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Treated ballast water and its impact on port water quality

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Summary

The International Convention for the Control and Management of Ships' Ballast Water and Sediments, sponsored by the International Maritime Organisation (IMO), came into force on the 8 September 2017. The Convention regulates the treatment of ballast water to address concerns that ballast water facilitates the spreading of harmful aquatic organisms and pathogens (IMO, 2004). Australia has recently amended the Biosecurity Act 2015 to ratify the Convention and when it comes into force will require domestic and international ballast water to be managed to the Convention's standards (DAWR, 2016).

Concerns have been raised by state environmental protection authorities about the prospect of large volumes of chemically treated ballast water being discharged in Australian ports. ABARES has been commissioned by the Aquatics and Marine Pests Unit in Biosecurity Animal Division to research environmental concerns arising from this transition in ballast water management. The aims of this report are:

1) Determine the chemical discharges from each of the 41 ballast water management systems (BWMS) approved by the IMO that use active substances and group the systems by chemical discharge type. Assess the likely concentrations of chemicals discharged by normal operation of these systems.

2) Assess the likely numbers of vessels visiting Australia that use each BWMS type, the destination ports and likely volumes of ballast water to be discharged.

3) Run three case studies of ports using the MAMPEC software package for modelling the distribution and fate of chemical discharges.

    3.1) Port Hedland

    3.2) Port Phillip Bay

    3.3) Port of Brisbane

MAMPEC (Marine Antifoulant Model for Predicted Environmental Concentration) is a software package built by Deltares, an environmental consulting company based in the Netherlands, and the Institute for Environmental Studies at the VU University in Amsterdam. The software is used in the IMO approval process for BWMS that use active substances to justify that the BWMS discharge concentrations pose 'no unacceptable' environmental risk. MAMPEC is a 2D hydrodynamical steady state and chemical fate model, which means that the maximum concentration predicted will likely be less than actuality, as it cannot account for heterogeneous discharge scenarios. The average concentrations will be accurate, however.

Guidelines for freshwater and marine water quality have been published by the Australian and New Zealand Environment Conservation Council (ANZECC). Trigger values have been set for a range of potentially toxic compounds and are intended to trigger a management response should the specified concentration be exceeded. As trigger values for many of the DBPs identified in the IMO reports have not yet been derived or are not yet available, equivalent trigger values from the IMO literature were used in many cases. These are not compliant with the ANZECC guidelines, but the method used to derive them is similar to how low reliability ANZECC trigger values are derived. As such these trigger values should be considered 'interim working levels' until more reliable trigger values are derived. The half-lives of DBPs are highly variable and it is therefore uncertain how accurately the maximal discharge concentrations for the BWMS reported in the IMO literature will capture discharge concentrations in the field.

Key Findings

- Concentrations that might cause environmental problems occurred under a worst-case scenario. This assumed all vessels used a hypothetical worst case BWMS, which discharged the maximum concentration of disinfectant by-products (DBPs) observed in approved systems.
- Using a more realistic scenario, which took into account the specific BWMS being used by ships visiting a port and their relative frequencies, it was predicted that the environmental concentrations of most DBPs would likely be below trigger levels for most of the compounds modelled.
- Three compounds were found to potentially exceed environmentally safe levels: dibromoacetonitrile, monochloroacetic acid and dibromoacetic acid.
- A physical sampling plan is recommended to determine the actual concentration of these chemicals as a result of BWMS discharge. It is also recommended that the environmental risk of BWMS is reviewed at some point in the future, as shipping traffic is forecast to increase and new technologies will emerge on the BWMS market with different DBPs and discharge rates.

Introduction

The worldwide transhipment of port water as ballast in shipping has been implicated in the transfer of many marine species, which have become invasive when released in the receiving port environments (Carlton and Geller, 1993, Bax et al., 2003). For example, the northern Pacific seastar (*Asterias amurensis*), a major invasive marine species in Australia, was probably first introduced to south-eastern Tasmania as larvae in ballast tanks of vessels visiting from Japan (Byrne et al., 2013).

Most modern ships carry ballast water. Three types of vessel carry large volumes of ballast water when they are not carrying cargo, to maintain stability, manage internal stresses in the vessel and to keep the propeller under water (Snell et al., 2015):

- Bulk carriers, including wood chip carriers;
- Tankers; and
- Liquefied Natural Gas (LNG) and Liquefied Petroleum Gas (LPG) carriers.

Other types of ships carry ballast water that is largely retained on board and used for maintaining trim and balancing loads. Container ships are the most numerous of this type of ship. Container ships almost invariably carry cargo as they load and discharge at every port they visit and ballast water is largely retained on board for trim purposes, is infrequently discharged, and then only in relatively small volumes (Verling et al., 2005).

The International Convention for the Control and Management of Ships' Ballast Water and Sediments, sponsored by the International Maritime Organisation (IMO), comes into force on the eighth of September 2017. The Convention regulates the discharge of ballast water to address concerns that ballast water facilitates the spreading of harmful aquatic organisms and pathogens (IMO, 2004). Australia has recently amended the Biosecurity Act 2015 to ratify the Convention and when it comes into force will require domestic and international ballast water to be managed to the Convention's standards (DAWR, 2016).

Ballast water convention

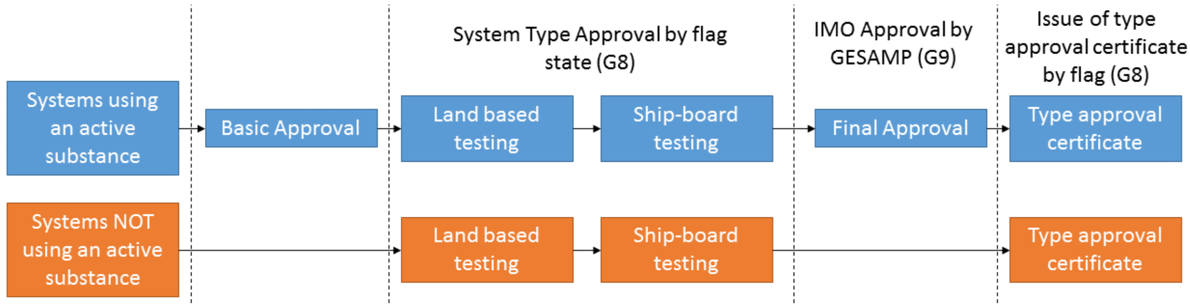
The Convention currently requires that the Ballast Water Exchange Standard is met. This regulation (D-1) requires that either 95 per cent of ballast water in the ship is exchanged with seawater, or that three times the volume of each ballast water tank is pumped through the ships ballast tanks before entering a port. Exchange is required to take place in water at least 200 metres deep and at a minimum distance of 50 nautical miles from the nearest land. This ensures that ballast water taken up at a coastal port is replaced by oceanic water, which will be unlikely to contain diseases and coastal species. The Convention also requires that a ship should not need to delay or deviate from its intended voyage in order to comply with this requirement. For voyages to Australia a delay or deviation should not normally be necessary.

As of the eighth of September 2017, ships will be required to meet the Ballast Water Performance Standard (Regulation D-2), though with some caveats relating to the age of the ship and the date of the ship's next renewal survey (IMO, 2017a). Regulation D-2 states that ships will discharge less than 10 viable organisms greater than 50 micrometres in any dimension per cubic metre of ballast water, and less than 10 viable organisms per millilitre between 10 and 50 micrometres. There are also a number of indicator microbes, including *E. coli*, which cannot exceed specified concentrations.

In order to meet this standard, ships will need to install and operate a ballast water management system (BWMS). The Convention states that each BWMS must be approved by the government of the state under whose authority the ship is operating. The IMO Marine Environmental Protection Committee (MEPC) has adopted the G8 guidelines to describe the process under which this approval is granted (MEPC, 2008a). This process ensures that the system meets the Ballast Water Performance Standard, and is called Type Approval by MEPC.

For BWMS that use an Active Substance the Convention states that they must obtain approval from the IMO. An Active Substance is defined as ‘a substance or organism, including a virus or a fungus that has a general or specific action on or against harmful aquatic organisms and pathogens’. The G9 guidelines outline the criteria for this approval and have a two tiered structure, with Basic Approval being granted before Final Approval (MEPC, 2008b). Figure 1 shows a graphical summary of this process.

Figure 1: IMO Approval procedure for BWMS to be compliant with regulation D-3 of the ballast water convention (Lloyd's Register Marine, 2015).



The joint Group of Experts on Scientific Aspects of Marine Pollution – Ballast Water Working Group on Active Substances (GESAMP-BWWG) was established in 2005 to review proposals submitted to the IMO for approval and report on whether the proposed BWMS could adversely affect ship safety, human health and the aquatic environment according to the G9 guidelines. The process for this approval under the G9 guidelines is given in the Methodology for Information Gathering and Conduct Work of the GESAMP-BWWG, which will be referred to as the Methodology (IMO, 2015).

This is a rigorous process, especially when it comes to considering human health. It covers risks to ship crew and exposure to the public undertaking activities such as swimming and through biomagnification in seafood. For environmental risk assessments, however, only a generic discharge scenario is required to be considered. The applications for Basic and Final approval and reports of the GESAMP-BWWG meetings are publically available from the IMO website. However, these dossiers are incomplete as some of the information has been classified as commercial in confidence and is therefore not available. These dossiers have formed the basis of this report for assessing these BWMS.

Australian water quality guidelines

Australian water quality management is underpinned by the ANZECC water quality guidelines (the Guidelines) (ANZECC, 2000). These guidelines are designed to help determine if the water quality of a particular water resource is sufficient for use by humans, food production or aquatic ecosystems. The document includes trigger values for a number of compounds that can be tailored to suit local requirements and conditions. These values are derived for both fresh and marine waters from toxicity data, and are intended to trigger a management response should the specified concentration be exceeded. Depending on the amount of data available, these trigger values can be classified as low, medium or high reliability. Ballast water discharge in Australia occurs only in marine waters.

There is a large number of disinfection by-products produced by BWMS. These include halogenated organic compounds, and inorganic compounds such as bromate, chlorate and chlorite. Where possible trigger values from the Guidelines were used, although for most compounds discharged in ballast water a relevant trigger value was not available or had not yet been derived.

Disinfection by-products

In addition to the active substances used in or produced by BWMS, the chemical reactions between these substances and the molecules found naturally in sea water produce disinfection by-products (DBPs). (Land-based water treatment facilities often have experience with these treatment by-products.) The G9 guidelines require manufacturers test the discharges from their systems for likely DBPs.

The formation of DBPs has long been recognised as potentially toxic and a risk to human health and the environment (Boorman, 1999). Halo-organics produced from drinking water treatment are recognised as potential carcinogens that can disrupt the replication of cells (Komaki et al., 2014). It has been recognised that bromo-organics are more toxic than their chloro-organic counterparts (Sharma et al., 2014), and this will be of particular of concern in ballast water as the presence of bromide ions in higher concentrations in marine waters facilitates their formation. There is also the potential for halo-inorganic by-products to be produced by these systems such as bromate, chlorate and chloropicrin. These have also been identified as potentially genotoxic and carcinogenic (Richardson et al., 2007).

Project background

Concerns have been raised by state environmental protection authorities about the prospect of large volumes of chemically treated ballast water being discharged in Australian ports. ABARES has been commissioned by the Aquatics and Marine Pests Unit in Biosecurity Animal Division to research environmental concerns arising from this transition in ballast water management. The aims of this report are:

1) Determine the chemical discharges from each of the 41 systems with Final Approval and group the systems by chemical discharge type. Assess the likely concentrations of chemicals discharged by normal operation of these systems.
2) Assess the likely numbers of vessels visiting Australia that use each BWMS type, the destination ports and likely volumes of ballast water to be discharged.
3) Run three case studies of ports using the MAMPEC software package for modelling the distribution and fate of chemical discharges.

- Port Hedland (Section 3.1)
- Port Phillip Bay (Section 3.2)
- Port of Brisbane (Section 3.3)

Important note

With the IMO Ballast Water Convention about to come into force developments in this field are occurring rapidly. As a consequence some elements of this report, such as numbers and types of BWMS installed and volumes of ballast water treated will go out of date quickly.

1 Ballast Water Management Systems (BWMS)

Ballast water management systems (BWMS) are generally adapted from conventional land-based water treatment systems and modified for shipboard use. As of November 2016, there were 69 BWMS with G8 (Type) Approval. These systems have been approved by a number of countries including Norway, Germany, Malta, South Korea, Japan, China, South Africa, the United Kingdom, Greece, Denmark, the Netherlands, France and Singapore. In the G9 (use of active substances) approval regime, 41 BWMS have been granted Final Approval and a further 56 have obtained Basic Approval. These systems can cost anywhere between $500,000 and $5 million, and the estimated market size is around $50 billion (LiveMint, 2015).

BWMS with G9 approval (use Active Substances)

In the systems that have so far undergone G9 approval there are six different types. The number of systems approved for each type is given in Table 1.

Table 1: Categories of systems that have received G9 approval (IMO, 2016).

Category	Systems with Final Approval	Comments
Chlorination	26	6 injection systems and 20 electrolysis/electrocatalysis systems.
Ozonation	5	Includes 2 hybrid systems. One additionally uses electrolysis and another additionally uses UV.
UV	5	Includes a hybrid system that additionally uses plasma.
Peracetic acid	3	PERACLEAN is the brand name for a commercial mixture of hydrogen peroxide, peracetic acid and acetic acid used in ballast water treatment.
Chlorine dioxide	1	
Coagulation-flocculation	1	

1. Chlorination

Chlorination systems add chlorine (Cl_2) to the water. Chlorine is in equilibrium with hypochlorous acid and hypochlorite; these three compounds are collectively referred to as free chlorine. Chlorination is commonly used as a disinfectant in swimming pools, drinking and waste water treatment (Ebenezer and Ki, 2013). There are two main types of shipboard chlorination systems:

- Injection

- Electrolysis/electrocatalysis

Injection systems work by adding a chemical agent that introduces free chlorine directly into the ballast water. The agents currently in use are calcium/sodium hypochlorite and sodium dichloroisocyanurate. These systems require the storage of chemicals on board the ship, and some injection systems are approved for more than one chemical agent. In contrast, electrolysis/electrocatalysis systems do not require the storage of any chemicals, but use an electric current to produce free chlorine in the ballast water. Because this reaction involves chloride ions, most of these systems can only operate when the incoming water has sufficient salinity and may require holding additional salt water or brine for this purpose. These systems also have a minimum water temperature in which they can operate (Echardt and Kornmueller, 2009, DNVGL, 2016). Other oxidants can also be produced by this process, such as hydroxyl radicals, hydrogen peroxide and ozone, which can also contribute to disinfection (Lacasa et al., 2013).

Free chlorine is toxic to organisms and results in the disinfection of the water (Ebenezer and Ki, 2013), but also results in the production of disinfection by-products (DBP). In marine environments, bromide ions are also present in the water and can react with free chlorine to produce hypobromite, hypobromous acid and bromine, which are collectively known as free bromine (Taylor, 2006). Ammonia is also naturally present in marine waters, particularly estuarine environments, and this can lead to the production of bromamines and chloramines. Other secondary oxidants produced include chlorate, bromate and chlorite. Additionally, free chlorine and bromine can react with dissolved organic matter to produce a wide range of halogenated organic compounds such as halomethanes, haloacetic acids and haloacetonitriles (Taylor, 2006). There is also the potential for industrial pollutants from harbour waters such as benzene, phenols and toluene to be halogenated (Abarnou and Miossec, 1992).

2. Ozonation

Ozonation systems inject ozone gas into the treatment water. Ozone is a powerful oxidant known to kill micro-organisms, and these systems are commonly used in drinking water treatment plants (Camel and Bermond, 1998). In freshwater, ozone gas is the primary disinfectant. However, in marine environments ozone quickly reacts with the available bromide ions to produce bromate and free bromine (Jung et al., 2014). Similarly to chlorination systems, this leads to the production of brominated organic compounds as DBPs in marine waters.

3. Hydrogen peroxide, acetic acid and peracetic acid (PERACLEAN)

Peracetic acid is a strong biocide, and has been used in wastewater treatments as an antimicrobial (Kitis, 2004). PERACLEAN is the brand name for a commercial mixture of hydrogen peroxide, peracetic acid and acetic acid used in ballast water treatment. These compounds are all in chemical equilibrium, and peracetic acid acts as the primary biocide in the system. Peracetic acid can react with bromide and chloride ions in water to produce free bromine and chlorine, however in the presence of hydrogen peroxide these are reduced back to bromide and chloride (von Gunten and Oliveras, 1998). Theoretically, this means a lower concentration of DBPs will be produced in comparison to chlorination and ozonation systems.

4. Chlorine dioxide

Chlorine dioxide has been used in water treatment facilities as an alternative to chlorination to lower the concentrations of total trihalomethanes produced. In shipboard systems sodium chlorate, hydrogen peroxide and sulfuric acid are mixed to produce chlorine dioxide, which is then injected into the ballast water. Similarly to peracetic acid systems, chlorine dioxide systems have the added advantage of not generating free chlorine or bromine during the disinfection process to reduce the amount of DBPs formed. However, chlorine dioxide does decompose to produce chlorite and chlorate, which are also potentially toxic inorganic by-products (Aieta and Berg, 1986).

5. Coagulation-flocculation

Coagulation-flocculation is used in wastewater and drinking water treatment to disinfect and remove suspended matter (RELLER et al., 2003, Edzwald, 1993). The shipboard treatment system adds chemicals to coagulate any suspended solids, including microscopic organisms in the ballast water. These bind together and precipitate from solution, allowing them to be filtered. This system also has the advantage of not producing free chlorine or bromine, reducing the concentration of halogenated DBPs produced. It also physically removes the added Active Substances from the ballast water, but requires the disposal of additional waste products and on-board storage of chemicals.

6. UV

UV systems are used in land based wastewater and drinking water treatment facilities (Lazarova and Savoys, 2004). These systems use UV lamps to produce concentrated UV light that kills waterborne pathogens as they pass through it (Hijnen et al., 2006). Photons from these UV lamps damage DNA and also produce free radicals, such as hydroxyl radicals. Some systems also use a titanium dioxide catalyst that facilitates the formation of hydroxyl radicals under UV light when submerged in water (Zhang and Nosaka, 2014). Although these radicals are short lived, their reaction with other components in the ballast water have been found to lead to the production of DBPs (Werschkun et al., 2012) with the result that some systems are required to obtain G9 approval. There is also the possibility that photo transformations induced by the UV photons will also lead to the formation of DBPs (Canonica et al., 2008). For UV systems to work effectively ballast water must have a low concentration of suspended solids to allow a high level of UV transmissivity otherwise the system will be less effective and the Ballast Water Performance Standard may not be met (DNVGL, 2016).

