# The effect of scrubber water from cruise ships in the ports of Stockholm

Bachelor thesis for Marine Engineering Program

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DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
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# PREFACE

This report is a bachelor thesis in marine engineering at Chalmers University of Technology written by Anton Bolin and Oscar Ekström. The marine engineering program is a four-year program with three years of studies and one year internship. The topic of the thesis is the environmental effect of scrubbers in the port of Stockholm and that was a combined idea from us as students and our supervisor Anna Lunde Hermansson. We would like to deeply thank our supervisor Anna Lunde Hermansson for lots of both feedback and support during the whole process. We would also like to thank our examiner Kent Salo for feedback along the progression of our work.

**The effect of scrubber water from cruise ships in the ports of Stockholm**

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# SAMMANDRAG (in Swedish)

Skrubbrar används ombord fartyg för att rengöra avgaser från svavel, för att på så sätt kunna undgå gränserna på svavelhalt i bränslet. Detta eftersom det tillåter fartygen att använda billigare bränslen som annars inte hade uppnått standarden i dagens regelverk kring svavelutsläpp. Problematiken med skrubbrar är att de istället förflyttar utsläppen från luften till havet. I denna rapport gjordes modeller av två hamnar i mjukvaran MAMPEC (Marine Antifoulant Model for Predicted Enviromental Concentration). Koncentrationerna av ett urval av metaller och polycykliska aromatiska kolväten i utloppsvattnet användes med hjälp av MAMPEC för att beräkna koncentrationerna av ämnena i vattnet för de specifika hamnarna. Resultatet visar på högre koncentrationer i Stockholms hamnar jämfört med EU:s modellnamn från OECD, varav den högsta koncentrationen uppnåddes i Värtahamnen. Resultatet visar att OECD-EU modellhamnen inte är lämplig som modell för Stockholms hamnar eller andra mindre, instängda hamnar i Östersjön med låg volym och litet vattenutbyte. Koncentrationerna är även så pass höga att de kan påverka det marina ekosystemet och vissa koncentrationer gick över gränserna definierade i Vattendirektivet, vilket indikerar att det råder en oacceptabel risk i området. När lagar och regler kring skrubberutsläpp stiftas längs Östersjön så bör resultat från flera hamnar analyseras som representerar östersjömiljön bättre än den befintliga modellhamnen för EU. Denna rapport fokuserar på Stockholms hamnar och kryssningsfartyg då de har flera hundra anlöp per år samt att flertalet kryssningsfartyg är utrustade med skrubbers.

**Nyckelord:** Skrubbers, Miljöpåverkan, Fartygs förorening, Riskbedömning

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# ABSTRACT

Scrubbers are used onboard ships to clean the exhaust gases from sulphuric compounds, since this allows ships to use cheaper fuels that do not meet the regulations regarding the sulphur content in the fuel. The problem with scrubbers is that they move the emissions from the air to the sea instead. In this report, models of two ports in Stockholm were defined in the software Marine Antifoulant Model for Predicted Environmental Concentration (MAMPEC). Then, the concentrations of a selected number of metals and Polycyclic Aromatic Hydrocarbons (PAHs) in the discharge water were applied in the model to calculate the predicted environmental concentrations within the specific ports. The result shows higher concentrations in the Stockholm ports compared to the OECD-EU model port, with the highest concentrations in Värtahamnen. The result also shows that the OECD-EU port is not suited as a representative for the ports of Stockholm or any other small, confined ports in the Baltic Sea area due to the small water volumes and low water exchange. In some cases, the predicted concentrations reached levels high enough so that they may impact the marine ecosystem and even exceed the limits defined in the Water Framework Directive, yielding an unacceptable risk to the environment. The importance of this is that when legislation regarding scrubber water discharge is made it is crucial to consider different ports and not only the OECD-EU port. This report focus on the ports of Stockholm and cruise ships since there are several hundred arrivals per year and several of the cruise ships are equipped with scrubbers.

**Keywords:** Scrubber, Environmental impact, Ship pollution, Risk assessment

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# ACRONYMS AND TERMINOLOGY

| | |
|---|---|
| 95% concentration | The upper limit of the 95% confidence interval |
| As | Arsenic |
| BaA | Benzo[a]anthracene |
| BaP | Benzo[a]pyrene |
| BghiP | Benzo[ghi]perylene |
| Chr | Chrysene |
| Cr | Chromium |
| Cu | Copper |
| DahA | Dibenzo[a,h]anthracene |
| DOC | Dissolved Organic Carbon |
| EQS | Environmental Quality Standards |
| Fla | Fluoranthene |
| GT | Gross Tonnage |
| HFO | Heavy Fuel Oil |
| IMO | International Maritime Organization |
| InP | Indeno[1,2,3-cd]pyrene |
| MAMPEC | Marine Antifoulant Model for Predicted Environmental Concentration |
| MW | Mega Watt |
| MWh | Mega Watt hour |
| Ni | Nickel |
| PAH(s) | Polycyclic Aromatic Hydrocarbon(s) |
| PEC | Predicted Environmental Concentration |
| PNEC | Predicted No Effect Concentration |
| POC | Particulate Organic Carbon |
| PSU | Practical Salinity Unit |
| Pyr | Pyrene |
| SECA | Sulphur Emission Control Area |
| $SO_x$ | Sulphur oxides |
| SPM | Suspended Particulate Matter |
| V | Vanadium |
| Zn | Zink |

# 1. INTRODUCTION

In 2020, the International Maritime Organization (IMO) changed the maximum allowable fuel content in marine fuels to 0.5% worldwide, accordingly to the adoption of Marine Environmental Protection Committee (MEPC) resolution 280(70) (International Maritime Organization [IMO], 2016). Sulphur Emission Control Areas, such as the Baltic Sea, have stricter regulations, and since 2015 the fuel sulphur limit is 0.1% (IMO, 2020). This means that ship owners must use a fuel that complies to the new sulphur regulations (IMO, 2016). The legislation regarding sulphur limits exists because of the harmful health and environmental effects of Sulphur Oxides ($SO_x$) (United States Environmental Protection Agency, 2021). Heavy Fuel Oil (HFO) is a residual fuel that is a rest product from the refining, which have previously dominated as the mainly used fuel in the marine sector. Since HFO is a residual fuel, it has been enriched in sulphur but also metals and ash. The high sulphur content results in more $SO_x$ emitted after combustion and it is not allowed to use since the new regulations (Lunde Hermansson, 2021). However, an alternative method to use low sulphur fuels is to install a system for cleaning the exhaust from the sulphuric compounds. This is resulting in exhaust gases that are within the sulphur cap. The common name for these systems is scrubbers.

The scrubbers clean the exhaust gases from $SO_x$ and Particulate Matter (PM) by injecting a water spray into the exhaust gas that binds these pollutants (Turner et al., 2017). Therefore, scrubbers are used to clean the exhaust to lower the $SO_x$ levels to a legal level according to regulations from IMO. This is allowed by IMO as an equivalent alternative method, as specified in MEPC.259(68), which opens the possibility for shipping companies to use high sulphur fuels in their engines instead of low sulphur fuels (IMO, 2015). There are different scrubber technologies, varying on how they handle the washing media. For example, open loop scrubbers use seawater that is most often discharged to the sea directly after use. Closed loop systems use freshwater in recirculation and add an alkali to counter the acidification. However, these systems have a ¨bleed off¨ where they slowly discharge the washing media to aftertreatment and afterwards either overboard or to a holding tank. Then there is hybrid systems that can switch between open and closes loop modes (see figure 2). In all systems the pollutants are removed from the exhaust gases and discharged to the seawater, the recipient is changed from the air to the sea.

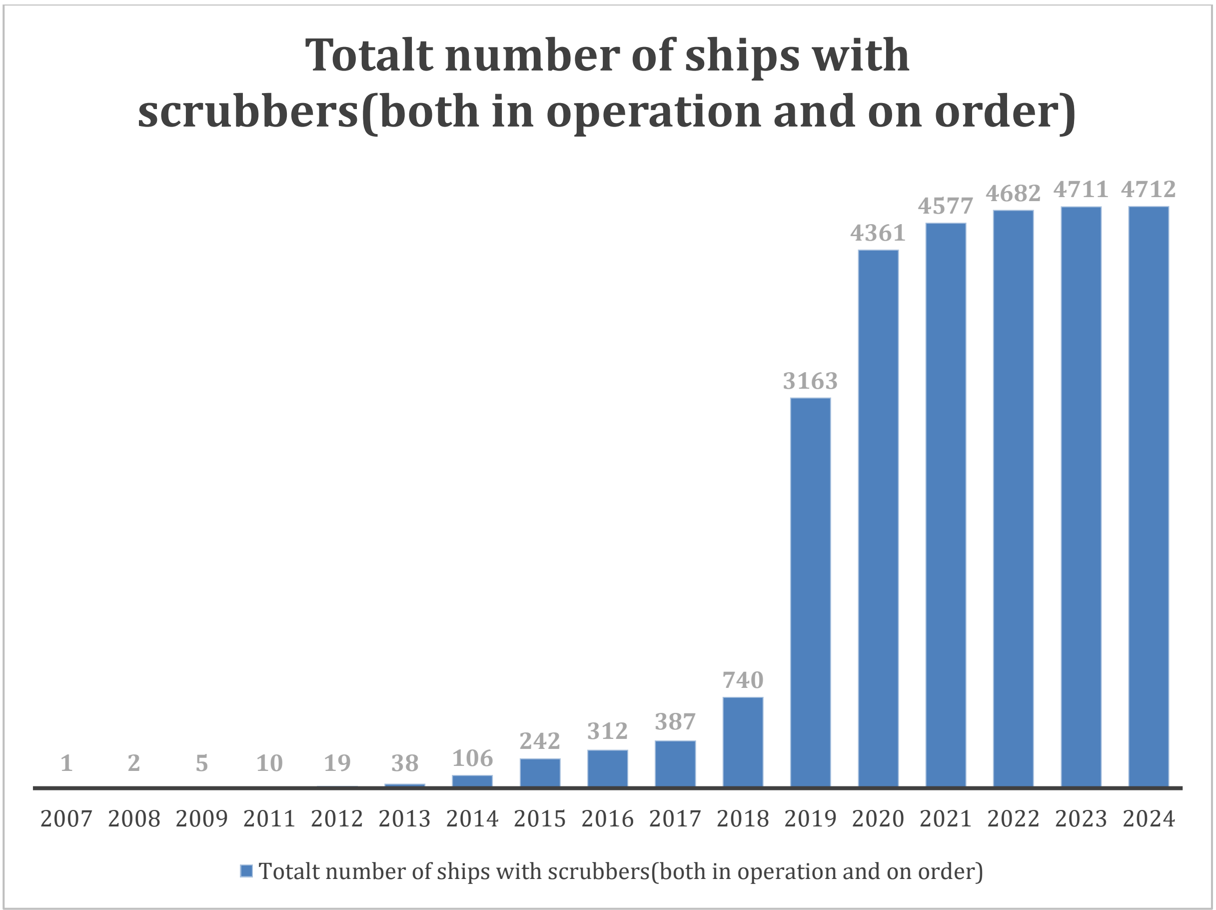
Scrubber discharge water contains several substances that are present in the Directive 2008/105/EC of the European parliament and of the councils list of priority substances. This EU directive contains concentration limits on these priority substances, and they should be followed to maintain a good water chemical status and the aim of the directive is to achieve good surface water chemical status. This includes pollutants such as lead (Pb), benzo[a]pyrene (BaP) and nickel (Ni). Nickel and Vanadium (V) are metals present in scrubber discharge and since these elements are more abundant in HFO compared to distilled fuels and other sources of emission to the sea water, they can be used as markers for HFO combustions and thus scrubber discharge (Lunde Hermansson et al., 2021). A study by Koski et al. (2017) shows that there is a significant impact from the combined pollutants from the wash water on several organisms and even synergistic effects between the pollutants that lower the lethal concentration with several orders of magnitude. Some of the pollutants might bioaccumulate in the food chain and transfer and concentrate in higher trophic levels.

Globally, it is allowed to discharge scrubber wash water following a few criteria. These criteria cover the allowed pH-value and turbidity as well as the content of PAHs, nitrates and additives (IMO, 2015). However, some nations have used their right to adopt their own environmental laws to either limit or forbid scrubber discharge in their ports and/or coastal waters (IMO, n.d.). For example, in Germany it is forbidden to discharge scrubber water in the inland waterways and ports connected to those with a few exceptions (Transportstyrelsen, 2020).

According to DNV (2022) there are 4577 ships worldwide that uses scrubbers as of 2021 and a majority of these are either open loop (81.22%) or hybrid systems (16.82%). This can be compared to 2018, before the new sulphur cap, when only 740 ships used scrubbers. However, the increase in scrubber units is not so dramatic in the coming years since DNVs predictions for 2022 is that 4678 ships will have scrubbers installed (see figure 1).

**Figure 1**

*A graph showing the number of ships using scrubbers worldwide for each year*




*Note.* The graph shows the number of ships that uses scrubbers and scrubbers that are on order (DNV, 2022)

One of the industries that uses scrubbers to comply with the sulphur regulations is the cruise ship industry (DNV,2022), and in the port of Stockholm several of the ships with scrubber systems are cruise ships. Since there are 300 arrivals of cruise ships for the 2022 season (Stockholms Hamnar, 2021), this report focuses on the cruise ship's impact in the port of Stockholm.

