Assessing Pollutants in Scrubber Discharge Water

Informing the Regulation of Ships' Exhaust Gas Cleaning Systems

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About Us

Clear Seas Centre for Responsible Marine Shipping (Clear Seas) is an independent Canadian not-for-profit research centre that provides impartial and fact-based information about marine shipping.

Clear Seas' work focuses on identifying and sharing best practices for safe and sustainable marine shipping, encompassing the human, environmental and economic impacts of the shipping industry.

Clear Seas research and publications are available at clearseas.org.

About this Report

Clear Seas Centre for Responsible Marine Shipping (Clear Seas) conducted this research study, **Assessing Pollutants in Scrubber Discharge Water: Informing the Regulation of Ship's Exhaust Gas Cleaning Systems**, to better understand the information and methods available to characterize scrubber discharge water and the guidelines seeking to mitigate impacts from the discharge of scrubber washwater to the marine environment. This technical report, authored by Clear Seas, outlines the research methodology and results of the meta-analysis on scrubber discharge water.

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Message from the Executive Director

While Exhaust Gas Cleaning Systems (EGCS), commonly known as "scrubbers," are an effective means of removing sulphur oxide pollution from ship engine exhaust, the environmental impact of the discharge water – sometimes called washwater – produced by these devices, and how to manage and regulate it, has sparked controversy.

Scrubbers create operating cost savings by enabling the continued use of cheaper heavy fuel oil instead of more expensive low-sulphur fuel, so the debate centres on whether the true cost of discharging potentially polluted water produced by scrubbers into the marine environment is correctly factored into the business case – or if it should be tolerated at all. Of particular focus is the discharge of water containing heavy metals and polycyclic aromatic hydrocarbons (PAHs) into confined or near-shore waters like ports and anchorages. While some aspects of scrubber discharge water quality are regulated internationally, the current International Maritime Organization (IMO) guidelines only limit PAHs in aggregate and do not set limits for heavy metals. Faced with only partial restrictions at the international level, certain jurisdictions have already taken steps to restrict scrubber use. But how high are the levels of PAHs and heavy metals in scrubber discharge water?

This report by Clear Seas is intended to provide a reference guide for those seeking a better understanding of how scrubber discharge water compares to water quality guidelines. While water quality guidelines aren't conventionally used to assess the discharge directly from industrial processes they do provide a valuable reference point for comparison.

The primary goal of scrubber deployment is reducing sulphur oxide (SO_x) pollution of the air from ship engine exhausts – and scrubbers turn out to be very effective in this goal. There are two SO_x targets to meet: a more stringent 0.1% limit inside sulphur emissions control areas (SECAs) around Europe and North America, and the 0.5% limit in effect everywhere else since 2020. Ships without scrubbers need to burn one fuel inside SECAs – ultra low sulphur Marine Gas Oil (MGO) for example – and 0.5% sulphur Very Low Sulphur Fuel Oil (VLSFO) everywhere else. Both MGO and VLSFO are more expensive than the conventional high sulphur Heavy Fuel Oil (HFO) that ships equipped with scrubbers burn all the time, with the scrubber taking care of the sulphur emissions in the air. And tests of scrubbers have shown that they can be very effective at removing SO_x – more effective than even burning the lowest sulphur MGO.

But in other areas of air pollution performance like particulate matter (PM) and greenhouse gases (GHGs), scrubbers fall roughly between the two common low-sulphur fuel options. While scrubbers mostly outperform ships burning the commonly-used VLSFO, the air pollution performance of ships burning MGO – the most expensive fuel typically reserved for use in SECAs – has been found to be superior.

However, a complete assessment of the impact of scrubbers can't just focus on air emissions, and needs to also factor in their impact on the water through the discharge of scrubber wastewater into the marine environment. The sulphur removed from VLSFO, MGO and other low-sulphur fuels stays at the oil refinery, but in the case of a scrubber, it is discharged directly into the ocean. The research literature seems to be in harmony that sulphur – naturally occurring in seawater – can itself be absorbed, but the acidification caused by the low-pH discharge water is a source of concern. Measures to dilute the scrubber discharge water only protects the local environment from the potentially harmful effects of extreme low pH but ultimately don't change the total mass of acid entering the ocean. This study focuses on the potential local impacts of scrubber discharge by collecting pH data and comparing it to the established standards.

The remaining pollutants of concern in the scrubber discharge water are PAHs and heavy metals. These pollutants can accumulate to levels that are harmful to the environment, marine life and human health and are therefore a significant focus of this research report. A somewhat startling conclusion from the scrubber inlet water measurements surveyed is that the seawater in many jurisdictions is already highly polluted with heavy metals and PAHs, from anthropogenic activities but also from naturally-occurring sources. PAHs and heavy metals are a product of fossil fuel use and are contained in the combustion products of HFO, VLSFO and MGO but in declining quantities as fuels are more refined. The detailed analysis of the scrubber discharge water is a stark reminder of the fact that fossil fuels contain heavy metals and PAHs. This report highlights the difficulty in setting standards for PAHs because specific fuel samples may contain levels of an individual PAH that exceeds guidelines even though the total PAHs are within acceptable limits.

The use of fossil fuels, and particularly residual fuels like VLSFO and HFO, has consequences on the environment not only due to GHG emissions and other harmful air pollutants, but also in introducing PAHs and heavy metals into the environment. Scrubbers direct those pollutants straight into the water whereas exhaust emissions travel through air to be later deposited into the water and onto land. Low-sulphur fuel alternatives are not somehow free from these same damaging pollutants. The most expensive low sulphur alternatives like MGO are cleaner, but currently these are only used in the SECAs around Europe and North America.

Protecting sensitive coastal areas from the harmful effects of accumulating pollutants like PAHs and heavy metals should be a priority. The evidence from this report supports the conclusions of policy makers and local regulatory bodies who are restricting the discharge from scrubbers in confined waters like estuaries, harbours, and anchorages.

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Acronyms and Abbreviations

°C	Degrees Celsius
B.C.	British Columbia
B.C. WQGs	British Columbia Water Quality Guidelines
CCME	Canadian Council of Ministers of the Environment
CEGQs	Canadian Environmental Quality Guidelines
CO_2	Carbon dioxide
EGCS	Exhaust Gas Cleaning System
EGCSA	Exhaust Gas Cleaning System Association
IMO	International Maritime Organization
LOD	Limit of detection
m^3	Cubic metres
MEPC	Marine Environmental Protection Committee
mg	Milligram
MGO	Marine Gas Oil
mL	Millilitre
MW	Megawatt
MWh	Megawatt hour
PAHs	Polycyclic aromatic hydrocarbons
PAH_{phe}	Phenanthrene equivalents
ppb	Parts per billion
t	Tonnes
U.S.	United States
USEPA	United States Environmental Protection Agency
UV	Ultraviolet light
VLSFO	Very Low Sulphur Fuel Oil
WQG	Water quality guideline
µg	Microgram

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Assessing Pollutants in Scrubber Discharge Water

Informing the Regulation of Ships' Exhaust Gas Cleaning Systems

1.0 Introduction

While the International Maritime Organization (IMO) permits scrubber use as an alternative to low sulphur fuel, there is continuing debate on their use and the potential impacts scrubber discharge water – also called washwater – has on aquatic ecosystems. Clear Seas completed the research project that resulted in this report to explore levels of contaminants in scrubber discharge water from different types of scrubbers and assess the effectiveness of current IMO guidelines as a basis for regulating the impact of scrubbers on the marine environment and water quality.

The use of scrubbers to remove sulphur from ship exhaust gas after combustion rather than in the fuel refining process allows ship operators to continue to use fuels that exceed the 0.5% sulphur standard (0.1% within Sulphur Emissions Control Areas) while still meeting IMO regulatory requirements. The in-situ removal of sulphur from ship engine exhaust requires the installation of scrubber equipment at an upfront cost that needs to be recovered through fuel cost savings incurred due to the discount high-sulphur heavy fuel oil sells at compared to both Very Low Sulphur Fuel Oil (VLSFO) and Marine Gas Oil (MGO) that respectively meet the 0.5% and 0.1% limits on sulphur content in fuel. Operation of scrubbers permit ship operators to meet even the more stringent 0.1% effective sulphur limits while using high-sulphur heavy fuel oil (Comer et al., 2020).

Higher sulphur content in the fuel may have some advantages by reducing engine wear and improving reliability due to its increased lubricity. Some concerns were originally raised about the safety of low sulphur fuels, such as engine reliability due to the absence of the lubrication provided by sulphur in fuel, and an IMO correspondence group was established to consider fuel oil safety issues and quality standards and guidance issued on best practice for fuel oil suppliers (IMO, n.d.).

While scrubbers are a recognized and approved technology, concerns have been raised regarding the impacts of scrubber discharge water on aquatic environments. The discharged effluents from both open-loop and closed-loops systems are more acidic than the surrounding seawater and contain potential polluting compounds, including heavy metals and polycyclic aromatic hydrocarbons (PAHs). While the IMO has established the 2015 Guidelines for Exhaust Gas Cleaning Systems (Resolution MEPC.259(68) (IMO, 2015) which specify discharge limits for pH, total PAHs, turbidity and nitrates, the current guidelines do not include comprehensive discharge specifications for suspended particulate matter, individual PAHs and heavy metals, or other potential pollutants in scrubber discharge water such as sulfates, other hydrocarbons and oil. Furthermore, studies have reported varying conclusions on whether or not there are potential environmental impacts from scrubber effluent discharges. The concerns over the adequacy of the IMO guidelines and the ongoing debate on discharge water impacts have led to overall uncertainty as to whether scrubbers are a threat to the environment, and if so, to what extent.