BWMS with G8 approval in Australia (do not use Active Substances)

There are a number of categories of system that do not use active substances and require only G8 approval (MEPC, 2008a). Only 21 systems in four categories, two of which overlap (deoxygenation and membrane), have been installed in vessels visiting Australia to date (Table 2). The majority of these are UV systems that were not required to undergo G9 approval.

Table 2: Categories of systems that currently have received G8 approval and have visited Australian ports.

Category	Visiting systems with G8 approval.
UV	18
Membrane	1
Deoxygenation	1
Membrane and Deoxygenation	1

Maximum allowable discharge of Active Substances and other chemicals

The emission of Active Substances is controlled by Maximum Allowable Discharge Concentrations (MADC) that have been specified for each BWMS by the GESAMP-BWWG. MADCs are specified for each individual system but are similar between different types. MADCs were not specified for UV or coagulation-flocculation systems as no substances are directly added to the ballast water in UV systems. Coagulation-flocculation systems recover added compounds as filtered sediments. The current MADC values that have been set are shown in Table 3.

Table 3. Maximum allowable discharge concentrations for BWMS that use Active Substances.

Category	Maximum Allowable Discharge Concentration (MADC)
Chlorination	0.02–0.2mg/L Total Residual Oxidant (TRO) as Cl2
Ozonation	0.45mg/L TRO as Br2
Chlorine dioxide	0.2mg/L Chlorine dioxide
Peracetic acid	0.5 mg/L Hydrogen peroxide and 0.3 mg/L peracetic acid.

In the case of chlorination and ozonation systems, the maximal allowable discharge for the active substance is specified as total residual oxidant (TRO). This is because ozone and chlorinating compounds are oxidising species that can react with seawater to create a number of secondary oxidants, and TRO can be easily measured using several different methods (Zimmer-Faust et al., 2014).

Most systems have a measurement and neutralisation system that ensures that these compounds are discharged below their MADC. The neutralization chemicals used in chlorination and ozone systems are sodium thiosulfate and sodium bisulfate; sodium sulfite is used in peracetic acid systems. Within the G9 approval process these neutralisers are referred to as "other chemicals". These react with oxidants in the ballast water to neutralise them and produce sodium sulphate, which is naturally found in high concentrations (close to 3g/L) in seawater (Hitchcock, 1975).

Disinfection by-products

The G9 guidelines require manufacturers to test discharges from their systems for likely disinfection by-products (DBPs). A total of 53 DBPs were identified in the 41 Final Approval applications, including TRO as Cl_2 and TRO as Br_2 from chlorination and ozonation systems respectively. Also included were 40 halo-organic DBPs and a number of other associated chemicals, such as isocyanuric acid (a by-product of treatment with sodium dichloroisocyanurate) and ammonium, nitrate, nitrite, acetaldehyde and formaldehyde. These last five chemicals are naturally found in seawater, but it is possible that operation of the BWMS can elevate their levels in the discharged ballast water (Richardson et al., 2007).

A selection of DBPs and their discharge concentrations are shown in Table 4. This shows that chlorination systems generally discharge the highest concentrations of DBPs, followed by systems using ozonation, peracetic acid and UV. The chlorine dioxide system is unique in its discharge of DBPs, as it discharges relatively large concentrations of chlorate, in higher concentrations than most chlorination systems, and chlorite, but very small concentrations of the tested halo-organics. These two by-products may potentially be safer for the environment, as they have not been found to be carcinogenic (Condie, 1986). It is important to emphasise that if a BWMS discharges a DBP classified as a persistent, bioaccumulative and toxic (PBT) substance, it cannot obtain G9 approval. The PBT criteria are given in Appendix A.

Table 4: Concentrations of various DBPs reported discharged for the different types of systems. The values in bold are the highest average concentrations for each chemical.

Compound	UV			Peracetic Acid			Chlorine Dioxide	Ozonation			Chlorination		
	Avg	Min	Max	Avg	Min	Max	Avg	Avg	Min	Max	Avg	Min	Max
Halo-organics	10.2	0.0	29.9	284.4	1.7	837.8	36.0	371.7	28.8	892.4	**664.1**	25.1	1 428.6
Chloro-organics	8.2	0.0	24.5	52.1	0.0	152.3	0.0	23.0	0.0	63.9	**76.4**	0.0	651.5
Trichloro-methane	2.3	0.5	4.2	2.1				15.8	15.8	15.8	**41.6**	0.1	236.2
Trichloroacetic acid	19.6			**150.0**				18.4	1.0	51.4	20.6	0.5	92.2
Dichloroaceto-nitrile	0.4										**2.1**	0.0	12.1
Bromo-organics	1.6	0.0	5.4	219.4	1.5	647.0	36.0	332.4	13.6	826.8	**528.7**	25.1	1 404.0
Tribromo-methane	0.0	0.0	0.1	121.0	1.4	360.0		142.0	0.1	255.0	**332.9**	12.0	890.0
Tribromoacetic acid	0.2							5.2			**117.1**	0.1	970.0
Dibromoaceto-nitrile								**674.0**			32.7	0.5	164.0
Bromate								63.9	2.0	150.0	**152.1**	7.2	920.0
Chlorate							**1 470.0**	60.0			1 041.5	170.0	2 800.0
Chlorite							**3 600.0**						
Perchlorate								2.1			**4.6**		
Chloropicrin								1.9			**5.0**	0.1	18.3

Note: Average, minimum and maximum values are across different models of BWMS, and are the maximal concentrations observed at any point during testing for each system. All concentrations are in µg/L.

From Table 4 it can be seen that concentrations of DBPs recorded were extremely variable between systems, even systems within the same category. For example, the emission of trichloromethane between two chlorination systems spans four orders of magnitude (0.1-236.2 µg/L). These large differences may be due to differences between systems, but are also likely to be affected by different source water being used in the testing process. Factors that are known to influence the concentration of DBPs produced include temperature, dissolved organic carbon and particulate organic carbon (Sadiq and Rodriguez, 2004).

When interpreting the concentrations from this table it should be noted that, in the publically available G9 approval documentation, some systems detailed the range of concentrations measured while others only reported the maximal concentration observed during testing. For consistency between systems, the discharge concentrations reported in Table 4, and that are used in this report, are the maximal concentrations found during the land-based testing required for G9 approval, as reported in the final approval documentation for the system.

Sodium sulphite and acetic acid were determined to pose no unacceptable environmental risk by the GESAMP-BWWG and discharge concentrations of these chemicals were absent in most reports that concerned them.

2 MAMPEC

MAMPEC (Marine Antifoulant Model for Predicted Environmental Concentration) is a software package built by Deltares, an environmental consulting company based in the Netherlands, and the Institute for Environmental Studies at the VU University in Amsterdam. It was originally designed to predict concentrations of chemicals leaching from antifouling coatings on vessel hulls in ports and marinas. It was modified in 2010 for the International Maritime Organization (IMO) and Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) to accommodate emissions from ballast water. The software is used in the G9 approval process to justify that the BWMS discharge concentrations pose 'no unacceptable' environmental risk.

MAMPEC functionality

MAMPEC is a 2D hydrodynamical and chemical fate model. It is a steady state model, which means it predicts the final concentration of the chemical when it is discharged continuously. This means the model does not predict the timescale over which this concentration will be reached and neglects dynamic effects. The model comprises three categories of input data, each of which has multiple input parameters (Table 5).

Table 5: Examples of the parameters required to model a port in MAMPEC.

Category	Parameters
Environment (Port)	Hydrodynamic parameters: tidal data, layout, wind and river flush. Water parameters: Suspended Particulate Matter (SPM), Particulate Organic Matter (POC), Dissolved Organic Carbon (DOC), chlorophyll concentrations and salinity, pH and temperature. Sediment parameters: sediment depth, density, rate of organic carbon degradation and nett sedimentation velocity. Other parameters: Latitude.
Compound	Volatility: Henry's constant and molecular weight. Degradation: Overall half-life, or half-life of abiotic degradation, biodegradation and photolysis. Sedimentation: Organic carbon-water partitioning coefficient (K_{oc}).
Emission	Volume of ballast water discharged. Concentration of discharged chemical.

The model includes three different chemical fates for the chosen compound; sedimentation, degradation and volatilization. In sedimentation, some of the chemical leaches into the sediment. The sedimentation model is not steady state and predicts accumulation in the sediment after a certain number of years at the steady state concentration of the chemical in the water. In degradation, the chemical is removed from the system, and in volatilization the chemical escapes from the water into the atmosphere.

The output of MAMPEC is given as maximal, ninety fifth percentile, median, average and minimum predicted environmental concentrations (PECs) in the harbour water, sediment and also absorbed to silt particles and dissolved organic carbon. MAMPEC also provides a breakdown of environmental fate, and a profile of the concentration gradient in the surrounding marine environment.

Parameter sensitivity analysis

To identify which environmental parameters are important, a sensitivity analysis was conducted using the GESAMP-BWWG Model Harbour for the 58 identified discharge chemicals.

It was found that changing latitude and chlorophyll concentration had no effect on the results. This is because these variables are only used in advanced photolytic degradation, which was not enabled as there was insufficient data for the compounds. Changing pH and salinity also had no effect, and similarly these variables are only used for modelling copper compounds. The maximal increase observed by changing the default values by an order of magnitude is shown in Table 6 and Table 7. Temperature at 1.5°C and 50°C was compared to the default of 15°C.

Table 6: Maximum percent change in predicted harbour environmental concentrations across 58 discharge chemicals, with varying environmental parameters.

Harbor Environmental Concentrations		Total Concentration	Freely Dissolved	DOC-bound	Suspended Matter	Sediment after 10 Years
Sediment Depth	↑	0.0%	0.0%	0.0%	0.0%	–71.5%
	↓	0.0%	0.0%	0.0%	0.0%	4.3%
Sediment Density	↑	0.0%	0.0%	0.0%	0.0%	–71.5%
	↓	0.0%	0.0%	0.0%	0.0%	4.3%
Nett Sedimentation Velocity	↑	0.0%	0.0%	0.0%	0.0%	4.3%
	↓	0.1%	0.1%	0.1%	0.1%	–71.5%
SPM	↑	0.0%	0.0%	0.0%	–90.0%	–89.6%
	↓	0.7%	0.0%	1.0%	0.0%	4.3%
DOC	↑	0.4%	0.0%	911.1%	0.0%	0.0%
	↓	0.0%	0.0%	0.0%	0.0%	0.0%
POC	↑	0.7%	0.0%	1.0%	900.0%	900.0%
	↓	0.1%	0.2%	8.3%	–90.0%	–90.0%

Temperature	↑	3.27%	3.27%	3.39%	3.25%	3.45%
	↓	114.8%	114.8%	114.8%	114.8%	114.8%

Note: The arrows indicate an increase and decrease by an order of magnitude in the parameter. The parameter changes that resulted in a positive maximal change in one of the modelled variables are highlighted in green, and a negative maximal change are highlighted in yellow.

Table 7: Maximum percent change in predicted environmental fate across 58 discharge chemicals, with varying environmental parameters.

Chemical Fate		Hydrodynamic Exchange	Overall Degradation	Sedimentation	Volatilisation
Sediment Depth	↑	0.0%	0.0%	0.0%	0.0%
	↓	0.0%	0.0%	0.0%	0.0%
Sediment Density	↑	0.0%	0.0%	0.0%	0.0%
	↓	0.0%	0.0%	0.0%	0.0%
Nett Sedimentation Velocity	↑	0.0%	0.0%	1300.0%	0.0%
	↓	0.1%	0.1%	0.0%	0.1%
SPM	↑	0.0%	0.0%	0.0%	0.0%
	↓	0.4%	0.0%	1300.0%	0.0%
DOC	↑	0.2%	0.0%	25.0%	0.0%
	↓	0.0%	0.0%	0.9%	0.0%
POC	↑	0.4%	0.0%	1300.0%	0.0%
	↓	0.0%	0.2%	0.0%	0.2%
Temperature	↑	1.94%	945.13%	3.66%	0.00%
	↓	49563.9%	0.0%	149.4%	155.8%

Note: The arrows indicate an increase and decrease by an order of magnitude in the parameter.

From these tables it can be seen that the total concentration in the harbour is most sensitive to temperature. Decreasing temperature to 1.5°C from 15°C results in a maximal 115 per cent increase in the total concentration of the compound in the port. On the other hand increasing it to 50°C also leads to a modest maximal increase of 3 per cent, because compounds are more volatile in warmer waters. The other parameters considered only lead to maximal increase of less than one per cent. There was a much larger number of parameters that had a significant impact on the maximal sediment concentration of the chemical; the only parameter that did not was the DOC concentration.

MAMPEC in the G9 approval process

The GESAMP-BWWG Methodology mandates that MAMPEC is used to calculate predicted environmental concentrations (PEC), using the concentrations of DBPs measured as part of the G9 approval process. For the environmental risk assessment, the highest discharged concentrations of DBPs at any point during the testing process are used.

This risk assessment is done on a generic commercial harbour, called the GESAMP-BWWG Model Harbour, which was designed by the GESAMP-BWWG to be a conservative scenario indicative of many ports around the world. A ballast water discharge of 100,000 cubic metres per day (36.5 million cubic metres per year) is used in this modelling, which is also intended to be conservative (IMO, 2015). The parameters for the GESAMP-BWWG Model Harbour are given in Appendix C.

The maximum or 95th percentile PEC is taken and compared to a predicted no effect concentration (PNEC). The derivation of PNEC values are described in the Methodology, using an assessment factor method comparable to low reliability trigger values in the ANZECC guidelines. The derivation method is outlined in Appendix and compared to the low reliability ANZECC approach. Low reliability trigger values in the ANZECC framework are intended to be used as indicative interim working concentrations (ANZECC, 2000).

MAMPEC validation and shortcomings

A number of validation exercises have been conducted for the environmental concentrations from antifoulant leaching predicted by MAMPEC. These have found that MAMPEC is accurate to within an order of magnitude, and generally overestimated the environmental concentrations (Deltares, 2016). Validation studies have not yet been conducted on the ballast water version of MAMPEC, though it has been used extensively worldwide.

For the MEPC final approval risk assessments, the maximum concentration predicted by MAMPEC is generally used. However, Zipperle et al. (2011) have found that while the average concentration predicted by MAMPEC using a homogenous discharge scenario is similar when dynamic discharge scenarios are considered, the maximal concentration is underestimated. They suggested using a 'near-sea' empirical formula as a correction to the MAMPEC maximal concentration value, and the G9 process has been amended to include the incorporation of near-sea PNECs and this formula to account for this, as shown in Appendix B:.

An additional shortcoming of MAMPEC is the constrictive nature of the available port layouts. They all assume the port area is a rectangle, and opens out onto a river or the sea. The program appears to be designed for doing generic risk assessments, rather than modelling specific ports. The port of Brisbane, considered as a case study, was quite a poor match to the layouts available in MAMPEC, and this will be discussed further in this report.

Nevertheless, MAMPEC is easy to learn and use, and does not require specialized training. If the default water characteristic parameters are used, it is quite simple to build a model for a port based on data from hydrographic charts and tidal information. Interpretation of the results is more complex, however, and requires trigger values or PNECs to compare the output PECs against. For the purposes of this project, MAMPEC was a useful tool to provide indications of the likely concentrations of discharged DBPs in the environment, albeit unverified and un-validated. It is recommended that in-water sampling be conducted to verify these results.

3 Vessel arrivals

Maritime Arrivals Reporting System (MARS)

Data on shipping arrivals in Australia, the numbers and capacities of ballast water tanks, information on whether and how the ballast water has been managed (that is by mid-ocean exchange or on-board ballast water treatment system) and details of the tanks the ship is intending to discharge is now being captured by the Maritime Arrivals Reporting System (MARS). MARS is an online web portal developed by the Department of Agriculture and Water Resources to be used by commercial vessel masters and shipping agents to submit pre-arrival documents required of all international vessels seeking Australian biosecurity clearance. Data from MARS and Lloyds List Intelligence were used extensively to quantify vessel arrivals, ship types and arrival ports.

Ballast water discharge

The amount of ballast water discharged by vessel type was calculated using data from MARS, provided by Compliance Division in the Department of Agriculture and Water Resources. The dataset covered the period from August 2016 to June 2017. This allowed the calculation of ratios of ballast water discharged to deadweight tonnage (DWT) (Table 8). The average ratio was then calculated for each ship type and applied to data in the Lloyd's database of vessel arrivals to calculate ballast water discharge volumes for the required ports. (MARS data were not being collected for all ports during the phase-in stage). It was assumed that tanks that were intended to be discharged were in fact fully emptied.

Table 8: Ratios of ballast water discharged to deadweight tonnage for ships that intended to discharge ballast water

Vessel Type	Minimum	10% Percentile	Median	Average	90% Percentile	Maximum	Recorded Visits
Bulk carrier	0.0%	26.6%	30.8%	32.9%	43.6%	114.6%	5 949
Tanker	0.0%	7.2%	55.0%	46.4%	63.4%	70.9%	623
Container ship	0.0%	2.5%	9.0%	9.9%	19.1%	41.4%	357
General cargo	0.1%	3.0%	21.3%	20.9%	38.5%	43.9%	92
Cruise vessel	0.0%	4.2%	10.0%	10.8%	19.4%	25.4%	86
Livestock carrier	2.2%	2.2%	5.7%	9.4%	19.1%	20.5%	10
Ro-Ro cargo	5.9%	6.4%	26.4%	23.7%	33.6%	38.1%	10

The volume of ballast water carried in a bulk carrier is generally about 33 per cent of its deadweight tonnage (Snell et al., 2015) and is fully discharged on loading. This does not necessarily apply to other types of ships, however (David, 2015). This has been confirmed by our analysis in Table 8. By contrast, tankers discharge a much higher ratio and container vessels discharge a much smaller ratio, on average. Tankers and container ships also have much more variable discharges, as shown in Figures 2, 3 and 4.