## 1.1 Background

The release of scrubber water is not nationally regulated in Sweden. However, individual ports have made their own regulation that prohibits the release of scrubber water. Among these are the port of Trelleborg and the port of Gothenburg (Transportstyrelsen, 2020). Several other EU ports have also done this. The port of Stockholm has no regulations today, even though they have several ships with scrubber entering the port every year (Stockholms Hamnar, 2022a). Their view on scrubbers is rather positive as stated on their website

*"Several companies also take their own initiatives and make large investments in measures to improve the environment that goes further than the laws and regulations requires. Now comes different types of solutions and technologies such as battery operation, the use of fuel cells, scrubbers and so on."* (Stockholms Hamnar, n.d.).

This suggest that they do not see the environmental problem with scrubbers or their discharge water.

## 1.2 Aim of the study

The aim of this report is to provide a better understanding on how pollutants from scrubber water discharge can accumulate in ports with low water exchange and in brackish conditions, such as the ports of Stockholm. How the concentrations of the pollutants might affect the ecosystems with respect to risk will also be examined. This study aims to add knowledge that can support further decisions for regulations regarding the use of scrubbers in ports.

## 1.3 Research questions

- At what concentrations will the selected PAHs and metals from scrubbers, both open and closed loop, accumulate in ports?
- How well does the modelled EU-OECD port represent a typical Baltic port such as the port of Stockholm in the model MAMPEC?
- What is the relative risk associated to cruise ships equipped with scrubber systems to the marine environment in the ports of Stockholm?

## 1.4 Delimitations

The modelling will be limited to the ports of Stockholm and the EU model port. The port of Stockholm will be divided into two ports. One at Stadsgårdskajen, which is placed inside the city on the north side of the island Södermalm. The other port is the harbour basin shared between Värtahamnen and Frihamnen, henceforth called Värtahamnen. This port is placed just outside the city, in a strait between the mainland and the island of Lidingö. The EU model port that is based on the port of Rotterdam will be used for comparison. The modelling will be based on certain selected pollutants, including both PAHs and metals, which according to preliminary calculations accounts to a large contribution to the risks associated to scrubber discharge. The selected pollutants are mentioned in table 2.

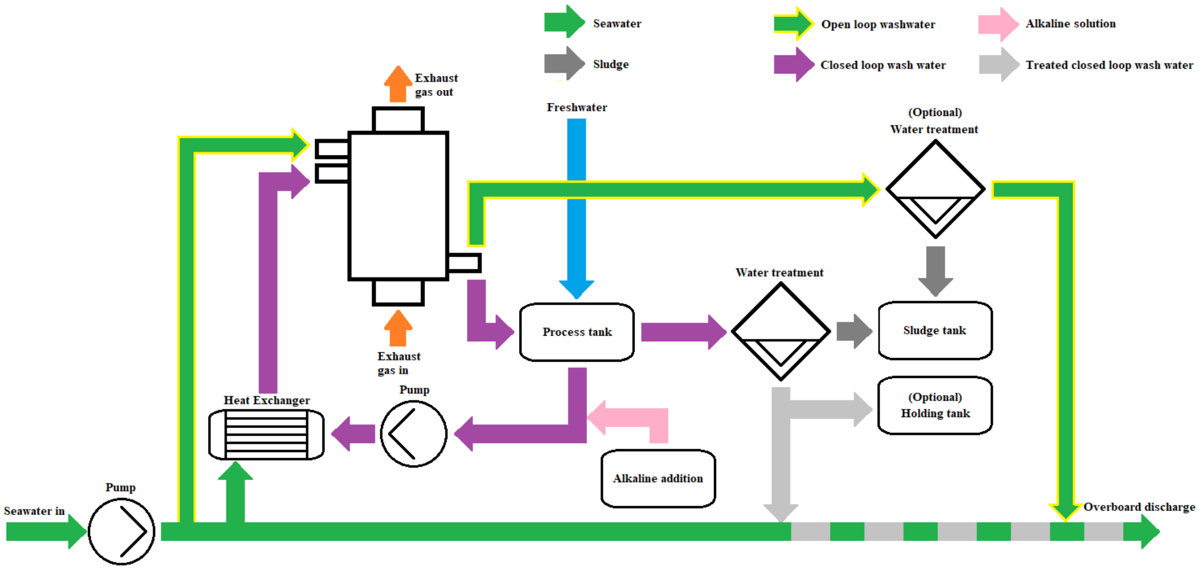
# 2. THEORY

## 2.1 Scrubber technology

The main principle of the scrubbers used on ships, so called wet scrubbers, is that water is sprayed into the exhaust gas column through several nozzles creating a fine mist (see figure 2). Pollutants, mainly $SO_x$ and PM, are scavenged by the fine water droplets. This way the exhaust gas is cleaned from these pollutants and thus the airborne emissions are complying with present IMO regulations. What happens later with the wash water including the pollutants are depending on the scrubber type. On ships, there are three major types of the wet scrubbers that are used. These are open loop, closed loop, and hybrid scrubbers (Transportstyrelsen, 2020).

**Figure 2**

*Diagram of hybrid scrubber system*




*Note*. This figure shows of a diagram of a hybrid scrubber with both open loop and closed loop.

The open loop system works by using a high flow of seawater directly in the scrubbing process. For a medium-sized vessel equipped with a scrubber the flow of wash water can be between 500-1000 $m^3/h$. The seawater is taken from a sea chest and is pumped up to the scrubber unit (Transportstyrelsen, 2020). After it has gone through the unit in the scrubbing process, the wash water is discharged back to the ocean without any cleaning step (Lunde Hermansson et al., (2021). $SO_x$ are strongly acidifying and thus when the wash water is discharged it has a low pH-value. However, seawater that usually have a high alkalinity and salinity acts as a buffer and therefore neutralizes the acidifying compounds after discharge and creates sulphates which is a natural and common compound in the oceans. In waters with less salinity, the release of these acidic solutions may be of higher concern (Transportstyrelsen, 2020).

Transportstyrelsen (2020) describes closed loop systems as using freshwater in a circulatory system, where the water is pumped from a process tank through a heat exchanger and then up to the scrubber. After the scrubber process, it is returned to the process tank. An alkali such as sodium hydroxide, caustic soda, is injected into the process water to counter the acidification from the sulphuric compounds and ensure a sufficient efficiency of the sulphur removal. A small portion of the process water is continuously drained to be treated, called bleed-off, which is compensated by refill with freshwater. This bleed-off is then treated and afterwards being discharged or transferred to a holding tank. The third type of wet scrubber on board is the hybrid scrubbers, which is a combination of both closed loop and open loop (see figure 2). This allows to choose mode depending on sea area (Transportstyrelsen, 2020).

## 2.2 MAMPEC

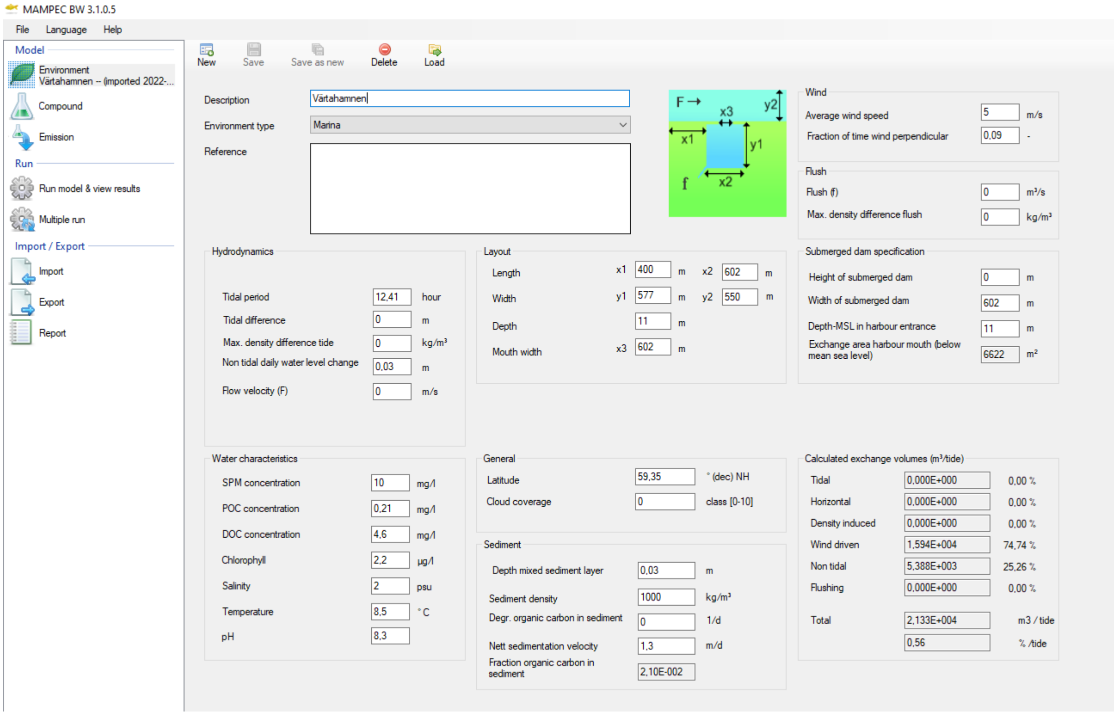
For the modelling in this report, Marine Antifoulant Model for Predicted Environmental Concentration (MAMPEC) was used. MAMPEC was initially developed to calculate the leakage of substances from antifouling paint from ships to water in specific areas (Deltares, n.d.). It is also used with a similar purpose for ballast water modelling. Here, MAMPEC was applied to calculate the Predicted Environmental Concentration (PEC) of pollutants based on emissions of scrubber water discharge, multiplying the discharge flow rate with the pollutant concentration of the scrubber water, of both open and closed loop systems. The methodology is essentially the same as when calculating emissions from ballast water. The model calculates a predicted environmental concentration at equilibrium between the input and output of these substances in the port. Since MAMPEC is a steady state model, this means the PEC is calculated for a scenario when the input of the selected pollutant is equal to the pollutant that flow out of the port (Van Hattum et al., 2018a).

The MAMPEC model consists of three parts that need to be defined to run the program. The first one is the environment module which offers a generalised and simplified model of a port. This port needs to be parametrised on several different aspects such as depth, length and width but also factors such as wind, wind direction, and currents see (figure 3) as these parameters impact the water exchange (Van Hattum et al., 2018a). Several water properties must be entered as well, these are then used for the calculations. Factors such as temperature and salinity may create gradients due to the resulting density difference that affect the water exchange. Temperature, salinity and pH also impact the fraction of the compound in the water column that are freely dissolved (Van Hattum, 2002). As many of the pollutants bind to Dissolved Organic Carbon (DOC), the concentration of DOC impacts the fraction that are freely dissolved (Allison & Allison, 2005). For organic compounds, the temperature, salinity, and pH affect the biodegradation as well. Parameters such as Particulate Organic Carbon (POC) and Suspended Particulate Matter (SPM) impact the sedimentation of the compound (Van Hattum et al., 2002). Van Hattum et al., (2018a) writes that the concentration of chlorophyll a is only used for calculations regarding photolysis, which is not regarded in this report.

The second part that needs to be parametrised in MAMPEC is the compound module and that need to be defined with a name, molar mass and the substance must be defined as a metal, or an organic substance (see figure 4). The third and last part is the emission module that needs to be defined with a concentration of the compound in the waste stream, i.e., in the scrubber water, and a discharge flow rate in $m^3$ per day to yield a daily mass input (see figure 5). All these modules are needed to run the model and to get the predicted concentrations of the compound in the receiving water and the sediment in the port.

