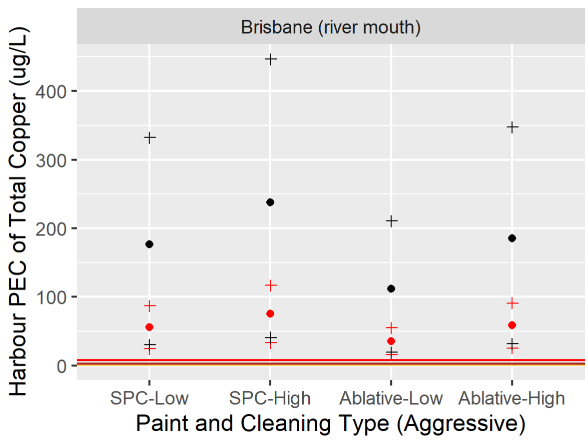
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

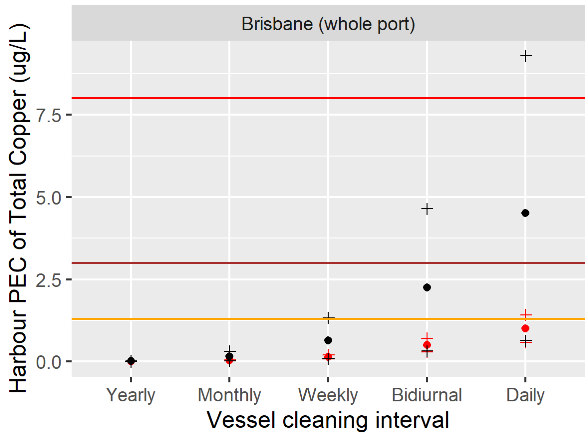


(e) Paint type and level of copper in the leached layer, with soft cleaning.

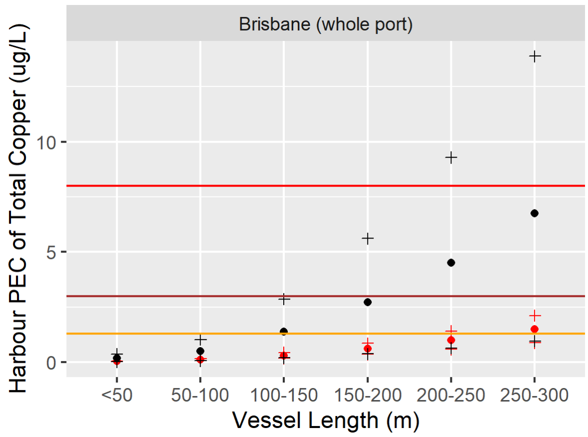


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

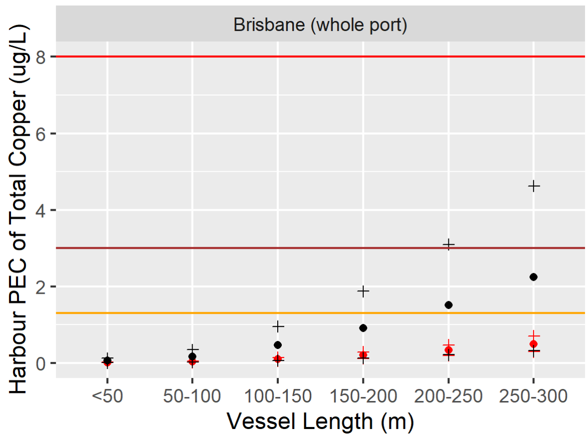
Figure A.2.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Brisbane. Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



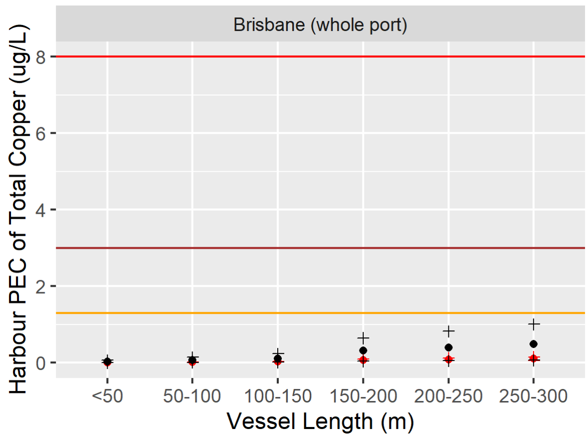
(a) Frequency of ship cleans.



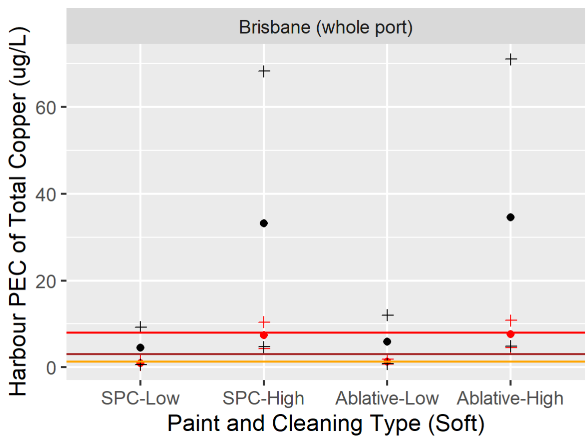
(b) Length of ship.



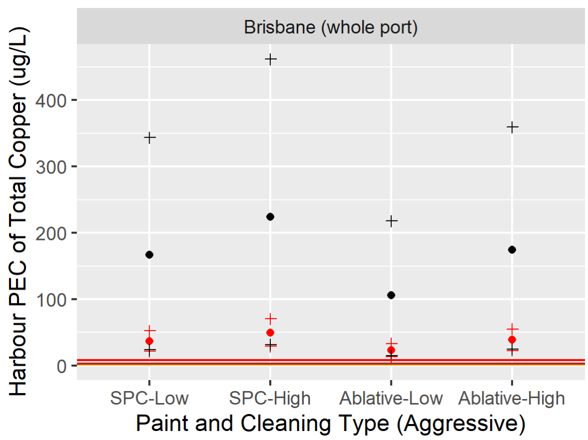
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

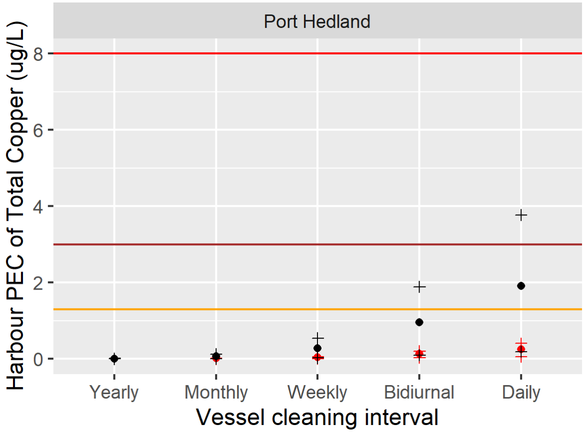


(e) Paint type and level of copper in the leached layer, with soft cleaning.

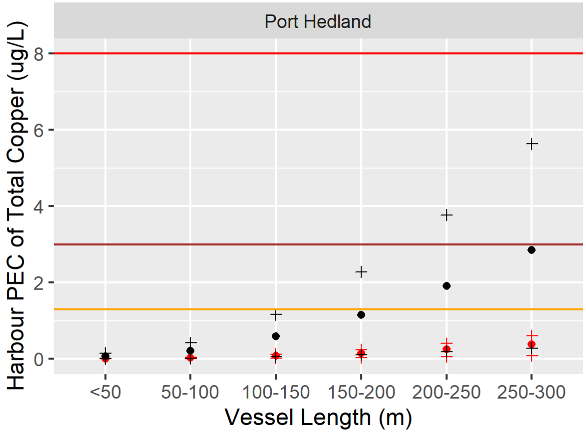


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

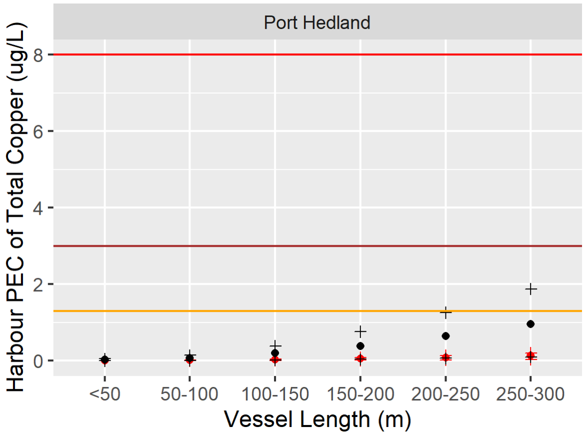
Figure A.3.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Brisbane (whole port model). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



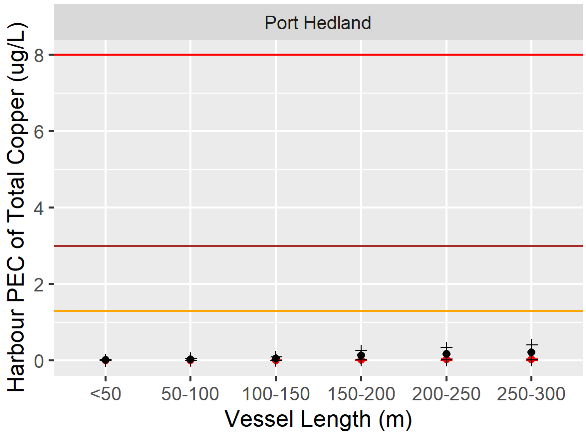
(a) Frequency of ship cleans.