Figure 2: Frequency distribution of the ratio of ballast water discharged to DWT: bulk carriers

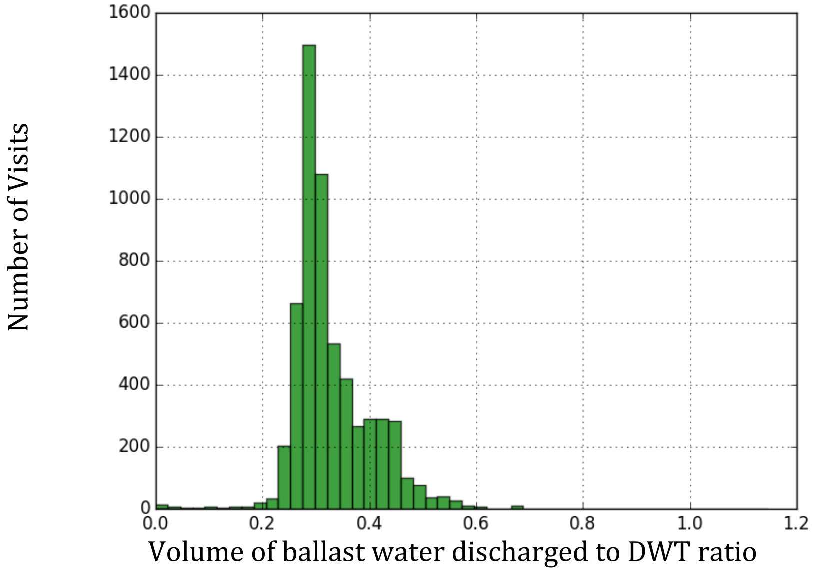


Figure 3: Frequency distribution of the ratio of ballast water discharged to DWT: tankers

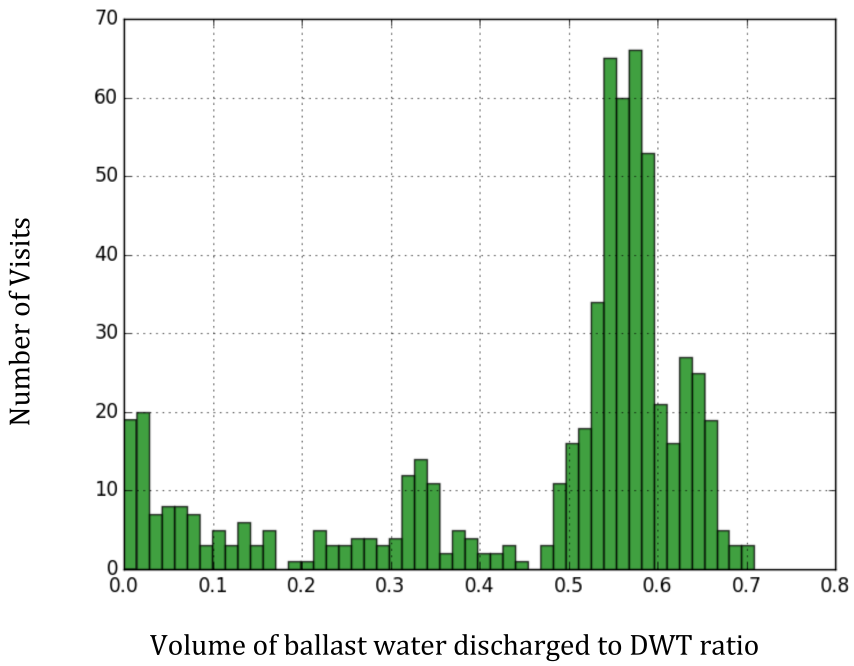
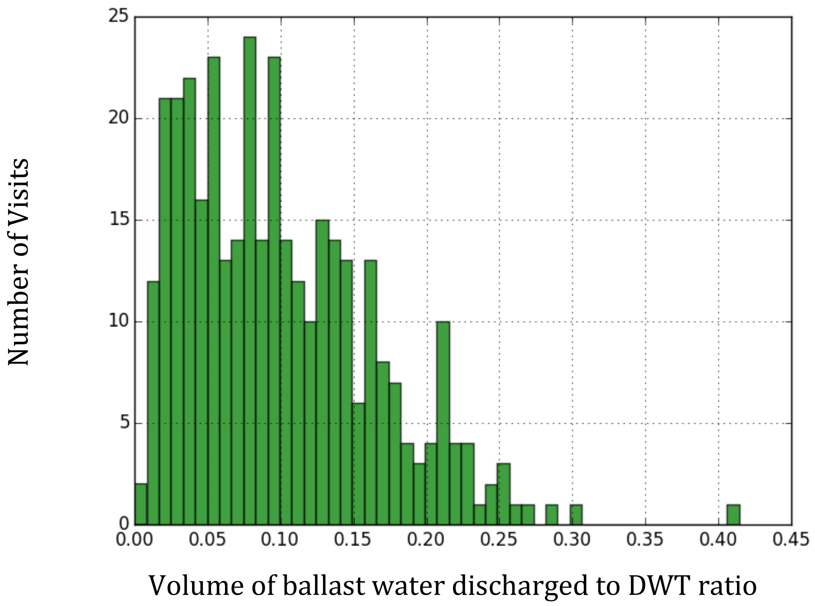


Figure 4: Frequency distribution of the ratio of ballast water discharged to DWT: container ships



Ship types

Table 9 lists the top five vessel types visiting Australian ports in terms of numbers of visits. This includes both international and domestic arrivals. Modern ships almost invariably carry ballast water both for stability and to maintain trim as cargo is off-loaded and other cargo, with different weight, is loaded in a different part of the ship. Container ships, Ro-Ro (roll on-roll off) vessels and other cargo ships are typical of this type of ship, which may only discharge ballast water occasionally. Bulk carriers are the most numerous vessel type. These vessels generally arrive empty of cargo and carry roughly one third of their deadweight tonnage as ballast water to maintain stability, to keep the propeller underwater and to manage internal stresses (Snell et al., 2015). Tanker movements are more difficult to classify because there are many different types of tanker (for example asphalt, chemical, crude oil, product) and it is often unknown what cargo they are carrying. The volumes of ballast water discharged were derived from the Lloyds database using the average ratio of ballast water to deadweight tonnage for each ship-type as calculated in Table 8.

Table 9: Types of ships, number of visits and calculated ballast water discharge in Australian ports in 2016.

Vessel Type	Arrivals		Ballast water discharged (m^3)	
Bulk Carrier	15 983	44.8%	563 069 271	76.8%
Container Vessel	6 057	17.0%	25 947 937	3.5%
Tanker	5 559	15.6%	132 002 522	18.0%
Ro-Ro Cargo	4 236	11.9%	4 350 465	0.6%
General Cargo	2 416	6.8%	6 365 731	0.9%

Total	35 651		732 795 513	

Note: Only the top five visiting ship types are shown.

As can be seen in Table 9, even though bulk carriers make up about 45 per cent of visits, they are calculated to discharge about 75 per cent of all ballast water in Australian ports.

Arrival ports

The number of visits to a port does not correlate well with the amount of ballast water discharged. As can be seen in Table 10, even though Melbourne is the most visited port in Australia, with eight per cent of all traffic, only four per cent of all ballast water discharged in Australian waters was estimated to be discharged there in 2016. In contrast, Port Hedland received nearly eight per cent of all traffic, but over 20 per cent of all ballast water discharged. This is because Port Hedland is almost exclusively visited by bulk carriers exporting iron ore. A number of ports around Australia are specialised bulk export ports, these include Port Hedland, Port Walcott and Dampier in Western Australia, Gladstone and Hay Point in Queensland and Newcastle in New South Wales. These ports have the largest amounts of ballast water discharged (Table 10).

Table 10: Table of top 10 Australian ports by number of ship visits in 2016. Calculated ballast water discharge at each port also shown.

Port	**Arrivals**		**Ballast Water Discharged (m^3)**	
	Numbers	Per cent	Volume	Per cent
Melbourne	3 278	9.2%	19 353 846	2.6%
Port Hedland	2 786	7.8%	164 783 265	22.5%
Brisbane	2 720	7.6%	25 723 102	3.5%
Gladstone	2 420	6.8%	61 782 473	8.4%
Newcastle	2 274	6.4%	69 098 399	9.4%
Dampier	1 872	5.3%	66 103 151	9.0%
Botany Bay	1 673	4.7%	12 809 377	1.7%
Fremantle	1 524	4.3%	13 296 418	1.8%
Adelaide	1 214	3.4%	9 042 400	1.2%
Hay Point	1 162	3.3%	45 674 520	6.2%
Totals top 10 ports	20 923	58.8%	487 666 951	66.3%
Total arrivals	35 651	100%	732 795 513	100%

Note: Only the top ten ports by number of visits are shown. The data include both domestic and international arrivals.
Data source: Lloyds

BWMS arrivals data

Data on ship arrivals and installed BWMS were acquired by MARS and provided by Compliance Division, Department of Agriculture and Water Resources. Although the Ballast Water Convention has not yet come into force, ships have started fitting BWMS in preparation for it. Not all ships are equipped with BWMS yet and not all BWMS are currently in use. However these figures, which cover visits by vessels fitted with BWMS over the period from August 2016 to the April 2017, are currently the best indicator of the trend in BWMS installations. UV systems (including systems that only underwent G8 approval) are currently the type of system that has been installed in most vessels visiting Australia, closely followed by chlorination systems (Table 11).

Table 11: BWMS visits to Australian ports by BWMS category.

BWMS Category	Visits		Number of Systems
Chlorination	427	42.2%	15
UV (G8)	249	24.6%	16
UV (G9)	217	21.4%	5
Ozonation	105	10.4%	1
Membrane + deoxygenation (G8)	12	1.2%	1
Filtration + Membrane (G8)	2	0.2%	1
Deoxygenation (G8)	1	0.1%	1
Total	1 013		40

Note: Visits are the numbers of voyages, not the numbers of individual vessels. Some vessels may make numerous visits to the same or different ports.
Data source: MARS

Of the systems that discharge active substances (G9 approval), ozonation systems appear to be the least popular; there has only been one type of ozonation system installed on vessels visiting Australia. A list of the individual systems with G9 approval is given in Appendix D:

BWMS arrival vessel types

Table 12: Vessel type with BWMS and number of recorded visits to Australian ports. Only the top five vessel types are shown.

Vessel Type	Visits	
Bulk Carrier	652	64.36%
Tanker	143	14.12%
Container Vessel	79	7.80%
Cruise Vessel	58	5.73%
Ro-Ro Cargo	50	4.94%

Data source: MARS

The proportions of arrivals of different vessel types in the MARS data are different to those in the Lloyds data, which is mostly due to the phased implementation of MARS. As a consequence the proportions of bulk carriers to other vessels is higher in the MARS data, which also therefore includes more arrivals at bulk export ports. Port Hedland has the most recorded visits, with Melbourne the 6th most visited port in Australia (Table 13).

BWMS arrival ports

Table 13: Recorded vessels fitted with BWMS visits to Australian ports by destination. Only top six destinations are shown.

Arrival Port	Visits	
Port Hedland	116	11.45%
Gladstone	112	11.06%
Brisbane	99	9.77%
Newcastle	80	7.90%
Fremantle	71	7.01%
Melbourne	61	6.02%

Data source: MARS

4 Case studies

Methodology and MAMPEC parameter choices

Compound

The relevant DBPs were identified from the public Final Approval documentation of the 41 systems that received G9 approval from MEPC. These documents were obtained via the IMO document portal (IMO, 2017b). 58 DBPs were identified in total. Their discharge concentrations were taken as the **maximum** reported in each approval dossier. Compounds below the detection limit were assumed not to be present.

It was found there was generally little data on the toxicity of these compounds and authoritative trigger values were not readily available. Only three DBPs (Ammonium, Nitrate and TRO as Cl_2 (Hepplewhite, 2017)) had relevant trigger values published in the National Water Quality Management Strategy (ANZECC, 2000). A number of trigger values were derived according to the ANZECC guidelines by Deveney and Wiltshire (2012) for DBPs, and three of these were used in cases where other values could not be found (chlorate, chlorine dioxide and TRO as Br_2). In the case of these medium to high reliability trigger values a 95 per cent species protection level was chosen, which is suitable for slightly to moderately disturbed environments.

For the rest of the compounds, predicted no effect concentrations (PNEC) had to be used as trigger values, as was done in the G9 approval process. Two PNECs were obtained from the European Chemicals Agency (ECHA), as they are not available elsewhere: nitrite and 1,1-dichloroethene (ECHA, 2017). The rest of the PNECs were sourced from the GESAMP-BWWG Chemical Database (IMO, 2014) or, if not listed in this database, in the Basic and Final Approval documentation from the IMO document portal (IMO, 2017b). In a number of instances it was found one compound had multiple PNECs according to different applications, and to resolve this the lowest PNEC was used in each case, as the most conservative concentration. Compound parameters were also obtained from the latter two sources, and any that were not available there were found in the ECHA and Syracuse Research Corporation FatePointer databases or estimated with the Estimation-Program-Interface suite (ECHA, 2017, SRC, 2013, EPA, 2016).

In cases where the half-life could not be found, it was assumed the compound did not break down, and when the organic carbon-water partitioning coefficient (log K_{oc}) was unavailable and the octanol water partitioning coefficient (log K_{ow}) was less than 3, log K_{oc} was set to one as the compound was unlikely to partition significantly in the sediment. Similarly, when the Henry's constant was unavailable zero was used, which meant that the compound was non-volatile and could not escape into the atmosphere from the port. For the discharge of TROs it was assumed that they were primarily composed of sodium hypochlorite, in the case of chlorination systems, and sodium hypobromite in the case of ozonation systems.

Emission

Two emission scenarios were developed for Port Hedland: a worst case and a more realistic "plausible" scenario. In both cases, the amount of ballast water discharged by a ship was assumed to be a ratio of its deadweight tonnage (DWT), every time it visited a port, as given by the average for each ship type in Table 8. Both international and domestic arrivals were included. For the MAMPEC model, the ballast water discharge volume per day was obtained by averaging the estimated ballast water discharged in the port over the entire 2016 year.

- Worst Case Discharge: This scenario is equivalent to assuming all ships are using a hypothetical worst-case BWMS, in which the discharged ballast water was assumed to contain the maximum DBP concentrations reported from all the 41 BWMS with final approval. This scenario was developed in the Port Hedland case study to determine if, in the first instance, there was likely to be a potential problem from discharging DBPs. In the event of the worst case discharges being within the limits of PNECs no further work would be necessary. This was not the case, however, and more realistic (plausible) scenarios were developed for all case study ports to examine potential impacts. For the other case study ports, only a plausible scenario was employed.
- Plausible Discharge: The ships with BWMS installed currently visiting the port are assumed to be indicative of the BWMS that will be used when the Convention comes into force. Under this assumption the amount of ballast water discharged by a particular BWMS is the proportion of visits from ships using that system, multiplied by the discharge volume per day. This calculation is valid as the concentration of a particular compound in solution is additive, due to the conservation of matter.

For the JFE BallastAce BWMS, two possible Active Substances have been approved for use; sodium hypochlorite and sodium dichloroisocyanurate. The type of active substance used was not recorded in the MARS dataset so the largest discharge concentration for each compound by the two systems was used.

Environment parameters

The parameters used for each port are in Appendix C. The data and methods used to determine the MAMPEC model parameters are as follows:

Temperature

Port water temperature was estimated using satellite sea surface temperature data for 2011, the most recent date for which data had already been collected. The average annual sea surface temperature at the closest latitude and longitude to the port with sufficient data was taken to be the port temperature.

Hydrodynamic

Tidal range and period were obtained from the National Land and Water Resources Audit (1998) dataset provided online by OzCoasts, an online coastal information database provided by Geoscience Australia (OzCoasts, 2015). River flow volumes for the Brisbane, Maribyrnong and Yarra rivers were obtained from National Water Account (2013) data provided online by the Bureau of Meteorology (BOM, 2017b).

Data for the maximum density difference between tidal and river flows and port water could not be found. This value was left at zero to simulate a worst case scenario where density driven exchange of port water with the surroundings does not occur. Similarly, wind driven exchange and non-tidal daily water level change were also ignored in the model ports constructed, as adequate data could not be found.

Layout

Hydrographic charts from the Australian Hydrographic Service were used to determine the port layout and water depths.

Water characteristics

For the other parameters (Sediment Depth, Sediment Density, Nett Sedimentation Velocity, SPM, DOC, POC), data could not be found for any of the case studies. However, the sensitivity analyses showed that these parameters had minimal effect (less than a maximum of one per cent increase) on the total concentration of the compound in the port for all 58 chemicals. However, they had quite a large effect on the concentration of the chemical in the sediment.

In the G9 approval guidelines, it is stated that a toxicity assessment of sediment species is not required if the potential of a substance to partition into the sediment is low (MEPC, 2008b). The criterion given is that the organic carbon-water partitioning coefficient (K_{oc}) is less than a certain threshold (500 L/kg). In the GESAMP-BWWG Methodology, there is a similar criterion that uses the octanol-water partitioning coefficient (K_{ow}) (IMO, 2015). This criterion states that sediment toxicity testing is considered relevant only if log K_{ow} is greater than a threshold (3). It is also noted that the same criterion applies to testing for the bioaccumulation potential of the compound. Within the 58 discharge chemicals, only six compounds meet these two criteria; these are listed in Table 14.

Table 14: Compounds that meet sediment toxicity testing and risk assessment criteria.

Compound	Log K_{ow} / K_{oc}	Number and (make) of systems	Maximum Discharge Concentration (ug/L)	PNEC (ug/L)	Reported in control (at lower levels)
1,2,3-trichlorobenzene	3.93 / 2 040	1 (Smart Ballast)	9.62	3	Yes
1,2,4-trichlorobenzene	3.93 / 1 964	1 (Smart Ballast)	13.4	20	Yes
2,4-dibromophenol	3.22 / 724	1 (Electro-Cleen)	0.02	0.0012	Yes
2,6-dibromophenol	3.36 / 741	1 (Electro-Cleen)	0.02	0.0012	Yes
4-chlorotoluene	3.42 / 447	1 (ARA Ballast)	0.12	0.19	No
2,4,6-Tribromophenol	3.89 / 1 185	7*	1.32	2	In some

*These systems are Oceanguard, Aquarius, Balpure, Ecogaurdian, Electro-Cleen, Bluezone and Sky-System.