**Figure 3**

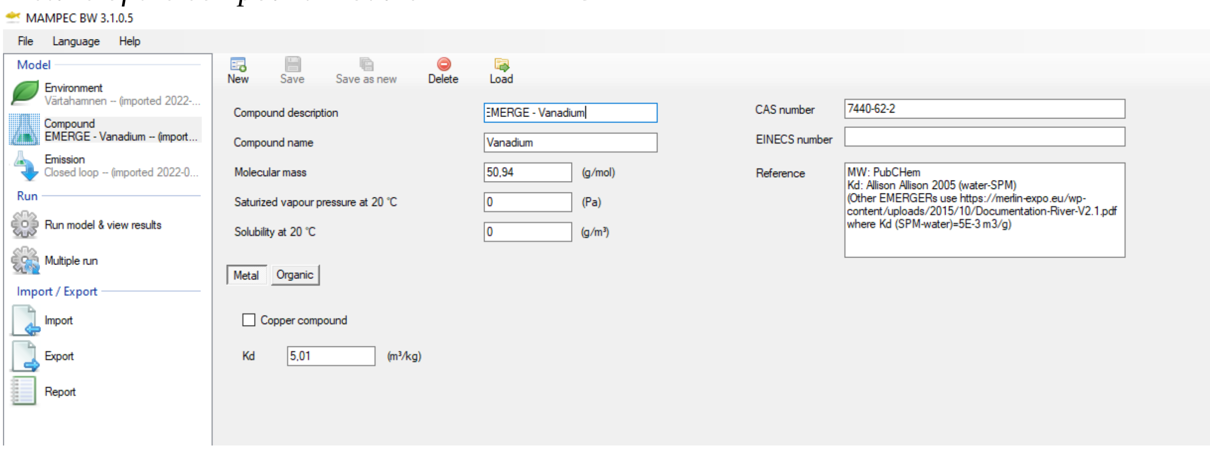
*Picture of the environmental module in MAMPEC*




*Note.* Van Hattum et al., (2018b)

**Figure 4**

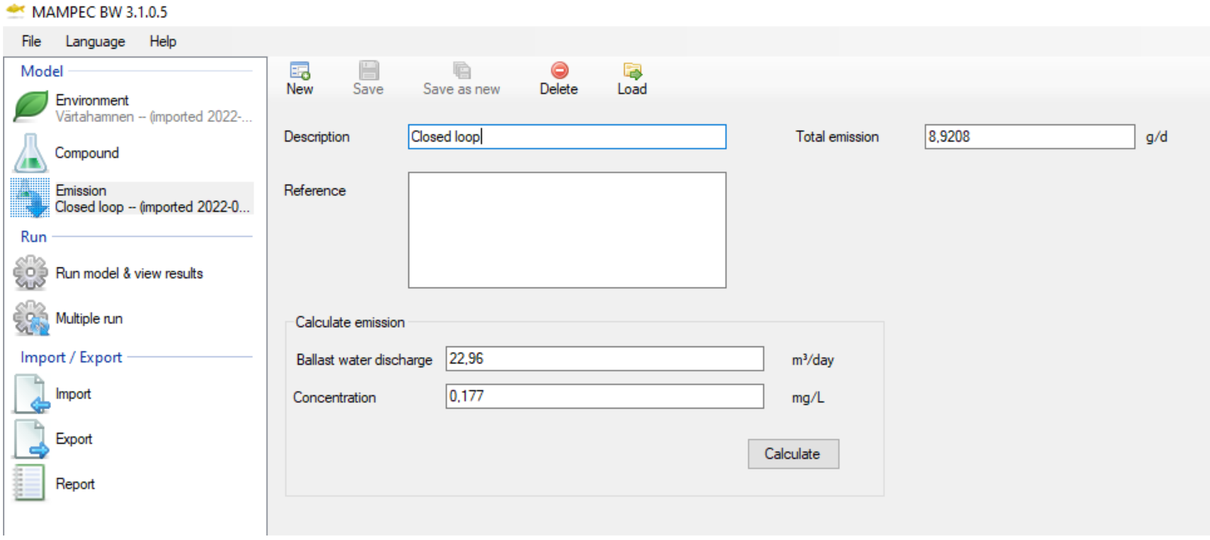
*Picture of the compound module in MAMPEC*




*Note.* Van Hattum et al., (2018b)

**Figure 5**

*Picture of the emission module in MAMPEC*




*Note.* Van Hattum et al., (2018b)

## 2.3 Scrubber wash water content and impact

While scrubbers are used to remove $SO_x$ from the exhaust gas and thus minimize the air pollution with respect to $SO_x$, other pollutants bind to the wash water in varying degree as well (Lunde Hermansson et al., 2021). This includes, but is not limited to, metals and PAHs of which several are known to cause ecological damage to different degrees (Turner et al., 2017). For example, PAHs are known to be toxic and several of them carcinogenic and mutagenic (Honda and Suzuki, 2020).

The impact of scrubber water has been tested on zooplankton and were observed to increase the predicted mortality of the zooplankton at concentrations several orders of magnitude lower compared to single metal studies. This is most likely due to the synergetic effect of all compounds of the scrubber water (Koski, Stedmon and Trapp, 2017). Synergetic effects have also been shown between salinity variations and compounds such as cadmium (Hall et al., 1995) and copper (Kwok & Leung, 2005). For metals such as cadmium, which are pollutants from scrubber discharge as well, a lower salinity might increase the proportions of the compound that is in a state of free ions. Free ions have been showed to be the most bioavailable and toxic form of metals (Hall et al., 1995). Kwok & Leung (2005) also discussed that osmotic regulation might impact the organisms water intake and therefore the intake of toxic substances.

## 2.4 Risk characterisation

When assessing environmental risks, a ratio between the Predicted Environmental Concentration PEC and the Predicted No Effect Concentration PNEC is most often used (Swedish Chemicals Agency, 2022). This ratio, PEC/PNEC, should not exceed 1. If PEC/PNEC exceeds 1, this would mean that the exposure concentration PEC is above the reference value PNEC, which is regarded as unacceptable risk and that actions is considered to be a necessity. If opposite, the ratio is below 1, the risk is considered acceptable (Swedish Chemicals Agency, 2022).

### 2.4.1 PNEC

The Swedish Chemicals Agency (2022) writes that when assessing environmental hazards, data from singe species laboratory tests are most often used. The single species tests test for the concentration of pollutant where a certain percentage (x) mortality or inhibition of functions occurs on the tested group of a species. These are named as $LC_x$ (Lethal Concentration) and $EC_x$ (Effect Concentration) respectively. The $LC_x$-value is most often determined from short term tests, while the $EC_x$-value is determined from long term tests in order to see impact on functions, such as reproduction or growth. Since the purpose of the environmental hazard assessments is to protect the ecosystem as a whole and not all species are tested, there is a need for assessment factors.

Within the EU, the PNEC-value is used as a reference value regarding the toxicity. Below this value, harmful effects will most probably not occur. Most often when calculating PNEC; $LC_{50}$, $EC_{10}$ or NOEC (No Observed Effect Concentration) for the most sensitive organism tested is divided by the assessment factor (Swedish Chemicals Agency, 2022). Some of these produced PNEC-values are used as Environmental Quality Standards (EQS) in the Water Framework Directive, where the EQS are supposed to protect the water environment from both acute and chronic effects. The EQS are therefore used by member states evaluate whether their waters reach a good chemical status (Directive 2008/105/EC of the European parliament and of the council of 16 December 2008 on environmental quality standards in the field of water policy).

### 2.4.2 PEC

Environmental exposure assessment is based on concentrations of toxicants in the environmental media. The exposure can be measured during monitoring campaigns or be modelled with computer programs. While real-life measurements at the first glance may seem to yield more accurate results; analyses such as these are performed at specific locations and at times which may impact the results compared to the “average” concentration. This is not the case for computer-based models, which generally reflect the “average” concentration. The Predicted Environmental Concentration, PEC, is expressing an estimated environmental exposure level (Swedish Chemicals Agency, 2022).

# 3. METHODS

For this study, the ports of Stockholm were chosen because of their confined location and low water exchange. This combined with high cruise ship activity during a large part of the year.

The MAMPEC version 3.1.0.5 model was used to calculate the emissions in the harbours and the resulting concentrations. The predicted concentrations were then compared to levels known to affect organisms that are a part of the marine ecosystem, i.e. PNECs, following the risk characterisation approach described in section 2.4.

## 3.1 Environment modules

Two ports in Stockholm were defined, one for the port of Värtahamnen and two different environments were made for the port of Stadsgårdskajen.

Nautical charts from Eniro (n.d.) was used to estimate the depth. For one version of Stadsgårdskajen (Stadsgårdskajen small), the depth was estimated by taking the depth at the dock and 40 m from the dock, this was done at three sections of the dock. The outer third had an average of 12.1 m and the two inner thirds both hade an average of 11.2 m. The average depth was estimated to 11.5 m at Stadsgårdskajen. By using the measurement tool on Google Maps(n.d.) the length of the dock comes out to 1770 m and the width was determined to 40m out from the dock which results in an area of 70 800 m$^2$, (see figure 6).

**Figure 6**

*Map of Stadsgårdskajen with the small defined harbour.*

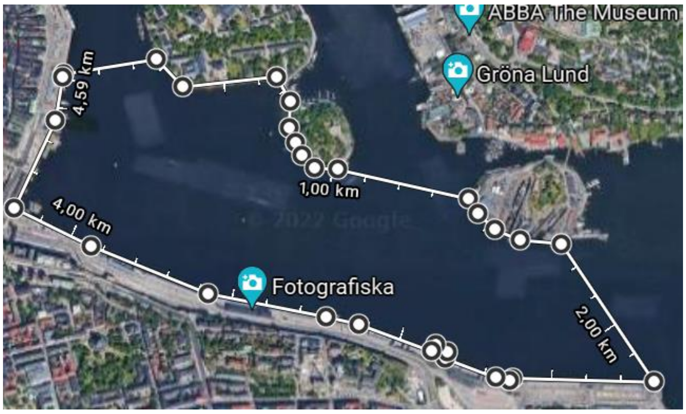

*Note.* Defined harbour within the lines.

Map Data ©2022 Google; Images ©2022, CNES / Airbus, Lantmäteriet/Metria, Maxar Technologies

As a second approach, a larger model of Stadsgårdskajen was made that measured out to 806 570 m$^2$ according to the measurement tool of Google Maps (n.d.), (see figure 7). The average depth of this was more difficult to calculate as it was estimated by studying the nautical charts from Eniro (n.d.) and the estimated depth was 20 m

**Figure 7**

*Map of Stadsgårdskajen with the large defined harbour.*




*Note.* Defined harbour within the lines

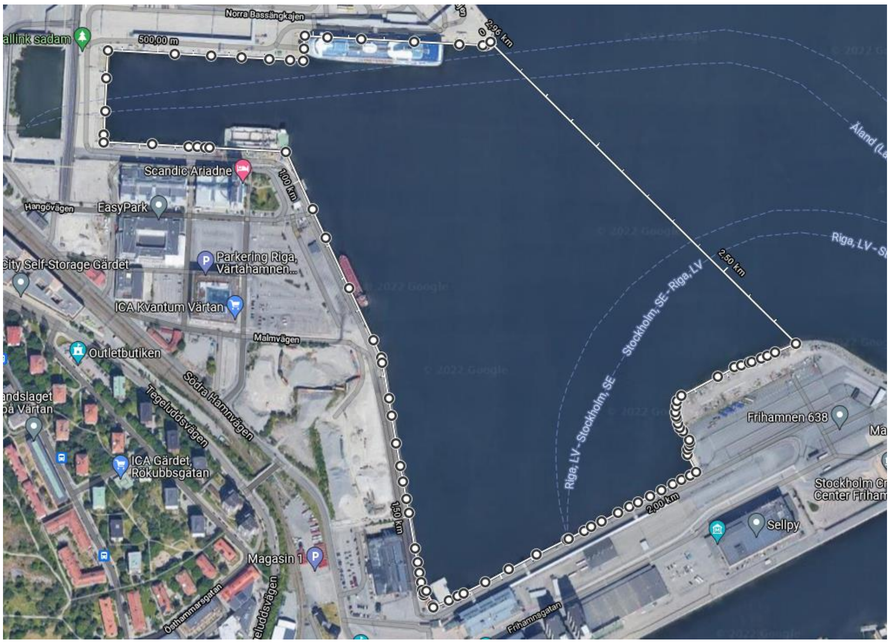
Map Data ©2022 Google; Images ©2022, CNES / Airbus, Lantmäteriet/Metria, Maxar Technologies

For Värtahamnen, as seen in figure 8, the shallowest point was 6 m at the dock and deepest point was 15 m further out in the basin. The average depth of 11m was applied. The total surface area was 347 560 $m^2$ according to the measurement tool of Google Maps (n.d.) and the opening to the strait outside was 602 m wide. With this, the other side of the square for the MAMPEC environment could be calculated as (see x3 in figure 3).

$$\frac{347\,560}{602} = 577m$$

**Figure 8**

*Map of Värtahamnen with defined harbour within the lines.*




*Note.* Defined harbour within the lines.

Map Data ©2022 Google; Images ©2022, CNES / Airbus, Landsat / Copernicus, Lantmäteriet/Metria, Maxar Technologies

The average wind speed (5 m/s) was calculated from SMHI, over an average of 30 years (1961-1990) (Sveriges Meteorologiska och Hydrologiska Institut [SMHI], 2017)

The current in Stadsgårdskajen was calculated to 154.71 $m^3$/s and the resulting flow speed was calculated to 0.02 m/s. This was calculated by taking the narrowest point between Beckholmen and Masthamnen (380 m) and estimating the average depth at 20 m yielding a cross section of 7 600 $m^2$ (Eniro, n.d.). The average annual flow output from Stockholms ström is 4 879 000 000 $m^3$. This average is based on the annual flow for the last 5 years (Stockholms Stad, 2021a). It was calculated as:

$$Flow\ speed\left[\frac{m}{s}\right] = \frac{\left(\frac{Average\ annual\ flow[m^3]}{Time\ in\ a\ year\ [s]}\right)}{Cross\ section\ area\ [m^2]} = \frac{\left(\frac{4\ 879\ 000\ 000}{365 * 24 * 3600}\right)}{380 * 20}$$

The salinity was 2 Practical Salinity Unit (PSU) for all the harbour environments, based on an assumed average at Slussen in the port of Stockholm in 2020 (Stockholm Vatten och Avfall, 2021). The average daily non tidal water level change was 3 cm in 2020 and that was applied for all the MAMPEC environments (Stockholm Vatten och Avfall, 2021). The average temperature in 2020 was 8.5 degrees, this was determined by viewing a graph of the monthly average and then using these to estimate an average for the whole year. The temperatures were derived from the water column between 0-4 m (Stockholm Vatten och Avfall, 2021).

The concentrations of SPM, POC, DOC and chlorophyl as well as the pH-value was collected from an already existing MAMPEC module of the port of Oxelösund (Swedish Chemicals

Agency, 2017). The SPM was 10 mg/l, POC was 0.21 mg/l, DOC was 4.6 mg/l, pH was 8.3 and chlorophyl was 2.2 µg/l.

