The impacts of EGCS washwater discharges on port water and sediment

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Glossary

AA	Annual Average
CAS	Chemical Abstracts Service
CLIA	Cruise Lines International Association
BW	Ballast Water
D	Detect
DL	Detection Limit
ECHA	European Chemicals Agency
AHEE	Ad hoc WG on Environmental Exposure
EGCS	Exhaust Gas Cleaning System
EQS	Environmental Quality Standard
EU	European Union
FNU	Formazin Nephelometric Units
GESAMP-BWWG	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection - Ballast Water Working Group
Hz	Hertz
IMO	International Maritime Orgainisation
ISO	International Orgainization for Standardization
MAC	Maximum Allowable Concentration
MAMPEC	Marine Antifoulant Model to Predict Environmental Concentrations
MARPOL	The International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MEPC	Marine Environmental Protection Committee
MGPS	Marine Growth Protection System
NTU	Nephelometric Turbidity Units
OECD	Organisation for Economic Co-operation and Development
PAH	Polycyclic Aromatic Hydrocarbon
PAH_{phe}	phenanthrene equivalence
PEC	Predicted Environmental Concentration
pH	pH is a scale used to specify how acidic or basic a water-based solution is
PM	Particulate Matter
PNEC	Predicted No Effect Concentration
PPR	Pollution Prevention and Response
SO_x	Sulphur Oxides
SPM	Suspended Particulate Matter
Turbidity	Cloudiness of a fluid due to suspended particles
U	Non-detect
USEPA	United States Environmental Protection Agency
VGP	Vessel General Permit
WFD	Water Framework Directive

Foreword

To contribute to the ongoing discussion about the impact of Exhaust Gas Cleaning Systems (EGCSs) on the port water and sediment, the Cruise Lines International Association Europe (CLIA Europe) and Interferry have collaborated to sponsor a joint research project.

The aim of the project is to provide further knowledge on the impact of washwater discharges from open-loop EGCSs on port water and sediment in the North Sea and Baltic Sea regions.

The scope of the project is limited to the assessment of the impact of Exhaust Gas Cleaning Systems on water quality. It does not make comparisons with the impact of other sulphur abatement options such as low sulphur fuel.

CE Delft were selected to conduct the project in partnership with Deltares. Deltares ran a series of generic simulations using the integrated hydrodynamic and chemical fate model Marine Antifoulant Model to Predict Environmental Concentrations – Ballast Water (MAMPEC-BW) to calculate the predicted environmental concentrations (PEC) of target substances that open-loop EGCS operations may contribute to the background concentrations of target substances in port water and sediment.

There are considered to be three study areas which lead to the understanding of the potential environmental impact of scrubber washwater on the marine environment:

1. *Washwater quality evaluation*, comparing washwater sample results to important existing water quality standards, both national and international.

2. *Washwater impact on the marine environment*, evaluating how the target substances for metals and Polycyclic Aromatic Hydrocarbons (PAH) can impact marine organisms, including evaluation against established predicted no effect concentrations (PNEC).

3. *Washwater Accumulation* in Ports, assessment through computer modelling the potential accumulation of the target substances for metals and PAHs in EGCS washwater that can be expected in a given port's water column and sediment.

While there are a number of studies that address Items 1 and 2, the aim of this study is to address Item 3 and consider accumulation of both water and sediment concentrations from a scientific standpoint.

By The Cruise Lines International Association (CLIA) and Interferry

Executive summary

One of the options to comply with the MARPOL Annex VI regulation on the sulphur content of marine fuels is to use an Exhaust Gas Cleaning System (EGCS) that removes Sulphur Oxides (SO_x) from the exhaust gas. Apart from SO_x, an EGCS also removes other harmful air emissions such as Particulate Matter (PM) and Polycyclic Aromatic Hydrocarbons (PAHs) from the exhaust. When an EGCS is operated in a so-called open-loop mode, the washwater from the scrubbers is discharged into the sea, sometimes after filtering and buffering with seawater.

Concerns have been raised about the environmental impact of washwater discharges, especially in port areas. This report analyses the long-term impacts of EGCS discharges on concentrations of eleven metals and sixteen Polycyclic Aromatic Hydrocarbons (PAHs) in the water and the sediment. It uses empirical data from almost 300 washwater sample analyses and feeds them into the MAMPEC model, which is widely used by regulators to assess the environmental risks of various activities which impact port water and sediment. The model was set up for a variety of ports and with a washwater discharge rate that is much higher than most ports are expected to experience.

The predicted equilibrium concentrations in the port water have been compared to EU Environmental Quality Standards (EQS) for priority substances under the Water Framework Directive. Figure 1 shows the predicted maximum concentrations as a percentage of the 2021 maximum allowable concentration for the four model ports.

Figure 1 - Maximum concentrations as a percentage of 2021 MAC-EQS limits (100% = MAC-EQS limit)
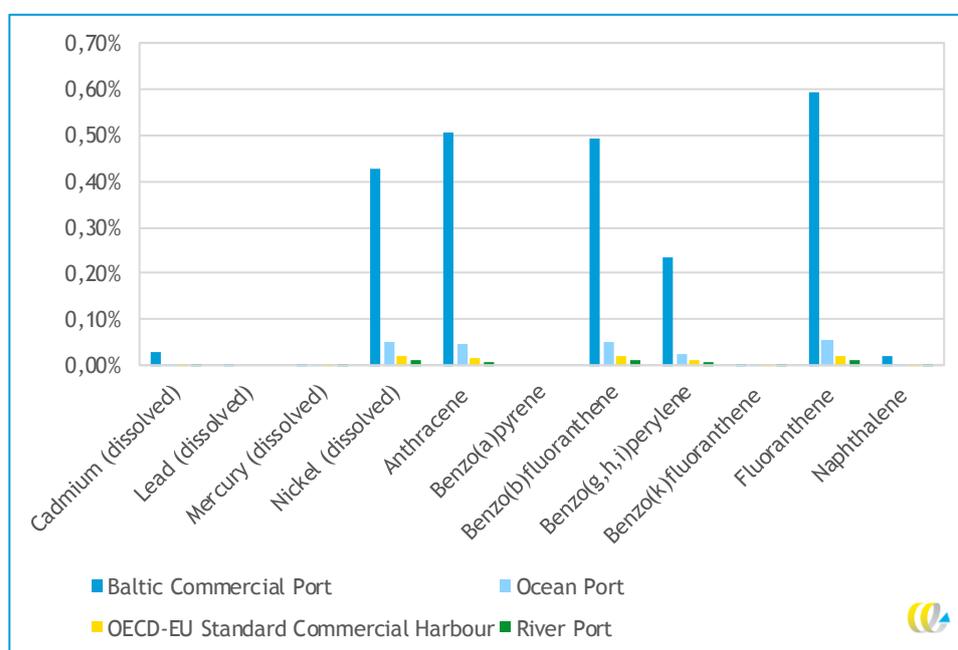
In most ports and for most substances, the increase in concentrations caused by continuous discharge of a relatively high amount of EGCS washwater is less than 0.1% of the limit value. However, in ports with low hydrodynamic exchange, and especially for a few Polycyclic Aromatic Hydrocarbons, the increase in concentration can increase to 0.6% of the limit value.

A comparison of the increase in concentration in the sediment, assuming zero background concentrations, with different national standards shows that the increase is below 0.5% of any standard.

1 Introduction

The International Maritime Organisation (IMO) has regulated emissions of sulphur oxides (SO$_x$) from ships since updates to The International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI entered into force in 2005. It sets limits for the sulphur content of fuels but also allows ships to use alternative compliance options other than low-sulphur fuels, as long as the SO$_x$ emissions in the exhaust gas meet the requirements of regulation 14.1 and 14.4 of MARPOL Annex VI when the alternative compliance option is used.

One of the main alternative compliance options is an Exhaust Gas Cleaning System (EGCS). An EGCS utilises water to remove SO$_x$ and other harmful air emissions such as Particulate Matter (PM) and Polycyclic Aromatic Hydrocarbons (PAHs)from the exhaust in a chemical-mechanical process known as scrubbing, the water that has been used to clean the exhaust is referred to as the washwater.

There are three main types of EGCS, open loop, closed loop and hybrid. An open-loop EGCS utilises seawater to scrub the exhaust and the resultant washwater is then often mixed with fresh seawater and in some instances further filtered before discharge into the sea, particularly in ports. A closed-loop EGCS utilises fresh or seawater and an alkaline chemical to scrub the exhaust. Closed-loop systems can operate for limited periods with zero discharges to the sea; however, they produce small volumes of residual process water (washwater) that must be discharged ashore or treated and discharged overboard. A hybrid system is an EGCS that can operate in either open or closed-loop configurations.

Washwater discharges may contain some suspended matter and dissolved substances. Although current EGCS designs and installations have been proven capable of consistently meeting the IMO washwater criteria for acidity (pH), turbidity and phenanthrene equivalence (PAHphe) concentrations, which were adopted to safeguard water quality, discussions continue about the possible impact of EGCS washwater on port water and sediment, and the subsequent environmental impacts of changes in the port water and sediment.

When a limit of 0.10% m/m for fuel oil sulphur content came into force for Emission Control Areas in 2015, the number of ships equipped with EGCSs increased. In anticipation of a worldwide sulphur limit of 0.50%, entering into force in 2020, the number of EGCS installations has been increasing steadily in preparation for the 2020 deadline. As the 2020 deadline approaches, shipowners and operators are making investments to ensure compliance with international emission regulations and to mitigate the risks associated with uncertainty on the availability and price of low-sulphur fuels. Mid-2019, there were between 3,000 and 4,000 ships equipped with EGCSs and the numbers are projected to increase further by 2020 (Clarksons, 2019; DNVGL, 2019). This represents a significant investment in EGCS technology.

This increase in the number of ships using EGCSs has prompted discussion about the need to study possible environmental impacts of potential changes in the background concentrations of substances in port water and sediment as a result of EGCS operations. This study focuses on open-loop EGCS operations as the washwater samples provided by the sponsors were collected from open-loop EGCSs or hybrid systems operating in open-loop mode.

In order to contribute to the scientific basis for ongoing discussions about the operation of open-loop EGCSs in ports, the Cruise Lines International Association (CLIA) and Interferry have commissioned this study from CE Delft which assesses the impact of open-loop EGCS washwater discharges, from ships at berth, on the port water and sediment. The study has a specific focus on the North Sea and Baltic Sea regions.

This study reports on the substances that are present in open-loop EGCS washwater discharges, the volumes of the substances, and the resultant contribution that open-loop EGCS operations make to the background concentrations of substances in the port water and sediment. A specific ecological assessment of any changes in background substance concentrations is not directly included as part of this study, however the water and sediment criteria used for evaluation of the resultant concentrations are set at levels which are considered protective of marine organisms and their ecosystem.

A number of studies have previously been published which relate to the potential environmental impacts of open-loop EGCS operations in ports. However, as it is only since 2017 that global EGCS installations and operating hours have increased dramatically, most of these published studies did not have access to large numbers of EGCS washwater samples. In contrast this study has benefited from the global growth in EGCS installations and operating hours as nearly 300 washwater samples have been made available for analysis.

Another differentiating factor of this study compared to the majority of earlier published studies is that this study has applied the MAMPEC-BW modelling tool to predict long-term variations in substance concentrations in the water and sediment.

Laboratory analysis results for 291 EGCS washwater samples were provided for this study, and 38 of these were discarded as they were not supplied with the necessary supporting technical information required for the adopted analysis method, and therefore 253 samples have been used. The laboratory analysis was conducted by ISO-certified laboratories utilizing, in the vast majority of cases, approved USEPA and/or ISO methods.

The samples have been analysed for concentrations of 27 substances: 16 different Polycyclic Aromatic Hydrocarbons (PAHs) and 11 metals. The 27 substances meet and in some cases exceed the requirements for washwater data collection as specified by the IMO in MEPC 259(68), and by the United States Environmental Protection Agency Vessel General Permit (US EPA; OW; OWM; Water Permits Division, 2013).

The impacts of open-loop EGCS discharges on port water and sediment were modelled for four model ports using the industry and IMO recognised mathematical exposure assessment model MAMPEC-BW and a reference ship loading. The MAMPEC model was originally developed for the exposure assessment of antifouling substances, and at a later stage the model was adapted to be used for ballast water; this version is referred to as MAMPEC-BW, and was used for this study.

The MAMPEC models are validated steady-state 2D integrated hydrodynamic and chemical fate models commonly used for environmental risk assessments of antifouling susbtances and substances in ballast water. The models are currently recognized and used by regulatory authorities in the EU, USA, Japan, and other OECD countries and are publicly available. The EU, in a submission to MEPC 74, specifically referenced the MAMPEC model as the model for assessing the marine environmental risk of the discharge of EGCS effluents (MEPC 74/14/1).

During the development of MAMPEC for the study of antifouling substances, a worst-case approach was adopted. The effect of a worst-case approach is that concentrations are generally over-predicted (Hattum, et al., 2016).The reason for adopting this worst-case approach was to prevent under-prediction that may have resulted in the approval of antifouling substances that at a later date were shown to have exceeded allowable concentrations. In a Tiered Assessment, MAMPEC is suitable as a First Tier screening model, which means its main purpose is to identify areas that are of no concern and areas that may need further investigation.

One of the key aims of study is to provide a method which can be used by others for assessment of the impact that open-loop EGCSs may have on port water and sediment. Whilst this study is focused on the North Sea and Baltic Sea, the methodology that has been developed can be applied to any port anywhere in the world as long as the port geometry, water characteristic and hydrodynamic water exchanges used in the modelling are representative of the location being assessed.

1.1 Outline of the report

Chapter 2 presents a description of the methodology of the study. Chapter 3 presents the results. Conclusions are drawn in Chapter 4.

2 Project methodology

2.1 Overall methodology

The project consisted of a number of defined tasks/steps which can be separated into two main areas: first, the calculation of predicted equilibrium water and five year sediment concentrations; and second, the evaluation of these concentrations against water and sediment environmental standards and other contributors.

1. Calculation of predicted concentrations:
   - define reference scenario for ship loading in the port (Section 2.2);
   - calculation of mean emission factors for substances in the EGCS washwater (Section 2.3);
   - define substance loads in EGCS washwater for reference scenario (Section 2.3);
   - define model ports (Section 2.4);
   - calculate in-port water and sediment substance concentrations (Chapter 3).
2. Evaluation of projected increases in concentrations (Chapter 3):
   - assess EGCS washwater samples against IMO washwater discharge criteria;
   - compare increases in concentrations in ports with Environmental Quality Standards (EQS) under the European Union (EU) Water Framework Directive (WFD);
   - compare water substance loads from ships with loads from other contributors;
   - compare sediment concentrations with national standards.

A graphical representation of the methodology to calculate the predicted concentrations is provided in Figure 2.

Figure 2 - Methodology for calculation of predicted concentrations
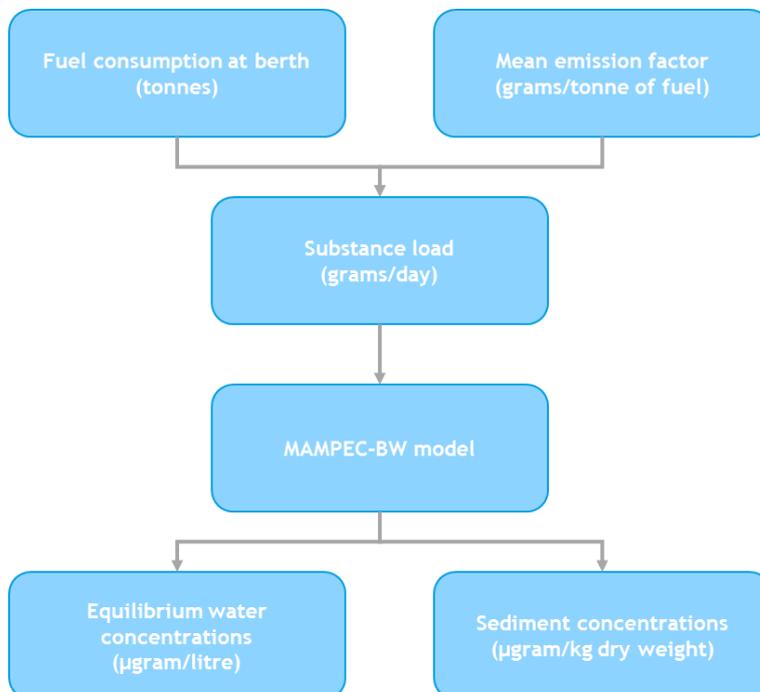
2.2   Define reference scenario for ship loading on the port

The reference scenario for the ship loading on the port was required in order to provide reference inputs to the MAMPEC-BW model that would facilitate the prediction of changes in the concentrations of both PAHs and metals as a result of a ship loading on the port. A conservative approach was taken to use a ship loading that represents a number of EGCS ships and systems which is beyond what can be projected for the foreseeable future in the specified regions.

This study only considers ships at berth and therefore the reference ship loading is the total power consumed by hotel services or during port operations such as cargo handling operations for all the ships using EGCSs in the port each day. In reality, the daily ship loading will vary all the time as the combination of ship types and sizes in port changes all the time and regularly several times a day. However, MAMPEC-BW only accepts an averaged daily input so an approximation of the daily ship load has been made.

The project sponsors provided information on the estimated port load for the ships types that were relevant to them and the Third IMO Greenhouse Gas Study 2014 provided reference information on the estimated port load for a selection of other ship types.

The auxiliary loading at berth varies significantly between ship type and size. The information from the sponsors is presented in Table 1, and Table 2 presents the information taken from the Third IMO Greenhouse Gas Study 2014.