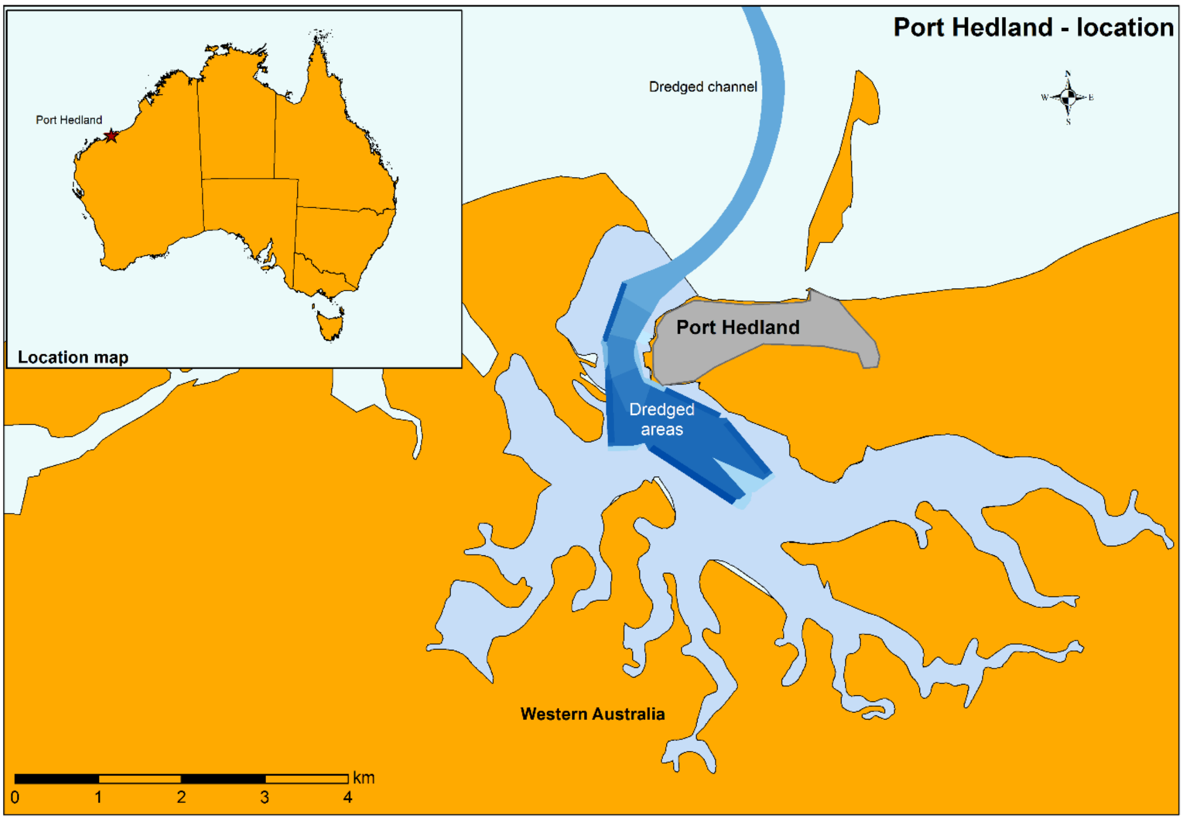
The compounds in Table 14 were reported to be in small concentrations close to the same order of magnitude as their PNECs in a small number of systems and are not characterised as persistent, bioaccumulative and toxic (PBT) substances (Appendix A). In many cases, these compounds were also detected in the control water, and so polluted port water may be contributing to their production, rather the individual systems themselves. It was also identified that the trichlorobenzene and chlorotoluene species are quite volatile and this is expected to mitigate their potential to accumulate in sediment. The bromophenol species also partially ionize in water, which will promote their existence in the water column rather than sediment.

Ideally, the modelling in this report would address the sediment toxicity concerns associated with these compounds. However, the sensitivity analysis (Chapter 2) showed that sediment accumulation of a DBP is much more sensitive to the water characteristics of the port than the total concentration. Without port data for these parameters, and noting the mitigating factors above, it was decided to focus on only the total concentration in the port. The values of these water characteristics parameters were therefore left at the default settings in the GESAMP-BWWG Model Harbour for all the case studies examined.

Port Hedland

Port Hedland is situated in the tropics on the north-west coast of Western Australia (Figure 5). The climate is arid, with low annual rainfall (mean = 315.5 mm) and high temperatures (mean maximum = 33.3 °C (BoM, 2017a)). It is the world's largest iron ore export port; in 2016 nearly 480 million metric tonnes of iron ore were exported. The port also handles other bulk commodities including manganese ore, copper concentrates and salt (PPA, 2017). The port can service ships up to 330 m and 260,000 DWT. To allow such large ships to dock, the area of the port (2.2 million metres squared) is dredged (Figure 6). This equates to 16 per cent of the total surface area of the network of creeks that make up the original inlet. Port Hedland has an average tidal range of 5.9 m so virtually all the area outside the dredged area within the tidal prism (the volume of water that flows into and out of an estuary with the flood and ebb of the tide (Hume, 2005)), is below the low water line at chart datum.

Figure 5. Port Hedland location (inset). The main map shows the location of the dredged area of the port within the network of creeks, which comprise the tidal prism.



The depths the port is dredged to vary from 5.7 m in the tug haven to 19.8 m along the length of Anderson Point Wharf (Figure 6). The total volume of water in the dredged area is 32 million cubic metres, which equates to 59 per cent of the tidal prism, which is the total volume of water within the port area.

The dredged area of Port Hedland was used as the basis for the representation of the port in MAMPEC and is shown in more detail in Figure 6. This is likely a conservative model, as it under predicts the inflow of water, as the port has a larger tidal prism than just the dredged area. The marina environment from MAMPEC was chosen to represent the port as it closely matches the port layout. The current flowing outside the port was taken to be the typical speed of the Leeuwin Current (0.5m/s) (CSIRO, 2001). The MAMPEC parameterisation for Port Hedland is given in Table 40 (Appendix C), and the MAMPEC results for all DBPs is given in Appendix E.

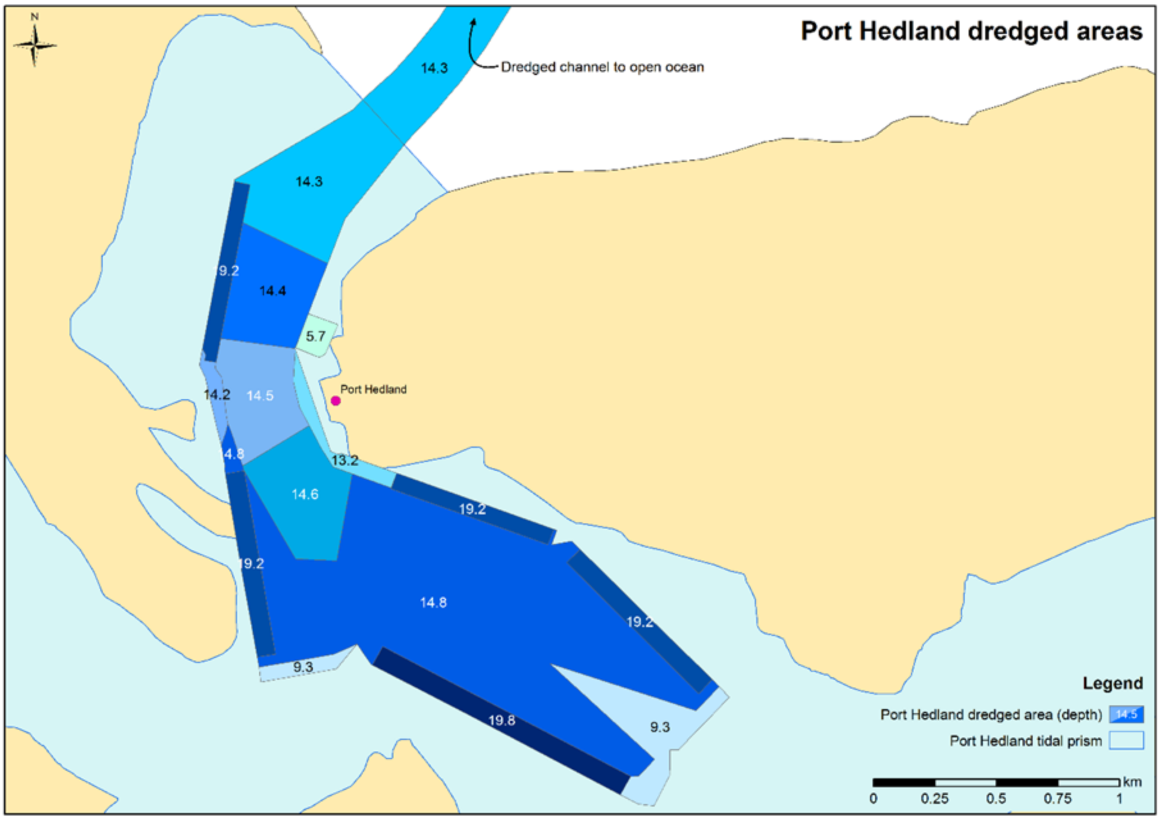


Figure 6. Dredged areas within Port Hedland and the depths to which they are dredged. (Data source: RAN Hydrographic Service chart AUS 54).

Arrivals data

Lloyds data show that in 2016 there were 2 795 recorded vessel visits to Port Hedland (Table 15). Of these, 2 694 (96 per cent) were bulk carriers and it is estimated that greater than 99 per cent of ballast water discharged was from this source. The large volume of ballast water discharged at this port is four times larger than the conservative discharge scenario suggested by the GESAMP-BWWG for G9 approval (IMO, 2015) (36.5 M m^3/year), and also five times the volume of the dredged area of the port.

Table 15: Vessel visits to Port Hedland in 2016, from Lloyds data.

Vessel Type	Arrivals		Ballast Water Discharged (m^3)	
Bulk Carrier	2 694	96.7%	163 447 136	99.2%
Tanker	51	1.8%	1 228 296	0.7%

General Cargo	39	1.4%	105 508	0.1%
Cruise Vessel	2	0.1%	2 325	0.0%
Total	2 786		164 783 265	

BWMS in use

There is a larger proportion of chlorination and ozonation systems visiting Port Hedland compared to the national proportions with the difference being made up by a greater proportion of ship visits using UV systems and systems that did not report any emissions (Table 16).

Table 16: Vessel visits to Port Hedland by BWMS category (August 2016 – April 2017).

BWMS Category	Visits		Number of Systems
Chlorination	71	61.2%	11
Ozonation	23	19.8%	1
UV (G8)	14	12.1%	2
UV (G9)	7	6.0%	5
Deoxygenation (G8)	1	0.9%	1
Total	116		20

Results

Worst case scenario

The MAMPEC modelling predicted that, in the worst case scenario, seven compounds were of concern, of which the five with the highest PEC/PNEC ratio are shown in Table 17. The PNEC threshold is exceeded if the PEC/PNEC ratio is above 1, and all ratios for which this is the case are highlighted in **bold**. If the average concentration in the port is considered instead of the maximum, four compounds breach their trigger values (dibromoacetonitrile, chloropicrin, monochloroacetic acid, and sodium bisulfite). Outside the harbour only three compounds are above their thresholds (dibromoacetonitrile, monochloroacetic acid and chloropicrin).

Table 17: Port Hedland worst case scenario MAMPEC results for compounds that exceeded their PNEC.

Compound	Effective Discharge Concentration (μ/L)	PNEC (μ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (μ/L)	PEC/PNEC	PEC (μ/L)	PEC/PNEC	PEC (μ/L)	PEC/PNEC
Dibromoacetonitrile	674.000	0.055	10.604	**192.801**	6.271	**114.015**	0.764	**13.882**
Monochloroacetic acid	517.000	0.580	10.545	**18.182**	6.600	**11.380**	0.856	**1.476**
Chloropicrin	18.300	0.025	0.358	**14.326**	0.222	**8.894**	0.029	**1.144**

Peracetic acid	300.000	0.220	0.705	**3.205**	0.167	0.759	0.002	0.008
Sodium bisulfite	5 800.000	59.000	122.548	**2.077**	77.217	**1.309**	10.089	0.171

Plausible scenario

In the plausible scenario, only dibromoacetonitrile was predicted to exceed its PNEC. The results for the five compounds with the highest PEC/PNEC ratios are shown in Table 18.

Table 18: Port Hedland plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	**Effective Discharge Concentration (µ/L)**	**PNEC (µ/L)**	**Harbour (maximum)**		**Harbour (average)**		**Surroundings (maximum)**	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromoacetonitrile	34.012	0.055	0.535	**9.729**	0.316	**5.754**	0.039	0.701
Monochloroacetic acid	10.796	0.580	0.220	0.380	0.138	0.238	0.018	0.031
TRO (Cl2)	81.207	0.900	0.118	0.131	0.022	0.024	0.000	0.000
Dibromoacetic acid	39.587	6.900	0.813	0.118	0.510	0.074	0.066	0.010
Sodium thiosulfate	3 188.086	805.000	64.287	0.080	40.149	0.050	5.196	0.006

Discussion

There was a larger proportion of chlorination systems in use in vessels visiting Port Hedland compared to the national proportions. Bulk carriers arrivals in Australia combined are summarised in Table 19, which shows that bulk carriers, as a vessel type, have a higher proportion of chlorination systems installed, but not as high as in those vessels visiting Port Hedland.

Table 19: Visits by bulk carriers nation-wide, by BWMS category.

BWMS Category	**Visits**		**Number of Systems**
Chlorination	361	55.4%	13
UV (G8)	133	20.4%	12
UV (G9)	94	14.4%	5
Ozonation	54	8.3%	1
Membrane + deoxygenation (G8)	7	1.1%	1
Filtration + Membrane (G8)	2	0.3%	1
Deoxygenation (G8)	1	0.2%	1
Total	652		34

One possibility is that for bulk carriers, and particularly for the large bulk carriers visiting Port Hedland, UV systems are not practicable for the larger flow rates required to fill and empty their large ballast tanks without delays. They also require treatment to be conducted at both intake and discharge. In comparison, electro-chlorination systems only require treatment on uptake and potentially neutralisation on discharge, and may be more suited to higher flow rates (gCaptain, 2016).

The greater proportion of chlorination systems, in conjunction with the large volumes of ballast water discharged, predispose Port Hedland to be the recipient of some chemicals that are likely to breach their trigger values. This is partly offset by the large tidal range of the port that facilitates mixing of port water with surrounding oceanic water and further dilutes any DBPs that may be present. The MAMPEC model for Port Hedland exchanges 41 per cent of its water with the surroundings each tidal cycle.

The worst-case scenario shows that the environmental risks of these systems cannot be immediately discounted. It shows that the large volume of water discharged is not mediated by the large amount of flush in the port, and in particular dibromoacetonitrile, chloropicrin and monochloroacetic acid stand out as compounds that may pose an environmental risk. However, the worst-case scenario greatly exaggerates the amount of DBP likely to be discharged. As a consequence the more realistic study was carried out as described above.

In comparison, the results of the plausible scenario show that the large tidal range mostly offsets the ballast water discharge. With the exception of dibromoacetonitrile, it is predicted that these compounds will likely be in concentrations below their trigger values. The two compounds that came closest to their trigger values were dibromoacetonitrile and dibromoacetic acid.

Port Phillip Bay

Port Phillip Bay is a large bay in southern Victoria. It covers almost 2,000 km^2, has an average depth of 13 m and a volume of 25 cubic kilometres. Its coastline is densely populated, with 3.2 million people living around the bay. Within the bay area are a number of marine reserves, and it is home to a wide variety of marine life including dolphins, whales, seals and penguins (Parks Victoria, 2017, CSIRO et al., 1996). The port infrastructure itself is clustered in two main areas: Geelong and Melbourne (Figure 7).

Figure 7. The locations of docks in the Port of Melbourne (main map) and Corio Bay in Geelong (inset).

To model the DBP concentrations in Port Phillip Bay a number of dock locations were selected in addition to the bay itself. In Geelong, Corio Quay was selected as it was the only semi-enclosed body of water in the port, and thus would be the most likely to have a concentration build-up of DBPs.

The Port of Melbourne comprises several docks and wharves. Webb, Swanson and Appleton Docks (Figure 7) were used in this case study and were modelled separately. It was noted that they are not directly flushed by a river; the Yarra River flows past but not through these docks. The flow rate of the Yarra River was obtained by taking the average yearly discharge, and dividing by the cross-section in metres squared of the river mouth. The tidal data for the Yarra river from OzCoasts (2015) was used for these three docks. Lloyds data does not distinguish between the different docks so the amount of ballast water discharged in the whole of Port Melbourne was used for each of them, which is a deliberate over-estimate of vessel traffic.

MAMPEC is not designed to model a large volume of water like Port Phillip Bay so to account for the long residence time of water within Port Phillip Bay, the 'whole bay' model was set up with no tidal range or river flush. This was intended to simulate a worst case flushing scenario, where the only exchange of water between the bay and the surrounding sea was through diffusion. The MAMPEC parameterisation for the individual docks modelled in Port Phillip Bay and the bay itself are given in Table 41-42 (Appendix C). The MAMPEC results for all DBPs and each port area are given in Appendices F to J.

Arrivals data

Port of Melbourne

The ships most frequently visiting the Port of Melbourne during 2016 were container ships and Ro-Ros. The two largest sources of ballast water were calculated to be tankers and container ships (Table 20).

Table 20: Port of Melbourne vessel visits from Lloyds data 2016.

Vessel Type	Arrivals		Ballast Water Discharged (m^3)	
Container Vessel	1 424	43.4%	6 165 756	31.9%
Ro-Ro Cargo	1 028	31.4%	1 862 157	9.6%
Tanker	399	12.2%	8 019 704	41.4%
Bulk Carrier	293	8.9%	2 964 701	15.3%
Cruise Vessel	77	2.3%	69 116	0.4%
Total	3 278		19 353 846	

Note: Only the top five types of vessel arrivals are shown.

The most common BWMS systems used by vessels visiting the Port of Melbourne are those that did not report any emissions. Together with UV systems, these make up over 75% of BWMS used by vessels visiting this port (Table 21).

Table 21: BWMS installed on vessels visiting the Port of Melbourne, by category.

BWMS Category	Visits		Number of Systems
UV (G9)	26	42.6%	4
UV (G8)	20	32.8%	6
Chlorination	11	18.0%	5
Ozonation	4	6.6%	1
Total	61		16

Geelong

Compared with the Port of Melbourne, Geelong is a much smaller port in terms of traffic. It is most frequently visited by tankers and bulk carriers, and these make up the majority of ballast water discharge in the estimation used in this report (Table 22).

Table 22: Geelong vessel visits from Lloyds data 2016.

Vessel Type	Arrivals		Ballast Water Discharged (m^3)	
Tanker	294	52.2%	6 044 602	63.7%
Bulk Carrier	196	34.8%	3 088 794	32.6%
General Cargo	54	9.6%	331 477	3.5%
Container Vessel	11	2.0%	14 610	0.2%
Livestock Carrier	5	0.9%	3 970	0.0%
Total	563		9 485 049	

Note: Only the top five types of vessel arrivals are shown.

The most common BWMS categories in ship visits to Geelong are UV systems, which make up nearly 60 per cent of all systems visiting Geelong (Table 23).

Table 23: BWMS visits to Geelong by category.

BWMS Category	Visits		Number of Systems
UV (G8)	12	57.1%	5
Chlorination	6	28.6%	2
Ozonation	2	9.5%	1
UV (G9)	1	4.8%	1
Total	21		9

Results

The MAMPEC modelling results of the plausible scenario are shown for Corio Quay, Webb, Swanson and Appleton Docks and Port Phillip Bay (Tables 24–28). (Input parameters are listed in Appendix C). There were no compounds that were expected to exceed their PNECs in Port Phillip Bay, but a number of compounds were predicted to exceed their PNECs when discharges were concentrated within certain port areas. Dibromoacetonitrile exceeded its PNEC in all of these docks, monochloroacetic acid exceeded its PNEC in all the docks in Melbourne, and dibromoacetic acid exceeded its PNEC in Appleton Dock.