The wind direction and the resulting wind factor was collected from Asp (2017). The wind factor is depending on the percentage of the total time that the wind is directed perpendicular against the port. For both Stockholm ports the wind factor was estimated as 15% for Stadsgårdskajen small, 11% for Stadsgårdskajen large and 9% for Värtahamnen.

**Table 1**

*All values used in the MAMPEC models*

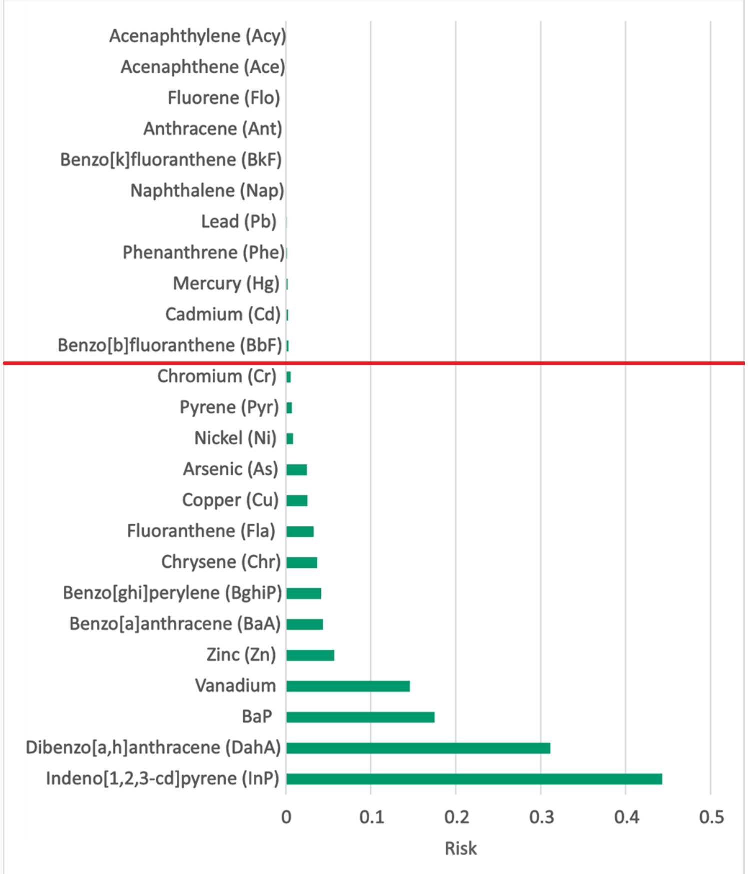
| | Stadsgårdskajen (small) | Stadsgårdskajen (large) | Värtahamnen | OECD-EU Commercial Harbour |
|---|---|---|---|---|
| Area [$m^2$] | 70 800 | 806 570 | 347 560 | 5 000 000 |
| Average Depth [m] | 11.5 | 20 | 11 | 15 |
| Water flow [m/s] | 0.02 | 0 | 0 | 1 |
| Water Flow (flush) [$m^3$/s] | 0 | 154.7 | 0 | 0 |
| Wind speed [m/s] | 5 | 5 | 5 | 0 |
| Wind factor | 0.15 | 0.11 | 0.09 | 0 |
| Salinity [PSU] | 2 | 2 | 2 | 34 |
| Tidal Difference [m] | 0 | 0 | 0 | 1.5 |
| Non tidal water level change [m] | 0.03 | 0.03 | 0.03 | 0 |
| Water temperature (0-4m) [°C] | 8.5 | 8.5 | 8.5 | 15 |
| SPM [mg/l] | 10 | 10 | 10 | 35 |
| POC [mg/l] | 0.21 | 0.21 | 0.21 | 1 |
| DOC [mg/l] | 4.6 | 4.6 | 4.6 | 2 |
| Chlorophyll [µg/l] | 2.2 | 2.2 | 2.2 | 3 |
| pH-value | 8.3 | 8.3 | 8.3 | 7.5 |
| Calculated exchange volumes [%/Tide] | 147.78 | 74.78 | 0.56 | 68.25 |

*Note.* Table 1 contains all the parameters of all the ports that were used in the MAMPEC software.

## 3.2 Compound module

**Figure 9**

*Risk associated with substances chosen for calculations.*




*Note.* Preliminary results of the risks associated to scrubber water discharge in the port of Copenhagen from 2018, based on MAMPEC calculations. All the substances below the red line were chosen for the calculations in this study, since they were found to pose the highest risk figure from Lunde Hermansson (2022).

The metals used in the MAMPEC model were Chromium (Cr), Nickel (Ni), Arsenic (As), Copper (Cu), Zinc (Zn) and Vanadium (V). The selected PAHs were Pyrene (Pyr), Fluoranthene (Fla), Chrysene (Chr), Benzo[ghi]perylene (BghiP), Benzo[a]anthracene (BaA), Benzo[a]pyrene (BaP), Bibenzo[a,h]anthracene (DahA) and Indeno[1,2,3-cd]pyrene (InP). These substances were selected since they pose the highest risk (see figure 9). For complete data on substances, see Appendix 1.

## 3.3 Emission module

The concentration of chemicals in the scrubber discharge water that were applied in the emission module was collected from previous studies of scrubber water (see table 2) (Ytreberg, E., Lunde Hermansson, A. & Hassellöv, I.-M., 2020).

The flowrates of scrubber water that were used to estimate loads in MAMPEC was 0.35 $m^3$/MWh for the closed loop scenarios or 68 $m^3$/MWh for the open loop scenarios (Lunde Hermansson et al., 2021). These flowrates were chosen since the average flowrates from IMO (0.25 $m^3$/MWh for closed loop and 45 $m^3$/MWh for open loop) does not correctly represent actual flowrates and might lead to underestimated calculations. The 0.35 $m^3$/MWh for the closed loop scenarios or 68 $m^3$/MWh values were chosen because they represent scenarios where engines operated at loads over 50%. This is most likely the case for these ships since ships preferably run on an optimal load on the generator to be both cost-effective and protect the engines from unnecessary wear. The power of the cruise ships at port was calculated by this formula:

$$P = GT \times 0.084 + 242.85$$

Where GT is the gross tonnage and P is the power in kW (Danmarks miljøundersøgelser, 2007).

The example ship for this study, was based on an average of two cruise ships that are planned to dock in Stockholm most frequently during the 2022 season. The two ships are Aidamar with 22 planned visits and Aidadiva with 21 visits both of the ships are equipped with scrubbers both for their main and auxiliary engines (International Maritime Organization, 2022) (Stockholms Hamnar, 2021). The gross tonnage of Aidamar is 71 304 (Marinetraffic, 2022b) and the gross tonnage of Aidadiva is 69 203 (Marinetraffic, 2022a). Based on these two vessels, the average gross tonnage was calculated to 70 253.5.

The equation from Danmarks miljøundersøgelser (2007) and the gross tonnage from the hypothetical ship was used to calculate the effect. The formula includes gross tonnage and a factor of 0.084 and a constant of 242.85 and that comes out to

$$70\,253.5 \times 0.084 + 242.85 = 6142.632\ kW$$

That will be rounded off to 6 MW for the rest of the calculations.

To estimate how many ships that could be expected to have scrubbers for the cruise ship season of 2022, all cruise ships planned in May were checked to see if they are equipped with scrubbers or not. 26 out of the total of 40 arrivals have some kind of scrubber system installed (Stockholms Hamnar, 2022b) (International Maritime Organization, 2022). That equals 65% of all arrivals in May and the same percentage was used as a proxy over the whole season, resulting in a total of 195 arrivals equipped with scrubbers out of the total of 300 arrivals of cruise ships planned.

The period that the emissions was calculated from was from April to the end of November which is 214 days. This is because the first cruise ships arrive at Stockholm in April except one that arrives in March; therefore, March will not be part of the cruise ship season (Stockholms Hamnar, 2022b)

By examining the planed port stay from Stockholms Hamnar (2022b), an average of 12 hours per ships is assumed.

To summarise, that result in 6 MW per ship for 12 hours per day and 195 ships with scrubber for the season, which gives a total energy consumption of

$$6MW \times 12h \times 195 = 14\,040 \text{ MWh}$$

It was estimated that all the exhaust gases pass through a scrubber. The calculated energy consumption was used to calculate a flow for an open loop scenario and a closed loop scenario. The total flow for the open loop scenario was 954 720 $m^3$/season while the total flow for the closed loop scenario was 4 914 $m^3$/season. The flow that was used in MAMPEC was the total flow of the season divided with the all the days of the season. That results in a daily flow of 4 461 $m^3$ for open loop systems and 22.96 $m^3$ for closed loop systems.

**Table 2**

*Discharge concentration of pollutants included in this study and PNEC-values*

| | Open Loop Discharge | Closed Loop Discharge | PNEC-value |
|---|---|---|---|
| | $\bar{X}$ ± 95% CI (µg/L) | $\bar{X}$ ± 95% CI (µg/L) | [µg/l] |
| As | 6.99 ± 3.58 | 23.00 ± 10.21 | 0.55 |
| BaA | 0.13 ± 0.06 | 0.16 ± 0.20 | 1.2E-3 |
| BaP | 0.05 ± 0.02 | 0.04 ± 0.04 | 1.7E-4 |
| BghiP | 0.02 ± 0.01 | 0.02 ± 0.02 | 8.2E-4 |
| Chr | 0.19 ± 0.07 | 0.11 ± 0.08 | 7.0E-3 |
| Cr | 14.53 ± 6.35 | 1250 ± 2045 | - |
| Cu | 38.75 ± 12.45 | 519.42 ± 243.64 | 1.45 |
| DahA | 0.03 ± 0.02 | 0.02 ± 0.02 | 1.4E-4 |
| Fla | 0.16 ± 0.05 | 0.35 ± 0.28 | 6.3E-3 |
| InP | 0.07 ± 0.06 | 0.02 ± 0.02 | 2.7E-4 |
| Ni | 46.86 ± 11.25 | 2623 ± 854 | - |
| Pyr | 0.32 ± 0.12 | 0.37 ± 0.27 | - |
| V | 176.59 ± 49.96 | 1402 ± 3450 | 2.5 |
| Zn | 110.84 ± 60.87 | 387.71 ± 222.64 | 1.1 |

*Note.* The discharge data in table 2 was collected from Ytreberg, E., Lunde Hermansson, A. & Hassellöv, I.-M. (2020), the PNEC-Values were collected from the European Chemicals Agency (n.d), European Chemicals Agency (2008), Havs- och vattenmyndigheten (2019) and Directive 2013/39/EU of the European parliament and of the council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy.

These values were used to calculate the PEC/PNEC, and the PEC values came from the result. The PEC/PNEC was calculated with both the average concentration and the 95% concentration to see the differences between average and worst case.

# 4. RESULTS

In all the tables of the results it is possible to read the predicted average concentrations and the predicted 95% concentrations for both open loop systems and closed loop systems for all metals and PAHs that were used.

The result from Stadsgårdskajen small shows the lowest predicted environmental concentrations of all the ports. This is due to the large water exchange (see table 3). These values are also lower that the OECD-EU port which indicates that this is not as representative for the port Stadsgårdskajen as the model Stadsgårdskajen large.

**Table 3**

*Result from the MAMPEC model of Stadsgårdskajen (small defined harbour)*

| Substance | Average conc. Open Loop [µg/l] | 95% conc. Open Loop [µg/l] | Average conc. Closed Loop [µg/l] | 95% conc. Closed Loop [µg/l] |
|---|---|---|---|---|
| **As** | 1.35E-4 | 1.82E-4 | 2.29E-6 | 3.08E-6 |
| **BaA** | 2.76E-6 | 3.71E-6 | 1.75E-8 | 2.35E-8 |
| **BaP** | 1.06E-6 | 1.43E-6 | 4.38E-9 | 5.88E-9 |
| **BghiP** | 4.26E-7 | 5.72E-7 | 2.19E-9 | 2.95E-9 |
| **Chr** | 4.05E-6 | 5.44E-6 | 1.21E-8 | 1.62E-8 |
| **Cr** | 3.10E-4 | 4.16E-4 | 1.37E-4 | 1.84E-4 |
| **Cu** | 5.50E-4 | 7.39E-4 | 3.80E-5 | 5.10E-5 |
| **DahA** | 6.4E-7 | 8.58E-7 | 2.19E-9 | 2.94E-9 |
| **Fla** | 3.41E-6 | 4.58E-6 | 3.84E-8 | 5.15E-8 |
| **InP** | 1.49E-6 | 2.00E-6 | 2.19E-9 | 2.95E-9 |
| **Ni** | 8.33E-4 | 1.12E-3 | 2.40E-4 | 3.22E-4 |
| **Pyr** | 6.81E-6 | 9.14E-6 | 4.05E-8 | 5.44E-8 |
| **V** | 3.77E-3 | 5.05E-3 | 1.54E-4 | 2.06E-4 |
| **Zn** | 1.05E-3 | 1.40E-3 | 1.88E-5 | 2.53E-5 |

*Note.* The table 3 contains the result from the MAMPEC model of Stadsgårdskajen small. All the results are written for open loop discharge and closed loop discharge. The concentrations are written in the average concentration and 95% concentration. The concentration of As, Cu, Ni and Zn are written as feely dissolved whiles the rest are written in total concentration.

