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AIR POLLUTION PREVENTION

Evaluation and harmonization of rules and guidance on the discharge of liquid effluents from EGCS into waters, including conditions and areas

Submitted by Greece

SUMMARY	
Executive summary:	This document summarizes the key findings of the bulk of a bigger study on options to meet 2020 fuel sulphur regulations. This study was carried out by a team of researchers affiliated with the Massachusetts Institute of Technology (MIT), the United States. The bulk of the study (Part B-Sections 1 and 2) was devoted to assessing the environmental impact of Exhaust Gas Cleaning Systems (EGCS), also known as scrubbers, effluent discharges by modelling pollutant dispersion. The key findings are summarized in paragraphs 7 and 8 of this document. The relevant Part of the study is included in the annex to this document.
Strategic direction, if applicable:	1
Output:	1.12
Action to be taken:	Paragraph 9
Related documents:	MEPC 74/14/1, MEPC 74/14/7, MEPC 74/14/8, MEPC 74/14/9, MEPC 74/INF.10, MEPC 74/INF.24, MEPC 74/INF.27 and PPR 7/12

Introduction and background

1 MEPC approved, in principle, at its seventy-fourth session, a new output on "Evaluation and harmonization of rules and guidance on the discharge of liquid effluents from EGCS into waters, including conditions and areas" in the 2020-2021 biennial agenda of the Pollution Prevention and Response (PPR) Sub-Committee, and the provisional agenda for PPR 7, with a target completion year of 2021, and referred documents MEPC 74/14/1, MEPC 74/14/7, MEPC 74/14/8, MEPC 74/14/9, MEPC 74/INF.10, MEPC 74/INF.24 and MEPC 74/INF.27 to PPR 7 for further consideration, with a view to refining the title and the scope of the output (MEPC 74/18, paragraph 14.11).

2 The Committee further identified the need for more scientific research and instructed the Secretariat to liaise with GESAMP and to establish a task team of experts to assess the available evidence relating to the environmental impacts of discharges of EGCS effluent, with a view to reporting its findings to PPR 7 (MEPC 74/18, paragraph 14.14).

3 The assessment being undertaken by the GESAMP task team should cover the analyses and results from available research projects, such as the scrubber environmental impact literature review (MEPC 74/INF.10) submitted by Panama, earlier submitted studies to the PPR Sub-Committee (PPR 6/INF.20) and the results of available simulations for predicting the environmental concentrations of target substances.

4 This document summarizes the key findings of the bulk of a bigger study on options to meet 2020 fuel sulphur regulations that was carried out by a team of researchers affiliated with the Massachusetts Institute of Technology (MIT), the United States. The bulk of the study (Part B-Sections 1 and 2) was devoted to assessing the environmental impact of Exhaust Gas Cleaning Systems-Scrubbers (EGCS) effluent discharges by modelling pollutant dispersion.

5 The submitting delegation views the above-mentioned research and literature review assessment as being very pertinent to the ongoing work of the PPR Sub-Committee to enable it to draw objective conclusions from different studies. The final report of PPR 7 is relevant.

6 The above-mentioned study aims to provide technical data that can be used in the context of potential further developments, based on sound technical evidence.

Key findings of the study

7 Two potential environmental issues related to open-loop EGCS as an alternative to low sulphur marine fuels in order to meet the 2020 IMO mandate were examined. The first issue is whether discharged effluent can cause adverse health effects on marine life (water emissions). The relevant Part B-Sections 1 and 2 of the study, focusing on the environmental impact of EGCS effluent discharges, is included in the annex to this document.

8 Despite the currently limited available toxicological data on the marine impacts of EGCS effluent, the attached study uses a predicted no-effect concentration (PNEC) limit of 1/5000 for all effluent dilutions. Using this presumed safe concentration reference and the results of near-field dispersion calculations for different locations, it is a plausible hypothesis that there is no likely risk of acute toxicity effects from short-term exposure in target organisms. However, for higher traffic zones, bays and ports, the study points to the likelihood that the presumed safe concentration threshold may be exceeded.

Action requested of the Committee

9 The Committee is invited to take note of the information provided in the annexed study.

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Environmental Impact Assessment of EGCS effluent discharges

Submitted by Dr. Emmanuel Kasseris, Dr. Dayang Wang, Yiqi Zhang, Dr. Eric Adams and Professor John Heywood

Massachusetts Institute of Technology, January, 2020

Executive Summary

This study is a part of a bigger study on options to meet 2020 fuel sulfur regulations. The bulk of the study (Part B-Sections 1 and 2) was devoted to assessing the environmental impact of Exhaust Gas Cleaning Systems-Scrubbers (EGCS) effluent discharges by modeling pollutant dispersion. The key findings can be summarized as follows:

Despite the currently limited available toxicological data on the marine impacts of EGCS effluent, the attached study uses a predicted no effect concentration (PNEC) limit of 1/5000 for all effluent dilution. Using this presumed safe concentration reference and the results of near-field dispersion calculations for different locations; it is a plausible hypothesis that there is no likely risk of acute toxicity effects from short-term exposure in target organisms. However, for higher traffic zones, bays and ports, the study points to the likelihood that the presumed safe concentration threshold may be exceeded.

More detail on the findings on the environmental impact of Exhaust Gas Cleaning Systems-Scrubbers (EGCS) effluent discharges is provided below:

<u>EGCS Effluent discharge:</u>

This study was carried out to address the environmental impact assessment of open-loop EGCS discharge washwater concerning both the near - and far-field, and in so doing help determines the viability of EGCS as a method of reducing atmospheric sulfur admissions. In this context, near field analysis refers to the immediate ship wake accounting for the fact that multiple ships may follow closely behind, while far field refers to cumulative background pollutant accumulation in geographically enclosed locations such as enclosed bays and ports that experience high shipping traffic (Figure 1). Two models have been developed – one to simulate the near-field and one for the far-field. These models were applied to multiple locations internationally. In both cases, the simulated concentrations are compared with toxicological limits, often expressed as dilution rates (original pollutant concentrations over final), found in the literature to assess the impacts of using EGCS on the marine environment. The few available studies on the effects of scrubber effluent on marine life (Koski et al, MEPC 74/INF .24, IVL) suggest that there are synergistic effects between the different pollutants in scrubber effluent (heavy metals, polyaromatic hydrocarbons, pH). Thus, there are significant effects on marine life at levels below what individual pollutant concentrations would suggest. Scrubber effluent should therefore be treated as a pollutant itself instead of looking at individual pollutant concentrations. The first two studies established a concentration limit of about 20% effluent concentration in terms of mortality (LC50). This limit was based on relatively short-term exposure (24 hours for Koski, 96h for MEPC74/INF24). The third study [IVL] performed longer exposure experiments and could not establish a minimum below which no mortality effects on marine life were observed. The lowest effluent concentrations tested (that still caused health effects) were 1% for open loop scrubbers and 0.04% for closed loop. More research is clearly needed in this area but we decided to follow the practice of MEPC 74/INF24 and use a safety factor of one thousand. The resulting acceptable predicted no-effect concentration (PNEC) for scrubber effluent in sea water is thus one over five thousand (1/5000). This PNEC is computed as 1/5 (the scrubber effluent concentration at which the mortality rate becomes 50% in the three tested marine organisms) x 1/1000 (an assumed factor to extrapolate to long-term effects on all organisms). The longest exposure time used in the study is 96 hours, and to determine the level of harm based on such a time scale may be

conservative for mobile organisms (e.g., pelagic fish) which live in the water column and pass quickly through the wash water plume; conversely such an assessment may be non-conservative for demersal fish or infauna. Therefore, further research may well be required to more suitably determine whether a ‘safe concentration’ threshold exists.

The near-field model computes the 3D, steady-state concentration distribution resulting from the EGCS wash water discharged by a fleet of ships in busy open waters such as straits and canals. The model is constructed to consider the shipping channel geometry and diffusion properties, ship traffic density and ship categories (effluent discharge rates) through these channels, as well as the lateral spread of discharge sources (ships using scrubbers). The lateral spread of discharging vessels further depends on the combined effect of two factors. First, the ship crossing pattern/navigation rules in the busy waterway; for example, a ‘line astern’ arrangement would mean no lateral spread of the effluent source and hence least dilution. Secondly, any external factors, such as ambient currents at an angle to the line of travelling vessels, or secondary currents in a curved channel, would introduce lateral spread of the effluent, thus promoting dilution.

Five study sites, namely Tokyo Bay, the Strait of Malacca, the Persian Gulf, the Strait of Gibraltar and the Panama Canal, have been chosen for the near-field investigation based on their high traffic activities and the ease of comparison with predicted concentrations found in the literature. A site of particular interest is Tokyo Bay, where we have been able to obtain a similar value for dilution for Tokyo Bay as reported in the aforementioned study submitted by Japan (no. MEPC 74/INF .24) when using their parameter values. Extending the scope of the MEPC 74/INF .24 study, which assumed a tight “line astern” ship arrangement, our study, as explained, takes possible lateral spread of polluting vessels into consideration. Using parameter values best representing the conditions observed at the five sites mentioned, the model shows that the near-field washwater concentration is generally below the inferred, somewhat arbitrary dilution threshold of 5000 used. We thus conclude that EGCS discharge is unlikely to cause ecological concern from a near field perspective (in the immediate wake of vessels). However, sensitivity analysis suggests that under particular circumstances, such as a tight ‘line astern’ arrangement of ships, washwater concentrations may go above the threshold. It should also be emphasized that these conclusions all depend strongly on the chosen PNEC limit used. For example, the [IVL] study, using a more conservative PNEC threshold based on their toxicology results, concludes that there is cause for concern in the immediate wake of ships in busy waterways.

The far-field model addresses the cumulative equilibrium wash water concentration in enclosed waterbodies such as bays and ports, where background build-up of effluent due to poor flushing (water exchange) could be significant. A far-field model simulates cases where a waterbody of interest sees continuous release from an average number of vessels (Figure 1). The model is a function of the vessel arrival frequency and vessel type, the vessel residence time inside the location (which includes both the time spent moving or at berth, each with different levels of loading), the size and shape of the water body, as well as the pollutant residence time. Four study sites were used in the far-field study, Tokyo Bay, Persian Gulf, Port of Galveston and Port of Qingdao, which are intended to represent adverse scenarios for far-field concentration due to relatively high traffic and low flushing. For all four locations examined (Tokyo Bay, Persian Gulf, Port of Galveston and Port of Qingdao), the steady state effluent concentrations exceeded the 1/5000 effluent concentration threshold, which indicates a clear cause for ecological concern. However, EGCS use will not be a cause for ecological concern everywhere. Our model predicts much lower concentrations for the two sites studied by the Danish Environmental Protection Agency (Danish EPA) in their 2012 report [Kattegat and Aarhus Bight], providing support to that report’s conclusion that ‘compared to current environmental acceptability levels, the releases from scrubbers can be expected to be considerably below the levels of ecological concern’.

It is important to stress the importance of taking the synergistic effects of effluent pollutants into account. Looking at individual pollutants may give a false sense of safety. For example, in the far field analysis in [MEPC74/Inf. 24], although Whole Effluent Toxicity was used to

evaluate the near field problem, the far field analysis for locations in Japan switched to examining concentrations of individual pollutants and concluded that there is no cause for concern. Our results show that when whole effluent toxicity is used for the same locations, the 1/5000 predicted no effects threshold is exceeded. As [Koski] showed and [MEPC74/Inf. 24] and [IVL] toxicology studies confirmed, adverse effluent effects on marine life start at individual pollutants concentrations orders of magnitude below safe limits.
The removal of pollutant constituents from the water column (defined as the water body between the surface and the ocean floor) through means of decay, photodegradation and settling, was initially ignored in the model as there is not yet a good understanding of what the rates for these pollutant removal mechanisms are. It should be noted that sensitivity analysis suggests that non-zero values of removal rates could potentially be significant in decreasing the equilibrium concentration. The rates of removal would be different for individual constituents (and depend on the mechanism) and to determine the removal rate for the effluent as a whole may be challenging and require further investigation. The loss of effluent pollutants needs to be accounted for to better estimate the equilibrium pollutant concentration. However, even in the case when settling removes some of the pollutants from the water column, the pollutants may still enter the food chain (e.g., through contact with contaminated sediments) and cause health effects. More research is needed in this area.

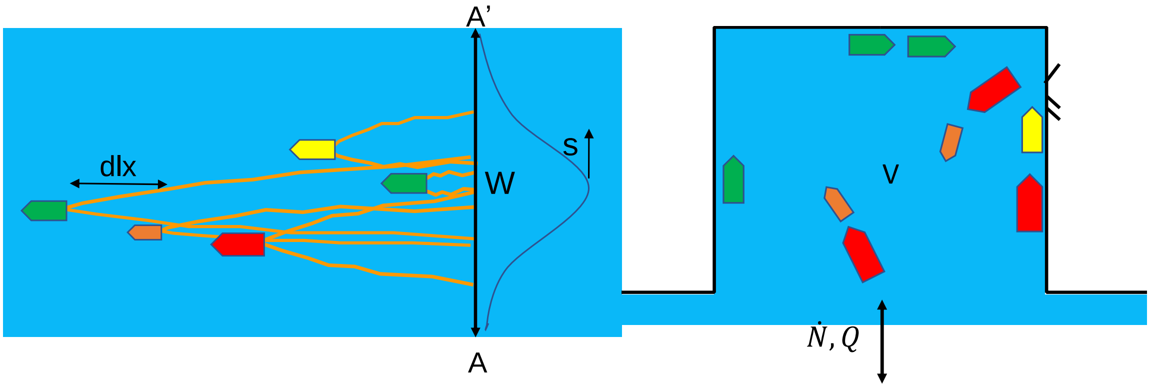

Figure 1 Schematics of (left) the near-field and (right) the far-field model in top-view. Vessels in different colors denote different ship types (thus engine load capacities). (Left) vessels cross a line AA' normal to a shipping lane of width W and following a Gaussian distribution with a mean crossing location in the middle of the lane and a lateral spread with a standard deviation of σ. (Right) vessels move and berth inside an enclosed waterbody (of volume V) that receives on average number of vessels per time $\dot{N}$ and has a flushing rate of Q.

Dr. Dayang Wang led the modeling and analysis on the effluent dispersion side. Dr. Emmanuel Kasseris had the general coordination of the research effort and led the air emissions evaluation as well as the lifecycle and slow steaming analysis. Yiqi Zhang performed the shipping traffic data calculations. Dr. Eric Adams and Professor Heywood supervised the work.

References Used in the Executive Summary

1. M. Koski, Colin Stedmon, Stefan Trapp "Ecological effects of scrubber water discharge on coastal plankton: Potential synergistic effects of contaminants reduce survival and feeding of the copepod Acartiatonsa", Marine Environmental Research 129 (2017)
2. "Report on the environmental impact assessment of discharge water from exhaust gas cleaning systems, Submitted by Japan to the 74th MEPC of the International Maritime Organization, MEPC 74/INF.24, 8 March 2019
3. Kerstin Magnusson, Peter Thor and Maria Granberg "Scrubbers: Closing the loop Activity 3: Task 2 Risk Assessment of marine exhaust gas scrubber water", IVL Report No. B 2319, December 2018
4. Jesper Kjølholt, Stian Aakre, Carsten Jürgensen, Jørn Lauridsen "Assessment of possible impacts of scrubber water discharges on the marine environment" Environmental Project No. 1431, 2012, Danish Environmental Protection Agency

Contents

Part B: Potential Environmental Issues with Exhaust Gas Cleaning Systems (EGCS, "Scrubbers")[1]

1. Background

1.1 EGCS (Scrubber) Operation

Almost all commercial EGCS use alkaline water[2] to remove sulfur oxides from engine exhaust gas. Sulfur oxide gases (SO_2, SO_3) are soluble in water. After dissolving in water sprayed into exhaust gas, they form acids that react with the alkalinity in the water to produce salts. There are two main types of scrubbers-open loop (depicted in Figure 2) and closed loop (depicted in Figure 3). Open loop uses sea water as the scrubbing medium due to its natural alkalinity. Scrubber effluent is mildly processed, essentially, sludge and oil are removed and then it is diluted onboard with more fresh seawater before being discharged back into the sea. Closed loop scrubbers reuse most of the water and maintain alkalinity by adding NaOH, however they still need to discharge some processed effluent and replenish it with make-up water.

[1] This section includes material from an earlier (Dec 2018) Literature Review Study by our team [Kasseris and Heywood]

[2] Dry Scrubbers that use a solid alkaline medium instead of water have been proposed but have only been implemented commercially on two Vessels-We will focus on wet scrubbing.

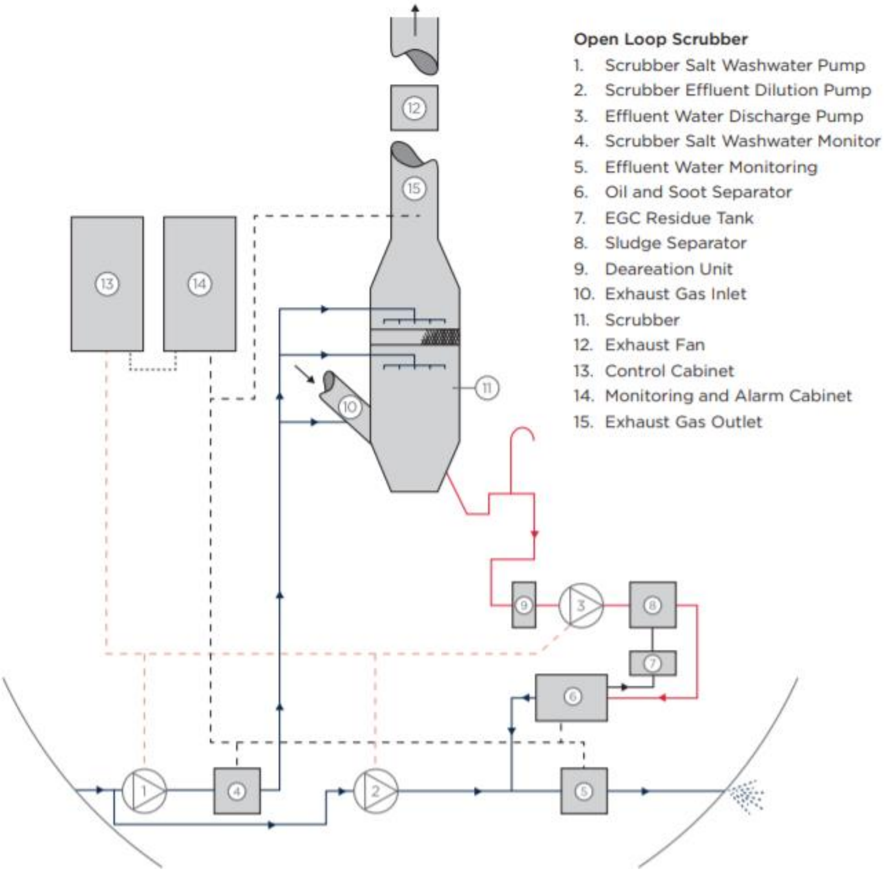

Figure 2: Open Loop EGCS (Scrubber) Source: [ABS]

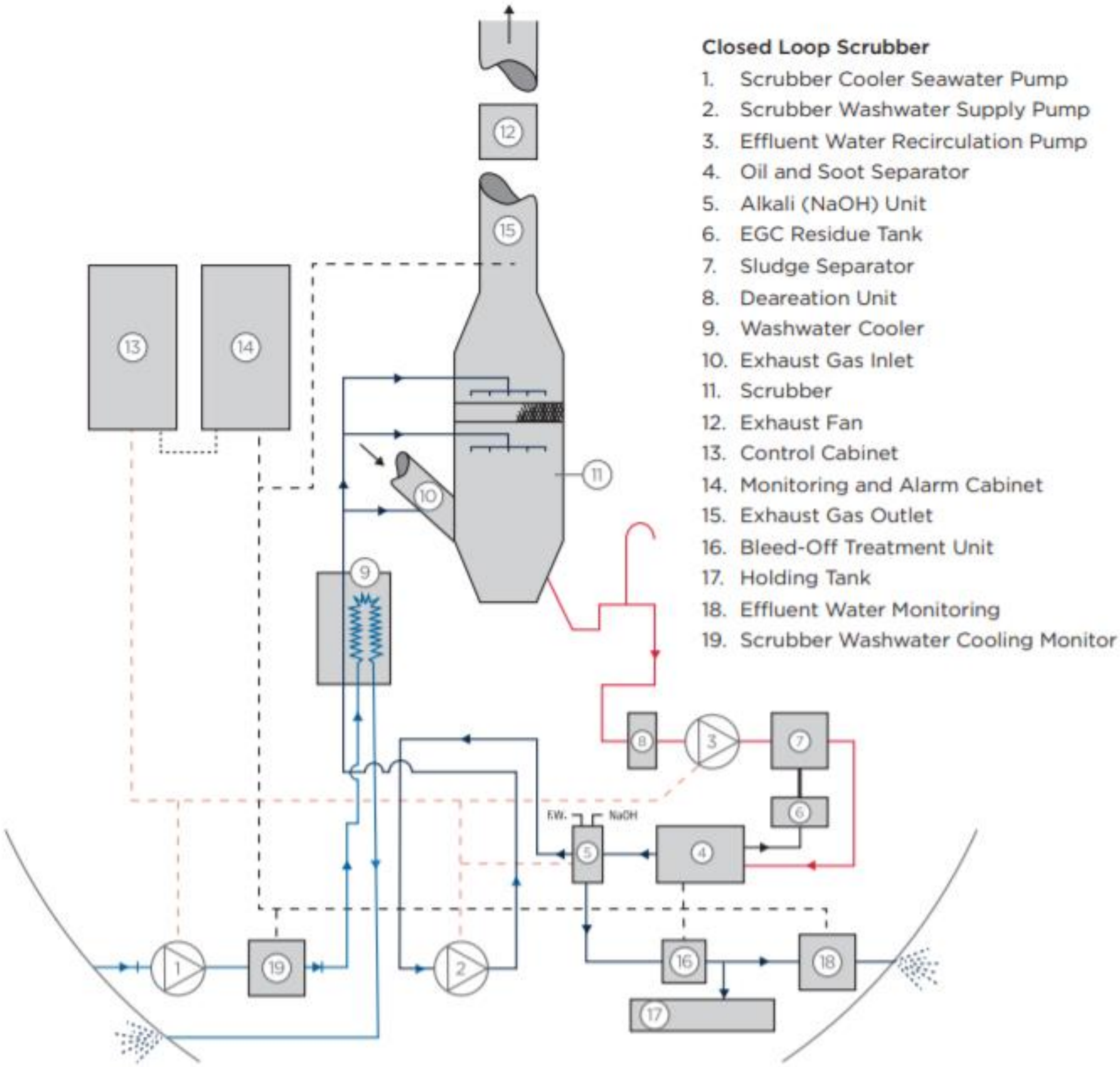

Figure 3: Closed Loop EGCS (Scrubber) Source: [ABS]

The IMO Guidelines [MEPC 184(57) 2009] specify the discharge washwater quality criteria and monitoring requirements for a number of parameters. They are summarized in Table 1 [US EPA 2011].

