National Institute for Public Health
and the Environment
*Ministry of Health, Welfare and Sport*

# **Environmental risks** of scrubber discharges in Dutch waters

## A follow-up study

RIVM letter report 2023-0466
M. Faber

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# Synopsis


## Environmental risks of scrubber discharges in Dutch waters

A follow-up study

Scrubbers remove sulphur from ship exhaust gases and collect it in wastewater. This prevents more sulphur being emitted into the air than is permitted. Most ships use an open-loop system that discharges wastewater at sea or in a harbour. The disadvantage of this is that other pollutants from exhaust gases also end up in the water.

RIVM has calculated whether the discharge of this wastewater is harmful to the environment of the Port of Amsterdam. For this study, it examined polycyclic aromatic hydrocarbons (PAH) and metals. The calculated concentrations remain well below environmental standards. These results are in line with research that RIVM previously carried out in three other areas. These were the port of Rotterdam, a heavily sailed area of the North Sea, and an area in the Caribbean with vulnerable nature, such as the Saba Bank.

The contribution of the wastewater was then compared with the pollution already present in the water. PAH and metals also end up in the water from other sources, such as industry. The wastewater appears to contribute relatively little to the total level of pollution. However, these types of discharges are undesirable because poorly degradable substances end up in the environment. The effect of all pollutants combined may have environmental consequences.

The study was commissioned by the Ministry of Infrastructure and Water Management (I&W). The reason for the study is the increased use of scrubbers on seagoing vessels. This results in more wastewater being discharged into the sea. Internationally, there has been much discussion about the use of scrubbers and the requirements they must meet.


Keywords: scrubbers, ships, metals, PAH, environment, water, sediment

# Publiekssamenvatting


## Milieurisico's van scrubberlozingen in Nederlandse wateren

Een vervolgstudie

Scrubbers halen zwavel uit de uitlaatgassen van schepen en verzamelen deze in afvalwater. Dit gebeurt om te voorkomen dat er meer zwavel in de lucht komt dan is toegestaan. De meeste schepen gebruiken een open systeem waarmee ze het afvalwater op zee of in een haven lozen. Hierbij komen ook andere vervuilende stoffen uit de uitlaatgassen in het water terecht.

Het RIVM heeft berekend of de lozing van dit afvalwater in de haven van Amsterdam schadelijk is voor het milieu. Hierbij is gekeken naar polycyclische aromatische koolwaterstoffen (PAK's) en metalen. De berekende concentraties blijven ruim onder de milieunormen. Deze resultaten zijn in lijn met het onderzoek dat het RIVM eerder deed over drie andere gebieden. Dat waren de haven van Rotterdam, een drukbevaren deel van de Noordzee, en een gebied in de Caraïben met kwetsbare natuur, zoals de Sababank.

Daarna is de bijdrage van het afvalwater van schepen vergeleken met de vervuiling die al in het water zit. Want ook door andere bronnen dan zeevaart, zoals de industrie, komen PAK's en metalen in het water terecht. Het afvalwater blijkt relatief weinig bij te dragen aan de totale vervuiling. Toch zijn dit soort lozingen niet wenselijk, omdat daardoor slecht afbreekbare stoffen in het milieu terechtkomen. Alle verontreinigende stoffen samen kunnen gevolgen hebben voor het milieu.

Het onderzoek is uitgevoerd in opdracht van het ministerie van Infrastructuur en Waterstaat (IenW). De aanleiding is dat steeds meer zeeschepen scrubbers gebruiken. Hierdoor komt er meer geloosd afvalwater in de zee. Internationaal is er veel discussie over het gebruik van scrubbers en de eisen waar ze aan moeten voldoen.


Kernwoorden: scrubbers, schepen, metalen, PAK, milieu, water, sediment

# Contents

# 1 Introduction

## 1.1 Background of the report

In 2021, RIVM published a report on environmental effects of scrubber washwater discharges on Dutch water bodies (Faber et al., 2021). Scrubbers, also known as exhaust gas cleaning systems (EGCS), are used by seagoing vessels to remove sulphur dioxide ($SO_2$) from exhaust gases. The sulphur and other pollutants that are removed from exhaust gases, such as metals and polycyclic aromatic hydrocarbons (PAH), are collected in washwater. Depending on the type of scrubber, washwater may be stored or is directly discharged into open water. The study from 2021 presented calculations on the discharge of metals and PAH by scrubbers. Expected environmental concentrations were modelled for three study areas, namely a large seaport, in this case Rotterdam, a heavily sailed area of the North Sea, and an area in the Caribbean with vulnerable nature, such as the Saba Bank. The authors concluded that the expected increase in concentrations in surface water and sediment is limited and remains below existing environmental quality standards (EQS). The results therefore showed that mere use of EGCS does not lead to exceedance of EQS. Scrubbers are further referred to as EGCS.

In the previous study one seaport was investigated. The port of Rotterdam was chosen as it is the largest port of Europe with a total of 29,029 seagoing ships visiting the port in 2022 (Havenbedrijf Rotterdam N.V., 2023). The Netherlands however has more ports which are frequently accessed by seagoing ships. The Dutch ministry of Infrastructure and Water Management (I&W) has designated five ports as being of national importance. These are the Ports of Rotterdam, Moerdijk, Amsterdam/Noordzeekanaalgebied, Groningen (Eemshaven and Delfzijl) and the North Sea Port (Vlissingen and Terneuzen) (I&W, 2020). Each port has its own characteristics, e.g., size and tide, but also number and types of ships visiting may differ from previously modelled port of Rotterdam. For these ports it is therefore not self-evident that there are also limited effects of EGCS on the water bodies. I&W has commissioned RIVM to perform an additional study on the environmental risks of emissions from EGCS for surface water and sediment in Dutch ports.

Primary focus of the present study is to estimate potential risks of EGCS washwater discharges for the Port of Amsterdam. This study also provides insights into potential risks for the Eemshaven. For the Port of Amsterdam, as well as locations researched earlier by Faber et al. (2021), also information is provided on concentrations of contaminants already present in the environment. This information is used to investigate the contribution of EGCS discharges to levels of chemical pollution in the aquatic environment.

## 1.2 Policy context

The impact of shipping on the environment is being addressed by IMO’s International Convention for the Prevention of Pollution from Ships (MARPOL) since 1973. Annex VI of the treaty focusses on prevention of air pollution from ships. Emission Control Areas (ECAs) are designated areas in which stricter rules apply to reduce emissions of sulphur oxide ($SO_x$) and nitrogen oxide ($NO_x$) to air. Since 2020, fuels with a maximum of sulphur content of 0.10% mass by mass[1] need to be used inside Sulphur Emission Control Areas (SECAs). Outside these areas, a maximum sulphur content of 0.50% m/m is allowed. Fuels with higher sulphur content may still be used by vessels in these areas when emissions are as limited as when using fuels with low sulphur content. For this purpose, EGCS are installed to clean exhaust gases and reduce $SO_x$ emissions to desired levels.

The effectiveness of EGCS in reducing environmental pollution is considered ambiguous. EGCS reduce air pollution, however contaminants are collected in washwater which, in the case of open-loop EGCS, is directly discharged to the aquatic environment. Regulatory efforts are made to limit the impact of EGCS. IMO's Marine Environment Protection Committee (MEPC) has addressed environmental concerns by publishing guidelines for EGCS. In 2008 the first resolution with requirements for testing, surveying and verification of EGCS was accepted, to ensure compliance to MARPOL legislation (MEPC, 2008). The resolution was recalled and replaced by new resolutions in 2009 and 2015 (MEPC, 2009, MEPC, 2015). In 2022 the latest guideline was published by IMO (IMO, 2022). This guideline has become a lot more elaborate compared to the first guideline from 2008, with more stringent requirements and guidance on how to perform a risk and impact assessment for discharged water.

Simultaneously to the development of guidelines, various countries and ports have banned or restricted use of EGCS. As of February 2023, more than 90 regulations against (discharges of) EGCS are in force worldwide (ICCT, 2023). The most implemented measure is a ban (86%), the majority of which specifically concerns open-loop EGCS (64% of the bans). Other bans apply to discharge of washwater (29%), which can also apply to other types of EGCS, or to release of contaminated water and wastewater in general (8%). Restrictions (14%) include for example requiring authorization for entering a port, or allowing only the use of closed-loop EGCS (ICCT, 2023). Depending on the country, bans or restrictions apply on a national, sub-national or port level. In Europe seven countries have bans/restrictions implemented at a port level, ten countries for their territorial waters and/or port areas. In the Netherlands no measures have been implemented.

Next to legislation and regulations specifically focussing on shipping, there is also legislation on water quality. Most important for Europe are the Marine Strategy Framework Directive (MSFD; 2008/56/EC) and the Water Framework Directive (WFD; 2000/60/EC), which aim to preserve and improve marine and freshwater environment. For a more elaborate description of these frameworks, see previous report (Faber et al., 2021).

During the last decade, the number of installed EGCS on ships worldwide has increased rapidly, from 242 in 2015 to almost 4,800 in

[1] Mass of the element (in this case sulphur) by mass of the solute (in this case fuel).

2022 (ICCT, 2023), and the environmental impact of EGCS washwater discharges has become a more relevant and studied topic in recent scientific literature (see next section).

## 1.3 Scientific research on environmental effects of EGCS washwater discharges

Potential effects of EGCS on the aquatic environment have also been recognized in the scientific literature during the last decade. Lange et al. (2015) assessed the environmental impact by comparing concentrations of contaminants in discharged washwater with EQS for WFD-priority (hazardous) substances from Directive 2013/39/EU. The concentration of metals and PAH in washwaters of two vessels assessed were all below available EQS. However, the authors note that these compounds may cause long-term effects as non-biodegradable compounds may accumulate over time. In addition, the authors highlight that for priority substances lead, nickel, and naphthalene, which have been detected in washwaters, the WFD requires progressive reduction of discharges, emissions, and losses. Mercury and PAH (excluding naphthalene) are priority hazardous substance for which emissions, discharges and losses should be ceased or phased out. For some of aforementioned compounds the European commission (EC) has also proposed revised EQS for surface waters (European Commission, 2022). When approved, EQS may become more stringent, e.g., in the case of nickel and its compounds.

Similar to the methodology of Lange et al. (2015), Ushakov et al. (2020) assessed concentrations of metals and PAH in washwater with limit values. Instead of EQS, the authors collected PNEC (Predicted No Effect Concentrations) from an OPSAR regulation (OSPAR Commission, 2012) and for some compounds PNEC were estimated with in-silico tools. It was concluded that for some compounds concentrations in washwater were higher than the PNEC. With that, the authors note that dilution in the environment was not taken into account, leading to a ‘dramatic overestimation’ of risks.

Other studies retrieved from scientific literature assess (expected) concentrations in the environment to estimate risks. Most studies calculate predicted environmental concentrations (PEC), either with the model MAMPEC (Faber et al., 2019, Faber et al., 2021, Bolin and Ekström, 2022, Hermansson et al., 2023), a time-scale model (Kjølholt et al., 2012) or by dividing discharged load of pollutants by water flow rate (Teuchies et al., 2020). Despite differences in study set-ups, such as marine environment of interest and emissions scenarios, Faber et al. (2019), Faber et al. (2021), Kjølholt et al. (2012) and Teuchies et al. (2020) conclude that impact of emitted hazardous substances on marine waters is limited when compared to EQS. It is however recognized by the authors that substantial amounts of pollutants enter the marine environment via EGCS washwater which lead to increases in surface water concentrations. Bolin and Ekström (2022) identified risks for multiple metals and PAH when modelling the impact of emissions of EGCS on two ports of Stockholm and comparing resulting concentrations in water with PNEC. These ports were assessed because of ‘their confined location and low water exchange’ and ‘high cruise ship activity during a large part of the year' (Bolin and Ekström, 2022). To make the assessment more realistic, new environments were defined in MAMPEC to represent these ports. Also Hermansson et al. (2023) showed that shipping activities may impact the marine environment. In this study emissions of EGCS washwater, bilge water, atmospheric deposition and antifouling paint were assessed with four defined port environments in MAMPEC (OECD EU commercial harbour, OECD Baltic harbour, port of Copenhagen and port of Gdynia[2]). It was concluded that both antifouling paint and EGCS washwater are main contributors to environmental risks, with risks being found for all environments except the OECD EU commercial harbour. Conclusions are however based on combined risks of contaminants (expressed as sum of risks of individual compounds), which is different than the studies focussing on risks of individual compounds.

EGCS are also considered a contributor to acidification of marine ecosystems due to discharge of sulphuric acid. Marine organisms are sensitive to ocean acidification, and it is suggested that long-term functioning of marine ecosystems may be altered (Guinotte and Fabry, 2008, Mostofa et al., 2016, Doo et al., 2020). However, Kjølholt et al. (2012) assessed effects of EGCS discharges on pH and buffering capacity of water in two modelled environments (Kattegat and Aarhus Bight) and concluded that the impact is limited. For the Kattegat around 0.01% of buffering capacity would be needed to neutralize sulphuric acid of EGCS washwater. For the Bay of Bothnia, which is considered a more critical area regarding alkalinity as it has 1/3rd of alkalinity of Kattegat, impact on buffering capacity would still be less than 0.1% in a conservative scenario. Turner et al. (2018) also considered acidification effects as limited for aforementioned areas and other areas of the Baltic Sea. In a scenario where all ships use an EGCS and sulphur-rich fuels, highest acidification was expected in the Belt Sea, with a decrease of 0.004 pH-units. Claremar et al. (2017) estimate a decrease of 0.0003 pH-units for the Kattegat in a worst-case scenario. While the decrease seems comparable to the other studies, the authors of this study conclude that 'the effects of scrubbers on acidification is evident'. Teuchies et al. (2020) on the other hand conclude that pH and alkalinity of marine waters may significantly be affected by EGCS, with a decrease of 0.015 units in pH and 0.16% in alkalinity when 20% of the vessels operate an EGCS in the Antwerp harbour (Belgium). Even higher drops in pH were estimated by Dulière et al. (2020) for the Belgian and Dutch coasts, with a decrease ranging from 0.005 to 0.088 pH-units depending on traffic density and number of ships with an (open-loop) EGCS. For whole southern North Sea and English Channel, a decrease ranging from 0.004 to 0.010 pH-units was estimated.
The studies above show that discharge of EGCS washwaters may lead to acidification of aquatic environments, but the impact seems to be limited. For the present study it is therefore considered that chemical pollutants have a more prominent role.

[2] The OECD EU commercial harbour is a default environment available in MAMPEC, and its properties are based on the Port of Rotterdam. OECD Baltic is an adapted version of the commercial harbour, while the two other ports were newly defined in MAMPEC.

## 1.4 Outline and scope of the study

This study is a follow-up on Faber et al. (2021) in which effects of EGCS washwater discharges on the Port of Rotterdam, a shipping lane in the North Sea, and the Saba Bank were assessed. In this follow-up effects of EGCS washwater discharges on the marine environment of the Port of Amsterdam are assessed. To gain comparable results, methods used in former report are used in this report as well. This means that environmental concentrations as a result of EGCS discharges are predicted with MAMPEC and compared with existing EQS. This is largely in line with the methodology of the most recent IMO guideline on assessing quantitative risks of EGCS washwater discharges on water bodies (IMO, 2022). Where appropriate, similar data as in the previous study is used as well. This includes, for example, concentration contaminants in washwater (see section 2.3.2) which are used to model environmental concentrations. To increase the relevance of the results, a new MAMPEC environment representing the Port of Amsterdam is created (see further section 2.2.1).