In the absence of more comprehensive regulations, many jurisdictions have implemented partial or complete bans on the use of scrubbers and effluent discharge within their waters due to the uncertainty of the discharge water's possible impact on the marine environment; as of April, 2021, 30 countries and three U.S. states have established measures (Britannia P&I, 2021). In Canada, the iron ore port of Sept-Îles, Quebec has already banned open-loop scrubber discharges within the port limits (this restriction does not apply to closed-loop scrubbers) (Iron Ore Company of Canada, 2021), and the Port of Vancouver implemented measures to restrict the discharge of scrubber discharge washwater that came into effect in March 2022 (Vancouver Fraser Port Authority, 2022). Yet because scrubbers offer ship owners a cost-effective alternative to switching to more expensive low sulphur fuels, scrubbers continue to generate interest from the shipping industry. Despite installation and retrofit costs, scrubbers still offer significant potential savings and a viable way for ship owners to extend the operational lifespan of existing fleets while ensuring compliance with the IMO regulations.

1.1. Research Objectives

To shed light on this complex issue and to attempt to provide clearer information for those making decisions on scrubber use, Clear Seas conducted a comprehensive study to characterize existing knowledge on the potential environmental impacts of scrubber discharge water. The purpose of Clear Seas scrubber research is to better understand the current knowledge and information available on scrubber discharge water to assist in the assessment of potential environmental impacts of scrubber use in Canadian and global waters.

By including data from multiple sources, this project brings together the best available information on the chemistry of scrubber discharge water from open-loop and closed-loop scrubber systems. In taking a closer look at the constituents of scrubber discharge water and the types of scrubber systems they are collected from, this technical study seeks to characterize the known levels of contaminants in scrubber discharge waters and to provide a baseline dataset for comparison to water quality guidelines. By comparing the combined scrubber effluent data to the IMO EGCS guidelines as well as local water quality guidelines, this research aims to characterize the pollution levels of scrubber discharge water and contribute new information to help inform those making decisions on restricting scrubber use or discharges.

By taking an in depth look at the different data and analytical methods used across a range of studies to support different conclusions on scrubber impacts, this work also aims to identify differences and sources of uncertainty between the different assessments, to bring clarity to conflicting perspectives that exist on whether or not scrubbers are safe from an environmental standpoint. In this way, this project seeks to contribute new findings to the debate on scrubber effluent water impacts, to support effective planning and the use and regulation of scrubber systems in Canadian waters and beyond.

1.2. Research Scope and Approach

Clear Seas initially commissioned Serco Canada Marine to conduct a study on the use of EGCS, commonly known as scrubbers, to reduce sulphur emissions from ships. The study included a search of recent environmental assessments, some of which reported analytical data on scrubber discharge water quality. Building on the results of Serco's work, Clear Seas conducted further research to augment the literature search and source analytical datasets from additional sources for a detailed exploration on scrubber discharge water.

The scrubber discharge water data from ten different studies, including government, academic, and industry sources, were compiled and a meta-analysis was conducted on the combined data. This meta-analysis allowed for the assessment of scrubber discharge water quality from multiple sources. The comparison between inlet and outlet water and between open-loop and closed-loop systems, provides an understanding of what compounds are present is scrubber discharge water and how scrubber discharge water varies by scrubber type and operations.

The combined dataset was compared to the 2015 IMO Guidelines for Exhaust Gas Cleaning Systems (Resolution MEPC.259(68) (IMO, 2015) ("IMO guidelines") to assess scrubber discharge water versus the international discharge criteria. In addition, the data were compared to a set of Canadian environmental water quality guidelines as relatable criteria used for assessing impacts to marine species and system health.

1.3. Report Structure

Section 2.0 below outlines the methods used to gather, process and analyze data related to scrubber discharge water, including the studies used in the meta-analysis and relevant guidelines used to evaluate water quality guidelines in the Canadian context. Section 3.0 outlines study limitations.

Results of the analytical studies assessment, including key findings and recommendations for methods related to scrubber discharge water monitoring and analysis, are provided in Section 4.0. A corresponding summary table providing a detailed comparison of the ten analytical studies is provided in Appendix A.

Results of the scrubber discharge water analysis, including key findings and recommendations regarding controlling the pollution from scrubber discharges and the effectiveness of the current IMO guidelines, are discussed in Section 5.0. Supporting figures designed to visualize the discharge water results compared across studies and to Canadian water quality guidelines are provided.

2.0 Methods

2.1. Literature Search

A review of recent peer-reviewed literature and environmental assessment studies was conducted to characterize and compare existing knowledge and areas of uncertainty on the environmental impacts of scrubber discharge water. This review included studies and results on the impacts scrubber discharge water from a variety of different sources, including:

- Submissions to the IMO Marine Environmental Protection Committee (MEPC) and Sub-Committee on Pollution Prevention and Response (PPR)
- Governmental agency environmental assessments
- Industry and trade publications
- NGO publications
- Academic journal articles

The publications discovered in the literature search formed the basis and starting point for the technical study outlined in this report. The review provided an understanding of the different ways in which the environmental impacts of scrubber discharges were assessed, including in comparison to the IMO and other water quality guidelines, through effluent toxicity studies, and through modeling of pollution loads to and dispersion in the marine environment. The review also provided insight on the current issues related to onboard scrubber discharge water monitoring and concerns raised regarding limitations in the IMO guidelines as a mitigation measure. The studies were also used to inform the research objectives and assessment approach taken in this study.

From the total body of research surveyed, a set of ten studies was selected that provided sufficient analytical data on scrubber discharge water quality to compare between different analytical studies and scrubber types, as well as to compare discharge water pollution levels to the IMO guidelines and a set of Canadian and provincial water quality guidelines, which for this study served to provide an equivalent basis for comparison between different pollution types. The literature search included a review of a recent study by the International Council on Clean Transportation (ICCT) (Comer et al., 2020) which similarly assessed scrubber discharges using data compiled from multiple studies. Comer et. al. limited their investigation to ten studies that included flow rate of discharge, because the objective of this analysis was to determine the total mass of pollution in scrubber discharges and to assess compliance with the IMO guidelines. The ICCT dataset included seven studies that reported values for at least one heavy metal and four studies with usable information on PAHs. Given the broader objectives of this study to explore variation in scrubber effluent results through measures other than just the IMO guidelines, we relaxed this requirement to include analytical studies without data on engine power and flow rates to provide a larger data set, including ten studies for heavy metals and eight studies for individual PAHs.

2.2. Data Compilation, Processing and Visualization

To better understand the constituents of scrubber discharges and the types of scrubber systems and ship operations that they represent, analytical data on scrubber discharge water – including pre- and post-treatment water – were sourced from the literature search studies. Analytical data were identified in ten different studies and were compiled into a master database. Summary details for the studies from which analytical data were sourced are provided Appendix A.

2.2.1. Data Compilation

Data compilation steps included to identify, sort and match the results from individual studies to a common set of parameters for use in this meta-analysis. As well as the scrubber discharge water analytical data, parameters relevant to the assessment objectives of this study were gathered, including scrubber type and operational conditions. Analytical test results were sorted and matched by compound analyzed to ensure alignment across the studies. The results were grouped together by study and plotted according to sample type by the following three categories:

- Seawater Inlet: scrubber system water collected prior to use as washwater for exhaust gas treatment
- Open-loop Discharge: discharge water from scrubbers operating in open-loop mode
- Closed-loop Discharge: discharge water from scrubbers operating in closed-loop mode

Sample type was assigned based on the sample descriptions provided in the source dataset. Pre-treatment system water includes sample types identified as seawater or inlet water. Post-treatment includes sample types identified as discharge, washwater from scrubber, or bleed-off. Two results identified as "circulation" were not used in the combined dataset for this study as these samples were assumed to represent recirculated water not discharged to the environment.

2.2.2. Data Processing

Data processing steps included:

- Converting analytical results to a consistent unit as needed (e.g., metal results provided in mg were adjusted to µg). Units was selected to align to the unit of measure used for the corresponding water quality guidelines each parameter was compared to.
- Calculating total PAHs as the sum of individual PAHs using the United States Environmental Protection Agency's (USEPA) 16 priority PAHs.
- Calculating total PAHs normalized to engine power and flow in µg/MWh, for the analytical results for which sufficient data were provided. As the IMO guidelines for total PAH discharge concentration limit varies by washwater flow rate through the EGCS unit, this enabled for comparison of all total PAH results to a single value.