The result from of Stadsgårdskajen large has a significantly higher concentrations compered to Stadsgårdskajen small (see Table 3 and Table 4). Stadsgårdskajen large also has more parameters describing it such as flush and non-tidal daily water level change (see table 1), thus suggesting that it is more representative for the port of Stadsgårdskajen

**Table 4**

*Result of the MAMPEC modelling of Stadsgårdskajen (large defined harbour).*

| Substance | Average conc. Open Loop [µg/l] | 95% conc. Open Loop [µg/l] | Average conc. Closed Loop [µg/l] | 95% conc. Closed Loop [µg/l] |
|---|---|---|---|---|
| **As** | 2.86E-2 | 3.39E-2 | 4.85E-4 | 5.73E-4 |
| **BaA** | 7.33E-5 | 1.39E-4 | 4.64E-7 | 8.79E-7 |
| **BaP** | 3.85E-5 | 6.61E-5 | 1.59E-7 | 2.72E-7 |
| **BghiP** | 8.01E-5 | 9.60E-5 | 4.12E-7 | 4.94E-7 |
| **Chr** | 4.91E-4 | 6.29E-4 | 1.46E-6 | 1.87E-6 |
| **Cr** | 6.11E-2 | 7.28E-2 | 2.70E-2 | 3.22E-2 |
| **Cu** | 8.47E-2 | 1.04E-1 | 5.84E-3 | 7.20E-3 |
| **DahA** | 8.65E-5 | 1.09E-4 | 2.97E-7 | 3.73E-7 |
| **Fla** | 3.00E-4 | 4.09E-4 | 3.38E-6 | 4.60E-6 |
| **InP** | 2.78E-4 | 3.34E-4 | 4.09E-7 | 4.91E-7 |
| **Ni** | 1.57E-1 | 1.89E-1 | 4.54E-2 | 5.43E-2 |
| **Pyr** | 2.45E-4 | 4.20E-4 | 1.46E-6 | 2.50E-6 |
| **V** | 8.54E-1 | 1.00 | 3.49E-2 | 4.09E-2 |
| **Zn** | 1.30E-1 | 1.66E-1 | 2.34E-3 | 2.98E-3 |

*Note.* The table 4 contains the result from the MAMPEC model of Stadsgårdskajen large. All the results are written for open loop discharge and closed loop discharge. The concentrations are written in the average concentration and 95% concentration. The concentration of As, Cu, Ni and Zn are written as freely dissolved whiles the rest are written in total concentration.

The result from Värtahamnen shows high concentration for all substances this is due to the low water exchange. Some of the values are higher than allowed in Directive 2008/105/EC of the European parliament and of the councils list of priority substances.

**Table 5**

*Result from the MAMPEC modelling of Värtahamnen.*

| Substance | Average conc. Open Loop [µg/l] | 95% conc. Open Loop [µg/l] | Average conc. Closed Loop [µg/l] | 95% conc. Closed Loop [µg/l] |
|---|---|---|---|---|
| **As** | 6.00E-1 | 1.63 | 3.09E-3 | 8.38E-3 |
| **BaA** | 2.26E-4 | 1.91E-3 | 1.43E-6 | 1.21E-5 |
| **BaP** | 1.30E-4 | 1.04E-3 | 5.36E-7 | 4.27E-6 |
| **BghiP** | 1.10E-3 | 3.60E-3 | 5.68E-6 | 1.85E-5 |
| **Chr** | 3.31E-3 | 1.62E-2 | 9.87E-6 | 4.81E-5 |
| **Cr** | 9.73E-1 | 2.96 | 4.31E-1 | 1.31 |
| **Cu** | 7.54E-1 | 3.08 | 5.20E-2 | 2.13E-1 |
| **DahA** | 6.57E-4 | 2.97E-3 | 2.25E-6 | 1.02E-5 |
| **Fla** | 1.55E-3 | 9.09E-3 | 1.74E-5 | 1.02E-4 |
| **InP** | 3.77E-3 | 1.24E-2 | 5.54E-6 | 1.82E-5 |
| **Ni** | 2.20 | 7.11 | 9.38E-2 | 3.04E-1 |
| **Pyr** | 8.25E-4 | 6.58E-3 | 4.91E-6 | 3.92E-5 |
| **V** | 2.66E+1 | 6.28E+1 | 1.09 | 2.57 |
| **Zn** | 8.65E-1 | 4.21 | 1.56E-2 | 7.59E-2 |

*Note.* The table 5 contains the result from the MAMPEC model of Värtahamnen. All the results are written for open loop discharge and closed loop discharge. The concentrations are written in the average concentration and 95% concentration. The concentration of As, Cu, Ni and Zn are written as feely dissolved whiles the rest are written in total concentration.

The result from the OECD-EU port shows the values that the other model port will be compared to. This shows that the concentrations are lower in the OECD-EU port compared to the other model reports in the report, suggesting that this is not representative for any of the Stockholm ports.

**Table 6**

*Result from the MAMPEC modelling of OECD-EU commercial harbour.*

| Substance | Average conc. Open Loop [µg/l] | 95% conc. Open Loop [µg/l] | Average conc Closed Loop [µg/l] | 95% conc. Closed Loop [µg/l] |
|---|---|---|---|---|
| **As** | 4.35E-4 | 8.00E-4 | 7.37E-6 | 1.35E-5 |
| **BaA** | 6.27E-6 | 1.28E-5 | 5.71E-6 | 1.17E-5 |
| **BaP** | 2.90E-6 | 5.71E-6 | 1.16E-4 | 2.28E-4 |
| **BghiP** | 1.64E-6 | 3.02E-6 | 8.43E-9 | 1.55E-8 |
| **Chr** | 1.51E-5 | 2.79E-5 | 4.49E-8 | 8.32E-8 |
| **Cr** | 1.21E-3 | 2.23E-3 | 5.37E-4 | 9.87E-4 |
| **Cu** | 1.15E-3 | 2.12E-3 | 7.93E-5 | 1.46E-4 |
| **DahA** | 2.39E-6 | 4.42E-6 | 8.19E-9 | 1.52E-8 |
| **Fla** | 1.13E-5 | 2.14E-5 | 1.28E-7 | 2.41E-7 |
| **InP** | 5.73E-6 | 1.06E-5 | 8.43E-9 | 1.55E-8 |
| **Ni** | 2.29E-3 | 4.22E-3 | 6.60E-4 | 1.22E-3 |
| **Pyr** | 1.78E-5 | 3.54E-5 | 1.06E-7 | 2.10E-7 |
| **V** | 1.50E-2 | 2.75E-2 | 6.12E-4 | 1.12E-3 |
| **Zn** | 1.65E-3 | 3.05E-3 | 2.97E-5 | 5.50E-5 |

*Note.* The table 6 contains the result from the MAMPEC model of OECD-EU commercial harbour. All the results are written for open loop discharge and closed loop discharge. The concentrations are written in the average concentration and 95% concentration. The concentration of As, Cu, Ni and Zn are written as feely dissolved whiles the rest are written in total concentration.

**Table 7**

*Result from MAMPEC regarding daily load*

| | Open Loop Load | Closed Loop Load |
|---|---|---|
| Substance | g/day | g/day |
| As | 31.18 | 0.53 |
| BaA | 0.58 | <0.01 |
| BaP | 0.22 | <0.01 |
| BghiP | 0.09 | <0.01 |
| Chr | 0.85 | <0.01 |
| Cr | 64.82 | 28.70 |
| Cu | 172.86 | 11.93 |
| DahA | 0.13 | <0.01 |
| Fla | 0.71 | 0.01 |
| InP | 0.31 | <0.01 |
| Ni | 209.04 | 60.22 |
| Pyr | 1.43 | 0.01 |
| V | 787.77 | 32.19 |
| Zn | 494.46 | 8.90 |

*Note*. The table 7 contains the daily load of each substance that was used in the MAMPEC model.

**Table 8**

*Result of PEC/PNEC*

| | Stadsgårdskajen(large) | | Värtahamnen | | OECD-EU | |
|---|---|---|---|---|---|---|
| | 95% | Average | 95% | Average | 95% | Average |
| As | 0.06 | 0.02 | 2.96 | 1.09 | <0.01 | <0.01 |
| BaA | 0.12 | 0.06 | 1.59 | 0.19 | 0.01 | <0.01 |
| BaP | 0.39 | 0.23 | 6.11 | 0.76 | 0.03 | 0.02 |
| BghiP | 0.12 | 0.10 | 4.39 | 1.24 | <0.01 | <0.01 |
| Chr | 0.09 | 0.07 | 2.31 | 0.47 | <0.01 | <0.01 |
| Cu | 0.07 | 0.06 | 2.12 | 0.52 | <0.01 | <0.01 |
| DahA | 0.78 | 0.62 | 21.21 | 4.69 | 0.03 | 0.02 |
| Fla | 0.06 | 0.05 | 1.44 | 0.25 | <0.01 | <0.01 |
| InP | 1.24 | 1.02 | 45.93 | 13.96 | 0.04 | 0.02 |
| V | 0.40 | 0.34 | 25.12 | 10.64 | 0.01 | 0.01 |
| Zn | 0.15 | 0.12 | 3.83 | 0.79 | <0.01 | <0.01 |
| **Total** | 3.48 | 2.69 | 117.01 | 34.6 | 0.12 | 0.07 |

*Note.* The table 8 only contains the result regarding open loop PEC/PNEC for a selected number of substances and ports and the total sum of the PEC/PNEC values.

# 5. DISCUSSION

The result shows great variation of concentrations resulting from the scrubber water discharge in the different ports when the same volume of scrubber water is injected in all the ports. This is due to the different size of the ports and the different percentages of water exchange per day. All the factors, such as current, that transport the water affects the percentage of water exchange. The ports with more water exchange will have lower concentrations because the new water will dilute the pollutants in the harbour. This does not mean that the pollutants disappear, just that they are flushed out of the port. Furthermore, the concentrations of pollutants covered in this report are only based on scrubber discharge and does not account for any other sources of pollutants. This suggests that the concentrations of some pollutants may be higher if other waste streams as well as the actual background concentrations would have been accounted for.

The result from the OECD-EU port shows concentrations that are one to two orders of magnitude smaller compared to the port of Värtahamnen and Stadsgårdskajen large and has a volume more than 4 times larger than Stadsgårdskajen large. This indicates that the OECD-EU port is not a representative port that should be use for calculations for the ports of Stockholm. However, the result from Stadsgårdskajen small shows more diluted concentrations compared to all the other harbours. This is due to the high water exchange resulting from the defined port area that is smaller and only accounts for the area closest to the dock which means that much of the pollutants gets diluted into the surroundings. The type of harbour has an impact as well, since Stadsgårdskajen small was defined as an open harbour in MAMPEC, which results in more flushing. Because of this, the small definition is not accurate to use since it is not an open harbour because of its rather confined location in Saltsjön. Therefore, the Stadsgårdskajen small is not the most representative model for Stadsgårdskajen. Stadsgårdskajen large is more representative since it contains more of the surroundings and has a different flow through it compared to Stadsgårdskajen small. The risk of using Stadsgårdskajen small is that its higher water exchange leads to underestimations since Saltsjön where it is located is a confined body of water.

The result from the port of Värtahamnen shows the highest concentrations of all the ports. The concentrations of BghiP and InP exceeds the concentrations in the Directive 2008/105/EC of the European parliament and of the councils list of priority substances. The concentrations of BghiP and InP are more than twice the value of the directive. However, Directive 2013/39/EU amended some legislation and limits from the earlier directive, now both BghiP and InP along with other heavier PAHs are regulated under the concentrations of BAP (Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 amending Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy). However, that it exceeds the EQS from the earlier directive should be an indication that scrubber water should not be allowed due to the high concentrations. Especially since it is the cruise ships alone that is the reason for these concentrations, since background concentrations or other emission sources have not been regarded. However, the high concentrations could also imply that the model had a water exchange that is lower than reality. Since the water exchange is less than 1% per tide with the factors that MAMPEC can account for, the addition of other factors that would move small volumes of water such as ship movement would have a large impact on the port of Värtahamnen since a small increase in exchanged volume would be a large increase on the percentage of the calculated exchange volume. This might decrease the actual concentrations; however, it is worth to remember that the daily load stays the same and that the same amount of the toxic pollutants is emitted to the water. Thus, if the water exchange is increasing, the toxic substances are only diluted in the surrounding environment. Stromma (2020) recommends both Fjäderholmarna and a beach at the northern part of Djurgården as bathing places close to the city. Fishing is also a common activity, since Stockholm is a large city in combination with the fact that Saltsjön is open to the public for sportfishing (Stockholms Stad, 2021b). Therefore, the pollutants spread to the surrounding environment might not only impact the ecosystem, but also people.

When calculating the PEC/PNEC-value from the result of Stadsgårdskajen large it shows that one of the PAHs, InP has a PEC/PNEC-value of 1.23 which is a risk for the environment. Some other PAHs also hade PEC/PNEC-values close to 1 (see table 8). The metals V and Zn also have high PEC/PNEC values 0.4 and 0.15 respectively. Even though none of the metal concentrations exceeds the predicted no effect concentrations there are still the possibility for synergetic effects and should there for still be considered a risk to the environment. The cumulative risk ratio was still exceeding 1, thus meaning an unacceptable risk.