This study also comprises additional assessments. First, existing environmental concentrations of contaminants in the Port of Amsterdam are collected, further referred to as 'ambient concentrations'. The IMO guideline stipulates that background concentrations of chemical substances should be added when calculating PECs (IMO, 2022). From the guideline it is not clear whether the term 'background concentrations' refers to naturally occurring concentrations due to e.g., weathering, or to ambient concentrations including anthropogenic emissions, but latter is assumed in this report. While concentrations due to EGCS discharges are estimated using a modelling approach, ambient concentrations are collected in regular monitoring programs which are not necessarily designed to address specific emission sources. Because a formal EQS-assessment is outside the scope of this report, summed PECs as a result of EGCS washwater discharges and ambient concentrations will not be compared with EQS in this report. Instead, predicted additions resulting from EGCS washwater discharges ($PEC_{add}$) will be compared with ambient concentrations to estimate the relative contribution of EGCS emissions to existing contaminant levels.

Secondly, effects of EGCS washwater discharges on the marine environment are assessed for the Eemshaven, a local port in the North-East of the Netherlands. As the primary focus of the report is on the Port of Amsterdam, for this port no predictions with MAMPEC are made. Since environmental characteristics and expected yearly discharge of EGCS washwater in the Port of Amsterdam are worst-case as compared to the Eemshaven, further dedicated modelling with MAMPEC was deemed unnecessary.

Thirdly, as ambient concentrations were collected in the former report of Faber et al. (2021), this study, where possible, also addresses the relative impact of EGCS use on former three investigated environments (Port of Rotterdam, Shipping Lane and Saba bank).

## 1.5 Reader's guide

Chapter 2 describes the derivation of predicted environmental concentrations for the Port of Amsterdam, including the development of an adapted MAMPEC-scenario and input parameters for emission estimates. This chapter also introduces the contaminants investigated and physico-chemical data used for model predictions. Chapter 3 presents the risk assessments for the Port of Amsterdam, presenting environmental quality standards and ambient concentrations for the chemicals under consideration, and comparisons with predicted environmental concentrations. Chapter 4 focusses on several additional risks assessment for three environments, namely the Eemshaven, Port of Rotterdam and a shipping lane. Chapter 5 gives the discussion and conclusions.

# 2 Predicted Environmental Concentrations Port of Amsterdam

## 2.1 Contaminants

The same compounds as in the previous study (Faber et al., 2021) are assessed in this study. This implies that in total 11 metals and 16 PAH are investigated (see Table 2.1). The choice of compounds is in line with the list of 24 targeted chemical substances which should at least be considered in the environmental risk assessment according to IMO 2022 guideline (IMO, 2022). Three metals (arsenic, thallium, vanadium) are supplementary to that list.

*Table 2.1 List of metals and PAH investigated in this study.*

| Metals | CAS no. | PAH | CAS no. |
|---|---|---|---|
| Arsenic | 7440-38-2 | Acenaphthene | 83-32-9 |
| Cadmium | 7440-43-9 | Acenaphthylene | 208-96-8 |
| Chromium | 7440-47-3 | Anthracene | 120-12-7 |
| Copper | 7440-50-8 | Benzo(a)anthracene | 56-55-3 |
| Lead | 7439-92-1 | Benzo(a)pyrene | 50-32-8 |
| Mercury | 7439-97-6 | Benzo(b)fluoranthene | 205-99-2 |
| Nickel | 7440-02-0 | Benzo(g,h,i)perylene | 191-24-2 |
| Selenium | 7782-49-2 | Benzo(k)fluoranthene | 207-08-9 |
| Thallium | 7440-28-0 | Chrysene | 218-01-9 |
| Vanadium | 7440-62-2 | Dibenzo(a,h)anthracene | 53-70-3 |
| Zinc | 7440-66-6 | Fluoranthene | 206-44-0 |
| | | Fluorene | 86-73-7 |
| | | Indeno(1,2,3-c,d)pyrene | 193-39-5 |
| | | Naphthalene | 91-20-3 |
| | | Phenanthrene | 85-01-8 |
| | | Pyrene | 129-00-0 |

## 2.2 MAMPEC

As in Faber et al. (2021), MAMPEC[3] is used to derive predicted environmental concentrations (PEC) of contaminants in water and sediment. MAMPEC-results represent concentrations added to the environment as a result of EGCS washwater discharges, without considering ambient concentrations of existing pollution. Therefore, MAMPEC-results are further referred to as $PEC_{add}$.

MAMPEC is a hydrodynamic and chemical fate model which calculates steady-state concentrations of contaminants in water, suspended matter and sediment after emissions from ship-related activities. As reaching steady-state may take several years to decades in sediment, the model calculates results for different time periods (van Hattum et al., 2016). Therefore, concentrations at longest modelled time period (20 years) are considered in this study. $PEC_{add}$ are selected in line with the way EQS are expressed, i.e., dissolved concentrations for metals, and total concentrations for PAH. The former includes the freely dissolved part and the fraction bound to dissolved organic carbon (DOC), the latter includes also the fraction bound to particulate matter. For sediment,

[3] MAMPEC 3.1.0.5.

$PEC_{add}$ is expressed as the settled fraction sorbed to suspended particulate matter.

### 2.2.1 *New model environment MAMPEC*

MAMPEC offers different default aquatic environments, such as harbours and marinas, to calculate PECs. Each environment has its own characteristics, such as size, hydrodynamics and water characteristics. While in the former study the default commercial harbour environment could be used to model environmental concentrations in the Port of Rotterdam[4], this and other default environments were not considered to be representative to model concentrations in the Port of Amsterdam. Therefore, RIVM commissioned Deltares to define a MAMPEC model environment which would be representative for the Port of Amsterdam. The results are shown in Appendix 1.

A new model environment was created in MAMPEC by duplicating the default commercial harbour environment and changing relevant parameters in line with the recommendations of Deltares (see Appendix 1). See Table 2.2 for the list with changed parameter values. Note that the mouth width was adapted to reflect the proposed renewal time (time before all water is renewed) of 2.8 days. Deltares recommended to include a worst-case renewal time of 3.7 days, but this was not deemed necessary upon further consideration (see Appendix 2). As MAMPEC is a simplified model, Deltares recommended additionally to perform a sensitivity analysis with two parameters:

1) 'Max. density difference tide', by applying values between 0.25-0.35 kg $m^{-3}$ in addition to the proposed value of 0.3 kg $m^{-3}$, and
2) 'Tidal difference', by applying values between 0.1 and 0.3 m in addition to the proposed value of 0.14 m.

Based on the limited impact of these input parameters on results (see Appendix 2), initially proposed values were used for final calculations.

*Table 2.2 Summary of relevant parameters for the MAMPEC default commercial harbour and newly created Port of Amsterdam.*

| Parameter | Unit | Default Commercial Harbour | Port of Amsterdam |
|---|---|---|---|
| Tidal Period | h | 12.41 | 24 |
| Tidal difference | m | 1.5 | 0.14 |
| Max. density difference tide | kg $m^{-3}$ | 0.8 | 0.3 |
| Flow velocity | m $s^{-1}$ | 1.5 | 0.03 |
| Length - x2 | m | 10,000 | 3,000 |
| Width - y2 | m | 500 | 300 |
| Depth | m | 20 | 15 |
| Mouth width - x3 | m | 5000 | 943[a] |

a: this value differs from the advised value of 900 in Appendix 1 in order to obtain the desired renewal time of 2.8 days.

[4] The default commercial harbour is based on e.g. the hydrodynamics and size of the Port of Rotterdam (Baart et al., 2008).

### 2.2.2 *Contaminant characteristics*

In MAMPEC (see Chapter 2 for more information) a sediment-water distribution coefficient ($K_d$) needs to be given for each metal, in order to calculate the distribution of metals between water and sediment. For PAH multiple physico-chemical parameters are needed, such as the octanol-water partition coefficient (log $K_{ow}$), organic carbon partition coefficient (log $K_{oc}$), water solubility, vapour pressure and Henry's law constant. For the present study, the same values are used as in Faber et al. (2021). Table 2.3 shows the distribution coefficients for metals, Table 2.4 summarises the physico-chemical characteristics of PAH.

*Table 2.3 Distribution coefficients ($m^3\ kg^{-1}$) for metals used in MAMPEC.*

| Compound | Partition coefficient ($K_d$) |
|---|---|
| Arsenic | 8 |
| Cadmium | 79 |
| Chromium | 126 |
| Copper | 50 |
| Lead | 501 |
| Mercury | 200 |
| Nickel | 25 |
| Selenium (IV) | 25.1 |
| Selenium (VI) | 6.3 |
| Thallium | 12.6 |
| Vanadium | 5 |
| Zinc | 100 |

*Table 2.4 Physico-chemical characteristics of PAH used in MAMPEC.*

| Compound | log $K_{ow}$ | log $K_{oc}$ | Vapour pressure (Pa) | Water solubility ($g\ m^{-3}$) | Henry coefficient ($Pa\ m^3\ mol^{-1}$) |
|---|---|---|---|---|---|
| Acenaphthene | 3.9 | 3.7 | 1.7E-01 | 2.5E+00 | 2.9E+01 |
| Acenaphthylene | 3.9 | 3.7 | 1.7E-01 | 2.5E+00 | 5.6E+00 |
| Anthracene | 4.5 | 4.2 | 2.9E-04 | 6.9E-01 | 5.2E+00 |
| Benzo(a)anthracene | 5.8 | 5.2 | 3.6E-05 | 2.9E-02 | 5.1E-01 |
| Benzo(a)pyrene | 6.1 | 5.8 | 1.3E-07 | 1.0E-02 | 8.2E-02 |
| Benzo(b)fluoranthene | 5.8 | 5.8 | 3.3E-06 | 2.1E-02 | 8.2E-02 |
| Benzo(g,h,i)perylene | 6.6 | 6.3 | 1.3E-08 | 2.8E-03 | 1.3E-02 |
| Benzo(k)fluoranthene | 6.1 | 5.8 | 1.0E-07 | 1.1E-02 | 8.2E-02 |
| Chrysene | 5.8 | 5.3 | 2.1E-07 | 2.6E-02 | 5.1E-01 |
| Dibenzo(a,h)anthracene | 6.8 | 6.3 | 1.9E-09 | 3.3E-03 | 5.0E-02 |
| Fluoranthene | 5.2 | 4.7 | 4.2E-04 | 1.3E-01 | 8.4E-01 |
| Fluorene | 4.2 | 4.0 | 4.4E-02 | 1.3E+00 | 1.7E+01 |
| Indeno(1,2,3-c,d)pyrene | 6.7 | 6.3 | 1.7E-08 | 2.5E-03 | 1.3E-02 |
| Naphthalene | 3.3 | 3.2 | 5.4E+00 | 1.4E+02 | 5.3E+01 |
| Phenanthrene | 4.5 | 4.2 | 5.8E-03 | 6.8E-01 | 5.2E+00 |
| Pyrene | 4.9 | 4.7 | 4.6E-05 | 2.2E-01 | 8.4E-01 |

## 2.3 Emission rates

### 2.3.1 *Discharged washwater*

In the former study, the amount of washwater discharged was estimated for each environment by combining data on e.g., operational characteristics of an EGCS, number of installed EGCS, and the number and type of sailing and stationary vessels present (Faber et al., 2021). In the present study new information is used from a report of the International Council on Clean Transportation (ICCT), with estimates of global scrubber washwater discharges in 2019. The supplemental data contains estimates for over 1600 ports, including the Port of Amsterdam and nine other Dutch ports (Osipova et al., 2021). Estimates of washwater discharges were based on ship traffic patterns in 2019 (pre-COVID-19), and all ships with an EGCS installed by the end of 2020 were taken into account. Washwater discharges were estimated from the hourly energy demand of each ship, in combination with the flow rates of each type of EGCS (open-loop, hybrid, closed-loop). For the Port of Amsterdam, ICCT estimated a total washwater discharge of 323,909 tonnes per year, with 100% of the emissions accountable to cruise ships (Osipova et al., 2021). All cruise ships in Amsterdam moor at one dock only (Passenger Terminal Amsterdam in the IJ-haven).

While the ICCT estimate is considered a useful point of departure, current discharges may be larger since the estimate was based on the number of ships equipped with EGCS visiting Amsterdam in 2020. Discharges could now be higher due to an increased use of EGCS in cruise ships (as the ICCT considered only those ships in their report) and/or an increase in port calls.

Since 2020 the number of EGCS on vessels has increased with almost 10%, from 4,362 to 4,794 in 2022, and is expected to increase to 5,061 in 2025 (ICCT, 2023). Although it is unclear which share of the expected increase can be attributed to cruise ships, it is likely that it is an important part since cruise ships had the largest share of fleet with EGCS in 2020 (34%) (Osipova et al., 2021). However, as there is no data on the number of cruise ships without EGCS that visit the Port of Amsterdam, the impact of the increase cannot be estimated.

An increase in port calls can also be anticipated. In total 117 cruise ships moored at the Amsterdam Passenger Terminal in 2019 (Port of Amsterdam, 2020). In 2021 and 2022 the number of cruise ships mooring was quite lower due to COVID-19 restrictions, with 6 and 105 cruise ships visiting the Port of Amsterdam (Port of Amsterdam, 2023). It is foreseen that the number will grow again, to a maximum of 190 ships[5]. This is an increase of more than 60% as compared to 2019.

Data on EGCS use was also obtained from a representative of the Port of Amsterdam. [6] He noted that besides cruise ships, other types of vessels with EGCS also enter the port, and that not all ships operate their EGCS in harbours. In the first three months of 2022, 52 vessels with an EGCS moored. 19 of these vessels were inspected by representatives of the Port of Amsterdam, and it appeared that six vessels did not operate their EGCS in harbours due to company policy. Extrapolating these number to the whole of 2022 would imply that around 200 vessels with an EGCS visited the Port of Amsterdam, with around 30% (60 vessels) switching off their EGCS in the harbour. This would come down to around 140 vessels per year using EGCS, although it might be an underestimate as cruise ships hardly moor during the first quarter of the year.

[5] https://www.parool.nl/amsterdam/er-is-straks-plek-voor-minder-cruiseschepen-in-amsterdam-maar-ze-kunnen-wel-aan-de-schonere-walstroom~bedc6fcff/
[6] Written communication.

Based on the available information, it can be foreseen that amounts of discharged washwater in 2022 and 2023 were higher than estimated by ICCT for 2019, potentially being double the amount. Therefore, it may be desirable to perform model calculations with higher tonnages. However, additional information on the IJ-haven showed that the daily renewal rate of 2.8 days used in the MAMPEC-calculations is conservative (see Appendix 2) and outweighs a (potential) increase in discharged amount of washwater. Therefore, a yearly discharge of 323,909 tonnes of washwater was used as input in MAMPEC.

### 2.3.2 *Washwater concentrations*

The same average, normalized concentrations of contaminants were used as in the previous study (Faber et al., 2021). These concentrations are based on Faber et al. (2019) and are given in Table 2.5.