Table 24: Geelong (Corio Quay) plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromoacetonitrile	7.093	0.055	0.425	**7.722**	0.217	**3.946**	0.008	0.143
Dibromoacetic acid	55.651	6.900	4.704	0.682	2.611	0.378	0.106	0.015

2,6-dibromophenol	0.004	0.001	0.000	0.273	0.000	0.152	0.000	0.006
2,4-dibromophenol	0.004	0.001	0.000	0.266	0.000	0.147	0.000	0.006
Monochloroacetic acid	1.570	0.580	0.131	0.227	0.073	0.126	0.003	0.005

Table 25: Port of Melbourne (Webb Dock) plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	**Effective Discharge Concentration (µ/L)**	**PNEC (µ/L)**	**Harbour (maximum)**		**Harbour (average)**		**Surroundings (maximum)**	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromoacetonitrile	2.974	0.055	0.296	**5.373**	0.135	**2.454**	0.011	0.196
Monochloroacetic acid	11.165	0.580	2.179	**3.756**	1.226	**2.114**	0.139	0.240
Dibromoacetic acid	19.039	6.900	3.817	0.553	2.161	0.313	0.248	0.036
2,6-dibromophenol	0.001	0.001	0.000	0.171	0.000	0.098	0.000	0.011
2,4-dibromophenol	0.001	0.001	0.000	0.158	0.000	0.089	0.000	0.010

Table 26: Port of Melbourne (Swanson Dock) plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	**Effective Discharge Concentration (µ/L)**	**PNEC (µ/L)**	**Harbour (maximum)**		**Harbour (average)**		**Surroundings (maximum)**	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromoacetonitrile	2.974	0.055	0.404	**7.338**	0.169	**3.076**	0.009	0.161
Monochloroacetic acid	11.165	0.580	3.373	**5.815**	1.860	**3.207**	0.171	0.294
Dibromoacetic acid	19.039	6.900	5.964	0.864	3.317	0.481	0.309	0.045
2,6-dibromophenol	0.001	0.001	0.000	0.277	0.000	0.157	0.000	0.015
2,4-dibromophenol	0.001	0.001	0.000	0.257	0.000	0.143	0.000	0.013

Table 27: Port of Melbourne (Appleton Dock) plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	**Effective Discharge Concentration (µ/L)**	**PNEC (µ/L)**	**Harbour (maximum)**		**Harbour (average)**		**Surroundings (maximum)**	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromoacetonitrile	2.974	0.055	0.491	**8.919**	0.188	**3.413**	0.009	0.169
Monochloroacetic acid	11.165	0.580	4.036	**6.958**	2.015	**3.473**	0.189	0.326
Dibromoacetic acid	19.039	6.900	7.125	**1.033**	3.586	0.520	0.342	0.050
2,6-dibromophenol	0.001	0.001	0.000	0.330	0.000	0.169	0.000	0.017
2,4-dibromophenol	0.001	0.001	0.000	0.307	0.000	0.155	0.000	0.015

Table 28: Port Phillip Bay plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Bromochloroacetic acid	2.791	16.000	4.035	0.252	0.403	0.025	0.000	0.000
Dichlorobromoacetic acid	0.455	60.000	1.988	0.033	0.199	0.003	0.000	0.000
Bromate	7.333	136.000	2.536	0.019	0.254	0.002	0.000	0.000
Monochloroacetic acid	8.707	0.580	0.011	0.018	0.001	0.002	0.000	0.000
Dibromoacetonitrile	4.029	0.055	0.000	0.009	0.000	0.001	0.000	0.000

Discussion

In the plausible scenario, three compounds were predicted to exceed environmentally acceptable concentrations in the docks considered. However, it is noted that the modelling for the Melbourne docks assumed all of the traffic going to the Port of Melbourne would discharge their ballast water in each of these locations. In reality, the destination of ships will depend on their type, as shown in Table 29.

Table 29: Vessel type and destination dock in the Port of Melbourne.

Vessel Type	Visits		Discharged Ballast Water (m^3)		Likely Dock of Arrival
Container ship	1 424	43.23%	6 165 756	31.90%	**Swanson**
Ro-Ro Cargo	1 028	31.21%	1 862 157	9.60%	**Webb**
Tanker	399	12.11%	8 019 704	41.40%	Maribyrnong
Bulk Carrier	293	8.89%	6 044 602	63.70%	**Appleton**/South Bank
Cruise Vessel	77	2.34%	69 116	0.40%	Station Pier
Cargo	56	1.70%	271 885	1.40%	South Bank

Taking this into consideration, a new set of ratios is obtained and shown in Table 30. In this case, only dibromoacetic acid and monochloroacetic acid now exceed their PNECs in Appleton and Swanson docks.

Table 30: Corrected PEC/PNEC ratios for Appleton, Swanson and Webb Docks in the likely scenario, taking into account destination of vessel traffic.

Compound	PNEC (µ/L)	Appleton (maximum)	Swanson (maximum)	Webb (maximum)

		PEC (µ/L)	PEC/ PNEC	PEC (µ/L)	PEC/ PNEC	PEC (µ/L)	PEC/ PNEC
Dibromoacetonitrile	0.055	0.313	**5.687**	0.129	**2.343**	0.028	0.517
Monochloroacetic acid	0.580	2.571	**4.433**	1.076	**1.855**	0.209	0.361
Dibromoacetic acid	6.900	4.539	0.658	1.903	0.276	0.366	0.053

Note: PEC/ PNEC ratios > 1.0 are shown in **bold**.

Swanson and Appleton docks (Port of Melbourne), in particular, and Corio Quay models are more sensitive to chemicals in discharged ballast water in comparison to the whole bay model. The whole bay model had a smaller PEC for most compounds, despite having no tidal or river induced exchange of water between the surroundings and the model port. This is likely due to the volume of the bay and spatial resolution of the model, and shows that the concentrations are likely to be small and persistence of these compounds is likely to be short, thereby representing a low risk in a large volume but slow flushing body of water. It is noted that apart from dibromoacetic acid, a worst case half-life (no degradation) was used for the other compounds in Table 28 as data was unavailable, and this has likely contributed to their relatively high PEC/PNEC ratios in the Port Phillip Bay model.

Port of Brisbane

The Port of Brisbane is located at the mouth of the Brisbane River, which drains into Moreton Bay. Moreton Bay is a popular destination for recreational fishermen and is also an important commercial fishery (Moreton Bay Trawl Fishery). It is also a destination for tourists to view its wildlife that include grey nurse sharks, manta rays and dugongs. The Moreton Bay Marine Park, which covers areas of the bay and some islands, is recognised as an internationally significant wetland under the Ramsar convention (SEQ, 2010). The port itself is Australia's fastest growing container port, the largest port in Queensland and the third largest in Australia. It also has wharf facilities for bulk carriers and tankers, as well as general cargo (Port of Brisbane, 2017).

The port layouts in MAMPEC all model a port as a rectangle with one opening. This does not fit the Port of Brisbane well, as it has two open sides and so two models were considered. The 'River Mouth' model assumes all ballast water is discharged within the river mouth, at the end of the area dredged for the port. The 'Whole Port' model takes into account the whole port, but neglects the fact that the port is open on two sides. The two different areas modelled are shown in Figure 8.

Figure 8. Port of Brisbane with modelled areas shown in blue (river mouth model) and red (whole port model).

Flushing from the Brisbane River is included in both models. MAMPEC parameterisation for the two models are given in Table 46 and Table 47 (Appendix C). The MAMPEC results for all DBPs and both models are given in Appendices K and L.

Arrivals Data

Container ships are the most common ship type visiting the Port of Brisbane, however the majority of ballast water discharge is calculated to be due to bulk carriers (Table 31).

Table 31: Vessel visits to the Port of Brisbane in 2016, from Lloyds data.

Vessel Type	Arrivals	Ballast Water Discharged (m^3)

Container Vessel	1 295	47.6%	5 445 782	21.2%
Bulk Carrier	626	23.0%	11 293 532	43.9%
Tanker	467	17.2%	8 262 822	32.1%
Cruise Vessel	185	6.8%	144 191	0.6%
General Cargo	130	4.8%	536 888	2.1%
Total	2 720		25 723 102	

Note: Only the top five types of vessel arrivals are shown.

Over 70 per cent of the vessel visits to the Port of Brisbane were from vessels with UV systems installed, while the majority of the rest had chlorination systems installed (Table 32).

Table 32: BWMS category in vessels visiting the Port of Brisbane during 2106.

BWMS Category	Visits		Number of Systems
UV (G8)	35	35.4%	8
UV (G9)	34	34.3%	5
Chlorination	29	29.3%	7
Ozonation	1	1.0%	1
Total	99		21

Results

The MAMPEC modelling results of the plausible scenario are shown for both modelled areas below (Table 33–Table 34). Dibromoacetonitrile was predicted to exceed its PNEC in the river mouth model but not in the whole port scenario.

Table 33: Port of Brisbane (river mouth) plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	Effective Discharge Concentration (μ/L)	PNEC (μ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (μ/L)	PEC/PNEC	PEC (μ/L)	PEC/PNEC	PEC (μ/L)	PEC/PNEC
Dibromoacetonitrile	6.791	0.055	0.089	**1.615**	0.053	0.960	0.016	0.298
Dibromoacetic acid	34.510	6.900	0.647	0.094	0.419	0.061	0.147	0.021
TRO (Cl_2)	42.626	0.900	0.045	0.050	0.008	0.008	0.000	0.000
Monochloroacetic acid	1.177	0.580	0.022	0.038	0.014	0.024	0.005	0.009
2,6-dibromophenol	0.001	0.001	0.000	0.019	0.000	0.013	0.000	0.004

Table 34: Port of Brisbane (whole port) plausible scenario MAMPEC results for the five compounds with the highest PEC/PNEC ratios.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromoacetonitrile	6.791	0.055	0.043	0.778	0.026	0.473	0.011	0.206
Dibromoacetic acid	34.510	6.900	0.393	0.057	0.278	0.040	0.149	0.022
Monochloroacetic acid	1.177	0.580	0.013	0.023	0.009	0.016	0.005	0.009
TRO (Cl2)	42.626	0.900	0.018	0.020	0.003	0.003	0.000	0.000
2,6-dibromophenol	0.001	0.001	0.000	0.012	0.000	0.009	0.000	0.005

Discussion

The two different model scenarios for the Port of Brisbane in MAMPEC both predicted that the compounds with the highest PEC/PNEC ratios were dibromoacetonitrile and dibromoacetic acid. In the case of the river mouth model, the concentrations were predicted to be roughly double the whole port model, and the concentration predicted for dibromoacetonitrile exceeded its PNEC in this case. The most likely reason for this elevated concentration in the river mouth model is that it is only a third of the volume in comparison to the whole port model. The lack of flexibility in MAMPEC to match the port layout in the Port of Brisbane may affect the accuracy of the modelling, and the two different results for the two models reflects this.

5 Discussion, conclusions and recommendations

This project has identified the major types of chemical discharges from the 41 BWMS with MEPC Final Approval and the likely chemicals and concentrations discharged by their use. The likely number of vessel arrivals, their destination ports, BWMS types and discharge concentrations of DBPs have also been identified and the quantity of ballast water discharged has been estimated. Three case studies have been conducted using this information to run MAMPEC models to obtain PECs for the identified DBPs, which were compared to PNECs to determine if the plausible discharge scenarios may be of environmental concern. Three DBPs were identified by the MAMPEC modelling procedure to have potential for environmental concern: dibromoacetonitrile, monochloroacetic acid and dibromoacetic acid. It should noted that these results were derived from modelling; recommendations for a sampling program to provide verification follow in the next section.

Nevertheless, there are a number of other uncertainties associated with the results obtained. Most importantly, in some cases minimal toxicity data are available for DBPs. For instance, the trigger value for dibromoacetonitrile is derived using an acute toxicity value for *Pimephales promelas*, a species of freshwater fish native to North America. There are also inconsistencies between the ANZECC approach and the calculation of PNECs (Appendix B). This can be seen by comparing trigger values between the GESAMP-BWWG chemical database (IMO, 2014) and those compiled by Deveney and Wiltshire (2012) (Table 35).

Table 35: Comparison of GESAMP-BWWG PNEC concentrations with Deveney and Wiltshire's ANZECC low reliability trigger values.

Compound	GESAMP-BWWG PNEC (ug/L)	Deveney and Wiltshire ANZECC low reliability trigger values (ug/L)
Dibromoacetonitrile	0.055	0.6
Monochloroacetic acid	0.58	32
Dibromoacetic acid	6.9	23

In the case of dibromoacetonitrile, the different trigger values are the result of different assessment factors being used (10,000 for the GESAMP-BWWG PNEC and 1000 for the ANZECC low reliability trigger value). On the other hand, for monochloroacetic acid, different toxicity data were used. Deveney and Wiltshire used data for *Daphnia magna*, a small freshwater crustacean found in the Northern Hemisphere, and the GESAMP-BWWG used additional data from a variety of fish species and *Scenedesmus subspicatus*, a freshwater green algae native to Europe. This last species was by far the most sensitive, with a no observed effect concentration of 5.8 ug/L, in comparison to the fish species (12.5mg/L) and *D. magna* (32mg/L).

The trigger values used in this report were sourced from the GESAMP-BWWG database PNECs in preference to the low reliability trigger values from Deveney and Wiltshire (2012), as the database is published, publically available and verifiable. Nevertheless, it is noted that if different values from this table were chosen as trigger values in this study, particularly for the three compounds in Table 35, the PECs obtained from the MAMPEC modelling in this report would no longer breach their trigger values.

There are also some inconsistencies in the GESAMP-BWWG PNECs. It is expected that compounds with similar functional groups will have similar toxicities, as their mode of action will be the same. However, for dibromoacetonitrile and monochloroacetic acid, the chemicals similar to them vary in their PNECs by orders of magnitude (Table 36). This highlights the fact that although these PNECs are currently the best available indication of environmentally safe concentrations, they are the equivalent of low reliability trigger values and should be considered as indicative interim working levels (ANZECC, 2000).

Table 36: Comparison of GESAMP-BWWG PNEC concentrations for dibromoacetonitrile and monochloroacetic acid alongside similar compounds.

Compound	GESAMP-BWWG PNEC (ug/L)
Dibromoacetonitrile	**0.055**
Dichloroacetonitrile	24.35
Tribromoacetonitrile	69
Dibromochloromethane	6.3
Monochloroacetic acid	**0.58**
Dichloroacetic acid	2.3
Monobromoacetic acid	16

Note: The compounds are grouped into two sets, the first being those most similar to dibromoacetonitrile and the second those most similar to monochloroacetic acid. The variation in PNECs between the PNECs indicated in bold and those related to them is unexpected given the similarities between them.

More work needs to be done to obtain relevant and authoritative trigger values for these compounds. These need to be derived using marine and estuarine species to ensure they are applicable and relevant, and cover a wide range of animal groups, including invertebrates and algae. Ideally different life stages would also be considered, such as larvae, to consider different sensitivities to environmental toxicity throughout an organism's lifespan. Until these higher quality trigger values are obtained it will be difficult to rule out environmental concerns associated with these compounds.

There was also additional uncertainty in relation to the degradation rate of the identified DBPs. It was found in the literature that half-lives of compounds could be highly variable depending on the temperature and a number of different factors. These include the presence of other mediating chemicals, bacteria and conditions such as pH and amount of sunlight (Bayless and Andrews, 2008, Reckhow et al., 2001, Themistokles D. Lekkas and Nikolaou, 2004).

The actual discharge concentration of DBPs in the field for many systems has also yet to be determined, and the variability and uncertainty in their half-lives contributes to this. As discussed in Chapter 2, the concentration of DBPs produced is influenced by the characteristics of the intake water, such as organic content, pollutants and temperature, and the concentration discharged will also be influenced by the time the ballast water is held on the ship. This means it is likely that the concentrations discharged by a particular system will be highly variable in practice. At the present time the concentrations reported in the G9 approval applications are the best possible indication of the maximum discharge concentrations of these systems, but it is possible that they might be an underestimate in some cases and an overestimate in others.

It should also be noted that MAMPEC is a steady state model, and cannot model the heterogeneous effects that would be expected in a real port. It assumes all processes happen at a constant rate, in particular river flows and ballast water discharge. This may be an issue if ballast water discharge in a port is highly variable, for example if most ships discharge their ballast water on a particular day of the week, or only a portion of the year. As discussed in Chapter 3, Zipperle et al. (2011) found that in these cases the average concentration in MAMPEC is still accurate but the maximal concentration is underestimated, and they present an empirical equation to correct this on a system by system basis. This is addressed through the G9 approval process (IMO, 2015), and as this report is concerned with the PECs resulting from the discharge of a wide range of systems, it was considered out of scope. With these caveats in mind the results of this project suggest that, under the current volume of vessel traffic, the following chemicals discharged by BWMS could potentially be of environmental concern: dibromoacetonitrile, monochloroacetic acid and dibromoacetic acid. All of these compounds breached their PNECs in one or more of the port areas considered.

Recommendations

It is recommended that a sampling plan be put in place to check if these chemicals are detectable in port waters once the convention comes into force. If they are, and are at levels that exceed the PNECs used in this report, it is also recommended that authoritative trigger values be derived for these compounds to determine if any action needs to be taken. Tribromomethane would be an ideal candidate for sampling, as it was produced by almost all the BWMS studied, and was predicted to be present in higher concentrations compared to other DBPs in discharged ballast water and also the environment. Dibromoacetonitrile, dibromoacetic acid and monochloroacetic acid should also be sampled for as they exceeded their PNECs in one or more of the scenarios modelled. Sediment sampling and sampling directly from the ballast tanks should also be considered.

It is likely that shipping to Australia will continue to increase, and as the BWMS market matures new systems will be approved and that the proportion of different types of BWMS installed in vessels visiting Australia will change. For example, a new system currently undergoing basic approval uses ‘brilliant green’, a triarylmethane dye with antiseptic properties, as a disinfectant. This will mean that the modelling conducted in this report will need to be re-examined and a plan should be put into place to conduct a review when discharges reach a pre-determined threshold. To support this review, current reporting systems should be improved to include the chemicals actually used by a ship’s BWMS, and not just the type of system, if it is approved to use multiple substances. This will be particularly important as more substances become available and if novel preparations are developed.