2.2.3. Data Visualization

Data visualization steps included plotting a series of figures representing the range of results for pH, metals, metal concentrations relative to pH, and individual and total PAHs. All figures are provided in Appendix B. Considerations for visualizing the analytical data included:

- Data are split out by the ten studies, in order to enable investigation of potential underlying factors affecting scrubber discharge results – such as analytical assessment methods (Section 4.0), or the variation in contaminants in seawater, which would depend on the waters ships were sailing through (Section 5.2.1).
- Data within each of the ten studies are grouped as seawater inlet, open-loop and closed-loop sample types, to illustrate the variation between different inlet and discharge water and between different scrubber types.
- Analytical results for both scrubber inlet and discharge water were plotted rather than the net difference between inlet and discharge water on a sample-by-sample basis (i.e. the net increase contributed from the exhaust gas stream), in order to illustrate if the same pollutants found in scrubber discharge water are present in marine waters and at what concentration range.
- Analytical results reported in the original analytical studies non-detectable (i.e., if anything was present it was at a concentration below the analytical detection limit of the analytical assay) were included in the initial screening of the combined dataset using both the value of the limit of detection (LOD) and the value of one half the LOD. Ultimately, the decision was made to exclude any results reported as less than the LOD from the study figures. This is because for many of the parameters analyzed, the analytical LODs both varied across the analytical studies and were greater than the corresponding guideline for comparison, the implications of which are discussed further in Section 0 below. This is a study limitation in that these results with low concentrations are not represented on the figures.
- Analytical data were plotted relative to the IMO guideline for parameters where a discharge limit in scrubber discharge water has been established as well as relative to the best available Canadian or B.C. water quality guideline (see Section 2.3.2 below). Figures are only provided for those individual metals and PAHs that had a corresponding Canadian or B.C. water quality guideline. Data for these additional parameters were available and compiled from the original studies, however figures were not prepared as there were no guidelines for comparison to and was therefore less relevant to the assessment objectives of this study.
- Analytical data for the total PAH normalized to flow were also plotted relative to two different benchmarks established specifically for this study to meet the objectives of understanding if the IMO guidelines are sufficient. These benchmarks include:
    - The IMO discharge limit represented as a range in concentration of total PAH (µg/mL), calculated using typical flow rates as reported in the literature (for a vessel operating with an engine power of 15 MW, at a typical flow rate 200-500 L s^{-1} for open-loop systems and 0.5-3 L s^{-1} for closed-loop systems) (Teuchies et al., 2020).

- An illustrative water quality guideline (WQG) sample calculated using the sum of the relevant Canadian and B.C. water quality guidelines, representing a total PAH concentration. By inference, a sample exceeding this illustrative WQG would exceed at least one of the individual PAH guidelines. Note that this is a conservative metric as it only includes the ten PAHs for which there are established Canadian and B.C. water quality guidelines, and does not include the full set of USEPA 16 priority PAHs or any other PAHs that could be present in scrubber discharges.

2.3. Selection of Water Quality Guidelines

2.3.1. IMO Guidelines for EGCS

The IMO has established EGCS guidelines (2015 Guidelines for Exhaust Gas Cleaning Systems (Resolution MEPC.259(68)), referred to as "IMO guidelines" going forward) which specify the requirements for the testing, survey certification and verification of exhaust gas cleaning systems to ensure that they provide effective equivalence in sulphur emissions. As scrubber discharge water has the potential to affect the marine ecosystem, these guidelines include criteria for the quality of scrubber effluent discharges. The current IMO guidelines specify the discharge requirements for four parameters: pH, total PAHs, turbidity and nitrates, yet do not stipulate discharge limits for heavy metals and individual PAHs. While the IMO Working Group on Prevention of Air Pollution from Ships discussed using turbidity as a potential indicator for heavy metals, articulating precise criteria for specific heavy metals was ultimately decided to be impractical (IMO, 2007b). Impracticalities cited in the correspondence group discussions included that it is unrealistic to measure heavy metals on board and that metal content in discharge water is determined by fuel quality and engine combustion condition (rather than scrubbers). It was further noted that setting criteria for metals may encourage the use of equipment that minimize particle reduction by the scrubber, counterproductive to the benefit scrubbers provide in minimizing emissions of particulate matter to the atmosphere (IMO, 2007a).

IMO guidelines on EGCS have progressively changed in the past years. The latest guideline on EGCS, MEPC.259(68), was published in 2015, superseding the previous guideline MEPC.184(59) released in 2009. A review of the 2015 guidelines by the Sub-Committee on Pollution Prevention and Response of the IMO MEPC was completed in 2020, however no changes to the discharge limits were proposed from the 2015 guidelines. They do note that discharge water quality criteria should be reviewed in the future as more data becomes available.

2.3.2. Canadian and Provincial Water Quality Guidelines

Given the lack of specific discharge limits provided for metals and PAHs in the IMO guidelines, and to provide context for assessing the impacts of scrubber discharges in Canadian waters, scrubber inlet and outlet water data for metals and PAHs were compared to relevant water quality guidelines established for Canadian and provincial waters. While these water quality guidelines are not specific to scrubber discharge, they can be helpful to characterize the general quality of the scrubber discharge water and provide a broader perspective than comparison to IMO requirements alone. The use of these guidelines in this assessment is to provide a reference benchmark relative to established levels of concern in aquatic environments.

National water quality guidelines used in this study include the Canadian Council of Ministers of the Environment (CCME) Canadian Environmental Quality Guidelines (CEGQs), specifically the water quality guidelines for the protection of aquatic life (CCME, 2022b). The CEQGs define numerical concentrations recommended as levels that should result in negligible risk to biota and fish habitat function and provide science-based goals for the quality of aquatic and terrestrial ecosystems (CCME, 2022a).

Since the CCME CEQGs do not provide a criteria for all parameters tested in the sampling campaigns considered in this study, additional provincial guidelines were selected from the province of British Columbia's Water Quality Guidelines (B.C. WQGs), specifically water quality guidelines for the protection of aquatic life (B.C. Ministry of Environment and Climate Change Strategy, 2020). The B.C. Ministry of Environment develops ambient water quality guidelines to promote healthy ecosystems and protect human health. These water quality guidelines are science-based levels of physical, biological, and chemical parameters for the protection of water uses such as aquatic life, wildlife, agriculture, drinking water, and recreation. The B.C. WQGs are used to assess and manage the health, safety and sustainability of B.C.'s aquatic resource. They include current approved guidelines, that serve as environmental benchmarks for safe levels of specific water quality parameters across B.C., and working guidelines, that provide benchmarks for those parameters not yet fully assessed and formally approved in B.C.

Both the CCME CEQGs and B.C. WQGs include guidelines established for marine and freshwater environments. Generally, guidelines are set separately for freshwater and marine environments because of the fundamental differences in the chemistry between the different water bodies and the different toxic effects that occur as a result. However, for substances for which no significant influence on chemical behaviour can be shown or reasonably anticipated, and where no differences in toxicity toward freshwater and marine organisms (by comparison of similar taxonomic groups) can be seen, toxicity data from freshwater organisms may be used in order to broaden the marine database (CCME, 2007).

Both the CCME CEQGs and B.C. WQGs include long-term and short-term guidelines. Long-term guidelines are based on average concentration levels and are intended to protect the most sensitive species and life stage against sub-lethal and lethal effects for indefinite or chronic exposures. Short-term guidelines are based on maximums level that should never be exceeded in order to meet the intended protection of the most sensitive species and life stage against severe effects such as lethality over a defined short-term exposure period (e.g. 96 hrs). Short-term maximum guidelines are intended to assess risks associated with infrequent exposure events such as spills (B.C. Ministry of Environment and Climate Change Strategy, n.d.).

The set of water quality guidelines used in this study for each analytical parameter are provided in Table 1 below. Because there are multiple guidelines for each individual parameter, the guideline used in this study was selected from the CEQGs and B.C. WQGs according to the following sequence:

- CEQGs were used in preference to B.C. WQGs as national guidelines.
- Guidelines specific to marine waters were used in preference to guidelines specific to freshwater, as scrubber discharge water from open-loop systems would be discharged to seawater with natural buffering capacity.
- Short-term guidelines were used in preference to long-term guidelines, as these guidelines are lower in value (therefore more conservative) and more relevant for measuring the acute impacts of an effluent discharge from a point source.
- For some of the individual PAHs measured in scrubber discharge water, neither a CEQG or B.C. WQG has been established. In these cases, figures comparing PAHs with CEQG or B.C. WQG were not prepared.