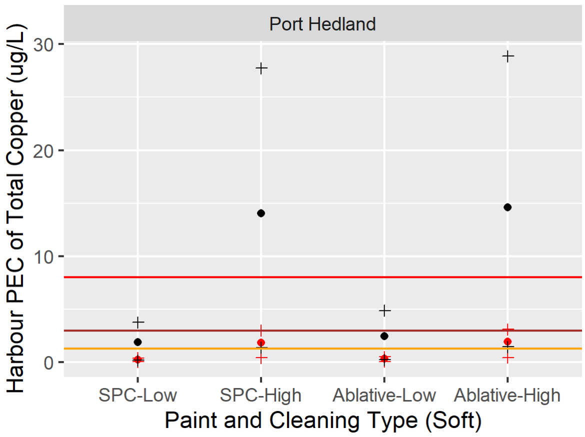
(b) Length of ship.



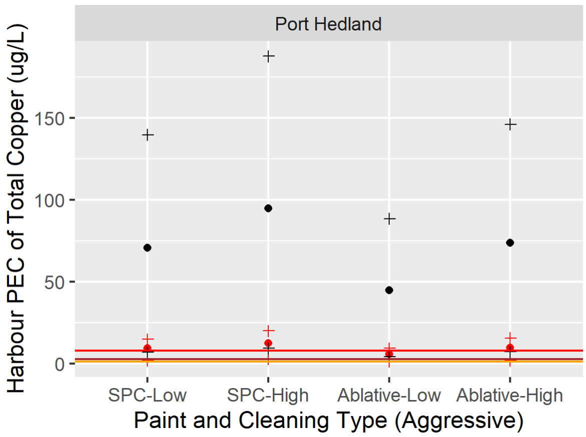
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

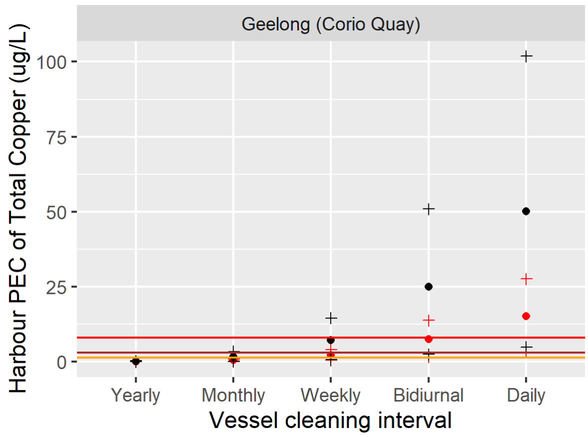


(e) Paint type and level of copper in the leached layer, with soft cleaning.

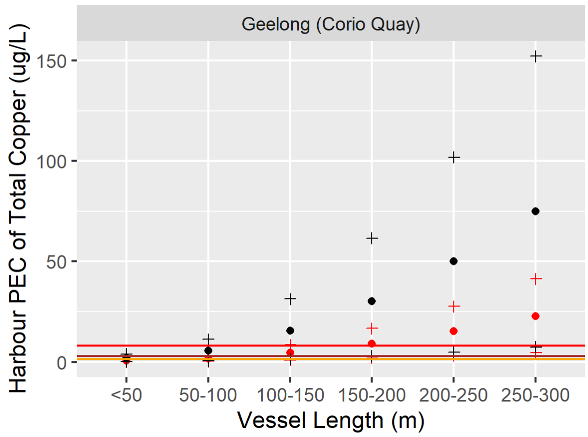


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

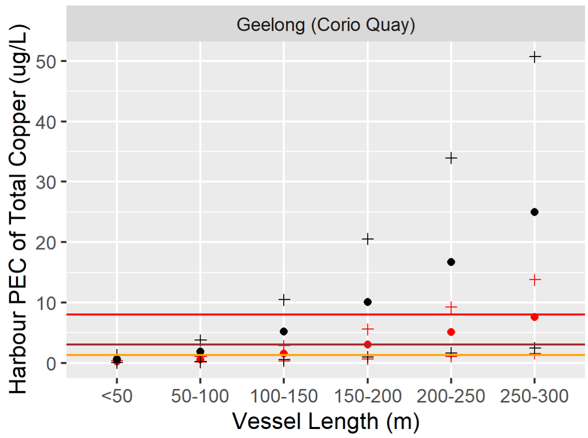
Figure A.4.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port Hedland. Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



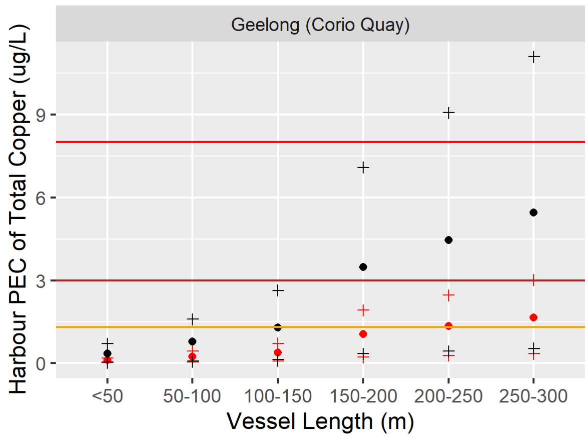
(a) Frequency of ship cleans.



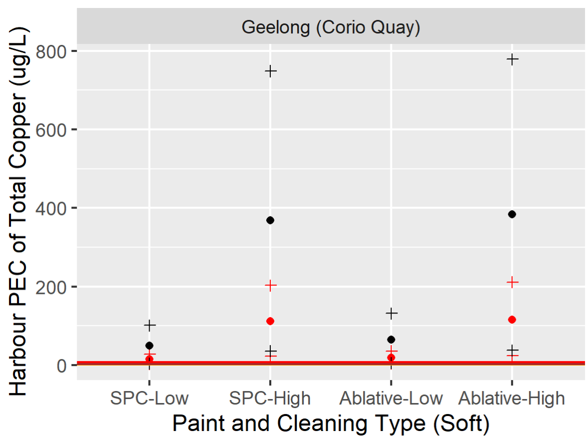
(b) Length of ship.



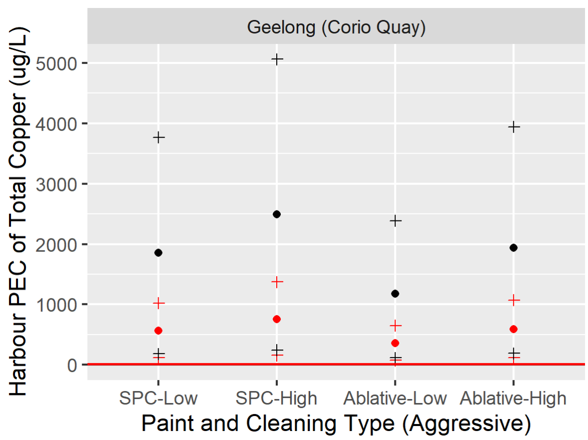
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

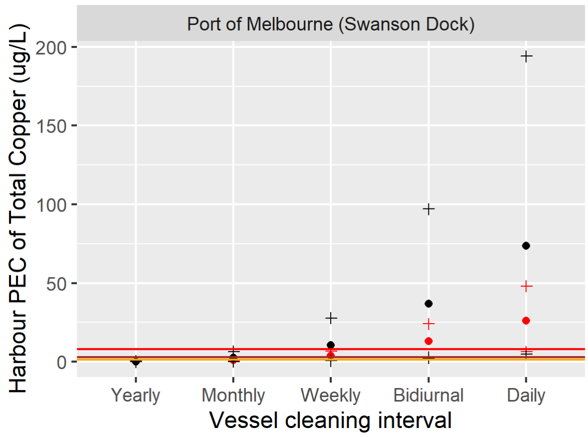


(e) Paint type and level of copper in the leached layer, with soft cleaning.

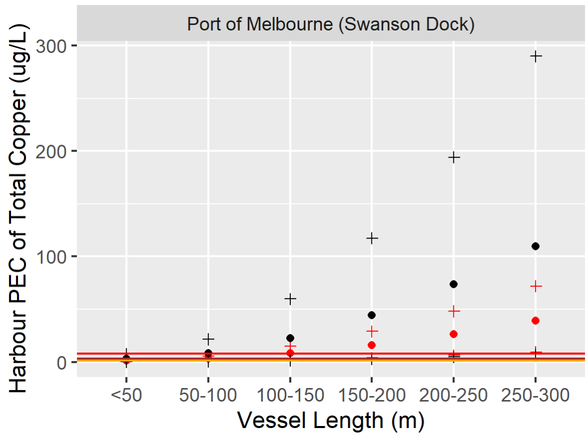


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

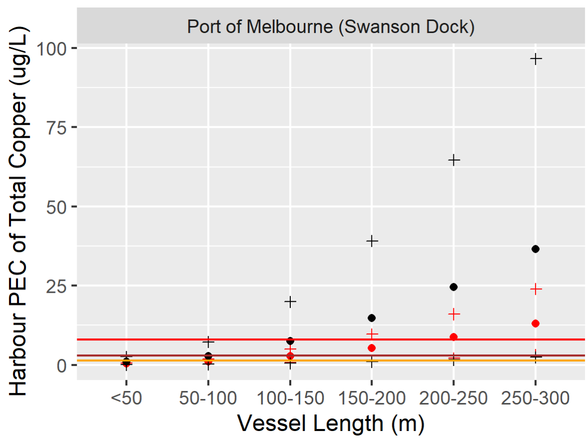
Figure A.5.: Copper loads within harbour under a number of different in-water cleaning scenarios for Geelong (Corio Quay). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



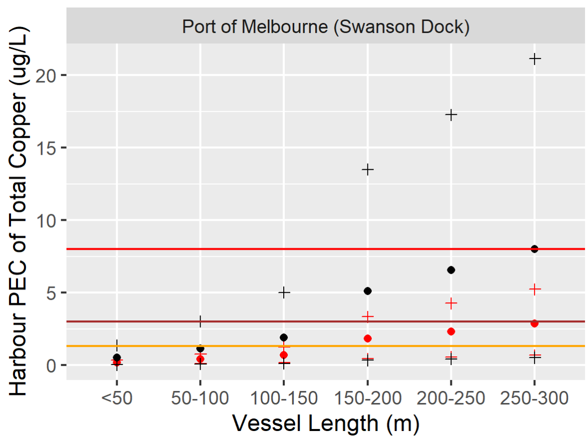
(a) Frequency of ship cleans.