- **pH:** The lowest pH allowed is 6.5 measured 4 meters from the discharge point except during maneuvering or transit where the pH difference between the ship's inlet and overboard discharge can be up to 2 pH units measured at the ship's inlet and overboard discharge. The acidity of scrubber washwater is around 3 and It needs to be either pre-diluted on board or mixed and diluted in the short distance (4 meters) to the measurement point to achieve the 6.5 pH value mandated. This necessary dilution increases the total volume of effluent discharge above 45 tons/ MWh. Some typical numbers can be seen in Table 2 [US EPA 2011, Hasselov]. For a 12 MW engine, a bit more than 50 tons/ MWh is discharged for open water alkalinity. Other measurements e.g. [UBA] that include effluent amount vs. engine output report a significant increase (up to 150 t/ MWh) for low load while high load values remain at 50t/MWh. We decided to simply use the MEPC value of 45 t/MWh as also used in the Japanese study [MEPC 74/INF.24]. [MEPC 74/INF.24] used [Ülpre] as a source which is a detailed study of how much the scrubber process water (pH~3) would need to be diluted to reach 6.5. In any case 45-50 t/MWh refers to process water, not discharge water which is more. Since the toxicology data as will be presented is based on process water, using 45 t/MWh is a valid assumption. In low alkalinity waters (such as the Baltic), the required process water is more as can be seen in Table 2.[3]

- **PAH (polyaromatic hydrocarbons):** The maximum allowed continuous concentration of PAH is 50µg/L PAHphe (phenanthrene equivalence) above the inlet water PAH concentration for EGCS washwater flow rates normalized to 45t/MWh. (i.e. higher concentrations allowed for lower discharge)
- **Turbidity/suspended particulate matter.** The turbidity of the EGCS washwater should not exceed 25 FNU (formazin nephelometric units) or 25 NTU(nephelometric turbidity units) above the inlet water turbidity
- **Nitrates:** Effluent samples are to be taken within three months of an EGC unit renewal survey and analyzed for nitrate discharge data. The maximum nitrates level allowed is equivalent to 12 percent removal of NOx from the exhaust or 60 mg/l normalized for a discharge flow rate of 45t/MWh.

Table 1: Discharge Requirements in accordance with MEPC 184 (57)2009: Guidelines for Exhaust Gas Cleaning Systems.[UBA]

Components	Limit	Criteria
pH value	Min. 6.5, max. 2 pH units per inlet	Measuring the value after the dilution unit
PAHs (Polycyclic Aromatic Hydrocarbons)	Max. 50 µg/l PAHphe (phenanthrene equivalents) to the inlet value (for a flow rate of 45 t/MWh)	Measurement in the inlet and outlet of the EGCS, before dilution unit
Turbidity / dissolved particles	Max. 25 FNU (formazine nephelometric units) or 25 NTU (nephelometric turbidity units)	Measurement in the outlet of the EGCS, before dilution unit
Nitrates	Max. 60 mg/l for a standard flow rate of 45 t/MWh	Values for nitrates must correspond to a min. 12% reduction of NO_x

Table 2: Approximate Amount of Water Affected by a Scrubber for a 12MW engine. [US EPA 2011], [Hassellov]

	Quantity of Water		
	Open Ocean	**Baltic Sea**	**Freshwater River**
Water for scrubbing	700	900	2,500
Water for dilution to pH = 6.5	1,400	1,700	15,000
Factor for dilution to ΔpH of 0.2	3	3.5	2.5
Total amount of water	6,300	9,100	44,000

Source: Hassellöv and Turner, 2007

[3] These numbers refer to open loop scrubbers. For closed loop [Wartsila 2015] suggests 0.1tons/MWh while [IVL] measured 35 times less discharge volume for closed loop compared to open loop.

1.2 Summary of Literature Review on Impact of Scrubber Effluent Discharge[4]
Literature on scrubber effluent effects on the marine environment can be separated in three main categories.

- **General Studies:** These evaluated existing experimental reports on individual pollutant concentration measurements in EGCS effluent and tried to establish whether there was cause for further concern and study using existing water quality standards. They did not perform their own toxicology experiments or ocean dispersion modeling. All of these studies, as will be explained, agreed that there is cause for concern and further study.
- **Toxicology Studies:** There has been very limited work on the effects of exposing marine life to EGCS effluent. The three studies that exist, showed that there are synergistic effects of the different pollutants in scrubber effluent, i.e. health effects are significantly more pronounced for effluent as a mixture, containing multiple pollutants than what would be expected based on individual pollutant concentrations.
- **Ocean Dispersion Modeling:** There has been limited work in this area, i.e. using fluid mechanical modeling to predict pollutant concentrations in the water column to compare to a presumed safe threshold established by toxicology. There have been only four studies so far. More are in the works and this study includes a significant ocean dispersion component we hope makes a real contribution to answering some of the existing questions.

1.2.1 General Studies
From our assessment of the literature, there is enough evidence to cause concern and warrant further research to evaluate the total environmental impact of discharging scrubber effluent into the sea. According to the reviewed literature, this is because scrubber effluent contains the following potential pollutants:

- pH of effluent: EGCS effluent is very acidic, (pH~3) [UBA] for process water[5]. Large effluent volume discharges could therefore as a result affect surrounding water pH. This could have adverse health effects on marine life but also potentially affect the ability of the ocean to absorb CO2 [Hassellöv]
- Metals: Scrubber water contains heavy metals from the fuel and oil as well as other sources. These can be toxic to marine life.
- PAH: Polyaromatic hydrocarbons. These are hydrocarbon compounds with multiple aromatic rings that can have serious health effects on marine life.
- PM. Some of particulate matter present in exhaust gases ends up in scrubber wash water. It can have negative health effects.
- Nitrates, temperature/ Eutrophication Agents: Nitrates in wash water come from NOx in the exhaust gases. If nitrate concentration in the ocean water increases too much, eutrophication effects can occur. Temperature rise from warm effluent discharge can cause similar effects [SOLAS study]

Studies have evaluated other substances as potential pollutants in scrubber effluent such as, sulfates, other hydrocarbons, oil, effects on dissolved oxygen etc.
We examined 5 different studies that we could find in the literature. A summary of the findings is presented in Table 3.
As can been seen in Table 3, all of the studies examined conclude that there is justification for concern and further study regarding heavy metals and PAH in the effluent. Four of the studies

[4] This section includes material from an earlier (Dec 2018) Literature Review Study by our team [Kasseris and Heywood]
[5]According to MEPC.184 (59) 2009, "2009 Guidelines for Exhaust Gas Cleaning Systems" on July 1, 2010., the pH limit 4 meters from the discharge point is no less than 6.5, so pre dilution may be necessary.

are concerned with acidification due to high effluent pH. Two of the studies state that nitrates could also cause issues.

Table 3: Summary of Literature findings on Scrubber Effluent Contaminants

		pH	**Metals**	**PAH**	**Nitrates**	**Notes**
1	**US EPA (2011)**	possibly a problem	possibly a problem	possibly a problem	NOT a problem	pH likely not a problem
2	**SOLAS study**	a problem	a problem	a problem	a problem	
3	**UBA**	a problem	a problem	a problem	a problem	temperature also an issue
4	**BSH**	Not available	possibly a problem	a problem	probably NOT a problem	Preliminary findings
5	**NABU**	possibly a problem	possibly a problem	possibly a problem	probably NOT a problem	

Generally, these studies compared actual field measurements of pollutants in scrubber effluent to established water quality standards regarding individual pollutants and estimated whether they could be exceeded without performing ocean detailed dispersion modeling. The original measurements that the conclusions of these studies were based on used measurements from five vessels equipped with scrubbers:

>MS Fjordshell (Buhag et al. 2006) and
>MS Ficaria Seaways (Danish EPA 2012, Hansen 2012)
>*Zaandam,*(USEPA, 2011).
>The *Pride of Kent (Hufnagl 2005)* and the
> MT *Suula (WartsilaA 2010)*

The US EPA (2011) study analyzed data from scrubber water chemical analyses from three different vessels and compared them against US NRWQC (US National recommended water quality criteria). The study concluded that for heavy metals and PAH, IMO guidelines wash water limits may not be sufficiently protective, since measured values exceeded US NRWQC. The study also raised some concern over suitability of measurement methods in IMO guidelines. pH is unlikely to be an issue according to the [US EPA 2011] study although large amounts of dilution water would be needed. Nitrates are not an issue according to the [US EPA 2011] study.

The SOLAS study is an extensive study of studies that examined existing scrubber effluent measurements from ships and expert opinions. This study states significant concerns about pH, metals, PAH as well as nitrates/eutrophication. This study also calls for tighter IMO regulations regarding scrubbers and raises issues regarding their implementation. This study was a part of the Surface Ocean - Lower Atmosphere Study (SOLAS) project. This is an international research initiative aiming to understand the key biogeochemical-physical interactions between the ocean and atmosphere.

UBA is a study by the German Federal Environment Agency. It compared measurements of pollutants in scrubber effluent with European Environmental Quality Standards (EQS). Although the values the study picks from the literature of effluent measurements are just below the EQS, the authors calculate the total mass flows of pollutants for typical vessel trips and state significant concerns about pH, metals, PAH as well as nitrates/eutrophication. These concerns are based on the precautionary principle of the European Water Framework and Marine Strategy Directives because of the potential to exceed average EQS values in waters near busy shipping lanes. Also some of the detected substances in scrubber effluent are on the list of persistent, bioaccumulative and toxic (PBT) substances, the discharge of which should be absolutely avoided.

BSH is a study by the German Federal Maritime and Hydrographic Agency (BSH), funded by the German Federal Environment Agency (UBA). Preliminary results were published in December 2018. The study will be completed in 2019. The study performed measurements on scrubber effluent from five ships and calculated based on the measurement data what the total pollutant discharge would be in the case of maximum scrubber installation. This is defined as all vessels for which it makes financial sense in the Baltic Sea, the North Sea and the English Channel being outfitted with scrubbers. Even though results are preliminary, the study concludes that increased application of EGCS-scrubbers will be a new direct pollution source to the marine environment which is a concern, especially for PAH.
NABU is a broader study commissioned by German nature conservation NGO (Non-Governmental Organization) NABU and performed by independent environmental consultancy CE Delft. It examined a similar set of data as UBA and concluded that there is potential to exceed European EQS for metals and PAH and there is potential for sea acidification even when the IMO criteria are met.
1.2.2 Toxicology
Most of the environmental assessment earlier work was based on water safety limits established on the effects of individual pollutants on marine life.

The study from Danish Technical University [Koski] was the first study where living marine organisms (copepods of the species Acartia Tonsa) were subjected to scrubber effluent to examine its effects on survival, feeding and reproduction. The study showed that “A direct exposure to discharge water increased adult copepod mortality and reduced feeding at metal concentrations which were orders of magnitude lower than the lethal concentrations in previous single-metal studies”. In other words, the different pollutants in scrubber effluent have synergistic effects on marine life compared with the effects individual pollutants have. This conclusion becomes very important because water quality standards used in all preceding studies were based on limits for individual pollutants. Adult mortality increased in all concentrations above 10% scrubber discharge water, with close to all individuals being dead at 30% scrubber discharge water in seawater as can be seen in Figure 4 after an exposure of only 24 hours. Median Lethal Dose (LD 50) in terms of concentration (LC 50-Median Lethal Concentration) for the whole effluent would therefore be somewhere between 20% and 30%. Equivalent LD50 concentrations of heavy metals were calculated and are presented in
Table 4. They are orders of magnitude less than the LD50 concentration values reported for individual heavy metal pollutants in the literature. This study did not measure PAH’s in the effluent although it did try to estimate their concentration. The study used water from an open loop scrubber.

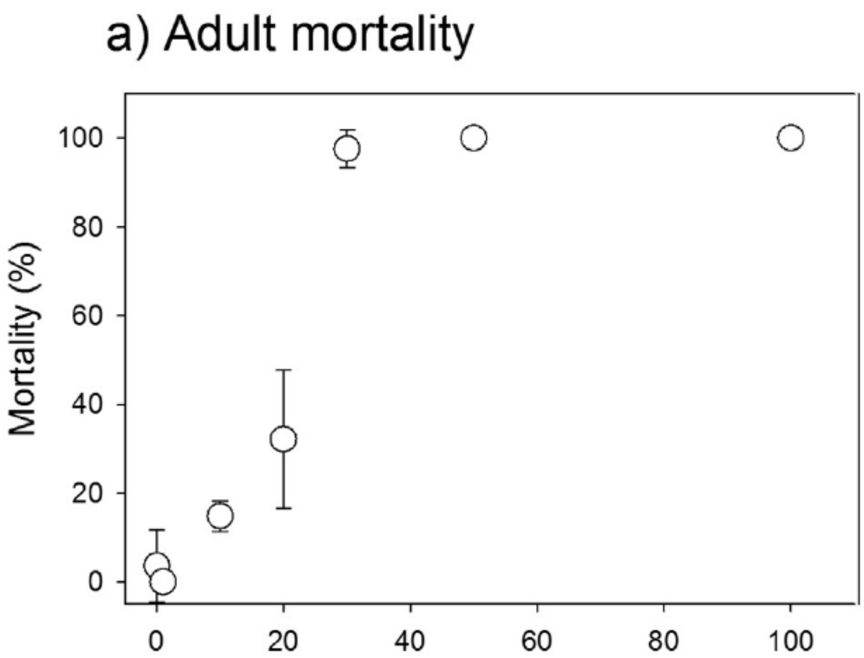

Figure 4:Lethal effects of scrubber discharge water. Mortality (% day^-1) of a) adults of the copepod Acartiatonsa as a function of scrubber discharge water concentration [Koski](% of dilution; mean ± SD).

Table 4: Threshold Concentrations inducing lethal effects from [Koski]

Table 4
Threshold concentrations of metals inducing lethal and sub-lethal effects on plankton in previous single-metal studies.

	Concentration (μg l^{-1})								Species	T	Reference
	V	Ni	Cr	Pb	Cu	Zn	Cd	As			
a. LD_{50}											
Freshwater			599		121				*N. conifer*	24 h	Gutierrez et al., 2010
		1191	510		75	240			*M. pehpeiensis*	48 h	Wong and Pak 2004
			>700			>890		≥3000	Groundwater copepods	96 h	Hose et al., 2016
Marine							47.9	27.5	*T. brevicornis*	96 h	Forget et al., 1998
		2580	14 130	6340	370	620	910		*T. holothuriae*	48 h	Verriopoulos and Dimas 1988
		531							*P. marinus*	24 h	Tlili et al., 2016
		250							*A. tonsa* (nauplii)	48 h	Zhou et al., 2016
			>8000						*A. clausi*	48 h	Moraïtou-Apostolopoulou and Verriopoulos, 1982
		2360							*A. pacifica*	48 h	Mohammed et al., 2010
	38	*11.5*	*1.1*	*BD*	*21.7*	*4.8*	*BD*	*1.4*	*A. tonsa*	24 h	This study

The next study that reported toxicology results was the one submitted on behalf of Japan to MEPC 74 [MEPC 74/INF.24]. This study tested the effects of scrubber water from a smaller (247 kW-not marine engine) on three different types of marine organisms, a type of algae, a crustacean and a fish species. The results are summarized in

Table 5. The lowest LC50 (lethal dosage concentration for 50% of the population) was 20% (1/5). Exposure time was 96 hours but the number of dead organisms did not change after the first 24 hours. In a sense therefore these results are quite comparable to [Koski]. This study used a hybrid scrubber operated in open loop mode.

The study subsequently proceeded to use a methodology developed for ballast water pollutants and accepted by the IMO [GESAMP BWWG] to establish a predicted no-effect concentration [PNEC]. A safety factor of 1000 was multiplied by the LC50 for long term effects (in closed waters) resulting in a PNEC of 1/5000 and a safety factor of 100 was used for short term effect (near the ship) resulting in a PNEC of 1/500.

Table 5: Summary of Toxicology results from [MEPC 74/INF.24]

		EC50 or LC50	NOEC	LOEC
Algae (micro-algae) 	Diatom (*Skeletonema costatum*)	49% (48 ~ 50%)	32%	100%
Invertebrates (crustacean) 	Ptilohyale (*Hyale barbicornis*)	20% 12.5 ~ 25%	12.5%	25%
Vertebrate (fish) 	Adrianichthyidae (*Oryzias javanicus*)	35% 25 ~ 50%	25%	50%

ErC50 Concentration: dilution area (calculated) estimated that the test species is at lethal 50% during the test period
NOEC Maximum dilution ratio not affected for the test species during the test period (selected from actual dilution cell)
LOEC Minimum dilution ratio dilution affected for the test species during the test period (selected from actual dilution cell)

Finally, a section on toxicology effects of scrubber effluent was included in a study by IVL [IVL]. This study used discharge water from both open and closed loop scrubbers and tested its effects on copepods (Calanushelgolandicus) and blue mussels (Mytilusedulis). Medium term (1-2 weeks) chronic effects of EGSE from closed- and open loop scrubber systems were investigated. The duration of the tests were continuously adjusted in relation to the detected toxicity in order to obtain the best dataset possible. It was 7 and 8 days for the closed loop tests and 14 days for the open loop test. The discharged volumes from the open loop scrubber were 35 times higher than those from the closed loop system. The closed loop scrubber effluent was thus more “concentrated” and caused effects at lower dilutions in the tests than the waters from the open loop scrubber. Many health parameters in addition to mortality were investigated for exposure times up to 35 days. The following is a summary of the study’s findings quoting directly:
“Mortality rate in juveniles (copepodite) stage CV of the copepod Calanushelgolandicus was found to be the most sensitive indicator of all measured endpoints in all toxicity tests of EGSE toxicity. Statistically significant toxic effects were observed at 0.04% EGSE in the experiments

with water from Stena Britannica (closed loop), and for copepodite stage CIII at 0.1% with water from Stena Transporter (closed loop) and 1.0% with water from Stena Forerunner (open loop). Neither pH nor alkalinity (AT) was different from the control treatment at these EGSE concentrations, so we conclude that effects on copepod mortality (as well as all other measured physiological processes in the copepods) were not caused by acidification but were primarily due to the toxic effects of EGSE. It should be noted that in both closed and open loop exposure the lowest tested concentration resulted in toxic effects on the copepodites. Thus, it cannot be excluded that even lower concentrations would have been harmful to the tested zooplankton species". In terms of establishing a predicted no effects concentration, this study used the lowest concentrations for which they could measure health effects (0.04% closed loop and 1% for open loop) multiplied by an assessment factor of 1000. The assessment factor is based on the European Water Framework Directive ((DIRECTIVE 2013/39/EU) that recommends a value of 1000. This is a more conservative approach than what used in [MEPC 74/INF.24] in that the lowest concentration that could be measured that still caused health effects was used instead of an LC50.
"Having the ability to quickly form strong and many byssus threads is crucial for the survival of the blue mussel (Mytilusedulis). Byssus strength was the only endpoint measured in blue mussels that showed a significant effect of the EGSE treatments. This effect was detected at a EGSE concentration of 1.25% and only in closed loop exposures from Stena Transporter (March 2018 trial)."
The conclusions that can be drawn from the three studies are:

- There are synergistic effects. Scrubber effluent needs to be treated as a pollutant itself. Examining the effects of individual pollutants contained in EGCS effluent gives a false indication of safety. This is because, marine life adverse health effects occur at individual pollutant concentrations that are one or two orders of magnitude lower than the safe limits for individual pollutants.
- For shorter term exposure, the LC50 mortality is reported around 20%. Copepods (different species) were used in two studies arriving at similar LC50's. Copepods seem to be more sensitive than fish or algae that have slightly higher LC50.
- Using ballast water methodology, a safety factor of 1/1000 has been proposed in [MEPC 74/ Inf. 24] for closed water- longer exposure effects and 1/100 for shorter time exposure near the vessel. This result~~s~~ in an overall, proposed, no effects concentration safe limit of 1/5000 for closed waters/ longer time exposure and 1/500 for near the vessel shorter time exposure in open waters. 1/5000 should be used for near field analysis as well when the vessel is travelling in busy waterways.
- For medium term exposure, no safe limit could be established. The lowest concentrations tested- 0.04% for closed loop (7 days exposure) and 1% for open loop (14 days exposure) still showed a statistically significant increase in mortality.
- An alternative, more conservative (than [MEPC74/ Inf.24]) approach to calculate a PNEC is presented in [IVL] where the lowest concentrations tested (0.04% for closed loop and 1% for open loop are multiplied by an assessment factor of 1000 based on the European Water Framework Directive.
- The closed loop scrubber effluent is "concentrated" and caused adverse effects at lower dilutions in the tests than the waters from the open loop scrubber. In addition to being more concentrated, it is also chemically different than the open loop effluent, which may cause different health effects on marine life - for example the effects on blue mussels.

There is obviously a need for longer duration toxicology experiments to help in developing a robust methodology for evaluating safe limits for EGCS effluent discharge. The safety factor methodology from [MEPC74//INF.24] was developed for ballast water which is quite different. Additionally, we know that the safety limit for medium term exposure is less than 1% for open loop scrubbers and 0.04% for closed loop, but we do not know what it is.

For the purposes of this study we decided to use the 1/5000 limit established in [MEPC74/INF.24] in the absence of more data. Additionally, we decided not to distinguish between open and closed loop scrubbers in our analysis and essentially treat closed loop scrubber effluent as an equivalent discharge-its lower volumetric flow rate balancing the fact that it is highly concentrated. That is also simply a hypothesis and needs to be investigated further.

1.2.3 Ocean Dispersion

There has been limited work in this area. To our knowledge there have been 4 studies.

1) The study from the Danish EPA[Danish EPA 2012] included ocean dispersion modeling for two high risk locations near Denmark to explore environmental effects if all shipping traffic in two relatively busy areas in Danish waters were to convert to using open loop scrubbers. The two areas examined were the Kattegat passage and the Arhus Bight seen in Figure 5. The authors used AIS data to calculate total shipping traffic and thus total effluent volume discharged if all shipping would convert to using scrubbers. A steady state, far field (background pollutant accumulation) model based on publicly available data on the hydrodynamics of the area is performed. When comparing the predicted concentrations of heavy metals and PAH's with the European AA-EQS, the conclusion is that there are no issues in terms of the far field in these locations. As will be seen in the results section, even if the synergistic effects of EGCS effect pollutants are taken into account based on our methodology, i.e. the effluent is treated as a pollutant itself, the background accumulation is still below the limit of 1/5000. Unlike when individual pollutants are used however, when the synergistic effects are taken into account, the background equilibrium calculation is of the same order of magnitude as the limit. An increase in shipping traffic therefore could lead to exceeding it.