The risk characterization for Värtahamnen showed that 11 of the 14 substances had a PEC/PNEC-ratio of above 1 when regarding the 95% concentration (see table 8). Especially the PAHs DahA and InP as well as the metal V had ratios far above. These stayed high even when regarding the average concentrations in the calculations instead. For the average concentrations in general, the risk ratio for several substances went below 1. However, the cumulative risk from these substances can still make an impact to the environment and especially in combination with the substances that still stayed above 1.

## 5.1 Scrubber systems on cruise ships

As of this report only a selection of scrubber water pollutants from cruise ships are accounted for, no other waste stream or pollutants from other sources are taken into an account. Neither is any background concentration accounted for. This suggest that the actual concentrations are higher, since there are several other sources of pollutants from shipping as shown in the report by Ytreberg et al. (2020).

According to our estimates, for every day when a cruise ship with an open loop scrubber is in port it releases 209g of Ni and several PAHs such as BaP, BghiP and InP all of which are listed in the Directive 2008/105/EC of the European parliament and of the councils list of priority substances. This directive was made to ensure a good water quality and have listed substances of concern. So regardless of the concentrations that they are released in it is still not reasonable that a single ship releases these substances directly into the water when they are listed by the European parliament as priority substances.

There are three types of scrubber systems used in this report: open loop systems, closed loop systems and hybrid systems. However, the hybrid system only makes it possible to switch between open loop mode and closed loop mode which means that it is not a different type of system. The result clearly shows that the daily load from open loop systems is significantly larger compared to the closed loop systems. With that information it would be reasonable to consider prohibiting at least the open loop scrubbers since both the discharge of pollutants and the flow of discharge water is considerably larger compared to the closed loop systems. One other possibility to stop the discharge of scrubber water in ports completely is to use shore power whenever a ship is docked, that would make the use of scrubbers at port unnecessary and therefore reduce the pollutants from scrubber discharge water in ports significantly. Stockholms Hamnar (2021) states that they are already working to be able to supply cruise ships with shore power, with two berthing points at Stadsgårdskajen installing high-voltage systems which is predicted to be finished 2023 and 2024 respectively. Afterwards, according to Stockholms Hamnar (2021), they will be able to supply a minimum of 45% of all cruise ships with green electricity. However, the scrubbers could still be used in the archipelago of Stockholm during entry and leave of the port. While the emissions would be lower since it is over a short time, it would be possible to lower the emissions even more by either requiring the use of closed loop or that the ships switch over to the use of distillate fuels.

The number of ships that are equipped with scrubbers increased greatly around the year 2020 but have since slowed down and the increase of new scrubber systems for 2022 is predicted to be 105 system and even less for 2023 (see figure 1). If the current trend continues and new scrubber installations stop, the number of ships equipped with scrubber that arrives in the ports of Stockholm will neither increase nor decrease in the following years to then decrease further in the future when the ships equipped with scrubbers are scrapped, but this would most likely be one or two decades away. The reduction of scrubber installations might be because of the recent studies on scrubbers that show their emissions, which might lead to harsher legislation regarding their use in the future making it a risky investment. Therefore, the legislation regarding scrubber discharge water need to come in to force now to make a difference otherwise it will not be necessary.

## 5.2 Method discussion

Since MAMPEC is a model, the results are only theoretical and only applies based on the input values entered in the model. However, the results should still show reasonable and realistic values when based on realistic and plausible input values. Therefore, future modelling or monitoring should validate these results. This since even if other assumptions should be made regarding some input values, there is only a certain interval that could be seen as realistic or plausible. The results might differ but would be within a certain interval as well.

There exist two versions of MAMPEC, one for antifoulant substances and one for ballast water. As of today, there is no software dedicated to calculations of scrubber emissions. Because of this, the MAMPEC version for ballast water was used for this report. While it is developed to calculate substance emissions from ballast water and not from scrubbers, it is still be possible to use it. This is since the ballast water model uses a ballast water discharge and the concentration of a pollutant in the emission-section to calculate the resulting concentrations in the surrounding area. The scrubber discharge could therefore be modelled as ballast water discharge containing the concentrations collected from the report by Ytreberg et al. (2020). The version made for antifoulant would not have been equally appropriate since the emission of antifoulant substances from paints are by leaching rather than an actual discharge.

Several input values were assumed, which may impact the accuracy of the results. For example, while several areas were calculated with the measurement tool of Google Maps all the depths used was assumed after observing the depths on a nautical chart. This is because to obtain an accurate average depth there would be a need for extensive research and calculations. While the assumed average depth may not be accurate, it would still be within reasonable margins and between the maximum and minimum depth. Therefore, the results will still be within reasonable margins as well and while they may not be exactly realistic, they will be able to give reasonable indications of how the pollutants accumulate in the harbour. For example, if the depth was one meter deeper at Stadsgårdskajen large the daily water exchange would be 4 percentage points less. Worth to note is that the average depth was assumed both in the calculation for the three harbours modelled by the authors of this report, as well as in the calculation of the cross-section area that was in turn used to calculate to speed of the flow velocity in Stadsgårdskajen (small).

For each calculation, it is assumed that all cruise ships go to the same harbour. Therefore, the results do not show the real concentrations since the ships would vary between the two actual harbours. However, there are a total of 195 ships equipped with scrubbers according to our assumption and it is still possible over the whole season that all cruise ships go to only one harbour. Therefore, the assumption that all ships go to the same port is theoretically possible.

The background concentrations of all selected pollutants were assumed to be zero. Therefore, the calculated concentrations only show the pollutants originating from the scrubber systems of the cruise ships. This results in a lower concentration than in reality since all pollutants would have a background concentration of varying degree. This may come from several different other sources, such as road dust carried by rain to storm drains supplying PAHs (Zhang et al., 2019) or anti-fouling paints leaching copper and zinc (Ytreberg et al., 2020)

# 6. CONCLUSION

With the result from the calculations, it is possible to conclude that the OECD-EU port is not representative for any of the ports in Stockholm and that the most representative model is the Stadsgårdskajen large since it contains more of the surroundings and more parameters are taken into an account.

From the result from all the models it is possible to conclude that switching from open loop scrubber systems to closed loop scrubber systems, would reduce most of the pollutants with two to three orders of magnitude except for the PAHs BaA and BaP.

With the result shown it is possible to conclude that in is not reasonable that cruise ships equipped with scrubbers uses them in port since the water exchange is low and the volume of water in the port is small.

## 6.1 Recommendations for further research

- To find a port that is suitable as an OECD-EU Baltic Port for future modelling. To make sure that the PECs are closer to reality.
- Further research regarding the effects on organisms and the impact on the marine ecosystems.

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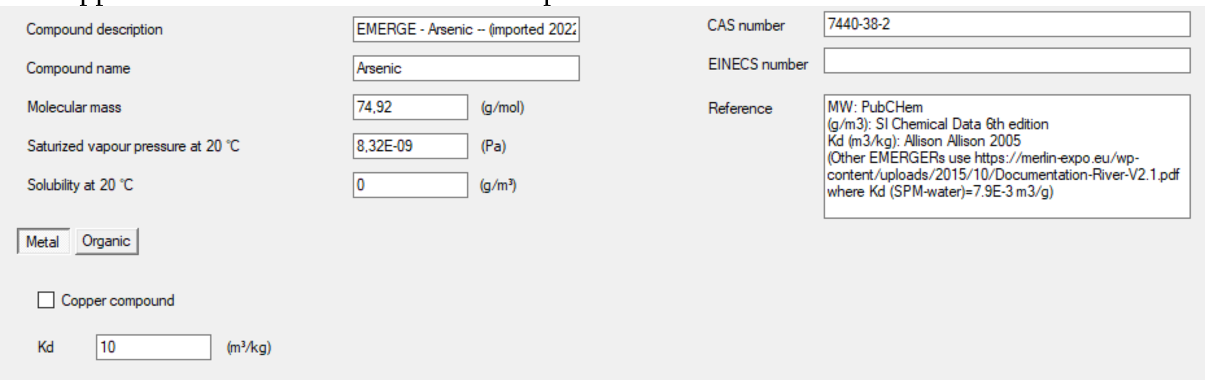
# APPENDIX 1

This appendix contains the data of all compounds with references.

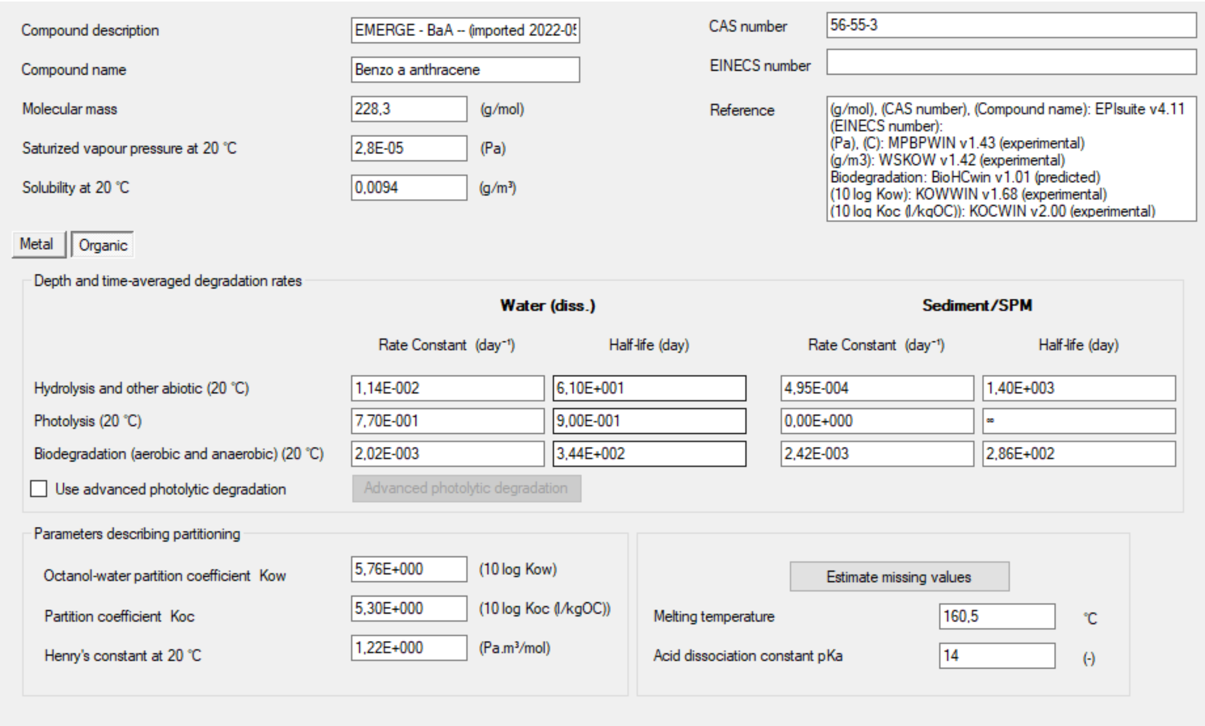


| | | | |
|---|---|---|---|
| Compound description | EMERGE - Arsenic -- (imported 202; | CAS number | 7440-38-2 |
| Compound name | Arsenic | EINECS number | |
| Molecular mass | 74,92 (g/mol) | Reference | MW: PubCHem<br>(g/m3): SI Chemical Data 6th edition<br>Kd (m3/kg): Allison Allison 2005<br>(Other EMERGERs use https://merlin-expo.eu/wp-content/uploads/2015/10/Documentation-River-V2.1.pdf where Kd (SPM-water)=7.9E-3 m3/g) |
| Saturized vapour pressure at 20 °C | 8,32E-09 (Pa) | | |
| Solubility at 20 °C | 0 (g/m³) | | |

Metal | Organic

☐ Copper compound

Kd 10 (m³/kg)



| | | | |
|---|---|---|---|
| Compound description | EMERGE - BaA -- (imported 2022-0! | CAS number | 56-55-3 |
| Compound name | Benzo a anthracene | EINECS number | |
| Molecular mass | 228,3 (g/mol) | Reference | (g/mol), (CAS number), (Compound name): EPIsuite v4.11<br>(EINECS number):<br>(Pa), (C): MPBPWIN v1.43 (experimental)<br>(g/m3): WSKOW v1.42 (experimental)<br>Biodegradation: BioHCwin v1.01 (predicted)<br>(10 log Kow): KOWWIN v1.68 (experimental)<br>(10 log Koc (l/kgOC)): KOCWIN v2.00 (experimental) |
| Saturized vapour pressure at 20 °C | 2,8E-05 (Pa) | | |
| Solubility at 20 °C | 0,0094 (g/m³) | | |

Metal | Organic

Depth and time-averaged degradation rates

| | Water (diss.) | | Sediment/SPM | |
|---|---|---|---|---|
| | Rate Constant (day⁻¹) | Half-life (day) | Rate Constant (day⁻¹) | Half-life (day) |
| Hydrolysis and other abiotic (20 °C) | 1,14E-002 | 6,10E+001 | 4,95E-004 | 1,40E+003 |
| Photolysis (20 °C) | 7,70E-001 | 9,00E-001 | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 2,02E-003 | 3,44E+002 | 2,42E-003 | 2,86E+002 |

☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

| | | |
|---|---|---|
| Octanol-water partition coefficient Kow | 5,76E+000 | (10 log Kow) |
| Partition coefficient Koc | 5,30E+000 | (10 log Koc (l/kgOC)) |
| Henry's constant at 20 °C | 1,22E+000 | (Pa.m³/mol) |