Table 1. Water Quality Guidelines Used in Study

Parameter	**Guideline**	**Source**		
pH	pH should not be less than 6.5	IMO 2015		
	7.0 to 8.7 & Narrative	CCME CEQG	Marine	Long-term
Metals				
Aluminum		-		
Arsenic	12.5 µg/L	CCME CEQG	Marine	Long-term
Cadmium	0.12 µg/L	CCME CEQG	Marine	Long-term
Chromium *(hexavalent)*	1.5 µg/L	CCME CEQG	Marine	Long-term
Copper	2 µg/L	B.C. WQG	Marine	Long-term
Iron	300 µg/L	CCME CEQG	Freshwater	Long-term
Lead	140 µg/L	B.C. WQG	Marine	Short-term
Mercury	0.016 µg/L	CCME CEQG	Marine	Long-term
Nickel	8.3 µg/L	B.C. WQG	Marine	Long-term
Selenium	1 µg/L	CCME CEQG	Freshwater	Long-term
Thallium	0.8 µg/L	CCME CEQG	Freshwater	Long-term
Vanadium	50 µg/L	B.C. WQG	Marine	Long-term
Zinc	10 µg/L	B.C. WQG	Marine	Long-term
Individual PAHs				
1-methylnaphthalene	-	-	-	-
2-methylnaphthalene	-	-	-	-
Acenaphthene	5.8 µg/L	CCME CEQG	Freshwater	Long-term
Acenaphthylene	-	-		
Anthracene	0.012 µg/L	CCME CEQG	Freshwater	Long-term
Benzo(a)anthracene	0.018 µg/L	CCME CEQG	Freshwater	Long-term
Benzo(a)pyrene	0.01 µg/L	B.C. WQG	Marine	Long-term
Benzo(b)fluoranthene	-	-	-	-
Benzo[b]fluoranthene + Benzo[j]fluoranthene	-	-	-	-
Benzo(g,h,i)perylene	-	-	-	-

Parameter	Guideline	Source		
Benzo(k)fluoranthene	-	-	-	-
Biphenyl	-	-	-	-
Chrysene	0.1 µg/L	B.C. WQG	Marine	Long-term
Dibenzo(a,h)anthracene	-	-	-	-
Dibenzothiophene	-	-	-	-
Hexachlorobenzene	-	-	-	-
Fluoranthene	0.04 µg/L	CCME CEQG	Freshwater	Long-term
Fluorene	12 µg/L	B.C. WQG	Marine	Long-term
Indeno(1,2,3-cd)pyrene	-	-	-	-
Naphthalene	1.4 µg/L	CCME CEQG	Marine	Long-term
Perylene	-	-	-	-
Phenanthrene	0.4 µg/L	CCME CEQG	Freshwater	Long-term
Pyrene	0.02 µg/L	B.C. WQG	Marine	Short-term
Total PAHs	50 µg/L (PHE)	IMO 2015		

PHE: Phenanthrene equivalence; IMO guidelines are normalized for an equivalent flow of 45 t/MWh.

3.0 Study Limitations

- The focus of this research study is to assess the quality of scrubber discharge water relative to reference criteria, including the IMO guidelines and relevant Canadian water quality guidelines. The CEQGs and B.C. WQGs applied in this study were for general comparison purposes only. These guidelines are not used as the basis for regulation of scrubbers and they are not specific to scrubber discharge water or other industry effluent.
- This study does not attempt to assess the resulting environmental impacts of scrubber discharge in Canadian waters. The comparison of scrubber discharge water to the Canadian water quality guidelines is done for general purposes only does not constitute an assessment of environmental impacts. This study does not account for any dilution factor in receiving waters or for the total volume of scrubber discharge water or attempt to assess the total load of contaminants reaching the marine environment, on an individual vessel basis or accounting for the number of vessels sailing in Canadian waters and accounting for the frequency of scrubber discharges.
- This study does not attempt to evaluate how scrubber discharge water quality varies with operational parameters, such as speed, engine load, % sulphur fuel content, as the main research objectives were to better characterize variation between studies and by different system type (open-loop versus closed-loop systems) and as the data and information needed to complete this analysis was not available from all the analytical studies. Notably, this study does not account for flow rate, which affects how concentrated or diluted scrubber discharge water is.
- No new analytical data on scrubber discharge water were generated as a part of this study. As this study draws on data from other sources, any issues or limitations within each of the individual primary studies would be propagated and compounded in this study.
- Many of the analytical results in the combined dataset were reported as non-detectable. Only analytical results reported as detectable levels were including the study figures. As a result, the data visualized in this study is not representative of the average or full range of concentrations for a given parameter in scrubber discharge water, and should be taken into consideration when reviewing and drawing conclusions from the figures and study results.
- The report figures plot scrubber discharge water results as both inlet and outlet water in order to illustrate the pollution contribution from source waters. They do not show the net increase by scrubber systems, which would account only for the pollutant load contributed by from exhaust gas via the scrubber discharge water.
- This research is specific to scrubber discharge water quality and does not include an assessment of air emissions, including scrubber effectiveness in reducing air emissions or an assessment of impacts to air quality.

4.0 Results of Analytical Studies Assessment

The ten analytical studies were categorised by scrubber system type, ship and engine details, sample type and the parameters assessed and available analytical data to characterize scrubber discharge water. The study comparison included a review of the different conclusions reached on the impacts of scrubbers to the marine environment. The ten analytical studies considered in this meta-analysis study are listed in Table 2 below, and a detailed summary comparison is provided in Appendix A.

The study comparison accounted for the guidelines which different studies used to draw conclusions on scrubber effluent impacts. Similar to how the Canadian and B.C. water quality guidelines are applied in this meta-analysis, studies from other jurisdictions have applied criteria other than the IMO guidelines as reference criteria that are not requirements for scrubber effluent compliance, for reasons including to assess parameters of interest that are not currently included in the IMO guidelines and to provide a basis for assessing potential impacts of scrubber discharges to the marine environment.

Six out of the ten analytical studies considered in this study compared scrubber discharge water results to the IMO guidelines for EGCS, and eight of the ten studies applied at least one set of water quality guidelines. These criteria vary by the intended water quality objective they serve, including for evaluating environmental water quality (protection of aquatic species and systems), industry effluent, and drinking water (protection of human health), as well as quality standards for application of sludge on agricultural soils. Because the studies were for vessels operating in different parts of the world, different national and regional guidelines applied to assess impacts to environmental quality. None to date have considered relative to Canadian water quality guidelines.

Table 2. Analytical Studies used in Meta-Analysis

Analytical Study	Study Title	Completed by	Reference
IVL (2018)	Scrubbers: Closing the loop. Activity 3: Summary Environmental analysis of marine exhaust gas scrubbers on two Stena Line ships	IVL Swedish Environment Research Institute	(Winnes et al., 2018)
Japan (2019)	Report by the expert board for the environmental impact assessment of discharge water from Scrubbers	Government of Japan (various ministries)	(Japanese Government, 2019)
Hansen (2012)	Exhaust Gas Scrubber Installed Onboard MV Ficaria Seaways	Danish Ministry of the Environment - Environmental Protection Agency	(Hansen, 2012)
Buhaug et al. (2007)	MARULS WP3: Washwater Criteria for seawater exhaust gas-SO_x scrubbers, in MEPC 56/INF.5 ANNEX 1	Norwegian Marine Technology Research Institute (MARITEK) for Norwegian Shipowners Association / Research Council of Norway	(Buhaug et al., 2007)
Kjølholt et al. (2012)	Assessment of the possible impacts of scrubber water discharges on the marine environment	Danish Ministry of the Environment - Environmental Protection Agency	(Kjølholt et al., 2012)

Analytical Study	Study Title	Completed by	Reference
Carnival (2019)	Compilation and Assessment of Lab Samples from EGCS Washwater Discharge on Carnival ships	Carnival Corporation; laboratory test data compiled and reviewed by DNV-GL Maritime Advisory Services	(Carnival, 2019)
EGCSA and Euroshore (2018)	Report on analyses of water samples from Exhaust Gas Cleaning Systems	Exhaust Gas Cleaning System Association (EGCSA) and Euroshore (Association representing port waste reception facility providers)	(EGCSA & Euroshore, 2018)
Teuchies et al. (2020)	The impact of scrubber discharge on the water quality in estuaries and ports	University of Antwerp; Royal Netherlands Institute for Sea Research and Utrecht University; Antwerp Port Authority; Delft University of Technology	(Teuchies et al., 2020)
Turner et al. (2017)	Shipping and the environment: Smokestack emissions, scrubbers and unregulated oceanic consequences	University of Gothenburg; Chalmers University of Technology; Uppsala University	(Turner et al., 2017)
Koski et al. (2017)	Ecological effects of scrubber water discharge on coastal plankton: Potential synergistic effects of contaminants reduce survival and feeding of the copepod Acartia tonsa	National Institute for Aquatic Resources and Department of Environmental Engineering, Technical University of Denmark	(Koski et al., 2017)

4.1. Analytical Study Shortcomings

The literature search, study comparison and subsequent meta-data analysis revealed certain problems with the way the data was collected and presented:

- The ten different studies included in the meta-analysis each set to test different hypotheses and assess the chemistry of scrubber discharge water, but without common parameters and test methods. As a result, the comparative dataset is smaller because it is divided into different types of scrubbers and analytes.
- Many of the studies do not report supporting data related to the ship and scrubber operations, such as fuel type, percent sulphur content, engine load, engine power, and scrubber discharge water flow rates. Significantly, both engine power and flow are parameters needed for comparison to IMO guidelines for PAH_{phe}, with only three of the ten studies providing sufficient information to make this assessment.
- Carnival (2019) reported results as the average across multiple vessels and not on an individual sample basis. This average was presented both for the full results and for a subset of results with statistical outliers removed (following a methodology consistent with the United States Geological

Survey's Statistical Methods in Water Resources), noting that only a small proportion of samples were affected and that statistical outliers were present in both inlet and outlet water samples.

- Japan (2019) used an experimental laboratory engine and a hybrid scrubber system, compared to the rest of the studies which reported results from real ships and operating conditions.

In addition to the data collection issue, challenges were observed with respect to the analytical methods used in each study, including that different analytical assays were also applied in the ten different studies.