Table 1 - Auxiliary load at-berth – sponsors information

Ship type	Auxiliary load at berth (kW)
Generic Ferry – ro-pax	1,500
Cruise ships 20,000–59,999 GT	3,400
Cruise ships 60,000–99,999 GT	5,900
Cruise ships 100,000–140,000 GT	8,650
Cruise ships 140,000+ GT	9,400

Table 2 - Auxiliary load at-berth – IMO GHG Study 2014

Ship type	Auxiliary loadat berth (kW)
General cargo 0–4,999 dwt	120
General cargo 5,000–9,999 dwt	330
General cargo 10,000+dwt	970
Bulk carrier 0–9,999 dwt	280
Bulk carrier 10,000–34,999 dwt	280
Bulk carrier 35,000–59,999 dwt	370
Bulk carrier 60,000–99,999 dwt	600
Bulk carrier 100,000–199,999 dwt	600
Bulk carrier 200,000+dwt	600
Container 0–999 TEU	340
Container 1,000–1,999 TEU	600
Container 2,000–2,999 TEU	700
Container 3,000–4,999 TEU	940
Container 5,000–7,999 TEU	970
Container 8,000–11,999 TEU	1,000
Container 12,000–14,499 TEU	1,200
Container 14,500+TEU	1,320

Source: Third IMO Greenhouse Gas Study 2014.

It was decided that the calculation of the reference scenario and subsequent daily (24 hrs) total fuel consumption in the port by ships using open loop EGCSs would be based on a continuous (24 hrs per day) 8 MW port load. This 8 MW continuous loading takes consideration of the port sizes, shipping operations in the North Sea and Baltic Sea regions combined with the information in Table 1 and Table 2.

The MAMPEC-BW model is a steady-state modelling tool with regard to the water concentrations. The model calculates the equilibrium state for the substance concentrations in the water, suspended particulate matter (SPM), and sediment based on a continuous inflow of the substances and continuous hydrodynamic water exchanges. So the defined ship loading represents 40.32 tonnes of fuel being consumed every day for 365 days per year; year after year indefinitely for the calculation of the substances concentrations in the port water.

Table 3 summarises how the reference ship loading on the port is derived and the total daily fuel consumption calculated.

Table 3 - Reference ship loading

Reference	Value	Unit
Combined hotel/auxiliary load from ship(s) in port	8	MW
Time ship(s) in port per day	24	Hours
SFOC	210	g/kWh
Total power/day	192,000	kWh/day
Fuel consumed/day	40.32	Tonnes/day

The reference ship loading of 40.32 tonnes/per day used in the study is considered high for a North Sea or Baltic Sea port, some theoretical combinations or combinations thereof of what this loading could represent are included here:
— 10 Ferry – ro-pax (generic) at berth for 12 hrs/day 365 days/yr; or
— 7 Cruise ships (20,000–59,999 GT) at berth for 8 hrs/day 365 days/yr; or
— 4 Cruise ships (60,000–99,999 GT) at berth for 8 hrs/day 365 days/yr, or
— 24 General cargo ships (5,000–9,999 dwt) at berth for 24 hrs/day 365 days/yr; or
— 28 Bulk carriers (10,000-34,999 dwt) at berth for 24 hrs/day 365 days/yr; or
— 16 Container ships (8,000-11,999 TEU) at berth for 12 hrs/day 365 days/yr.

For this study, MAMPEC was configured to calculate the sediment concentrations after five years as this is considered a common time period between dredging activities in North Sea and Baltic Sea ports. The defined ship loading represents 40.32 tonnes of fuel being consumed every day for 365 days per year for five years, for the calculation of the substances concentrations in the port sediment.

It is noted that MAMPEC-BW can calculate sediment concentrations for given time periods between one and 20 years (1, 2, 5, 10 and 20 years), and that due to the underlying logic within the MAMPEC model, the sediment concentrations do not scale linearly between zero and 20 years, sediment modelling is explained in more detail in Section 2.4.8.

2.3 Calculation of mean emission factors for substances in the EGCS washwater

The aim of this task was to define the mean emission factors for each of the substances in the EGCS washwater. The mean emission factors are defined as grams per tonne of fuel consumed for each substance and are derived from washwater sample data provided by the project sponsors.

2.3.1 Sample data

CE Delft was provided with chemical water analysis reports for 291 washwater samples from 53 different ships; the samples were collected from cruise ships, bulk carriers and ferries. Samples were taken when ships were in service in different locations in the Caribbean, the eastern Pacific, the Tasman Sea, the Strait of Malacca, the Atlantic Ocean, the North Sea and the Baltic. Often, ships will have bunkered near these locations and as a result, the samples likely reflect a wide range of fuel origins and qualities.

The majority of the samples were collected by the respective ships' engineers in accordance with the US Environmental Protection Agency (EPA) or ISO test procedures for the parameters analysed as per the requirements of IMO MEPC 259(68) Annex 3 'Washwater Data Collection'. The chemical analysis was undertaken by industry-recognized ISO-certified laboratories.

Sample Reference Points: In line with the IMO's request to shipowners on the collection of washwater discharge samples for periodical analysis, for each EGCS the water samples were collected at three different reference points, namely: the inlet water (for background); EGCS tower outlet (before any treatment system(s)); and at the overboard discharge.

Sample Technical Information: Along with the sample laboratory results, CE Delft was also provided with relevant technical information that provides more insight into the EGCS operation at the time of sampling. The EGCSs sampled were manufactured by various vendors and represent both multi- and single-stream units depending on the EGCS maker and ship's configuration.

The technical information that was taken into account during the collection of the samples included: the total number of diesel engines connected to an EGCS (both single- and multi-stream systems); the number of diesel engines operating during the collection of samples; the load of the particular diesel engine (or combination of diesel engines) during the time of the sample; the type of fuel and its corresponding sulphur content and the pH, Turbidity, PAHphe at the seawater inlet, EGCS tower outlet and the overboard discharge; and the SO_2/CO_2 ratio of the exhaust.

For 38 of the 291 samples, some information was missing that was essential for the study's methodology, e.g. data on the washwater flow rate or fuel consumption. Subsequently, these 38 samples were discarded and the remaining 253 samples were used for the study. The substances which have been considered for this study are presented in Table 4 and Table 5; all of these substances are included in the laboratory analysis of each sample.

Table 4 - Analysed Metals

Metal	CAS No.	Metal	CAS No.
Arsenic (As)	7440-38-2	Nickel (Ni)	7440-02-0
Cadmium (Cd)	7440-43-9	Selenium (Se)	7782-49-2
Chromium (Cr)	7440-47-3	Thallium (Tl)	7440-28-0
Copper (Cu)	7440-50-8	Vanadium (V)	7440-62-2
Lead (Pb)	7439-92-1	Zinc (Zn)	7440-66-6
Mercury (Hg)	7439-97-6		

Table 5 - Analysed PAHs

PAH	CAS No.	PAH	CAS No.
Acenaphthene	83-32-9	Chrysene	218-01-9
Acenaphthylene	208-96-8	Dibenz(a,h)anthracene	53-70-3
Anthracene	120-12-7	Fluoranthene	206-44-0
Benzo(a)anthracene	56-55-3	Fluorene	86-73-7
Benzo(a)pyrene	50-32-8	Indeno(1,2,3-cd) pyrene	193-39-5
Benzo(b)fluoranthene	205-99-2	Naphthalene	91-20-3
Benzo(g,h,i)perylene	191-24-2	Phenanthrene	85-01-8
Benzo(k)fluoranthene	207-08-9	Pyrene	129-00-0

The substances considered for this study include the substances set out in the IMO guidelines for washwater data collection as detailed in Annex 3 of MEPC 259(68) and listed in Table 6.

Table 6 - IMO Washwater analysis parameters

Annex 3 MEPC 259(68) – Washwater Analysis Parameters	
pH	Nickel (Ni)
PAH and oil (detailed GC-MS analysis)	Lead (Pb)
Nitrate	Zinc (Zn)
Nitrite	Arsenic (As)
Cadmium (Cd)	Chromium (Cr)
Copper (Cu)	Vanadium (V)

With respect to PAH and oil, the IMO through MEPC 259(68) specifies criteria for just one PAH — phenanthrene — which is prevalent in the exhaust from diesel internal combustion engines and is an indicator for the possible presence of others. This study considers phenanthrene as well as a further 15 PAHs and makes an assessment of the samples set against the IMO washwater criteria for PAHphe.

MEPC 259(68) does not contain any criteria for the concentrations of metals in EGCS washwater discharges since turbidity is monitored as a surrogate for suspended solids such as metals. This study includes an assessment of the sample set against the IMO washwater criteria for turbidity.
The sample set is also assessed against the IMO washwater criteria for pH and Nitrates.

Selenium and Thallium are not specified by the IMO but are required under US EPA Vessel General Permit (VGP) for EGCS periodic monitoring, hence their inclusion in this study.

2.3.2 Calculation of mean emission factors

This section explains how the sample data is processed and the steps taken to calculate the mean emission factors.

Net concentrations: The aim of this study is to identify the impact of open-loop EGCSs on port water and sediment. Therefore, in the analysis of the sample data we isolate what is being added by the scrubbing process from what is already in the port water. This approach calculates the net change in substance concentrations between the EGCS tower outlet and inlet water, i.e. before any treatment of the washwater or buffering.

The 'net concentration' approach deducts the inlet water concentrations for each substance from the EGCS tower outlet values; we do not consider the overboard discharge as we wish to avoid the effects of any post-scrubbing washwater treatment systems in the analysis.

Washwater treatment: EGC Systems vary between different manufacturers and are often tailored to ship-specific requirements; however, fundamentally, when we consider open-loop EGCSs today most of these systems include washwater filtration to reduce substances added to the washwater by the scrubbing process, and many also have the ability to buffer the washwater pH in order to meet IMO or US regulations. For this study, the effects of washwater treatment systems are not included and the study can therefore be considered to represent a worst case with regard to the calculation of the mean emission factors, although it is recognized that the capability of washwater treatment systems to remove substances has improved in recent years and these systems are increasingly commonplace.

It is noted that the PAHs and turbidity criteria set out by IMO are also designed in a way that requires the washwater to be measured downstream of the scrubbing equipment but upstream of any washwater treatment prior to discharge.

Sample detects and non-detects: In the laboratory analysis results, each substance in each sample is reported as being either a 'detect', in which case it has a value or a 'non-detect' in which case it is not assigned a value. The detection limit (DL) of the equipment used for analysis is also reported. In the data set a detect is assigned a "D" and a non-detect is assigned a 'U'.

A non-detection does not imply that the substance is absent from the sample, rather that its concentration is below the limit that the analysis equipment can detect.

How the non-detects are treated is a key part of the calculation process for the net concentration, and the logic used for calculation of the net concentration is as follows:
a   If a substance is detected ('D') at both the seawater inlet and the EGCS tower outlet, the net concentration is the concentration at the EGCS tower outlet minus the concentration at the seawater inlet.
b   If a substance is a non-detect ('U') at the seawater inlet and a detect ('D') at the EGCS tower outlet, the net concentration is the concentration at the EGCS tower outlet minus a proxy for the non-detect of 50% of the detection limit for the equipment used to analyse the sample at the seawater inlet. This approach is in line with common practice (Hites, 2019).
c   If a substance is a detect ('D') at the seawater inlet and a non-detect ('U') at the EGCS tower outlet, the net concentration is 50% of the detection limit for the equipment used to analysis the sample at the EGCS tower outlet minus the concentration at the seawater inlet.

d   If a substance is not detected ('U') at both the seawater inlet and the EGCS tower outlet, we have set the value to zero. This does not necessarily mean that the value of the particular substance is zero, but as the values are below the detectable limit this is consider a practical approach.

Table 7 - Logic for non-detects and detects

Scenario	Seawater inlet	EGCS tower outlet	Net concentration
A	D	D	EGCS tower outlet – Seawater inlet
B	U	D	EGCS tower outlet – 50% DL
C	D	U	50% DL – Seawater inlet
D	U	U	Zero

In some cases, the calculation of the net concentration produced a negative value which could give the indication that the scrubbing process is actually removing substances from the incoming seawater; as this is not considered probable and poses a threat to the authenticity of the calculations, any negative net concentration values were removed from the data set.

The above assumptions allowed us to recognize the non-detects and negative net concentrations and treat them in a consistent manner. In total, the data validation process (i.e. discarding the 38 samples that were missing key technical information and the elimination of negative values) resulted in the elimination of 1,348 possible values, representing approximately 17% of the maximum possible number of values (291 samples X 27 substances).

The average net concentrations for metals in the post EGCS tower washwater are presented in Table 8 and the average net concentrations for PAHs in the post EGCS tower washwater are presented in Table 9. The concentrations in Table 8 and Table 9 are before any post-scrubber washwater filtration or addition of buffering water (washwater treatment).

Table 8 - Average metal concentration increase in washwater samples

Substance	Mean net concentration increase (mg/l)	Minimum – maximum net concentration increase (mg/l)
Arsenic	0.0064	0-0.044
Cadmium	0.0019	0-0.020
Chromium	0.018	0-0.57
Copper	0.25	0–11
Lead	0.00020	0-0.00050
Mercury	0.00010	0-0.00023
Nickel	0.12	0-7.3
Selenium	0.015	0-0.23
Thallium	0.0053	0-0.054
Vanadium	0.14	0-3.5
Zinc	0.32	0-23

Table 9 - Average PAH concentration increase in washwater samples

Substance	Mean net concentration increase (µg/l)	Minimum – maximum net concentration increase (µg/l)
Acenaphthene	0.20	0-0.93
Acenaphthylene	0.12	0-2.1
Anthracene	1.8	0-15
Benzo(a)anthracene	0.3	0-12
Benzo(a)pyrene	0.042	0-0.12
Benzo(b)fluoranthene	0.048	0-0.32
Benzo(g,h,i)perylene	0.047	0-0.19
Benzo(k)fluoranthene	0.01	0-0.02
Chrysene	0.25	0-1.6
Dibenz(a,h)anthracene	0.019	0-0.06
Fluoranthene	0.21	0-6
Fluorene	0.57	0-7
Indeno(1,2,3-cd)pyrene	0.049	0-0.31
Naphthalene	3.5	0-140
Phenanthrene	2.0	0-11
Pyrene	0.36	0-5

Mean emission factors: The method used to calculate the mean emission factors for each substance is based on a mass balance and can be broken down into eight steps. The steps are:
1. Calculate the net concentration of the particular metal (mg/l) or PAH (µg/l) as described above.
2. Calculate a daily EGCS flow rate for each sample (litres of water per 24 hrs) on the basis of the flow rate during sampling.
3. Calculate the emissions per day (mg/day) or (µg/day) based on the daily EGCS flow rate and the net concentration increase.
4. Using the total power of the diesel engine(s) that is/are connected to the EGCS and the engine percentage load at the time of sampling, calculate the Specific Fuel Oil Consumption (SFOC) (g/kWh)[1] and the power produced per day (kWh/day). Combine the SFOC and power produced per day to calculate the tonnes of fuel consumed per day.
5. Use the emissions per day and fuel consumption per day to calculate the emission factor (g/tonne of fuel) for each substance in each sample.
6. Discard the negative values which were created due to our adopted net concentration logic.
7. Discard the outliers. The exclusion of statistical outliers has been performed by identifying three standard deviations from the mean emission factor value for each substance. This methodology is consistent with generally accepted practice, e.g. the United States Geological Survey's statistical method for water resources.
8. Recalculate the mean emission factors (g/tonne fuel) for each substance with the outliers removed.

The mean emission factors (g/tonne of fuel consumed) are combined with the total ship load in the port for the reference scenario (192 MWh/day = 40.32 tonnes of fuel/day) to derive the substance load in the EGCS washwater. The resultant substance loads are input

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[1] The engine load data was used to calculate the SFOC at the relevant engine load by using equation (3) from the third IMO GHG study. The formula is SFOC (load) = SFOCbase × (0.455 × load 2 - 0.71 × load + 1.28) (IMO, 2014), SFOCbase is taken as 210 g/kWh.

into the MAMPEC-BW model which calculates the equilibrium water and five-year sediment concentrations for each substance and each model port.

2.3.3 Substance frequency of detection

Presented in this section are the frequencies at which each substance is detected in the washwater samples. Figure 3 shows that metals are detected frequently both in the seawater inlet and post-EGCS. For nickel and vanadium the difference is larger than for other metals, indicating that these metals are more often present in fuel than in seawater, while arsenic, cadmium, lead and mercury appear to be coming predominantly from the seawater. Figure 4 presents the frequency for the detection of PAH, in the seawater, these substances are in most cases below the detection limit, while they are present in the washwater at the EGCS tower outlet.

It is noted that the substances present in the discharged washwater could come from sources other than the fuel, for example substances can also be introduced to the washwater from pipework or marine growth protection systems (MGPS).