Additionally, the study performs a very simple analysis of background accumulation in the port of Aarhus. Using just the water volume in the port and disregarding any flushing due to e.g. tides, they estimate that even in ideal conditions of in-port mixing, use of open loop scrubbers in port should be avoided.

Finally, the [Danish EPA 2012] study performs a simple analysis in the immediate wake of a vessel (near field analysis). Disregarding turbulent mixing details and simply using the size of the wake and continuity, they calculate heavy metal concentrations that based on EQS would not be an issue. The equivalent dilution is 3250 which based on the [GESAMP BWWG] methodology described earlier and adopted in [MEPC 74/ INF. 24] and our study, would be acceptable for open waters, but not for busy, closed waterways. The study, therefore, concludes that there is cause for ecological concern in the immediate wake of ships in busy waterways.

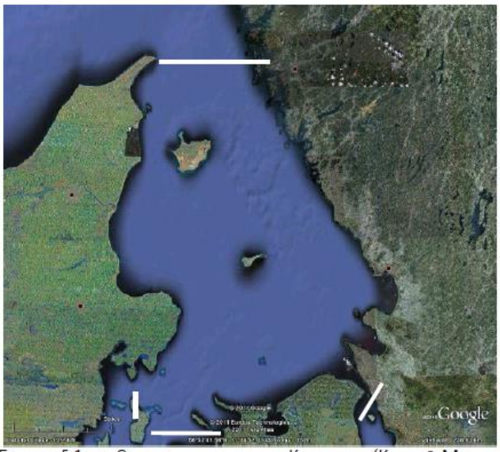

Figure 5-1 Study area for the Kattegat (Kort & Matrikelstyrelsen, 2000).

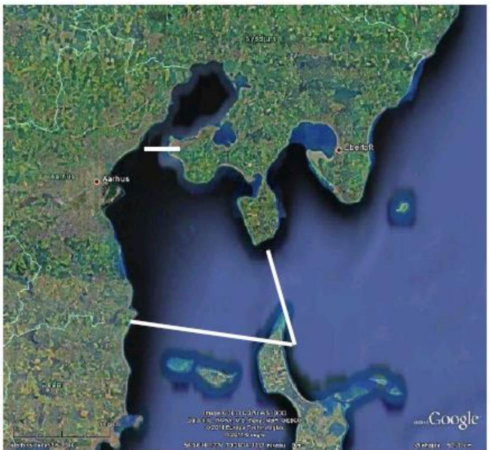

Figure 5-2 Study area for the Århus Bight (Kort & Matrikelstyrelsen, 2000).

Figure 5: Locations for the Dispersion Modeling Study in Danish [Danish EPA 2012]

2) The Study Submitted by Japan [MEPC 74/ INF. 24]. This study, in addition to the extensive toxicology analysis already described, also performed ocean dispersion modeling. The focus

was mostly on near field effects, examining acute, short-term concentration for marine life in the immediate wake for ships using scrubbers. The study used computational fluid dynamics (CFD) simulation near the ship to predict the turbulent diffusivity in the wake of a PANAMAX bulk carrier moving at 14.2 knots. An image is provided in Figure 6. Diffusivity was assumed to be constant for the entire length of the analysis. The vessel was assumed to be in the Nakanose passage in Tokyo Bay, an area with high shipping traffic (28 vessels per hour, one every 129 seconds). Even assuming two vessels one behind the other after 128 seconds (on the exact same trajectory), the dilution ratio reaches 5000 about 60 seconds after the passage of the third vessel. As explained in the toxicology section, the same study decided to use the 1/5 LD50 (lethal dosage) from the toxicology experiments times a safety factor of 1/1000 from the ballast water methodology resulting in an overall required dilution of scrubber water of 5000, treating the entire effluent as a pollutant to account for synergistic effects. Based on this analysis, the required dilution would be achieved 60 s after the passage of the ship, which is not considered a threat to marine life. The results of this near field analysis will be extensively compared with our results in Chapter2.3.
The same study also performed far field analysis on long term accumulation of pollutants for several locations in Japan. CFD code MAMPEC was used, but the details of the analysis are not provided so it cannot be compared directly with our results. Although, the near field analysis was performed on a total effluent dilution basis, the far field analysis without explanation is performed on individual pollutant concentrations and the increase in concentration of individual pollutants is considered small. As will be seen in Chapter2.3, when using the total effluent dilution basis, our results indicate that Tokyo Bay would be several times higher in terms of average effluent concentration than the limit of 1/5000.

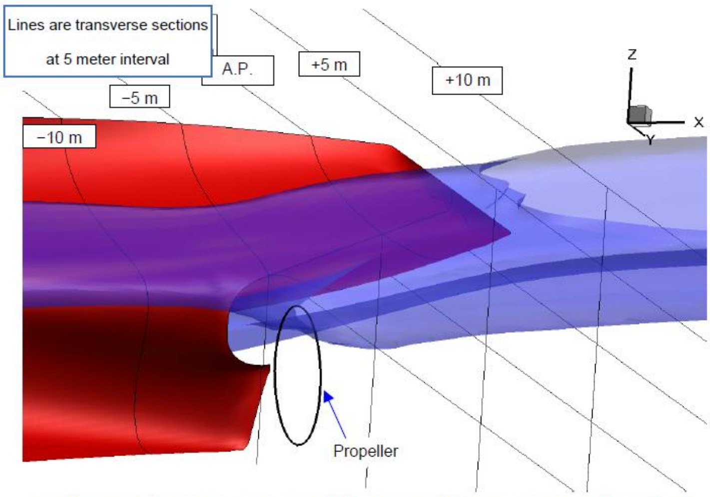

Figure 2-4 Distribution of coefficient of virtual viscosity around stern
(3D image of the distribution of 0.2 m^2/s, looking up diagonally from below the ship)

Figure 6: CFD simulations of scrubber effluent mixing in the wake of a ship.

3) [MARINTEK]. Another, older near field CFD study is described in [US EPA 2011] although we were not able to get a copy of the original. The methodology sounds similar to [MEPC74/Inf .24]. A 2000 dilution ratio was calculated at a distance of 50 m from a vessel equipped with a scrubber.
4) [IVL]. The IVL study did not perform CFD analysis of dispersion. They instead used an approach specifically aiming at estimating the mixing of discharges of water from ships proposed by a scientific advisory panel to assist the Alaska Department of Environmental Conservation in evaluating the effect of discharges of wastewater from cruise ships [Loehr et al. 2003]. The dilution is calculated as:

Dilution factor = (ship width x ship draught x ship speed)/ discharge rate

Although the calculated dilutions based on this formula for the three vessels that were measured were much higher than the dilutions calculated in MEPC74/ Inf. 24], because the toxicology limits used were more conservative, all three vessels equipped with scrubbers that were measured were several times above the PNEC.

2. Effluent Discharge Effect on Ocean Water

This study is carried out to address the environmental impact assessment of open-loop EGCS discharge washwater concerning both the near- and far-field, and in so doing helps determine the viability of EGCS as a method of reducing atmospheric sulfur admissions. In this context, near field analysis refers to the immediate ship wake accounting for the fact that multiple ships may follow closely behind while far field refers to cumulative background pollutant accumulation in geographically enclosed locations such as harbors and ports that experience high shipping traffic. The first step in determining potential near and far field effects of EGCS systems on ocean water is to accurately estimate shipping traffic in that location. Subsequently it can be assumed that a certain fraction of that traffic especially in some segments (e.g. larger vessels) will convert to using scrubbers and examine the effect from the effluent.

2.1 Shipping Data-Shipping traffic information

- Sources Introduction

Accurate estimates about the marine traffic are helpful in correctly identifying the global pollution hotspots as the study sites and ensuring reliable modeling outputs when the traffic information is used as inputs. The traffic data of interest to this study includes the traffic density, which is a measure of how frequently the ships visit a particular place, the traffic pattern (or trajectory), the traffic speed, the vessel category, which dictates the engine power (main and auxiliary) and the rate of effluent discharge.

In order to get the most reliable estimates of the traffic information required, the study compared data obtained from three sources, namely the Advanced Density Map purchased at www.marinetraffic.com, Satellite AIS data purchased from exact Earth Ltd, and AIS activity data processed and analyzed by Yiqi Zhang of the Hong Kong University of Science and Technology (HKUST).

By further crosschecking with publicly available information from several additional sources, we conclude that AIS data as processed by HKUST most accurately represents the traffic; therefore we will use data from this source. Our methodology is explained in detail below.

- AIS Activity Data

In this study, the ship activity data comes from a whole-year AIS dataset for 2017 (hereafter denoted as “AIS DB”), which is an integrated dataset of terrestrial and satellite AIS data. For each record, the key attributes can be divided into static and dynamic messages. The static messages, which include IMO number, Maritime Mobile Service Identity (MMSI), call sign, ship name, ship type, length, and beam, should be consistent for every voyage, as they are input when the AIS instrument is installed and cannot be modified without a valid password. In contrast, the dynamic messages, which include real-time speed, latitude, longitude, movement date and time, are real-time tracking data. It is assumed that both static and dynamic AIS messages are transmitted automatically unless the AIS equipment is turned off (UK Maritime & Coastguard Agency, 2002). The key parameters of the AIS DB are summarized in Table 6. The shading attributes (AIS-based Ship Type and Length) are available for nearly all AIS records, including the unidentified ships that are not listed in the World Register of Ships database (hereafter WRS DB).

Among all the parameters, IMO number and MMSI are the key for the ship identification in the AIS database. IMO number is the ship identification number for propelled, sea-going merchant ships of 100 GT and above, assigned by IHS Fairplay (IHSF, previously named as Lloyd's Register Fairplay). It is a unique seven-digit identifier for a ship, which is never reassigned to another ship. Yet, ships with IMO number are not necessarily ocean-going vessels, as the IMO Scheme has been extended to domestic ships on a voluntary basis. MMSI, the abbreviation of

Maritime Mobile Service Identify, is a nine-digit identifier used for telecommunication. Each ship should have a universal unique MMSI at the report moment. However, a single ship may have multiple MMSIs associated with it during a 12-month period because the ship would be assigned a new MMSI if it is reflagged (International Telecommunications Union 2012). Similarly, Ship Name and Call Sign would be changed if the ship is reflagged.

Ship Parameter Data

In this study, the main source of ship parameter data is the WRS DB. This database is provided by IHS Maritime & Trade, which manages global ship registration, including IMO number assignment, on behalf of the IMO. The WRS DB is a global-level ship parameter database that covers all sea-going merchant ships of 100 GT and above with valid IMO numbers. However, it excludes most domestic ships without IMO registration including coastal ships traveling across domestic ports and inland river ships. There were around 196,000 ships in the year 2015 WRS DB, of which 70% had the status of Delivered or On Order and 30% had the status of Scrapped or Lost. The data of key parameters in the WRS DB is summarized in Table 6. The WRS DB includes identity, size, construction year, and main engine (ME) specifications for ship with IMO number. For the ships whose specifications are incomplete in the WRS DB, their missing values are filled in by the capacity-based estimation. The database does not include the specifications of auxiliary engines. In this study, the power data on the auxiliary engines (Table 9 and Table 10) are taken from the *Third IMO Greenhouse Gas Study* (IMO, 2014).

Estimation of Missing Ship Parameters

Capacity-based estimation is used to fill in the missing values for identified ships with incomplete specifications and to assign the power loads of the auxiliary engines to all ships. The categorical system of *Ship Class-Capacity Range* is adopted from the IMO study (IMO, 2014). A ship's ship class can be derived from the *Statcode5*, which is an industry-based ship coding system that is available for every ship in the WRS DB. For each ship class, the ship capacity is derived from the corresponding capacity-related field such as gross tonnage (*gt*), deadweight tonnage (*dwt*), TEU, volume of liquid, and number of cars. Ships of different ship classes use different schemes to measure ship capacity. For example, under the AIS ship type "Cargo", containers measure capacity in TEUs, whereas bulk carriers use *dwt* in the WRS DB.

There are two reasons to utilize this system to categorize the identified ships and fill in the missing values of their specifications. First, the information for ship class and capacity are available to all ships in the WRS DB; thus, all identified ships have ship class and capacity range information available. Second, the power loads of the auxiliary engines, which are not included in the WRS DB, are provided in the IMO study using this categorical system. Thus, using "ship class–capacity range" categorization, specification values and the power loads of the auxiliary engines can be obtained for all identified ships.

Table 6 Key Data Fields in AIS Database and WRS Database

Parameter Category	**Ship Activity Data AIS Database (AIS DB)**	**Ship Parameter Data World Register of Ships (WRS DB)**
Ship Identity	IMO Number	IMO Number
	MMSI	MMSI
	Ship Name	Ship Name
	Call Sign	Call Sign
Ship Type	--	Statcode-5 (industry-based coding system)
	AIS Ship Type (provider-based coding system)	--
Ship Size	Length	Length

	Beam	Beam
	--	Gt
	--	Dwt
	--	TEU
Engine-related Parameter	--	Main Engine Power (kW)
	--	Main Engine Speed (RPM)
	--	Main Engine Type
	--	Ship Construction Year
	--	Maximum Service Speed
Spatial Information	Real-time Speed	--
	Latitude	--
	Longitude	--
Temporal Information	Date time	--

Linking Ship Parameter Data to AIS Records

Emission estimation requires data on a ship's technical parameters to estimate the engine energy outputs and to determine the emission factors. As shown in Table 6, engine-related parameters such as main engine power are only available in the WRS DB, while real-time messages (location, date, time, and real-time speed) are only available in the AIS DB. To combine the two databases, the IMO number is used to match the AIS records with their corresponding technical parameters in the two databases. The IMO number is a unique seven-digit identifier for a ship that is never reassigned to another ship. Other ship identifiers, including MMSI, Ship Name and Call Sign, may change when the ship is reflagged (ITU, 2012).

Sometimes for simplicity of analysis, we use the main engine power provided in the Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model [GREET® Excel Model]. This analytical tool simulates the energy use and emission of various vehicle and fuel combinations. For more information please refer to https://greet.es.anl.gov/greet.models. Marine data is based on a survey of vessels entering US. Ports [GREET]

Ship Category

The categorization of ships may vary with areas and data providers. For ships with IMO number that are listed in the WRS DB, they are categorized by the Statcode-5 industrial coding system (as shown in

Table 7). The IMO study (IMO, 2014) also employs this categorization system to assign the power load values of auxiliary engine and to estimate emissions. The information of AIS ship type is available to all AIS records.

Table 7 Statcode-5 Ship Type and Capacity Bins

Statcode-5 Ship Type	Capacity	Unit
Bulk Carrier	0-34999	dwt
	35000-59999	dwt
	60000-600000	dwt
Chemical Tanker	0-4999	dwt
	5000-19999	dwt

	20000-600000	dwt
Container	0-999	TEU
	1000-1999	TEU
	2000-2999	TEU
	3000-4999	TEU
	5000-7999	TEU
	8000-11999	TEU
	12000-14500	TEU
	14500-600000	TEU
General Cargo	0-4999	dwt
	5000-9999	dwt
	10000-600000	dwt
Liquefied Gas Tanker	0-49999	cbm
	50000-600000	cbm
Oil Tanker	0-4999	dwt
	5000-9999	dwt
	10000-19999	dwt
	20000-79999	dwt
	80000-119999	dwt
	120000-199999	dwt
	200000-600000	dwt
Other Liquids Tankers	0-600000	dwt
Refrigerated Cargo	0-600000	dwt
Vehicle	0-600000	cars
Cruise	0-9999	gt
	10000-59999	gt
	60000-600000	gt
Ferry – passenger only	0-1999	gt
	2000-600000	gt
Ferry – cargo + passenger	0-1999	gt
	2000-600000	gt
Ro-ro	0-4999	gt
	5000-600000	gt
Yacht	0-600000	gt
Fishing	0-600000	gt
Tug	0-600000	gt
Offshore	0-600000	gt
Others	0-600000	gt

Table 8 AIS Ship Type from AIS provider

AIS Ship Type
Anti-pollution
Cargo
High Speed Craft
Law Enforcement

Medical Transport
Passenger
Pilot Boat
Search and Rescue
Tanker
Tender
Tug
Vessel
Wing In Ground-effect
Unknown

Table 9: Auxiliary Engine Power Load

Statcode-5 Ship Type	Capacity	Unit	Auxiliary Engine Load (kW)			
			Activity Mode			
			At berth	At anchorage	Maneuvering	At sea
Bulk Carrier	0-34999	dwt	280	190	310	190
	35000-59999	dwt	370	260	420	260
	60000-600000	dwt	600	420	680	420
Chemical Tanker	0-4999	dwt	160	80	110	80
	5000-19999	dwt	490	230	330	230
	20000-600000	dwt	1170	550	780	550
Container	0-999	TEU	340	300	550	300
	1000-1999	TEU	600	820	1320	820
	2000-2999	TEU	700	1230	1800	1230
	3000-4999	TEU	940	1390	2470	1390
	5000-7999	TEU	970	1420	2600	1420
	8000-11999	TEU	1000	1630	2780	1630
	12000-14500	TEU	1200	1960	3330	1960
	14500-600000	TEU	1320	2160	3670	2160
General Cargo	0-4999	dwt	120	60	90	60
	5000-9999	dwt	330	170	250	170
	10000-600000	dwt	970	490	730	490
Liquefied Gas Tanker	0-49999	cbm	240	240	360	240
	50000-600000	cbm	1710	1710	2565	1710
Oil Tanker	0-4999	dwt	250	250	375	250
	5000-9999	dwt	375	375	563	375
	10000-19999	dwt	625	625	938	625
	20000-79999	dwt	750	750	1125	750
	80000-119999	dwt	1000	1000	1500	1000
	120000-199999	dwt	1250	1250	1875	1250
	200000-600000	dwt	1500	1500	2250	1500
Other Liquids Tankers	0-600000	dwt	500	500	750	500

Refrigerated Cargo	0-600000	dwt	1080	1170	1150	1170
Vehicle	0-600000	cars	800	500	1125	500
Cruise	0-9999	gt	450	450	580	450
	10000-59999	gt	3500	3500	5460	3500
	60000-600000	gt	11480	11480	14900	11480
Ferry – passenger only	0-1999	gt	186	186	186	186
	2000-600000	gt	524	524	524	524
Ferry – cargo + passenger	0-1999	gt	105	105	105	105
	2000-600000	gt	710	710	710	710
Ro-ro	0-4999	gt	800	600	1700	600
	5000-600000	gt	1200	950	2720	950
Yacht	0-600000	gt	130	130	130	130
Fishing	0-600000	gt	200	200	200	200
Tug	0-600000	gt	50	50	50	50
Offshore	0-600000	gt	320	320	320	320
Others	0-600000	gt	190	190	190	190

Table 10: Auxiliary Boiler Power Load

Statcode-5 Ship Type	Capacity	Unit	Auxiliary Engine Load (kW)			
			Activity Mode			
			At berth	At anchorage	Maneuvering	At sea
Bulk Carrier	0-34999	dwt	50	50	50	0
	35000-59999	dwt	100	100	100	0
	60000-600000	dwt	200	200	200	0
Chemical Tanker	0-4999	dwt	125	125	125	0
	5000-19999	dwt	250	250	250	0
	20000-600000	dwt	250	250	250	0
Container	0-999	TEU	120	120	120	0
	1000-1999	TEU	290	290	290	0
	2000-2999	TEU	350	350	350	0
	3000-4999	TEU	450	450	450	0
	5000-7999	TEU	450	450	450	0
	8000-11999	TEU	520	520	520	0
	12000-14500	TEU	630	630	630	0
	14500-600000	TEU	700	700	700	0
General Cargo	0-4999	dwt	0	0	0	0
	5000-9999	dwt	75	75	75	0
	10000-600000	dwt	100	100	100	0
Liquefied Gas Tanker	0-49999	cbm	1000	200	200	100
	50000-600000	cbm	1500	300	300	150
Oil Tanker	0-4999	dwt	500	100	100	0
	5000-9999	dwt	750	150	150	0
	10000-19999	dwt	1250	250	250	0
	20000-79999	dwt	1500	300	300	150
	80000-119999	dwt	2000	400	400	200
	120000-199999	dwt	2500	500	500	250
	200000-600000	dwt	3000	600	600	300
Other Liquids Tankers	0-600000	dwt	1000	200	200	100
Refrigerated Cargo	0-600000	dwt	270	270	270	0
Vehicle	0-600000	cars	268	268	268	0
Cruise	0-9999	gt	250	250	250	0
	10000-59999	gt	1000	1000	1000	0
	60000-600000	gt	500	500	500	0
Ferry – passenger only	0-1999	gt	0	0	0	0
	2000-600000	gt	0	0	0	0
Ferry – cargo + passenger	0-1999	gt	0	0	0	0
	2000-600000	gt	0	0	0	0

Ro-ro	0-4999	gt	200	200	200	0
	5000-600000	gt	300	300	300	0
Yacht	0-600000	gt	0	0	0	0
Fishing	0-600000	gt	0	0	0	0
Tug	0-600000	gt	0	0	0	0
Offshore	0-600000	gt	0	0	0	0
Others	0-600000	gt	0	0	0	0

2.2 Models

- *Introduction of the Near-field and Far-field Problems*

Two models have been developed – one to simulate the near-field and one for the far-field. These models were applied to multiple locations internationally. In both cases, the simulated concentrations are compared with toxicological limits, often expressed as dilution rates (original pollutant concentrations above background over final concentrations above background), found in the literature to assess the impacts of using EGCS on the marine environment.

- *Near-field Model*

2.2..1 Formulation

We constructed a near-field model, which computes the 3D, steady-state concentration distribution resulting from the EGCS washwater discharged by a fleet of vessels in busy open waters such as straits and canals. The model depends on the shipping channel geometry and diffusion properties, ship traffic density and ship categories (effluent discharge rates) through these channels, as well as the lateral spread of discharge sources (ships using scrubbers).