Estimate missing values

| | | |
|---|---|---|
| Melting temperature | 160,5 | °C |
| Acid dissociation constant pKa | 14 | (-) |

| | | | |
|---|---|---|---|
| Compound description | EMERGE - BaP -- (imported 2022-0 | CAS number | 50-32-8 |
| Compound name | Benzo a pyrene | EINECS number | |
| Molecular mass | 252,32 (g/mol) | Reference | (g/mol), (CAS number), (Compound name): EPIsuite v4.11<br>(EINECS number):<br>(Pa), (C): MPBPWIN v1.43 (experimental)<br>(g/m3): WSKOW v1.42 (experimental)<br>Biodegradation: BioHCwin v1.01 (predicted)<br>(10 log Kow): KOWWIN v1.68 (experimental)<br>(10 log Koc (l/kgOC)): KOCWIN v2.00 (experimental) |
| Saturized vapour pressure at 20 °C | 0,000103 (Pa) | | |
| Solubility at 20 °C | 0,00162 (g/m³) | | |

Metal | Organic

Depth and time-averaged degradation rates

| | Water (diss.) | | Sediment/SPM | |
|---|---|---|---|---|
| | Rate Constant (day⁻¹) | Half-life (day) | Rate Constant (day⁻¹) | Half-life (day) |
| Hydrolysis and other abiotic (20 °C) | 5,25E-003 | 1,32E+002 | 4,62E-004 | 1,50E+003 |
| Photolysis (20 °C) | 7,80E-001 | 8,89E-001 | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 1,64E-003 | 4,22E+002 | 3,09E-003 | 2,24E+002 |

☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

| | | |
|---|---|---|
| Octanol-water partition coefficient Kow | 6,13E+000 | (10 log Kow) |
| Partition coefficient Koc | 5,95E+000 | (10 log Koc (l/kgOC)) |
| Henry's constant at 20 °C | 4,63E-002 | (Pa.m³/mol) |

Estimate missing values

| | | |
|---|---|---|
| Melting temperature | 176,5 | °C |
| Acid dissociation constant pKa | 14 | (-) |

| | | | |
|---|---|---|---|
| Compound description | EMERGE - BghiP -- (imported 2022- | CAS number | 191-24-2 |
| Compound name | Benzo(ghi)perylene | EINECS number | |
| Molecular mass | 276,34 (g/mol) | Reference | (g/mol), (CAS number), (Compound name): EPIsuite v4.11<br>(EINECS number):<br>(Pa), (C): MPBPWIN v1.43 (experimental)<br>(g/m3): WSKOW v1.42 (experimental)<br>Biodegradation: BioHCwin v1.01 (predicted)<br>(10 log Kow): KOWWIN v1.68 (experimental)<br>(10 log Koc (l/kgOC)): KOCWIN v2.00 (estimated) |
| Saturized vapour pressure at 20 °C | 1,33E-08 (Pa) | | |
| Solubility at 20 °C | 0,00026 (g/m³) | | |

Metal | Organic

Depth and time-averaged degradation rates

| | Water (diss.) | | Sediment/SPM | |
|---|---|---|---|---|
| | Rate Constant (day⁻¹) | Half-life (day) | Rate Constant (day⁻¹) | Half-life (day) |
| Hydrolysis and other abiotic (20 °C) | 1,26E-002 | 5,50E+001 | 4,45E-004 | 1,56E+003 |
| Photolysis (20 °C) | 0,00E+000 | ∞ | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 1,34E-003 | 5,17E+002 | 1,23E-003 | 5,63E+002 |

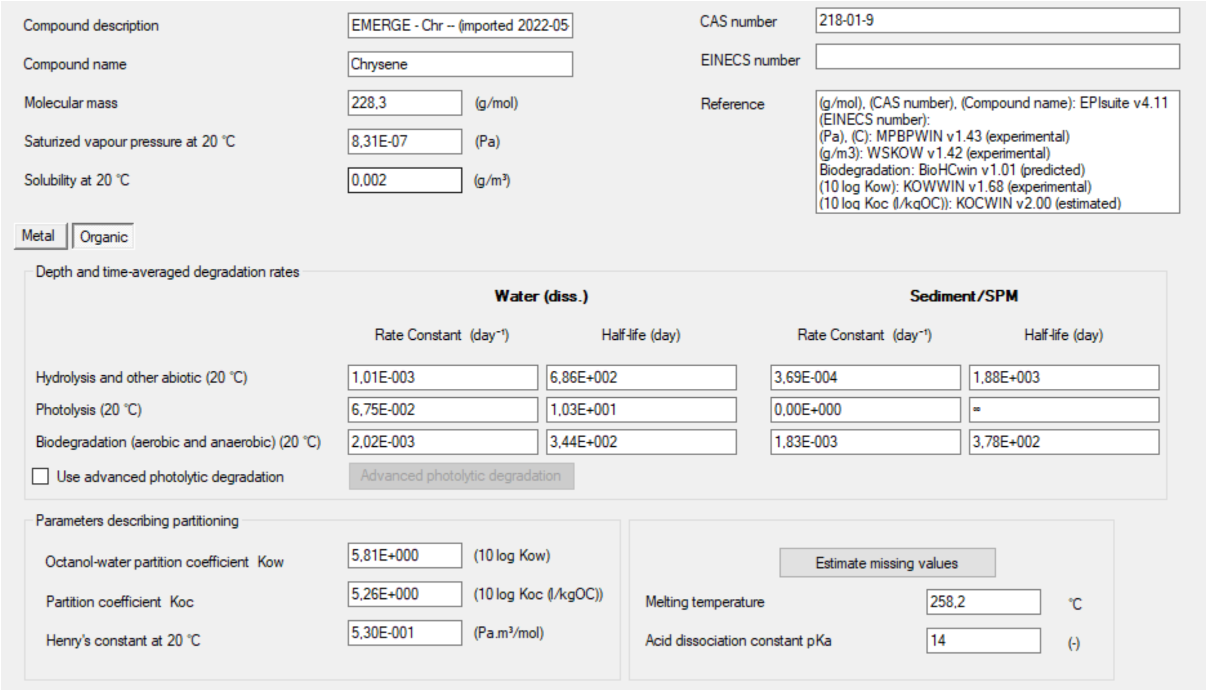
☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

| | | |
|---|---|---|
| Octanol-water partition coefficient Kow | 6,63E+000 | (10 log Kow) |
| Partition coefficient Koc | 6,29E+000 | (10 log Koc (l/kgOC)) |
| Henry's constant at 20 °C | 3,35E-002 | (Pa.m³/mol) |

Estimate missing values

| | | |
|---|---|---|
| Melting temperature | 278 | °C |
| Acid dissociation constant pKa | 14 | (-) |



Compound description: EMERGE - Chr -- (imported 2022-05

Compound name: Chrysene

Molecular mass: 228,3 (g/mol)

Saturized vapour pressure at 20 °C: 8,31E-07 (Pa)

Solubility at 20 °C: 0,002 (g/m³)

CAS number: 218-01-9

EINECS number:

Reference: (g/mol), (CAS number), (Compound name): EPIsuite v4.11
(EINECS number):
(Pa), (C): MPBPWIN v1.43 (experimental)
(g/m3): WSKOW v1.42 (experimental)
Biodegradation: BioHCwin v1.01 (predicted)
(10 log Kow): KOWWIN v1.68 (experimental)
(10 log Koc (l/kgOC)): KOCWIN v2.00 (estimated)

Metal | Organic

Depth and time-averaged degradation rates

| | Water (diss.) | | Sediment/SPM | |
|---|---|---|---|---|
| | Rate Constant (day⁻¹) | Half-life (day) | Rate Constant (day⁻¹) | Half-life (day) |
| Hydrolysis and other abiotic (20 °C) | 1,01E-003 | 6,86E+002 | 3,69E-004 | 1,88E+003 |
| Photolysis (20 °C) | 6,75E-002 | 1,03E+001 | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 2,02E-003 | 3,44E+002 | 1,83E-003 | 3,78E+002 |

☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

Octanol-water partition coefficient Kow: 5,81E+000 (10 log Kow)

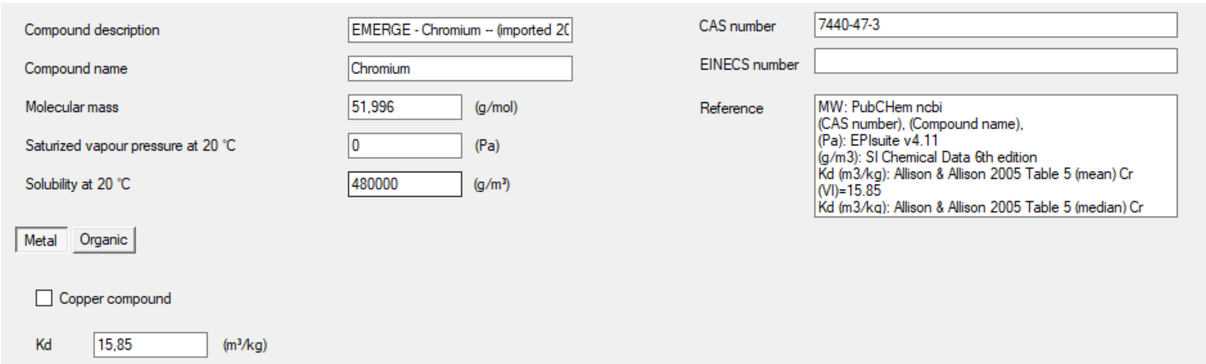
Partition coefficient Koc: 5,26E+000 (10 log Koc (l/kgOC))

Henry's constant at 20 °C: 5,30E-001 (Pa.m³/mol)

Estimate missing values

Melting temperature: 258,2 °C

Acid dissociation constant pKa: 14 (-)



Compound description: EMERGE - Chromium -- (imported 2(

Compound name: Chromium

Molecular mass: 51,996 (g/mol)

Saturized vapour pressure at 20 °C: 0 (Pa)

Solubility at 20 °C: 480000 (g/m³)

CAS number: 7440-47-3

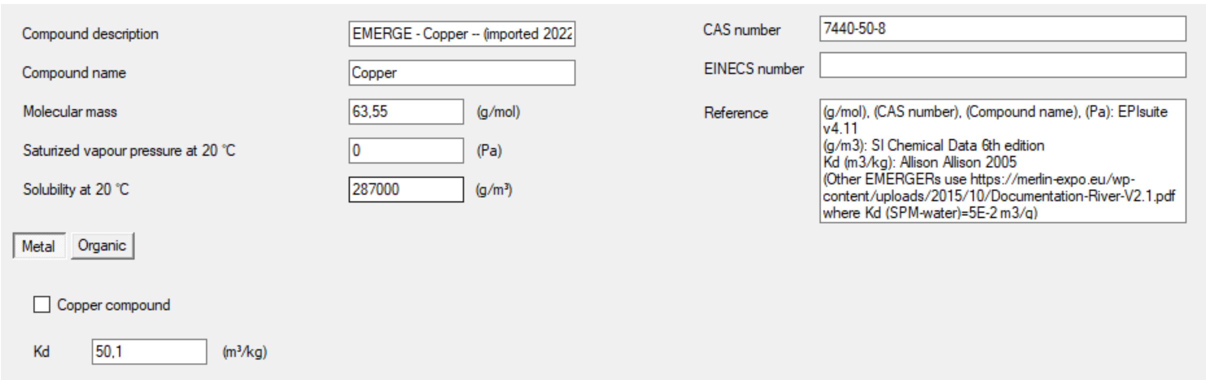
EINECS number:

Reference: MW: PubCHem ncbi
(CAS number), (Compound name),
(Pa): EPIsuite v4.11
(g/m3): SI Chemical Data 6th edition
Kd (m3/kg): Allison & Allison 2005 Table 5 (mean) Cr
(VI)=15.85
Kd (m3/kg): Allison & Allison 2005 Table 5 (median) Cr

Metal | Organic

☐ Copper compound

Kd: 15,85 (m³/kg)



Compound description: EMERGE - Copper -- (imported 2022

Compound name: Copper

Molecular mass: 63,55 (g/mol)

Saturized vapour pressure at 20 °C: 0 (Pa)

Solubility at 20 °C: 287000 (g/m³)

CAS number: 7440-50-8

EINECS number:

Reference: (g/mol), (CAS number), (Compound name), (Pa): EPIsuite v4.11
(g/m3): SI Chemical Data 6th edition
Kd (m3/kg): Allison Allison 2005
(Other EMERGERs use https://merlin-expo.eu/wp-content/uploads/2015/10/Documentation-River-V2.1.pdf where Kd (SPM-water)=5E-2 m3/g)

Metal | Organic

☐ Copper compound

Kd: 50,1 (m³/kg)

| | | | |
|---|---|---|---|
| Compound description | EMERGE - DahA -- (imported 2022-( | CAS number | 53-70-3 |
| Compound name | Dibenz(a,h)anthracene | EINECS number | |
| Molecular mass | 278,35 (g/mol) | Reference | (g/mol), (CAS number), (Compound name): EPIsuite v4.11<br>(EINECS number):<br>(Pa), (C): MPBPWIN v1.43 (experimental)<br>(g/m3): WSKOW v1.42 (experimental)<br>Biodegradation: BioHCwin v1.01 (predicted)<br>(10 log Kow): KOWWIN v1.68 (experimental)<br>(10 log Koc (l/kgOC)): KOCWIN v2.00 (experimental) |
| Saturized vapour pressure at 20 °C | 1,33E-08 (Pa) | | |
| Solubility at 20 °C | 0,00219 (g/m³) | | |