*Table 2.5 Average normalized metal and PAH concentrations in EGCS washwaters. All concentrations are given in μg $L^{-1}$, representing total concentrations in unfiltered samples.*

| **Metals** | | **PAH** | |
|---|---|---|---|
| Arsenic | 6.4 | Acenaphthene | 0.2 |
| Cadmium | 1.9 | Acenaphthylene | 0.12 |
| Chromium | 18 | Anthracene | 1.8 |
| Copper | 250 | Benzo(a)anthracene | 0.3 |
| Lead | 0.2 | Benzo(a)pyrene | 0.042 |
| Mercury | 0.1 | Benzo(b)fluoranthene | 0.048 |
| Nickel | 120 | Benzo(g,h,i)perylene | 0.047 |
| Selenium | 15 | Benzo(k)fluoranthene | 0.01 |
| Thallium | 5.3 | Chrysene | 0.25 |
| Vanadium | 140 | Dibenzo(a,h)anthracene | 0.019 |
| Zinc | 320 | Fluoranthene | 0.21 |
| | | Fluorene | 0.57 |
| | | Indeno(1,2,3-c,d)pyrene | 0.049 |
| | | Naphthalene | 3.5 |
| | | Phenanthrene | 2 |
| | | Pyrene | 0.36 |
| | | PAH total | 9.525 |

### 2.3.3 *Emission rates*

Emission rates were calculated by multiplying the annual washwater discharge in the Port of Amsterdam (323,909 tonnes) with normalized average concentrations of contaminants in EGCS washwater, these emission rates were used as input for MAMPEC after conversion to daily rates (see Table 2.6).

*Table 2.6 Daily emission rates of metals and PAH for the Port of Amsterdam, used as input for MAMPEC.*

| **Contaminant** | **Port of Amsterdam (g $d^{-1}$)** | **Contaminant** | **Port of Amsterdam (g $d^{-1}$)** |
|---|---|---|---|
| Arsenic | 5.7E+00 | Acenaphthene | 1.8E-01 |
| Cadmium | 1.7E+00 | Acenaphthylene | 1.1E-01 |
| Chromium | 1.6E+01 | Anthracene | 1.6E+00 |
| Copper | 2.2E+02 | Benzo(a)anthracene | 2.7E-01 |

| Contaminant | Port of Amsterdam (g d-1) | Contaminant | Port of Amsterdam (g d-1) |
|---|---|---|---|
| Lead | 1.1E+02 | Benzo(a)pyrene | 3.7E-02 |
| Mercury | 1.8E-01 | Benzo(b)fluoranthene | 4.3E-02 |
| Nickel | 8.9E-02 | Benzo(g,h,i)perylene | 4.2E-02 |
| Selenium (IV) | 6.7E+00 | Benzo(k)fluoranthene | 8.9E-03 |
| Selenium (VI) | 6.7E+00 | Chrysene | 2.2E-01 |
| Thallium | 4.7E+00 | Dibenzo(a,h)anthracene | 1.7E-02 |
| Vanadium | 1.2E+02 | Fluoranthene | 1.9E-01 |
| Zinc | 2.8E+02 | Fluorene | 5.1E-01 |
| | | Indeno(1,2,3-c,d)pyrene | 4.3E-02 |
| | | Naphthalene | 3.1E+00 |
| | | Phenanthrene | 1.8E+00 |
| | | Pyrene | 3.2E-01 |
| | | PAH total | 8.5E+00 |

## 2.4 Predicted Environmental Concentrations ($PEC_{add}$)

### 2.4.1 *Inside the harbour*

Figure 2.1 and Figure 2.2 show the $PEC_{add}$ for metals and PAH inside the harbour. For each contaminant, predicted average (mean) and 95% Upper Confidence Limit (95% UCL) values are given. A detailed overview of $PEC_{add}$ values is given in Appendix 3.

Highest metal concentrations in water are predicted for vanadium, copper, nickel and zinc. For PAH highest concentrations are found for naphthalene, phenanthrene and anthracene. These are also the compounds which are present in highest concentrations in EGCS washwater (see section 2.3.2).

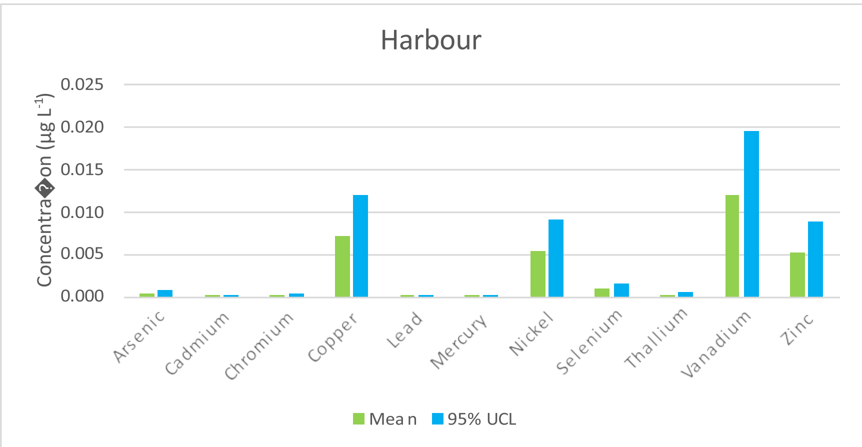


*Figure 2.1 Predicted increase in metal concentrations ($PEC_{add}$) in water of the Port of Amsterdam as a result of EGCS washwater discharges. Concentrations represent the freely dissolved and DOC-bound fraction, excluding particulate matter.*

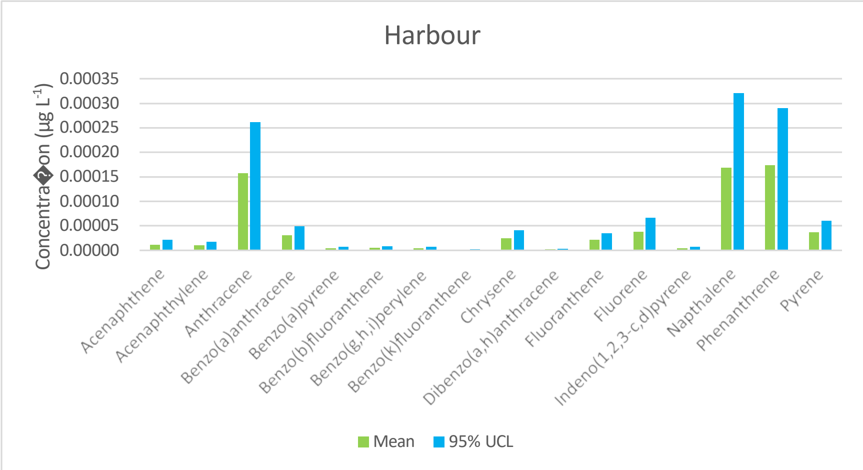


*Figure 2.2 Predicted increase in PAH concentrations ($PEC_{add}$) in water of the Port of Amsterdam as a result of EGCS washwater discharges. Concentrations represent total PAH, including the fraction bound to particulate matter.*

Figure 2.3 and Figure 2.4 show the $PEC_{add}$ for metals and PAH in sediment after 20 years. Similar to the water compartment, highest concentrations are found for zinc, copper and nickel. Due to the relatively low distribution coefficient (see Chapter 2.2.2) vanadium is less present in sediment. Benzo(a)anthracene, chrysene and phenanthrene are the PAH with highest concentrations in sediment. See Appendix 4 for the $PEC_{add}$.

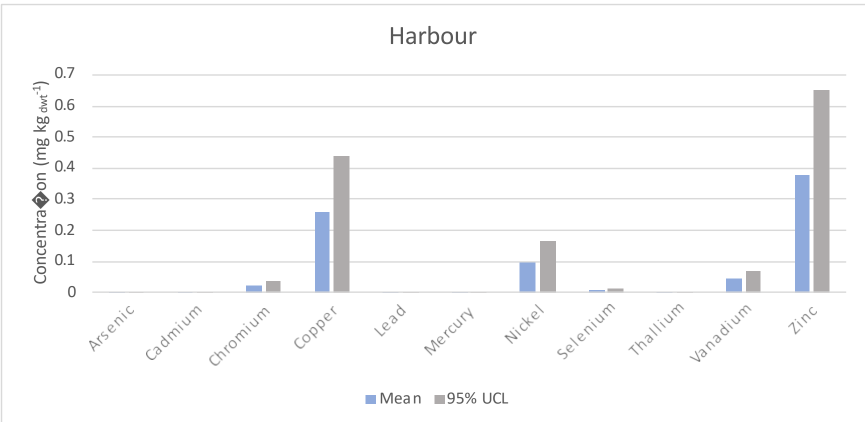


*Figure 2.3 Predicted increase in concentrations of metals ($PEC_{add}$) in sediment of the Port of Amsterdam after 20 years of EGCS washwater discharges.*

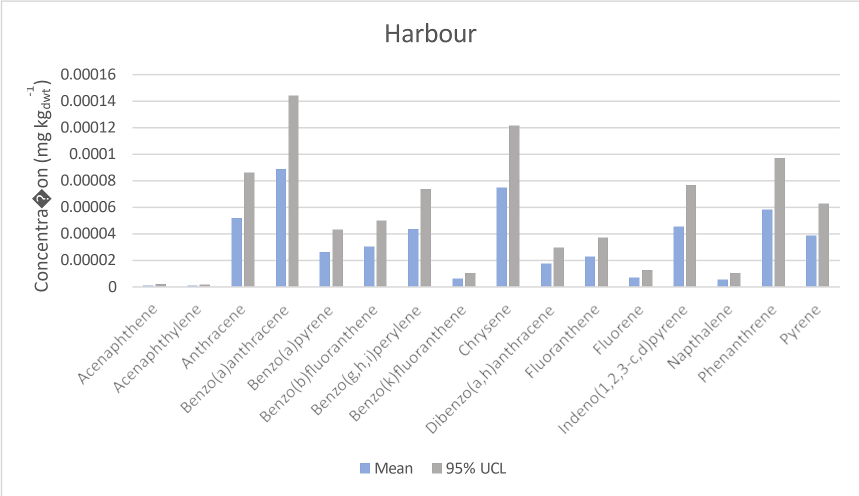


*Figure 2.4 Predicted increase in concentrations of PAH ($PEC_{add}$) in sediment of the Port of Amsterdam after 20 years of EGCS washwater discharges.*

### 2.4.2 *Surrounding environment*

Figure 2.5 and Figure 2.6 show the $PEC_{add}$ for metals and PAH in surrounding water of the Port of Amsterdam. A similar pattern in concentrations is found as inside the harbour, however concentrations are lower. Average and 95% UCL concentrations metals and PAH in surrounding water are approximately 3 to 5 times lower than inside the harbour. A complete overview of $PEC_{add}$ in surrounding waters is given in Appendix 3.

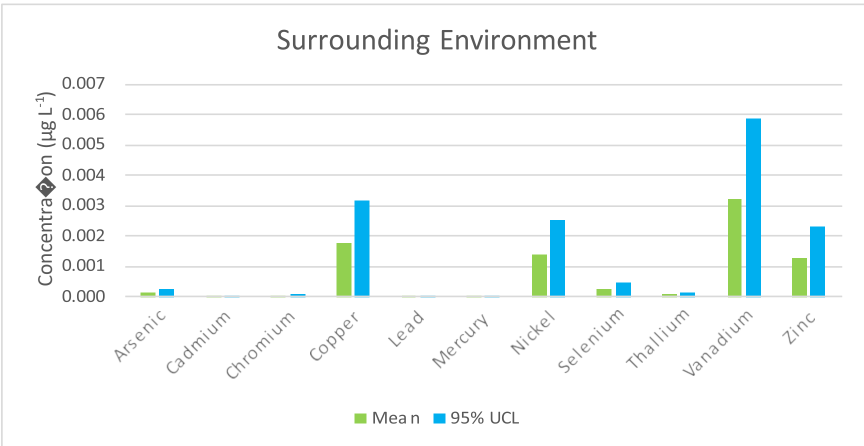


*Figure 2.5 Predicted increase in metal concentrations ($PEC_{add}$) in surrounding water of the Port of Amsterdam as a result of EGCS washwater discharges. Concentrations represent the freely dissolved and DOC-bound fraction, excluding particulate matter.*

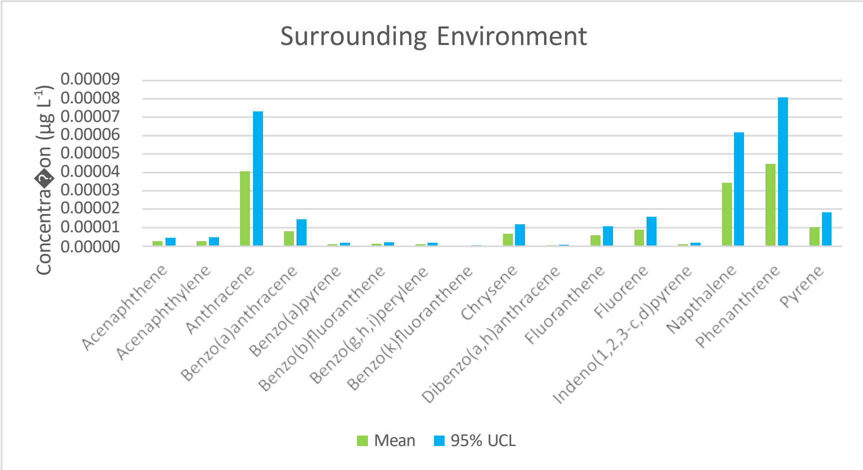


*Figure 2.6 Predicted increase in concentrations of PAH ($PEC_{add}$) in surrounding water of the Port of Amsterdam as a result of EGCS washwater discharges. Concentrations represent total PAH, including the fraction bound to particulate matter.*

Figure 2.7 and Figure 2.8 present $PEC_{add}$ for metals and PAH in surrounding sediment. The pattern of these results also matches with inside the harbour, as is the case for the water compartment. The concentrations are around 3 to 5 times lower than inside the harbour.