Figure 3 - Frequency of the detection of metals (100% = all washwater samples)
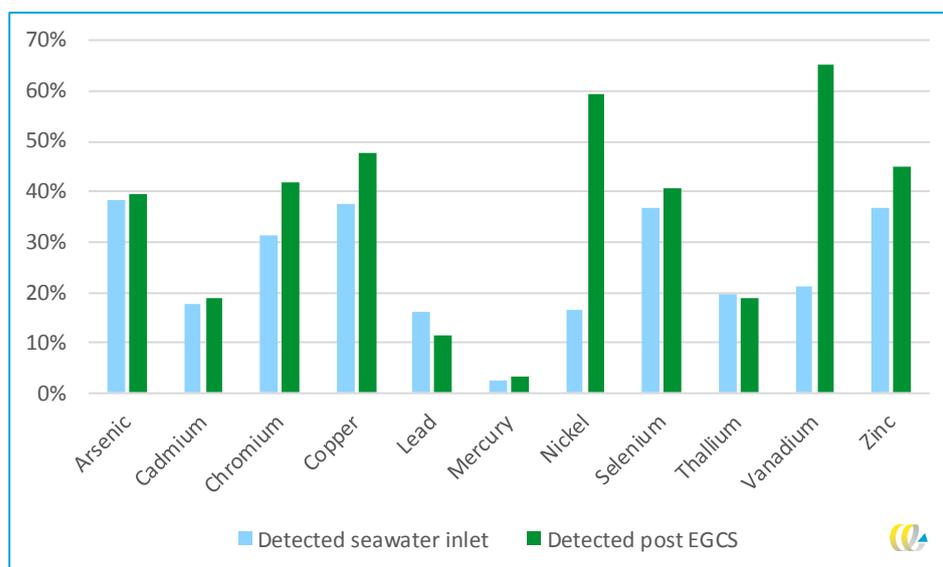
Figure 4 - Frequency of the detection of PAHs (100% = all washwater samples)
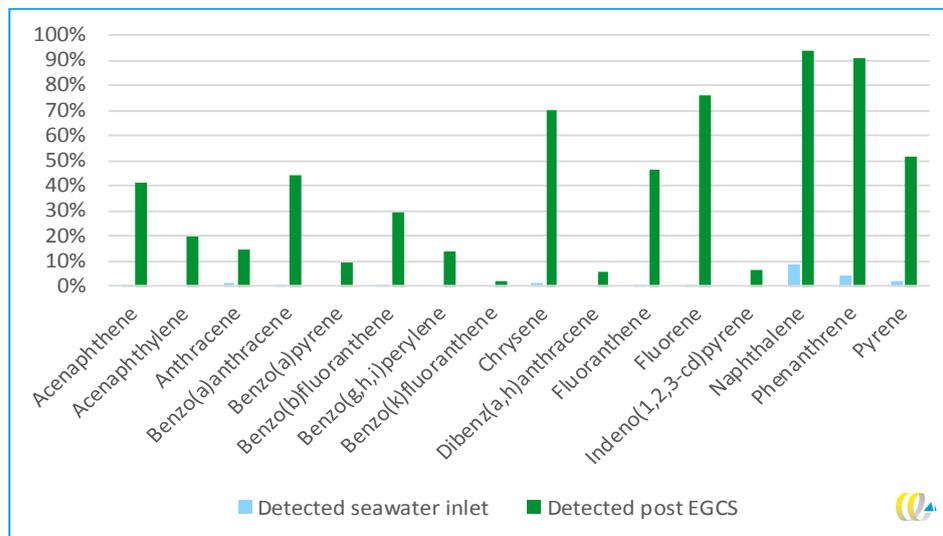
2.4 Introduction to MAMPEC

2.4.1 Background

MAMPEC is a validated steady-state 2D integrated hydrodynamic and chemical fate model commonly used for environmental risk assessment of biocides from antifouling paints and also for contaminants from ballast water treatment installations. The model and software have been developed and maintained by Deltares since 1999, in cooperation with the Institute for Environmental Studies of the VU University in Amsterdam. It was originally developed for the exposure assessment of antifouling substances. In 2011, on request of The Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection - Ballast Water Working Group (GESAMP-BWWG) and IMO, a special standardised version of MAMPEC (MAMPEC BW v3.0) was created for the exposure assessment of compounds emitted with discharges from ballast water treatment installations. MAMPEC-BW 3.1.0.5 is used for this study. The software and technical documentation is freely available and can be obtained from the support site: Deltares MAMPEC.

The most important difference between MAMPEC and MAMPEC-BW is that a default GESAMP-BWWG Model Harbour has been included together with a database, reviewed by GESAMP-BWWG, of environmental properties of ballast water specific chemicals. The GESAMP-BWWG model harbour was derived from the OECD-EU Commercial Harbour, which is one of the standard environmental emission scenarios used for evaluation of biocides under the Biocidal Products Directive (BPD, Directive 98/8/EC) and the more recent Biocidal Production Regulation (BPR, Regulation (EU) 528/2012). The standard OECD-EU Commercial Harbour is one of the model ports evaluated in this study.

MAMPEC is currently recognized and used by regulatory authorities in the EU, USA, Japan, and other OECD countries for exposure assessment of antifoulant substances.
It is also noted that MAMPEC was not originally designed to model specific, real-life ports, but was developed to represent generic ports that can be seen as typical for a specific geographical region; it was only later that work was conducted to develop the capability of the model to model specific ports in specific locations. The validation of MAMPEC for use on specific port locations as opposed to generic geographical regions is ongoing.

2.4.2 MAMPEC environment types

In MAMPEC, four different types of environments can be specified. These environments are illustrated in Table 10 along with details the hydrodynamic exchange mechanisms that are applicable to each environment.

Table 10 – MAMPEC environment types

Commercial Harbour	Marina	Open Sea Shipping Lane	Open Harbour
Hydrodynamic Exchanges			
Tidal	Tidal	Current	Current
Horizontal	Horizontal		Wind
Density	Density		Tidal
Flushing	Flushing		
Wind	Wind		
Other non-tidal	Other non-tidal		
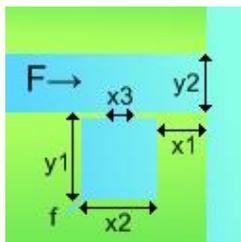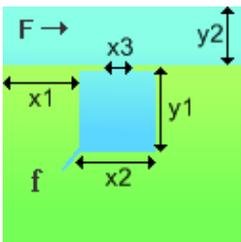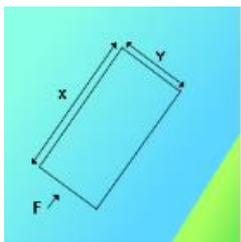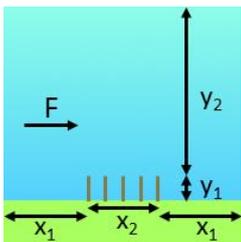
The Commercial Harbour, Marina and Open Harbour environments are used in this study as detailed in Section 2.5.

For each environment, inputs are required for the port geometry and environmental conditions; these inputs reflect the type of port being modelled e.g. river port, ocean port, as well as the geographical region or location. For this study, the ports modelled are representative of the North Sea and Baltic Sea regions rather than specific locations or ports.

2.4.3 Environmental inputs

A limited set of agreed standard scenarios for environmental inputs, substance properties and emission characteristics are included in MAMPEC and usually these are applied in approval procedures, together with regional scenarios as agreed in ECHA-AHEE (European Chemicals Agency – Ad hoc WG on Environmental Exposure) meetings (Cheng, et al., 2013; ECHA, 2016; 2017) or specific national scenarios (e.g. (Koivisto, 2003)).

In this study, the ECHA derived data for the Baltic Sea region was used to define the environmental inputs for the model port located in the Baltic Sea region. For the North Sea based model ports, the environmental inputs were taken from the Standard OECD-EU Commercial Harbour as this standard MAMPEC port is based on the Port of Rotterdam, and therefore the environmental inputs are applicable to the North Sea region.

2.4.4 Predicted Environmental Concentrations (PEC)

MAMPEC solves mass balance equations to calculate Predicted Environmental Concentrations (PEC) for two areas, one inside the port which is referred to as 'harbour' and the other outside the port which is referred to as 'surrounding'; these are illustrated in Figure 5 and Figure 6. The calculated concentrations are a function of the hydrodynamic exchanges between the harbour area and the surrounding area in combination with additional physical and chemical processes, such as adsorption and desorption to sediments, degradation, and volatilisation.

Figure 5 - MAMPEC area designations for commercial harbour and marina type environments
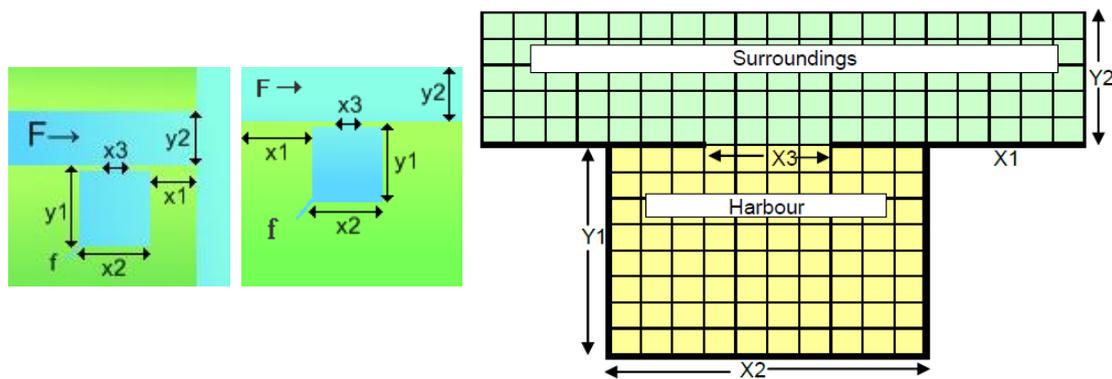
Figure 6 - MAMPEC area designations for open harbour type environment
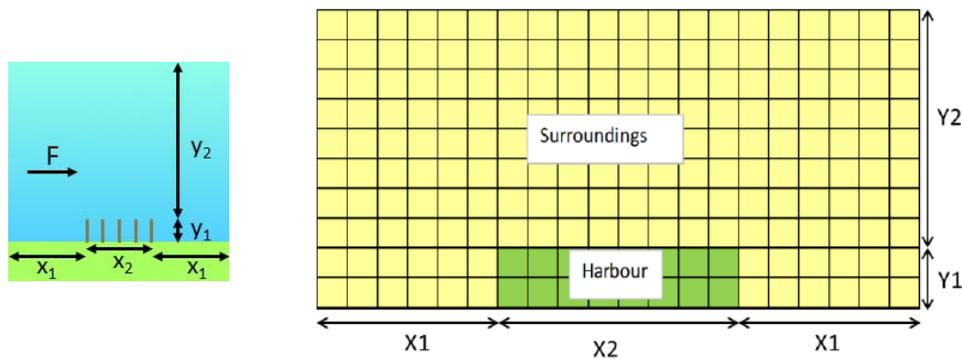
MAMPEC calculates dissolved and total (including the SPM bound fraction) equilibrium concentrations in the water for both the harbour area and the surrounding area. MAMPEC also calculates the concentration in the sediments in the harbour area which are due to the settling of suspended particulate matter (SPM) in which substances may be adsorbed and other processes such as biodegradation.

It was reported by ECHA (2016; 2017) that for the assessment of emissions during the service life of products used in commercial shipping at sea, the OECD Commercial Harbour scenario should be used as the single core scenario. Risk assessments should be based on average dissolved Predicted Environment Concentrations (PECs) derived for the wider environment simulated by MAMPEC as concentrations in the 'surrounding' area (i.e. for the

area immediately outside the 'harbour' area). This study reports and evaluates the substance concentrations for both the 'surrounding' and 'harbour' areas.

2.4.5 Hydrodynamic exchange processes in MAMPEC

The total exchange volume (m^3/tide) is often a very important driving force in the magnitude of the resultant predicted environmental concentrations, as it relates to the volume of water that is exchanged between the harbour area and the surrounding area during each tidal period (12.41 hrs); in general, the higher the exchange volume the lower the resultant predicted concentrations. In MAMPEC, the total exchange volume is a function of the following hydrodynamic exchange mechanisms (Hattum, et al., 2016):
1. Tidal - Tidal exchange and daily water level variation.
2. Horizontal or Current - Exchange due to horizontal current in front of the port entrance.
3. Density – Density-driven exchange.
4. Other non-tidal - Non-tidal daily water level variations.
5. Flushing – External inflows e.g. small stream or outflows e.g. cooling water.
6. Wind - Wind-driven exchange.
The environment type that the model port is based upon dictates which of these exchange mechanisms are used to calculate the total exchange volume and their dominance, as illustrated in Table 10.

Items 1-3 are generally considered the main exchange mechanisms (Hattum, et al., 2016). Under low tidal conditions, small currents and small or no density differences, Items 4, 5 and 6 can become important. It is possible to include additional flushing, Item 5, due to external inflows (e.g. rain, small streams), but though common flushing has not been included in any of the model ports in this study as part of the conservative approach (flushing would lower the equilibrium concentrations).

Small flows outside the port can have a significant effect on the residence time of the substances inside the port (harbour area), in particular when the port is relatively small. A flow velocity of 0.01 to 0.05 m/s can reduce residence times in such ports by a factor of ten compared to no flow. The residence time does not only depend on the flow, but also on other characteristics of the port such as the volume of the port and the width of the port entrance. Depending on the magnitudes of the other exchange mechanisms the residence times may vary significantly with small variations in the flow outside the port.

Whilst MAMPEC includes all the major hydrodynamic exchange volumes, there are 'additional factors' such as ship movements that also have an impact on the total exchange volumes but are not considered by MAMPEC. In most cases, when the total exchange volumes are high these 'additional factors' are not dominant, therefore excluding them is not significant in regard to the predicted concentrations. However, when the MAMPEC total exchange volume is very low, 'additional factors' become more significant and therefore the exchange volume is actually likely to be higher for a given scenario than MAMPEC uses. Subsequently, whilst all predicted concentrations from MAMPEC are generally considered as over-predictions, due to the worst-case nature of the model, the concentrations at low exchange volumes will be even more over-predicted than those at higher exchange volumes.

2.4.6 Spatial distribution of emissions in MAMPEC

In MAMPEC-BW, the spatial distribution of the emissions within the port is dependent upon on the environment type. For the commercial harbour type environment, the input substance load is evenly distributed along the far end of the harbour, opposite the entrance. For the open harbour and the marina type environments the input substance load is evenly distributed across the entire harbour. The spatial distribution of the input substance load is illustrated in Figure 7, Figure 8 and Figure 9.

**Figure 7 – Spatial distribution of input substance load – commercial harbour type environment**
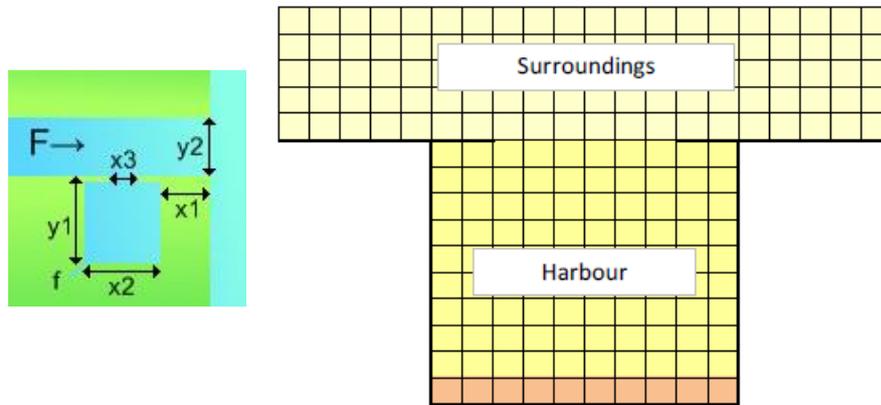
Figure 8 – Spatial distribution of input substance load – marina type environment
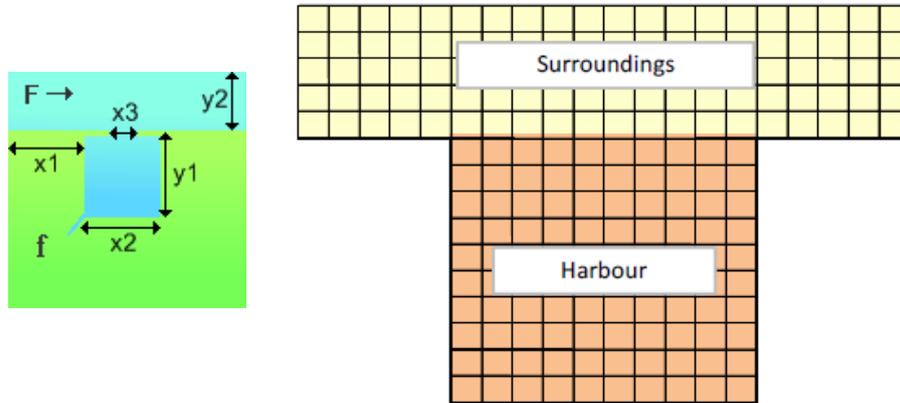

Figure 9 – Spatial distribution of input substance load – open harbour type environment
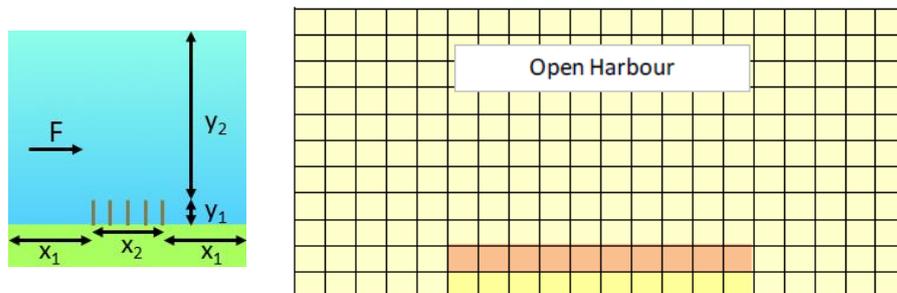
2.4.7 MAMPEC Chemical and biological processes and inputs

A detailed description of the chemical and biological processes and the required MAMPEC inputs is presented in Annex B. For most of the EGCS-specific compounds (metals and PAHs) the basic substance parameters (e.g. Kow, Koc, S, Vp, H, DT50 degradation, and Kd for metals) are not present in the existing MAMPEC databases for antifouling and ballastwater. Therefore, these parameters were derived from reviewed literature or the reviewed regulatory database. Reliable data for the biodegration of PAHs in the marine environment is not readily available in open literature, which is usually confined to well defined laboratory or experimental studies with micro-organisms that cannot easily be extrapolated. Therefore, in the MAMPEC-BW runs the worst case assumption of negligible biodegration was used and rate constants for the degradation terms were set to zero. The sediment-water distribution coefficient (Kd) is one of the main parameters determining the partitioning of metals. As Kd values vary largely between metals and environmental conditions a detailed and comprehensive review study of US-EPA (Allison & Allison, 2005) was used to derive representative parameter estimates. Further detailed information is provided in Annex B.

2.4.8 The MAMPEC sediment compartment

MAMPEC-BW can calculate the accumulation of a substance in the sediment for a specified time between one year and 20 years and a given background concentration. Sediment substances are of interest as dredged materials are subject to regulation when considering their disposal and, additionally, any disturbance of the sediment can release substances into the water. For this study, the sediment substance concentrations have been calculated after five years of continuous open-loop EGCS operations assuming zero sediment background concentrations and zero contributions from other sources. Five years was chosen as this is considered to be in general representative of the frequency of dredging activities in North Sea and Baltic Sea ports.