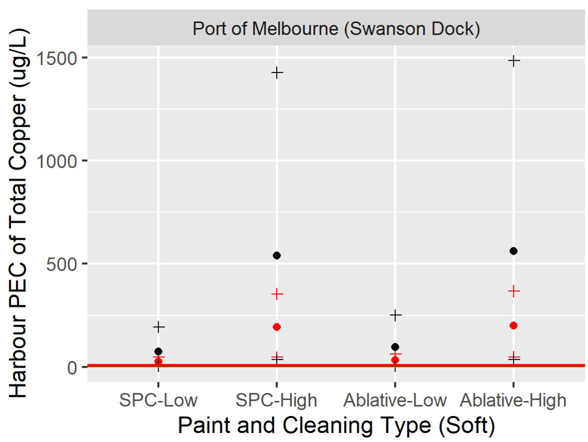
(b) Length of ship.



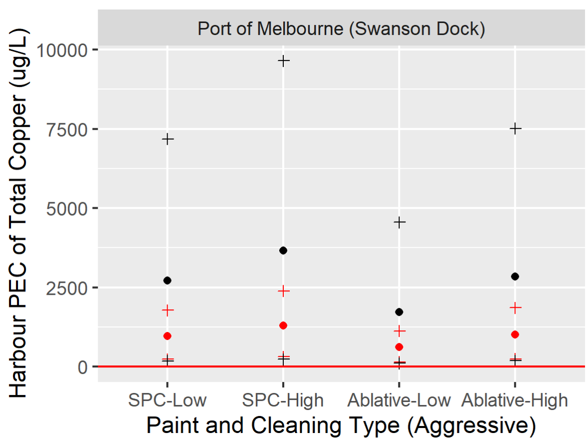
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

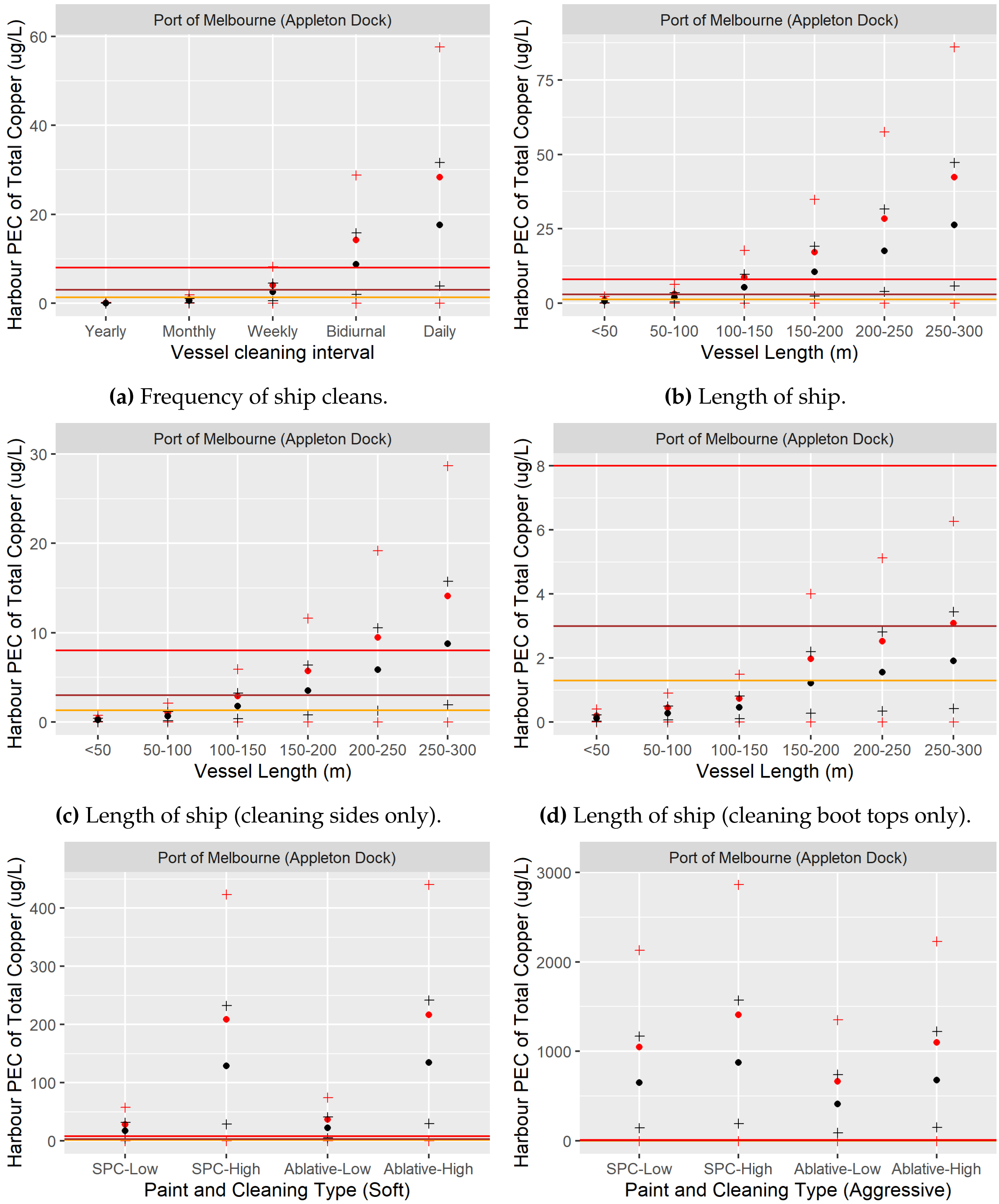


(e) Paint type and level of copper in the leached layer, with soft cleaning.



(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

Figure A.6.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Melbourne (Swanson dock). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



(a) Frequency of ship cleans.

(b) Length of ship.

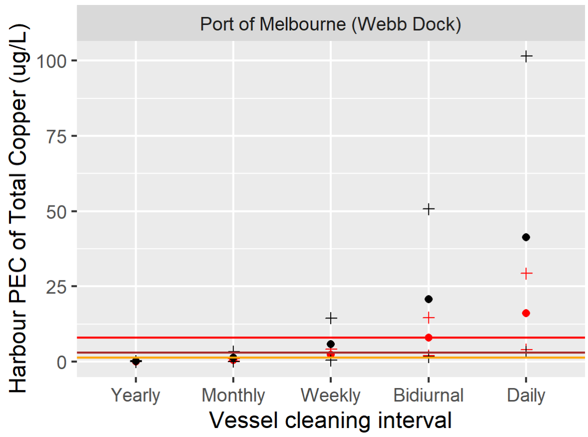
(c) Length of ship (cleaning sides only).

(d) Length of ship (cleaning boot tops only).

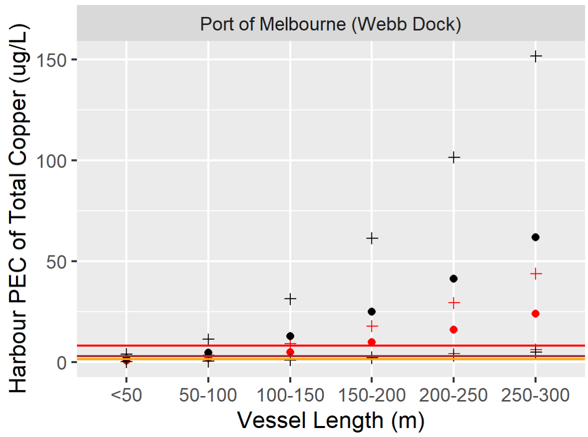
(e) Paint type and level of copper in the leached layer, with soft cleaning.

(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

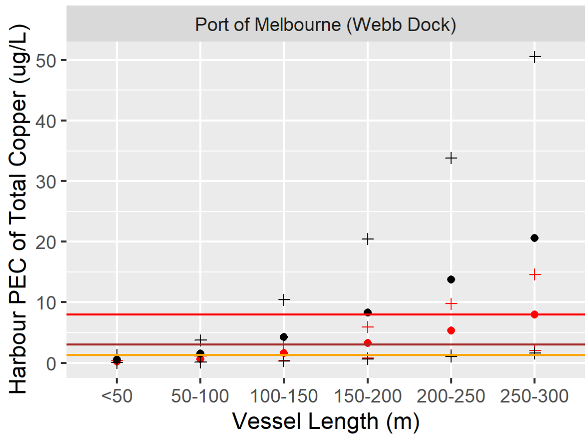
Figure A.7.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Melbourne (Appleton dock). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



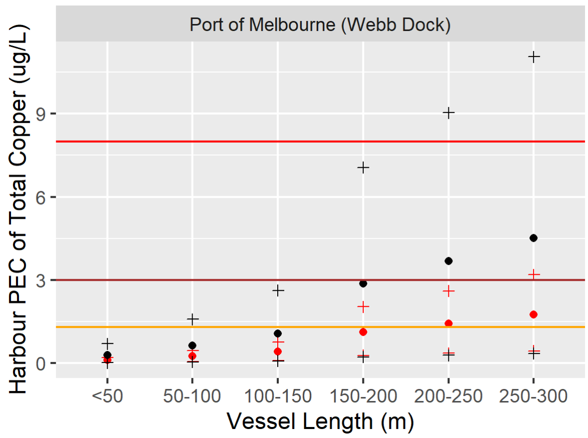
(a) Frequency of ship cleans.