- Method detection limits (or the limit of detection, (LOD)), meaning the lowest level or concentration at which the analytical equipment or method is sensitive enough to measure a particular analyte, are inconsistent both across studies and within a given study, as illustrated for Cadmium (Figure 1). This can make comparing between studies and to water quality guidelines challenging.
- How analytical results less than the LOD (<LOD, or "non-detects"), are handled can affect interpretation of the results when summarized as an aggregated dataset and as statistical values. Common practices are to exclude non-detects altogether, to use a value equal to the LOD, or to use half the LOD.
- Caution should be taken when comparing between different studies using different assay methods with different LODs – a particular ship, scrubber type, or operating conditions might look worse than another when really is a results of method sensitivity and how the detection limits are accounted for in analysis.
- In some cases, the method LODs are above the water quality guideline, meaning the analytical method used may not register the presence of an analyte at concentrations exceeding the guideline. If an LOD is above the guideline, plotting as half the LOD or as the full LOD value could be reported as a false exceedance of that guideline. This is an important consideration if comparing study conclusions and the interpretation of results versus the raw data itself.
- As outlined Section 2.2 above, the selected approach for this study was to exclude samples reported as less the LOD from any figures or statistical summaries. It should be taken into consideration that many of the analytical results in the combined dataset were reported as non-detectable and represent samples with low quantities of polluting compounds that are not include in the study figures and should be taken into consideration when reviewing and drawing further conclusions from these study results.

Recommendations from Analytical Studies Assessment

- Develop standardized sampling methods and analytical protocols, for consistent reporting across studies.
- Analytical methods, including any on-board monitoring of discharge water in real-time, need to be at a level of sensitivity that match that of concentration levels of concern.

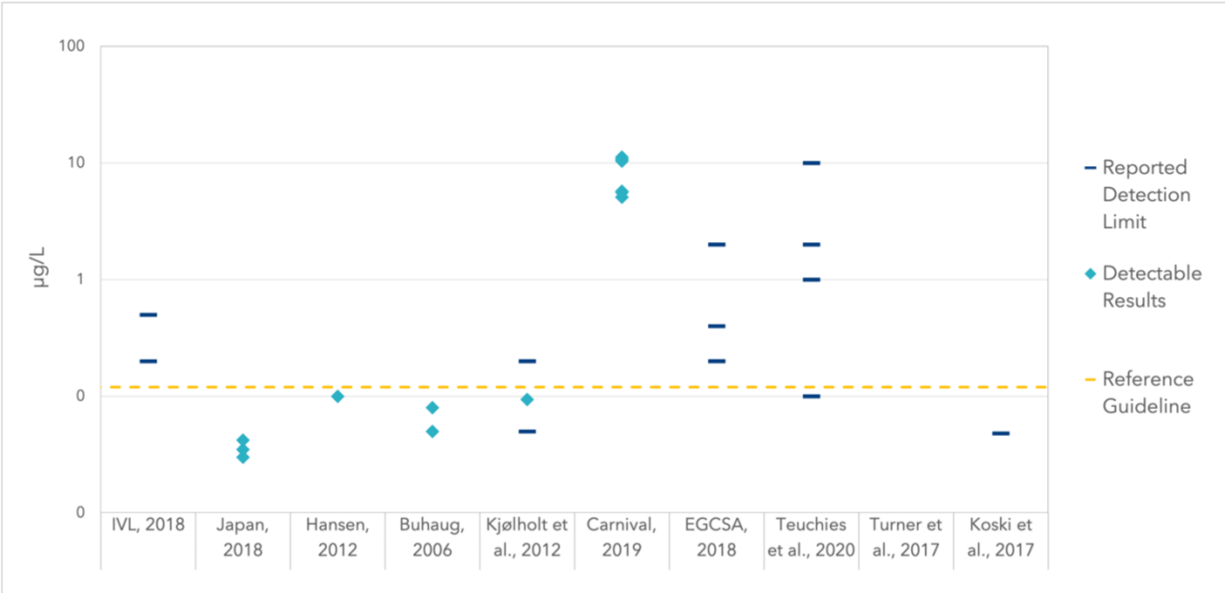


Figure 1. Method detection limits for cadmium from combined analytical studies, illustrating variation both across studies and within a given study

5.0 Results of Scrubber Discharge Water Meta-Analysis

5.1. pH

A particular issue of concern is low pH scrubber discharge water. Low pH water can be harmful to the ocean environment and could contribute more broadly to ocean acidification. The focus of the pH analysis in this study is on the pH of the discharge water and its potential impact on the local environment. Observations from the meta-analysis on scrubber discharge water pH include:

- Of the study results reviewed, it is mainly hybrid systems (systems which can switch between open- and closed-loop mode of operations) operating in open-loop mode that do not meet the IMO guideline. The guideline specifies that the discharge water should have a pH of no less than 6.5 measured at the ship's overboard discharge or as a maximum difference of 2 pH units between inlet and outlet water during maneuvering and transition. When a ship is stationary, the pH discharge limit is the value that will achieve as a minimum pH 6.5 at a distance of 4 m from the discharge point. As such, some of the samples which do not meet the IMO guideline at the point where the discharge water was monitored may meet the pH requirements in the 4 m plume.
- For closed-loop operations, pH can be directly and effectively controlled through neutralization using alkaline materials. This is demonstrated in the two studies which reported pH results from closed-loop scrubber effluent samples IVL (2018) and Teuchies et al. (2020) (Figure 2). pH meets the IMO guideline limit in all samples, with the exception of one very low pH outlier which is a bleed-off water sample at a very low flow rate (0.536 m^3/MWh, Teuchies et al. (2020)), therefore expected to be a small volume of discharge water.
- For open-loop operations, the approach for managing low pH scrubber effluent at the point of discharge is through dilution to increase pH to levels required in the IMO guidelines (EGCSA, n.d.). Increased dilution can be achieved through increased flow of scrubber discharge water, conventionally by diverting engine coolant water. Of the four studies with pH results for open-loop effluent samples, one study (Buhaug et al (2007)) predates the 2008 IMO guideline (Resolution MEPC.170(57)), at which point controlling for pH was first required. pH results for samples from the remaining three studies (Kjølholt et al. (2012), Teuchies et al. (2020), Koski et al. (2017)) are below (do not meet) the IMO guideline.
- While pH and sulphur are naturally buffered by the receiving seawater, the extent of ocean acidification affect from scrubbers is still being studied and remains a concern. Modeling studies show that the release of untreated scrubber effluent water can cause reductions in both pH and alkalinity in the marine environment (as modelled for the Baltic Sea) (Turner et al., 2018) reducing its ability to take up atmospheric CO_2. Teuchies et al., (2020) note that in restricted areas such as coastal waters or large harbours, the acidifying effect caused by SO_x (and NO_x) from scrubber discharge can exceed the acidifying effect of overall anthropogenic CO_2 emissions, with model simulations for open-loop scrubbers showing a decrease in pH caused by scrubber discharge water (as modelled for Antwerp (Belgium) harbour docks).

Recommendations from pH Analysis

- Low pH in scrubber effluent can be managed at the point of discharge if controls are put in place, either through increased dilution for open-loop operations or through neutralization using alkaline materials for closed-loop operations. Hybrid systems operating in open-loop mode tend not to meet the IMO guideline and rely on dilution in the receiving waters.

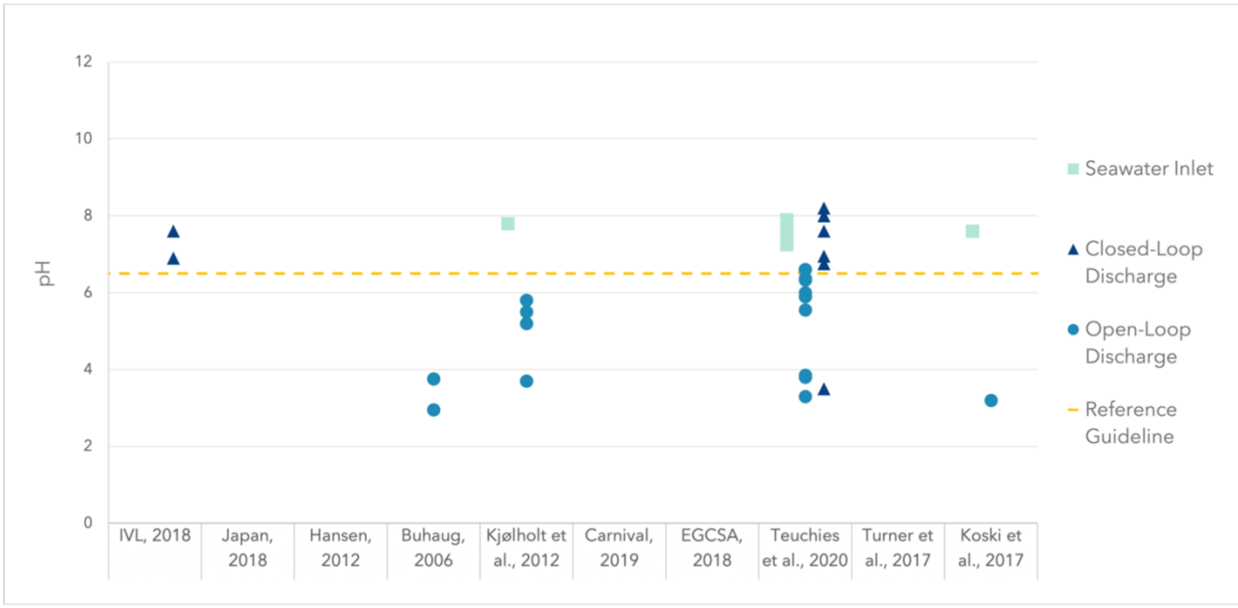


Figure 2. pH results from combined analytical studies, compared to IMO guideline (no less than 6.5)