In MAMPEC-BW, the concentrations of substances in the sediment will, after a period of time approach a maximum plateau value, as the substance concentrations in the sediment will reach an equilibrium condition. The time it takes to reach the equilibrium condition and the magnitude of the concentrations in the equilibrium condition depend on many different parameters, e.g. the thickness/depth of the sediment layer, the sedimentation velocity, characteristics of the suspended particulate matter, substance parameters (e.g. biodegradation rate) and the substance concentrations in the water. In general, the thicker the sediment layer, the longer it takes to reach the equilibrium condition and the higher the substance concentration in the water and suspended particulate matter (SPM), the higher the substance concentration in the sediment. It is noted that the substance concentrations and SPM used to calculate the sediment concentrations are as calculated by the MAMPEC for the model port in question. Therefore, different substance concentrations in the water and SPM are used for each of the four model ports in calculation of the sediment concentrations.

For more detailed information on the treatment of sedimentation in MAMPEC, we refer to the technical documentation of MAMPEC (Section 6.5 in Van Hattum et al. (2016)).

The concentrations of substances in the sediment in MAMPEC-BW follow a curve which plateaus as the substance concentrations in the sediment reach an equilibrium condition. Figure 10 shows two theoretical curves for two possible scenarios which illustrate how the concentrations in MAMPEC-BW changes over time.

The reason that one curve is shallower than the other is that the shallow curve assumes a thicker sediment layer and therefore in this scenario it will take longer to reach the equilibrium condition. The absence of biodegradation for a specific substance in sediment can also increase the time taken to reach the equilibrium condition when compared to substances with a significant biodegradation.

In addition to the factors already mentioned the sediment background substance concentrations are fundamental in calculating predicted concentrations, in reality there is almost always an existing background concentration and therefore the starting point is never actually zero, but it is likely to be some distance along the concentration curve as indicated in Figure 10.

Figure 10 - MAMPEC-BW concentrations of substances in the sediment
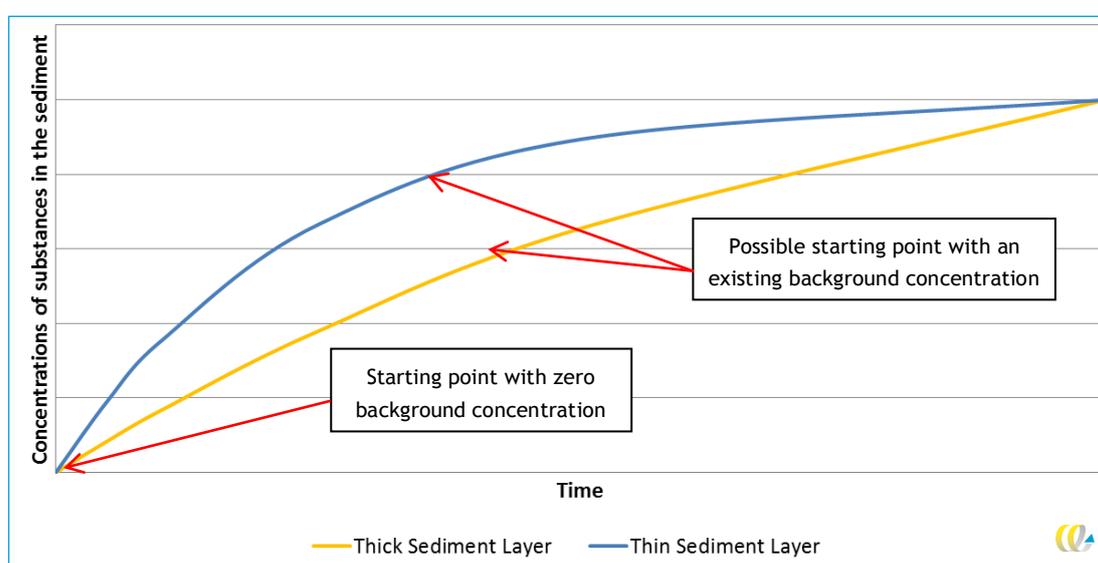
In practice, every port/location will have a unique curve for the accumulation of a substance in the sediment that is dependent on the background concentrations, the thickness of the sediment layer, the total substance load from all sources, shipping, industry, rivers et cetera, and the frequency of dredging activities.

2.5   Definition of port models

2.5.1   Port dimensions and hydrodynamic exchange

This study aims to assess the impact of open-loop EGCS operations on the port water and sediment in generic ports that represent the North Sea and Baltic Sea regions, four model ports have been defined to meet this aim:
1. Standard OECD-EU Commercial Harbour.
2. Baltic Commercial Port.
3. Ocean Port.
4. River Port.
The MAMPEC environment type and the source of the port geometry and environmental inputs is summarised in Table 11. The main reference port is the Standard OECD-EU Commercial Harbour and the other three ports are derived from this with systematic

changes made to the environment type, port geometry and environmental inputs, in order to cover a range of different port arrangements and the two specified geographical regions, North Sea and Baltic Sea.

Table 11 - Summary of four model ports

		MAMPEC Environment Type	Port Geometry Inputs	Environmental Inputs
1	**Standard OECD-EU Commercial Harbour**	Commercial Harbour 	Standard OECD-EU Commercial Harbour	Standard OECD-EU Commercial Harbour (North Sea)
2	**Baltic Commercial Port**	Commercial Harbour 	Standard OECD-EU Commercial Harbour	ECHA Spreadsheets for Baltic Sea
3	**Ocean Port**	Marina 	Representative of an Ocean Port	Standard OECD-EU Commercial Harbour (North Sea)
4	**River Port**	Open Harbour 	Representative of a River Port	Standard OECD-EU Commercial Harbour (North Sea)
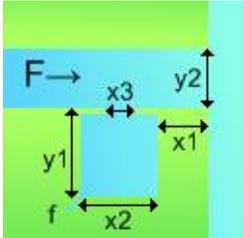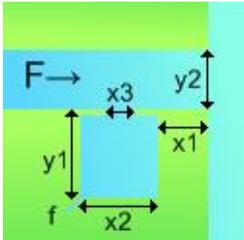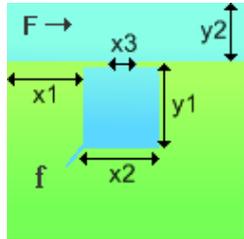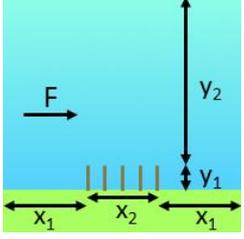
Table 12 summarises the main characteristics of the port geometry and hydrodynamic exchange mechanisms and the total exchange volumes. The total exchange volumes are expressed in terms of m^3/tide and as a percentage of the port volume, noting the tidal period for all four model ports is 12.41 hrs, and therefore the substance loads which are defined in g/d are influenced by approximately twice the exchanges volumes in Table 12 per day.

In Table 12 the symbol in brackets next to the dimensions relates to the symbol used to define the port geometry in MAMPEC-BW and as illustrated in Table 11.

Table 12 - Port characteristics

		Length (m)***	Width (m)	Mouth Width (m)	Tidal (m)	Current (m/s)	Exch. Vol. (m³/tide)
1	Standard OECD-EU Commercial Harbour	1,000(y1)	5,000(x2)	2,500(x3)	1.5	1	$5.119.10^7$ (68%)
2	Baltic Commercial Port	1,000(y1)	5,000(x2)	2,500(x3)	0.08	0.03	$1.281.10^6$ (1.7%)
3	Ocean Port	2,500(y1)	2,500(x2)	750(x3)	1.5	1	$1.514.10^7$ (16%)
4	River Port	1,000(x2)	50(y1)	-	0.0	1	$3.351.10^7$ (4468%)

The percentage of the port water that is exchanged every tide for the River Port is a very high number because this is not an enclosed port (so the port volume is small) and there is a continuous flow of water through/past the port/quayside. The other three port models are enclosed ports and the percentage of the port water that is exchanged every tide is less than 100%.

Screenshots of the MAMPEC-BW environment input settings as used in the calculations are provided in Annex A.

2.5.2 Standard OECD-EU Commercial Harbour

The base model port for this study is the Standard OECD-EU Commercial Harbour which is one of the standard ports in MAMPEC-BW and is often used in applications for the type approval of ballast water management systems. The geometry and environmental inputs for this standard port are derived from the Port of Rotterdam, which is a commercial port located in the Netherlands and on the North Sea coastline.

The port is located on an estuary quite close to the sea/ocean; there is a significant tide every 12.41 hrs with amplitude of 1.5 m and a significant current of 1 m/s flowing in front of the port entrance. A very significant factor in calculation of the exchange volume for this model port is the density difference between the water flowing in front of the port entrance and the water in the port. This density difference is caused by a horizontal salinity gradient that moves with the tide and it generates a density-driven flow which acts as a very effective hydrodynamic exchange mechanism.

The density difference is the dominant hydrodynamic exchange mechanism and is responsible for 67% of the total exchange volume for this port (see Annex A, Figure 33).

Of the four modelled ports the Standard OECD-EU Commercial Harbour has the second highest exchange volume at 51.2 million m^3 per tide; this volume is also a high percentage (68%) of the total volume of water in the port.

2.5.3 Baltic Commercial Port

As this study focuses on both the North Sea and Baltic Sea regions, one of the four model ports has been defined to represent a commercial port in the Baltic Sea. The Baltic Commercial Port is based on the Standard OECD-EU Commercial Port but the hydrodynamic and other environmental inputs have been changed to represent those found in the Baltic Sea rather than in the North Sea, however the geometry of the port remains unchanged.

The environmental inputs for this model port were derived by ECHA from the database that was presented by Cheng et al. (2013) specifically the data was taken from the 38 Baltic Sea spreadsheets that were developed and distributed by ECHA (2017). When examining this database in more detail, it is clear that worst-case assumptions were used for some of the data. For example, the derived wind conditions that have been assumed the same for all 38 ports and for the current velocity F where one value (0.03 m/s) is used for all ports in the Baltic database.

As a result of these worst-case environmental inputs for the Baltic Sea region the Baltic Commercial Port has a very low exchange volume of only 1.2 million m^3 per tide compared to the 51.2 million m^3 per tide for the Standard OECD-EU Commercial Harbour. Noting that the geometry of the Baltic Commercial Port is the same as the Standard OECD-EU Commercial Harbour, the fact that the exchange in the Baltic Commercial Port (Baltic Sea) is only 2.3% of the exchange in the Standard OECD-EU Commercial Harbour (North Sea) illustrates the significant impact that the lack of tides and the low currents in the Baltic Sea have on the exchange volumes.

In the setup of the Baltic environment, whilst there is no tide (Tidal difference = 0 m) and low current outside the port entrance (F = 0.03 m/s), there is a small daily water level variation of 8 cm; however, this generates a relatively small exchange volume. Additionally, an average wind speed of 3.8 m/s is included; however, the contribution of the wind-driven exchange is also relatively small due to the low fraction of the time that the wind is assumed to be perpendicular to the Port entrance (0.13). This fraction is determined from the general wind conditions and the orientation of the port entrance and is a sensitive parameter for calculating the wind-driven exchange. If the wind is assumed to be perpendicular all of the time (fraction = 1), then the relative contribution of the wind-driven exchange would increase from 5 to 30%.

The horizontal exchange is the dominant hydrodynamic exchange mechanism and is responsible for 78% of the total exchange volume for this port (see Annex A, Figure 34).

Of the four modelled ports, the Baltic Commercial Harbour has the smallest exchange volume at 1.2 million m^3 per tide; this volume is also only 1.7% of the total volume of water in the port. This means that of the four model ports, the Baltic Sea port is expected to represent the worst case and will result in the highest predicted concentrations.

It is also relevant to mention that in Cheng et al. (2013) and as highlighted by the ECHA, MAMPEC-BW calculations more significantly overestimate the concentrations in the Baltic Regions than in the equivalent Atlantic (North Sea) and Mediterranean Regions. The low exchange volumes in the Baltic are assumed to be the driver for these significant overestimates.

2.5.4 Ocean Port

The Ocean Port is based on the Standard OECD-EU Commercial Harbour but the port geometry and the environment type have been changed in order to represent an Ocean Port; the environmental inputs have not been changed and therefore this is a North Sea-based port. The environment type used for the Ocean Port is the 'Marina' environment type in which the port opens directly onto the open ocean rather than the 'Commercial Harbour' environment type which is used in the Standard OECD-EU Commercial Harbour and positions the port up an estuary.

The most important change to the port geometry is the change in the width of the port entrance from 2,500 m to 750 m, as this directly affects the horizontal and density-driven exchange processes. For the Standard OECD-EU Commercial Harbour the dominant exchange mechanism is the density-driven exchange (67%) but for the Ocean Port the tidal exchange is the dominating exchange mechanism (62%). The dimensions of the Ocean Port mean that the volume of water in the port is around 26% larger than the Standard OECD-EU Commercial Harbour.

The tidal exchange is the dominant hydrodynamic exchange mechanism and is responsible for 62% of the total exchange volume for this port (see Annex A, Figure 35).

Of the four modelled ports the Ocean Port has the third highest exchange volume at 15.1 million m^3 per tide, this volume is (16%) of the total volume of water in the port; it is, however, only around 30% of the exchange volume for the Standard OECD-EU Commercial Harbour.

2.5.5 River Port

The River Port is based on the Standard OECD-EU Commercial Harbour but the port geometry and the environment type have been changed in order to represent a River Port; the environmental inputs have not been changed and therefore this is a North Sea-based port. The environment type used for the River Port is the 'Open Harbour' environment type in which an unenclosed port is positioned in a river rather than the 'Commercial Harbour' environment type which is used in the Standard OECD-EU Commercial Harbour and positions an enclosed port up an estuary.

Compared to the other port definitions, the River Port definition yields the highest exchange volume. This is mainly due to a relatively small port volume when compare to the other model ports and which is less than 1% of the port volume for the Standard OECD-EU Commercial Harbour. The small port volume is reflective of the fact that the ships in this model port are berthed on a quay that is on the banks of a large river and is thus not enclosed in any way.

The horizontal exchange is the only hydrodynamic exchange mechanism and is thus responsible for 100% of the total exchange volume for this port (see Annex A, Figure 36).

Of the four modelled ports, the River Port has the highest exchange volume at 33.5 million m^3 per tide, this volume is (4,468%) of the total volume of water in the port, this percentage exchange volume is very high as the port is very small and there is a continuous flow of water through/past the port/quay. The high percentage exchange volume of 4,468% means that it is expected that this model port will generate the lowest predicted concentration.

2.6   Conclusion

In summary, for each of the 27 substances the equilibrium water concentrations and five-year sediment concentrations are calculated for each of the four model ports using the derived substance loads which relate to 40.32 tonnes of fuel being consumed every day 365 days a year by ships at berth operating open-loop EGCSs.

The methodology was deliberately designed to be conservative. The reference scenario has a relatively high use of EGCS in a port, equivalent to multiple large ships continuously at berth. Note that cruise ships consume much more energy at berth than cargo ships. Additionally, the MAMPEC-BW model uses conservative assumptions about degradation of substances and hydrodynamic exchange.

The output from MAMPEC-BW contains the calculated maximum, mean and minimum concentration within the harbour area as well as the surroundings area. MAMPEC-BW also generates total and dissolved concentrations and concentrations in the sediment.

It is noted here that a background concentration of zero is assumed for all compounds and for all scenarios as the calculations are only supposed to report what is added by open-loop EGCS operations. The concentrations as calculated by MAMPEC-BW should therefore be seen as an increase over a zero background concentration.

For each of the four model ports, the resulting maximum, mean and minimum concentrations are calculated for the following:
— **water harbour total**: Total concentrations in the harbour area (in µg/L);
— **water harbour diss**: Dissolved concentrations in the harbour area (in µg/L);
— **water surroundings total**: Total concentrations in the surrounding area (in µg/L);
— **water surroundings diss**: Dissolved concentrations in the surrounding area (in µg/L);
— **wediment harbour**: Concentrations in the sediments (after five years) in the harbour area (in µg/g dw).

The mean is the average of all the cells in the relevant area of the model, the maximum is the cell with the highest value and the minimum is the cell with the lowest value. Figure 7, Figure 8 and Figure 9 illustate how the areas with the ports are modelled using a grid made up of a number of individual cells.

3 Results and evaluation

3.1 Water results and evaluation

3.1.1 Assess EGCS washwater samples against IMO washwater discharge criteria

The washwater sample data derived from 291 ships has been analysed in order to assess the EGCS washwater against the 2015 IMO EGCS washwater discharge criteria as laid down in the 2015 IMO Guidelines for Exhaust Gas Cleaning Systems (Resolution MEPC 259(68)). The guidelines set washwater criteria for:

1. pH.
2. PAHphe.
3. Turbidity.
4. Nitrates.

The IMO washwater discharge compliance criteria are set based on continuous monitoring of the washwater, i.e. the washwater is sampled at least every 0.0035 Hz (4.76 minutes) for both Scheme B and Scheme A type approvals. In some instances a rolling average of the value is to be used for comparison against the compliance criteria and there are some allowances for short term exceedance of the criteria which may occur during standard ship operations. Considering the above as the washwater samples provided for this study are spot samples and a review of the the continuous monitoring data is beyond the scope of this study, conclusions on the compliance of the ship at the time of sampling can not be drawn. This section therefore presents an indication of the possible compliance rates only.

Table 13 indicates the limits set by the IMO for each of the substances but each subsequent section for each substance will explain the conditions under which the criteria limit should be satisfied and the exceptions.

Table 13 - IMO washwater criteria

Substance	IMO criteria limits
pH	Greater than or equal to 6.5
PAHphe (phenanthrene equivalence)	Lower than 50 µg/l PAH$_{phe}$
Turbidity	Below 25 FNU or NTU
Nitrates	Not more than 12 % removal or not above 60mg/l

pH criteria

As indicated in Table 13, the discharge washwater should have a pH of no less than 6.5 at 4 metres from the ship's overboard discharge with the ship stationary (i.e. in port) with the exception of manoeuvring and transit where the value between the inlet and outlet can deviate within the range of 2 pH units.