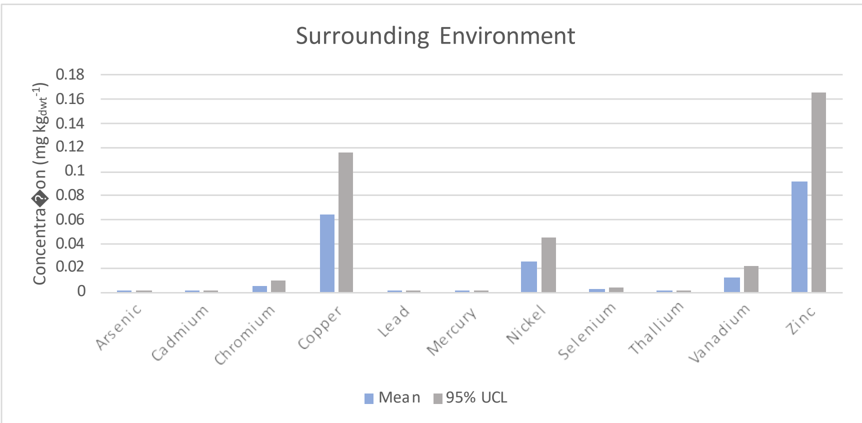


*Figure 2.7 Predicted increase in metal concentrations ($PEC_{add}$) in sediment in surrounding environment of the Port of Amsterdam after 20 years of EGCS washwater discharges.*

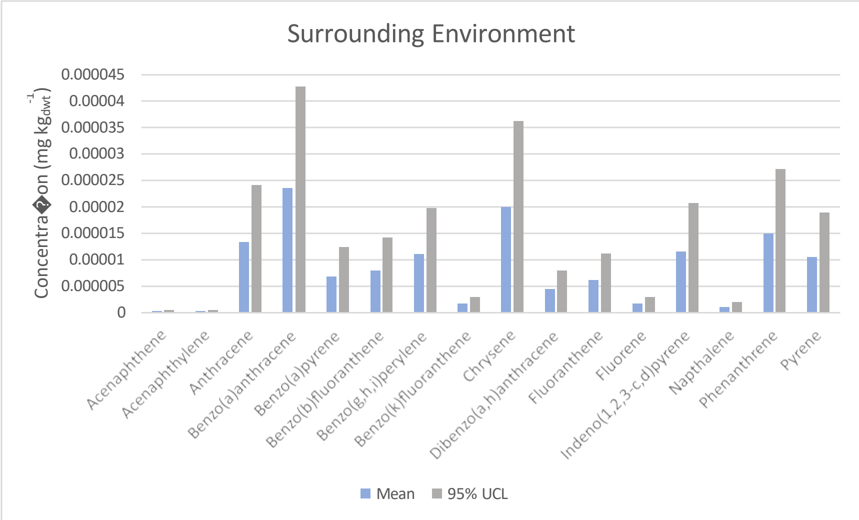


*Figure 2.8 Predicted increase in PAH concentrations ($PEC_{add}$) in sediment in surrounding environment of the Port of Amsterdam after 20 years of EGCS washwater discharges.*

# 3 Risk assessment Port of Amsterdam

## 3.1 Introduction

In this chapter the risks of EGCS discharges for the water and sediment compartment are assessed. Risks for surface water are assessed in two ways; by comparing $PEC_{add}$ with 1) EQS and 2) ambient concentrations. These data are presented in section 3.2.1 and section 3.3.

Established EQS for freshwater sediment are not available (see section 3.2.2), in addition the author is not aware of data on ambient concentrations metals and PAH in sediment in the Port of Amsterdam. Therefore, $PEC_{add}$ for the Port of Amsterdam are compared to the $PEC_{add}$ for the Port of Rotterdam and thus indirectly compared with risk limits for marine sediments.

## 3.2 Environmental quality standards (EQS)

### 3.2.1 *Freshwater*

The Port of Amsterdam is adjacent to the North Sea Channel (Noordzeekanaal) and the IJ. According to the WFD, the North Sea Channel (including the IJ) is currently classified as type O2b, a water system with a salt gradient.[7] In 2019 the classification was renewed to better fit the ecological situation. It is also expected that salinity will rise in the future. However, due to consequences for granting discharge permits, the surface water remains to be treated as freshwater when assessing the chemical status.[7] Therefore water and sediment quality standards for freshwater were collected.

Both EQS for long-term continuous exposure (AA-EQS) and short-term concentration peaks (MAC-EQS) are available under the WFD. Since MAMPEC modelling is based on average yearly emissions from EGCS, AA-EQS are considered most appropriate to assess environmental risks.

Available EQS for freshwater are given below in Table 3.1 and Table 3.2. In Faber et al. (2021) an elaborate explanation is given on the background of the EQS, including aspects to take into account when comparing measured concentrations of metals with EQS, e.g. the use of background concentrations and performing a bioavailability correction. Although here freshwater EQS are given instead of marine EQS, in most cases the same aspects apply. Some additional aspects are described below. All existing EQS and underlying scientific documentation can be found via the search engine at the RIVM website https://rvszoeksysteem.rivm.nl/.

For *cadmium* there is no fixed AA-EQS, but the AA-EQS is dependent on surface water hardness. The rationale behind this is that the toxicity of cadmium decreases with increasing water hardness.

7 https://waterkwaliteitsportaal.overheidsbestanden.nl/factsheets/Factsheets%202023/Oppervlaktewater/factsheet_OW_80_Ministerie_van_Infrastructuur_en_Waterstaat_Rijkswaterstaat_2023-09-20.pdf

*For copper, lead, nickel and zinc* the legally set AA-EQS are generic values representing critical conditions regarding bioavailability. When concentrations exceed the AA-EQS, it is possible to perform a refined assessment and apply a bioavailability correction taking into account local water characteristics (Maas and Ten Hulscher, 2019). For these metals, the generic AA-EQS refers to total dissolved concentrations, including natural background concentrations. Therefore, $PEC_{add}$ and officially set natural background concentrations (BC) have to be summed prior to comparison with AA-EQS.

For some other metals e.g., *arsenic* and *cadmium*, the AA-EQS are expressed as maximum permissible addition to the natural background concentrations. In these cases, the $PEC_{add}$ can be compared directly with the AA-EQS.

It should be noted that the ordinance on quality standards and monitoring water (*Besluit kwaliteitseisen en monitoring water 2009*; BKMW) and the decree on WFD-monitoring (*Regeling monitoring kaderrichtlijn water*; RMKrw) were in force until the end of 2023. From January 1, 2024, the Environment and Planning Act (Omgevingswet) has become into force, but this has no effect on the EQS or compliance check. However, the generic EQS for nickel may change when the draft priority substances under the WFD is accepted.

*Table 3.1 Annual Average Environmental Quality Standards (AA-EQS) and officially set Background Concentrations (BC) for metals. All values in μg $L^{-1}$, expressed as **dissolved** concentrations, unless stated otherwise. The fourth column indicates how MAMPEC modelling results should be compared with the EQS.*

| Compound | AA-EQS Fresh water | BC Freshwater[a] | Strategy for comparison $PEC_{add}$ with EQS[b] |
|---|---|---|---|
| Arsenic | 0.5 | 0.5 | $PEC_{add}$ ➔ AA-EQS |
| Cadmium | [c] | 0.08 | $PEC_{add}$ ➔ AA-EQS |
| Chromium | 3.4 | 0.2 | $PEC_{add}$ ➔ AA-EQS |
| Copper | 2.4 | 0.5 | BC + $PEC_{add}$ ➔ AA-EQS |
| Lead | 1.2[d] | 0.2 | BC + $PEC_{add}$ ➔ AA-EQS |
| Mercury | 0.00007 [e] | 0.01 | $PEC_{add}$ ➔ AA-EQS |
| Nickel | 4[d] | 1 | BC + $PEC_{add}$ ➔ AA-EQS |
| Selenium (IV)<br>Selenium (VI) | 0.052 | 0.04 | BC + $PEC_{add}$ ➔ AA-EQS |
| Thallium | 0.05 | 0.04 | BC + $PEC_{add}$ ➔ AA-EQS |
| Vanadium | 3.5 | 0.8 | $PEC_{add}$ ➔ AA-EQS |
| Zinc | 7.8 | 1.0 | BC + $PEC_{add}$ ➔ AA-EQS |

a: BC = Background Concentration
b: PEC = Predicted Environmental Concentration
c: dependent on water hardness class (Dutch: waterhardheidsklasse); ≤ 0.08 (Class 1 - < 40 mg CaCO3/L); 0.08 (Class 2 – 40 to < 50 mg CaCO3/L); 0.09 (Class 3 – 50 to < 100 mg CaCO3/L); 0.15 (Class 4 – 100 to < 200 mg CaCO3 /L); 0.25 (Class 5 - ≥ 200 mg CaCO3/L).
d: EQS for the biologically available concentration.
e: the AA-EQS for mercury is lower than the officially set 'natural' background concentration.

*Table 3.2 Annual Average Environmental Quality Standards (AA-EQS) for PAH. All values in µg $L^{-1}$, expressed as **total** concentrations, unless stated otherwise.*

| Compound | Freshwater AA-EQS | Notes |
|---|---|---|
| Acenaphthene | 3.8 | indicative value for freshwater; dissolved; not officially set |
| Acenaphthylene | 0.1 | officially set value, not included in WFD-legislation[b] |
| Anthracene | 0.1 | |
| Benzo(a)anthracene | 0.00064 | |
| Benzo(a)pyrene (BaP) | 0.00017 | |
| Benzo(b)fluoranthene | see BaP[a] | |
| Benzo(g,h,i)perylene | see BaP[a] | |
| Benzo(k)fluoranthene | see BaP[a] | |
| Chrysene | 0.0029 | |
| Dibenzo(a,h)anthracene | 0.00102 | indicative value for freshwater; dissolved; officially set value, not included in WFD-legislation[b] |
| Fluoranthene | 0.0063 | |
| Fluorene | 1.5 | officially set value, not included in WFD-legislation[b] |
| Indeno(1,2,3-c,d)pyrene | see BaP[a] | |
| Naphthalene | 2 | |
| Phenanthrene | 1.2 | |
| Pyrene | 0.028 | officially set value, not included in WFD-legislation[b] |

a: directive 2013/39/EU states the following: For the group of priority substances of polyaromatic hydrocarbons (PAH), the biota EQS and corresponding AA-EQS in water refer to the concentration of benzo(a)pyrene (BaP), on the toxicity of which they are based. Benzo(a)pyrene can be considered as a marker for the other PAH, hence only benzo(a)pyrene needs to be monitored for comparison with the biota EQS or the corresponding AA- EQS in water.

b: derived in the context of Dutch emission policy.

### 3.2.2 *Freshwater sediment*

In Faber et al. (2021) OSPAR[8] Background Assessment Concentrations (BAC) for marine sediment were used to evaluate risks. In addition, also Effect Range Low (ERL) and Derived ecotoxicological Risk Limits (DRL) (only for PAH) were collected and used. As the Port of Amsterdam needs to be assessed as a freshwater system, all afore threshold values are not considered appropriate for risk assessment.

Since 2009 freshwater sediment quality is not considered as independent goal anymore under the Soil Protection Act (Wet bodembescherming) (Hin et al., 2010). Sediments are now considered an integral part of the water system under the Dutch Water act (Waterwet). To assess sediment quality, an assessment framework has been developed and implemented (Hin et al., 2010). This framework distinguishes two stepwise assessment approaches, one from a water quality perspective and one from a soil quality perspective. As a result, sediment is indirectly assessed via either pathway. It should be noted that for some contaminants sediment EQS are available, however these are not considered representative to assess sediment quality. Most of

[8] Oslo and Paris Convention for the Protection of the Marine Environment of the North-East Atlantic.

these values were derived from freshwater-EQS using equilibrium partitioning. While freshwater-EQS have been updated since then, concurrent sediment values have not been set because sediment is not assessed separately as indicated above.

## 3.3 Ambient concentrations

In this section ambient concentrations of metals and PAH are displayed. As data on ambient concentrations contaminants in sediment were missing, only surface water concentrations are given. To collect data on current concentrations of metals and PAH in water, the Waterkwaliteitsportaal[9] was scrutinized. Waterkwaliteitsportaal is a website where information on Dutch water quality is collated.

For the Port of Amsterdam, the location with data closest to Passenger Terminal Amsterdam was location 'NL80_AMSDM'[10], which is in the river IJ, north-west of the IJ-haven (see Appendix 2). For each compound in total 13 measurements were available for 2022, which are the most recent data available. For some compounds one or multiple measurements were below the limit of Quantification (LOQ). For those measurements the exact concentrations are unclear. To be able to take into account these measurements in the average concentrations, it was assumed that these concentrations were 0.5x the LOQ. Table 3.3 shows the average and maximum concentrations.

*Table 3.3 Average and maximum concentrations of metals and PAH in the river IJ in 2022. All values in µg L$^{-1}$.*

| Metals | Average | Maximum | PAH | Average | Maximum |
|---|---|---|---|---|---|
| Arsenic | 1.9 | 2.9 | Acenaphthene | NA | NA |
| Cadmium | 0.01 | 0.022 | Acenaphthylene | NA | NA |
| Chromium | 0.2 | 0.50 | Anthracene | <LOQ[a] | |
| Copper | 2.7 | 3.2 | Benzo(a)anthracene | 0.0016 | 0.0022 |
| Lead | 0.028 | 0.068 | Benzo(a)pyrene | 0.0012 | 0.0024 |
| Mercury | 0.00048 | 0.0010 | Benzo(b)fluoranthene | 0.0034 | 0.0055 |
| Nickel | 1.4 | 1.9 | Benzo(g,h,i)perylene | 0.0017 | 0.0026 |
| Selenium | 0.15 | 0.17 | Benzo(k)fluoranthene | 0.0011 | 0.0018 |
| Thallium | 0.009 | 0.012 | Chrysene | <LOQ[a] | |
| Vanadium | 1.0 | 1.5 | Dibenzo(a,h)anthracene | <LOQ[b] | |
| Zinc | 4.5 | 7.1 | Fluoranthene | 0.0070 | 0.012 |
| | | | Fluorene | NA | NA |
| | | | Indeno(1,2,3-c,d)pyrene | 0.0016 | 0.0024 |
| | | | Naphthalene | <LOQ[c] | |
| | | | Phenanthrene | 0.0026 | 0.0034 |
| | | | Pyrene | 0.0068 | 0.011 |

NA Not Available (not analysed)
a: LOQ of 0.002-0.004 µg/L
b: LOQ of 0.002-0.003 µg/L
c: LOQ of 0.02-0.03 µg/L

[9] https://www.waterkwaliteitsportaal.nl/oppervlaktewaterkwaliteit. Last visited on 04-10-2023.
[10] Meetobject.code (Measurement Object Code).

## 3.4 $PEC_{add}$ versus EQS

### 3.4.1 *Freshwater*

In Table 3.4 the comparison of $PEC_{add}$ with EQS are given. None of the $PEC_{add}$ exceed the AA-EQS. For mercury and selenium $PEC_{add}$ are relatively highest: based on the average concentrations these amount to 1.3% and 1.0% of the AA-EQS, respectively. Based on the 95% UCL the increase in mercury amounts 2.2% of the AA-EQS, for selenium it amounts to 1.7%. For the surrounding environment $PEC_{add}$ are lower, representing lower fractions of the AA-EQS (percentages not given).

*Table 3.4 Average and 95% UCL $PEC_{add}$ for metals in freshwater inside the harbour, given as percentage (%) of the EQS.*

| **Compound** | **Inside the harbour** | |
|---|---|---|
| | Average | 95% UCL[a] |
| Arsenic | 0.10 | 0.16 |
| Cadmium | 0.015 | 0.026 |
| Chromium | 0.007 | 0.012 |
| Copper | 0.25 | 0.42 |
| Lead | 0.000053 | 0.000092 |
| Mercury | 1.3 | 2.2 |
| Nickel | 0.11 | 0.18 |
| Selenium | 1.0 | 1.7 |
| Thallium | 0.38 | 0.62 |
| Vanadium | 0.35 | 0.56 |
| Zinc | 0.07 | 0.12 |

a: Upper Confidence Limit

For PAH results are given in Table 3.5. For benzo(a)anthracene the highest increase is expected, with average concentration amounting to 4.7% of the AA-EQS, and 95% UCL to 7.6% of the AA-EQS. For various PAH – benzo(a)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene and indeno(1,2,3-c,d)pyrene –average increases amount to 2-3% of the EQS, for the other PAH it is less. For the surrounding environment $PEC_{add}$ are lower, representing lower fractions of the AA-EQS (percentages not given).