5.2. Metals

Heavy metals are a pollutant of concern yet the IMO guidelines do not currently specify discharge limits or require monitoring. Observations from the meta-analysis for consideration when assessing metal concentrations and discharge limits in scrubber effluent include:

5.2.1. Contamination in source waters needs to be considered

- Studies show that metals are found in both open ocean waters and coastal waters and ships operate in these un-pristine waters (Davis, 1993). Open-loop scrubber washwater sourced from the surrounding environment would include any local contamination and may exceed water quality guidelines. This is evident in the results for mercury (Figure 8) where inlet water samples from both the Kjølholt et al. (2012) and Carnival (2019) studies exceed the water quality guideline.
- Local contamination in the inlet waters results in elevated levels in the scrubber discharge samples. Changes in contamination levels in scrubber effluent may be small relative to the base levels in inlet water and without measurable increases from the exhaust gas emissions. A prime example is the results for lead (Figure 7). For the three studies (Hansen (2012), Carnival (2019) and Teuchies et al.

(2020)) that include inlet water samples, lead concentrations in the reference seawater are in range of effluent concentrations.

- Others have reported elevated levels of zinc in inlet water and noted there is evidence of contribution of zinc and copper likely from anodic protection and marine growth inhibition systems (EGCSA & Euroshore, 2018).
- This is observed in the elevated concentrations in inlet water for copper (Figure 6) in the Hansen (2012), Carnival (2019) and Teuchies et al. (2020) studies, and for zinc (Figure 11) in the Carnival (2019) and Teuchies et al. (2020) studies.
- Not all studies reported inlet water samples. The difference in concentration between in inlet and discharge water is important when assessing the quality of the scrubber effluent.

5.2.2. Recirculation of scrubber washwater in closed-loop system can concentrate heavy metals

- Whereas open-loop systems continuously release of high volumes of discharge water, recirculation of the scrubber washwater in closed-loop systems could concentrate contaminants and produce more heavily contaminated bleed-off water.
- This is observed in the results for arsenic from the two studies with both closed-loop and open-loop samples (Kjølholt et al. (2012) and Teuchies et al. (2020)), where the arsenic levels are greater in the close-loop discharge water samples.
- While concerns about scrubbers have been focused on open-loop scrubber systems, the intermittent release of the concentrated bleed-off water from closed-loop systems are also of concern.

5.2.3. Leaching of metals due to corrosion from the acidic scrubber discharge water

- Elevated concentrations were observed for metals which are not expected to be present in the fuel. A possible source of these is metal components built-in to the scrubber system, as has been noted by others:
    - Elevated concentrations of iron and zinc, which were higher than concentrations in the exhaust gas emitted or in the scrubber discharge water and assumed to be leached from the steel pipes by low pH water in effluent discharge lines (Japan, 2019).
    - Elevated concentrations of nickel, vanadium, copper, and zinc; in particular, the authors noted that copper and zinc were not detected in the fuel and the source of the enrichment remained unexplained, with contamination from the tap used for sampling suspected (Kjølholt et al., 2012).
- This observation is consistent with the study results, in particular:
    - Elevated concentrations of copper (Figure 6) in the Kjølholt et al. (2012) and Teuchies et al. (2020) studies, possibly a result of stripping of copper from brass fittings.
    - Elevated concentrations of zinc (Figure 11), unlikely to be from fuel.

- General trend of increasing metal concentrations for copper and nickel with decrease in pH (Figure 12, Figure 13, and Figure 14) for scrubber discharge water from open-loop systems.

- A similar trend of increasing vanadium concentrations is found with decrease in pH (Figure 14). Vanadium is a major contaminant of HFO and is unlikely be a result of corrosion from pipes and fittings. In this case, low pH could be a result of higher concentrations of what used to be exhaust; rather than the low pH resulting in more vanadium, the effluent sample may be acidic because it is particularly concentrated sample containing high concentrations of all pollutants (Bryan Comer, personal communication, April 15, 2022)

Recommendations from Metals Analysis

- This research highlights the importance of accounting for the contribution from contaminants present in inlet water.
- Closed-loop scrubbers may not provide a better alternative to open-loop scrubbers when it comes to concerns about metals contaminating local environments due to concentration in recirculated washwater released as concentrated bleed-off water.
- This research provides additional evidence to suggest metal leaching from scrubber systems under low pH conditions. Better scrubber design standards using materials resistant to corrosion are needed to prevent potential leaching.

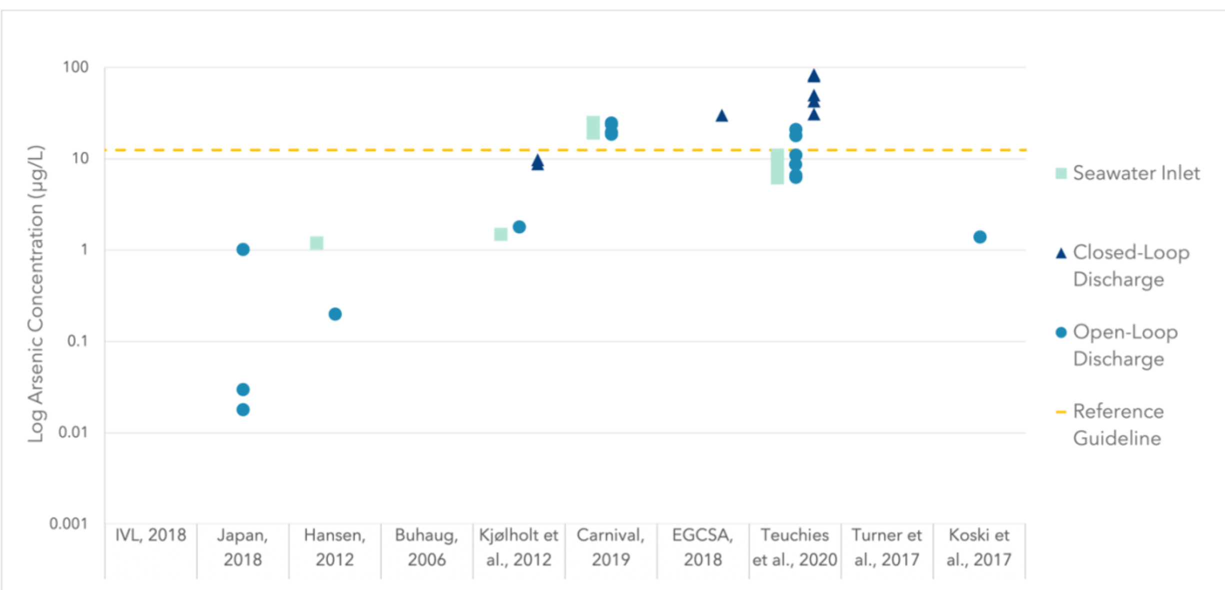


Figure 3. Arsenic results from combined analytical studies, compared to CCME CEQG Marine, Long-term guideline: 12.5 µg/L

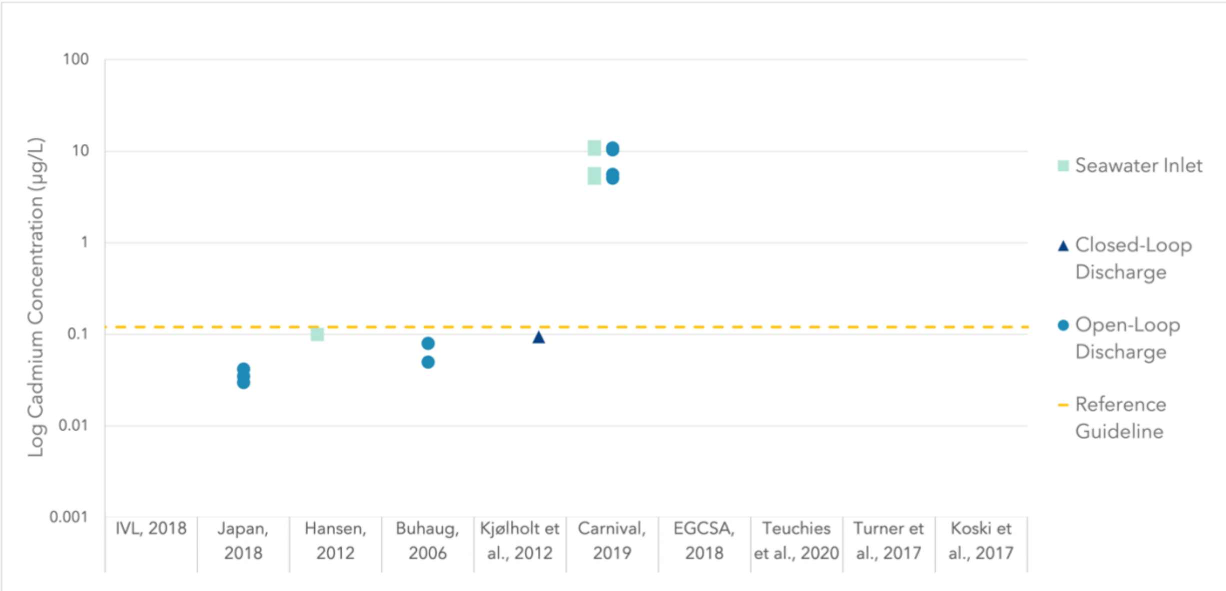


Figure 4. Cadmium results from combined analytical studies, compared to CCME CEQG Marine, Long-term guideline: 0.12 µg/L