Samples were taken at the washwater overboard discharge (ship side), not at a distance of 4 metres from the overboard discharge (ship side), and hence the sample is taken before further buffering by the surrounding seawater. In is noted that in some cases the washwater at the overboard discharge has already been buffered by water treatment system between the EGCS tower oulet and the overboard discharge.

Out of the 291 samples, 260 samples had values for pH. Figure 11 shows the distribution of the pH sample analysis.

**Figure 11 - Distribution of pH values of washwater samples**
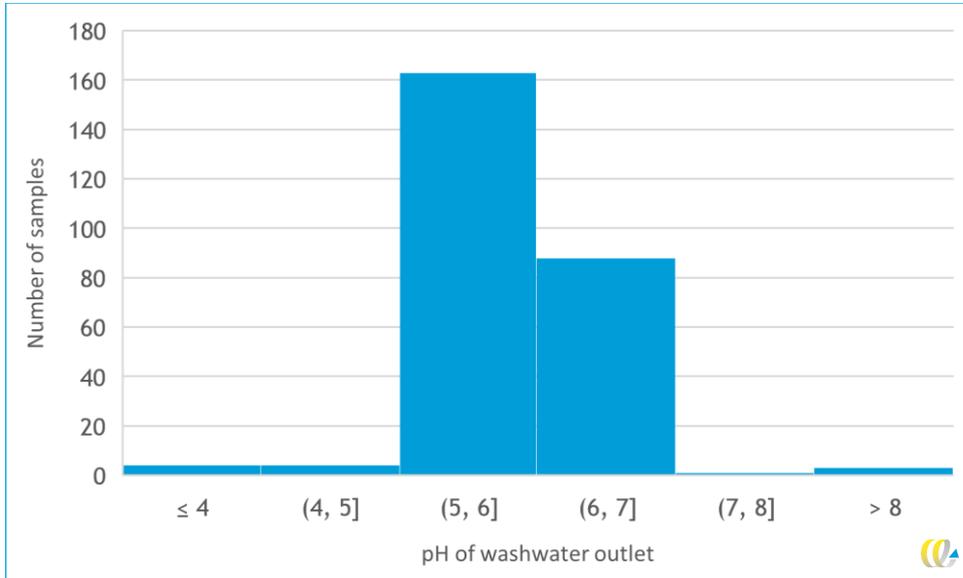
Figure 11 indicates that the majority of the samples fall between 5.0 and 7.0. Samples above 6.5 will always comply with the criteria because at 4 metres from the overboard discharge (ship side), the pH will be higher than at the overboard discharge. The Class approval procedure for open-loop EGCSs results in a pH limit at the ships side being specified, this can vary from ship to ship, and may be as low as pH 3.0, but typically a value of pH 4.0 at the overboard discharge corresponds to a minimum pH of 6.5 at 4 metres from the ship side. Hence, for this generic indicative assessment we only report samples with a pH below 4.0 at the overboard discharge (ship side) as not meeting the assessment criteria. Noting it is feasible for ships with a pH value at the overboard discharge of less than pH 4.0 to be fully compliant with the IMO continuous monitoring pH criteria. The results of the analysis are summarised in Table 14.

Table 14 - pH of washwater samples

Sample analysis info: pH	
Samples with pH data	263
Samples without pH data	28
Samples with pH greater than or equal to pH 4.0	259

PAH (Polycyclic Aromatic Hydrocarbons)

As indicated in Table 13, the maximum continuous PAH_{phe} (phenanthrene equivalence) concentration in the washwater sampled at the EGCS tower outlet should not be greater than 50 µg/L PAH_{phe} above the inlet water PAH_{phe} concentration. The 50 µg/L limit is normalized for a washwater flow rate through the EGCS of 45 t/MWh where the MW refers to the DGs Maximum Continuous Rating (MCR), therefore the limit is adjusted up and down depending on the washwater flow rate and DG size. For a 15-minute period in any 12-hour period, the PAH_{phe} concentration limit may exceed the limit by 100%. This would allow for an abnormal start-up of the EGCS.

Out of the 291 samples, 265 detected PAH_{phe} at the EGCS tower outlet; of which 261 were less than 50 µg/l PAH_{phe} above the seawater inlet concentration and 52 zero or less. Figure 12 shows the distribution of the PAHphe of the washwater samples.

Figure 12 - Distribution of Total PAH$_{phe}$ values of the washwater samples
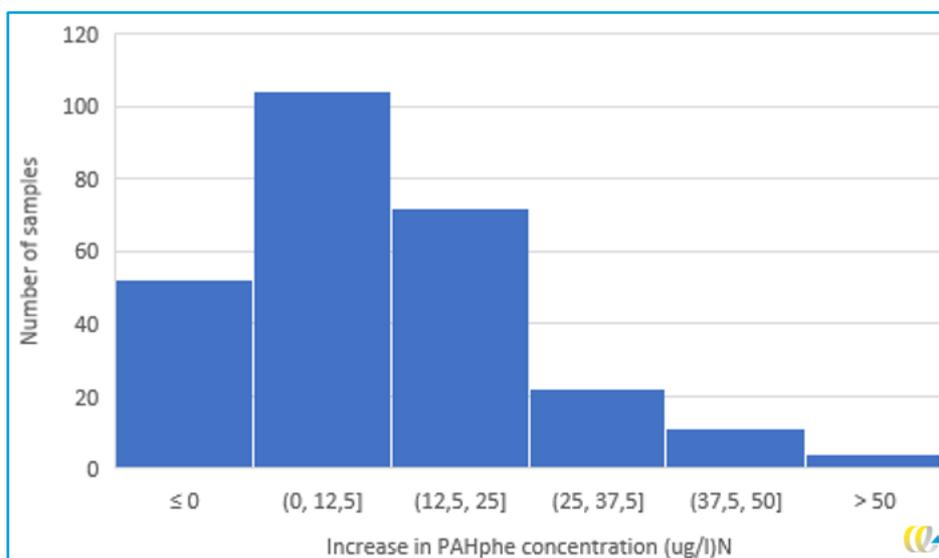

Figure 12 indicates that more than half of the samples showed an increase in PAH concentration of 25 µg/l or less. About 1.5% of the samples showed an increase of more than 50 µg/l. Note that these values were not normalised and that the samples were not taken continuously so the samples exceeding the 50 µg/l could still be compliant with the IMO Washwater discharge criteria. The results of the analysis are summarised in Table 15.

Table 15 - PAH$_{phe}$ of washwater samples

Sample analysis info: PAH$_{phe}$	
Samples that detected PAH$_{phe}$	265
Samples that showed an increase in PAH$_{phe}$	213
Samples with PAHphe less than 50µg/l	261

Turbidity/Suspended particle matter

As indicated in Table 13, the maximum continuous turbidity in the discharge washwater should not be greater than 25 FNU (Formazin Nephelometric Units) or 25 NTU (Nephelometric Turbidity Units) above the inlet water turbidity. This criterion comes with an exception that all turbidity difference readings should be a rolling average over a 15-minute period to a maximum of 25 FNU or NTU. As recommended by the IMO, the turbidity of the washwater samples has been taken downstream of the scrubber or, in other words, just after the EGCS tower and before any treatment or buffering takes places. For a 15-minute period in any 12-hour period, the continuous turbidity discharge limit may be exceeded by 20%.

Out of the 291 samples, 256 had values for Turbidity. Figure 13 shows the distribution of the turbidity sample analysis.

**Figure 13 - Distribution of Turbidity values of the washwater samples**
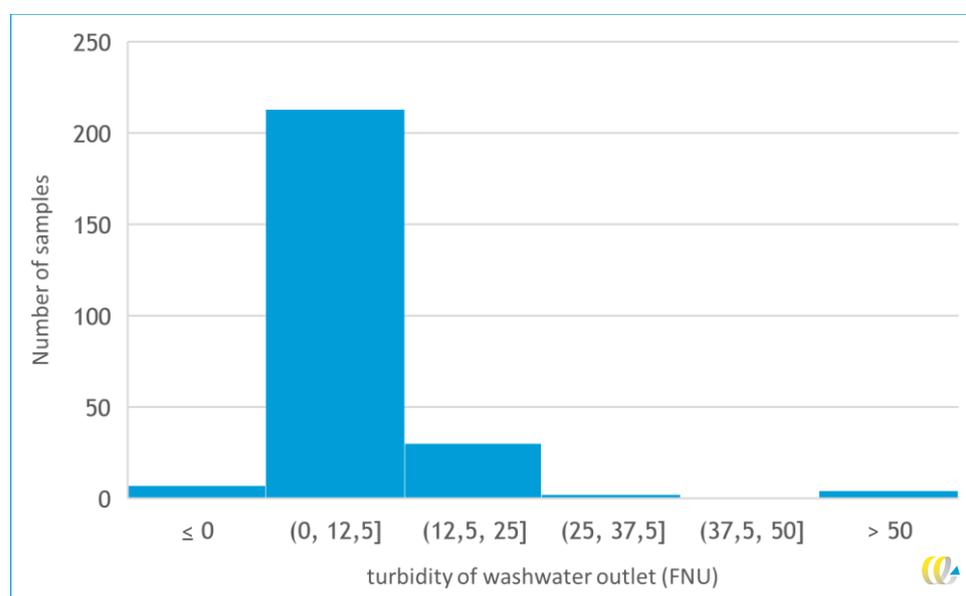
Figure 13 indicates that the majority of the samples fall between 25 FNU and -3, which is the lowest group in the analysis and that seven samples have fallen outside the IMO continuous monitoring washwater criteria. Of these seven, at least two and probably three can be regarded as outliers that may be attributable to analyser disfunction, sample contamination or other causes. It is noted that these are spot samples and the IMO methodology for assessment of the Turbidity uses a 15-minute rolling average rather than a spot value. As the 15-minute rolling average is unknown the spot values have been used for this assessment. The results of the analysis are summarised in Table 16.

Table 16 - Turbidity of washwater samples

Sample analysis info: Turbidity	
Samples with Turbidity data	256
Samples with Turbidity below 25 FNU	249

Nitrates

As indicated in Table 13 the discharge washwater should have a nitrate content below 60 mg/l. The 60 mg/l limit is normalised for a washwater flow rate through the EGCS of 45 t/MWh where the MW refers to the DGs Maximum Continuous Rating (MCR), therefore the limit is adjusted up and down depending on the washwater flow rate and DG size.

Out of the 291 samples, 35 did not report data on nitrogen, 108 samples did not detect nitrogen and 148 samples reported a nonzero concentration of nitrogen. Three samples were above the limit of 60 mg/l; however, in all these cases, the net concentration of nitrogen added by the EGCS was below 30 mg/l. Figure 14 shows the distribution of the nitrate sample analysis.

Figure 14 - Distribution of Total Nitrogen content of the washwater samples
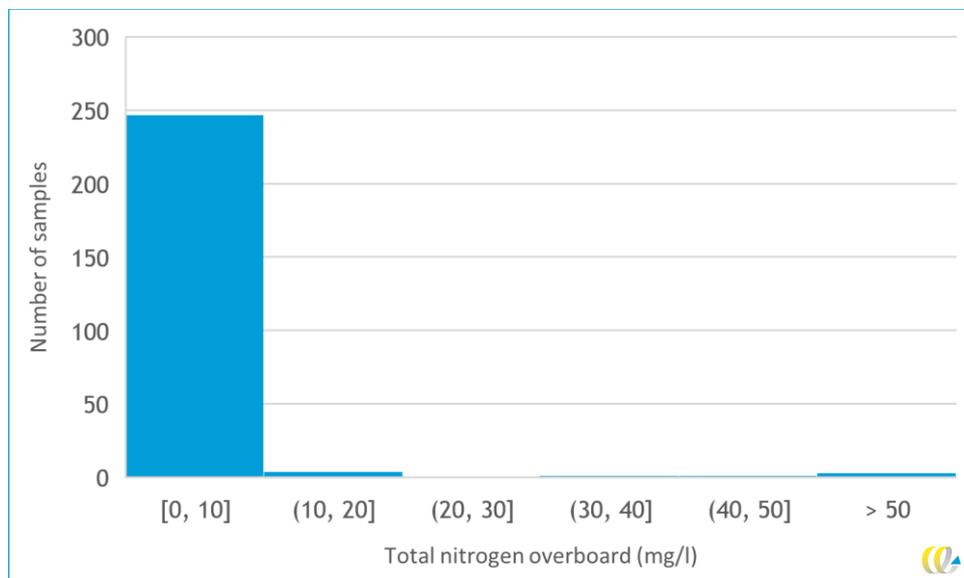

Figure 14 indicates that most of the samples contain nitrogen in concentrations below 60 mg/l. The results of the analysis are summarised in Table 17.

Table 17 - Total Nitrogen of washwater samples

Sample analysis info: Total Nitrogen	
Samples with Total Nitrogen data	148
Samples with Total Nitrogen below 60 mg/l	145

3.1.2 Water concentrations absolute values

For the defined ship loading scenario of 40.32 tonnes of fuel being consumed in port per day 365 days a year indefinitely by ships at berth using open-loop EGCSs, the contribution from the EGCS washwater to substance concentrations in the port water has been calculated for the four model ports and 27 substances. The concentrations reported are the accumulated equilibrium concentrations and therefore do not represent concentrations after a specific time frame.

Presented here are the absolute maximum and mean values for the total and dissolved portions in the harbour area for each model port; these are the values that have been used in the subsequent evaluations against various standards and background concentrations. The concentrations for the surrounding area are not presented or used in the evaluations of the results as the surroundings concentrations are all less that the corresponding harbour area concentrations, and the project scope is to assess impacts in port, i.e. not outside the port entrance.

Standard OECD-Commercial Harbour water concentrations

The increase in equilibrium concentrations due to open-loop EGCS operations in the Standard OECD-EU Commercial Harbour are presented in Figure 15 for the metals and Figure 16 for the PAHs. The graphs show the maximum and mean concentration increases for both the total and dissolved portion. For all substances, the increases in the total concentrations are higher than the increases in the dissolved portions.

For the metals, Vanadium and Nickel concentration increases are the highest; while for PAHs, naphthalene and phenanthrene exceed other PAHs. The difference between the dissolved and total concentration is generally larger for PAHs than it is for metals.

Note: the equilibrium concentrations are the concentrations added to the background concentrations by the washwater discharged from open-loop EGCS and therefore no background concentrations are input into the model; it effectively assumes the background concentration is zero.

Figure 15 – Metals concentrations in the Standard OECD-EU Commercial Harbour
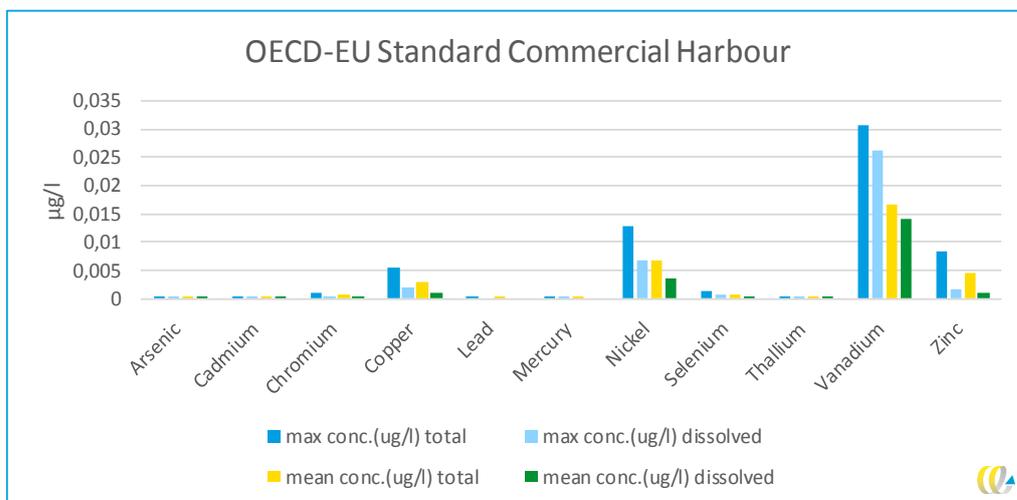
Figure 16 - PAH concentrations in the Standard OECD-EU Commercial Harbour
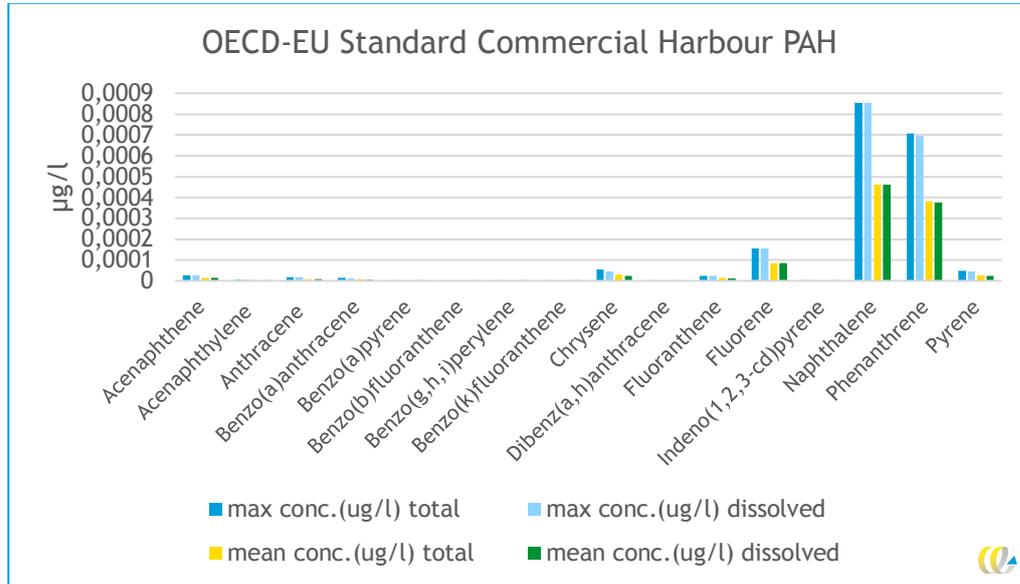
Baltic Commercial Port water concentrations

The increase in equilibrium concentrations due to open-loop EGCS operations in the Baltic Commercial Port are higher than in the North Sea-based Standard OECD-EU Commercial Harbour. The difference is caused by a lower hydrodynamic exchange volume used in the model for the Baltic Commercial Port. Figure 17 shows the concentrations for the metals and Figure 18 shows the concentrations for the PAHs.