The model computes the cumulative concentration from multiple ships by summing the contribution of individual ships. The effluent concentration field behind a single ship is depicted in Figure 7. The vessel (in green) moves through a channel in the negative x direction while continuously releasing washwater at a rate of$\dot{m}$to form a trailing jet that gets diluted by mixing with the receiving ambient water. The washwater mass flow rate $\dot{m}$ is dependent on the ship category and size (see previous sections). The difference in velocity between the discharge jet and the receiving water causes the ambient water to be entrained into the jet, causing the axisymmetric jet to expand in both y and z directions. A Gaussian distribution is assumed with initial dimensions σ_{y1}, σ_{z1}at location (1) and final dimensions σ_{y2}, σ_{z2}at location (2), resulting in dilution of the effluent concentration from C_o to C. The rate at which the jet expands depends on the eddy diffusivity of the ambient water (Figure 7).

To compute the near-field concentration corresponding to a single vessel, the model adopts the value for diffusion coefficient, E used in the MEPC 74/INF. 24 study, which is a constant determined through CFD simulations. This value is applied in all base case analysis in different locations (more detail in later chapters) and it accounts for the initial mixing induced by the propeller. The model then predicts the dilution in the near-field zone, across the water depth and along the y direction for a given location in x. Because the EGCS discharge is located near the surface, the maximum concentration is found near the surface, and hence the modeling results for the near-field concentration herein correspond to the surface concentration (y = 0).

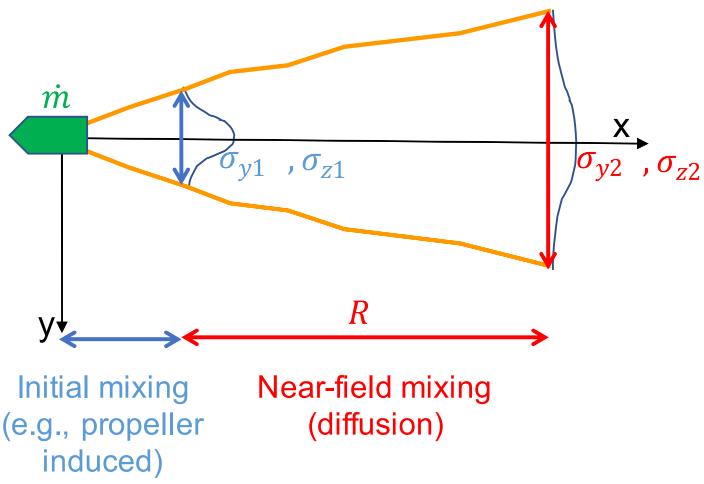

Figure 7.The schematic concentration field of discharge effluent downstream of a single vessel continuously releasing washwater at a rate of $\dot{m}$.

To compute the concentration corresponding to a fleet of vessels at a location, the individual concentration fields of vessels passing through the location are superimposed (Figure 8). For a cross section of a shipping channel AA' of width W depicted in Figure 8, vessels cross at an average distance dlx apart from each other. dlx is set by the amount of traffic typically observed at the location (See earlier chapter on shipping data). The traffic composition of different ship categories is also taken into account since effluent discharge rate depends on ship size and type.

The simulated lateral spread of discharging vessels depends on the combined effect of two factors. First, the ship crossing pattern in the busy waterway – vessels are assumed to follow a normal (Gaussian) distribution while crossing the shipping channel AA' where there is a higher likelihood to find vessels crossing from the center of the channel than from the edges. Therefore, the crossing positions of the vessels are generated randomly by the model with a mean of $W/2$ and a standard deviation of σ (Figure 8). This allows us to simulate vessels that are not exactly aligned and have different degrees of misalignment. In the special case where the vessels are expected to align exactly in a shipping channel, such as in a 'line astern' arrangement observed in some locations, would mean no lateral spread of the effluent source (σ is zero) and hence least dilution. This was the scenario assumed in the MEPC 74/INF .24 study in their concentration analysis of Tokyo Bay.

Secondly, any external factors, such as ambient currents at an angle to the line of travelling vessels, or secondary currents in a curved channel, would introduce lateral spread of the effluent, thus promoting dilution; and this effect is also accounted for in the standard deviation σ.

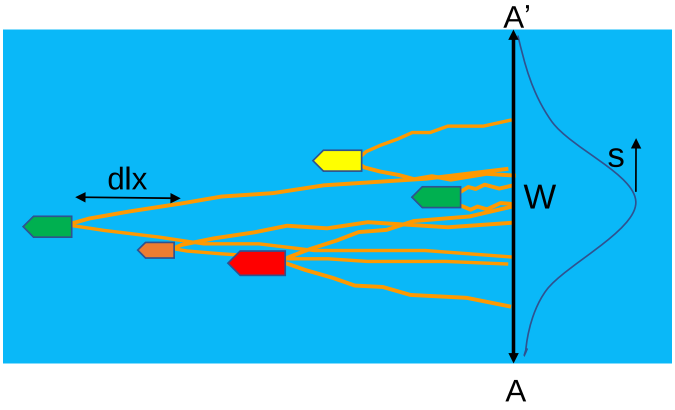

Figure 8.Schematics of the near-field model in top-view. Vessels in different colors denote different ship types (thus engine load capacities). (Left) vessels cross a line AA' normal to a shipping lane of width W and following a Gaussian distribution with a mean crossing location in the middle of the lane and a lateral spread with a standard deviation of σ.

The model is thus formulated as follows:
If assuming one ship type and a total N number of ships of this type,

$$C(x,y,z) = \sum_i^N \frac{\dot{m}_i}{u\pi\sigma_i^2} e^{-\frac{(y-y_0)^2}{2\sigma_i^2}} [e^{\frac{(z-z_0)^2}{2\sigma_i^2}} + e^{\frac{(z+z_0)^2}{2\sigma_i^2}}] \quad \text{0-1}$$

where

$$\sigma_i^2 = 2E\tau_i = 2E\frac{x_i}{u_s} = \frac{2E(i-\frac{1}{2})\tau u_s}{u_s} = 2E(i-\frac{1}{2})\tau \quad \text{0-2}$$

So $C(x,y,z)$ can be expressed in terms of τ and E

$$C(x,y,z) = \sum_i^N \frac{\dot{m}_i}{2u\pi E(i-\frac{1}{2})\tau_i} e^{-\frac{(y-y_0)^2}{4E(i-\frac{1}{2})\tau}} [e^{\frac{(z-z_0)^2}{4E(i-\frac{1}{2})\tau}} + e^{\frac{(z+z_0)^2}{4E(i-\frac{1}{2})\tau}}] \quad \text{0-3}$$

$$C/C_o = \sum_i^N \frac{Q_{oi}}{2u\pi E(i-\frac{1}{2})\tau_i} e^{-\frac{(y-y_0)^2}{4E(i-\frac{1}{2})\tau}} [e^{\frac{(z-z_0)^2}{4E(i-\frac{1}{2})\tau}} + e^{\frac{(z+z_0)^2}{4E(i-\frac{1}{2})\tau}}] \quad \text{0-4}$$

If we now assume there are J different ship types, then the near-field model becomes

$$C/C_o = \sum_{j=1}^{J} \sum_{i=1}^{I=\dot{N}f_j} \frac{Q_{oj}}{2u_j \pi E(i-\frac{1}{2})\tau_j} e^{-\frac{(y-y_o)^2}{4E(i-\frac{1}{2})\tau_j}} [e^{\frac{(z-z_o)^2}{4E(i-\frac{1}{2})\tau_j}} + e^{\frac{(z+z_o)^2}{4E(i-\frac{1}{2})\tau_j}}] \quad \text{0-5}$$

I is the total number of ships belonging to ship type j, f_j is the protion (as a fraction) of the total number of ships crossings N belonging to type j. $C/C_o$is the near-field cumulative concentration$C$ normalized against the initial C_o. $\dot{N}$is the ship arrival frequency (vessel /s). J is the number of different ship categories present. Q_{oi} is the volumetric flow rate of discharged water (m^3/s), with i denoting the i-th ships$u$ is the ship velocity (m/s). E is the diffusion coefficient (m^2/s), assuming homogeneous and isotropic diffusion in x, y and z directions. τ is the time interval at which vessels arrive (s). z and y are vertical and lateral positions for computing the concentration, with subscript 0 denoting the vertical and lateral positions of the source. z is set to zero in the simulations for maximum concentration, which takes place on the free surface.

2.2..2 Assumptions

Due to the limited data available from literature, estimates best representing he field conditions are sometimes made for the model parameter values. The major assumptions are outlined below.
The amount of traffic and the traffic composition that is the percentage of each ship category, at each study site is taken as the typical values recently observed at that site and therefore represent the current concentration without projection into future levels. We also assume uniform distribution of arrival in time for all ship types and the arrival do not exhibit any group effects, that is, the vessels of the same type do not appear in a clustered fashion. Any seasonal variation in the traffic is also ignored. Out of all types, only vessels of medium to large size, namely cargos, tankers and cruise ships, are assumed to have installed EGCS and are therefore considered as discharge sources in the near-field calculations. This is based on the financial analysis by (Lindstad & Bø, 2017) where it is presented that EGCS systems are financially more attractive for larger vessels. In the base case simulations, the speed at which all ships travel in the model is taken as 11 m/s, the arithmetic average of the speed range typically observed in the study sites of interest (see next section). The trajectory of the vessel is assumed such that the vessels move in a straight line along the x direction.
We further assume that the effluent consists of conservative substances (no decay or loss of suspended particles through settling into the sedimentary seafloor) and that there is no background concentration of the individual effluent component. Simulations presented here are for surface concentrations (z = 0), and assume that the plume does not reach the channel bottom. However, calculations could be made for concentration on the bottom of the channels, c_{bot} by setting z = h (depth of the channel) and applying images distributed in the vertical (assume no-flux boundary condition on the bottom and free boundary condition on the surface). Literature should be surveyed to distinguish impacts to typical benthic versus surface organisms, and to consider the duration of exposure.

2.2..3 Applications (Open Waters)

Five study sites, namely Tokyo Bay, the Strait of Malacca, the Persian Gulf, the Strait of Gibraltar and Panama Canal, have been chosen for the near-field investigation for their high traffic activities, thus high environmental impact in the vicinity of the ships, the available data on the locations and for the ease of comparison with predicted concentrations found in the literature - some of these locations.

- Far-field Model

2.2..1 Formulation

We also constructed a far-field model to simulate the background buildup (assume well-mixed) of effluent concentration with time, specifically in the relatively enclosed geographic locations such as bays and ports where accumulation of effluent due to poor water exchange could be significant. When the effluent leaves the near-field mixing zone, they start to act as passive sources. A passive source is one in which the introduction of the tracer or contaminant does not appreciably alter the ambient flow and turbulence level. At the transition from near- to far-field, the source velocity and turbulence level approach their ambient values and the subsequent history can be treated as a passive source. In other words, the "far-field", is the zone in which advection and diffusion are governed by ambient conditions.

Our far-field model simulates cases where a water body of interest sees continuous release from an average number of vessels (Figure 9), either moving or at berth at any given time. When the vessels move (for the purposes of arriving at or departing from the port/harbor), they emit more washwater per time (cruise load) than when they are anchored or at berth (hotel load). In addition to the vessel moving status, the washwater flow rate is also dependent on the ship category and size (see previous sections). The far-field model takes into account the vessel arrival frequency into the enclosed waters and vessel type, the vessel residence time inside the location (which includes both time spent moving or at berth, each with different levels of loading), the pollutant residence time (as determined by the water exchange rate at the location), the removal rate of pollutants through decay or settling, as well as the size and shape of the waterbody.

The model for the equilibrium background concentration is thus formulated as follows:

$$C_{FF} / C_o = \frac{\dot{N} T_r \sum_{j=1}^{J} f_j \left(T_{jv\_anch} Q_{jv\_anch} + T_{jv\_mov} Q_{jv\_mov} \right)}{V(1 + kT_r)} \qquad 0\text{-}6$$

Q_j is the volumetric flow rate of discharged water (m^3/s), with j denoting the j-th ship out of a total of N ships (not to be confused with the flushing rate of the embayment, Q in Figure 9); 'anch and mov' refer to the anchored and moving status of the vessel, respectively. f_j is the fraction of each vessel category. T_v is the vessel residence time or the amount of time vessels spend in port); T_r is the pollutant residence time; V is the volume of the port.; and k is the removal (decay, settling) rate of effluent substances.

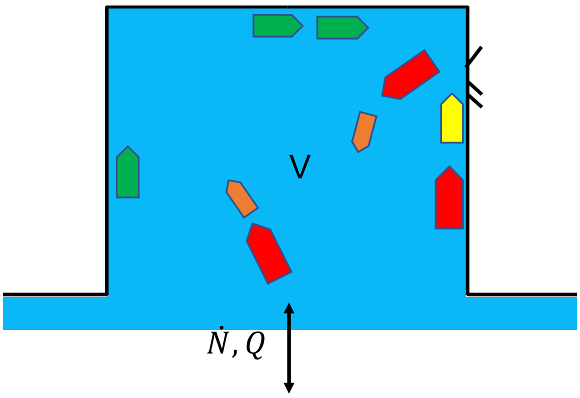

Figure 9.Schematics of the far-field model in top-view. Vessels in different colors denote different ship types (thus engine load capacities). Vessels move and berth inside an enclosed waterbody (of volume V) that receives on average number of vessels per time $\dot{N}$ and has a flushing rate of Q.

2.2..2 Assumptions

As for the near-field model, the far-field model also assumes that the traffic frequency and composition (by type) stay constant over time for a given location. Only cargoes, tankers and cruise ships are considered in the far-field calculations due to the high likelihood of EGCS installation in larger vessels only. We use a single value for the time vessels spent moving and berthing, as well as for the effluent discharge rates corresponding to these two statuses. The same values are applied to all ship types that are considered as discharge sources.

The water exchange rates, and thus the effluent residence times of the investigated waterbodies, are taken as the most up-to-date values found in the literature (more detail in the next chapter). Local residence times are sometimes adopted for different parts of a same large embayment when change in flushing properties becomes significant from place to place within the domain.

The far-field model assumes removal of effluent substances from the water column through settling and decay processes. Fine particles in the effluent may settle on their own, while dissolved substances may settle after first sorbing to ambient particles.

2.2..3 Applications (Enclosed Waters)

Three study sites used in the far-field study are Tokyo Bay, Persian Gulf, Port of Galveston and Port of Qingdao, which are intended to represent adverse scenarios for calculating far-field concentration due to relatively high traffic and low flushing rate.

2.3 Simulated Results

- *Global pollution hotspots for case study*

The models developed for the near- and far-field have been applied to potentially problematic regions in terms of effluent accumulation and water quality. We identified the study sites primarily based on their high traffic density and high percentage of larger vessels (we assume only larger vessels are fitted with scrubbers) in the traffic in comparison to global averages.

- *Near-field Analysis Results*

2.3..1 Persian (Arabian) Gulf

2.3..1.1 Base Case Results

For the near-field analysis of the region, we more specifically focus on the Strait of Hormuz. The domain is shown in the left of Figure 10. As the only passage through which the Persian Gulf is connected to the open sea, the strait is of great strategic and economic importance and is vital to the livelihood of the seaborne trade in the Middle East (www.britannica.com). The strait sees high shipping traffic density year-round, and is thus interesting to investigate from a pollution emission standpoint.

Despite minor fluctuations observed in traffic counts across seasons (AIS data analysis), we assume an annual average traffic count of 15 vessels/hour for simulating the base case scenario. The traffic composition, according to exact Earth, mostly consists of medium to large vessels with 35% cargo ships and 44% tankers, as expected from the resource-driven transport activities around the gulf region.

The width of the strait is between 55 and 59 km. The traffic map shown in Figure 10 suggests that the vessels entering and leaving the gulf follow fixed shipping lanes, as evident by the distinctive yellow lines (high traffic region) in the middle of the strait. The shipping lane is estimated to be 2 km wide in each direction (in and out of the gulf).

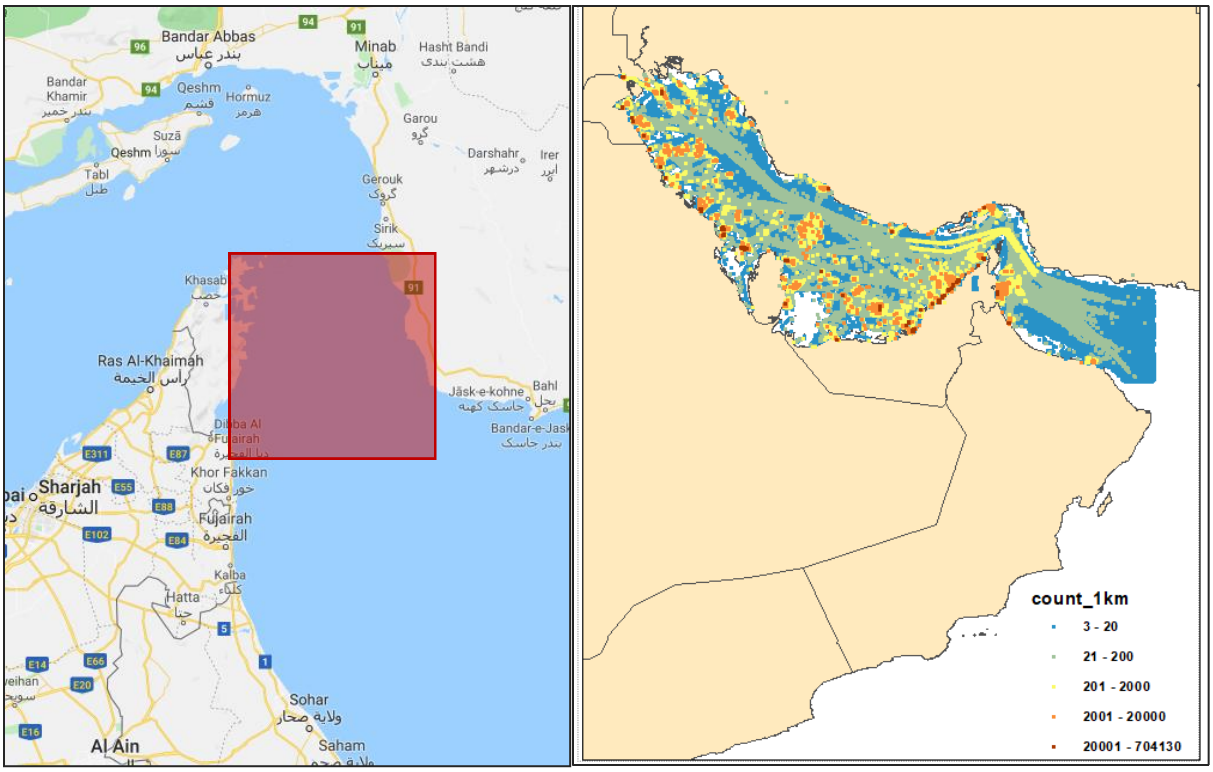

Figure 10. (Left) The domain of Study (red area) near the Strait of Hormuz. (Right) Total shipping traffic count in the Persian Gulf in 2015 with warmer colors denoting higher recorded number of vessels in each 1km by 1km area.

Across the 2-km-wide shipping lane, we assume ships traverse with lateral displacements from the center of the lane following a Gaussian distribution as illustrated in Figure 8. In the case of the strait, we apply a standard deviation that is taken as one-tenth of the channel width.
The number of ships in the channel for which the cumulative effect is computed is assumed to be 300 for a reference. This value is chosen because it is the number of vessels likely to fit within the study domain (Figure 10) at the given ship traffic density. In other words, 300 is the average number of vessels expected to be found in the study domain at any given time. This is likely a very conservative (high) estimate.
Finally, we adopt the aforementioned value of the diffusion coefficient (developed in the MEPC 74/INF .24 study) for both the horizontal and vertical directions.
The base case parameter values for the Persian (Arabian) Gulf are summarized in Table 11.

Table 11. Near-field parameters for the Persian Gulf used in the reference case simulation

Parameters	Values	Units
$\dot{N}$, ship arrival frequency	15	Vessels/hour
f_c, percentage of traffic (cargo)	35	%
f_t, percentage of traffic (tanker)	44	%
J, total number of ship types	2	-
W, shipping lane width	2000	m
σ,standard deviation (= *W/10*)	200	m
E, diffusion coefficient	0.29	m^2/s
u, ship speed	11	m/s
Effluent flow rate	45	t/MWh
N, total number of vessels	300	vessels

The near-field model equation (0-5) computes the cumulative concentration (normalized against discharge concentration) of multiple vessels arriving in the channel in sequence, at a distance dlxm behind each other and in a fashion illustrated in Figure 8. Using the reference parameter values presented in the previous section, the reference case simulation result is generated. This simulation, as well as every simulation hereafter, is repeated 100 times as the crossing position is randomly generated for each vessel in every realization. The average of the 100 realizations is taken and presented as the reference case (Figure 11). The cumulative concentration of a fleet of vessels in the reference case appears to be below the threshold under the assumed conditions as far as the near-field is concerned.

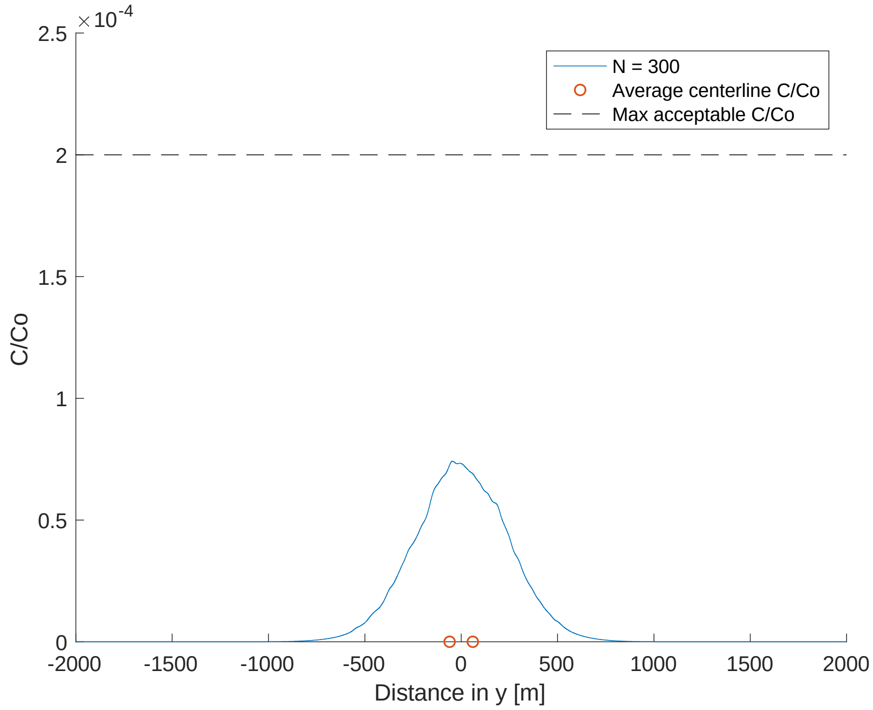

Figure 11. Near-field reference case for the Strait of Hormuz, assuming a total of 300 vessels. The maximum acceptable concentration for the chosen PNEC of this study is shown as a dashed line. The peak concentration across the channel (y = [-1000m, 1000m]) width is observed to be in the center (y = 0), as expected.