*Table 3.5 Average and 95% UCL $PEC_{add}$ for PAH in freshwater inside the harbour, given as percentage (%) of the EQS.*

| **Compound** | **Inside the harbour** | |
|---|---|---|
| | Average | 95% UCL[a] |
| Acenaphthene | 0.00030 | 0.00055 |
| Acenaphthylene | 0.010 | 0.017 |
| Anthracene | 0.16 | 0.26 |
| Benzo(a)anthracene | 4.7 | 7.6 |
| Benzo(a)pyrene | 2.3 | 3.7 |
| Benzo(b)fluoranthene | 2.6 | 4.2 |
| Benzo(g,h,i)perylene | 2.3 | 3.8 |
| Benzo(k)fluoranthene | 0.54 | 0.88 |
| Chrysene | 0.86 | 1.4 |
| Dibenzo(a,h)anthracene | 0.15 | 0.26 |
| Fluoranthene | 0.34 | 0.55 |
| Fluorene | 0.0025 | 0.0045 |
| Indeno(1,2,3-c,d)pyrene | 2.4 | 4.0 |

| Compound | Inside the harbour | |
|---|---|---|
| Naphthalene | 0.0084 | 0.016 |
| Phenanthrene | 0.014 | 0.024 |
| Pyrene | 0.13 | 0.21 |

a: Upper Confidence Limit

### 3.4.2 *Sediment*

In section 3.2.2 it was noted that for freshwater sediment no EQS are available, nor are available marine threshold values relevant. If we assume that freshwater organisms are comparably sensitive to pollutants as saltwater organisms, we can use the results for the Port of Rotterdam (assessed as marine water system), as proxy for risks for the Port of Amsterdam (to be assessed as freshwater system). For the Port of Rotterdam it was concluded that $PEC_{add}$ are small and that 'emissions result in limited increases of sediment concentrations' (Faber et al., 2021). $PEC_{add}$ for the Port of Amsterdam are between a factor of 1.8 and 4.2 higher, depending on the compound, and are therefore also considered low. In Appendix 4 an overview of $PEC_{add}$ for harbour sediment are given for the Port of Amsterdam and Port of Rotterdam.

## 3.5 $PEC_{add}$ versus ambient concentrations

In Table 3.6 worst-case comparisons of $PEC_{add}$ with ambient concentrations are given for metals. From the results it is clear that the $PEC_{add}$ are only a fraction of the ambient concentrations in the Port of Amsterdam. For thallium relative largest amounts are predicted: the 95% UCL concentration is 6.2% of the average ambient concentration in the Port of Amsterdam. The second highest is vanadium, with a 95% UCL of 2.0% of the average ambient concentration.

*Table 3.6 Average and 95% UCL $PEC_{add}$ for metals in freshwater inside the harbour, given as percentage (%) of average ambient concentration.*

| Compound | Inside the harbour | |
|---|---|---|
| | Average | 95% UCL[a] |
| Arsenic | 0.026 | 0.042 |
| Cadmium | 0.38 | 0.65 |
| Chromium | 0.12 | 0.21 |
| Copper | 0.26 | 0.45 |
| Lead | 0.0026 | 0.0046 |
| Mercury | 0.18 | 0.32 |
| Nickel | 0.39 | 0.65 |
| Selenium | 0.63 | 1.0 |
| Thallium | 3.8 | 6.2 |
| Vanadium | 1.2 | 2.0 |
| Zinc | 0.12 | 0.20 |

a: Upper Confidence Limit

In Table 3.7 the results are given for PAH. Not for all compounds a comparison could be made as ambient concentrations were missing. For phenanthrene highest contributions are found: the predicted 95% UCL is 11% of the average measured concentration. Also, for benzo(a)anthracene a relative high percentage (3.1%) was found when comparing aforementioned values.

*Table 3.7 Average and 95% UCL $PEC_{add}$ for PAH in freshwater inside the harbour, given as percentage (%) of average ambient concentration.*

| **Compound** | **Inside the harbour** | |
|---|---|---|
| | Average | 95% UCL[a] |
| Acenaphthene | NP | |
| Acenaphthylene | NP | |
| Anthracene | NP | |
| Benzo(a)anthracene | 1.9 | 3.1 |
| Benzo(a)pyrene | 0.31 | 0.52 |
| Benzo(b)fluoranthene | 0.13 | 0.21 |
| Benzo(g,h,i)perylene | 0.23 | 0.39 |
| Benzo(k)fluoranthene | 0.080 | 0.13 |
| Chrysene | NP | |
| Dibenzo(a,h)anthracene | NP | |
| Fluoranthene | 0.31 | 0.50 |
| Fluorene | NP | |
| Indeno(1,2,3-c,d)pyrene | 0.26 | 0.43 |
| Naphthalene | NP | |
| Phenanthrene | 6.6 | 11 |
| Pyrene | 0.54 | 0.88 |

NP Not Possible (no ambient concentrations available)
a: Upper Confidence Limit

# 4 Additional risk assessments

## 4.1 Introduction

In this chapter the additional risks assessments are presented. This includes the risk assessment for the Eemshaven (section 4.2), for which risks are estimated based on the results for the Port of Amsterdam, and a comparison between the port characteristics. Supplementary to Faber et al. (2021) risk assessments for the water compartment, based on a comparison of $PEC_{add}$ with ambient concentrations, are presented for the Port of Rotterdam (section 4.3) and shipping lane (section 4.4). As the author is not aware of data on ambient concentrations contaminants in surface water near the Saba bank, no additional assessment is performed for this area. Also, no additional assessments were performed for sediment due to absence of ambient concentration data.

## 4.2 Eemshaven

In Chapter 3 the effects of EGCS discharges on concentrations contaminants in water and sediment of the Port of Amsterdam are given. To assess whether these results are also representative for the Eemshaven, two characteristics of both ports are compared: 1) the annual discharged amounts of EGCS washwater and 2) water renewal time (time before all port water is renewed). These characteristics were expected to have the most impact on the concentration of contaminants in ports. Other characteristics for which data were available were not considered, either because these had limited impact on $PEC_{add}$ (e.g., density difference and tidal difference', see section 2.2.1 and Appendix 2) or these were assumed to be alike (e.g., concentration contaminants in washwater).

Table 4.1 shows that the annual amount of washwater discharged, and with that the load of contaminants, in the Eemshaven is 48% lower than in the Port of Amsterdam. The water renewal time for the Eemshaven is also significantly shorter than the average water renewal time of the Port of Amsterdam, therefore lower $PEC_{add}$ are expected for the Eemshaven. Considering the generally low EQS for marine waters, contribution of washwater discharges to the EQS are limited.

*Table 4.1 Annual discharged EGCS washwater and water renewal time for the Eemshaven and Port of Amsterdam.*

| Characteristic | Unit | Eemshaven | Port of Amsterdam |
|---|---|---|---|
| Discharged washwater[a] | tonnes $year^{-1}$ | 171,477 | 332,909 |
| Water renewal time | day | 0.03.1.90[b] | 2.8[c] |

a: based on the supplemental data of Osipova et al. (2021).
b: based on https://www.immissietoets.nl/berekening/immissietoets.
c based on https://www.immissietoets.nl/berekening/immissietoets the values for the IJ-haven are 0.25-0.37.

## 4.3 Port of Rotterdam

In Table 4.2 and Table 4.3 worst-case comparisons of $PEC_{add}$ with ambient concentrations are presented. In Appendix 5 more background information on ambient concentrations is provided, and also $PEC_{add}$ from Faber et al. (2021) are given.

The predicted metal and PAH concentrations are a low fraction of ambient concentrations. Thallium has the highest contribution of all metals, with a predicted 95% UCL of 1.1% of the average ambient concentration. For anthracene contribution is highest with 2.3%. Note that some PAH could not be assessed as ambient concentrations were not available.

*Table 4.2 Average and 95% UCL $PEC_{add}$ for metals in freshwater inside the harbour, given as percentage (%) of average ambient concentration.*

| Compound | Inside the harbour | |
|---|---|---|
| | Average | 95% UCL[a] |
| Arsenic | 0.012 | 0.017 |
| Cadmium | 0.077 | 0.11 |
| Chromium | 0.041 | 0.060 |
| Copper | 0.11 | 0.17 |
| Lead | 0.0010 | 0.0014 |
| Mercury | 0.070 | 0.10 |
| Nickel | 0.17 | 0.25 |
| Selenium | 0.15 | 0.22 |
| Thallium | 0.76 | 1.1 |
| Vanadium | 0.38 | 0.55 |
| Zinc | 0.046 | 0.067 |

a: Upper Confidence Limit

*Table 4.3 Average and 95% UCL $PEC_{add}$ for PAH in freshwater inside the harbour, given as percentage (%) of average ambient concentration.*

| Compound | Inside the harbour | |
|---|---|---|
| | Average | 95% UCL[a] |
| Acenaphthene | NP | |
| Acenaphthylene | NP | |
| Anthracene | 1.5 | 2.3 |
| Benzo(a)anthracene | 0.13 | 0.19 |
| Benzo(a)pyrene | 0.021 | 0.030 |
| Benzo(b)fluoranthene | 0.012 | 0.018 |
| Benzo(g,h,i)perylene | 0.025 | 0.037 |
| Benzo(k)fluoranthene | 0.0077 | 0.011 |
| Chrysene | 0.11 | 0.16 |
| Dibenzo(a,h)anthracene | 0.041 | 0.059 |
| Fluoranthene | 0.031 | 0.046 |
| Fluorene | NP | |
| Indeno(1,2,3-c,d)pyrene | 0.027 | 0.039 |
| Naphthalene | 0.42 | 0.61 |
| Phenanthrene | 0.52 | 0.76 |
| Pyrene | 0.069 | 0.10 |

NP Not Possible (no ambient concentrations available)
a: Upper Confidence Limit

## 4.4 Shipping lane

In Table 4.4 and Table 4.5 worst-case comparisons of $PEC_{add}$ with ambient concentrations are presented. In Appendix 6 more background information on ambient concentrations is provided, and also $PEC_{add}$ from Faber et al. (2021) are given.

Concentrations of EGCS washwater discharges contribute little to ambient concentrations. For mercury the highest contribution is found, with a predicted 95% UCL concentration of 0.14% of the average measured concentration. For PAH the highest contribution is indeno(1,2,3-c,d)pyrene with 0.1%. Note that some PAH could not be assessed as ambient concentrations were not available or when all measurements were below the limit of quantification.

*Table 4.4 Average and 95% UCL $PEC_{add}$ for metals in freshwater inside the harbour, given as percentage (%) of average ambient concentration.*

| **Compound** | **Inside the harbour** | |
|---|---|---|
| | Average | 95% UCL[a] |
| Arsenic | 0.000032 | 0.00024 |
| Cadmium | 0.0062 | 0.047 |
| Chromium | 0.011 | 0.087 |
| Copper | 0.010 | 0.077 |
| Lead | 0.00094 | 0.0071 |
| Mercury | 0.018 | 0.14 |
| Nickel | 0.0058 | 0.044 |
| Selenium | 0.0023 | 0.017 |
| Thallium | 0.0047 | 0.036 |
| Vanadium | 0.00054 | 0.0041 |
| Zinc | 0.011 | 0.086 |

a: Upper Confidence Limit

*Table 4.5 Average and 95% UCL $PEC_{add}$ for PAH in freshwater inside the harbour, given as percentage (%) of average ambient concentration.*

| **Compound** | **Inside the harbour** | |
|---|---|---|
| | Average | 95% UCL[a] |
| Acenaphthene | NP | |
| Acenaphthylene | NP | |
| Anthracene | NP | |
| Benzo(a)anthracene | NP | |
| Benzo(a)pyrene | NP | |
| Benzo(b)fluoranthene | 0.0025 | 0.019 |
| Benzo(g,h,i)perylene | 0.011 | 0.084 |
| Benzo(k)fluoranthene | 0.0015 | 0.011 |
| Chrysene | NP | |
| Dibenzo(a,h)anthracene | NP | |
| Fluoranthene | NP | |
| Fluorene | NP | |
| Indeno(1,2,3-c,d)pyrene | 0.013 | 0.10 |
| Naphthalene | NP | |
| Phenanthrene | 0.00095 | 0.0072 |
| Pyrene | NP | |

NP Not Possible (no ambient concentrations available)
a: Upper Confidence Limit

# 5 Discussion and conclusions

This study evaluates the potential risks of metals and PAH in washwater of exhaust gas cleaning systems (EGCS) on the aquatic environment of the Port of Amsterdam. It is a follow-up study of a previous study by RIVM focussing on marine environments (Faber et al., 2021). The results of the current study show that EGCS contribute in a limited way to concentrations of metals and PAH in surface water in and outside the Port of Amsterdam, both when compared to environmental quality standards (EQS) and ambient concentrations. Definitive conclusions for the sediment compartment cannot be drawn since EQS for freshwater sediment or ambient concentrations were not available. However, predicted environmental concentrations for the Port of Amsterdam are comparable with earlier results for the Port of Rotterdam. Since for the latter no risk was identified, it may be assumed that the same can be concluded for the present case.

One of the differences between both studies is the calculation of the discharged amounts of washwater. While in former report calculations were performed to estimate this parameter, in this study a precalculated value by Osipova et al. (2021) was used. As Osipova et al. (2021) used multiple shipping datasets to track each ship’s location and estimate ship-specific power consumption hour by hour for each ship, their calculated values are considered more accurate than the more generic calculations performed in Faber et al. (2021). Estimated washwater discharge for the Port of Rotterdam from Osipova et al. (2021) are lower than used by Faber et al. (2021), which suggests that the result from former report can be considered as a worst-case.

Another difference between the two studies is the fact that the Port of Amsterdam is considered a freshwater environment when assessing the chemical status. Different EQS were used than in the previous assessment of marine waters in the Port of Rotterdam and other environments. However, in line with the previous results no substantial increase in concentrations compared to EQS was demonstrated.

Some of the limitations in former report have not been resolved in this report. This includes uncertainty around concentrations of contaminants in washwaters and the metal distribution coefficients. Also, mixture toxicity, as well as acidification and local acute effects due to EGCS washwater discharges, were out of scope in this report.

A new limitation is that Dutch assessment methodologies for freshwater sediment are not suitable for a direct assessment of contaminant concentrations in sediment. Because the sediment compartment is an integral part of the aquatic system, it is assessed indirectly via the chemical surface water status. When surface water quality is sufficient, there are no incentives to assess sediment individually. In view of the limited availability of experimental ecotoxicity data on sediment organisms, using aquatic data is generally seen as the best or only option to derive risk limits for sediment. There is uncertainty, however, whether the sensitivity of freshwater organisms is sufficiently representative for sediment organisms. Moreover, food chain transfer to biota may differ between water and sediment. This means that there is uncertainty whether current methodologies are sufficiently protective. Still, the large margin of safety between predicted concentrations in freshwater sediment and available risk limits for marine sediment is an indication that EGCS emissions of metals and PAH are likely not leading to environmental risks.

The results of this study are in line with most of former studies on impact of EGCS discharges on water systems (see section 1.3). This study confirms the earlier conclusions on the impact of EGCS on Dutch waters. While from a risk perspective the impact of EGCS discharges on waters is limited, from a policy perspective the emissions may still be undesired. The emissions contribute to the presence of persistent and partly bioaccumulative compounds in ports and other coastal waters, and an increase in EGCS use of ships is foreseen based on forecasting data. It is important to keep track of developments on EGCS usage and verify, and if needed adjust, model calculations for reliable and relevant results on the impact of washwater discharges. Again, it should be noted that MAMPEC is a steady-state model with a simplified characterisation of ports and emissions, which implies that the estimates may not represent actual concentrations that arise due to EGCS washwater discharges. However, it is useful as a first indication for expected contamination.