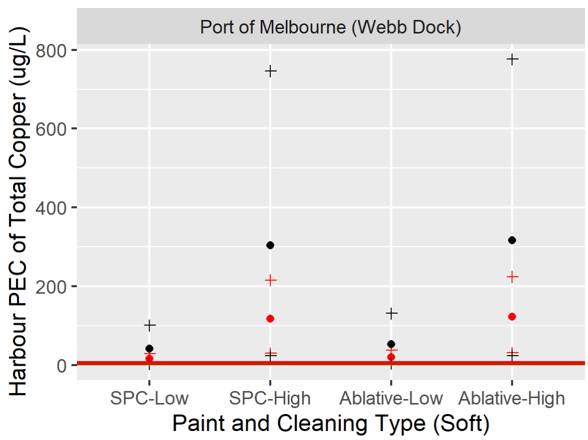
(b) Length of ship.



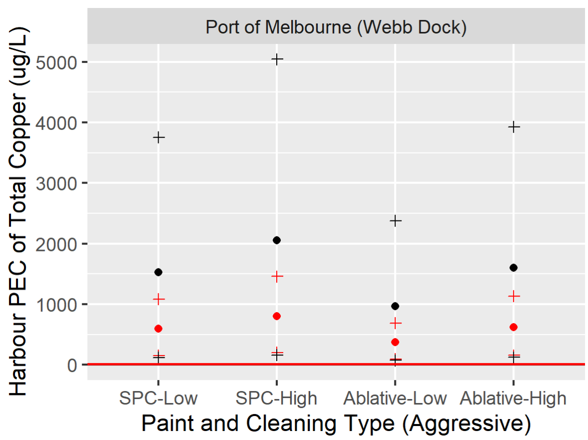
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

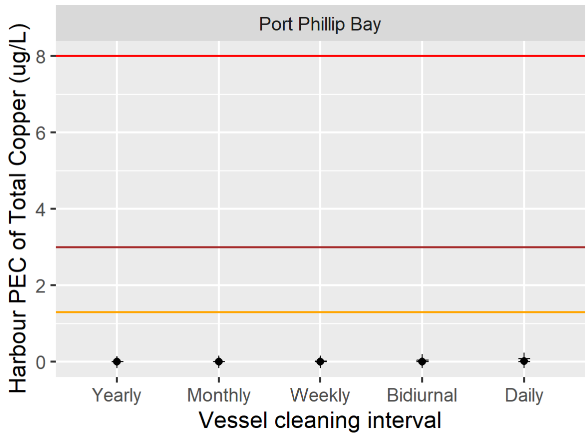


(e) Paint type and level of copper in the leached layer, with soft cleaning.

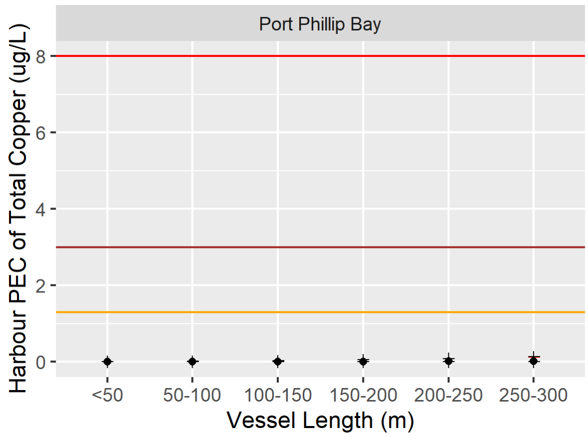


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

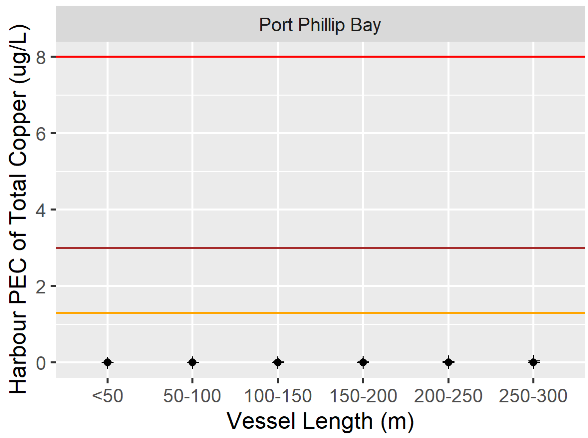
Figure A.8.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Melbourne (Webb dock). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



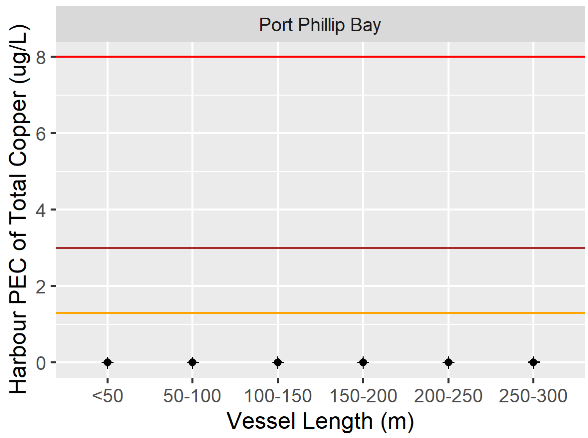
(a) Frequency of ship cleans.



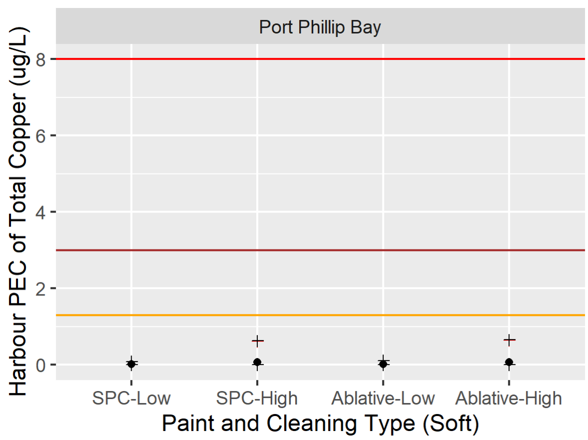
(b) Length of ship.



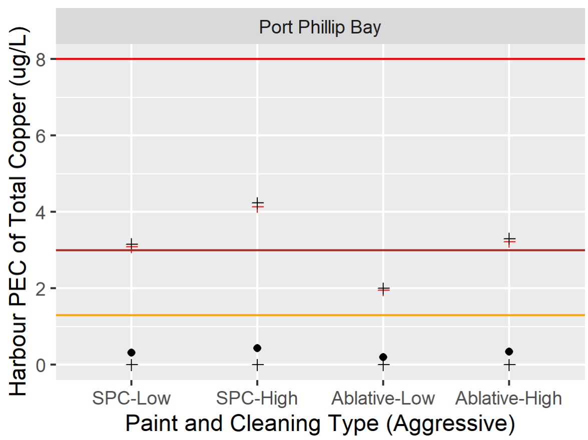
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).



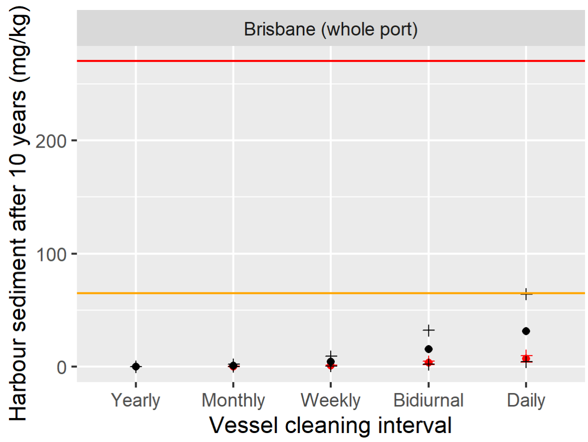
(e) Paint type and level of copper in the leached layer, with soft cleaning.



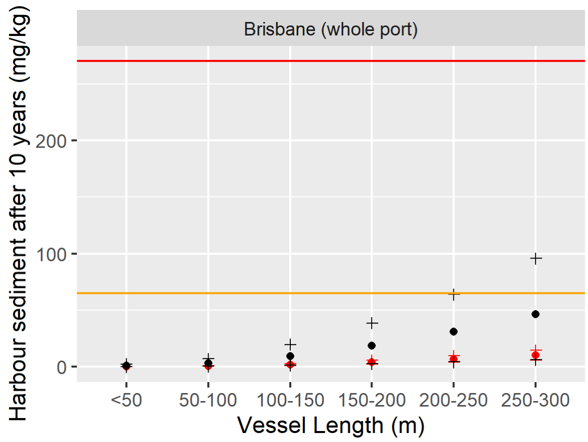
(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

Figure A.9.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port Phillip Bay. Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.