2.3..1.2 Sensitivity Analysis

The parameter values used in the reference case best represent the current real-life condition to the best of our knowledge. Nonetheless, uncertainties can exist, and that the real-life conditions themselves may change over time. A sensitivity analysis is therefore carried out to identify the key parameters that the near-field concentration is most dependent on and to determine the variation in the simulated concentrations with varying parameter values.

The value of the diffusion coefficient in the reference case was taken as a constant; however, non-constant diffusion coefficients which vary with distance downstream of the discharge, as formulated by (Okubo, 1971) and by Tennekes and Lumleyin the book *A First Course in Turbulence* for 3D axisymmetric wakes, can be suitable to use in this case. For this reason, a range of values for the diffusion coefficient may be applicable in real-life, and we seek the corresponding change in concentration to a range of E values (Figure 12). As can be seen in the figure, the concentration is inversely proportional to the E value. In other words, the effluent jet experiences more diffusion and thus retains lower concentration at large E values. Only when E is 10 times smaller than the reference value is the near-field concentration likely to be higher than the threshold. This suggests that the variation in E is unlikely to change the conclusions about the near-field impact of scrubbers since E in the field is unlikely to undergo similar magnitudes of change. It should be noted that the mass is conserved between each simulation with different E if diffusion in depth is also considered (only the surface concentration is shown in Figure 12 since only the most polluted region is of interest).

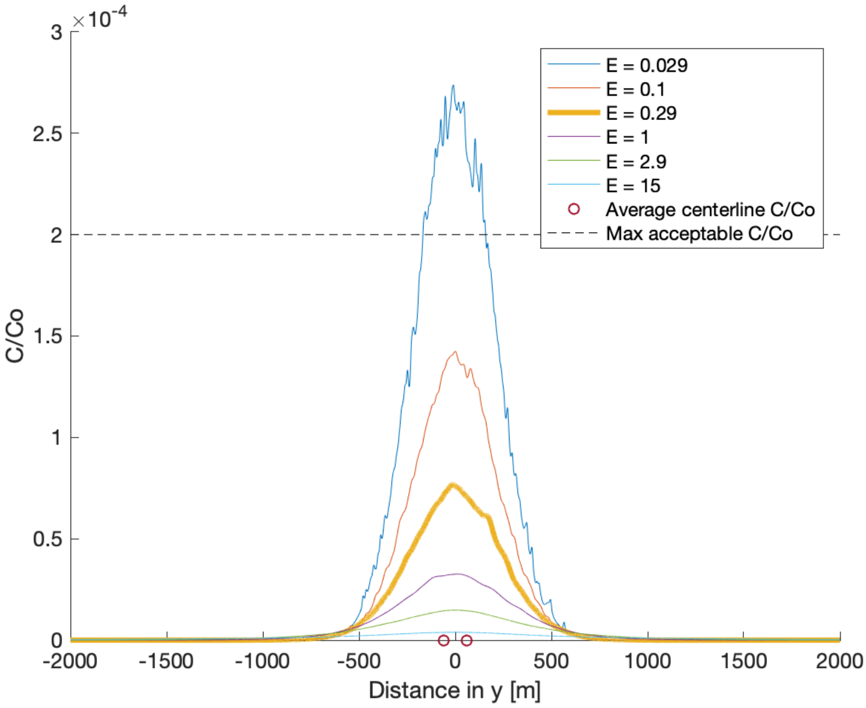

Figure 12. The sensitivity of near-field concentrations (normalized again discharge concentration) in the Strait of Hormuz to changing diffusion coefficients, E. The bolded yellow line denotes the reference case value (Figure 11) where E = 0.29.

The sensitivity to the total number of vessels in the channel at any given time has also been investigated. The change in N reflects a change in traffic density, which may occur across days of the week and season and with changes in trade activities over time. A range of values for N is used in the analysis and the resulting change in concentrations is shown in Figure 12.

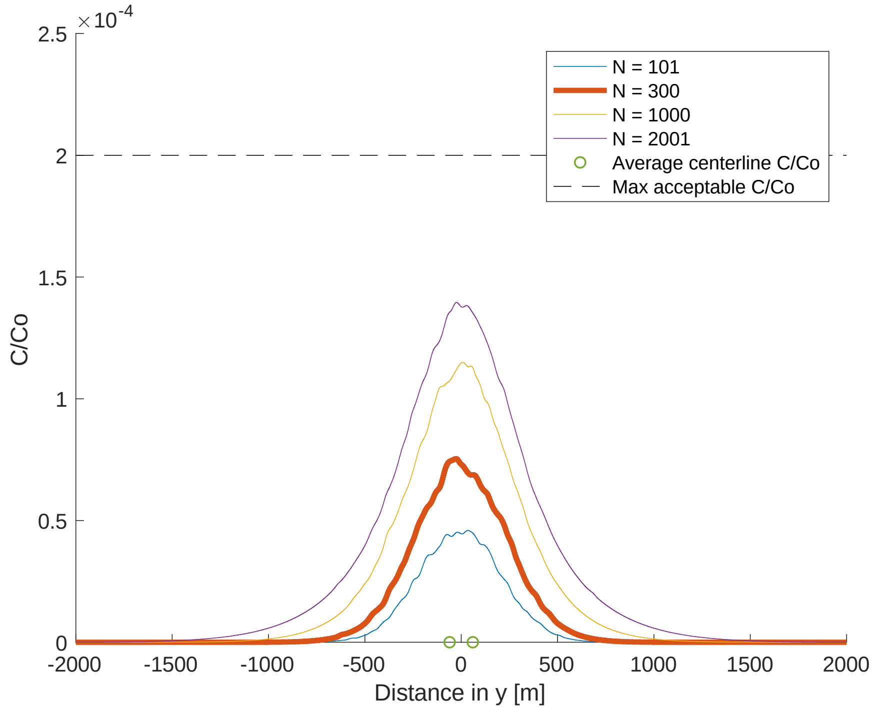

Figure 13. Cumulative near-field concentration (normalized again discharge concentration) for a varying number of vessels. Bolded red line is the reference case shown in Figure 12, for which N = 300.

As evident in Figure 13, it is improbable that the simulated concentration will begin to cause ecological concerns with an order-of-magnitude increase in the fleet size.

Lastly, we examined the dependence of near-field concentration on the standard deviation. Standard deviation is a combined measure of how ‘lined up’ the vessels are with each other while travelling in the channel and the external forcing that acts to displace the discharge laterally, as explained in Section 2.2..1. The results are presented in Figure 14, with the base case value highlighted in purple. The results suggest that the near-field concentration can be significantly affected by the varying standard deviation. Notably, when ships assume a “line astern” arrangement, which corresponds to a standard deviation of zero and can be common practice in narrow geographic locations, the concentration exceeds the threshold considerably.

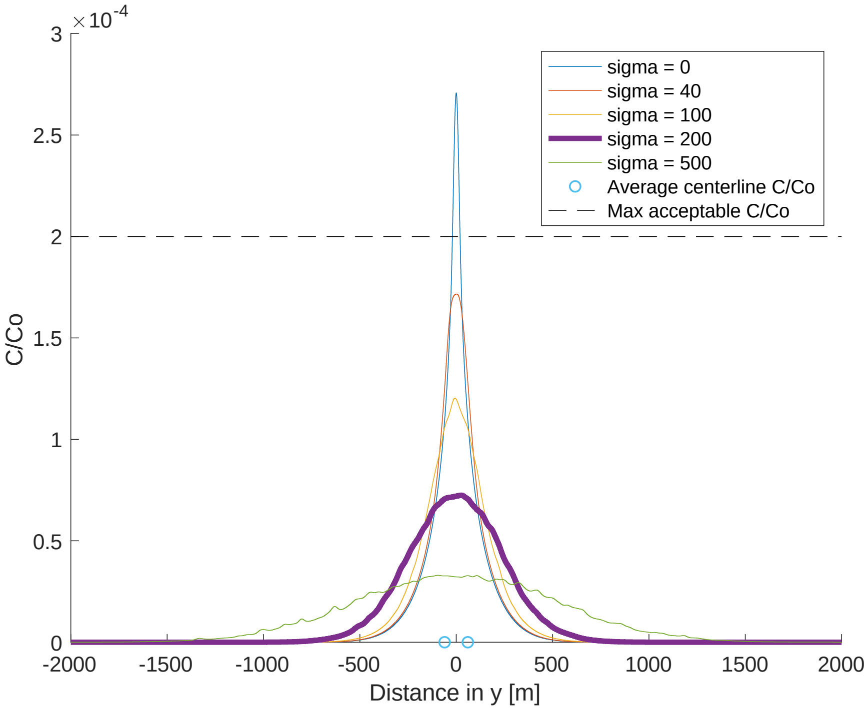

Figure 14.Near-field concentration (normalized again discharge concentration) for varying standard deviation. The base case value of 200 (one tenth of the channel width) is depicted in purple.

2.3..1.3 Conclusions

Under the current set of assumed conditions about the Strait of Hormuz, the model, which assesses the environmental impact of the effluent as a whole, shows that the near-field washwater concentration is generally above the semi-arbitrary dilution threshold of 5000. Sensitivity analysis further suggests that under particular circumstances, such as a tight 'line astern' arrangement of ships, washwater concentration may go above the threshold of 1/5000. We thus conclude that EGCS discharge is unlikely to cause ecological concern from a near-field perspective (in the immediate wake of vessels), based on the current level of seaborne traffic through the strait and on other assumptions made in the reference scenario, as well as on the reference PNEC of 1/5000 that the current study compares to. The use of this limit is inferred, and therefore, the conclusions may differ should more suitable PNEC be established and be available for comparison in the future.

2.3..2 Tokyo Bay

2.3..2.1 Base Case Results

For the near-field analysis of Tokyo Bay, the study domain is shown in Figure 15. As the most populated and largest industrialized region in Japan, like the Persian (Arabian) Gulf, Tokyo Bay plays a vital role in sea transport in the country. The bay experiences high shipping traffic density year-round, and has been studied (MEPC 74/INF .24) previously, making it an interesting location to investigate for result comparison and validation purposes.

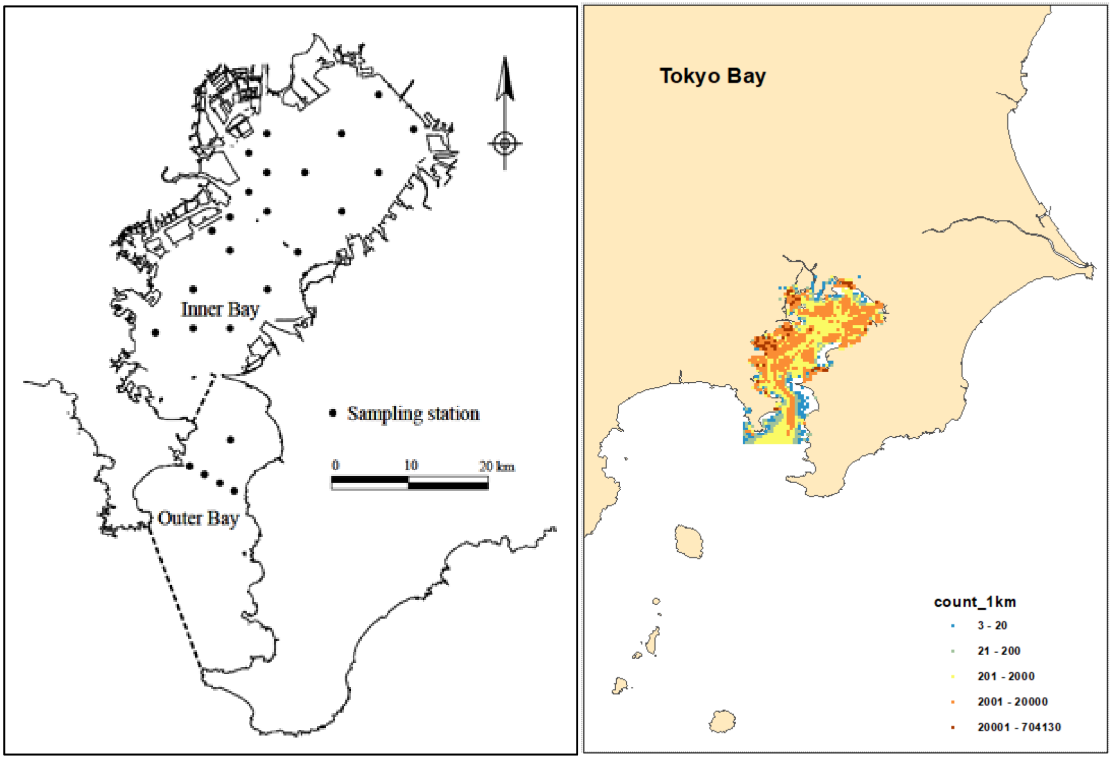

Figure 15. (Left) The map of Tokyo Bay showing both the inner and outer bays. Adopted from (OKADA, TAKAO, NAKAYAMA, & FURUKAWA, 2007)*. (Right) The traffic heatmap showing total shipping traffic count in Tokyo Bay in 2015 with warmer colors denoting higher recorded number of vessels in each 1km by 1km area.*

In reality, the daily ship arrival varies all the time as the combination of ship types and sizes in the bay changes regularly. However, the near-field model only accepts a single daily input so an approximation of the traffic frequency has been made. For this frequency, our study adopts the same value of 28 vessels/hour as the MEPC 74/INF .24 study for the base case scenario in order to be consistent. The traffic breakdown by ship type (size), according to Exact Earth traffic data for July 2015, predominantly consists of medium to large vessels with 62% cargo ships and 28% tankers, and the remaining is made up of fishing and passenger vessels. We assume only cargo ships and tankers are fit with scrubbers and we use above percentages of traffic in the base case simulations, though these percentages are expected to fluctuate over months and years and be considered as a source of uncertainty.

Despite the apparent uniform traffic density inside the bay, Figure 15 suggests that the vessels entering and leaving through the mouth (Nakanose Passage) follow fixed shipping lanes, as evident by the distinctive yellow lines in the middle of the mouth crossing shown on the right figure. The shipping lane is estimated to be 2 km wide in each direction (in and out of the Bay) and the average length of the lane, which is taken as the distance from the bay opening to the Port of Tokyo, is about 55 km.

Across the 2 km-wide shipping lane, we assume ships traverse with lateral displacements from the center of the lane following a Gaussian distribution as illustrated in Figure 8. In the case of the bay, we apply a standard deviation that is taken as one-tenth of the channel width, 200 m. The number of ships in the simulated fleet is assumed to be 39 for a reference. This value is chosen because it is the number of vessels that would fit within the length of the ship lane (55 km) at the given ship traffic frequency. In other words, 39 is the average number of vessels expected to be found the shipping lane in or out of Tokyo Bay at any given time. 55 km/ (3600/28*11) ≈ 39 ships.

Finally, we adopt the aforementioned value of diffusion coefficient (developed in the MEPC 74/INF .24 study) for both the horizontal and vertical directions.

The base case parameter values for Tokyo Bay are summarized in Table 12.

Table 12. Near-field parameters for Tokyo Bay used in the reference case simulation

Parameters	Values	Units
$\dot{N}$, ship arrival frequency	28	Vessels/hour
f_c, percentage of traffic (cargo)	62	%
f_t, percentage of traffic (tanker)	28	%
J, total number of ship types	2	-
W, shipping lane width	2000	m
σ,standard deviation (= *W/10*)	200	m
E, diffusion coefficient	0.29	m^2/s
u, ship speed	11	m/s
Effluent flow rate	45	t/MWh
N, total number of vessels	39	vessels

The near-field model equation (0-5) computes the cumulative concentration (normalized by discharge concentration) of multiple vessels arriving in the channel in sequence, at a distance dlxm behind each other and in a fashion illustrated in Figure 8. Using the reference parameter values presented in the previous section, the reference case simulation result is generated (Figure 11). This result, as for the Persian (Arabian) Gulf, is the average of 100 realizations. As evident in Figure 16, the cumulative concentration of a fleet of vessels in the reference case appears to be below the threshold under the assumed conditions as far as the near-field is concerned.

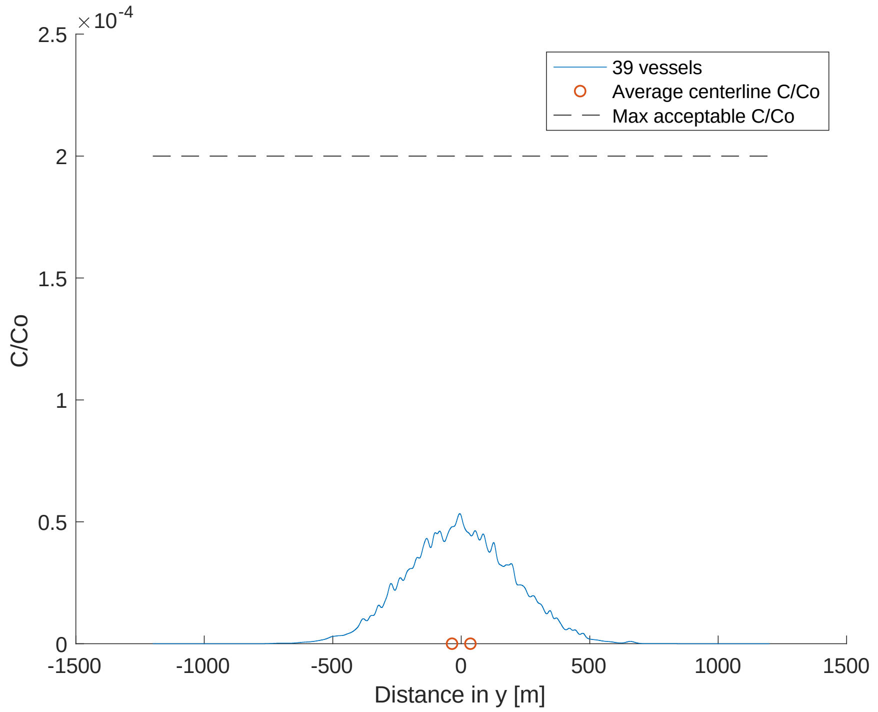

Figure 16. Near-field reference case for Tokyo Bay, assuming a total of 39 vessels. The maximum acceptable concentration for the chosen PNEC of this study is shown as dashed line. The peak concentration across the channel (y = [-1000m, 1000m]) width is observed to be in the center (y = 0), as expected.

2.3..2.2 Sensitivity Analysis

Due to the inevitable uncertainties that exist in the parameter values used, a sensitivity analysis is carried out to identify the key parameters for the near-field concentration and to determine the variation in the simulated concentration corresponding to a range of parameter values. The diffusion coefficient in the reference case was taken as a constant; however, a range of values for diffusion coefficient may be applicable in the field at different distances downstream of the discharge point. Here, the corresponding change in concentration to a range of E values is shown in Figure 17. Similar to the Strait of Hormuz, the effluent jet experiences more diffusion and thus retains less concentration at large E values. The variation in E is unlikely to change the conclusions about the near-field impact of scrubbers since the concentration is not sensitive to changing E and E in the field is unlikely to undergo larger magnitude change than in the sensitivity analysis. It should be noted that the mass is conserved, but since only the surface concentration is shown, the area under each curve is not the same.

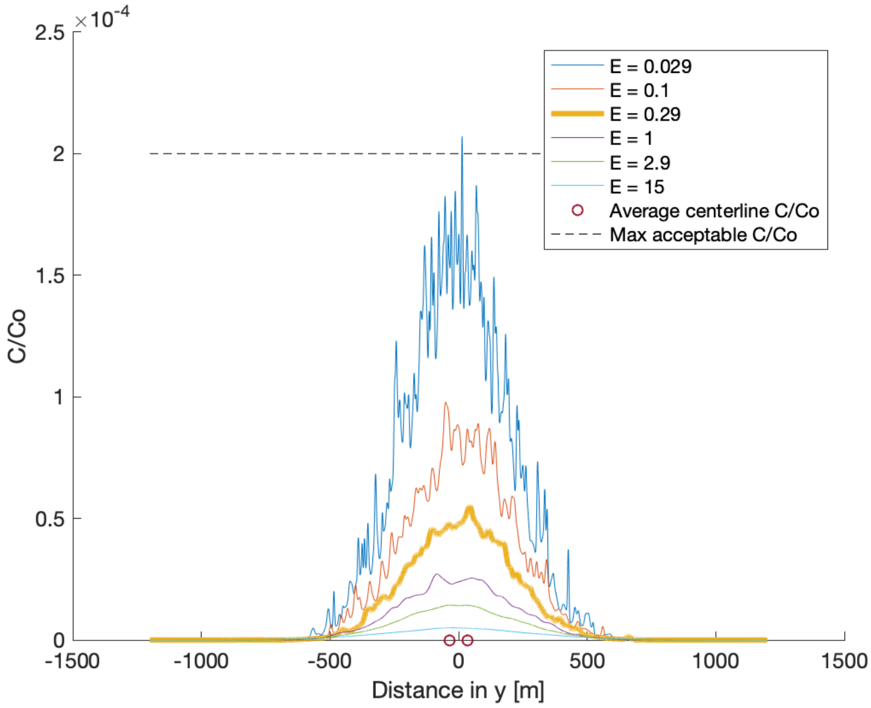

Figure 17. The sensitivity of near-field concentration (normalized again discharge concentration) in Tokyo Bay to changing diffusion coefficient, E. The bolded yellow line denotes reference case value (Figure 16) where E = 0.29.

The sensitivity to the total number of vessels in the channel at any given time has also been investigated. The change in N is a combined reflection of the change in traffic frequency and composition, both of which may occur across day of the week, month, season and over longer terms. A range of values for N is used in the analysis and the resulting change in concentration is shown in Figure 18.