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# Appendix 1 Design of MAMPEC environment Port of Amsterdam

Deltares

## Memo

| | |
|---|---|
| Date | 18 January 2024 |
| Our reference | 11208964-002-ZKS-0002 |
| Contact person | Frank Kleissen |
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| Subject | MAMPEC environment for Dutch harbours |

## A1.1 Introduction

his memo proposes a MAMPEC environment for characterizing a typical port, based on the Amsterdam harbour area. The default environment included in MAMPEC concerns a commercial harbour that is based on the Rotterdam harbour area (see also RIVM, 2021 and the MAMPEC technical manual (Deltares, 2016)). Because the Amsterdam harbour basins are connected to the North Sea Canal, a water body separated from the sea by a complex of sluices, the hydraulic conditions differ from those in Rotterdam where there is an open connection to the sea. The influence of tides and salinity gradients on the water exchange in the Amsterdam harbour basins is therefore smaller. This makes them potentially more sensitive to the accumulation of pollutant discharges.

It is noted that MAMPEC is not intended to represent any specific port, but provides a generic schematization of a certain type of ports (in this case larger ports with limited tidal influence).

## A1.2 Approach

Based on the experience from building the existing MAMPEC environment using the conditions in Rotterdam, the conditions in Amsterdam were examined. This concerned the port dimensions and the hydraulic boundary conditions. For Rotterdam, the hydraulic boundary conditions are determined by the characteristics of the Nieuwe Waterweg. In Amsterdam these are determined by the North Sea Canal.

To define a generic port environment, MAMPEC requires a “translation” of the harbour-specific data into a simplified representation. The hydraulic conditions in the North Sea Canal, such as the currents along the harbour entrance, are important for determining the water exchange between the port and its surroundings and therefore for determining the concentrations in the port as a result of pollutant discharges.

MAMPEC was designed as a simple tool for a first-tier risk assessment. This implies MAMPEC aims at providing simple worst-case estimates. This guiding principle was also used while setting up the Amsterdam port environment. Furthermore, MAMPEC also offers the possibility to conduct sensitivity studies. Therefore, the variability of conditions within the Amsterdam port was also characterized.

## A1.3 The default MAMPEC commercial harbour

The MAMPEC database includes a standard commercial harbour based on the port of Rotterdam with a geometry as in Figure A1.1.

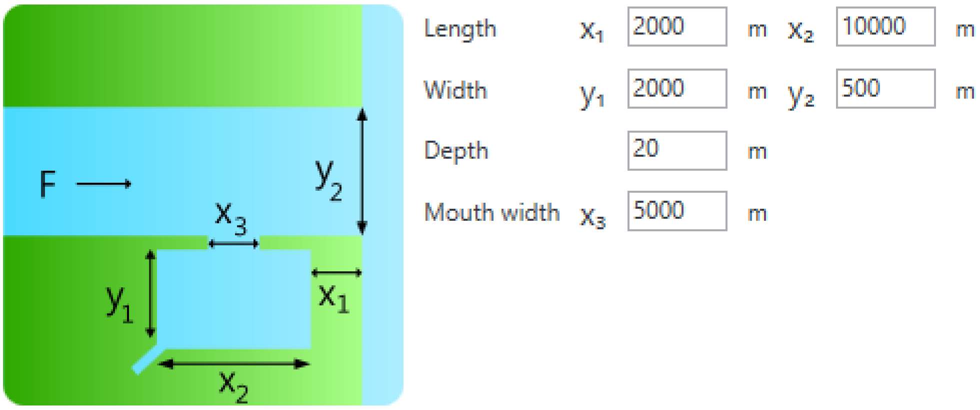


*Figure A1.1 The geometry of the default MAMPEC commercial harbour environment*

The schematization of the standard commercial harbour does not refer to any of the specific ports in the Rotterdam port area (Van Hattum and Baart, 2001), but provides a global picture of the largest 6 basins together:

- Maasvlakte (12.5 $km^2$)
- Eemhaven (1.5 $km^2$)
- 1st (0.5 $km^2$) and 2nd Petroleumhaven (0.5 $km^2$)
- Botlekhaven (3 $km^2$)
- Waalhaven (2.5 $km^2$).

The horizontal surface area of the standard port is 20 $km^2$ and the width of the port entrance is 5000m. This is approximately equal to the total width of the entrances to the 6 basins.

The total water exchange between the port and its surroundings consists of three parts:

a) One part driven by variations in the density of the passing water.
b) Another part driven by circulation patterns (eddies) caused by the current velocity gradients near the port entrance.
c) A final part depending on water level variations (including tides).

The default commercial harbour was designed to have a water renewal of 65% of the port volume per tidal period. The precise background of this number could not be traced. This total exchange is for 74% determined by the density exchange, supplemented by exchange due to eddies (14%) (in the MAMPEC interface this is called 'Horizontal') and tidal exchange (12%).

## A1.4 MAMPEC environment for the Amsterdam Port

### A1.4.1 *Information used*

The Amsterdam harbours are located on the North Sea Canal, where there is virtually no tide. Information to characterize the Amsterdam harbour area was derived from the so-called "immissietoets" (V1.10.4; https://immissietoets.nl/). This tool has been set up to assess whether a discharge into Dutch surface waters can be permitted given the water quality criteria. The port of Amsterdam is included in this tool. Part of the information for the Amsterdam harbour in the embedded database was derived from a numerical model of the North Sea Canal (Arcadis, 2014). Relevant information on the larger ports in the western part of Amsterdam is listed in Table A1.1.

*Table A1.1 Characteristics of Amsterdam harbour basins with a surface area exceeding 0.5 km2 (source: Immissietoets V1.10.4)*

| | Density variation ($kg/m^3$) | Water level variation (m) | Mean width (m) | Mean depth (m) | Water renewal time (d) | Surface area ($km^2$) |
|---|---|---|---|---|---|---|
| Mercuriushaven | 0.303 | 0.13 | 382 | 13.5 | 1.51 | 0.7 |
| Usselincxhaven | 0.296 | 0.13 | 288 | 11.5 | 0.39 | 0.6 |
| Westhaven | 0.264 | 0.12 | 385 | 12.7 | 3.73 | 1.9 |
| Amerikahaven | 0.350 | 0.28 | 500 | 15.8 | 3.51 | 2.2 |
| Afrikahaven | 0.247 | 0.14 | 610 | 15.8 | 1.46 | 0.7 |

A MAMPEC environment also needs some characteristics of the area "surrounding" the harbour basin. For the Amsterdam harbour, this is the North Sea Canal, separated from the sea by the ship locks at IJmuiden. The Immissietoets database defines the width of the North Sea Canal as approximately 300 m. The average flow velocity is approximately 3.5 cm/s, varying between 2 and 4.5 cm/s along the Canal.

### A1.4.2 *Renewal of water*

The standard commercial harbour (based on the ports of Rotterdam) was designed by choosing the dimensions, and in particular the width of the port entrance, to achieve a target renewal rate (van Hattum and Baart, 2001). We follow the same method here.

Like MAMPEC, the Immissietoets is also a first-tier assessment tool, and therefore uses a worst-case approach. The renewal times in Table A1.1 can therefore be expected to reflect worst-case conditions. The renewal times for the individual basins are between 0.4 and 3.7 days, with an area-weighted average (over all ports) of approximately 2.8 days. These 2.8 days can be considered to reflect a representative average situation in the port of Amsterdam. The highest and lowest occurring renewal times can be used to characterize the variation within the port. The value of 3.7 days can be used to represent extreme worst-case conditions.

Using the dimensions and characteristics listed in Section A1.4.1, MAMPEC calculates the renewal rate of the port (in % per day). This value can be converted to a renewal time:

$$\tau = V/Q$$

where $\tau$ is the renewal time (in days), V is the volume and Q is the exchange rate ($m^3/d$). The renewal rate of the port, expressed as a percentage of the port volume per day, is then equal to 1/τ*100%. This renewal rate, called exchange percentage in MAMPEC, is displayed in this way in the MAMPEC User Interface. The renewal rate reflecting a renewal time of 2.8 days is 36%, and for a renewal time of 3.7 days it is 27%.

A1.4.3 *Definition of the harbour environment*

The total surface area of the Amsterdam harbour basins > 0.5 $km^2$ amounts to 6.1 $km^2$ (Table A1.1). The length (X2 in MAMPEC) of the basins varies and is generally between about 1 and 3 km. The total width of the harbour entrances is approximately 1500m (measured from available maps). If it is assumed that the port has an average width (using the definition of MAMPEC: Y2) of 2 km (i.e. comparable to Rotterdam), this results in a length (X2) of approximately 3 km. The width of the North Sea Canal is approximately 300m. This sets the relevant dimensions for MAMPEC as follows (see Figure A1.1 for the definition of these dimensions):

X2 = 3000
X3 = 1500
Y1 = 2000
Y2 = 300

There is no reason to change the parameter X1 (2000m) as compared to the default commercial harbour. In MAMPEC, this dimension defines an area outside the port ('Surroundings') that is located downstream of the port but has no influence on the port itself. The proposed water depth of 15m is close to the surface average depth of the basins.

The hydraulic boundary conditions are directly derived from the conditions in the North Sea Canal:

| | | |
|---|---|---|
| Tidal period | 24 | hour |
| Tidal difference | 0.14 | m |
| Max. density difference tide | 0.3 | $kg/m^3$ |
| Non tidal daily water level change | 0 | m |
| Flow velocity (F) | 0.03 | m/s |

With the above dimensions and hydraulic boundary conditions, the renewal rate is 57%. An adjustment to the width of the port entrance is necessary to achieve the desired renewal rate of 36%. The optimal value for X3 was obtained by varying the width of the harbour mouth in steps of 100 m and checking the renewal rate. The value of X3 = 900 m was found to provide a renewal rate of approximately 34% per day. This value was adopted for the recommended definition of the MAMPEC environment (Figure A1.2).

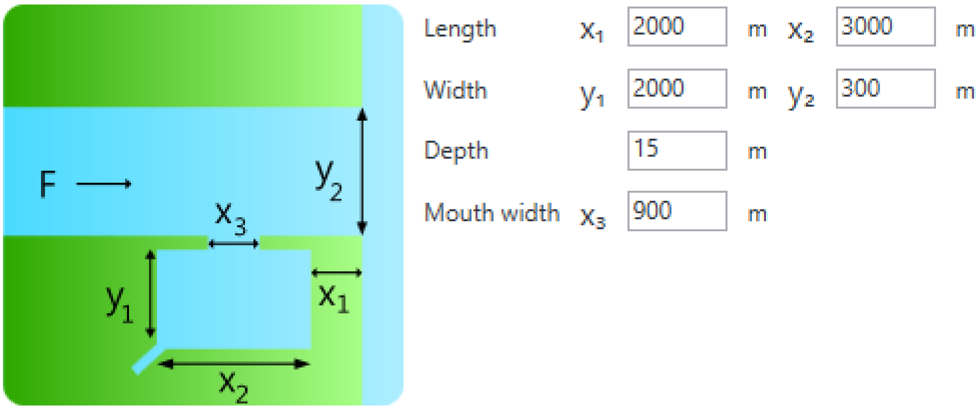


*Figure A1.2 The proposed geometry of the MAMPEC environment representing Amsterdam harbour conditions.*

For an extreme worst-case approach that aims for a renewal of 27%, a width of the port mouth of 700 m is required. This provides a renewal in MAMPEC of about 26%.

### A1.4.4 MAMPEC parameter sensitivity

A1.4.4.1 *Hydraulic boundary conditions*

Because MAMPEC represents harbour basins in a simplified manner, it is advised to use the option in MAMPEC to perform a parameter sensitivity analysis. This is especially important for density variation (between 0.25 and 0.35 kg/m$^3$) and water level variation (between 0.1 and 0.3 m), because the hydrodynamic conditions in the North Sea Canal are variable and dependent on the locks at IJmuiden. The density variation in particular produces the greatest exchange between the ports and the North Sea Canal. The current speed is less important because it is quite low in the North Sea Canal.

A1.4.4.2 *Variability within the harbour area*

MAMPEC calculations provide concentrations in the port, without spatial patterns. An impression of the spatial patterns can be obtained by considering not just the average concentrations, but also the median, minimum and maximum concentrations. For the port as a whole, this gives an impression of the spatial variability within the port. The highest concentrations will be around the discharge point. Whether a MAC standard (acute toxicity) is exceeded cannot be said with certainty, even though the maximum concentration calculated by MAMPEC remains below the standard. This is mainly due to the schematization of the underlying model. To determine whether such an acute standard is being exceeded (at a relatively small distance), plume calculations (which, for example, are included in the "immissietoets") will have to be used. This allows concentrations to be estimated at a small distance from the discharge point. For individual scrubber systems, possible recirculation within the port must also be taken into account. MAMPEC was not developed for this purpose. It is therefore outside the scope of the current analysis.

## A1.5 Conclusion

Based on available data from the North Sea Canal derived from the "Immissietoets" database, a proposal has been formulated for the use of MAMPEC for discharges in the Amsterdam port area. To arrive at this proposal, the same methodology was used as when the default commercial harbour was derived based on the characteristics of the Rotterdam port area. It is recommended to apply MAMPEC for both average conditions in the port (harbour entrance 900m, renewal time 2.8 days) and for adverse conditions (harbour entrance 700m, renewal time 3.7 days). It is also recommended to include a sensitivity assessment for, in particular, density differences and water level variations.

## A1.6 Cited literature

Arcadis (2014) Vullen database webapplicatie immissietoets havens, rapport 077683379:0.1 (C03041.002949.0100) van 28 april 2014, Arcadis Nederland BV

Deltares (2016) MAMPEC 3.1 HANDBOOK, Technical Documentation, (https://cms.deltares.nl/assets/common/downloads/MAMPEC-Handbook-3.1.0.2-October-2016-1-1.pdf)

RIVM (2021) Environmental risks of scrubber discharges for seawater and sediment - Preliminary risk assessment for metals and polycyclic aromatic hydrocarbons RIVM letter report 2021-0048, Authors: M. Faber | W. Peijnenburg | C.E. Smit

Van Hattum, B and A. Baart. (2001). TBT - a compound currently in the lime light. In : J. Gandrass and W. Salomons (Eds.). Dredged Material in the Port of Rotterdam – Interface between Rhine Catchment Area and North Sea. GKSS Research Centre, Geesthacht (Germany), p.277-288.

# Appendix 2 Selection input MAMPEC environment Port of Amsterdam

In this appendix choices for three input parameters for the MAMPEC environment Port of Amsterdam are discussed. These are parameters for which Deltares has recommended multiple values (daily renewal rate) or for which it was advised to perform a sensitivity analysis (tidal difference and max. density difference tide). For more information on the recommendations of Deltares, see Appendix 1.