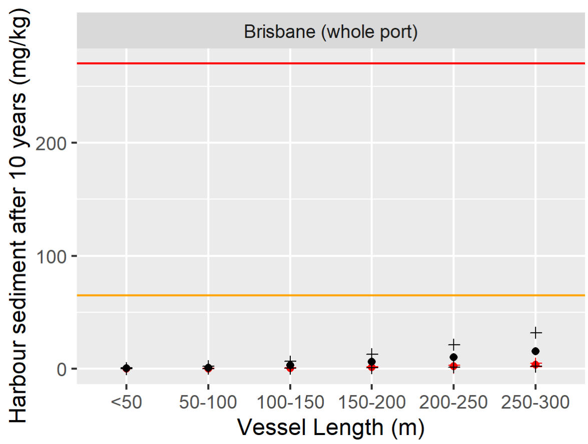
A.2.2.2. Copper concentration in sediments after 10 years



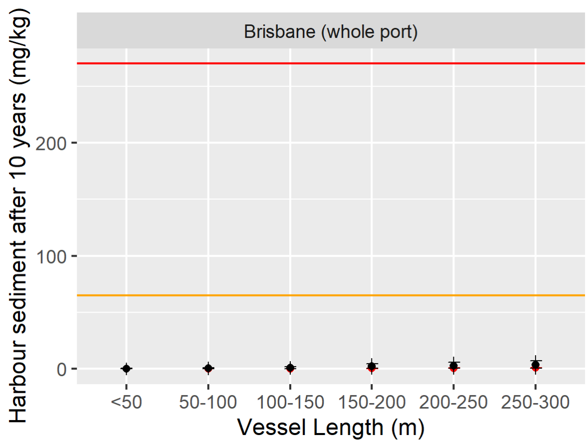
(a) Frequency of ship cleans.



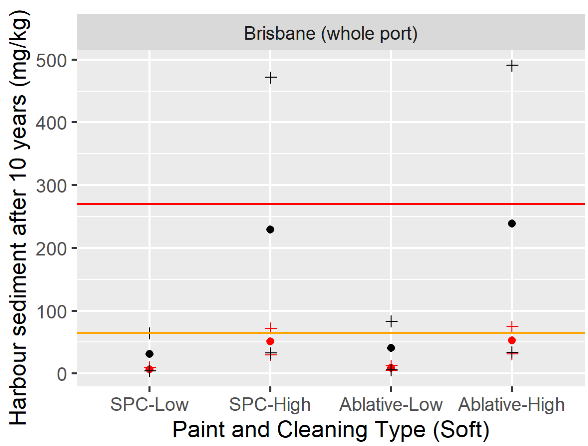
(b) Length of ship.



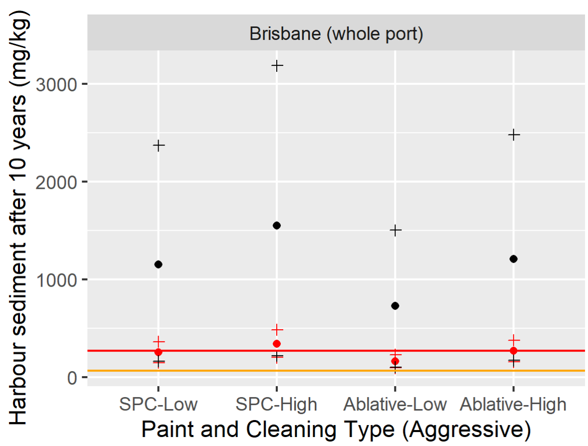
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

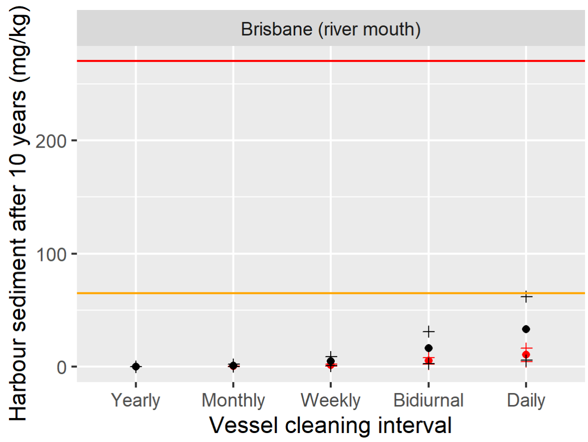


(e) Paint type and level of copper in the leached layer, with soft cleaning.

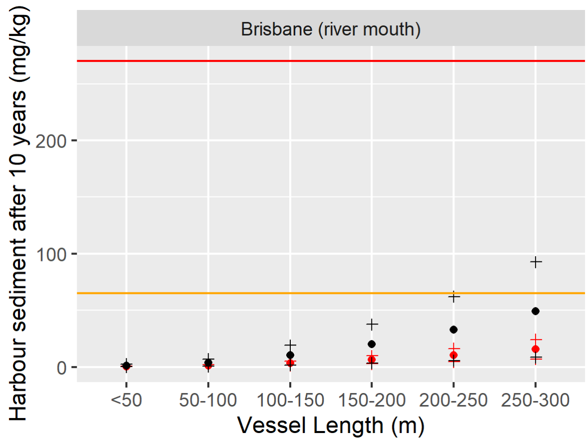


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

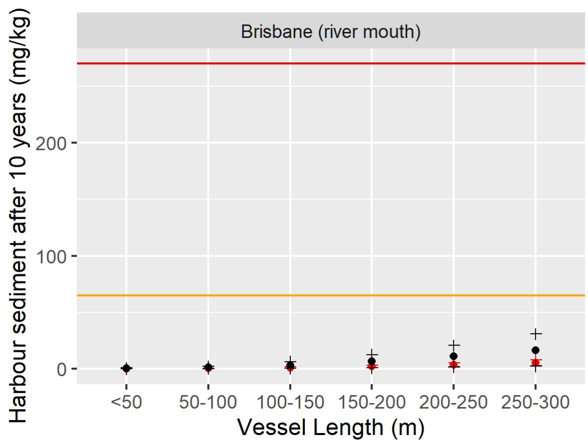
Figure A.10.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Brisbane (whole port model) (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



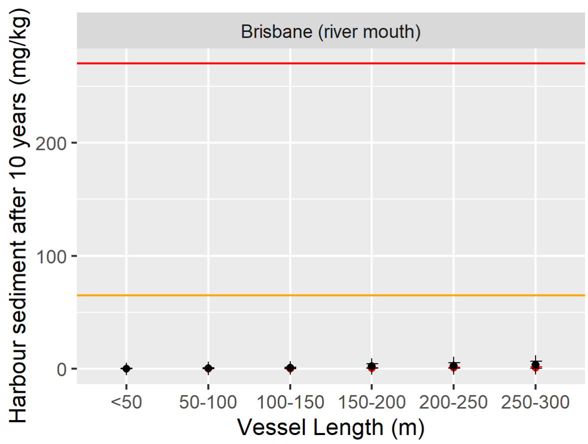
(a) Frequency of ship cleans.



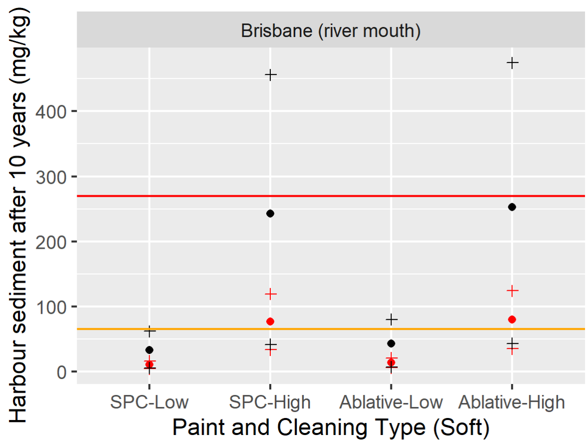
(b) Length of ship.



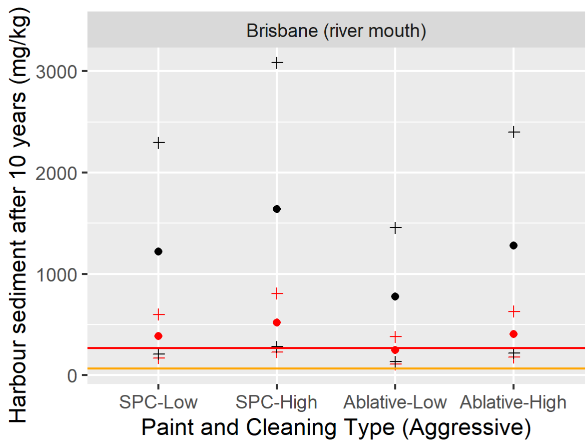
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

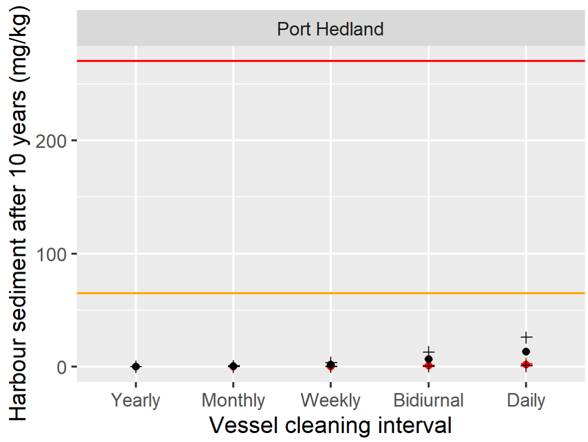


(e) Paint type and level of copper in the leached layer, with soft cleaning.