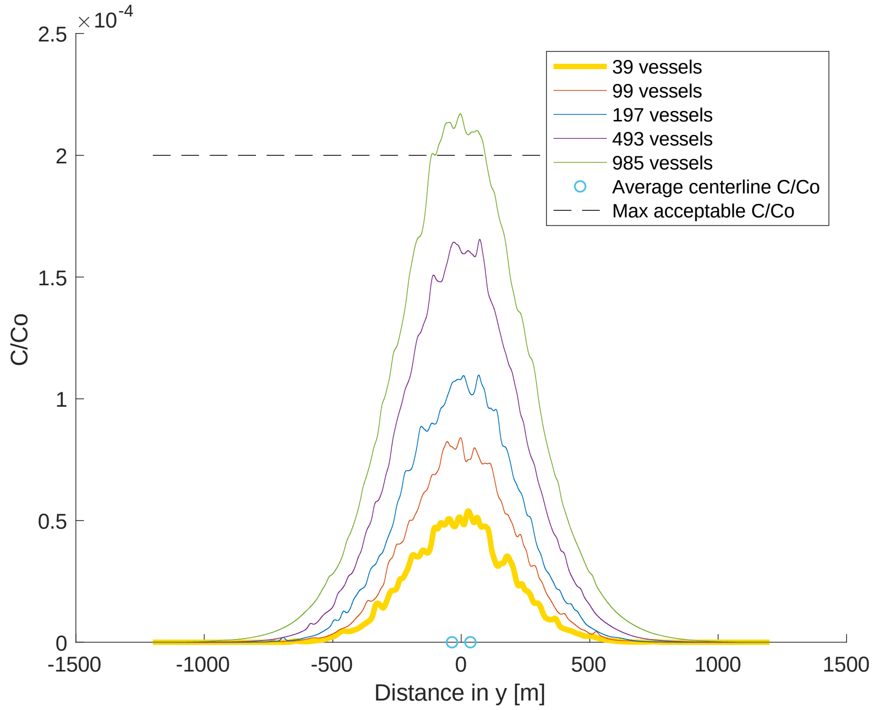

Figure 18. Cumulative near-field concentration (normalized again discharge concentration) for a varying number of vessels. Bolded yellow line is the reference case shown in Figure 17, for which N = 39.

As evident in Figure 18, the simulated concentration will begin to cause ecological concerns with nearly two orders of magnitude increase in the fleet size.

Lastly, the dependence of near-field concentration on the standard deviation is examined. Standard deviation is a combined measure of the alignment of the vessels while travelling in the channel and any external forcing responsible for displacing the discharge laterally, an effect equivalent of ship misalignment. The results are presented in Figure 19, with the base case value highlighted in yellow. The near-field concentration shows sensitivity to the varying standard deviation. Notably, when the standard deviation is zero, the concentration is capable of exceeding the threshold considerably.

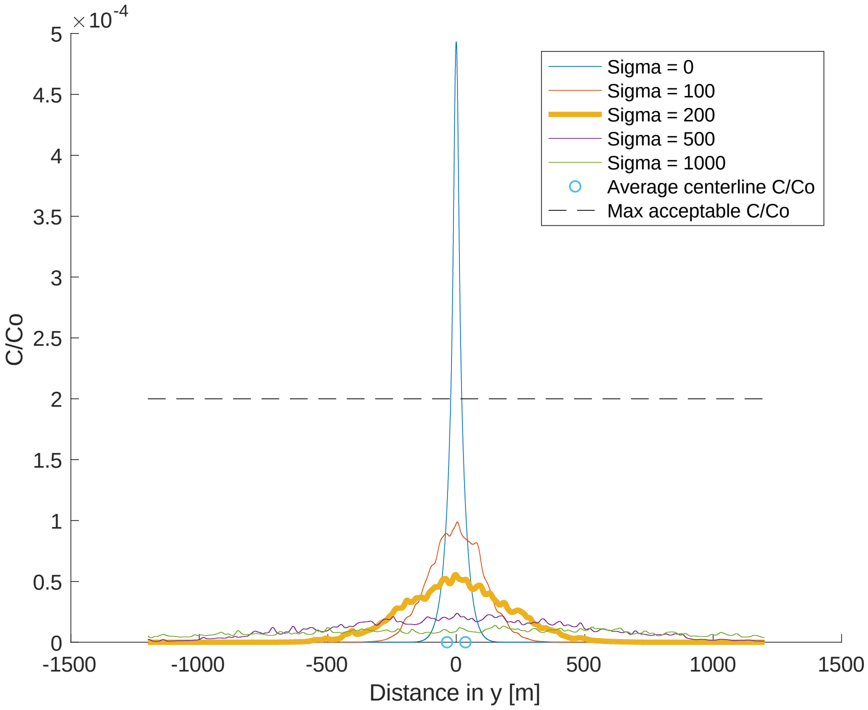

Figure 19. Near-field concentration (normalized again discharge concentration) for varying standard deviation. The base case value of 200 (one tenth of the channel width) is highlighted in yellow.

2.3..2.3 Conclusions

The model, which assesses the environmental impact of the effluent as a whole, shows that the near-field washwater concentration is generally below the concentration threshold of 1/5000, given the assumptions made. However, sensitivity analysis further suggests that under particular circumstances, such as a tight 'line astern' arrangement of ships, washwater concentration may go above the threshold. The use of this threshold is semi-arbitrary, and the establishment of a minimum concentration below which no toxicity effects could be observed is still an active area of research. We thus conclude that EGCS discharge is unlikely to cause ecological concern from a near-field perspective (in the immediate wake of vessels), based on the current level of marine traffic through Tokyo Bay and on other assumptions made in the reference scenario, and when compared to the PNEC of 1/5000.

2.3..3 The Panama Canal

Following a similar analysis procedure as described in Section 2.3..1.1, the near-field concentration for the Panama Canal has been conducted. A list of the parameter values used for simulating the reference case is highlighted in Table 13. The far-field analysis is not applicable for this location as it is open water where an equilibrium concentration may not be established.

Notably, due to the extreme narrow channel width, a 'line astern' arrangement is assumed to be the base case that closely represents the field conditions.

Table 13. Near-field base case parameters for the Panama Canal

Parameters	Values	Units
$\dot{N}$, ship arrival frequency	1.54	Vessels/hour
f_c, percentage of traffic (cargo)	70	%
f_t, percentage of traffic (tanker)	23	%
J, total number of ship types	2	-

W, shipping lane width	30	m
σ,standard deviation	0	m
E, diffusion coefficient	0.29	m^2/s
u, ship speed	4.11	m/s
Effluent flow rate	45	t/MWh
N, total number of vessels	8.5	vessels

The reference case simulation result is shown in Figure 20. From the figure, it is evident that the near-field concentration is unlikely to cause ecological concerns when compared against the PNEC and under the current assumptions.

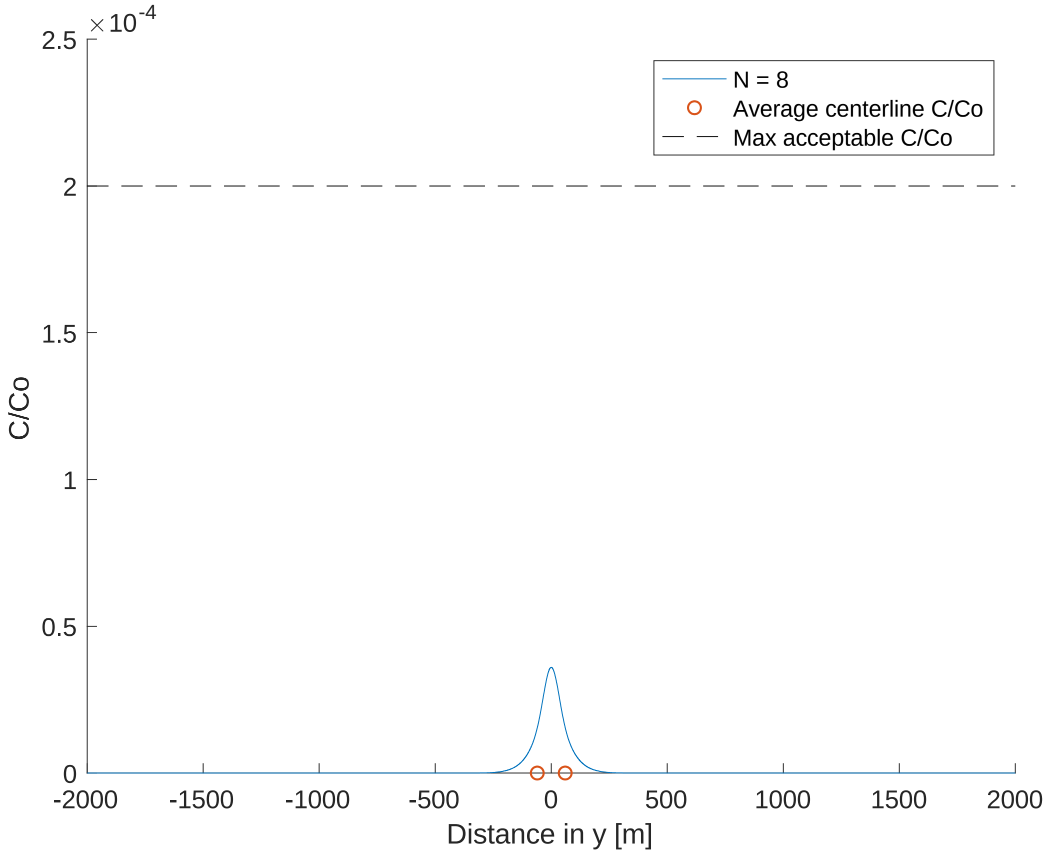

Figure 20. Reference case simulation for the Panama Canal.

2.3..4 The Strait of Malacca

Similarly, for the Strait of Malacca, the parameter values and results for the near-field concentration are presented in Table 14 and Figure 21. The near-field concentration is not likely to cause adverse environmental effects despite being one of the busiest straits in the world. The far-field analysis is not applicable for this location due to the geographic characteristics.

Table 14. Near-field base case parameters for the Strait of Malacca

Parameters	Values	Units
$\dot{N}$, ship arrival frequency	10.7	Vessels/hour
f_c, percentage of traffic (cargo)	66	%
f_t, percentage of traffic (tanker)	33	%
J, total number of ship types	2	-
W, shipping lane width	5000	m

σ,standard deviation	250	m
E, diffusion coefficient	0.29	m^2/s
u, ship speed	11	m/s
Effluent flow rate	45	t/MWh
N, total number of vessels	241	vessels

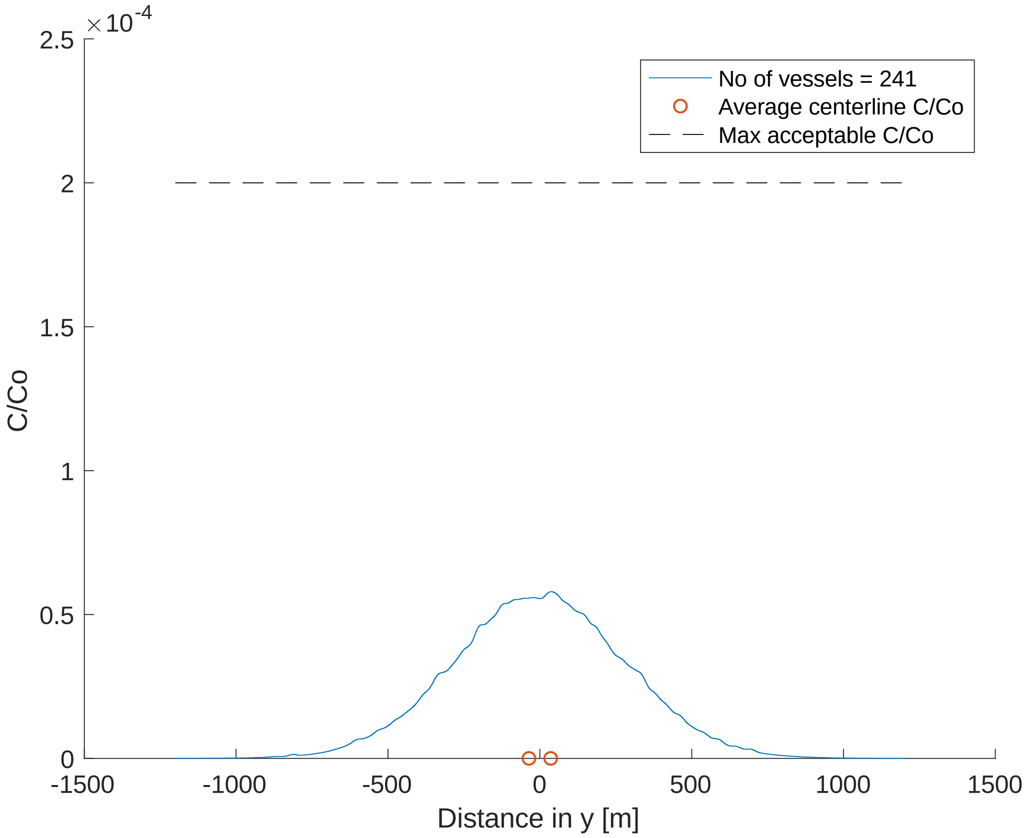

Figure 21. Reference case simulation for the Strait of Malacca

2.3..5 The Strait of Gibraltar

Lastly, the same near-field analysis is carried out for the Strait of Gibraltar and the results are presented below. And like all other study sites, the near-field concentration is unlikely to be problematic for the Strait of Gibraltar.

Table 15. The near-field parameter values for the Strait of Gibraltar concentration

Parameters	Values	Units
$\dot{N}$, ship arrival frequency	8.9	Vessels/hour
f_c, percentage of traffic (cargo)	66	%
f_t, percentage of traffic (tanker)	24	%
J, total number of ship types	2	-
W, shipping lane width	3500	m
σ,standard deviation	350	m
E, diffusion coefficient	0.29	m^2/s
u, ship speed	11	m/s

Effluent flow rate	45	t/MWh
N, total number of vessels	11	vessels

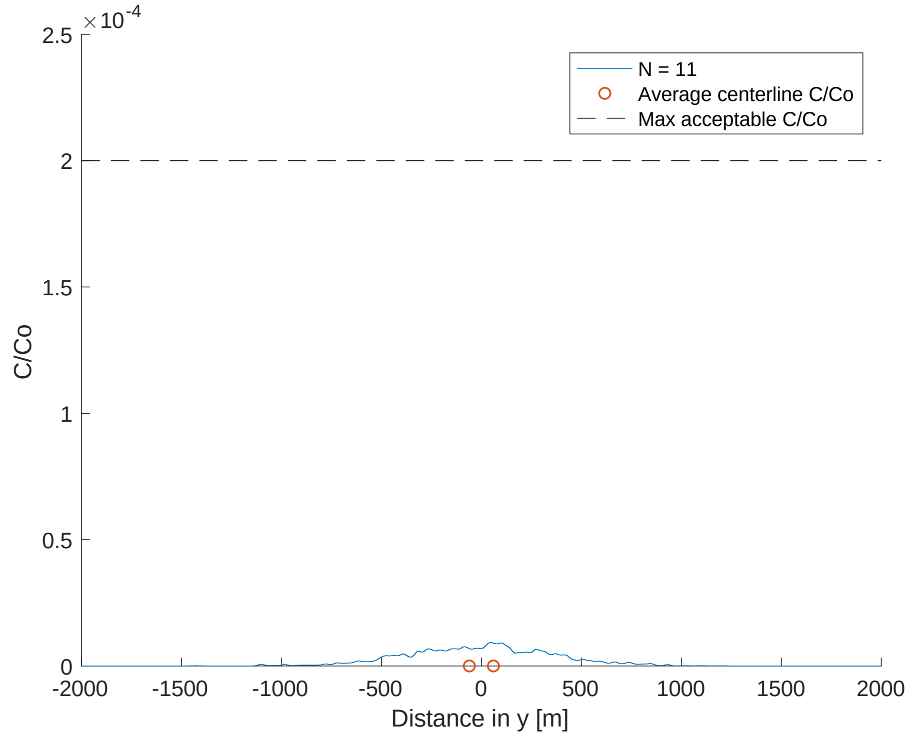

Figure 22. The near-field concentration for the reference case in the Strait of Gibraltar.

- *Far-field Analysis Results*

2.3..1 Persian (Arabian) Gulf

For the far-field analysis, the study domain of focus is the entire Persian (Arabian) Gulf as shown in Figure 23.

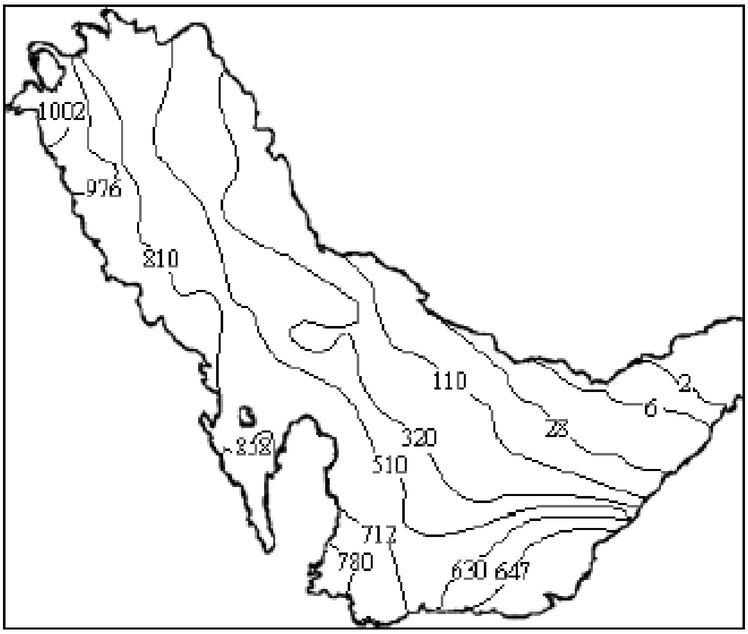

Figure 23.The far-field study domain of the Persian (Arabian) Gulf with contour lines showing pollutant residence times (in days) for different parts of the gulf (Alosairi, Imberger, & Falconer, 2011)*. Inner gulf region generally has longer residence times due to poor flushing and shallow water depth.*

We assume an equilibrium state of traffic within the gulf. As with the near-field analysis, we use an annual average traffic count of 15 vessels/ hour entering the gulf through the Strait of Hormuz in our base case analysis. The assumed traffic composition is consistent with the near-field analysis - 35% cargo ships and 44% tankers (according to the exact Earth data), which means on average there are 5.3 cargo ships and 6.6 tankers per hour arriving to the gulf.
Furthermore, we assume all vessels (of all types) travel at an average speed of 11 m/s in the gulf. This assumption is backed by an investigation of the vessel speed data from 2015 (Figure 24). Illustrated in the figure is the observed annual vessel speed averaged over each 1km by 1km pixel in the study domain. As can be seen, vessels travel at a speed between 12.1 - 40.0 knots for the most part, and thus, the arithmetic mean of 21 knots (11 m/s) is used in our analysis.

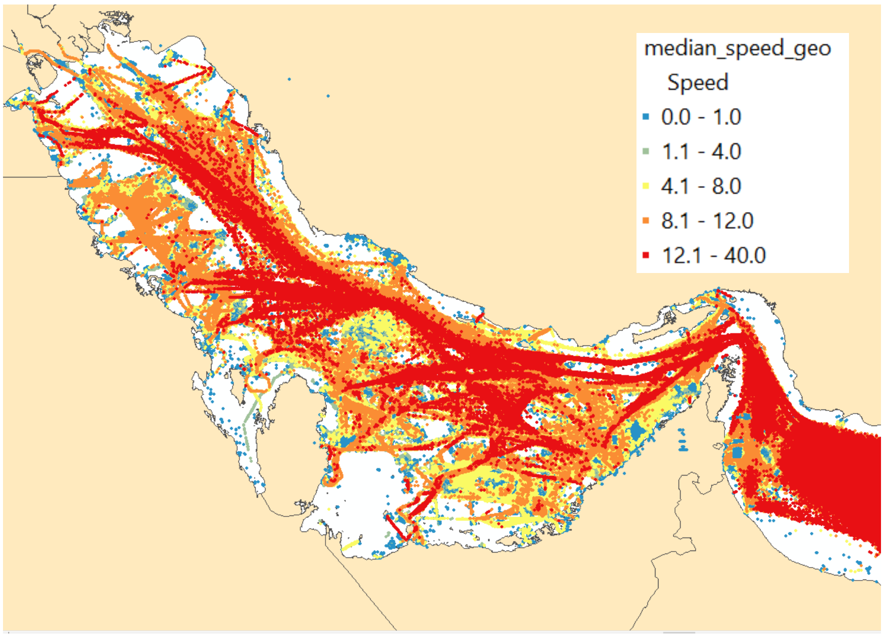

Figure 24. The median speed range (in knots) of traffic in the Persian Gulf, with warmer color indicating higher speed (Zhang, Fung, Chan, & Lau, 2019).

To compute concentrations in enclosed waters such as ports, bays, and harbors, we must track of the status of the vessels - anchored or moving - as these would have different implications in terms of engine load, and hence effluent discharge rate. The effluent discharge rate at berth is typically 10 to 20% (GREET Excel model developed by Argonne National Laboratory. For details, see https://greet.es.anl.gov/greet.models) of the rate when operating at main engine load (moving). For this reason, we split vessel residence time, T_v, into time spent at berth and time spent moving, as introduced earlier in model formulation. For the Persian (Arabian) Gulf, however, the discharge concentration at berth has been ignored when computing far-field concentration, C_{FF} using equation (0-6). To make this decision we examine the relative time scales at berth and moving. Computing the time vessel spent moving requires the distance travelled. As shown in Figure 25, the destination for cargo ships, as suggested by the high traffic density spots (yellow and warmer colors) are different than for tankers. The main stop for cargoes is on the southern coast close to the mouth of the gulf, whereas for tankers, it is further into the gulf away from the mouth.

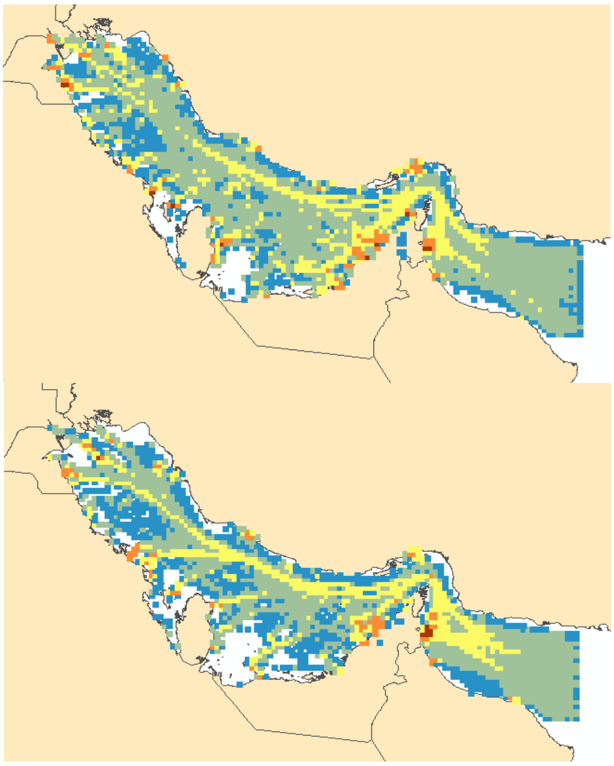

Figure 25. Traffic density maps in the Persian (Arabian) Gulf for (Left) cargo ships and (right) tankers, with warmer color representing higher traffic.