*Daily renewal rate*

Two relevant average renewal times were defined by Deltares; an average of 2.8 days and a worst-case of 3.7 days. These renewal times are equal to daily renewal rates of 0.357 $d^{-1}$ and 0.285 $d^{-1}$. Five different ports were assessed by Deltares to define these values. During this study, it was, however, noted that the most relevant port – the IJ-haven - was not considered in defining the daily renewal rates. This harbour is most relevant as all EGCS emissions can be attributed to cruise ships (see section 2.3.1) and all moor at one dock only in Amsterdam (Passenger Terminal Amsterdam, see Figure A2.1). Therefore daily renewal rates for different areas of the IJ-haven and adjacent river IJ (see Figure A2.1) were additionally collected from the immissietoets tool[11] (see Table A2.1). The expected relevant renewal times (<0.4 days) are more than seven times faster than the average value of 2.8 days. A sensitivity analysis was performed with the metal arsenic and PAH benzo(a)anthracene to determine the influence of the daily renewal rate on the concentrations in water and sediment. The results show that adjusting the renewal time from 2.8 days to 0.33 days (daily renewal rate of 3 $d^{-1}$) decreases the estimated concentrations in water and sediment to 34-43% of the default scenario (see Tables A2.2 to A2.5). In other words, applying the advised renewal time of 2.8 days overestimates the PEC by a factor of more than 2.

While it would have been more sensible to use the faster renewal time of < 0.4 days, the advised value of 2.8 days was used as input parameter in MAMPEC. In this way the potential doubling in washwater discharges (see section 2.3.1) was considered taken into account.

*Table A2.1 Different locations in the Port of Amsterdam with their renewal rate. The locations are shown in Figure A2.1.*

| Location | Area | Daily renewal rate ($d^{-1}$) | Renewal time (d) |
|---|---|---|---|
| 1 | IJ | 5.5 | 0.18 |
| 2 | IJ | 6.6 | 0.15 |
| 3 | IJ | 8.3 | 0.12 |
| 4 | IJ | 2.8 | 0.36 |
| 5 | IJ-haven | 4.0 | 0.25 |
| 6 | IJ-haven | 2.7 | 0.37 |

[11] Immissietoets v1.12.0 https://www.immissietoets.nl/berekening/immissietoets

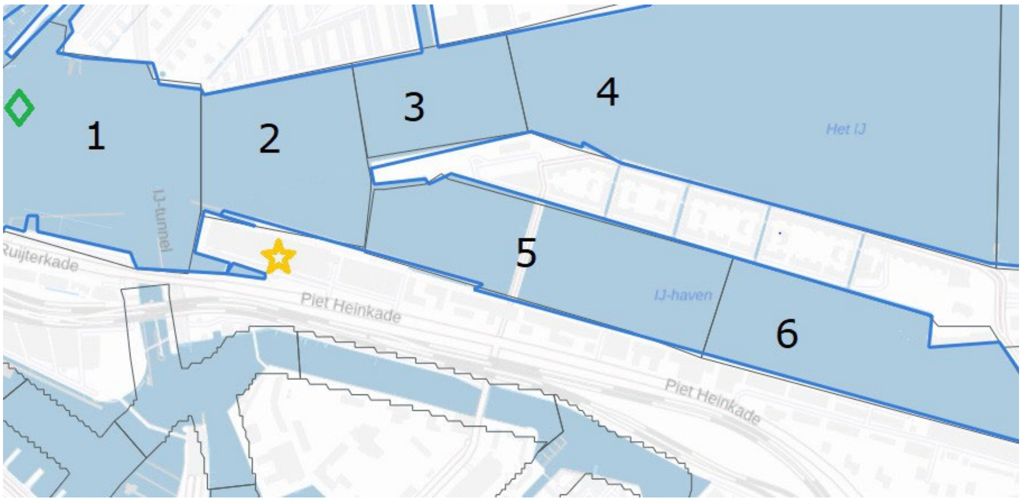


*Figure A2.1 Location of Passenger Terminal Amsterdam (orange star), next to the harbour 'IJ-haven' en river 'IJ', and location 'NL80_AMSDM' (green diamonds) for which data on concentrations PAH and metals is available (see further section 3.3). The numbers indicate different aquatic areas defined by the immissietoets[11].*

*Tidal difference*

A sensitivity analysis was performed for the parameter 'tidal difference'. Calculations were performed with values of 0.10, 0.14 (default) and 0.30 m, for both the metal arsenic as PAH benzo(a)anthracene. The results show that for each individual parameter the modelled concentrations in water and sediment increase/decrease with around 10% compared to the default value (see Tables A2.2 to Table A2.5). As the effect of the parameter on modelled concentrations is relatively low, only the default value of 0.14 m was used as input for MAMPEC.

*Max density difference tide*

A sensitivity analysis was performed for the parameter 'Max. density difference tide'. Calculations were performed with values of 0.25, 0.30 (default) and 0.35 kg $m^{-3}$, for both the metal arsenic and PAH benzo(a)anthracene. The results show that for each individual parameter the modelled concentrations in water and sediment increase/decrease with around 10% compared to the default value (see Tables A2.2 to Table A2.5). As the effect of the parameter on modelled concentrations is relatively low, only the default value of 0.30 kg $m^{-3}$ was used as input for MAMPEC.

*Table A2.2 Sensitivity analysis modelling arsenic with different parameters for the designed Port of Amsterdam environment. Average modelled concentrations for arsenic are given in the table.*

| Scenario | Compound | Load (g $d^{-1}$) | Renewal time (d) | Tidal difference (m) | Max. density difference tide (kg $m^{-3}$) | Freely dissolved concentration (µg $L^{-1}$) | % of default scenario | Sediment concentration after 20 years (mg $kg^{-1}$ dw) | % of default scenario |
|---|---|---|---|---|---|---|---|---|---|
| Default | Arsenic | 0.106 | 2.8 | 0.14 | 0.3 | 9.08E-06 | 100 | 5.24E-05 | 100 |
| Faster refreshment | Arsenic | 0.106 | 0.33 | 0.14 | 0.3 | 3.87E-06 | 43 | 2.23E-05 | 43 |
| Higher tidal difference | Arsenic | 0.106 | 2.8 | 0.3 | 0.3 | 8.82E-06 | 97 | 5.09E-05 | 97 |
| Lower tidal difference | Arsenic | 0.106 | 2.8 | 0.1 | 0.3 | 9.13E-06 | 101 | 5.27E-05 | 101 |
| Lower max. density difference tide | Arsenic | 0.106 | 3.1[a] | 0.14 | 0.25 | 1.00E-05 | 110 | 5.77E-05 | 110 |
| Higher max. density difference tide | Arsenic | 0.106 | 2.6[a] | 0.14 | 0.35 | 8.39E-06 | 92 | 4.84E-05 | 92 |

a: the renewal time changed due to the adjustment of the parameter 'max. density difference tide'.

*Table A2.3 Sensitivity analysis modelling arsenic with different parameters for the designed Port of Amsterdam environment. 95% modelled concentrations for arsenic are given in the table.*

| Scenario | Compound | Load (g $d^{-1}$) | Renewal time (d) | Tidal difference (m) | Max. density difference tide (kg $m^{-3}$) | Freely dissolved concentration (µg $L^{-1}$) | % of default scenario | Sediment concentration after 20 years (mg $kg^{-1}$ dw) | % of default scenario |
|---|---|---|---|---|---|---|---|---|---|
| Default | Arsenic | 0.106 | 2.8 | 0.14 | 0.3 | 1.48E-05 | 100 | 8.55E-05 | 100 |
| Faster refreshment | Arsenic | 0.106 | 0.33 | 0.14 | 0.3 | 5.03E-06 | 34 | 2.90E-05 | 34 |
| Higher tidal difference | Arsenic | 0.106 | 2.8 | 0.3 | 0.3 | 1.43E-05 | 96 | 8.25E-05 | 96 |
| Lower tidal difference | Arsenic | 0.106 | 2.8 | 0.1 | 0.3 | 1.49E-05 | 101 | 8.61E-05 | 101 |
| Lower max. density difference tide | Arsenic | 0.106 | 3.1[a] | 0.14 | 0.25 | 1.67E-05 | 113 | 9.63E-05 | 113 |
| Higher max. density difference tide | Arsenic | 0.106 | 2.6[a] | 0.14 | 0.35 | 1.34E-05 | 91 | 7.74E-05 | 91 |

a: the renewal time changed due to the adjustment of the parameter 'max. density difference tide'.

*Table A2.4 Sensitivity analysis modelling arsenic with different parameters for the designed Port of Amsterdam environment. Average modelled concentrations for benzo(a)anthracene are given in the table.*

| Scenario | Compound | Load (g $d^{-1}$) | Renewal time (d) | Tidal difference (m) | Max. density difference tide (kg $m^{-3}$) | Total concentration (µg $L^{-1}$) | % of default scenario | Sediment concentration after 20 years (mg $kg^{-1}$ dw) | % of default scenario |
|---|---|---|---|---|---|---|---|---|---|
| Default | Benzo(a)anthracene | 0.106 | 2.8 | 0.14 | 0.3 | 2.99E-05 | 100 | 8.86E-05 | 100 |
| Faster refreshment | Benzo(a)anthracene | 0.106 | 0.33 | 0.14 | 0.3 | 1.26E-05 | 42 | 3.73E-05 | 42 |
| Higher tidal difference | Benzo(a)anthracene | 0.106 | 2.8 | 0.3 | 0.3 | 2.90E-05 | 97 | 8.60E-05 | 97 |
| Lower tidal difference | Benzo(a)anthracene | 0.106 | 2.8 | 0.1 | 0.3 | 3.00E-05 | 101 | 8.90E-05 | 101 |
| Lower max. density difference tide | Benzo(a)anthracene | 0.106 | 3.1[a] | 0.14 | 0.25 | 3.30E-05 | 110 | 9.77E-05 | 110 |
| Higher max. density difference tide | Benzo(a)anthracene | 0.106 | 2.6[a] | 0.14 | 0.35 | 2.75E-05 | 92 | 8.17E-05 | 92 |

a: the renewal time changed due to the adjustment of the parameter 'max. density difference tide'.

*Table A2.5 Sensitivity analysis modelling arsenic with different parameters for the designed Port of Amsterdam environment. 95% modelled concentrations for benzo(a)anthracene are given in the table.*

| Scenario | Compound | Load (g $d^{-1}$) | Renewal time (d) | Tidal difference (m) | Max. density difference tide (kg $m^{-3}$) | Total concentration (µg $L^{-1}$) | % of default scenario | Sediment concentration after 20 years (mg $kg^{-1}$ dw) | % of default scenario |
|---|---|---|---|---|---|---|---|---|---|
| Default | Benzo(a)anthracene | 0.106 | 2.8 | 0.14 | 0.3 | 4.85E-05 | 100 | 1.44E-04 | 100 |
| Faster refreshment | Benzo(a)anthracene | 0.106 | 0.33 | 0.14 | 0.3 | 1.64E-05 | 34 | 4.86E-05 | 34 |
| Higher tidal difference | Benzo(a)anthracene | 0.106 | 2.8 | 0.3 | 0.3 | 4.68E-05 | 96 | 1.39E-04 | 96 |
| Lower tidal difference | Benzo(a)anthracene | 0.106 | 2.8 | 0.1 | 0.3 | 4.89E-05 | 101 | 1.45E-04 | 101 |
| Lower max. density difference tide | Benzo(a)anthracene | 0.106 | 3.1[a] | 0.14 | 0.25 | 5.48E-05 | 113 | 1.62E-04 | 113 |
| Higher max. density difference tide | Benzo(a)anthracene | 0.106 | 2.6[a] | 0.14 | 0.35 | 4.39E-05 | 90 | 1.30E-04 | 90 |

a: the renewal time changed due to the adjustment of the parameter 'max. density difference tide'.

# Appendix 3 $PEC_{add}$ Port of Amsterdam

*Table A3.1 Predicted increase in dissolved concentrations ($PEC_{add}$) of metals inside the harbour of the Port of Amsterdam. All values in μg $L^{-1}$, representing the freely dissolved and DOC-bound fraction.*

| **Compound** | **$PEC_{add}$ Inside the harbour** | | **$PEC_{add}$ Surrounding environment** | |
|---|---|---|---|---|
| | Average | 95% UCL[a] | Average | 95% UCL[a] |
| Arsenic | 4.86E-04 | 7.94E-04 | 1.29E-04 | 2.33E-04 |
| Cadmium | 3.79E-05 | 6.50E-05 | 9.28E-06 | 1.67E-05 |
| Chromium | 2.40E-04 | 4.16E-04 | 5.82E-05 | 1.05E-04 |
| Copper | 7.12E-03 | 1.21E-02 | 1.77E-03 | 3.19E-03 |
| Lead | 7.36E-07 | 1.29E-06 | 1.75E-07 | 3.14E-07 |
| Mercury | 8.80E-07 | 1.53E-06 | 2.11E-07 | 3.80E-07 |
| Nickel | 5.45E-03 | 9.11E-03 | 1.39E-03 | 2.51E-03 |
| Selenium | 9.51E-04 | 1.56E-03 | 2.50E-04 | 4.52E-04 |
| Thallium | 3.40E-04 | 5.61E-04 | 8.91E-05 | 1.61E-04 |
| Vanadium | 1.21E-02 | 1.96E-02 | 3.24E-03 | 5.86E-03 |
| Zinc | 5.22E-03 | 9.01E-03 | 1.27E-03 | 2.29E-03 |

a: Upper Confidence Limit

*Table A3.2 Predicted increase in concentrations ($PEC_{add}$) for PAH for the Port of Amsterdam. All values in μg $L^{-1}$, expressed as total concentrations.*

| **Compound** | **$PEC_{add}$ Inside the harbour** | | **$PEC_{add}$ Surrounding environment** | |
|---|---|---|---|---|
| | Average | 95% UCL[a] | Average | 95% UCL[a] |
| Acenaphthene | 1.15E-05 | 2.09E-05 | 2.55E-06 | 4.59E-06 |
| Acenaphthylene | 1.01E-05 | 1.69E-05 | 2.58E-06 | 4.66E-06 |
| Anthracene | 1.57E-04 | 2.62E-04 | 4.04E-05 | 7.29E-05 |
| Benzo(a)anthracene | 2.99E-05 | 4.85E-05 | 7.98E-06 | 1.44E-05 |
| Benzo(a)pyrene | 3.83E-06 | 6.32E-06 | 9.97E-07 | 1.80E-06 |
| Benzo(b)fluoranthene | 4.36E-06 | 7.21E-06 | 1.14E-06 | 2.05E-06 |
| Benzo(g,h,i)perylene | 3.83E-06 | 6.47E-06 | 9.66E-07 | 1.74E-06 |
| Benzo(k)fluoranthene | 9.10E-07 | 1.50E-06 | 2.37E-07 | 4.28E-07 |
| Chrysene | 2.49E-05 | 4.05E-05 | 6.65E-06 | 1.20E-05 |
| Dibenzo(a,h)anthracene | 1.55E-06 | 2.62E-06 | 3.92E-07 | 7.07E-07 |
| Fluoranthene | 2.16E-05 | 3.49E-05 | 5.83E-06 | 1.05E-05 |
| Fluorene | 3.80E-05 | 6.69E-05 | 8.92E-06 | 1.60E-05 |
| Indeno(1,2,3-c,d)pyrene | 4.00E-06 | 6.75E-06 | 1.01E-06 | 1.82E-06 |
| Naphthalene | 1.68E-04 | 3.21E-04 | 3.43E-05 | 6.18E-05 |
| Phenanthrene | 1.74E-04 | 2.89E-04 | 4.47E-05 | 8.06E-05 |
| Pyrene | 3.71E-05 | 5.99E-05 | 1.00E-05 | 1.81E-05 |

a: Upper Confidence Limit

# Appendix 4 $PEC_{add}$ sediment comparisons

*Table A4.1 Predicted increase in sediment concentrations ($PEC_{add}$) of metals inside the harbour of the Port of Amsterdam and Port of Rotterdam after 20 years of EGCS washwater discharges. All values in mg kg $dwt^{-1}$.*

| Compound | Port of Amsterdam | | Port of Rotterdam[a] | |
|---|---|---|---|---|
| | Average | 95% UCL[b] | Average | 95% UCL[b] |
| Arsenic | 2.81E-03 | 4.58E-03 | 8.33E-04 | 1.22E-03 |
| Cadmium | 2.16E-03 | 3.71E-03 | 8.05E-04 | 1.17E-03 |
| Chromium | 2.18E-02 | 3.78E-02 | 8.41E-03 | 1.22E-02 |
| Copper | 2.57E-01 | 4.37E-01 | 9.22E-02 | 1.34E-01 |
| Lead | 2.66E-04 | 4.66E-04 | 1.07E-04 | 1.56E-04 |
| Mercury | 1.27E-04 | 2.21E-04 | 5.23E-05 | 7.61E-05 |
| Nickel | 9.82E-02 | 1.64E-01 | 3.28E-02 | 4.78E-02 |
| Selenium | 8.93E-03 | 1.48E-02 | 2.86E-03 | 4.18E-03 |
| Thallium | 3.09E-03 | 5.09E-03 | 9.59E-04 | 1.40E-03 |
| Vanadium | 4.36E-02 | 7.06E-02 | 1.25E-02 | 1.82E-02 |
| Zinc | 3.77E-01 | 6.50E-01 | 1.43E-01 | 2.08E-01 |

a: $PEC_{add}$ for the standard scenario, based on the average number of vessels with an EGCS estimated in 2019 (for further information on the scenario, see Faber et al. (2021)).
b: Upper Confidence Limit