Note: the scales on the graphs for the Baltic Sea model port concentrations (Figure 17 and Figure 18) are a factor of ten bigger than on the graphs for the three other model ports which are based on the North Sea oceanography.

**Figure 17 - Metals concentrations in the Baltic Commercial Port**
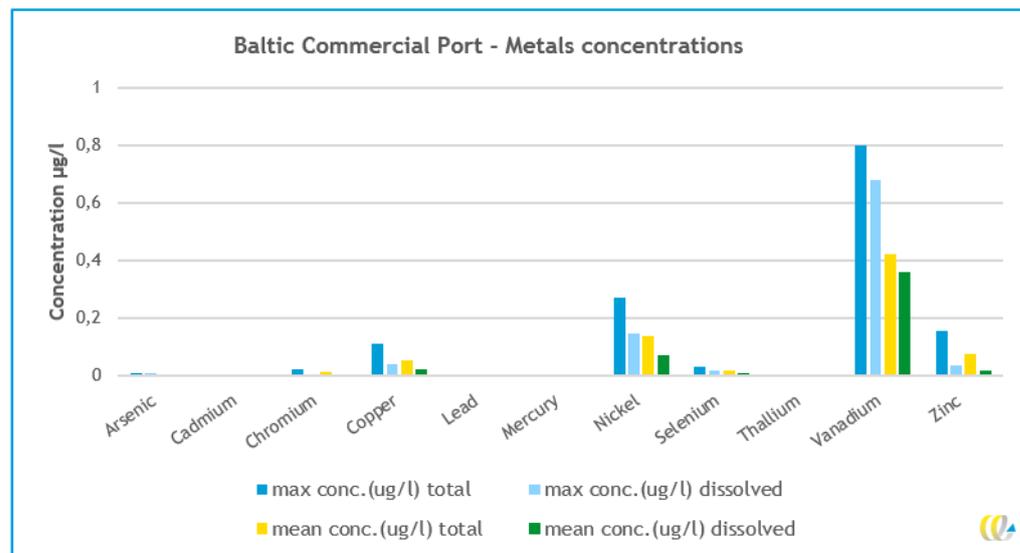
Figure 18 - PAH concentrations in the Baltic Commercial Port
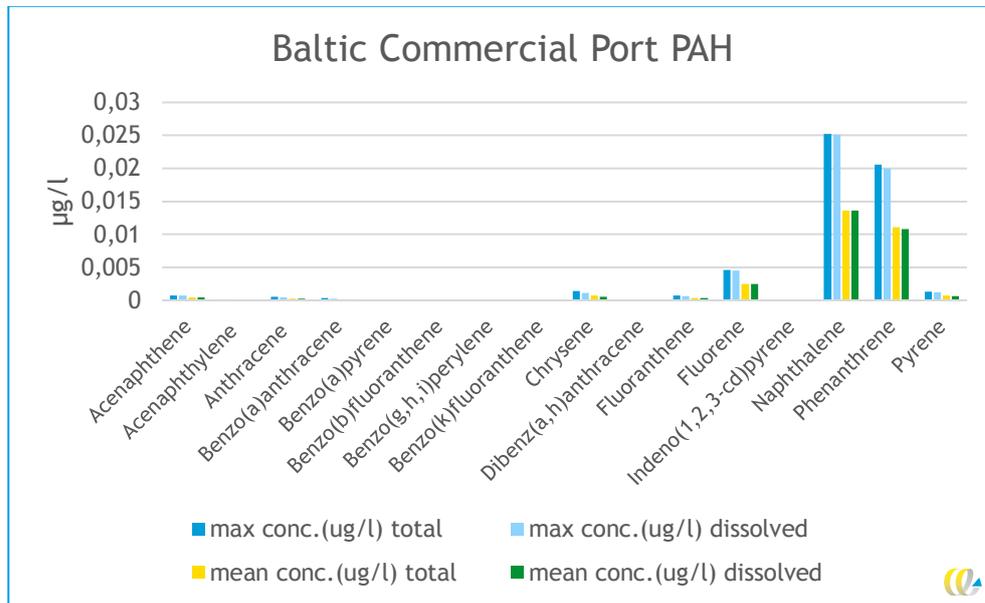
Ocean Port water concentrations

The increase in equilibrium concentrations due to open-loop EGCS operations in the Ocean Port are higher than in the OECD-EU Standard Commercial Harbour, although the difference is not as large as with the Baltic Commercial Port. The difference is caused by the low hydrodynamic exchange volume used in the model for the Ocean Port.

The hydrodynamic exchange for the Ocean Port is lower than that for the Standard OECD-EU Commercial Harbour largely because the port entrance is smaller for the Ocean Port (750 m) than for the Standard OECD-EU Commercial Harbour (2,500 m).
Figure 19 shows the concentrations for the metals and Figure 20 shows the concentrations for the PAHs.

**Figure 19 - Metals concentrations in the Ocean Port**
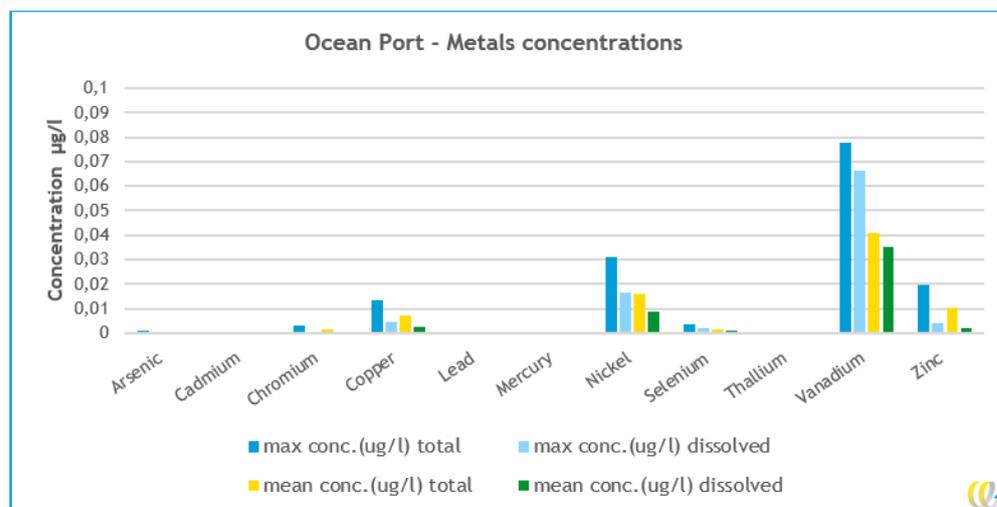
Figure 20 - PAH concentrations in the Ocean Port
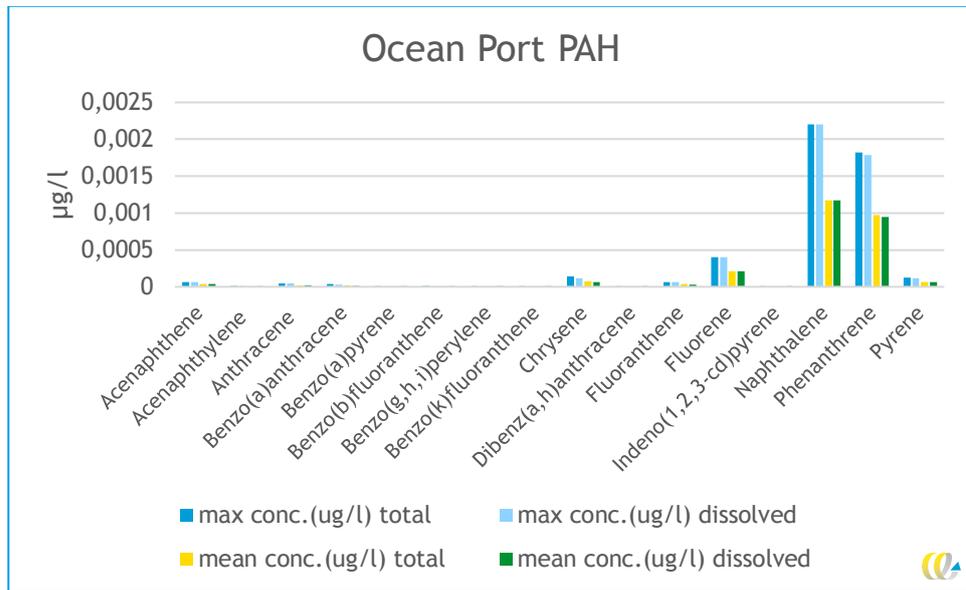
River Port water concentrations

Of the four model ports in this study, the increase in equilibrium concentrations due to open-loop EGCS operations is the lowest in the River Port. This is because the River Port has the highest hydrodynamic exchange volume as a result of the port being unenclosed; all the other three ports are enclosed. Figure 21 show the concentrations for the metals and Figure 22 shows the concentrations for the PAHs.

**Figure 21 - Metals concentrations in the River Port**
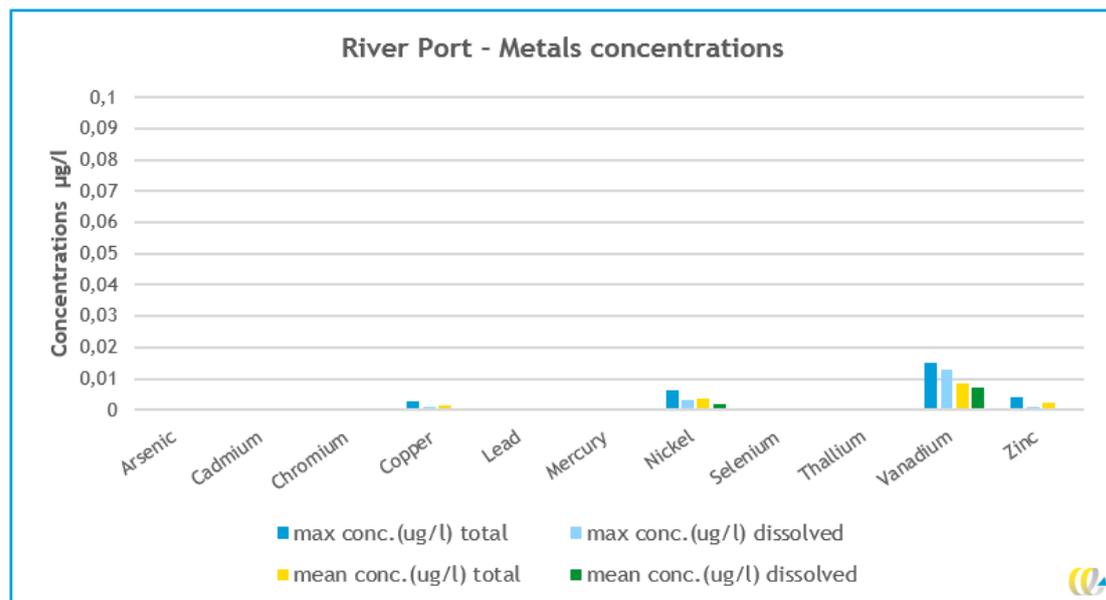
Figure 22 - PAH concentrations in the River Port
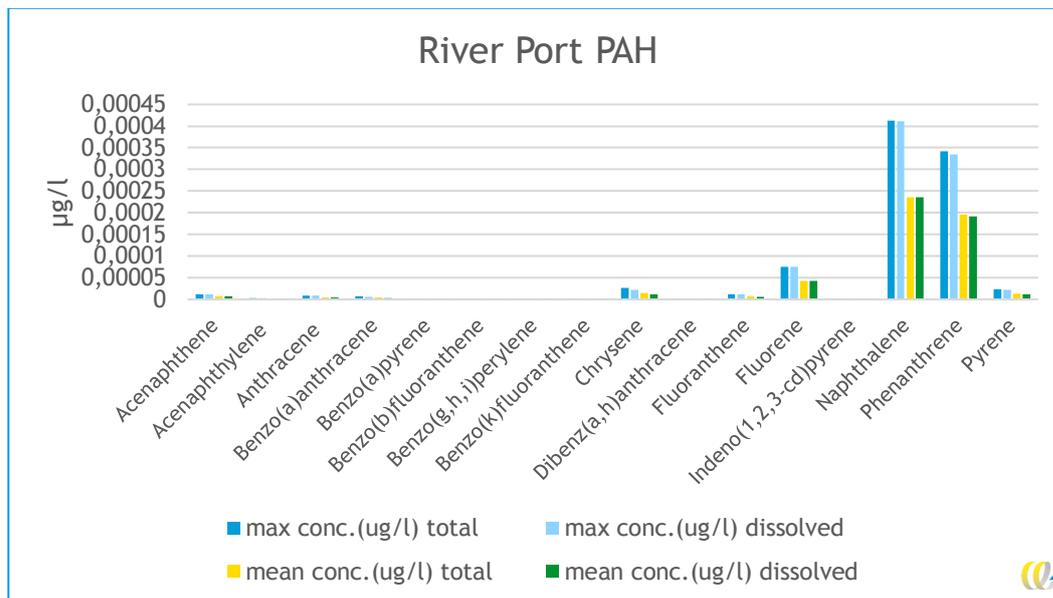
3.1.3 Water concentrations in comparison with EU Environmental Quality Standards (EQS)

For the defined ship loading scenario of 40.32 tonnes of fuel being consumed in port per day 365 days a year indefinitely by ships at berth using open-loop EGCSs the contribution from the EGCS washwater to substance concentrations in the port water has been assessed against the EQS criteria of the EU WFD.

For a number of substances, the EU WFD 2013/39/EU sets limit values for allowable concentrations in inland surface waters, which, according to the Directive 'encompass rivers and lakes and related artificial or heavily modified water bodies'. In order to evaluate the impact of open-loop EGCS operation on port water, this study has compared the concentration increase calculated by MAMPEC-BW with the Environmental Quality Standard (EQS) for both the Maximum Allowable Concentration (MAC) and the Annual Average (AA) from 2021 onwards as laid down in Directive 2013/39/EU for Inland Surface Waters. When the 2021 criteria are compared to the current 2015 criteria, in most cases the 2021 criteria are more stringent and this is considered the most stringent standard available. It is noted that for the AA-EQS of Benzo(a)pyrene and Fluoranthene and the MAC-EQS of Benzo(g,h,i)perylene are less than 1 part per trillion (ppt) which is lower than what can be measured using currently available analytical methods.

Table 18 details the reference criteria and it is noted that for the metals the criteria uses the dissolved portion whereas for the PAHs the total concentration is used.

Table 18 - EU Water Framework Directive criteria for Inland Surface Waters

Substance	MAC-EQS (µg/l)	AA-EQS (µg/l)
Cadmium (dissolved)	0.45	0.08
Lead (dissolved)	14	1.2
Mercury (dissolved)	0.07	
Nickel (dissolved)	34	4
Anthracene	0.1	0.1
Benzo(a)pyrene	0.27	0.00017
Benzo(b)fluoranthene	0.017	
Benzo(k)fluoranthene	0.017	
Benzo(g,h,i)perylene	0.0082	
Fluoranthene	0.12	0.0063
Naphthalene	130	2

Maximum concentrations and MAC-EQS limits

Figure 23 show the maximum equilibrium concentrations as a percentage of the 2021 maximum allowable concentration as laid down in Directive 2013/39/EU for Inland Surface Waters for all four model ports, Figure 24 shows the same but only for the North Sea ports. Note the scale in Figure 24 is a factor of ten smaller than Figure 23.

Figure 23 - Maximum concentrations as a percentage of 2021 MAC-EQS limits: All four model ports
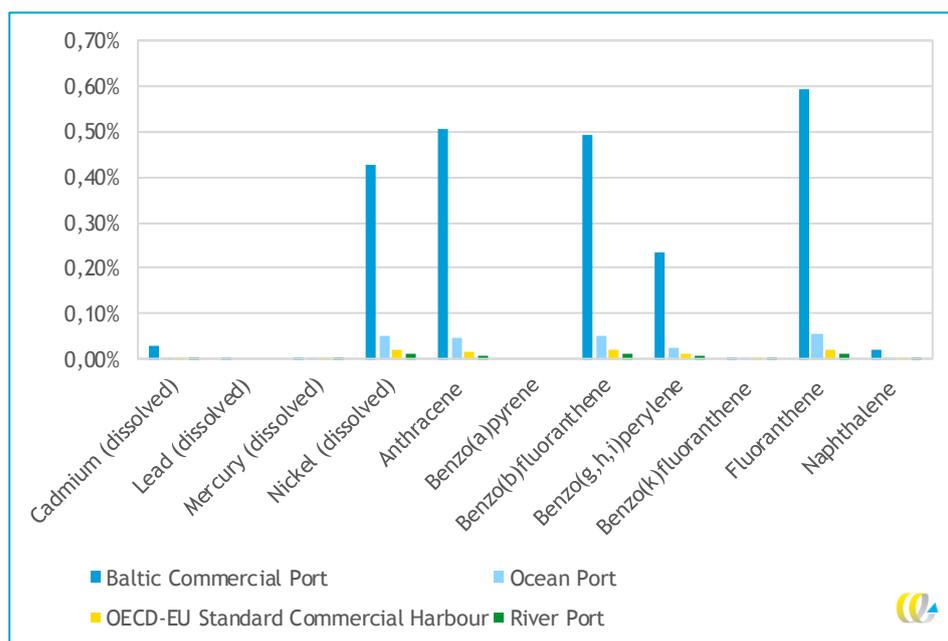
Figure 24 - Maximum concentrations as a percentage of 2021 MAC-EQS limits: North Sea model ports
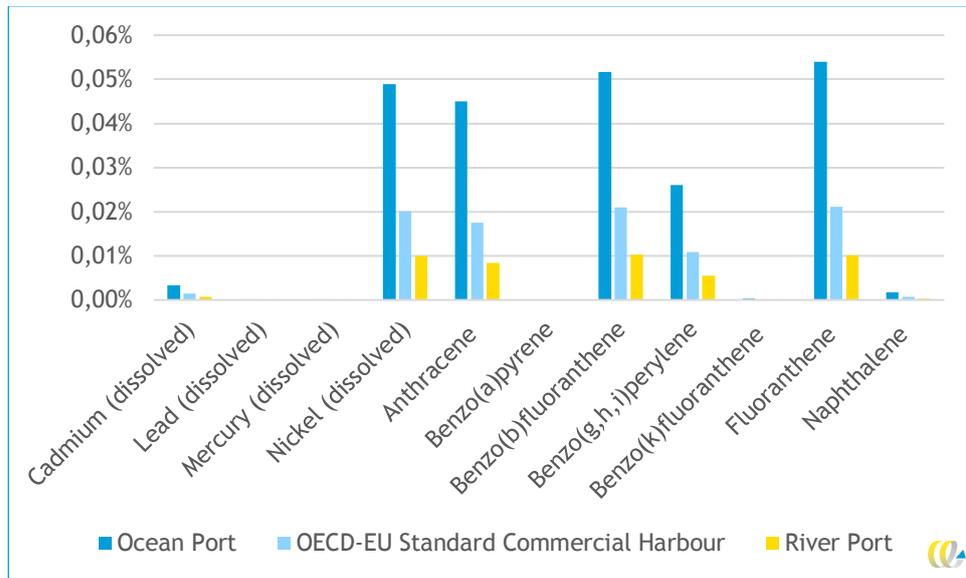
Mean concentrations and AA-EQS limits

Figure 25 show the mean equilibrium concentrations as a percentage of the 2021 allowable annual average concentration as laid down in Directive 2013/39/EU for Inland Surface Waters for all four model ports, Figure 26 shows the same but only for the North Sea ports. Note the scale in Figure 26 is a factor of ten smaller than Figure 25.