Therefore, we assume the average distance travelled by cargo ships is 800 km (total distance of a return trip from the strait to the coast of U.A.E.). Thus, the time spent moving for cargo ships is then 800km / 11m/s ≈ 20 hours. Similarly, for tankers, a distance of 2400 km (double the distance between the strait and the Saudi Arabian coast) is used, and the corresponding time spent is about 61 hours.

If we assume all vessels spend on average a day at berth in the gulf, then the time scale is comparable to that when the ship is moving, but the discharge rate at berth is at a maximum 20% of the rate of discharge while moving. Therefore, it is deemed justified to ignore the effluent concentration from when the vessels are at berth for simplicity of computation.

The pollutant residence time, T_r, takes on different values for different parts of the gulf (Figure 23) due to the significant variation in water exchange abilities – residence time increases away from the Strait of Hormuz. The T_r relevant for cargo ships is taken as 110 days, and 810 days for tankers.

The list of parameter values as well as the simulated reference case result is summarized in below tables.

Table 16.Far-field reference case parameters for the Persian (Arabian) Gulf

Parameters	Values	Units
u, ship speed	11	m/s
Effluent flow rate	45	t/MWh
V, volume of the gulf	9000	km^3
$\dot{N}$, ship arrival frequency	15.3	vessels/hour
f_c, percentage of traffic (cargo)	35	%
f_t, percentage of traffic (tanker)	44	%
J, total number of ship types	2	-

Table 17. Reference case simulation results for the Persian (Arabian) Gulf

Ship type, j	fj (%)	$\dot{Q}$, moving (m^3/s/vessel)	Tv, vessel residence time (hours)	Tr, effluent residence time, days	C/Co
Cargo	35	0.29	20	110	2.3E-05
Tanker	44	0.19	61	810	4.1E-04
Combined	80	-	-	-	4.3E-04

The combined total far-field concentration in the Persian (Arabian) Gulf likely exceeds the PNEC of 1/5000 by around 2 times.
In the reference case, the rate of removal is conservatively set to zero due to the fact there are several mechanisms by which the effluent substances can be removed and the corresponding removal rate may be different for each mechanism and require further investigation. It is also difficult to incorporate such rates into the whole effluent model setup and therefore is omitted in the reference case simulation. We acknowledge this is a very conservative assumption.
A sensitivity analysis has been conducted to quantify the change in the simulated concentration with varying removal rate values (Figure 26). For the Persian (Arabian) Gulf, the pollutant residence times (for different parts of the gulf) is on the order of 10^2 days, which is on the same order of magnitude as the removal rate at which far-field concentration becomes acceptable.

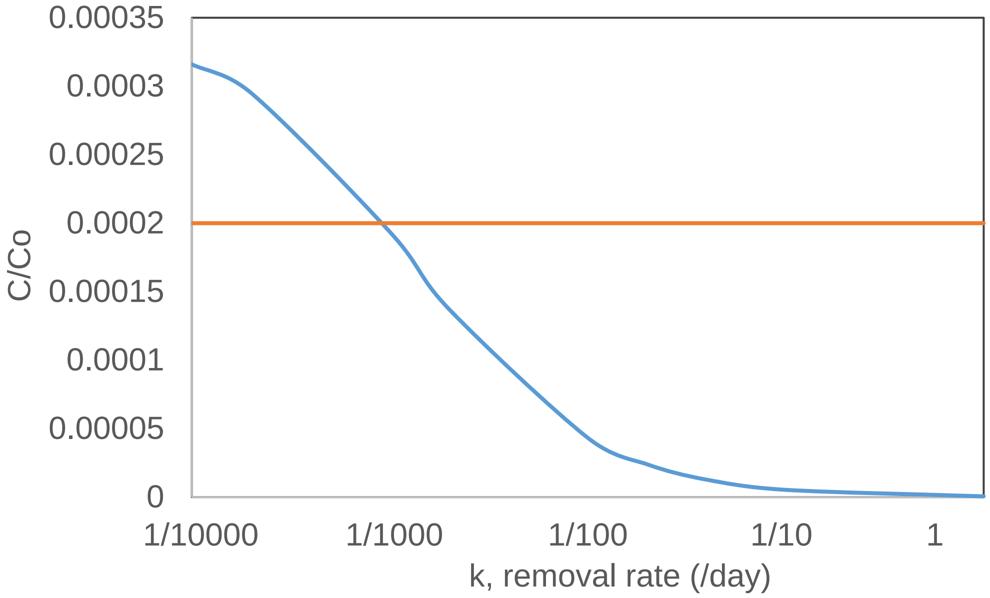

Figure 26. Sensitivity of the far-field concentration (normalized again discharge concentration) in the Persian (Arabian) Gulf to the rate of removal, k. Red solid line refers to the PNEC value of 1/5000.

2.3..1.1 Conclusions

The far-field model, which assesses the environmental impact of the effluent as a whole, suggests that the EGCS wastewater discharges could cause issues for marine life in the Persian (Arabian) Gulf due to background accumulation (low flushing rate) and high shipping traffic activity, based on the same PNEC limit.

2.3..2 Tokyo Bay

We assume an equilibrium state of traffic within the bay. As in the near-field analysis, we use an observed high traffic frequency of 28 vessels/ hour for the far-field base case analysis. The

assumed traffic composition is kept consistent with the near-field analysis - 62% cargo ships and 28% tankers, which means on average there are 17.4 cargo ships and 8.0 tankers per hour arriving to the bay. We assume all remaining vessel types, which are relatively smaller in size, do not have scrubber installed and therefore do not contribute to effluent discharge.
Furthermore, we assume all vessels (of all types) travel at an average speed of 11 m/s. This assumption is backed by an investigation of the vessel speed data from 2015 (Figure 27). Illustrated in the figure is the observed annual vessel speed averaged over each 1km by 1km pixel in the study domain. As can be seen, vessels travel at a speed between 12.1 - 40.0 knots for the most part, and thus, the arithmetic mean of 21 knots (11 m/s) is used in our analysis.

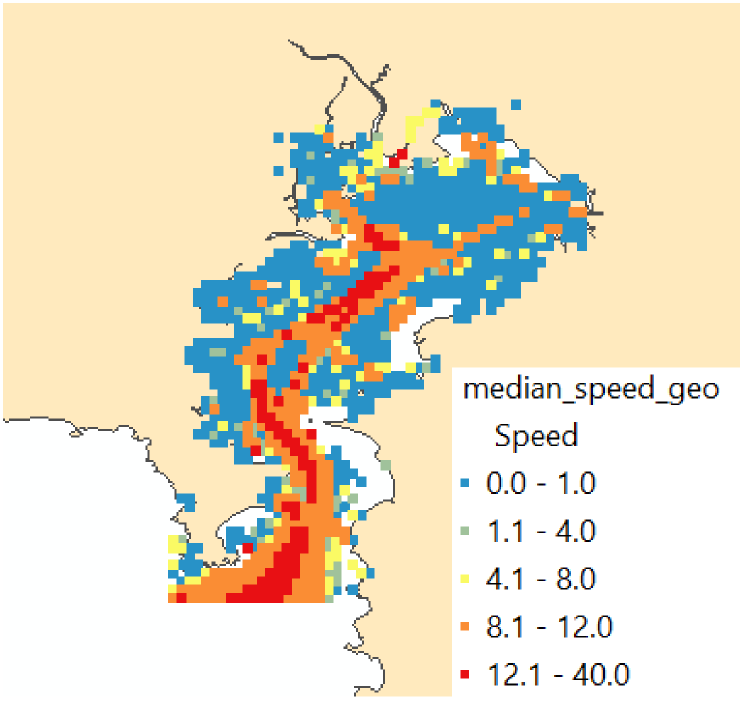

Figure 27. Median speed (in knots) of traffic in Tokyo Bay in 2015, with warmer color indicating higher speed (Zhang et al., 2019).

To compute concentrations in enclosed waters such as ports, bays, and harbors, the status of the vessels is split into two categories - anchored or moving, as these would have different implications in terms of engine load, and hence effluent discharge rate. The effluent discharge rate at berth, for cargoes (bulk carriers and containers) and tankers, is typically 10 to 20% (GREET model) of the rate when operating at main engine load (moving). For this reason, we split vessel residence time,T_v, into time spent at berth and time spent moving, as introduced earlier in model formulation.
For Tokyo Bay, however, the discharge concentration at berth has been ignored when computing far-field concentration, C_{FF} using equation (0-6) since the rate of discharge from cargo and tanker types of ships at berth is low compared to the discharge under main engine load. Then, to compute the time vessel spent moving, the distance travelled is required. As the distribution of vessels by type is fairly uniform in the bay, we assume the average distance travelled by all vessels is the same and take an average of 55 km (one way). Therefore, the time spent moving is then 55 km x 2 / 11m/s ≈ 2.8 hours.
The pollutant residence time, T_r of the bay is between 28 to 79 days depending on the season (OKADA et al., 2007) and could be longer or shorter based on the location inside the bay – inner or outer bay. Here, an annual average of 48 days for both the inner and outer bay is use for simplicity.
The list of parameter values as well as the simulated reference case results are summarized in below tables.

Table 18. Far-field parameter values for simulating Tokyo Bay effluent concentration

Parameters	Values	Units
u, ship speed	11	m/s
Effluent flow rate	45	t/MWh
V, volume of the bay	60	km^3
$\dot{N}$, ship arrival frequency	28	vessels/hour
f_c, percentage of traffic (cargo)	62	%
f_t, percentage of traffic (tanker)	28	%
J, total number of ship types	2	-

Table 19. Simulation results for far-field concentration in Tokyo Bay

Ship type, j	fj (%)	$\dot{Q}$, moving (m^3/s/vessel)	Tv, vessel residence time (hours)	Tr, effluent residence time, days	C/Co
Cargo	62	0.29	2.8	48	9.67E-04
Tanker	28	0.19	2.8	48	2.86E-04
Combined	90	-	-	-	1.25E-03

The combined total far-field concentration in Tokyo Bay likely exceeds the PNEC of 1/5000 by about 8 times.
The rate of removal is conservatively set to zero in the reference case for reason mentioned in the previous section (See Persian (Arabian) Gulf). A sensitivity analysis has been conducted to quantify the change in the simulated concentration with varying removal rate values (Figure 28). For Tokyo Bay, the pollutant residence time is on the order of 10 days, which is on the same order of magnitude as the removal rate at which far-field concentration becomes acceptable.

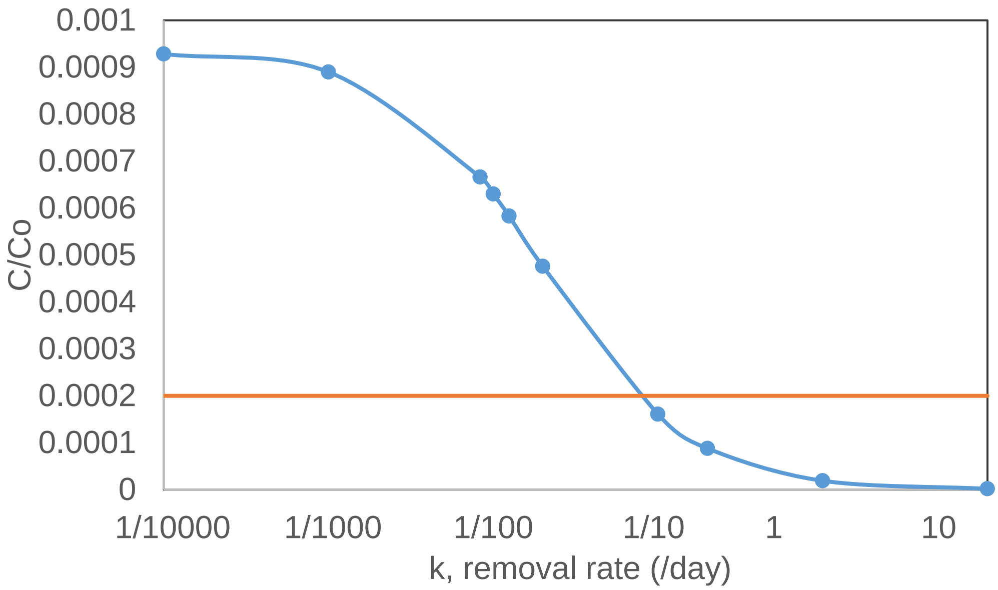

Figure 28. Sensitivity of the far-field concentration (normalized again discharge concentration) in Tokyo Bay to the rate of removal, k. Red solid line refers to the PNEC value of 1/5000.

2.3..2.1 Conclusions

The far-field model, which assesses the environmental impact of the effluent as a whole, suggests that the EGCS wastewater discharges could cause issues for marine life in Tokyo Bay due to background accumulation (low flushing rate) and high shipping traffic activity, based on the same PNEC limit grounded on Whole Effluent Toxicity (WET). In contrast, the MEPC 74/INF .24 study used a different far-field model (MAMPEC), which was applied to examine the impact of individual contaminants such as COD, NOx. They found the fact that concentrations are only slightly above the background suggests no impact. Hence, the different methods of risk assessment could lead to different conclusions.

2.3..2.2 Further Discussion on Far-field Analysis

- [MEPC 74/INF.24] Far Field Analysis for Japanese Waters

Taking the MEPC 74/INF .24 analysis further, the current study is able to determine a correlation between dilution rate, S (original pollutant concentrations over final) and the increase in the current concentration by long-term release (far-field concentrations increase from the current over current concentration). Suppose the long-term release of effluent increases from the current concentration of individual substance by a factor of $1/A$, where A can be between 100 and 1000 (depending on the substance), that is, the additional concentration is $1/A$ times the current concentration, then is follows that

$$\frac{C_F - C_b}{C_b} = \frac{1}{A} \qquad \text{0-7}$$

where C_F denotes the far-field concentration and C_b is the current background concentration of the substance of interest. The dilution rate, S can then be expressed in terms of these parameters as follows:

$$\frac{C_F - C_b}{C_o - C_b} = \frac{1}{S} \qquad \text{0-8}$$

where C_o is the discharge concentration of the substance at the source. By rearranging the above equations, it can be shown that

$$\frac{C_o - C_b}{SC_b} = \frac{1}{A} \qquad \text{0-9}$$

Thus, 0-10

$$S = \frac{A(C_o - C_b)}{C_b}$$

If $A = 100$, 0-11

$$S = \frac{100(C_o - C_b)}{C_b}$$

If $A = 1000$, 0-12

$$S = \frac{1000(C_o - C_b)}{C_b}$$

As our far-field analysis for Tokyo Bay shows that as a whole effluent, $S = 660$ (8 times lower than the dilution limit of 5000), we get

$$660 = \frac{A(C_o - C_b)}{C_b} \qquad \text{0-13}$$

If $A = 100$, 0-14

$$C_o = 7.6C_b$$

If $A = 1000$, 0-15

$$C_o = 1.6C_b$$

Therefore, for a target substance in the discharge, if the additional concentration introduced by the long-term release is $1/100$ times the current concentration, then with a simulated far-field dilution rate of 660 (below the minimum dilution limit of 5000), it implies that the discharge concentration could be 7.6 times higher than the current background concentration. Whereas if the long-term contribution is only 1/1000 folds higher instead, then at the same dilution rate, the discharge concentration would have been only 1.6 times higher the current background concentration. With increasing dilution rate, the discharge concentration allowed increases relative to the current ambient concentration. For instance, at the dilution limit of 5000, the concentration allowed at discharge is many times the ambient and hence highly depends on the actual value of the current ambient concentration. While the current ambient concentration values are known for some substances that are regulated, the values remain unknown for the majority of the discharge constituents. Therefore, the environmental impact assessment of far-field concentration by individual substances is not conclusive and would require more information about the receiving water in order to determine if the discharge is likely to have adverse effects on marine lives in the long term.

2.3..3 Port of Qingdao

The study domain specifically is Qianwan Bay (QWB), the outer bay located on the side of the main channel across from Qingdao City, where the majority of the port activities take place (Figure 29).

The entrance to the port, or the start of the inner bay, is denoted on the map (Figure 29) by the dashed vertical line across the main channel. Figure 29 reflects the coastline after the latest large-scale land reclamation activity in 2008. The water depth is the deepest towards the center of the bay (and dredged regularly in the main channel) and gradually becomes shallower closer to the shore. The average depth in the model is assumed to be 14 m, despite the variation within the port region.

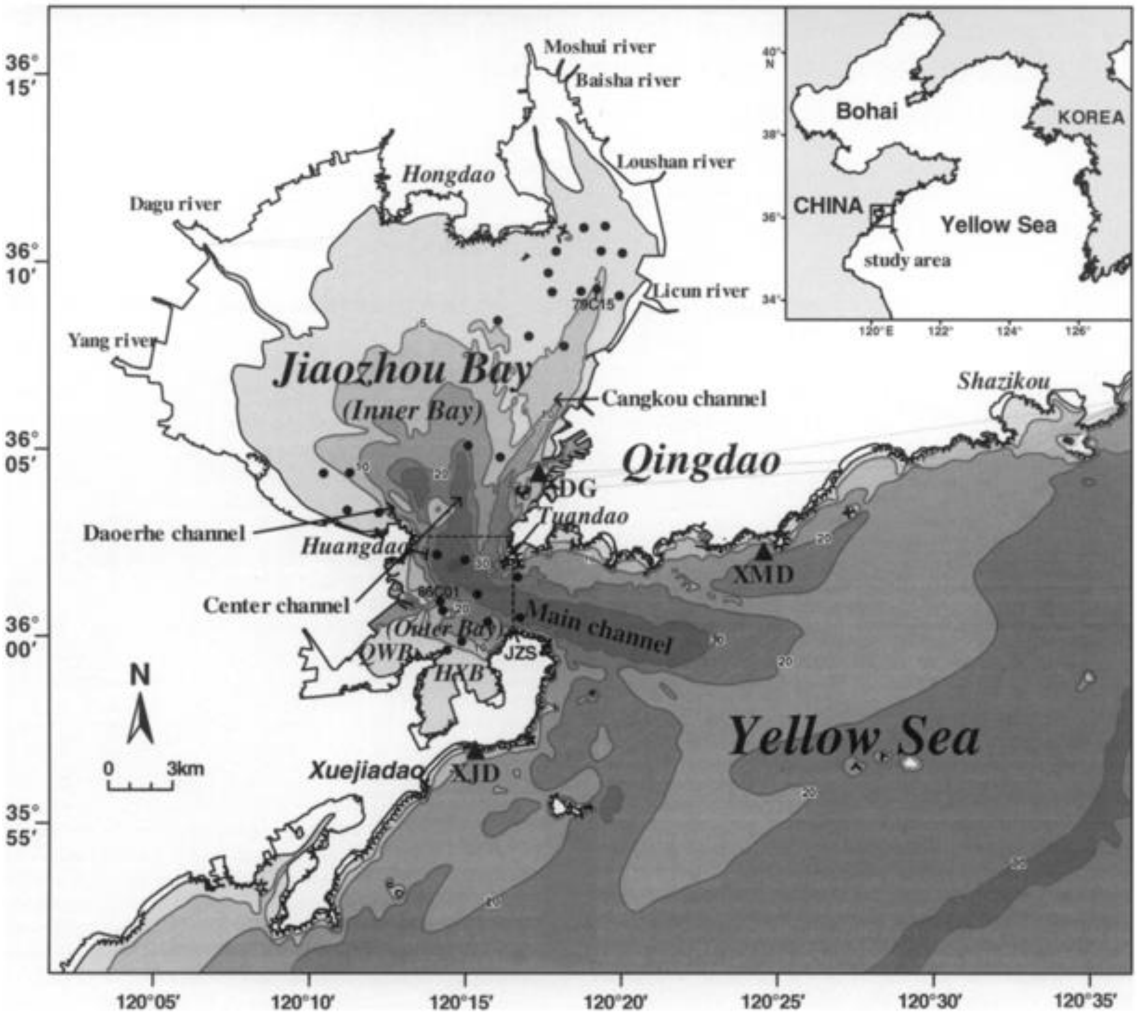

Figure 29. Bathymetry map of the study area adopted from (Ying, Li, Li, & Liu, 2018)*. Port of Qingdao in this study refers to QWB (the outer bay located on the side of the main channel across from the land of Qingdao) since it is the main bay for hosting port activities. Water depth on the bathymetry contours is in meters and is deeper towards the center of the channel.*

We assume an equilibrium state of traffic within the port. The average traffic observed is about 6 vessels/ hour (AIS data) entering or departing from the port in our base case analysis. The traffic breakdown by vessel type is 32% cargo ships and 6% tankers (AIS data), with the remaining 62% of the traffic consisted mostly of fishing vessels that do not typically install scrubbers, and therefore are omitted from the analysis.
Here, we acknowledge that while QWB (our study domain) hosts a significant amount of the 6 vessels/hour ship loading, some of this traffic may end up at ports located all along the coastline of both the inner and outer bay.

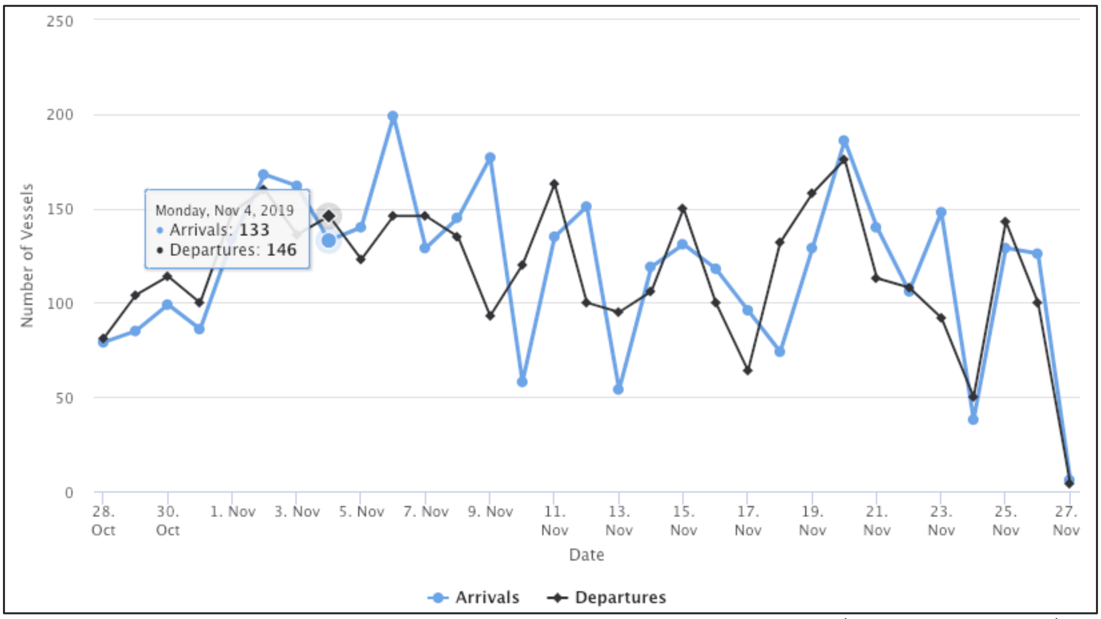

Figure 30. The total number of vessel arrivals and departures between October 28th and November 27th, 2019. The average arrival frequency is about 6 vessels/hour.