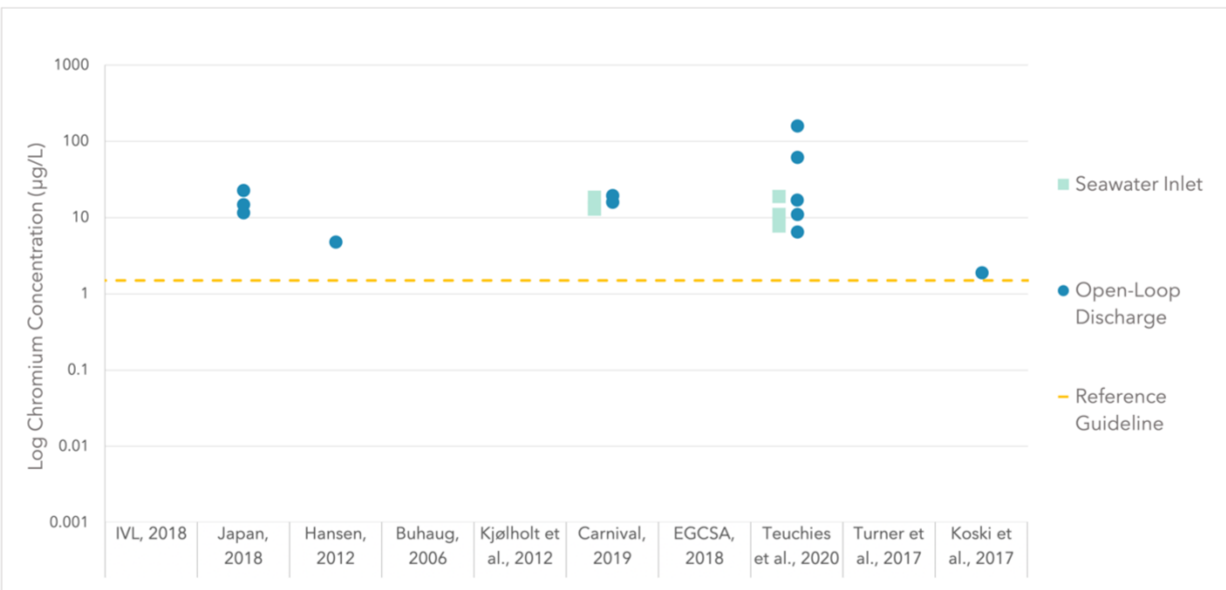


Figure 5. Chromium results from combined analytical studies, compared to CCME CEQG Marine, Long-term guideline: 1.5 µg/L

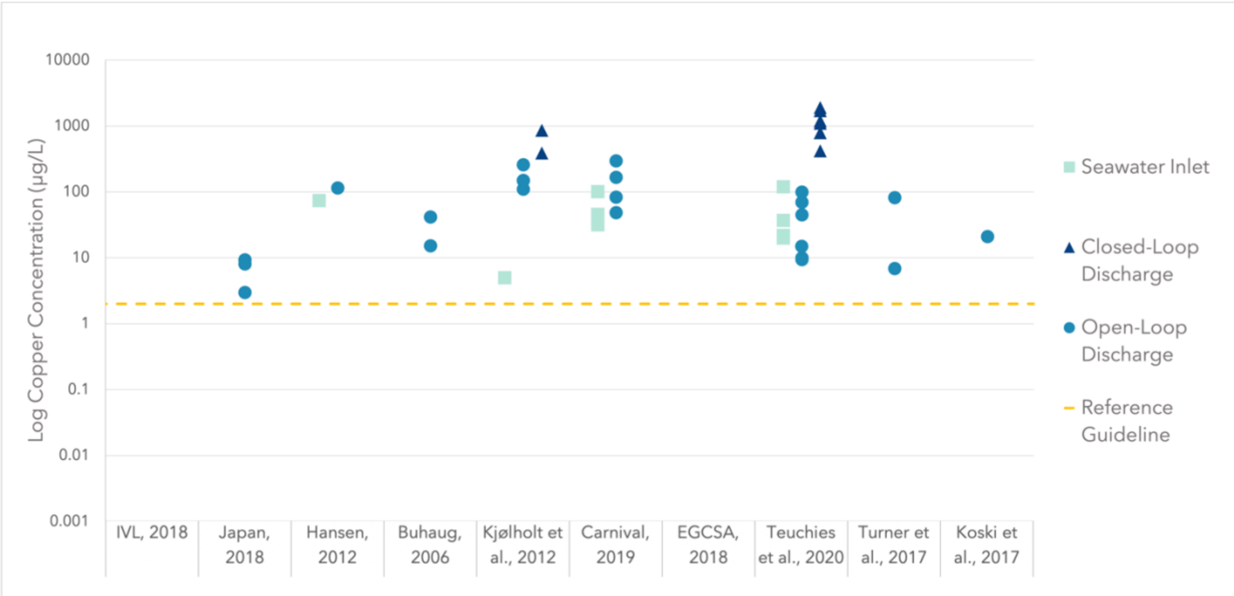


Figure 6. Copper results from combined analytical studies, compared to B.C. WQG Marine, Long-term guideline: 2 µg/L

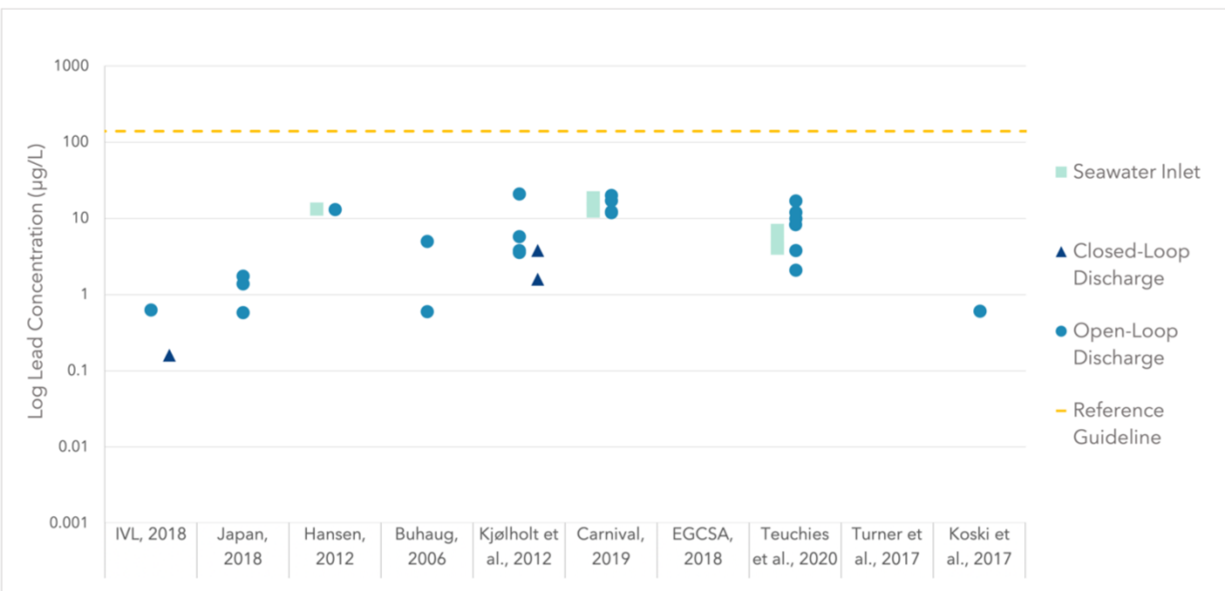


Figure 7. Lead results from combined analytical studies, compared to B.C. WQG Marine, Short-term guideline: 140 µg/L