**Figure 25 - Mean concentrations as a percentage of 2021 AA-EQS limits: All four model ports**

3.2 Sediment results and evaluation

3.2.1 Sediment concentrations absolute values

For the defined ship loading scenario of 40.32 tonnes of fuel being consumed in port per day 365 days a year for five years by ships at berth using open-loop EGCSs, the contribution from the EGCS washwater to substance concentrations in the port sediment has been calculated for the four model ports and 27 substances, assuming zero background concentrations. It is noted at this point that the substance concentrations in the sediment do not increase linearly over time indefinitely, therefore to accurately assess the sediment concentrations in any given port using MAMPEC-BW a background concentration must be entered into the model (see Section 2.4.8). The results presented in this study are, however, a useful if generic indication of the magnitude of the substances in open-loop EGCS washwater that could, depending on the background concentrations, be laid down to the port sediment.

The concentrations presented here are as calculated by MAMPEC-BW for the maximum and mean total concentrations in the harbour area accumulated after five years. Five years is considered to be a common dredging interval for ports in the North Sea and Baltic Sea regions, therefore the five-year concentrations are relevant for the disposal and management of dredged materials.

The concentrations for the surrounding area, i.e. outside the port entrance, are not presented or used in the evaluations of the results as the surrounding area concentrations were not calculated as part of this study. It is noted that, as with the water concentrations, the sediment concentrations in the surrounding area are highly likely to be less than the harbour area concentrations.

Maximum metals sediment concentrations after five years

Figure 27 and Figure 28 show the modelled increase in the concentrations in the sediment of metals after five years assuming zero background concentrations. The sediment substance concentrations in the Baltic Commercial Port are higher than in the other model ports, because of the relatively high modelled substance concentrations in the water column for the Baltic Commercial Port compared to the other ports, and we know that the water substance concentrations is one of the key factors in the sedimentation of substances. In addition the modelled sediment layer is thinner in the Baltic Sea than in the North Sea (refer to Annex A) and therefore the sedimentation rate is faster than for the North Sea ports so when we start from zero concentration in the sediment the predicted concentration after five years will be higher than if the sedimation rate was lower.

Figure 27 - Maximum metals concentrations in the sediment after five years, all four ports, assuming zero background concentrations
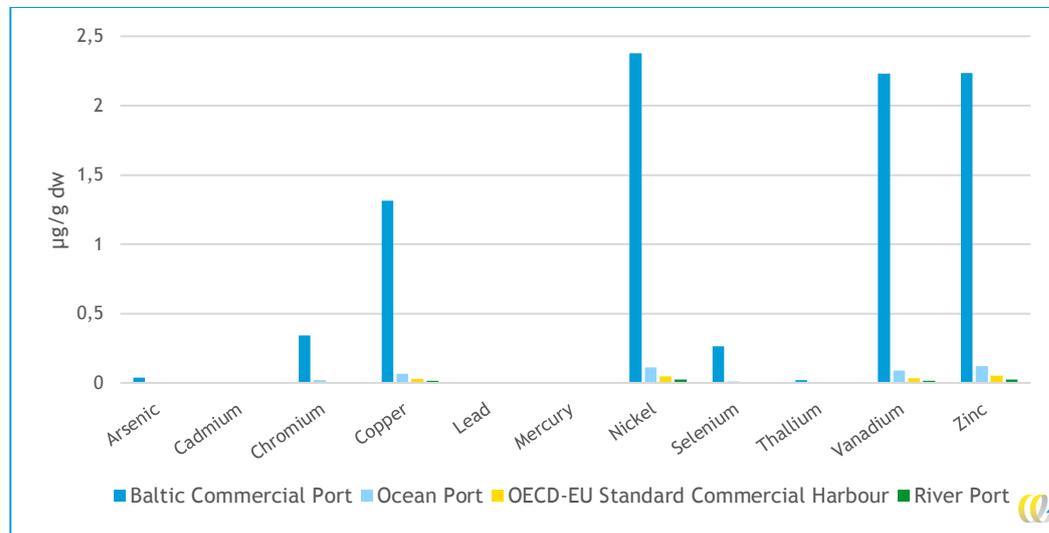
Figure 28 - Maximum metal concentrations in the sediment after five years, North Sea ports, assuming zero background concentrations
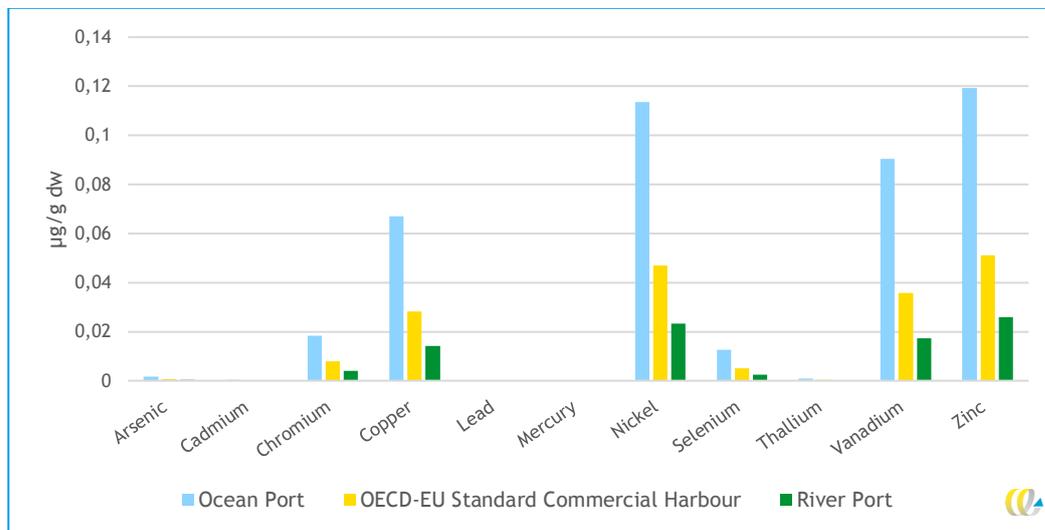
Maximum sediment PAH concentrations after 5 years

Figure 29 and Figure 30 show the modelled increase in the concentrations in the sediment of PAHs after five years assuming zero background concentrations. Because of the relatively high water concentrations in the Baltic Commercial Port, the sediment concentrations in the Baltic port are higher than in the other ports.

Figure 29 - Maximum PAH concentrations in the sediment after five years, all four ports, assuming zero background concentrations
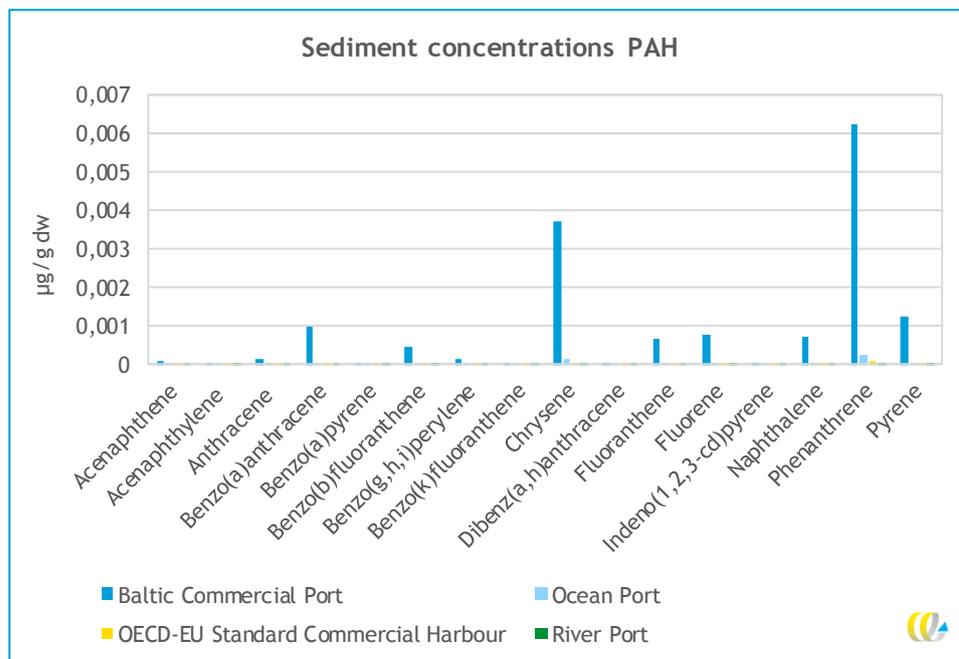
Figure 30 - Maximum PAH concentrations in the sediment after five years, North Sea ports, assuming zero background concentrations
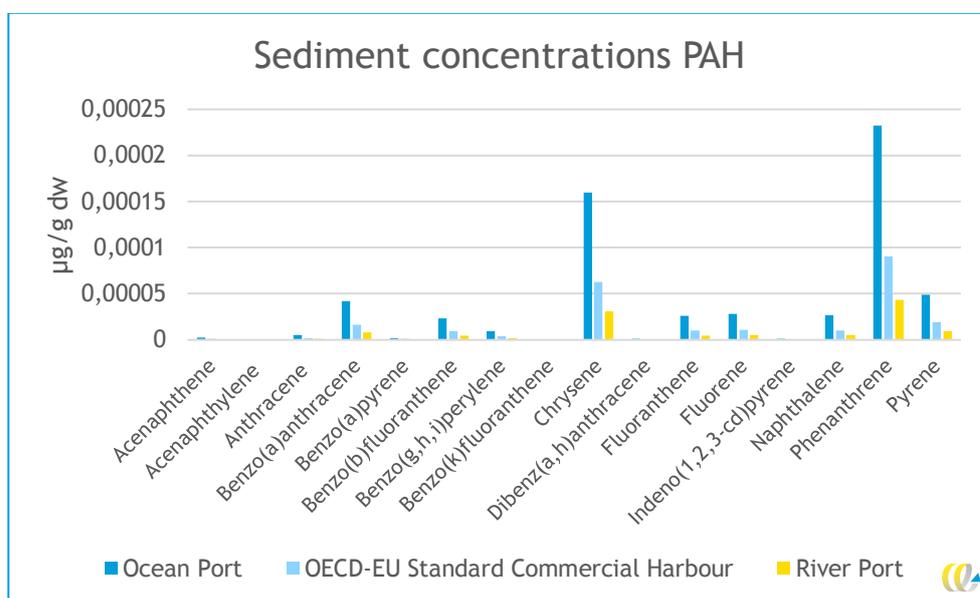
3.2.2 Compare sediment concentrations with national standards

Many countries set standards for the contamination of sediment that relate to the assessment of dredged material prior to its disposal; the focus of these standards is the potential environmental impact that the disposal of the dredged material could have on the disposal location. Table 22 shows the UK, Canadian and Dutch standards for the assessment of dredged material.

Sediment national standards for dredged material

UK Cefas Action Levels (cALs)

In the UK, cALs are used as part of a 'weight of evidence' (WOE) approach to licensing the disposal of dredged material. The UK Marine Management Organisation (MMO) is advised on the application of actions levels in marine licensing by their scientific advisors, the Centre for Environment, Fisheries and Aquaculture Science (Cefas).

The current action levels applied in the UK were proposed by Cefas and provide threshold values for sediment contaminants that are referred to as the 'Cefas Action Levels', and are divided into a lower and upper threshold level as follows:
— Action Level 1 (AL 1) – Contaminant levels in dredged material below this lower threshold level are generally assumed to be of no concern and are unlikely to influence the licensing decision.
— Action Level 2 (AL 2) – Dredged materials with contaminant levels above this higher threshold level are generally considered unsuitable for sea disposal.
— Contaminant levels between Action Level 1 and 2 generally trigger further investigation of the material proposed for disposal at sea.

The UK cALs provide criteria for metals; however, they do not provide criteria for PAHs.

Dutch Guidelines

The Dutch guidelines specify the maximum level for disposal in a saltwater environment. The so-called zoute-baggertoets (ZBT) is based on the chemical toxicity of substances (Deltares, 2012). For most substances, the limit value is based on the Effect Range Median, i.e. the level above which biological impacts are considered to be likely. Because of the existence of prior limits for some substances, the Dutch government has decided not to apply the same risk level for all compounds. The limits for metals are below the maximum acceptable risk; whereas the limits for PCBs (not evaluated in this report) are above the maximum acceptable risk.

Canadian Interim Sediment Quality Guidelines (SQAs)

The Canadian Interim Sediment Quality Guidelines were developed by the Canadian Council of Minister of the Environment as protective tools to support the functioning of healthy aquatic ecosystems (CCME, 1999).

The Canadian approach involves the derivation of the following set of levels from an extensive database containing direct measurements of toxicity of contaminate sediments to a range of aquatic organisms exposed in laboratory tests and under field conditions.
— Threshold Effect Level (TEL) – Exposure to this level is likely to affect some sensitive species.
— Probable Effect Level (PEL) – Exposure to this level is likely to cause adverse effects to a wider range of organisms.
— The three ranges of chemical concentrations (below TEL, between TEL and PEL, and above PEL) indicate those that are rarely, occasionally and frequently associated with adverse biological effects.

The Canadian Interim Sediment Quality Guidelines provide criteria for metals and individual PAHs but do not provide a specific criterion for the sum of the PAHs.

Table 19 - Standards for assessment of dredged materials for disposal (mg/kg dry weight)

Substance	UK Cefas Guidelines		Dutch Standards	Canadian Guidelines	
	AL 1	AL 2	Maximum Salt Water Level	TEL	PEL
Metals					
Arsenic	20	100	29	7.24	41.6
Cadmium	0.4	5	4	0.7	4.2
Chromium	40	400	120	52.3	160
Copper	40	400	60	18.7	108
Lead	50	500	110	30.2	112
Mercury	0.3	3	1.2	0.13	0.7
Nickel	20	200	45	15.9	42.8
Zinc	130	800	365	124	271
Polycyclic Aromatic Hydrocarbons					
Acenaphthene	-	-	-	0.00671	0.0889
Acenaphthylene	-	-	-	0.00587	0.128
Anthracene	-	-	-	0.0469	0.245
Benzo(a)anthracene	-	-	-	0.0748	0.693
Benzo(a)pyrene	-	-	-	0.0888	0.763
Chrysene	-	-	-	0.108	0.846

Substance	UK Cefas Guidelines		Dutch Standards	Canadian Guidelines	
	AL 1	AL 2	Maximum Salt Water Level	TEL	PEL
Dibenz(a, h)anthracene	-	-	-	0.00622	0.135
Fluoranthene	-	-	-	0.113	1.497
Fluorene	-	-	-	0.0212	0.144
2-Methylnaphthalene	-	-	-	0.0202	0.201
Naphthalene	-	-	-	0.0346	0.391
Phenanthrene	-	-	-	0.0867	0.544
Pyrene	-	-	-	0.153	1.398
Sum of total PAHs[2]	-	-	8	-	-

Source: (PLA, ongoing); (CCME, 1999); (RIVM, 2008).

Comparison of sediment concentration with the different standards

This section provides a generic assessment of the sediment concentrations by comparing them against three national standards that are commonly used for initial assessment of sediment concentrations. It is highlighted that in the same manner that background concentrations are fundamental for calculations of the changes in sediment concentrations using MAMPEC-BW, the calculated concentrations should only be compared against standards and background concentrations which are relevant for the location being assessed.

Taking consideration of the above; for this study the Standard OECD-EU Commercial Harbour has been used for comparison against common sediment standards. The Standard OECD-EU Commercial Harbour has been accepted by the IMO as representative of a global port in regard to supporting environmental risk assessments and is therefore appropriate for a generic assessment.

We have calculated the maximum increase in sediment concentrations after five years from a zero starting point (zero background concentration) as the basis for the comparison and compared these against the Dutch Standard and the stricter criteria for both the UK (AL 1) and Canadian standards (TEL).

For metals, the maximum increase, expressed as a percentage of the criteria, is always less than 0.30% (see Figure 31) and for PAHs, it is always less than 0.12% (Figure 32).