Glossary

Term	Explanation
BWMS	Ballast water management system, a system for treating ballast water
Colloid	A mixture in which microscopically dispersed insoluble particles is suspended throughout another substance, such as water. Milk is an example of a colloid.
DBP	Disinfection by-product of ballast water treatment
DOC	Dissolved organic carbon
DWT	Deadweight tonnage. A measurement of the weight a ship can safely carry. It does not include the weight of the ship itself.
Floc	Flakes of aggregated solids that precipitate from solution
GESAMP	Group of Experts on the Scientific Aspects of Marine Environmental Protection
MADC	Maximum Allowable Discharge Concentration
MAMPEC	Marine Antifoulant Model for Predicted Environmental Concentration
MARS	Maritime Arrivals Reporting System (Department of Agriculture and Water Resources)
PEC	Predicted Environmental Concentration
PNEC	Predicted No Effect Concentration
POC	Particulate organic carbon
Ro-Ro	Roll on – roll off. Vessels that are fitted with loading ramps for vehicles to drive on and drive off.
SPM	Suspended Particulate Matter
TRO	Total residual oxidant

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Appendix A: Persistence-Bioaccumulation-Toxicity Criteria (PBT)

The criteria for PBT substances are shown in Table 37. If any chemical associated with a BWMS is classified as PBT, it cannot obtain G9 approval. A substance must meet all three criteria to be classified as PBT.

Table 37: GESAMP-BWWG PBT Criteria

Criterion	PBT Criteria
Persistence	Half-life (time for half of compound to decompose): > 60 days in marine water, or > 40 days in fresh water,* or > 180 days in marine sediments, or > 120 days in freshwater sediments
Bioaccumulation	Experimentally determined Bioconcentration Factor (BCF) > 2000, or if no experimental BCF has been determined, Log Kow (Octanol Water Partitioning coefficient) ≥ 3.
Toxicity (environment) **Toxicity (human health, CMR)**	Chronic No Observed Effect Concentration (NOEC) < 0.01mg/L Carcinogenic (category 1A or 1B), Mutagenic (category 1A or 1B) or Toxic for reproduction (category 1A, 1B or 2) According to GHS classification.

* For the purpose of marine environmental risk assessment, half-life data in fresh water and freshwater sediment can be overruled by data obtained under marine conditions.

Appendix B: Derivation of Predicted No Effect Concentrations and low reliability ANZECC trigger values.

The process for deriving a Predicted No Effect Concentration (PNEC) for the G9 approval process is given in Table 38 (IMO, 2015). An L(E)50 value is defined as the lethal concentration required to kill 50% of the test population, and a chronic No Observed Effect Concentration (NOEC) is the highest tested concentration that shows no statistically significant difference from the control.

Table 38: Derivation of PNEC for the G9 approval process.

Data-set	**Assessment Factor (AF)**		**Rule Number**
	PNEC general	PNEC near ship	
Lowest* short-term L(E)C50 from freshwater or marine species representing one or two trophic levels	10 000	1 000	1
Lowest* short-term L(E)C50 from three freshwater or marine species representing three trophic levels	1 000	100	2
Lowest* short-term L(E)C50 from three freshwater or marine species representing three trophic levels + at least two short-term L(E)C50 from additional marine taxonomic groups	100	10	3
Lowest* chronic NOEC from one freshwater or marine species representing one trophic level, but not including micro-algae	100		4
Lowest* chronic NOEC from two freshwater or marine species representing two trophic levels, which may include micro-algae	50		5
Lowest* chronic NOEC from three freshwater or marine species representing three trophic levels, which may include micro-algae	10		6

* If the lowest value is not used, based on expert judgement, a scientific rationale should be submitted.

For example, for a particular compound there was LC50 concentrations for a fish (1 mg/L), crab (5 mg/L) and a micro-algae (0.5 mg/L). To derive a PNEC for this compound the assessment factor in rule two would be used, and taking the lowest value (micro-algae) would obtain a PNEC of 0.5 µg/L. The near ship PNEC accounts for toxic effects from ballast water that has just been discharged, and is compared to a corrected maximal concentration derived by Zipperle et al. (2011).

$Cmax = (CBW + (S\text{-}1)\ CMean)/S$

Where Cmax is the corrected maximal concentration, CBW is the concentration in the ballast water, CMean is the average concentration from MAMPEC, and S is a dilution factor that will vary on the port. A value of S = 5 is recommended for the GESAMP-BWWG model harbour.

For low reliability ANZECC trigger values a similar process is used, with a different table for assessment factors. These are consistent with OECD Environmental Concern Levels (ANZECC, 2000).

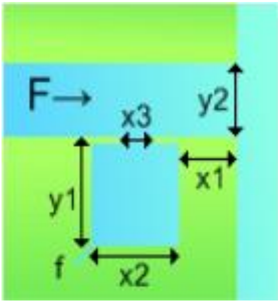
Data-set	Assesement Factor
Lowest of at least three chronic NOEC values	20
Lowest of three acute LC50 or EC50 values	100
Insufficient data: Lowest acute LC50 or EC50 value.	1 000

Appendix C: MAMPEC Inputs

GESAMP-BWWG Model Harbour

Default emissions scenario of 100 000 cubic metres a day, or 36.5 million cubic metres a year.

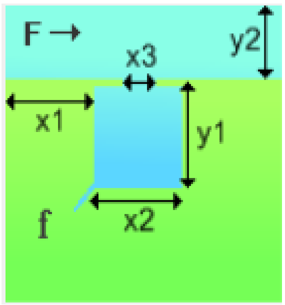
Table 39: GESAMP-BWWG Model Harbour Parameters.

Environment Type	**Commercial harbour** 
Temperature (°C)	15
Tidal Range (m)	1.5
Tidal Period (Hours)	12.41
Flush (f) (m^3/s)	0
Flow velocity (F) (m/s)	1
Depth (m)	15
Mouth width (x3) (m)	1000
x1 (m)	5000
x2 (m)	5000
y1 (m)	1000
y2 (m)	500
Other hydrodynamic parameters	
Maximum density difference tide (kg/m^3)	0.4
Non tidal daily water level change	0
Water characteristic parameters	
Maximum density difference tide (kg/m^3)	0.4
Suspended particulate matter (SPM) concentration (mg/L)	35

Particulate organic carbon (POC) concentration (mg/L)	1
Dissolved organic carbon (DOC) concentration (mg/L)	2
Chlorophyll (µg/L)	3
Salinity (PSU)	34
pH	8
Sediment parameters	
Depth mixed sediment layer (m)	0.2
Sediment density (kg/m³)	1000
Degradation of organic carbon in sediment (1/d)	0
Nett sedimentation velocity (m/d)	1

Port Hedland

Table 40: Port Hedland MAMPEC Parameters.

Environment Type	**Marina** 
Temperature (°C)	25.5 (–20.268, 118.582)
Tidal Range (m)	5.9
Tidal Period (Hours)	12.5 (Semi Diurnal)
Flush (f) (m³/s)	0
Flow velocity (F) (m/s)	0.5 (Leeuwin Current)
Depth (m)	14.3
Mouth width (x3) (m)	290
x1 (m)	885

x2 (m)	570
y1 (m)	4100
y2 (m)	2050

Port Phillip Bay

Table 41: Geelong (Corio Quay) MAMPEC Parameters.

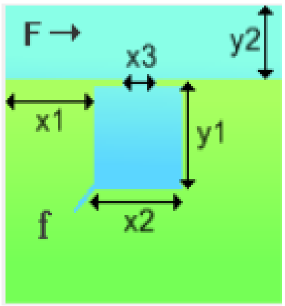
Environment Type	**Marina** 
Temperature (°C)	15.8 (–38.096842, 144.55906)
Tidal Range (m)	1.2
Tidal Period (Hours)	12.5 (Semi Diurnal)
Flush (f) (m^3/s)	0
Flow velocity (F) (m/s)	0
Depth (m)	11
Mouth width (x3) (m)	230
x1 (m)	345
x2 (m)	230
y1 (m)	570
y2 (m)	290

Table 42: Port of Melbourne (Webb Dock) MAMPEC Parameters.

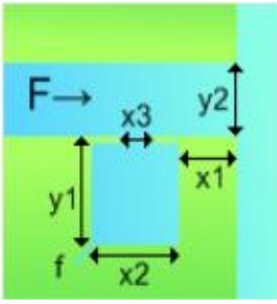
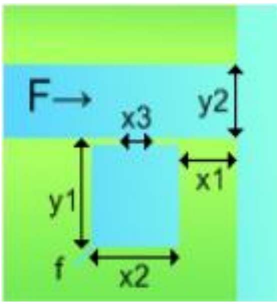
Environment Type	**Estuarine Harbour** 
Temperature (°C)	15.9 (–37.923014, 144.874746)
Tidal Range (m)	0.8
Tidal Period (Hours)	25 (Diurnal)
Flush (f) (m^3/s)	0
Flow velocity (F) (m/s)	0.005 (Yarra River)
Depth (m)	10
Mouth width (x3) (m)	300
x1 (m)	460
x2 (m)	300
y1 (m)	1100
y2 (m)	200

Table 43: Port of Melbourne (Appleton Dock) MAMPEC Parameters.

Environment Type	**Estuarine Harbour** 
Temperature (°C)	15.9 (–37.923014, 144.874746)
Tidal Range (m)	0.8

Tidal Period (Hours)	25 (Diurnal)
Flush (f) (m^3/s)	0
Flow velocity (F) (m/s)	0.005 (Yarra River)
Depth (m)	14.6
Mouth width (x3) (m)	800
x1 (m)	1000
x2 (m)	800
y1 (m)	200
y2 (m)	200

Table 44: Port of Melbourne (Swanson Dock) MAMPEC Parameters.

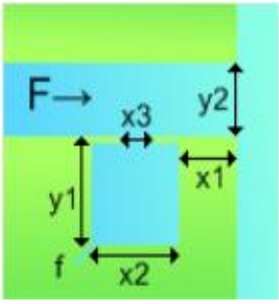
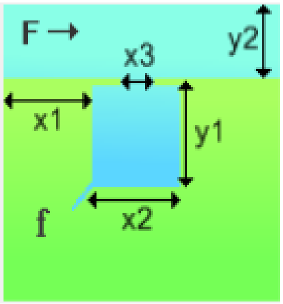
Environment Type	**Estuarine Harbour** 
Temperature (°C)	15.9 (−37.923014, 144.874746)
Tidal Range (m)	0.8
Tidal Period (Hours)	25 (Diurnal)
Flush (f) (m^3/s)	0
Flow velocity (F) (m/s)	0.005 (Yarra River)
Depth (m)	14.6
Mouth width (x3) (m)	200
x1 (m)	1000
x2 (m)	200
y1 (m)	1000
y2 (m)	200

Table 45: Port Phillip Bay MAMPEC Parameters.

Environment Type	**Marina** 
Temperature (°C)	15.8 (−38.096842, 144.55906)
Tidal Range (m)	0
Tidal Period (Hours)	12.5 (Semi Diurnal)
Flush (f) (m^3/s)	0
Flow velocity (F) (m/s)	0
Depth (m)	12.5
Mouth width (x3) (m)	4000
x1 (m)	60,000
x2 (m)	40,000
y1 (m)	50,000
y2 (m)	25,000

Port of Brisbane

Table 46: Port of Brisbane (River Mouth) MAMPEC Parameters.

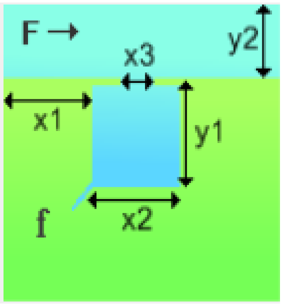
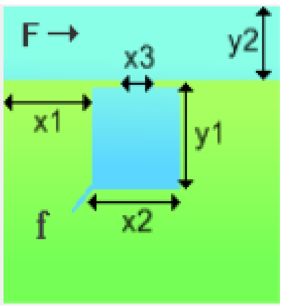
Environment Type	**Marina** 
Temperature (°C)	21.9 (–27.339391, 153.176979)
Tidal Range (m)	1.8
Tidal Period (Hours)	12.5 (Semi Diurnal)
Flush (f) (m^3/s)	25.6 (Brisbane River)
Flow velocity (F) (m/s)	0
Depth (m)	14
Mouth width (x3) (m)	420
x1 (m)	765
x2 (m)	510
y1 (m)	1400
y2 (m)	700

Table 47: Port of Brisbane (Whole Port) MAMPEC Parameters.

Environment Type	**Marina** 
Temperature (°C)	21.9 (–27.339391, 153.176979)

Tidal Range (m)	1.8
Tidal Period (Hours)	12.5 (Semi Diurnal)
Flush (f) (m^3/s)	25.6 (Brisbane River)
Flow velocity (F) (m/s)	0
Depth (m)	14
Mouth width (x3) (m)	510
x1 (m)	765
x2 (m)	510
y1 (m)	3900
y2 (m)	1950

Appendix D: Ballast Water Management Systems

Table 48: List of BWMS with G9 approval as of November 2016 (IMO, 2016).

System	Method	Neutralisation System	Final Approval Application	MEMPEC Meeting	Date Approved
PureBallast	UV		MEPC 56/2/1	MEPC 56/2/2, annex 5	13/07/2007
SEDNA	Peracetic acid, hydrogen peroxide and acetic acid		MEPC 57/2/5	MEPC 57/2/10, annex 7	4/04/2008
Electro-Cleen	Electrolysis	Yes	MEPC 58/2	MEPC 58/2/7, annex 7	10/10/2008
OceanSaver BWMS	Electrolysis		MEPC 58/2/1	MEPC 58/2/8, annex 4	10/10/2008
CleanBallast 500-1	Electrolysis	Yes	MEPC 59/2	MEPC 59/2/16, annex 5	17/07/2009
ClearBallast	Coagulation-flocculation		MEPC 59/2/5	MEPC 59/2/19, annex 4	17/07/2009
Greenship Sedinox	Electrolysis		MEPC 59/2/6	MEPC 59/2/19, annex 5	17/07/2009
NK-O3 BlueBallast System	Ozonation		MEPC 59/2/3	MEPC 59/2/16, annex 6	17/07/2009
JFE BallastAce (TG Ballastcleaner)	Sodium Hypochlorite Solution	Yes	MEPC 60/2/2	MEPC 60/2/12, annex 5	26/03/2010
EcoBallast	UV		MEPC 60/2/1	MEPC 59/2/16, annex 8	26/03/2010
GloEn-Patrol	UV		MEPC 59/2/7	MEPC 60/2/11, annex 4	26/03/2010
Resource Ballast	Electrolysis and Ozonation		MEPC 59/2/10	MEPC 60/2/11, annex 7	26/03/2010
BalClor BWMS	Electrolysis	Yes	MEPC 61/2/4	MEPC 61/2/15, annex 9	1/10/2010
BalPure BP-500	Electrolysis	Yes	MEPC 61/2/9	MEPC 61/2/21, annex 7	1/10/2010
OceanGuard	Electrocatalysis	Yes	MEPC 61/2/7	MEPC 61/2/21, annex 5	1/10/2010
ARA Ballast	Plasma and UV		MEPC 61/2/5	MEPC 61/2/15, annex 8	1/10/2010
EcoChlor	Chlorine Dioxide		MEPC 61/2/8	MEPC 61/2/21, annex 6	1/10/2010
SP-Hybrid BWMS Ozone	Ozonation		MEPC 61/2/2	MEPC 61/2/15, annex 6	1/10/2010
HiBallast BWMS	Electrolysis	Yes	MEPC 62/2/5	MEPC 62/2/18, annex 5	15/07/2011

Purimar	Electrolysis	Yes	MEPC 62/2/6	MEPC 62/2/18, annex 6	15/07/2011
Aquastar	Electrolysis	Yes	MEPC 63/2/3	MEPC 63/2/11, annex 7	2/03/2012
ERMA FIRST	Electrolysis	Yes	MEPC 63/2/1	MEPC 63/2/11, annex 5	2/03/2012
Microfade	Calcium Hypochlorite Solution	Yes	MEPC 63/2/2	MEPC 63/2/11, annex 6	2/03/2012
Neo Purimar	Electrolysis	Yes	MEPC 63/2/6	MEPC 63/2/21, annex 6	2/03/2012
SiCURE	Electrolysis	Yes	MEPC 62/2/10	MEPC 63/2/10, annex 6	2/03/2012
Smart Ballast	Electrolysis	Yes	MEPC 64/2/2	MEPC 64/2/7, annex 6	5/10/2012
DESMI Ocean Guard	UV and Ozonation		MEPC 63/2/7	MEPC 64/2/6, annex 4	5/10/2012
JFE BallastAce (NEO-CHLOR)	Sodium Dichloroisocyanurate	Yes	MEPC 64/2/1	MEPC 64/2/7, annex 5	5/10/2012
AQUARIUS	Electrolysis	Yes	MEPC 65/2/1	MEPC 65/2/9, annex 5	17/05/2013
EcoGuardian	Electrolysis	Yes	MEPC 65/2/4	MEPC 65/2/19, annex 5	17/05/2013
OceanDoctor	UV		MEPC 65/2/6	MEPC 65/2/19, annex 7	17/05/2013
Evonik	Peracetic acid, hydrogen peroxide and acetic acid	Yes	MEPC 65/2/5	MEPC 66/2/10, annex 5	4/04/2014
SKY-SYSTEM	Peracetic acid, hydrogen peroxide and acetic acid	Yes	MEPC 66/2	MEPC 66/2/7, annex 4	4/04/2014
BlueZone	Ozonation	Yes	MEPC 67/2/1	MEPC 67/2/4, annex 5	17/10/2014
Kurita	Sodium Hypochlorite Solution	Yes	MEPC 67/2/2	MEPC 67/2/4, annex 6	17/10/2014
Marinomate	Electrolysis	Yes	MEPC 67/2	MEPC 67/2/4, annex 4	17/10/2014
Ecomarine-EC	Electrolysis	Yes	MEPC 68/2/5	MEPC 68/2/21, annex 5	15/05/2015
ATPS-BLUE	Electrolysis	Yes	MEPC 69/4/2	MEPC 69/4/5, annex 6	22/04/2016
ECS-HYCHLOR	Electrolysis	Yes	MEPC 69/4	MEPC 69/4/5, annex 4	22/04/2016
NK-Cl BlueBallast	Sodium Dichloroisocyanurate	Yes	MEPC 69/4/1	MEPC 69/4/5, annex 5	22/04/2016
ECS-HYCHEM	Sodium Dichloroisocyanurate	Yes	MEPC 70/4/1	MEPC 70/4/6, annex 5	28/10/2016