*Table A4.2 Predicted increase in sediment concentrations ($PEC_{add}$) of PAH inside the harbour of the Port of Amsterdam and Port of Rotterdam after 20 years of EGCS washwater discharges. All values in mg/kg $dwt^{-1}$.*

| Compound | Port of Amsterdam | | Port of Rotterdam[a] | |
|---|---|---|---|---|
| | Average | 95% UCL[b] | Average | 95% UCL[b] |
| Acenaphthene | 1.18E-06 | 2.15E-06 | 5.52E-07 | 8.02E-07 |
| Acenaphthylene | 1.04E-06 | 1.74E-06 | 3.50E-07 | 5.10E-07 |
| Anthracene | 5.18E-05 | 8.64E-05 | 1.69E-05 | 2.47E-05 |
| Benzo(a)anthracene | 8.86E-05 | 1.44E-04 | 2.57E-05 | 3.75E-05 |
| Benzo(a)pyrene | 2.63E-05 | 4.34E-05 | 8.23E-06 | 1.20E-05 |
| Benzo(b)fluoranthene | 3.03E-05 | 5.01E-05 | 9.46E-06 | 1.38E-05 |
| Benzo(g,h,i)perylene | 4.36E-05 | 7.35E-05 | 1.50E-05 | 2.18E-05 |
| Benzo(k)fluoranthene | 6.25E-06 | 1.03E-05 | 2.06E-06 | 3.00E-06 |
| Chrysene | 7.49E-05 | 1.22E-04 | 2.18E-05 | 3.18E-05 |
| Dibenzo(a,h)anthracene | 1.76E-05 | 2.96E-05 | 6.08E-06 | 8.86E-06 |
| Fluoranthene | 2.31E-05 | 3.72E-05 | 6.51E-06 | 9.50E-06 |
| Fluorene | 7.08E-06 | 1.25E-05 | 2.92E-06 | 4.25E-06 |
| Indeno(1,2,3-c,d)pyrene | 4.54E-05 | 7.67E-05 | 1.59E-05 | 2.32E-05 |
| Naphthalene | 5.35E-06 | 1.02E-05 | 2.89E-06 | 4.19E-06 |
| Phenanthrene | 5.84E-05 | 9.73E-05 | 1.92E-05 | 2.80E-05 |
| Pyrene | 3.89E-05 | 6.28E-05 | 1.10E-05 | 1.60E-05 |

a: $PEC_{add}$ for the standard scenario, based on the average number of vessels with an EGCS estimated in 2019 (for further information on the scenario, see Faber et al. (2021)).
b: Upper Confidence Limit

# Appendix 5 Ambient concentrations and $PEC_{add}$ Port of Rotterdam

To collect data on current concentrations of metals and PAH the Waterkwaliteitsportaal[12] was scrutinized. Waterkwaliteitsportaal is a website where information on Dutch water quality is collated. For the Port of Rotterdam three locations were at first considered relevant for assessing ambient concentrations. These were, from left to right in Figure A5.1 'NL80_BEERKNMDN' (Beerkanaal midden), 'NL80_MAASSS' (Maassluis) and 'NL80_BRIENOD' (Brienenoord (kilometer 996)). At all locations PAH and metals were measured in 2022. For 'NL80_BEERKNMDN' the least number of measurements were available, therefore this location was not selected. It should be noted that for that location also the lowest concentrations were found, potentially due to dilution with seawater. The choice in data was based on the exact locations where data was gathered. Location 'NL80_MAASSS' is not located in the river Meuse but in a tributary coming from a residential area. Location 'NL80_BRIENOD' is in the river Meuse, however further upstream than most of the ports in Rotterdam. The latter was considered more relevant due to potential pollution coming from upstream activities, in addition it was noted that concentrations of metals and PAH seemed higher. In Table A5.1 and Table A5.2 the ambient concentrations for metals and PAH at location 'NL80_BRIENOD' are given, and also $PEC_{add}$ from Faber et al. (2021).


*Figure A5.1 Three locations (blue squares) near the Port of Rotterdam which were considered as data source for the background concentrations. From left to right: 'NL80_BEERKNMDN' (Beerkanaal midden), 'NL80_MAASSS' (Maassluis) and 'NL80_BRIENOD' (Brienenoord (kilometer 996)).*

*Table A5.1 $PEC_{add}$ (predicted) and ambient (measured) concentrations of dissolved metals in water for the Port of Rotterdam. All values in μg $L^{-1}$.*

| Compound | $PEC_{add}$[a] | | Ambient concentrations | |
|---|---|---|---|---|
| | Average | 95% UCL[b] | Average | Maximum |
| Arsenic | 1.44E-04 | 2.11E-04 | 1.21E+00 | 1.95E+00 |
| Cadmium | 1.41E-05 | 2.06E-05 | 1.83E-02 | 5.97E-02 |
| Chromium | 9.26E-05 | 1.35E-04 | 2.24E-01 | 3.55E-01 |
| Copper | 2.56E-03 | 3.73E-03 | 2.24E+00 | 6.20E+00 |
| Lead | 2.97E-07 | 4.33E-07 | 3.08E-02 | 5.36E-02 |
| Mercury | 3.62E-07 | 5.28E-07 | 5.17E-04 | 9.10E-04 |

[12] https://www.waterkwaliteitsportaal.nl/oppervlaktewaterkwaliteit. Last visited on 04-10-2023

| Compound | PECadd[a] | | Ambient concentrations | |
|---|---|---|---|---|
| Nickel | 1.82E-03 | 2.65E-03 | 1.06E+00 | 1.58E+00 |
| Selenium | 2.91E-04 | 4.25E-04 | 1.91E-01 | 2.29E-01 |
| Thallium | 1.06E-04 | 1.54E-04 | 1.39E-02 | 2.83E-02 |
| Vanadium | 3.45E-03 | 5.04E-03 | 9.15E-01 | 1.35E+00 |
| Zinc | 1.98E-03 | 2.89E-03 | 4.28E+00 | 1.57E+01 |

a: $PEC_{add}$ for the standard scenario, based on the average number of vessels with an EGCS estimated in 2019 (for further information on the scenario, see Faber et al. (2021)).
b: Upper Confidence Limit

*Table A5.2 $PEC_{add}$ (predicted) and ambient (measured) concentrations of total PAH in water for the Port of Rotterdam. All values in μg $L^{-1}$.*

| Compound | PECadd[a] | | Ambient concentrations | |
|---|---|---|---|---|
| | Average | 95% UCL[b] | Average | Maximum |
| Acenaphthene | 5.37E-06 | 7.80E-06 | NA | |
| Acenaphthylene | 3.40E-06 | 4.96E-06 | NA | |
| Anthracene | 5.12E-05 | 7.47E-05 | 3.31E-03 | 7.99E-03 |
| Benzo(a)anthracene | 8.67E-06 | 1.27E-05 | 6.79E-03 | 2.54E-02 |
| Benzo(a)pyrene | 1.20E-06 | 1.75E-06 | 5.75E-03 | 2.02E-02 |
| Benzo(b)fluoranthene | 1.36E-06 | 1.99E-06 | 1.10E-02 | 3.05E-02 |
| Benzo(g,h,i)perylene | 1.32E-06 | 1.92E-06 | 5.22E-03 | 1.34E-02 |
| Benzo(k)fluoranthene | 3.00E-07 | 4.37E-07 | 3.89E-03 | 1.23E-02 |
| Chrysene | 7.24E-06 | 1.06E-05 | 6.83E-03 | 2.41E-02 |
| Dibenzo(a,h)anthracene | 5.38E-07 | 7.84E-07 | 1.33E-03 | 3.93E-03 |
| Fluoranthene | 6.10E-06 | 8.91E-06 | 1.94E-02 | 5.31E-02 |
| Fluorene | 1.57E-05 | 2.28E-05 | NA | |
| Indeno(1,2,3-c,d)pyrene | 1.40E-06 | 2.04E-06 | 5.19E-03 | 1.48E-02 |
| Naphthalene | 9.10E-05 | 1.32E-04 | 2.17E-02 | 3.00E-02 |
| Phenanthrene | 5.70E-05 | 8.31E-05 | 1.10E-02 | 2.47E-02 |
| Pyrene | 1.05E-05 | 1.53E-05 | 1.52E-02 | 4.60E-02 |

NA Not Available (not analysed)
a: $PEC_{add}$ for the standard scenario, based on the average number of vessels with an EGCS estimated in 2019 (for further information on the scenario, see Faber et al. (2021)).
b: Upper Confidence Limit

# Appendix 6 Ambient concentrations and $PEC_{add}$ Shipping Lane

To collect data on current concentrations of metals and PAH the Waterkwaliteitsportaal[13] was scrutinized. Waterkwaliteitsportaal is a website where information on Dutch water quality is collated. For the shipping lane, the concentrations at location 'NOORDWK20' were first gathered. This is a location 20 kilometre away from the Dutch shoreline. According to van Duin et al. (2007), the North Sea just outside the 12-mile (~20 kilometre) zone is heavily sailed by ships. It appeared, however, that in 2022 no data on metals and PAH was collected on this location. Therefore, data was gathered for location 'NOORDWK10', 10 kilometres from the shoreline. In Table A6.1 and Table A6.2 the ambient concentrations for metals and PAH at location 'NoordWK10' are given, and also $PEC_{add}$ from Faber et al. (2021).

*Table A6.1 $PEC_{add}$ (predicted) and ambient (measured) concentrations of dissolved metals in water for the shipping lane. All values in µg $L^{-1}$.*

| **Compound** | **$PEC_{add}$** | | **Ambient concentrations** | |
|---|---|---|---|---|
| | Average | 95% UCL[a] | Average | Maximum |
| Arsenic | 4.52E-07 | 3.45E-06 | 1.42E+00 | 2.15E+00 |
| Cadmium | 9.89E-07 | 7.54E-06 | 1.59E-02 | 2.29E-02 |
| Chromium | 1.28E-05 | 9.74E-05 | 1.13E-01 | 1.96E-01 |
| Copper | 9.19E-05 | 7.00E-04 | 9.09E-01 | 1.61E+00 |
| Lead | 2.63E-07 | 2.00E-06 | 2.81E-02 | 6.84E-02 |
| Mercury | 9.19E-08 | 7.00E-07 | 5.02E-04 | 1.03E-03 |
| Nickel | 2.45E-05 | 1.87E-04 | 4.24E-01 | 5.94E-01 |
| Selenium | 1.96E-06 | 1.49E-05 | 8.65E-02 | 1.17E-01 |
| Thallium | 5.77E-07 | 4.40E-06 | 1.24E-02 | 1.51E-02 |
| Vanadium | 6.27E-06 | 4.78E-05 | 1.16E+00 | 1.51E+00 |
| Zinc | 1.96E-04 | 1.49E-03 | 1.72E+00 | 2.72E+00 |

a: $PEC_{add}$ for the standard scenario, based on the average number of vessels with an EGCS estimated in 2019 (for further information on the scenario, see Faber et al. (2021)).
b: Upper Confidence Limit

*Table A6.2 $PEC_{add}$ (predicted) and ambient (measured) concentrations of total PAH in water for the shipping lane. All values in µg $L^{-1}$.*

| **Compound** | **$PEC_{add}$*** | | **Ambient concentrations** | |
|---|---|---|---|---|
| | Average | 95% UCL[a] | Average | Maximum |
| Acenaphthene | 5.50E-10 | 4.19E-09 | NA | |
| Acenaphthylene | 3.34E-10 | 2.54E-09 | NA | |
| Anthracene | 1.61E-08 | 1.23E-07 | NF[b] | |
| Benzo(a)anthracene | 2.77E-08 | 2.11E-07 | NF[c] | |
| Benzo(a)pyrene | 1.14E-08 | 8.66E-08 | NF[d] | |
| Benzo(b)fluoranthene | 1.35E-08 | 1.03E-07 | 5.35E-04 | 1.28E-03 |
| Benzo(g,h,i)perylene | 3.04E-08 | 2.32E-07 | 2.76E-04 | 6.69E-04 |
| Benzo(k)fluoranthene | 2.52E-09 | 1.92E-08 | 1.72E-04 | 4.02E-04 |
| Chrysene | 2.34E-08 | 1.78E-07 | NF[e] | |
| Dibenzo(a,h)anthracene | 1.20E-08 | 9.16E-08 | NF[f] | |

[12] https://www.waterkwaliteitsportaal.nl/oppervlaktewaterkwaliteit. Last visited on 04-10-2023

| Compound | $PEC_{add}$* | | Ambient concentrations | |
|---|---|---|---|---|
| Fluoranthene | 6.29E-09 | 4.79E-08 | NF[g] | 4.00E-03 |
| Fluorene | 2.86E-09 | 2.18E-08 | NA | |
| Indeno(1,2,3-c,d)pyrene | 3.19E-08 | 2.44E-07 | 2.41E-04 | 6.13E-04 |
| Naphthalene | 2.95E-09 | 2.25E-08 | NF[h] | |
| Phenanthrene | 1.83E-08 | 1.39E-07 | 1.94E-03 | 4.00E-03 |
| Pyrene | 1.06E-08 | 8.10E-08 | NF[f] | |

NA Not Available (not analysed)
NF Not Found (all measurements are below the Limit of Quantification)
* $PEC_{add}$ for the standard scenario, based on the average number of vessels with an EGCS estimated in 2019 (for further information on the scenario, see Faber et al. (2021)).
a: Upper Confidence Limit
b: LOQ of 0.003/0.004 µg/L
c: LOQ of 0.001/0.003 µg/L
d: LOQ of 0.002 µg/L
e: LOQ of 0.002/0.004 µg/L
f: LOQ of 0.002/0.003 µg/L
g: only one out of eleven measurements above Limit of Quantification, therefore no average value is reported.
h: LOQ of 0.02/0.03 µg/L

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