Metal | Organic

Depth and time-averaged degradation rates

| | Water (diss.) | | Sediment/SPM | |
|---|---|---|---|---|
| | Rate Constant (day⁻¹) | Half-life (day) | Rate Constant (day⁻¹) | Half-life (day) |
| Hydrolysis and other abiotic (20 °C) | 1,14E-002 | 6,10E+001 | 4,07E-004 | 1,70E+003 |
| Photolysis (20 °C) | 8,45E-002 | 8,20E+000 | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 1,36E-003 | 5,11E+002 | 1,65E-003 | 4,21E+002 |

☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

| | | | |
|---|---|---|---|
| Octanol-water partition coefficient Kow | 6,75E+000 (10 log Kow) | Estimate missing values | |
| Partition coefficient Koc | 6,22E+000 (10 log Koc (l/kgOC)) | Melting temperature | 269,5 °C |
| Henry's constant at 20 °C | 1,43E-002 (Pa.m³/mol) | Acid dissociation constant pKa | 14 (-) |

| | | | |
|---|---|---|---|
| Compound description | EMERGE - Fla -- (imported 2022-05- | CAS number | 206-44-0 |
| Compound name | Fluoranthene | EINECS number | |
| Molecular mass | 202,26 (g/mol) | Reference | (g/mol), (CAS number), (Compound name): EPIsuite v4.11<br>(EINECS number):<br>(Pa), (C): MPBPWIN v1.43 (experimental)<br>(g/m3): WSKOW v1.42 (experimental)<br>Biodegradation: BioHCwin v1.01 (predicted)<br>(10 log Kow): KOWWIN v1.68 (experimental)<br>(10 log Koc (l/kgOC)): KOCWIN v2.00 (experimental) |
| Saturized vapour pressure at 20 °C | 0,00123 (Pa) | | |
| Solubility at 20 °C | 0,26 (g/m³) | | |

Metal | Organic

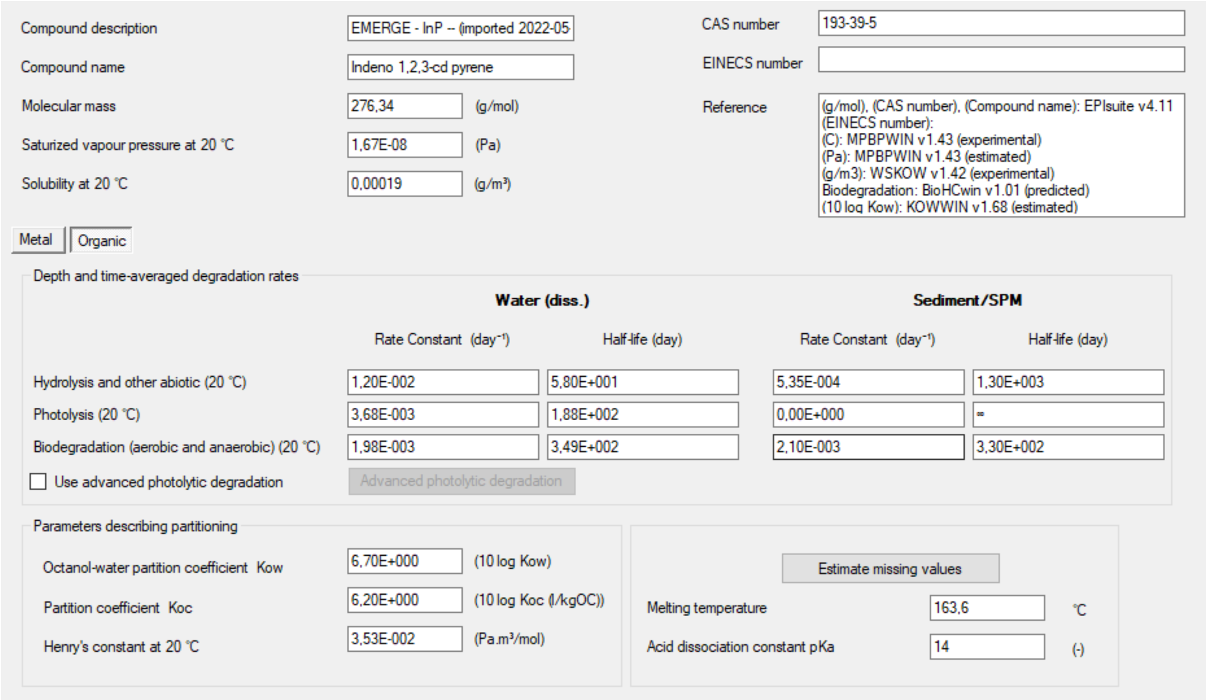
Depth and time-averaged degradation rates

| | Water (diss.) | | Sediment/SPM | |
|---|---|---|---|---|
| | Rate Constant (day⁻¹) | Half-life (day) | Rate Constant (day⁻¹) | Half-life (day) |
| Hydrolysis and other abiotic (20 °C) | 2,34E-001 | 2,96E+000 | 7,26E-003 | 9,55E+001 |
| Photolysis (20 °C) | 9,24E-003 | 7,50E+001 | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 3,62E-003 | 1,91E+002 | 4,72E-003 | 1,47E+002 |

☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

| | | | |
|---|---|---|---|
| Octanol-water partition coefficient Kow | 5,16E+000 (10 log Kow) | Estimate missing values | |
| Partition coefficient Koc | 4,80E+000 (10 log Koc (l/kgOC)) | Melting temperature | 107,8 °C |
| Henry's constant at 20 °C | 8,98E-001 (Pa.m³/mol) | Acid dissociation constant pKa | 14 (-) |



Compound description: EMERGE - InP -- (imported 2022-05

Compound name: Indeno 1,2,3-cd pyrene

Molecular mass: 276,34 (g/mol)

Saturized vapour pressure at 20 °C: 1,67E-08 (Pa)

Solubility at 20 °C: 0,00019 (g/m³)

CAS number: 193-39-5

EINECS number:

Reference: (g/mol), (CAS number), (Compound name): EPIsuite v4.11
(EINECS number):
(C): MPBPWIN v1.43 (experimental)
(Pa): MPBPWIN v1.43 (estimated)
(g/m3): WSKOW v1.42 (experimental)
Biodegradation: BioHCwin v1.01 (predicted)
(10 log Kow): KOWWIN v1.68 (estimated)

Metal | Organic

Depth and time-averaged degradation rates

| | Water (diss.) | | Sediment/SPM | |
|---|---|---|---|---|
| | Rate Constant (day⁻¹) | Half-life (day) | Rate Constant (day⁻¹) | Half-life (day) |
| Hydrolysis and other abiotic (20 °C) | 1,20E-002 | 5,80E+001 | 5,35E-004 | 1,30E+003 |
| Photolysis (20 °C) | 3,68E-003 | 1,88E+002 | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 1,98E-003 | 3,49E+002 | 2,10E-003 | 3,30E+002 |

☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

Octanol-water partition coefficient Kow: 6,70E+000 (10 log Kow)

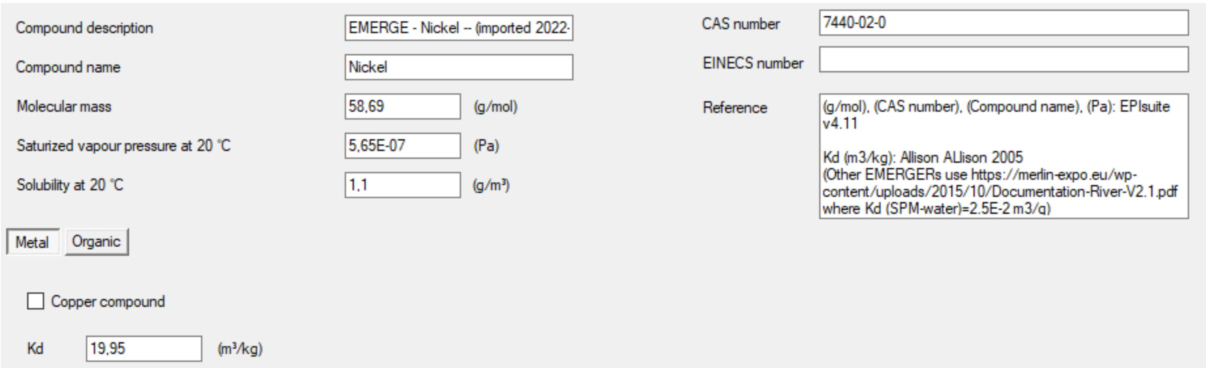
Partition coefficient Koc: 6,20E+000 (10 log Koc (l/kgOC))

Henry's constant at 20 °C: 3,53E-002 (Pa.m³/mol)

Estimate missing values

Melting temperature: 163,6 °C

Acid dissociation constant pKa: 14 (-)



Compound description: EMERGE - Nickel -- (imported 2022-

Compound name: Nickel

Molecular mass: 58,69 (g/mol)

Saturized vapour pressure at 20 °C: 5,65E-07 (Pa)

Solubility at 20 °C: 1,1 (g/m³)

CAS number: 7440-02-0

EINECS number:

Reference: (g/mol), (CAS number), (Compound name), (Pa): EPIsuite v4.11

Kd (m3/kg): Allison ALlison 2005
(Other EMERGERs use https://merlin-expo.eu/wp-content/uploads/2015/10/Documentation-River-V2.1.pdf where Kd (SPM-water)=2.5E-2 m3/g)

Metal | Organic

☐ Copper compound

Kd: 19,95 (m³/kg)

| | | | |
|---|---|---|---|
| Compound description | EMERGE - Pyr -- (imported 2022-05- | CAS number | 129-00-0 |
| Compound name | Pyrene | EINECS number | |
| Molecular mass | 202,26 (g/mol) | Reference | (g/mol), (CAS number), (Compound name): EPIsuite v4.11<br>(EINECS number):<br>(Pa), (C): MPBPWIN v1.43 (experimental)<br>(g/m3): WSKOW v1.42 (experimental)<br>Biodegradation: BioHCwin v1.01 (predicted)<br>(10 log Kow): KOWWIN v1.68 (experimental)<br>(10 log Koc (l/kgOC)): KOCWIN v2.00 (experimental) |
| Saturized vapour pressure at 20 °C | 0,0006 (Pa) | | |
| Solubility at 20 °C | 0,135 (g/m³) | | |

Metal | Organic

Depth and time-averaged degradation rates

| | Water (diss.) Rate Constant (day⁻¹) | Water (diss.) Half-life (day) | Sediment/SPM Rate Constant (day⁻¹) | Sediment/SPM Half-life (day) |
|---|---|---|---|---|
| Hydrolysis and other abiotic (20 °C) | 9,79E-003 | 7,08E+001 | 3,02E-004 | 2,29E+003 |
| Photolysis (20 °C) | 4,67E-001 | 1,48E+000 | 0,00E+000 | ∞ |
| Biodegradation (aerobic and anaerobic) (20 °C) | 2,45E-003 | 2,83E+002 | 2,92E-003 | 2,37E+002 |

☐ Use advanced photolytic degradation | Advanced photolytic degradation

Parameters describing partitioning

| | | |
|---|---|---|
| Octanol-water partition coefficient Kow | 4,88E+000 | (10 log Kow) |
| Partition coefficient Koc | 4,90E+000 | (10 log Koc (l/kgOC)) |
| Henry's constant at 20 °C | 1,21E+000 | (Pa.m³/mol) |

Estimate missing values

| | | |
|---|---|---|
| Melting temperature | 151,2 | °C |
| Acid dissociation constant pKa | 14 | (-) |

| | | | |
|---|---|---|---|
| Compound description | EMERGE - Vanadium -- (imported 2( | CAS number | 7440-62-2 |
| Compound name | Vanadium | EINECS number | |
| Molecular mass | 50,94 (g/mol) | Reference | MW: PubCHem<br>Kd: Allison Allison 2005 (water-SPM)<br>(Other EMERGERs use https://merlin-expo.eu/wp-content/uploads/2015/10/Documentation-River-V2.1.pdf where Kd (SPM-water)=5E-3 m3/g) |
| Saturized vapour pressure at 20 °C | 0 (Pa) | | |
| Solubility at 20 °C | 0 (g/m³) | | |

Metal | Organic

☐ Copper compound

Kd 5,01 (m³/kg)

| | | | |
|---|---|---|---|
| Compound description | EMERGE - Zinc -- (imported 2022-0! | CAS number | 7440-66-6 |
| Compound name | Zinc | EINECS number | |
| Molecular mass | 67,41 (g/mol) | Reference | (g/mol), (CAS number), (Compound name), (Pa): EPIsuite v4.11<br>(g/m3): SI Chemical Data 6th edition<br>Kd (m3/kg): Allison Allison 2005<br>(Other EMERGERs use https://merlin-expo.eu/wp-content/uploads/2015/10/Documentation-River-V2.1.pdf where Kd (SPM-water)=0.1 m3/g) |
| Saturized vapour pressure at 20 °C | 1,07E-20 (Pa) | | |
| Solubility at 20 °C | 2073156,273 (g/m³) | | |

Metal | Organic

☐ Copper compound

Kd 125,9 (m³/kg)

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