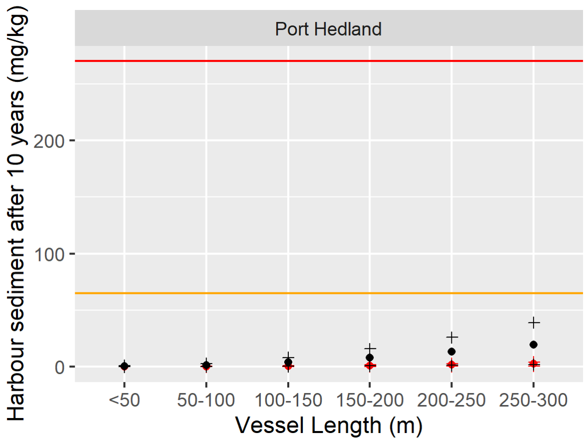


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

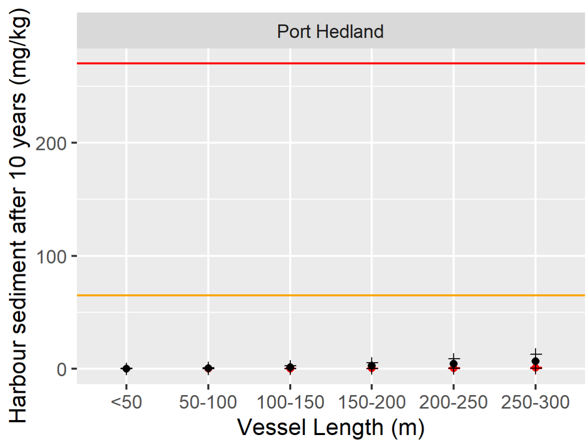
Figure A.11.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Brisbane (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



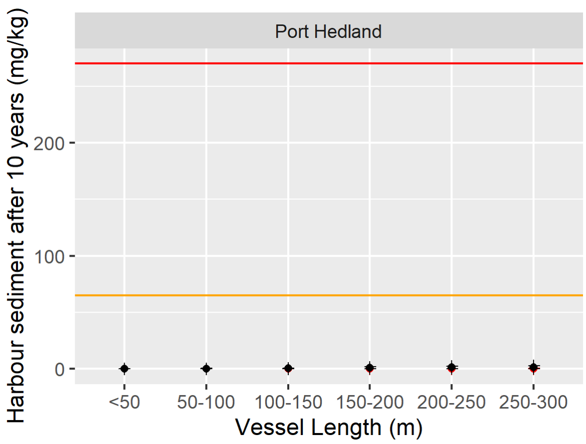
(a) Frequency of ship cleans.



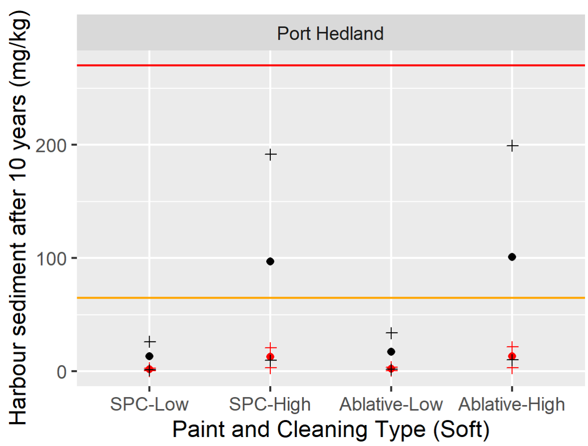
(b) Length of ship.



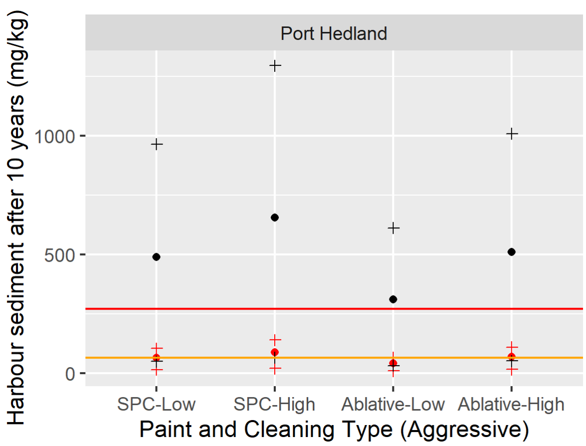
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

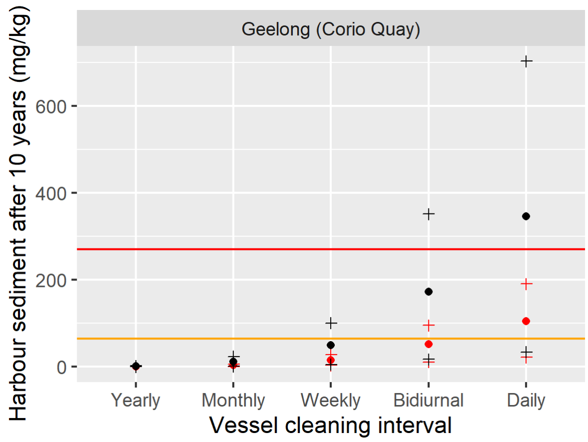


(e) Paint type and level of copper in the leached layer, with soft cleaning.

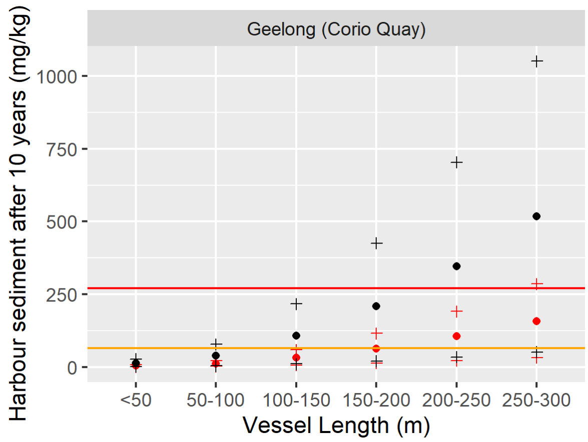


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

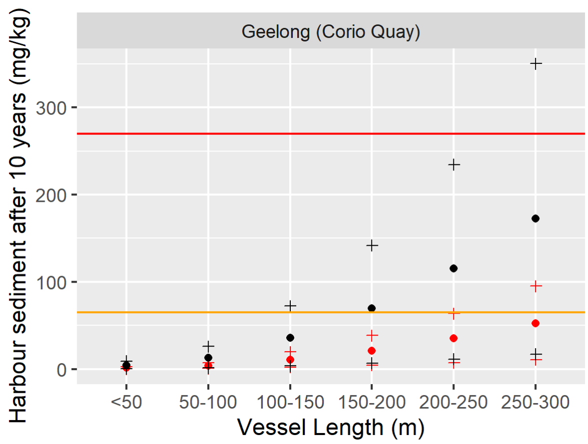
Figure A.12.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port Hedland (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



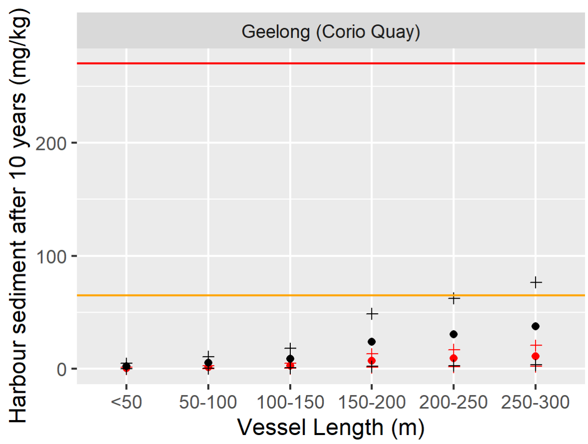
(a) Frequency of ship cleans.



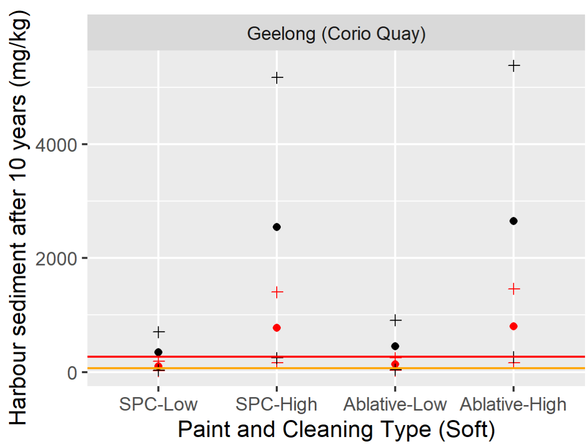
(b) Length of ship.



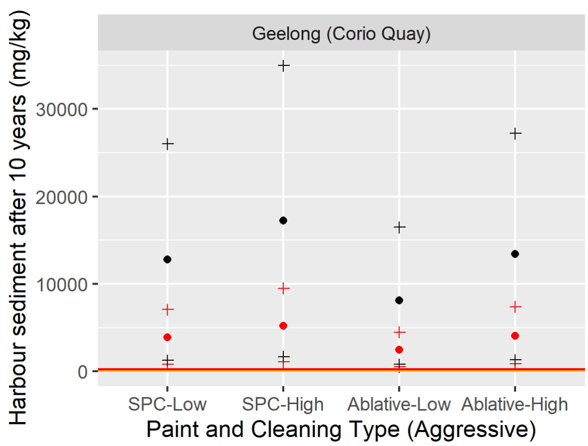
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

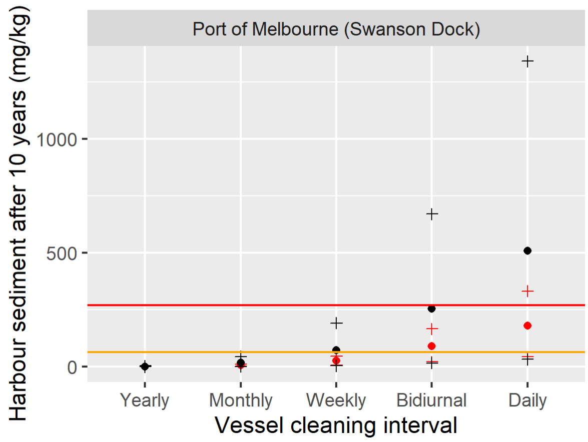


(e) Paint type and level of copper in the leached layer, with soft cleaning.