Appendix E: Port Hedland MAMPEC Results

Table 49: Port Hedland Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/ PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/ PNEC
Bromochloromethane	0.046	67.000	0.001	0.000	0.001	0.000	0.000	0.000
Dibromochloromethane	13.951	6.300	0.248	0.039	0.151	0.024	0.019	0.003
Dibromomethane	0.124	450.000	0.002	0.000	0.001	0.000	0.000	0.000
Dichlorobromomethane	0.875	78.000	0.015	0.000	0.009	0.000	0.001	0.000
Dichloromethane	0.156	124.000	0.003	0.000	0.002	0.000	0.000	0.000
Tribromomethane	255.717	96.000	4.998	0.052	3.102	0.032	0.399	0.004
Trichloromethane	1.576	146.300	0.023	0.000	0.013	0.000	0.002	0.000
Bromochloroacetic acid	7.850	16.000	0.166	0.010	0.105	0.007	0.014	0.001
Dibromoacetic acid	39.587	6.900	0.813	0.118	0.510	0.074	0.066	0.010
Dibromochloroacetic acid	5.961	60.000	0.126	0.002	0.079	0.001	0.010	0.000
Dichloroacetic acid	4.391	2.300	0.090	0.039	0.057	0.025	0.007	0.003
Dichlorobromoacetic acid	2.998	60.000	0.063	0.001	0.040	0.001	0.005	0.000
Monobromoacetic acid	7.600	16.000	0.156	0.010	0.098	0.006	0.013	0.001
Monochloroacetic acid	10.796	0.580	0.220	0.380	0.138	0.238	0.018	0.031
Tribromoacetic acid	33.034	60.000	0.681	0.011	0.427	0.007	0.056	0.001
Trichloroacetic acid	20.483	60.000	0.425	0.007	0.267	0.004	0.035	0.001
Bromochloroacetonitrile	0.205	0.690	0.004	0.006	0.003	0.004	0.000	0.001
Dibromoacetonitrile	34.012	0.055	0.535	**9.729**	0.316	**5.754**	0.039	0.701
Dichloroacetonitrile	0.131	24.350	0.003	0.000	0.002	0.000	0.000	0.000
Monobromoacetonitrile	0.016	23.000	0.000	0.000	0.000	0.000	0.000	0.000
Monochloroacetonitrile	0.004	0.160	0.000	0.001	0.000	0.000	0.000	0.000
Trichloroacetonitrile	0.048	6.000	0.001	0.000	0.001	0.000	0.000	0.000
1,2,3-trichloropropane	0.212	0.400	0.004	0.010	0.003	0.006	0.000	0.001
1,2-dichloroethane	0.014	220.000	0.000	0.000	0.000	0.000	0.000	0.000
2,4,6-tribromophenol	0.024	2.000	0.000	0.000	0.000	0.000	0.000	0.000
2,4-dibromophenol	0.001	0.001	0.000	0.018	0.000	0.011	0.000	0.001
2,6-dibromophenol	0.001	0.001	0.000	0.018	0.000	0.011	0.000	0.001
Chloral hydrate	0.001	96.600	0.000	0.000	0.000	0.000	0.000	0.000
Dalapon	0.101	11.000	0.002	0.000	0.001	0.000	0.000	0.000
Bromate	11.938	136.000	0.252	0.002	0.159	0.001	0.021	0.000

Chloropicrin	0.005	0.025	0.000	0.004	0.000	0.003	0.000	0.000
Sodium bisulfite	43.103	59.000	0.911	0.015	0.574	0.010	0.075	0.001
Sodium thiosulfate	3188.086	805.000	64.287	0.080	40.149	0.050	5.196	0.006
Isocyanuric acid	1172.414	320.000	23.643	0.074	14.766	0.046	1.911	0.006
Hydrogen peroxide	0.414	10.000	0.004	0.000	0.002	0.000	0.000	0.000
TRO (Br2)	89.382	28.000	0.133	0.005	0.025	0.001	0.000	0.000
TRO (Cl2)	81.207	0.900	0.118	0.131	0.022	0.024	0.000	0.000

Table 50: Port Hedland Worst Case Scenario MAMPEC Results.

Compound	Effective Discharge Conc. (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/ PNEC	PEC (µ/L)	PEC/ PNEC	PEC (µ/L)	PEC/ PNEC
Bromochloromethane	5.320	67.000	0.110	0.002	0.069	0.001	0.009	0.000
Dibromochloromethane	58.100	6.300	1.034	0.164	0.629	0.100	0.079	0.013
Dibromomethane	72.200	450.000	1.337	0.003	0.821	0.002	0.104	0.000
Dichlorobromomethane	95.000	78.000	1.658	0.021	1.005	0.013	0.126	0.002
Dichloromethane	13.400	124.000	0.243	0.002	0.149	0.001	0.019	0.000
Tetrachloromethane	0.790	9.800	0.015	0.002	0.009	0.001	0.001	0.000
Tribromomethane	890.000	96.000	17.395	0.181	10.797	0.112	1.388	0.014
Trichloromethane	236.200	146.300	3.397	0.023	1.963	0.013	0.233	0.002
Bromochloroacetic acid	40.500	16.000	0.856	0.053	0.539	0.034	0.070	0.004
Dibromoacetic acid	270.960	6.900	5.567	0.807	3.489	0.506	0.453	0.066
Dibromochloroacetic acid	32.700	60.000	0.691	0.012	0.435	0.007	0.057	0.001
Dichloroacetic acid	51.100	2.300	1.053	0.458	0.660	0.287	0.086	0.037
Dichlorobromoacetic acid	239.000	60.000	5.050	0.084	3.182	0.053	0.416	0.007
Monobromoacetic acid	204.000	16.000	4.191	0.262	2.627	0.164	0.341	0.021
Monochloroacetic acid	517.000	0.580	10.545	**18.182**	6.600	**11.380**	0.856	**1.476**
Tribromoacetic acid	970.000	60.000	19.999	0.333	12.544	0.209	1.631	0.027
Trichloroacetic acid	150.000	60.000	3.110	0.052	1.953	0.033	0.254	0.004
Bromochloroacetonitrile	25.200	0.690	0.522	0.757	0.328	0.475	0.043	0.062
Dibromoacetonitrile	674.000	0.055	10.604	**192.801**	6.271	**114.015**	0.764	**13.882**
Dichloroacetonitrile	12.080	24.350	0.254	0.010	0.160	0.007	0.021	0.001
Monobromoacetonitrile	23.500	23.000	0.496	0.022	0.312	0.014	0.041	0.002
Monochloroacetonitrile	0.420	0.160	0.009	0.055	0.006	0.035	0.001	0.005
Tribromoacetonitrile	1.000	69.000	0.021	0.000	0.013	0.000	0.002	0.000
Trichloroacetonitrile	1.530	6.000	0.029	0.005	0.018	0.003	0.002	0.000
1,1-dichloroethene	0.020	1.000	0.000	0.000	0.000	0.000	0.000	0.000
1,2,3-trichlorobenzene	9.620	3.000	0.181	0.060	0.112	0.037	0.014	0.005

1,2,3-trichloropropane	4.100	0.400	0.081	0.202	0.050	0.125	0.006	0.016
1,2,4-trichlorobenzene	13.400	20.000	0.252	0.013	0.155	0.008	0.020	0.001
1,2-dichloroethane	0.360	220.000	0.007	0.000	0.004	0.000	0.001	0.000
1,2-dichloropropane	1.800	410.000	0.033	0.000	0.020	0.000	0.003	0.000
2,4,6-tribromophenol	1.320	2.000	0.027	0.014	0.017	0.009	0.002	0.001
2,4-dibromophenol	0.020	0.001	0.000	0.346	0.000	0.218	0.000	0.028
2,6-dibromophenol	0.020	0.001	0.000	0.349	0.000	0.219	0.000	0.029
4-chlorotoluene	0.120	0.190	0.002	0.012	0.001	0.007	0.000	0.001
Bromobenzene	0.320	5.800	0.007	0.001	0.004	0.001	0.001	0.000
Chloral hydrate	17.840	96.600	0.377	0.004	0.238	0.002	0.031	0.000
Chlorobenzene	0.330	12.500	0.007	0.001	0.004	0.000	0.001	0.000
Cis-1,2-dichloroethene	0.200	90.000	0.004	0.000	0.002	0.000	0.000	0.000
Dalapon	105.000	11.000	2.218	0.202	1.398	0.127	0.183	0.017
Trans-1,2-dichloroethene	1.950	2200.000	0.040	0.000	0.025	0.000	0.003	0.000
Ammonium	25.000	964.000	0.528	0.001	0.333	0.000	0.043	0.000
Bromate	920.000	136.000	19.437	0.143	12.247	0.090	1.600	0.012
Chlorate	2800.000	11.080	3.476	0.314	0.601	0.054	0.000	0.000
Chlorite	3600.000	0.580	0.650	**1.121**	0.072	0.124	0.000	0.000
Chloropicrin	18.300	0.025	0.358	**14.326**	0.222	**8.894**	0.029	**1.144**
Nitrate	6030.000	700.000	127.407	0.182	80.279	0.115	10.489	0.015
Nitrite	114.000	6.000	0.170	0.028	0.032	0.005	0.000	0.000
Perchlorate	4.630	100.000	0.098	0.001	0.062	0.001	0.008	0.000
Sodium bisulfite	5800.000	59.000	122.548	**2.077**	77.217	**1.309**	10.089	0.171
Sodium thiosulfate	28000.000	805.000	564.610	0.701	352.614	0.438	45.638	0.057
Acetaldehyde	50.000	2.200	0.899	0.408	0.548	0.249	0.069	0.031
Formaldehyde	46.000	5.800	0.972	0.168	0.612	0.106	0.080	0.014
Isocyanuric acid	13500.000	320.000	272.239	0.851	170.023	0.531	22.006	0.069
Chlorine dioxide	200.000	99.300	0.099	0.001	0.013	0.000	0.000	0.000
Hydrogen peroxide	1300.000	10.000	13.984	**1.398**	7.388	0.739	0.780	0.078
Peracetic acid	300.000	0.220	0.705	**3.205**	0.167	0.759	0.002	0.008
TRO (Br2)	450.798	28.000	0.671	0.024	0.126	0.004	0.000	0.000
TRO (Cl2)	200.000	0.900	0.290	0.322	0.054	0.060	0.000	0.000

Table 51: MAMPEC modelled chemical fate of compounds in the harbour for Port Hedland.

Compound	Hydrolysis (%)	Sedimentation (%)	Volatilisation (%)
Bromochloromethane	2.56	0.00	0.00
Dibromochloromethane	11.38	0.00	10.20
Dibromomethane	5.65	0.00	11.23

Dichlorobromomethane	11.11	0.00	12.66
Dichloromethane	0.15	0.00	19.19
Tetrachloromethane	0.29	0.00	15.79
Tribromomethane	1.51	0.00	8.78
Trichloromethane	30.99	0.00	12.22
Bromochloroacetic acid	0.00	0.00	0.00
Dibromoacetic acid	3.80	0.00	0.00
Dibromochloroacetic acid	0.00	0.00	0.04
Dichloroacetic acid	3.44	0.00	0.00
Dichlorobromoacetic acid	0.00	0.00	0.00
Monobromoacetic acid	3.80	0.00	0.00
Monochloroacetic acid	4.76	0.00	0.00
Tribromoacetic acid	3.33	0.00	0.00
Trichloroacetic acid	2.56	0.00	0.00
Bromochloroacetonitrile	2.59	0.00	0.08
Dibromoacetonitrile	34.70	0.00	0.02
Dichloroacetonitrile	0.33	0.00	0.31
Monobromoacetonitrile	0.00	0.00	0.27
Monochloroacetonitrile	0.00	0.00	1.03
Tribromoacetonitrile	2.59	0.00	0.00
Trichloroacetonitrile	0.00	0.00	14.01
1,1-dichloroethene	0.00	0.00	19.32
1,2,3-trichlorobenzene	1.44	0.01	13.52
1,2,3-trichloropropane	0.00	0.00	9.44
1,2,4-trichlorobenzene	1.44	0.01	13.52
1,2-dichloroethane	0.00	0.00	16.72
1,2-dichloropropane	0.00	0.00	16.87
2,4,6-tribromophenol	3.44	0.01	0.00
2,4-dibromophenol	0.66	0.00	1.63
2,6-dibromophenol	0.67	0.01	0.61
4-chlorotoluene	0.58	0.00	16.30
Bromobenzene	0.00	0.00	0.00
Chloral hydrate	0.00	0.00	0.00
Chlorobenzene	0.00	0.00	0.00
Cis-1,2-dichloroethene	0.00	0.00	19.28
Dalapon	0.00	0.00	0.00
Trans-1,2-dichloroethene	2.59	0.00	0.00
Ammonium	0.00	0.00	0.00
Bromate	0.00	0.00	0.01
Chlorate	99.99	0.00	0.00

Chlorite	100.00	0.00	0.00
Chloropicrin	0.00	0.00	10.12
Nitrate	0.00	0.00	0.00
Nitrite	99.97	0.00	0.00
Perchlorate	0.00	0.00	0.00
Sodium bisulfite	0.00	0.00	0.00
Sodium thiosulfate	6.26	0.00	0.01
Acetaldehyde	20.44	0.00	0.01
Formaldehyde	0.00	0.00	0.05
Isocyanuric acid	6.26	0.00	0.00
Chlorine dioxide	100.00	0.00	0.00
Hydrogen peroxide	65.22	0.00	0.01
Peracetic acid	99.61	0.00	0.01
TRO (Br2)	99.97	0.00	0.00
TRO (Cl2)	99.97	0.00	0.00

Appendix F: Geelong (Corio Quay) MAMPEC Results

Table 52: Geelong (Corio Quay) Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/ PNEC	PEC (µ/L)	PEC/ PNEC	PEC (µ/L)	PEC/ PNEC
Dibromochloromethane	4.448	6.300	0.273	0.043	0.141	0.022	0.005	0.001
Dibromomethane	0.137	450.000	0.009	0.000	0.005	0.000	0.000	0.000
Dichlorobromomethane	0.135	78.000	0.008	0.000	0.004	0.000	0.000	0.000
Tribromomethane	179.842	96.000	12.616	0.131	6.719	0.070	0.258	0.003
Trichloromethane	0.048	146.300	0.002	0.000	0.001	0.000	0.000	0.000
Bromochloroacetic acid	3.379	16.000	0.297	0.019	0.166	0.010	0.007	0.000
Dibromoacetic acid	55.651	6.900	4.704	0.682	2.611	0.378	0.106	0.015
Dibromochloroacetic acid	1.333	60.000	0.117	0.002	0.065	0.001	0.003	0.000
Dichloroacetic acid	0.272	2.300	0.023	0.010	0.013	0.006	0.001	0.000
Dichlorobromoacetic acid	0.012	60.000	0.001	0.000	0.001	0.000	0.000	0.000
Monobromoacetic acid	5.050	16.000	0.427	0.027	0.237	0.015	0.010	0.001
Monochloroacetic acid	1.570	0.580	0.131	0.227	0.073	0.126	0.003	0.005
Tribromoacetic acid	55.175	60.000	4.687	0.078	2.605	0.043	0.106	0.002
Trichloroacetic acid	5.829	60.000	0.499	0.008	0.278	0.005	0.011	0.000
Dibromoacetonitrile	7.093	0.055	0.425	**7.722**	0.217	**3.946**	0.008	0.143
Monobromoacetonitrile	0.057	23.000	0.005	0.000	0.003	0.000	0.000	0.000
2,4,6-tribromophenol	0.082	2.000	0.007	0.003	0.004	0.002	0.000	0.000
2,4-dibromophenol	0.004	0.001	0.000	0.266	0.000	0.147	0.000	0.006
2,6-dibromophenol	0.004	0.001	0.000	0.273	0.000	0.152	0.000	0.006
Bromate	8.726	136.000	0.767	0.006	0.429	0.003	0.018	0.000
Sodium thiosulfate	814.857	805.000	67.154	0.083	37.084	0.046	1.496	0.002
Hydrogen peroxide	2.286	10.000	0.088	0.009	0.039	0.004	0.001	0.000
TRO (Br2)	42.933	28.000	0.200	0.007	0.031	0.001	0.000	0.000
TRO (Cl2)	22.857	0.900	0.103	0.115	0.016	0.018	0.000	0.000

Appendix G: Port of Melbourne (Webb Dock) MAMPEC Results

Table 53: Port of Melbourne (Webb Dock) Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Bromochloromethane	0.349	67.000	0.072	0.001	0.041	0.001	0.005	0.000
Dibromochloromethane	3.236	6.300	0.325	0.052	0.149	0.024	0.012	0.002
Dibromomethane	0.602	450.000	0.064	0.000	0.030	0.000	0.003	0.000
Dichlorobromomethane	0.673	78.000	0.062	0.001	0.028	0.000	0.002	0.000
Dichloromethane	0.879	124.000	0.078	0.001	0.034	0.000	0.002	0.000
Tribromomethane	100.348	96.000	12.733	0.133	6.363	0.066	0.600	0.006
Trichloromethane	0.670	146.300	0.046	0.000	0.018	0.000	0.001	0.000
Bromochloroacetic acid	2.589	16.000	0.579	0.036	0.336	0.021	0.040	0.002
Dibromoacetic acid	19.039	6.900	3.817	0.553	2.161	0.313	0.248	0.036
Dibromochloroacetic acid	0.929	60.000	0.207	0.003	0.120	0.002	0.014	0.000
Dichloroacetic acid	0.263	2.300	0.053	0.023	0.030	0.013	0.003	0.002
Dichlorobromoacetic acid	0.608	60.000	0.136	0.002	0.079	0.001	0.009	0.000
Monobromoacetic acid	2.268	16.000	0.455	0.028	0.257	0.016	0.030	0.002
Monochloroacetic acid	11.165	0.580	2.179	**3.756**	1.226	**2.114**	0.139	0.240
Tribromoacetic acid	16.803	60.000	3.413	0.057	1.938	0.032	0.223	0.004
Trichloroacetic acid	5.339	60.000	1.108	0.018	0.632	0.011	0.073	0.001
Bromochloroacetonitrile	0.276	0.690	0.057	0.082	0.032	0.047	0.004	0.005
Dibromoacetonitrile	2.974	0.055	0.296	**5.373**	0.135	**2.454**	0.011	0.196
Dichloroacetonitrile	0.018	24.350	0.004	0.000	0.002	0.000	0.000	0.000
Monobromoacetonitrile	0.020	23.000	0.004	0.000	0.002	0.000	0.000	0.000
Monochloroacetonitrile	0.000	0.160	0.000	0.001	0.000	0.000	0.000	0.000
Trichloroacetonitrile	0.104	6.000	0.011	0.002	0.005	0.001	0.000	0.000
1,2-dichloroethane	0.024	220.000	0.002	0.000	0.001	0.000	0.000	0.000
2,4,6-tribromophenol	0.022	2.000	0.004	0.002	0.003	0.001	0.000	0.000
2,4-dibromophenol	0.001	0.001	0.000	0.158	0.000	0.089	0.000	0.010
2,6-dibromophenol	0.001	0.001	0.000	0.171	0.000	0.098	0.000	0.011
Chloral hydrate	0.011	96.600	0.002	0.000	0.001	0.000	0.000	0.000
Dalapon	0.077	11.000	0.017	0.002	0.010	0.001	0.001	0.000
Bromate	6.853	136.000	1.532	0.011	0.888	0.007	0.105	0.001
Chloropicrin	0.010	0.025	0.001	0.048	0.001	0.024	0.000	0.002