Furthermore, we assume all vessels (of all types) travel at an average speed of 7 knots (3.6 m/s) once inside the port. This assumption is backed by tracking the speed of individual vessels inside the port through AIS.

For the reference case, the discharge concentration at berth has been ignored when computing far-field concentration, C_{FF} using equation (0-6) because the discharge rate at berth is considerably smaller than the rate discharge while vessels are moving. Therefore, the vessel residence time,T_v, in the reference case, only accounts for the time spent arriving at and departing from the location. It is computed as the distance required to travel by all vessels in and out of the port, which is approximated to be 6 km each way, divided by the speed at which the vessels travel. Therefore, the time spent moving is 6 km x 2 / 5m/s ≈ 40 minutes.

Lastly, we assume that the pollutant residence time,T_r, is 30 days, an average value, which experiences increasing flushing (shorter residence time) closer to the main channel (Figure 31). The average residence time not only fluctuates with seasons, the location around the port, but also increases significantly over time as triggered by several land reclamation events, which cause the water-exchange ability to decline rapidly (Ying et al., 2018).

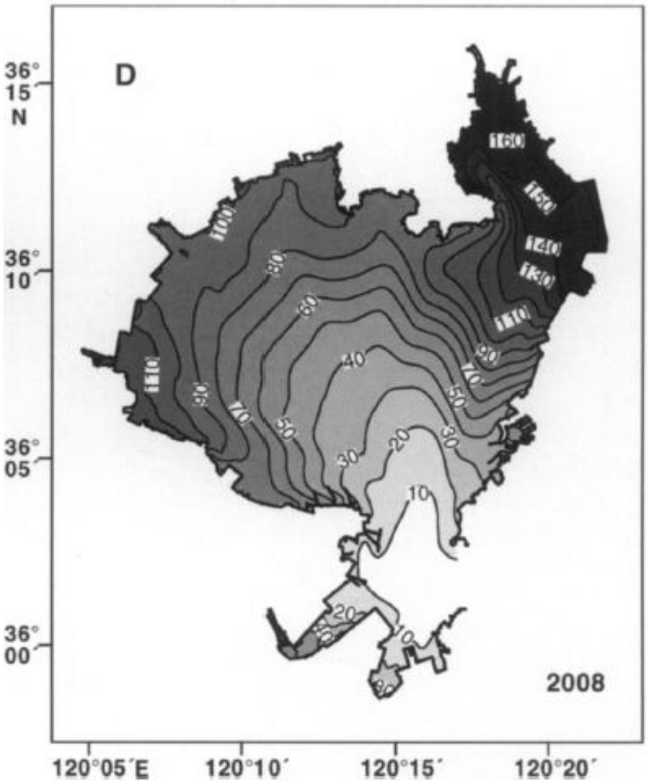

Figure 31. The average pollutant residence time in the Port of Qingdao, adopted from (Ying et al., 2018).

The list of parameter values as well as the simulated reference case results are summarized in below tables.

Table 20.Far-field reference case parameters for the Port of Qingdao

Parameters	Values	Units
u, ship speed	5	m/s
Effluent flow rate	45	ton/MWh
V, volume of the port	0.073	km^3
$\dot{N}$, ship arrival frequency	6	vessels/hour
f_c, percentage of traffic (cargo)	32	%
f_t, percentage of traffic (tanker)	6	%
J, total number of ship types	2	-

Table 21. Reference case simulation results for the Port of Qingdao

Ship type, j	fj (%)	$\dot{Q}$, moving (m^3/s/vessel)	Tv, vessel residence time (minutes)	Tr, effluent residence time, days	C/Co
Cargo	32	0.21	40	30	9.47E-03
Tanker	6	0.15	40	30	1.28E-03
Combined	38	-	-	-	1.07E-02

The combined total far-field concentration in the Port of Qingdao likely exceeds the PNEC of 1/5000 significantly at the present level of traffic loading and pollutant residence time. The situation is likely to worsen with the overall water-exchange capability continuing it decline (residence time increasing) into the future. Furthermore, if the volume of the port further decreases by reclamation activities and the rate of residence time increase stay constant, it is possible that the equilibrium concentration in the Port of Qingdao could exceed the PNEC by up to two orders of magnitude. This projected equilibrium concentration can be lower if the removal of pollutant substances is considered.

2.3..4 Port of Galveston

The Port of Galveston is interesting to study because the port/bay receives a high hotel load from commercialized cruise ships, making it unique when compared with other study sites where the traffic is dominated by cargo and tanker traffic. The study domain of Galveston Bay is presented in Figure 32. Though the majority of the cruise ship traffic arrives to the Galveston Ship Channel between the South of Pelican Island and the North of Galveston Island (narrow passage inside the yellow box on Figure 32), the far-field analysis uses the whole Galveston Bay as the study domain. This is in contrast to Port of Qingdao (Section 2.3..3) where the inner section of the bay is treated as a standalone region, and only the inner bay is used as the study domain. The reasons are two folds: first, the traffic entering Galveston Bay appears to be more uniformly distributed around the bay than for Qingdao; secondly, unlike the inner bay of Qingdao, the Galveston Ship Channel is open on both sides, and therefore does not constitute an embayment where effluent background buildup is likely the biggest concern.

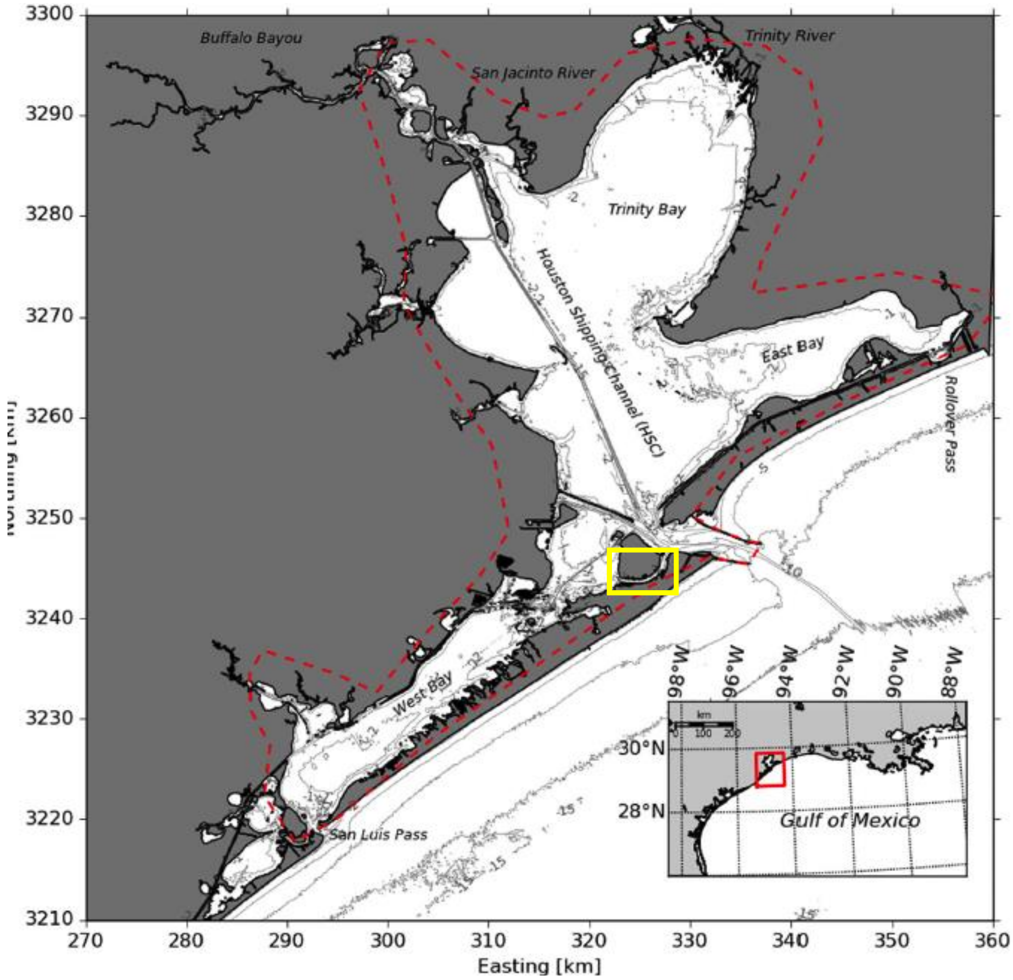

Figure 32. Map of Galveston Bay (Rayson, Gross, Hetland, & Fringer, 2016)*. Dashed red line indicates the boundary of the study domain. Solid yellow box indicates Galveston Ship Channel, the part of the bay where the majority of cruise ships arrive.*

Here, we wish to solve the 'inverse problem' with the aim to predict the level of ship traffic above which there would be ecological concerns. Starting with the maximum acceptable level of concentration (PNEC of 1/5000), we can derive the maximum acceptable level of traffic given other known parameter values such as the characteristics of the bay (the volume of the

bay, the pollutant residence time), the average traffic speed and composition by type arriving, we are able to compute for maximum safe traffic frequency.
The traffic breakdown by vessel type is 39% cargo ships and 32% cruise ships, which make up the majority of the traffic. For simplicity, we omit other large vessel types that can potentially be fitted with scrubbers such as tankers, but account for a smaller amount of traffic. The port is equipped to handle all types of cargo including containers. As of 2018, Galveston is the 4th-busiest cruise ship homeport in North America and one of the top 10 homeports in the world (https://www.galvnews.com/news/free/article_7a23c0c0-67f1-11e5-b928-238df9a43dd1.html). The port hosts several cruise lines, with an average tonnage of the cruises to be within the range of 60,000 – 99,999 GT. We assume this corresponds to a main engine power of 39,600 kW (when moving) and an auxiliary engine power of 11,480 kW (Table 9).
Since we are interested in evaluating the environmental impact of hotel discharge load, we split the vessel residence time, T_v, into time spent at berth (hotel load), and time spent moving, as introduced earlier in model formulation. Assume cruise ships spend on average 5.5 hours at berth (this is backed by checking the cruise operating schedules for multiple cruise lines). Assume the cargos spend one day on average at berth. Furthermore, we assume that all vessels (of all types) travel at an average speed of 3.6 m/s in the gulf. This assumption is backed by taking the average of the speed at which observing the. The average total distance any vessels travel while inside the bay is 40 km for a round trip, and thus the average time spent moving is $40\ \mathrm{km}/3.6\ \frac{\mathrm{m}}{\mathrm{s}} \approx 3\ \mathrm{hours}$.
The rate of discharge is also significantly different for moving and anchored vessels. We assume vessels operate at the auxiliary engine load while at berth, with a hotel load factor applied. When moving, the main engine load is applied with the corresponding cruise load factor.
The pollutant residence time, T_r, is assumed to be the same throughout the bay and the value is taken from (Rayson et al., 2016).
The list of parameter values as well as the simulated reference case result is summarized in below tables.

Table 22. Parameter values for simulating the far-field concentration of the Port of Galveston

Parameters	Values	Units
u, ship speed	3.6	m/s
Effluent flow rate	45	t/MWh
V, volume of the bay	4.8	km^3
f_c, percentage of traffic (cargo)	39	%
f_t, percentage of traffic (cruise)	32	%
J, total number of ship types	2	-
Main engine power	39,600	kW
Auxiliary engine power	11,480	kW
Hotel load factor for cruise (in port)	0.64	-
Hotel load factor for cargo (in port)	0.15	-

Table 23. Parameter values by vessel type

Ship type, j	fj, %	$\dot{Q}$, moving, m^3/s/vessel	$\dot{Q}$, berth, m^3/s/vessel	T_{jmov}, moving, hours	T_{janch}, berth, hours	Tr, effluent residence time, days
Cargo	39	0.21	0.01	3	24	40
Cruise	32	0.40	0.09	3	5.5	40

By rearranging equation (0-6), we get the following expression for predicting the maximum acceptable far-field concentration for Galveston Bay:

$$\dot{N}_{max} = \frac{C/C_oV}{T_r[f_c(\dot{Q}_{c_{anch}}T_{c_{anch}} + \dot{Q}_{c_{mov}}T_{c_{mov}}) + f_{cr}(\dot{Q}_{cr_{anch}}T_{cr_{anch}} + \dot{Q}_{cr_{mov}}T_{cr_{mov}})]} \qquad 0\text{-}16$$

The above subscripts ‘c’ and ‘cr’ denote cargo and cruise, respectively.
By substituting the parameter values into equation (*0-16*), we conclude that in order to comply with the PNEC of 1/5000, vessels should arrive at no more than 0.3 vessels per hour into the bay, which is exceeding the current observed level of 5 vessels per hour (AIS data) by 16 times. This is also likely an underestimate as we have not considered the ship loading from other vessel types. The assumption of zero substance removal, on the other hand, likely has to opposite effect of overestimating the concentrations.

3. Conclusions

We were mainly examined whether discharged effluent can cause adverse health effects on marine life (water emissions).

3.1.1 Water Emissions

A dispersion study is conducted to assess the environmental impact of open-loop scrubber washwater. Two models have been developed to simulate the near- and far-field ship washwater concentrations, respectively. The aim of the study is to compare the simulated concentrations for several identified study sites with the appropriate toxicological limits, often expressed as dilutions, found in the literature. The impacts of using EGCS on the marine environment can thereby be assessed, and thus also its feasibility as a solution for reducing atmospheric sulfur emission.

3.1.1 Near-field risks

The near-field model is applied to geographic locations around the world likely causing ecological concerns in the vicinity of the discharges, namely, the Persian Gulf, the Strait of Malacca, the Strait of Gibraltar, the Panama Canal, and Tokyo Bay. A reference scenario has been defined and simulated for each of these locations. The modelled steady-state concentrations have been compared with toxicological limits, which were developed by Koski et al., and MEPC 74/INF .24 using Whole Effluent Toxicity (WET) methodology carried out on samples taken from actual washwater from scrubbers. The same WET procedure has also been adopted in a third available toxicology study by [IVL]. It is therefore supported by all currently available toxicity studies. The safe limit according to MEPC 74/INF.24 is computed as 5 (the scrubber effluent dilution rate at which the mortality rate becomes 50% in the three tested marine organisms) x 1000 (an assumed factor to extrapolate to long-term effects on all organisms). Despite the currently limited available toxicological data on the marine impacts of EGCS effluent, the analysis uses a predicted no effect concentration (PNEC) limit of 1/5000 for all effluent dilution. Using this presumed safe concentration reference and the results of near-field dispersion calculations for different locations; it is a plausible hypothesis that there is no likely risk of acute toxicity effects from short-term exposure in target organisms. It should be noted that the toxicology literature is not yet conclusive. For example, the [IVL] study could not establish a minimum concentration below which no toxicity effects could be observed on marine life and uses a more conservative methodology based on the EU Water Framework Directive to derive a PNEC.

Our finding (of a lack of adverse ecological effect) for the near-field washwater concentration in Tokyo Bay is consistent with the MEPC 74/INF .24 study when the same assumptions are applied, which tends to validate findings. Furthermore, sensitivity analysis shows that, in Tokyo Bay and other studied waterways, under particular circumstances, such as a tight ‘line astern’ arrangement of ships inside the shipping channel, washwater concentration may go above the threshold. It should also be emphasized that these conclusions all strongly depend on the chosen PNEC limit used. For example, the [IVL] study, using a more conservative PNEC threshold based on their toxicology results concludes that there is cause for concern in the immediate wake of ships in busy waterways.

3.1.2 Far-field risks

Previous studies and this study compare their far-field results with different available limits to determine whether scrubber installation is likely to impose negative impact on the environment at present. In the current study, a far-field model has been developed to compute the cumulative equilibrium washwater concentrations in enclosed water bodies that experience high traffic and poor flushing, such as ports, harbors and bays. Four background buildup-prone regions, namely, Persian Gulf, Tokyo Bay, Qingdao port and port of Galveston are selected for the far-field study. We explored the effects on water quality if all large ships (cargo ships and tankers) were to install EGCS systems. The simulated far-field concentrations are compared with the same dilution threshold of 1/5000 as in the near-field assessment. Our assessment, which predicts far-field concentrations 8 and 2 times higher than the PNEC for Tokyo Bay and the Persian Gulf, respectively, while port of Qingdao and Galveston were 2 orders of magnitude and 4 times higher than the PNEC. This suggests that there could be an environmental risk caused by the far-field effluent concentration in these four locations, under the set of assumptions as described in Section 2.3. In comparison, our model suggests much lower concentrations for the two sites studied by the Danish Environmental Protection Agency (EPA) in their 2012 report. Our model provides support to the report's conclusion that far-field concentration is not likely to cause ecological concerns in these sites. We attribute the low predicted cumulative concentration for the Danish sites to lower traffic activity relative to the sites examined in the current study.

Referring to other far field studies, it is important to note that analysis based on individual substance toxicity gives different results than if the effluent discharge is treated as a whole in terms of assessing the environmental impact of scrubber washwater. For example, the MEPC 74/INF .24 study uses MAMPEC-BW to simulate the far-field effluent concentration for Tokyo Bay and two other coastal areas in Japan. Their assessment evaluates the environmental impact of target washwater constituents that are regulated by the Japanese national environmental standards, which were developed in accordance with the Basic Environment Act. They conclude that the additional concentration of the individual target substance, obtained from a simulation of a ten-year release, ranges between 1/100 and 1/1000 times the respective current background concentration, Thus, the marginal contribution by the far-field to the current level of concentration suggests that scrubbers are not likely to introduce ecological concerns in the long term, in contrast to the conclusion of the current analysis, which focuses on the whole effluent concentration. Although scrubber effluent toxicology is certainly an area that requires more research, all three toxicology studies so far indicate that Whole Effluent Toxicity is likely more appropriate to estimate risks to marine life. However, for higher traffic zones, bays and ports, the analysis points to the likelihood that the presumed safe concentration threshold may be exceeded.

3.1.3 Restate any major assumptions

The following section highlights the major assumptions adopted in the current study.

In both the near- and far-field analyses, it is assumed that all ships of the type's cargo and tanker found in the study areas have scrubbers fitted. This is a conservative assumption for the volume of scrubber washwater being discharged in the present, but may more accurately represent future scenarios in which either a high proportion of vessels install scrubbers or the shipping traffic increases significantly.

Another assumption concerns the toxicology limit being used for comparison in both the near- and far-field analyses. The adopted PNEC of 1/5000 has been developed through acute toxicity tests with different marine species. During the tests, the longest exposure time used is 96 hours, and to determine the level of harm based on such a time scale may be conservative for mobile organisms (e.g., pelagic fish) which live in the water column and pass quickly through the washwater plume; conversely, such an assessment may be non-conservative for demersal fish or infauna. Thus, further research may well be required to more suitably determine whether a 'safe concentration' threshold exists.

In both the near- and far-field models, the removal term is assumed to be zero. The removal of pollutant constituents from the water column (defined as the waterbody between the surface and the ocean floor) through means of decay, photodegradation and settling, is ignored in the model. This is a realistic assumption in the near-field, because the time scale is short. However, for the far-field, the removal rate for each loss mechanism is difficult to reconcile with the whole effluent toxicity criteria; therefore, the removal term has been omitted for the far-field.

It should be noted that sensitivity analysis suggests that non-zero values of removal rates could potentially be significant in decreasing the equilibrium concentration. The rates of removal would be different for individual constituents (and depend on the mechanism) and to determine the removal rate for the effluent as a whole may be challenging and require further investigation. The loss of effluents needs to be accounted for to better estimate the equilibrium pollutant concentration. However, even in the case when settling removes some of the pollutants from the water column, the pollutants may still enter the food chain (e.g., through exposure to contaminated sediments) and cause health effects.

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List of Acronyms

AIS: Automatic Identification System
AIS DB: AIS dataset
BSH: Bundesamt für Seeschifffahrt und Hydrographie, Federal Maritime and Hydrographic Agency of Germany
CCAI: Calculated Carbon Aromaticity Index
CARB: California Air Resources Board
DMA: Distillate Marine A
ECA: Emission Control Area
EIA: Energy Information Administration
EGCS: Exhaust Gas Cleaning System
EQS: Environmental Quality Standard (EU)
EU: European Union
FCC: Fluid Catalytic Cracker
FNU: Formazin Nephelometric Units
GHG: Greenhouse Gases
GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model
GT: Gross Tonnage
GWP: Global Warming Potential
HCO: Heavy Cycle Oil
HKUST: Hong Kong University of Science and Technology
IEA: International Energy Agency
IHSF: Lloyd's Register Fairplay
IMO: International Maritime Organization
LCA: Life Cycle Analysis
LC50: Lethal Concentration for 50% of the population (median)
LCO: Light Cycle Oil
LD50: Lethal Dose for 50% of the population (median)
LNG: Liquefied Natural Gas
LSMGO: Low-Sulfur Marine Gas Oil
MDO: Marine Diesel Oil
MEPC: Marine Environment Protection Committee
MGO: Marine Gas Oil
MMSI: Maritime Mobile Service Identity
MSFD: Marine Strategy Framework Directive (EU)
NOx: Nitrogen Oxides
NGO: Non-Governmental Organization
NRWQC: National recommended water quality criteria (US)
NTU: Nephelometric Turbidity Units
PAH: Polyaromatic Hydrocarbon
PBT: Persistent, Bioaccumulative and Toxic substance
PM: Particulate Matter
PNEC: Predicted No Effects Concentration
QWB: Qianwan Bay (Port of Qingdao)
REACH: Registration, Evaluation, Authorization and Restriction of Chemicals
SCR: Selective Catalytic Reduction
SECA: Sulfur Emission Control Area
SOLAS: Surface Ocean - Lower Atmosphere Study project
SOx: Sulfur Oxides
UBA: Umweltbundesamt, German Environment Agency
ULSMGO: Ultra-Low-Sulfur Marine Gas Oil
US EPA: United States Environmental Protection Agency
WC: Water Column

WFD: Water Framework Directive (EU)
WTT: Well to Tank
WTW: Well to Wake