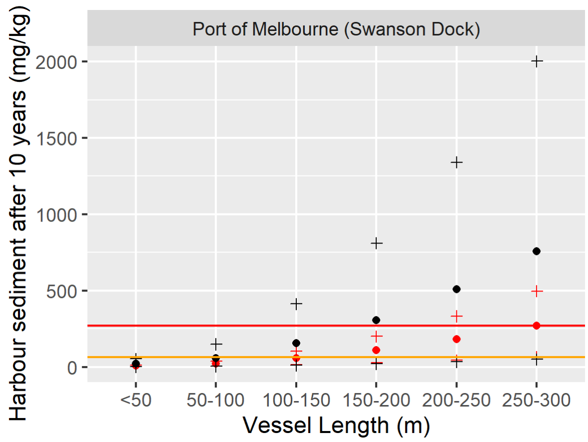


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

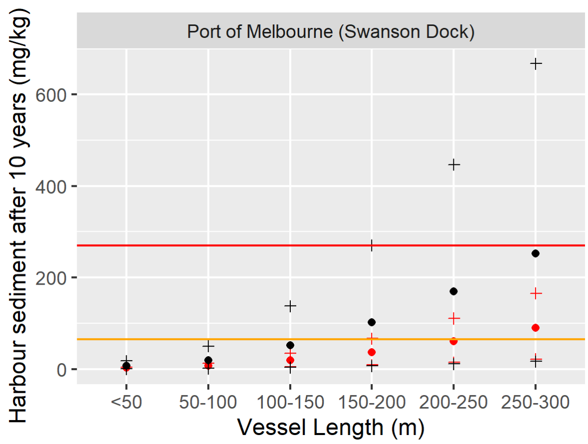
Figure A.13.: Copper loads within harbour under a number of different in-water cleaning scenarios for Geelong (Corio Quay) (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



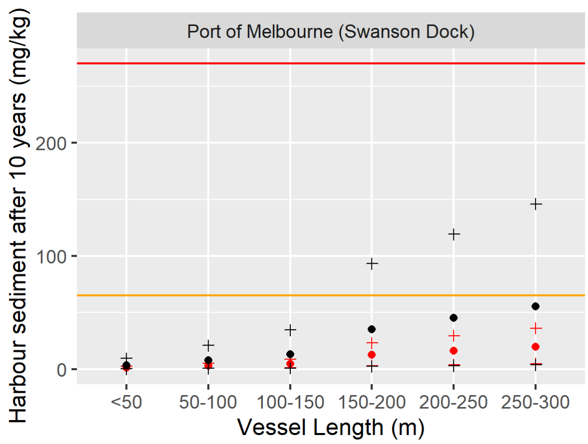
(a) Frequency of ship cleans.



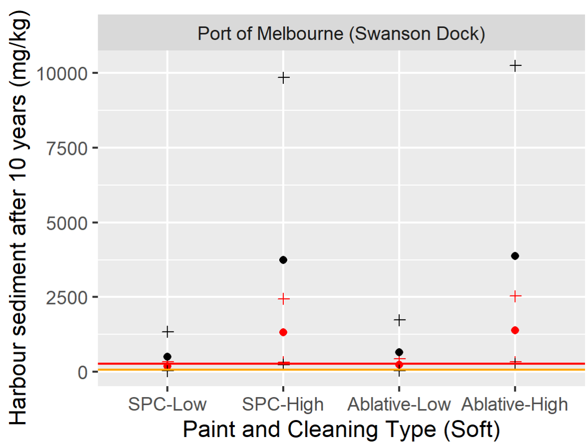
(b) Length of ship.



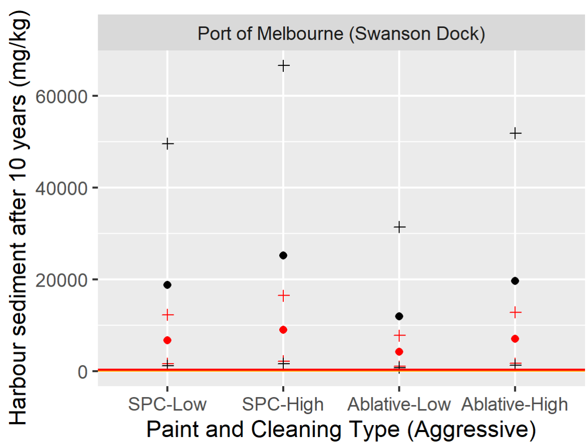
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

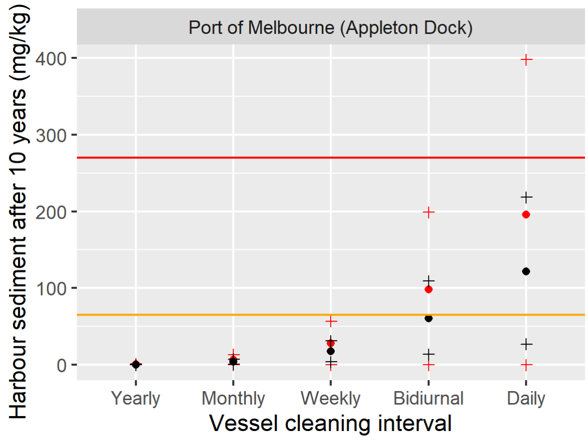


(e) Paint type and level of copper in the leached layer, with soft cleaning.

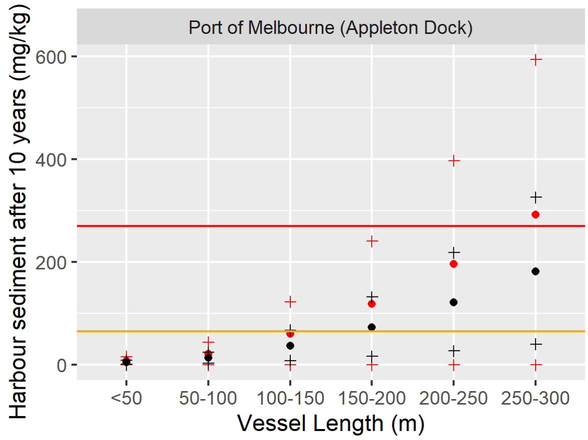


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

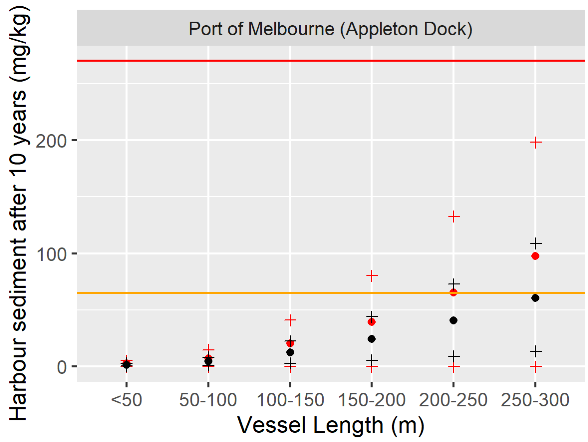
Figure A.14.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Melbourne (Swanson dock) (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



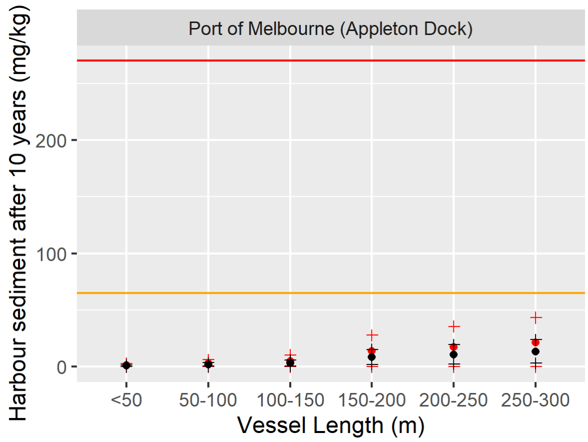
(a) Frequency of ship cleans.



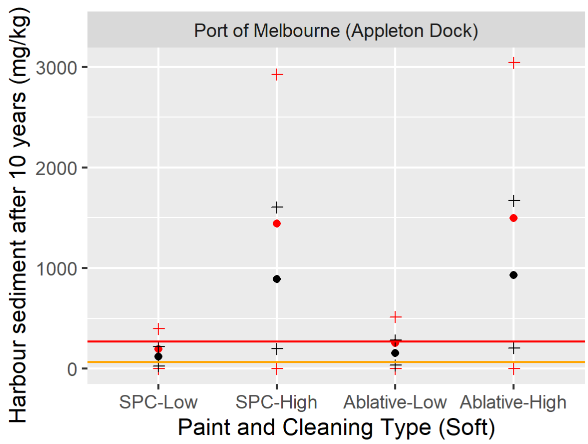
(b) Length of ship.



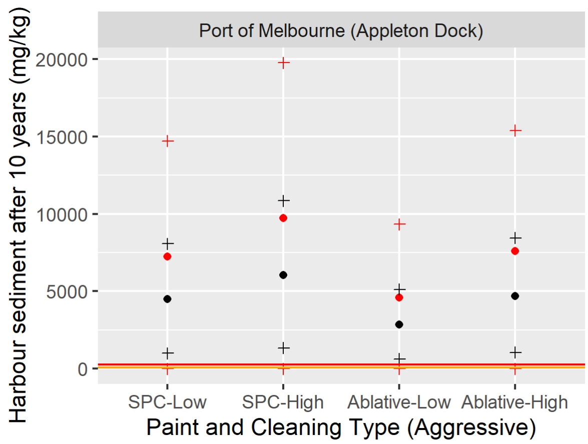
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

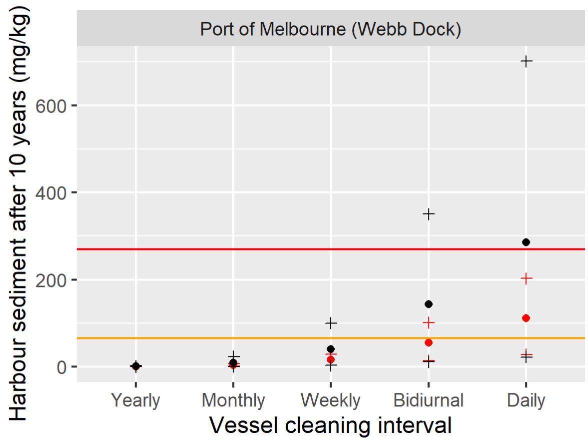


(e) Paint type and level of copper in the leached layer, with soft cleaning.