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[2] The sum is taken of the following 10 PAHs: Anthracene, Benzo(a)anthracene, Benzo(a)pyrene, Benzo(g,h,i)perylene, Benzo(k)fluoranthene, Chrysene, Fluoranthene, Indeno(1,2,3-cd)pyrene, Naphthalene, Phenanthrene (Regeling Bodemkwaliteit, Bijlage N).

Figure 31 - Maximum increase in concentration of metals in the sediment in the Standard OECD-EU Commercial Harbour as a percentage of three different standards for dredged materials
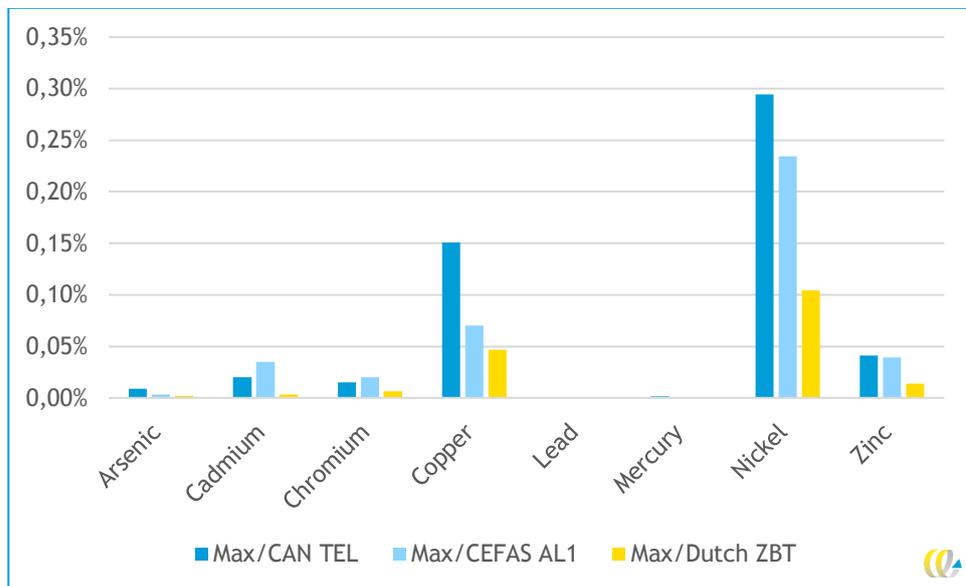

Figure 32 - Maximum increase in concentration of PAHs in the sediment in the Standard OECD-EU Commercial Harbour as a percentage of three different standards for dredged materials (100% = criteria limit)
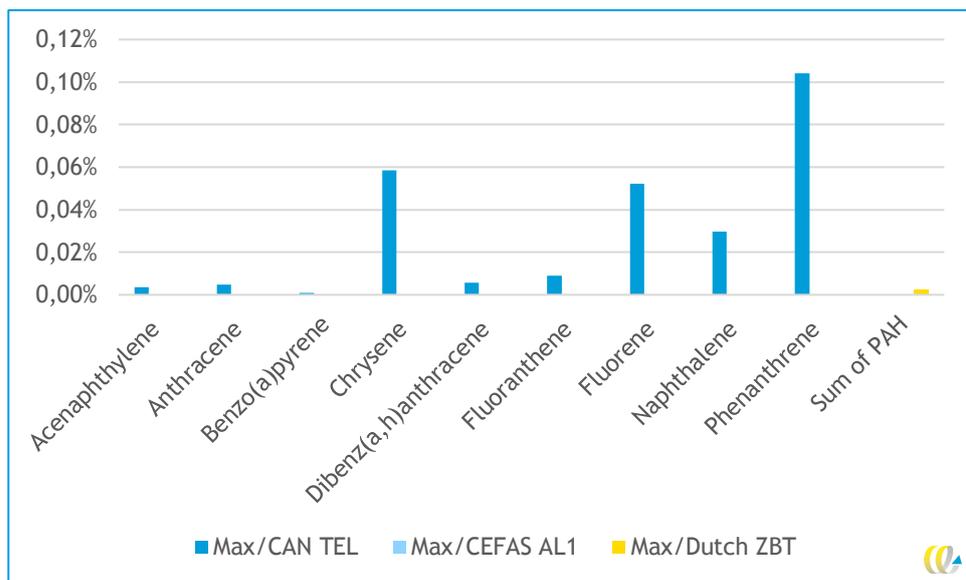
4 Conclusions

The aim of this study was to provide a method for evaluating the impacts of using open-loop exhaust gas cleaning systems in ports on water and sediment and to test the methodology conservatively in a series of model ports, using empirical data of almost 300 washwater samples as inputs for the MAMPEC-BW model.

Our results show that equilibrium concentrations of metals and PAHs in the water and the five year sediment concentrations depend predominantly on the hydrodynamic exchange of the port water with the surrounding waters. As an example a port with a wider port entrance will lead to lower concentrations than an enclosed port with a narrower port entrance. Additionally a river port which is not enclosed and has a continuous water exchange will lead to lower concentrations than an enclosed port with a wide port entrance.

A reference scenario has been defined in which just over 40 tonnes of fuel is consumed per day by ships at berth operating open-loop EGCSs. This level of fuel consumption is equivalent to over 28 small bulk carriers, or 6 large container ships, or two medium-sized cruise ships at berth for every day of the year, or any ship size and type combination which uses just over 40 tonnes of fuel per day in port in combination with an open-loop EGCS.

For the reference scenario, the modelled equilibrium concentrations of metals and PAHs in the water have been compared with European water standards that are applicable from 2021 onwards. In most ports and for most substances, the increase in concentrations is less than 0.1% of the limit value. However, in ports with low hydrodynamic exchange, and especially for a few Polycyclic Aromatic Hydrocarbons, the increase in concentration can increase to 0.6% of the limit value.

A portion of the substances discharged by open-loop EGCSs in ports ends up in the port sediment. Assuming a zero concentration to begin with, the modelling shows that for the Standard OECD-EU Commercial Harbour the increase in sediment concentrations of metals and PAHs after five years is less than 0.3% of the referenced standards for dredged materials. However, in ports with low hydrodynamic exchange, the increase can be higher.

The modelling results suggest that local hydrodynamic circumstances as well as background concentrations of priority substances should be taken into account when assessing the impacts of the use of open-loop exhaust gas cleaning system a specific port. The modelling results also suggest that in cases that are considered default cases for regulation in other areas (ballast water management systems, antifouling coating), the impacts of using open-loop exhaust gas cleaning systems are small in relation to the agreed water quality standards for 2021.

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A MAMPEC-BW environment input screens

Figure 33 - Environment input screen for the Standard OECD-EU Commercial Harbour

Figure 34 - Environment input screen for the Baltic Commercial Port

Field	Value	Unit
Description	OECD_comm-baltic_env	
Environment type	Commercial harbour	
Reference	OECD-EU Model harbour used for exposure assessment of antifouling compounds. ESD-PT21 Table 0.5, adapter with Baltic environmental values	

Wind
Average wind speed	3.8	m/s
Fraction of time wind perpendicular	0.13	-

Flush
Flush (f)	0	m³/s
Max. density difference flush	0	kg/m³
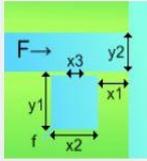
Hydrodynamics
Tidal period	12.41	hour
Tidal difference	0	m
Max. density difference tide	0	kg/m³
Non tidal daily water level change	0.08	m
Flow velocity (F)	0.03	m/s

Layout
Length	x1	1000	m	x2 5000	m
Width	y1	1000	m	y2 500	m
Depth		15	m		
Mouth width	x3	2500	m		

Submerged dam specification
Height of submerged dam	0	m
Width of submerged dam	0	m
Depth-MSL in harbour entrance	10	m
Exchange area harbour mouth (below mean sea level)	37500	m²

Water characteristics
SPM concentration	35	mg/l
POC concentration	1	mg/l
DOC concentration	5.4	mg/l
Chlorophyll	3	µg/l
Salinity	6	psu
Temperature	11	°C
pH	7.9	

General
Latitude	63	° (dec) NH
Cloud coverage	5	class [0-10]

Sediment
Depth mixed sediment layer	0.03	m
Sediment density	1000	kg/m³
Degr. organic carbon in sediment	0	1/d
Nett sedimentation velocity	0.5	m/d
Fraction organic carbon in sediment	2.86E-002	

Calculated exchange volumes (m³/tide)
Tidal	0.000E+000	0.00 %
Horizontal	1.005E+006	78.49 %
Density induced	0.000E+000	0.00 %
Wind driven	6.865E+004	5.36 %
Non tidal	2.068E+005	16.15 %
Flushing	0.000E+000	0.00 %
Total	1.281E+006	m3 / tide
	1.71	% /tide

Figure 35 - Environment input screen for the Ocean Port

Field	Value	Unit
Description	OECD-EU Commercial harbour_Ocean Harbour_1m-s	
Environment type	Marina	
Reference	OECD-EU Model harbour used for exposure assessment of antifouling compounds. ESD-PT21 Table 0.5	

Wind
Average wind speed	0	m/s
Fraction of time wind perpendicular	0	-

Flush
Flush (f)	0	m³/s
Max. density difference flush	0	kg/m³
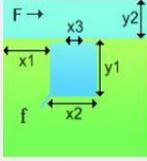
Hydrodynamics
Tidal period	12.41	hour
Tidal difference	1.5	m
Max. density difference tide	0.4	kg/m³
Non tidal daily water level change	0	m
Flow velocity (F)	1	m/s

Layout
Length	x1	1000	m	x2 2500	m
Width	y1	2500	m	y2 1000	m
Depth		15	m		
Mouth width	x3	750	m		

Submerged dam specification
Height of submerged dam	0	m
Width of submerged dam	750	m
Depth-MSL in harbour entrance	10	m
Exchange area harbour mouth (below mean sea level)	11250	m²

Water characteristics
SPM concentration	35	mg/l
POC concentration	1	mg/l
DOC concentration	2	mg/l
Chlorophyll	3	µg/l
Salinity	34	psu
Temperature	15	°C
pH	7.5	

General
Latitude	50	° (dec) NH
Cloud coverage	5	class [0-10]

Sediment
Depth mixed sediment layer	0.2	m
Sediment density	1000	kg/m³
Degr. organic carbon in sediment	0	1/d
Nett sedimentation velocity	1	m/d
Fraction organic carbon in sediment	2.85E-002	

Calculated exchange volumes (m³/tide)
Tidal	9.375E+006	61.93 %
Horizontal	1.325E+006	8.75 %
Density induced	4.438E+006	29.32 %
Wind driven	0.000E+000	0.00 %
Non tidal	0.000E+000	0.00 %
Flushing	0.000E+000	0.00 %
Total	1.514E+007	m3 / tide
	16.15	% /tide

Figure 36 - Environment input screen for the River Port

B MAMPEC chemical and biological processes and inputs

The selection of the substances (n=27) that were included in the MAMPEC-BW simulation runs was based on the sample washwater analysis provided by the project sponsors. The selected substances are listed in Table 20. Only single substances were included in the MAMPEC-BW simulation runs for the four model ports as MAMPEC-BW simulations are restricted to individual metals or organic substances.

Table 20 - Substance CAS numbers

	Substance	CAS		Substance	CAS
1	Arsenic (As)	7440-38-2	15	Fluorene	86-73-7
2	Cadmium (Cd)	7440-43-9	16	Phenanthrene	85-01-8
3	Chromium (Cr)	7440-47-3	17	Anthracene	120-12-7
4	Copper (Cu)	7440-50-8	18	Fluoranthene	206-44-0
5	Lead (Pb)	7439-92-1	19	Pyrene	129-00-0
6	Mercury (Hg)	7439-97-6	20	Benzo(a)anthracene	56-55-3
7	Nickel (Ni)	7440-02-0	21	Chrysene	218-01-9
8	Selenium (Se)	7782-49-2	22	Benzo(b)fluoranthene	205-99-2
9	Thallium (Th)	7440-28-0	23	Benzo(k)fluoranthene	207-08-9
10	Vanadium (V)	7440-62-2	24	Benzo(a)pyrene	50-32-8
11	Zinc (Zn)	7440-66-6	25	Dibenz(a,h)anthracene	53-70-3
12	Naphthalene	91-20-3	26	Benzo(g,h,i)perylene	191-24-2
13	Acenaphthylene	208-96-8	27	Indeno(1,2,3-c,d)pyrene	193-39-5
14	Acenaphthene	83-32-9			

A CAS Registry Number is a unique numerical identifier assigned by the Chemical Abstracts Service (CAS) to every chemical substance described in the open scientific literature.

For the organic substances, substance property data for Kow (n-octanol water partitioning coefficient), Koc (organic carbon adsorption coefficient), Vp (vapour pressure), S (solubility), and H (Henry's law constant) and biodegradation half-lives (DT50) was derived from Epi Suite TM version 4.11 (US Environmental Protection Agency, 2018; Meylan & Howard, 1999) provided by US-EPA. This software tool is based on reviewed databases of environmental properties for over 40,000 substances (PhysProp, CHEMFATE at SRC: Environmental Health Analysis : Scientific Databases) as well as up-to-date property estimation tools (QSARs). The values used in MAMPEC-BW for the PAH substances are indicated in Table 21 below and were generally in good agreement with values from recent review studies (Achten & Andersson, 2015) and data from popular web resources such as ChemSpider or ChemFinder. For rate constants or half-lives for biodegradation, hydrolysis and photolysis the worst-case situation of negligible degradation was chosen as a first approximation for the MAMPEC-BW simulations. The rate constants for the degradation process were set to zero. Experimental studies and reviews of biodegradation of PAHs are available (Ghosal, et al., 2016; Haritash & Kaushik, 2009; Dimitriou-Christidis, et al., 2008); and indicate in general slow or absent degradation for most PAHs, but also demonstrate highly variable results for substances depending on the type of environment and many other

factors. It is not possible to select a dataset that matches the conditions of the scenarios of the MAMPEC-BW simulations.

The biodegradation half-lives estimated with the BioCHwin v1.01 software module in Epi Suite TM in the review of Ghosal et al. (2016) exhibit values for the half-life of 5.7 days for naphthalene, 15-123 days for 3-ring PAHs, and values between 191 and 517 days for 4-6 ring PAHs. Given the kinetics of the hydrodynamic exchange, we expect that only for naphthalene and some of the 3 ring substances inclusion of biodegradation may lead to a significant decrease in predicted environmental concentrations.

Table 21 - Substance property data

	CAS nr	LOG(Kow)[1]	LOG(Koc)[2]	Vp[2] mm Hg	S[2] mg/L	H[2] atm-m^3/mole	DT50[3] days
Naphthalene	91-20-3	3.3	3.189	0.0404	142.1	5.26E-04	5.66
Acenaphthylene	208-96-8	3.94	3.701	0.00125	2.487	5.48E-05	18.8
Acenaphthene	83-32-9	3.92	3.701	0.00129	2.534	2.82E-04	30.7
Fluorene	86-73-7	4.18	3.962	0.00033	1.339	1.67E-04	15.1
Phenanthrene	85-01-8	4.46	4.222	4.32E-05	0.677	5.13E-05	15.0
Anthracene	120-12-7	4.45	4.214	2.17E-06	0.6905	5.13E-05	123
Fluoranthene	206-44-0	5.16	4.744	3.13E-06	0.1297	8.30E-06	191
Pyrene	129-00-0	4.88	4.735	3.44E-07	0.2249	8.30E-06	283
Benzo(a)anthracene	56-55-3	5.76	5.248	2.72E-07	0.02907	5.01E-06	511
Chrysene	218-01-9	5.81	5.256	1.56E-09	0.02635	5.01E-06	344
Benzo(b)fluoranthene	205-99-2	5.78	5.778	2.49E-08	0.02065	8.10E-07	285
Benzo(k)fluoranthene	207-08-9	6.11	5.769	7.85E-10	0.01079	8.10E-07	285
Benzo(a)pyrene	50-32-8	6.13	5.769	9.82E-10	0.01038	8.10E-07	422
Dibenz(a,h)anthracene	53-70-3	6.75	6.281	1.39E-11	0.003304	4.89E-07	511
Benzo(g,h,i)perylene	191-24-2	6.63	6.29	9.8E-11	0.002842	1.31E-07	517
Indeno(1,2,3-c,d)pyrene	193-39-5	6.7 [2]	6.29	1.25E-10	0.002491	1.31E-07	349
Benzene (µg/L)	71-43-2	2.13	2.164	87.2	2000	5.39E-03	4.5 [4]

1) Experimental values; 2) Predicted values; 3) Predicted with BioCHwin 1.01 in Ghosal et al. (2016); 4) Predicted with BioCHwin 1.01.

For the parameterisation of trace metals in MAMPEC-BW, the sediment water distribution coefficient (Kd) is the most important parameter. It describes the sediment-water and suspended particulate matter (SPM) to water distribution of the metals. The sediment water distribution coefficients of trace metals in estuarine systems vary largely between different metals and further depend on composition (e.g. clay, organic matter), grain-size and ageing of SPM or sediments, and environmental parameters such as salinity, pH, DOC and temperature. For the MAMPEC-BW simulations we used mean values of reported Kd values for suspended particulate matter from a detailed and comprehensive review study of US-EPA (Allison & Allison, 2005) see Table 22.

Table 22 - SPM-water distribution constants for trace metals

Element	CAS-nr	Log Kd (L/kg)	Kd (L/kg)	Kd (m^3/kg)
Arsenic	7440-38-2	3.9	7,943	8
Cadmium	7440-43-9	4.9	79,433	79
Chromium	7440-47-3	5.1	125,893	126
Copper	7440-50-8	4.7	50,119	50
Lead	7439-92-1	5.7	501,187	501
Mercury	7439-97-6	5.3	199,526	200
Nickel	7440-02-0	4.4	25,119	25
Vanadium	7440-62-2	3.7	5,012	5
Zinc	7440-66-6	5	100,000	100

Mean values reported for Log Kd (3rd column) from Table 5 from Allison J.D. and Allison T.L. (2005) and converted values used in the MAMPEC-BW simulations (last column).