Sodium thiosulfate	441.459	805.000	82.708	0.103	46.117	0.057	5.175	0.006
Isocyanuric acid	139.344	320.000	26.119	0.082	14.565	0.046	1.635	0.005
Hydrogen peroxide	3.934	10.000	0.215	0.022	0.073	0.007	0.003	0.000
TRO (Br2)	29.561	28.000	0.151	0.005	0.019	0.001	0.000	0.000
TRO (Cl2)	19.016	0.900	0.094	0.104	0.012	0.013	0.000	0.000

Appendix H: Port of Melbourne (Swanson Dock) MAMPEC Results

Table 54: Port of Melbourne (Swanson Dock) Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Bromochloromethane	0.349	67.000	0.115	0.002	0.064	0.001	0.006	0.000
Dibromochloromethane	3.236	6.300	0.505	0.080	0.225	0.036	0.014	0.002
Dibromomethane	0.602	450.000	0.102	0.000	0.047	0.000	0.003	0.000
Dichlorobromomethane	0.673	78.000	0.097	0.001	0.042	0.001	0.002	0.000
Dichloromethane	0.879	124.000	0.128	0.001	0.055	0.000	0.003	0.000
Tribromomethane	100.348	96.000	20.721	0.216	10.256	0.107	0.773	0.008
Trichloromethane	0.670	146.300	0.067	0.000	0.024	0.000	0.001	0.000
Bromochloroacetic acid	2.589	16.000	0.945	0.059	0.543	0.034	0.053	0.003
Dibromoacetic acid	19.039	6.900	5.964	0.864	3.317	0.481	0.309	0.045
Dibromochloroacetic acid	0.929	60.000	0.338	0.006	0.194	0.003	0.019	0.000
Dichloroacetic acid	0.263	2.300	0.083	0.036	0.047	0.020	0.004	0.002
Dichlorobromoacetic acid	0.608	60.000	0.222	0.004	0.127	0.002	0.013	0.000
Monobromoacetic acid	2.268	16.000	0.710	0.044	0.395	0.025	0.037	0.002
Monochloroacetic acid	11.165	0.580	3.373	**5.815**	1.860	**3.207**	0.171	0.294
Tribromoacetic acid	16.803	60.000	5.360	0.089	2.993	0.050	0.281	0.005
Trichloroacetic acid	5.339	60.000	1.753	0.029	0.986	0.016	0.093	0.002
Bromochloroacetonitrile	0.276	0.690	0.090	0.131	0.051	0.073	0.005	0.007
Dibromoacetonitrile	2.974	0.055	0.404	**7.338**	0.169	**3.076**	0.009	0.161
Dichloroacetonitrile	0.018	24.350	0.006	0.000	0.004	0.000	0.000	0.000
Monobromoacetonitrile	0.020	23.000	0.007	0.000	0.004	0.000	0.000	0.000
Monochloroacetonitrile	0.000	0.160	0.000	0.001	0.000	0.001	0.000	0.000
Trichloroacetonitrile	0.104	6.000	0.018	0.003	0.008	0.001	0.001	0.000
1,2-dichloroethane	0.024	220.000	0.004	0.000	0.002	0.000	0.000	0.000
2,4,6-tribromophenol	0.022	2.000	0.007	0.003	0.004	0.002	0.000	0.000
2,4-dibromophenol	0.001	0.001	0.000	0.257	0.000	0.143	0.000	0.013
2,6-dibromophenol	0.001	0.001	0.000	0.277	0.000	0.157	0.000	0.015
Chloral hydrate	0.011	96.600	0.004	0.000	0.002	0.000	0.000	0.000
Dalapon	0.077	11.000	0.028	0.003	0.016	0.001	0.002	0.000
Bromate	6.853	136.000	2.501	0.018	1.437	0.011	0.141	0.001
Chloropicrin	0.010	0.025	0.002	0.079	0.001	0.039	0.000	0.003

Sodium thiosulfate	441.459	805.000	126.458	0.157	68.838	0.086	6.178	0.008
Isocyanuric acid	139.344	320.000	39.916	0.125	21.728	0.068	1.950	0.006
Hydrogen peroxide	3.934	10.000	0.285	0.028	0.086	0.009	0.002	0.000
TRO (Br2)	29.561	28.000	0.180	0.006	0.021	0.001	0.000	0.000
TRO (Cl2)	19.016	0.900	0.112	0.125	0.013	0.015	0.000	0.000

Appendix I: Port of Melbourne (Appleton Dock) MAMPEC Results

Table 55: Port of Melbourne (Appleton Dock) Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Bromochloromethane	0.349	67.000	0.137	0.002	0.070	0.001	0.007	0.000
Dibromochloromethane	3.236	6.300	0.612	0.097	0.249	0.039	0.014	0.002
Dibromomethane	0.602	450.000	0.124	0.000	0.052	0.000	0.003	0.000
Dichlorobromomethane	0.673	78.000	0.118	0.002	0.046	0.001	0.002	0.000
Dichloromethane	0.879	124.000	0.155	0.001	0.061	0.000	0.003	0.000
Tribromomethane	100.348	96.000	25.027	0.261	11.252	0.117	0.840	0.009
Trichloromethane	0.670	146.300	0.082	0.001	0.027	0.000	0.001	0.000
Bromochloroacetic acid	2.589	16.000	1.123	0.070	0.583	0.036	0.059	0.004
Dibromoacetic acid	19.039	6.900	7.125	**1.033**	3.586	0.520	0.342	0.050
Dibromochloroacetic acid	0.929	60.000	0.402	0.007	0.208	0.003	0.021	0.000
Dichloroacetic acid	0.263	2.300	0.100	0.043	0.050	0.022	0.005	0.002
Dichlorobromoacetic acid	0.608	60.000	0.263	0.004	0.137	0.002	0.014	0.000
Monobromoacetic acid	2.268	16.000	0.849	0.053	0.427	0.027	0.041	0.003
Monochloroacetic acid	11.165	0.580	4.036	**6.958**	2.015	**3.473**	0.189	0.326
Tribromoacetic acid	16.803	60.000	6.398	0.107	3.233	0.054	0.311	0.005
Trichloroacetic acid	5.339	60.000	2.092	0.035	1.064	0.018	0.104	0.002
Bromochloroacetonitrile	0.276	0.690	0.107	0.156	0.055	0.079	0.005	0.008
Dibromoacetonitrile	2.974	0.055	0.491	**8.919**	0.188	**3.413**	0.009	0.169
Dichloroacetonitrile	0.018	24.350	0.007	0.000	0.004	0.000	0.000	0.000
Monobromoacetonitrile	0.020	23.000	0.008	0.000	0.004	0.000	0.000	0.000
Monochloroacetonitrile	0.000	0.160	0.000	0.001	0.000	0.001	0.000	0.000
Trichloroacetonitrile	0.104	6.000	0.022	0.004	0.009	0.002	0.001	0.000
1,2-dichloroethane	0.024	220.000	0.005	0.000	0.002	0.000	0.000	0.000
2,4,6-tribromophenol	0.022	2.000	0.008	0.004	0.004	0.002	0.000	0.000
2,4-dibromophenol	0.001	0.001	0.000	0.307	0.000	0.155	0.000	0.015
2,6-dibromophenol	0.001	0.001	0.000	0.330	0.000	0.169	0.000	0.017
Chloral hydrate	0.011	96.600	0.005	0.000	0.003	0.000	0.000	0.000
Dalapon	0.077	11.000	0.033	0.003	0.017	0.002	0.002	0.000
Bromate	6.853	136.000	2.970	0.022	1.543	0.011	0.157	0.001
Chloropicrin	0.010	0.025	0.002	0.096	0.001	0.043	0.000	0.003

Sodium thiosulfate	441.459	805.000	151.440	0.188	74.645	0.093	6.823	0.008
Isocyanuric acid	139.344	320.000	47.821	0.149	23.573	0.074	2.155	0.007
Hydrogen peroxide	3.934	10.000	0.348	0.035	0.096	0.010	0.001	0.000
TRO (Br2)	29.561	28.000	0.224	0.008	0.024	0.001	0.000	0.000
TRO (Cl2)	19.016	0.900	0.139	0.155	0.015	0.016	0.000	0.000

Appendix J: Port Philip Bay MAMPEC Results

Table 56: Port Phillip Bay Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (μ/L)	PNEC (μ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (μ/L)	PEC/PNEC	PEC (μ/L)	PEC/PNEC	PEC (μ/L)	PEC/PNEC
Bromochloromethane	0.260	67.000	0.001	0.000	0.000	0.000	0.000	0.000
Dibromochloromethane	3.546	6.300	0.001	0.000	0.000	0.000	0.000	0.000
Dibromomethane	0.483	450.000	0.000	0.000	0.000	0.000	0.000	0.000
Dichlorobromomethane	0.535	78.000	0.000	0.000	0.000	0.000	0.000	0.000
Dichloromethane	0.654	124.000	0.000	0.000	0.000	0.000	0.000	0.000
Tribromomethane	120.706	96.000	0.031	0.000	0.003	0.000	0.000	0.000
Trichloromethane	0.510	146.300	0.000	0.000	0.000	0.000	0.000	0.000
Bromochloroacetic acid	2.791	16.000	4.035	0.252	0.403	0.025	0.000	0.000
Dibromoacetic acid	28.415	6.900	0.043	0.006	0.004	0.001	0.000	0.000
Dibromochloroacetic acid	1.032	60.000	0.069	0.001	0.007	0.000	0.000	0.000
Dichloroacetic acid	0.265	2.300	0.000	0.000	0.000	0.000	0.000	0.000
Dichlorobromoacetic acid	0.455	60.000	1.988	0.033	0.199	0.003	0.000	0.000
Monobromoacetic acid	2.980	16.000	0.005	0.000	0.000	0.000	0.000	0.000
Monochloroacetic acid	8.707	0.580	0.011	0.018	0.001	0.002	0.000	0.000
Tribromoacetic acid	26.630	60.000	0.047	0.001	0.005	0.000	0.000	0.000
Trichloroacetic acid	5.465	60.000	0.013	0.000	0.001	0.000	0.000	0.000
Bromochloroacetonitrile	0.205	0.690	0.000	0.001	0.000	0.000	0.000	0.000
Dibromoacetonitrile	4.029	0.055	0.000	0.009	0.000	0.001	0.000	0.000
Dichloroacetonitrile	0.013	24.350	0.000	0.000	0.000	0.000	0.000	0.000
Monobromoacetonitrile	0.029	23.000	0.000	0.000	0.000	0.000	0.000	0.000
Monochloroacetonitrile	0.000	0.160	0.000	0.000	0.000	0.000	0.000	0.000
Trichloroacetonitrile	0.078	6.000	0.000	0.000	0.000	0.000	0.000	0.000
1,2-dichloroethane	0.018	220.000	0.000	0.000	0.000	0.000	0.000	0.000
2,4,6-tribromophenol	0.037	2.000	0.000	0.000	0.000	0.000	0.000	0.000
2,4-dibromophenol	0.002	0.001	0.000	0.002	0.000	0.000	0.000	0.000
2,6-dibromophenol	0.002	0.001	0.000	0.004	0.000	0.000	0.000	0.000
Chloral hydrate	0.008	96.600	0.689	0.007	0.069	0.001	0.000	0.000
Dalapon	0.057	11.000	0.027	0.002	0.003	0.000	0.000	0.000
Bromate	7.333	136.000	2.536	0.019	0.254	0.002	0.000	0.000
Chloropicrin	0.007	0.025	0.000	0.000	0.000	0.000	0.000	0.000

Sodium thiosulfate	537.085	805.000	0.486	0.001	0.049	0.000	0.000	0.000
Isocyanuric acid	103.659	320.000	0.094	0.000	0.009	0.000	0.000	0.000
Hydrogen peroxide	3.512	10.000	0.000	0.000	0.000	0.000	0.000	0.000
TRO (Br2)	32.985	28.000	0.000	0.000	0.000	0.000	0.000	0.000
TRO (Cl2)	20.000	0.900	0.000	0.000	0.000	0.000	0.000	0.000

Appendix K: Brisbane (River Mouth) MAMPEC Results

Table 57: Port of Brisbane (River Mouth) Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromochloromethane	4.591	6.300	0.068	0.011	0.042	0.007	0.014	0.002
Dibromomethane	0.045	450.000	0.001	0.000	0.000	0.000	0.000	0.000
Dichlorobromomethane	0.247	78.000	0.004	0.000	0.002	0.000	0.001	0.000
Tribromomethane	105.682	96.000	1.795	0.019	1.139	0.012	0.389	0.004
Trichloromethane	0.414	146.300	0.005	0.000	0.003	0.000	0.001	0.000
Bromochloroacetic acid	1.849	16.000	0.036	0.002	0.024	0.001	0.008	0.001
Dibromoacetic acid	34.510	6.900	0.647	0.094	0.419	0.061	0.147	0.021
Dibromochloroacetic acid	1.614	60.000	0.031	0.001	0.021	0.000	0.007	0.000
Dichloroacetic acid	0.801	2.300	0.015	0.007	0.010	0.004	0.003	0.001
Dichlorobromoacetic acid	0.634	60.000	0.012	0.000	0.008	0.000	0.003	0.000
Monobromoacetic acid	2.867	16.000	0.054	0.003	0.035	0.002	0.012	0.001
Monochloroacetic acid	1.177	0.580	0.022	0.038	0.014	0.024	0.005	0.009
Tribromoacetic acid	21.532	60.000	0.406	0.007	0.263	0.004	0.093	0.002
Trichloroacetic acid	2.956	60.000	0.056	0.001	0.036	0.001	0.013	0.000
Bromochloroacetonitrile	0.038	0.690	0.001	0.001	0.000	0.001	0.000	0.000
Dibromoacetonitrile	6.791	0.055	0.089	**1.615**	0.053	0.960	0.016	0.298
Dichloroacetonitrile	0.017	24.350	0.000	0.000	0.000	0.000	0.000	0.000
Monobromoacetonitrile	0.180	23.000	0.003	0.000	0.002	0.000	0.001	0.000
Monochloroacetonitrile	0.001	0.160	0.000	0.000	0.000	0.000	0.000	0.000
Trichloroacetonitrile	0.008	6.000	0.000	0.000	0.000	0.000	0.000	0.000
2,4,6-tribromophenol	0.031	2.000	0.001	0.000	0.000	0.000	0.000	0.000
2,4-dibromophenol	0.001	0.001	0.000	0.019	0.000	0.012	0.000	0.004
2,6-dibromophenol	0.001	0.001	0.000	0.019	0.000	0.013	0.000	0.004
Bromate	8.564	136.000	0.167	0.001	0.109	0.001	0.039	0.000
Sodium thiosulfate	442.707	805.000	8.076	0.010	5.201	0.006	1.814	0.002
Isocyanuric acid	257.576	320.000	4.699	0.015	3.026	0.009	1.056	0.003
Hydrogen peroxide	1.939	10.000	0.016	0.002	0.008	0.001	0.002	0.000
TRO (Br2)	4.554	28.000	0.005	0.000	0.001	0.000	0.000	0.000
TRO (Cl2)	42.626	0.900	0.045	0.050	0.008	0.008	0.000	0.000

Appendix L: Brisbane (Whole Port) MAMPEC Results

Table 58: Port of Brisbane (Whole Port) Likely Scenario MAMPEC Results.

Compound	Effective Discharge Concentration (µ/L)	PNEC (µ/L)	Harbour (maximum)		Harbour (average)		Surroundings (maximum)	
			PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC	PEC (µ/L)	PEC/PNEC
Dibromochloromethane	4.591	6.300	0.035	0.006	0.023	0.004	0.011	0.002
Dibromomethane	0.045	450.000	0.000	0.000	0.000	0.000	0.000	0.000
Dichlorobromomethane	0.247	78.000	0.002	0.000	0.001	0.000	0.001	0.000
Tribromomethane	105.682	96.000	1.001	0.010	0.681	0.007	0.348	0.004
Trichloromethane	0.414	146.300	0.002	0.000	0.001	0.000	0.000	0.000
Bromochloroacetic acid	1.849	16.000	0.023	0.001	0.016	0.001	0.009	0.001
Dibromoacetic acid	34.510	6.900	0.393	0.057	0.278	0.040	0.149	0.022
Dibromochloroacetic acid	1.614	60.000	0.020	0.000	0.014	0.000	0.008	0.000
Dichloroacetic acid	0.801	2.300	0.009	0.004	0.007	0.003	0.004	0.002
Dichlorobromoacetic acid	0.634	60.000	0.008	0.000	0.006	0.000	0.003	0.000
Monobromoacetic acid	2.867	16.000	0.033	0.002	0.023	0.001	0.012	0.001
Monochloroacetic acid	1.177	0.580	0.013	0.023	0.009	0.016	0.005	0.009
Tribromoacetic acid	21.532	60.000	0.248	0.004	0.176	0.003	0.095	0.002
Trichloroacetic acid	2.956	60.000	0.035	0.001	0.025	0.000	0.013	0.000
Bromochloroacetonitrile	0.038	0.690	0.000	0.001	0.000	0.000	0.000	0.000
Dibromoacetonitrile	6.791	0.055	0.043	0.778	0.026	0.473	0.011	0.206
Dichloroacetonitrile	0.017	24.350	0.000	0.000	0.000	0.000	0.000	0.000
Monobromoacetonitrile	0.180	23.000	0.002	0.000	0.002	0.000	0.001	0.000
Monochloroacetonitrile	0.001	0.160	0.000	0.000	0.000	0.000	0.000	0.000
Trichloroacetonitrile	0.008	6.000	0.000	0.000	0.000	0.000	0.000	0.000
2,4,6-tribromophenol	0.031	2.000	0.000	0.000	0.000	0.000	0.000	0.000
2,4-dibromophenol	0.001	0.001	0.000	0.012	0.000	0.008	0.000	0.005
2,6-dibromophenol	0.001	0.001	0.000	0.012	0.000	0.009	0.000	0.005
Bromate	8.564	136.000	0.106	0.001	0.076	0.001	0.042	0.000
Sodium thiosulfate	442.707	805.000	4.781	0.006	3.346	0.004	1.774	0.002
Isocyanuric acid	257.576	320.000	2.782	0.009	1.947	0.006	1.032	0.003
Hydrogen peroxide	1.939	10.000	0.007	0.001	0.003	0.000	0.001	0.000
TRO (Br2)	4.554	28.000	0.002	0.000	0.000	0.000	0.000	0.000
TRO (Cl2)	42.626	0.900	0.018	0.020	0.003	0.003	0.000	0.000