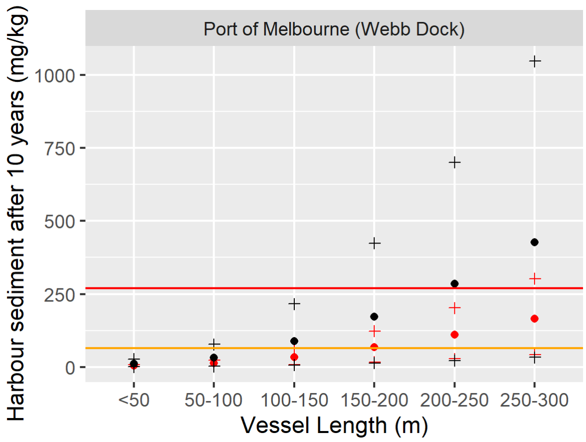


(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

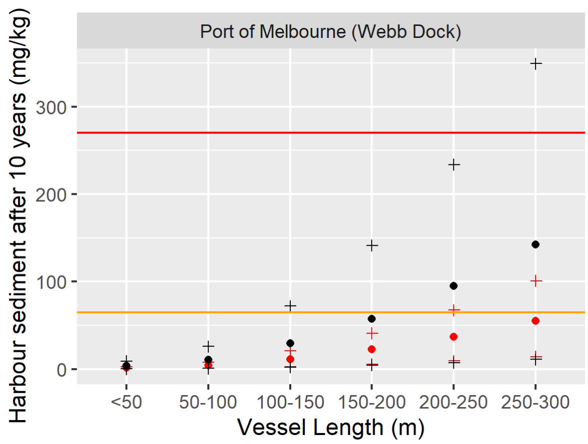
Figure A.15.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Melbourne (Appleton dock) (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



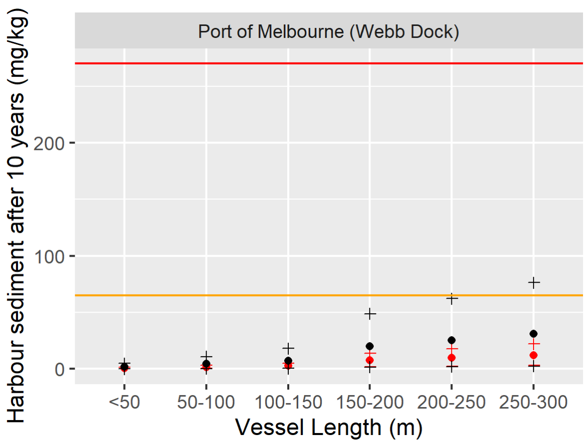
(a) Frequency of ship cleans.



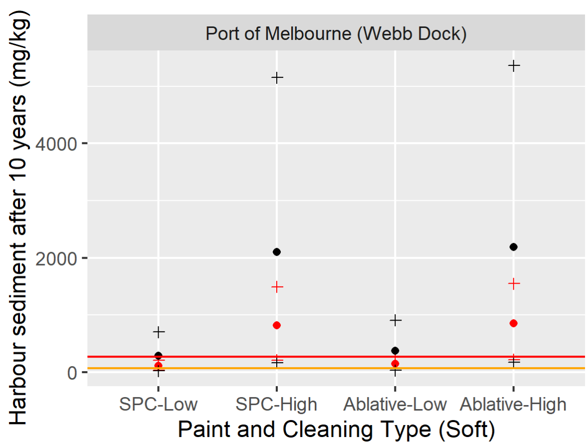
(b) Length of ship.



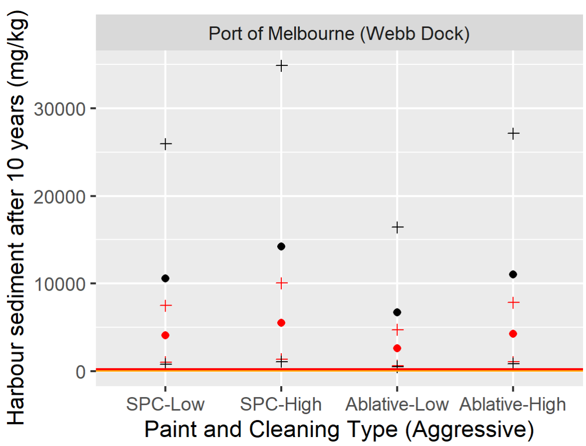
(c) Length of ship (cleaning sides only).



(d) Length of ship (cleaning boot tops only).

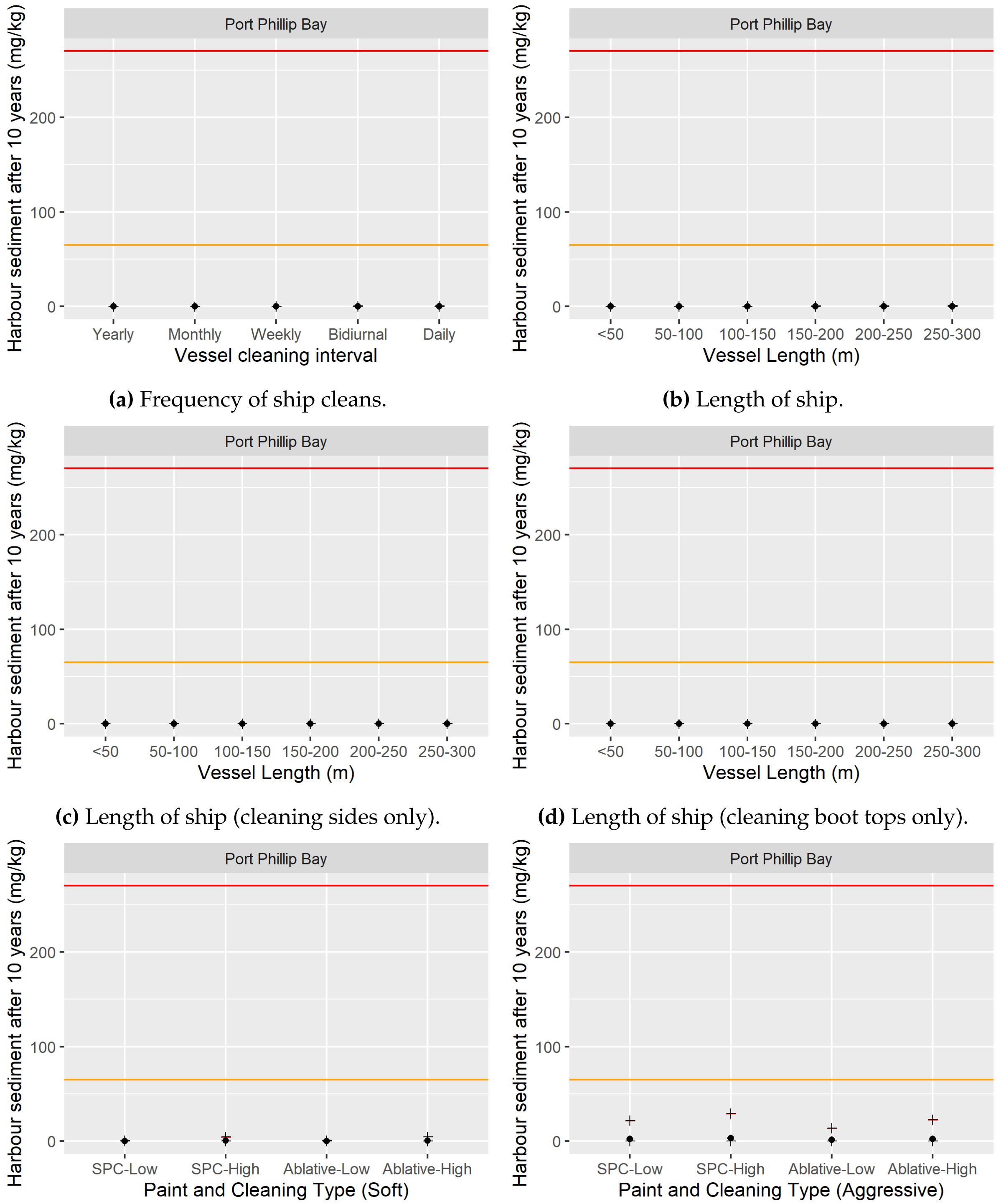


(e) Paint type and level of copper in the leached layer, with soft cleaning.



(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

Figure A.16.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port of Melbourne (Webb dock) (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.



(a) Frequency of ship cleans.

(b) Length of ship.

(c) Length of ship (cleaning sides only).

(d) Length of ship (cleaning boot tops only).

(e) Paint type and level of copper in the leached layer, with soft cleaning.

(f) Paint type and level of copper in the leached layer, with aggressive cleaning.

Figure A.17.: Copper loads within harbour under a number of different in-water cleaning scenarios for Port Phillip Bay (sediments). Red denotes MAMPEC version 3.0, and black is version 3.1. Circles denote average concentration, and crosses are the maximum and minimum. The horizontal lines are the ANZECC 95%, 90% and 80% guideline values for dissolved copper, or the screening and highly contaminated trigger concentrations for sediments from the dredging guidelines. Unless otherwise mentioned scenarios assume ships are 200-250m long, have an SPC antifoulant coating, use soft cleaning, have a low level (2%) of copper remaining in the leached layer, and a ship is cleaned in the port daily.