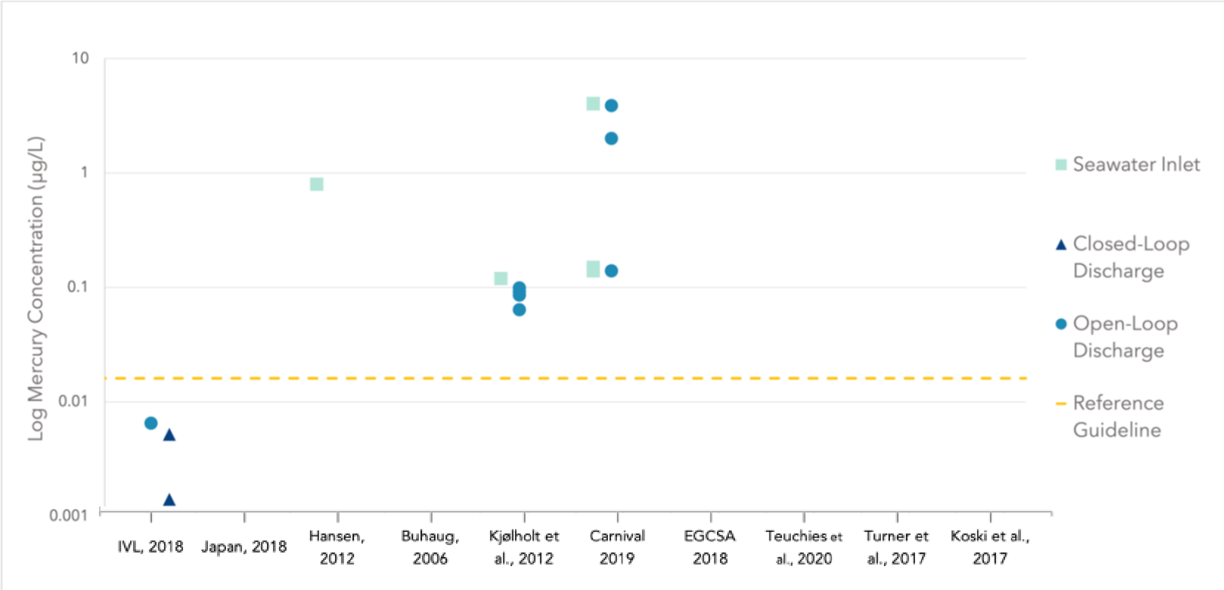


Figure 8. Mercury results from combined analytical studies, compared to CCME CEQG Marine Long-term guideline: 0.016 µg/L

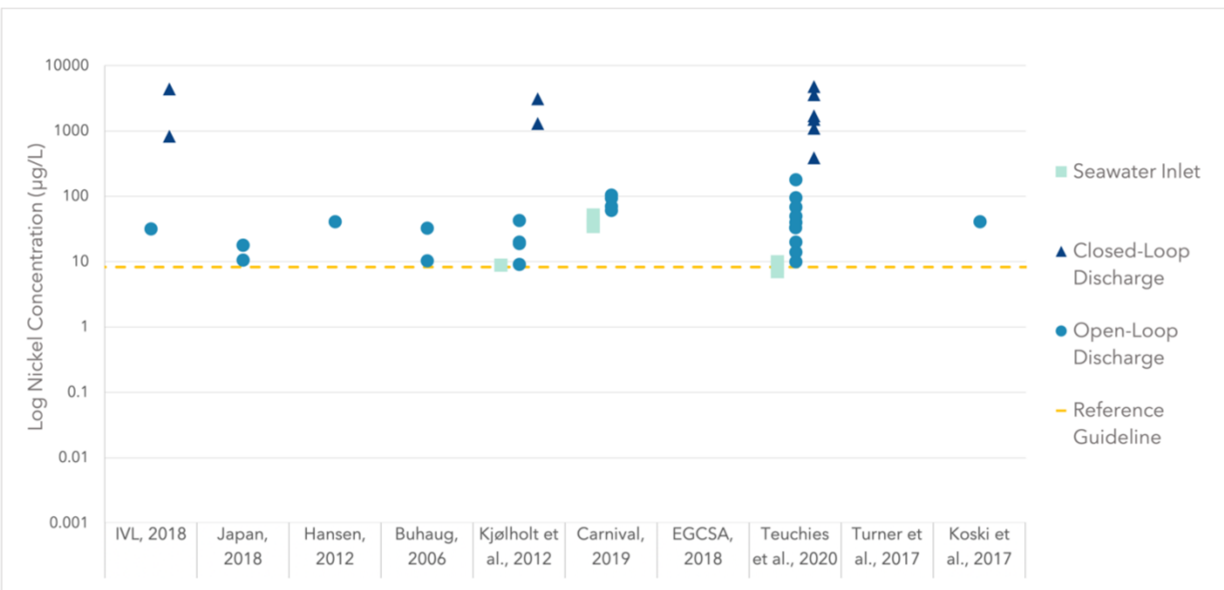


Figure 9. Nickel results from combined analytical studies, compared to B.C. WQG Marine Long-term guideline: 8.3 µg/L

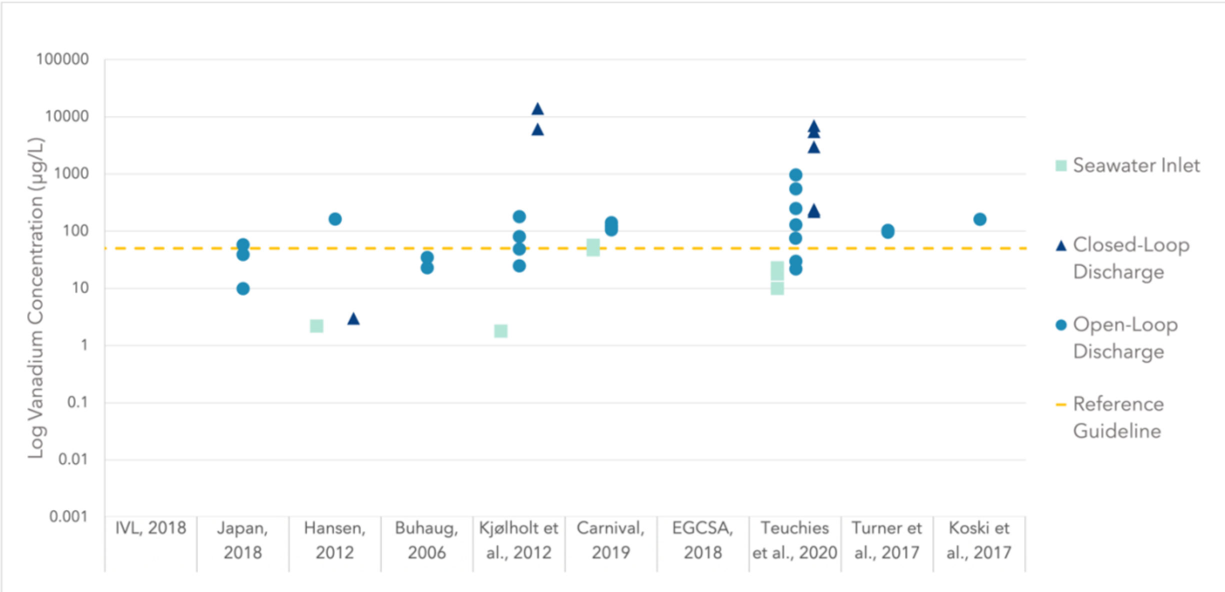


Figure 10. Vanadium results from combined analytical studies, compared to B.C. WQG Marine, Long-term guideline: 50 µg/L

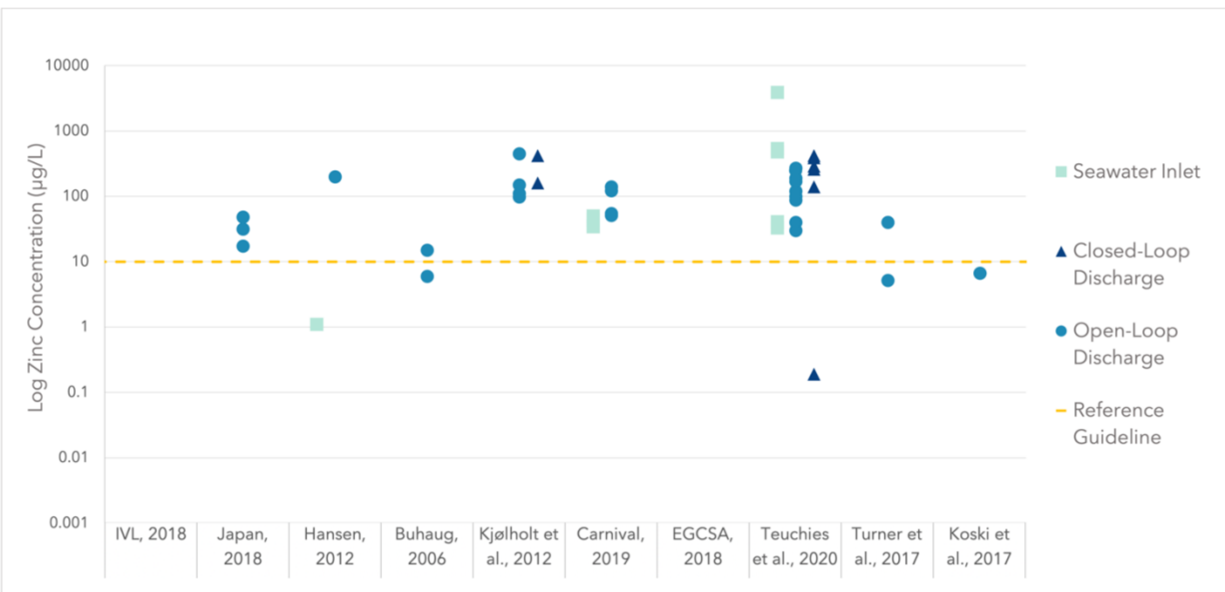


Figure 11. Zinc results from combined analytical studies, compared to B.C. WQG Marine Long-term guideline: 10 µg/L

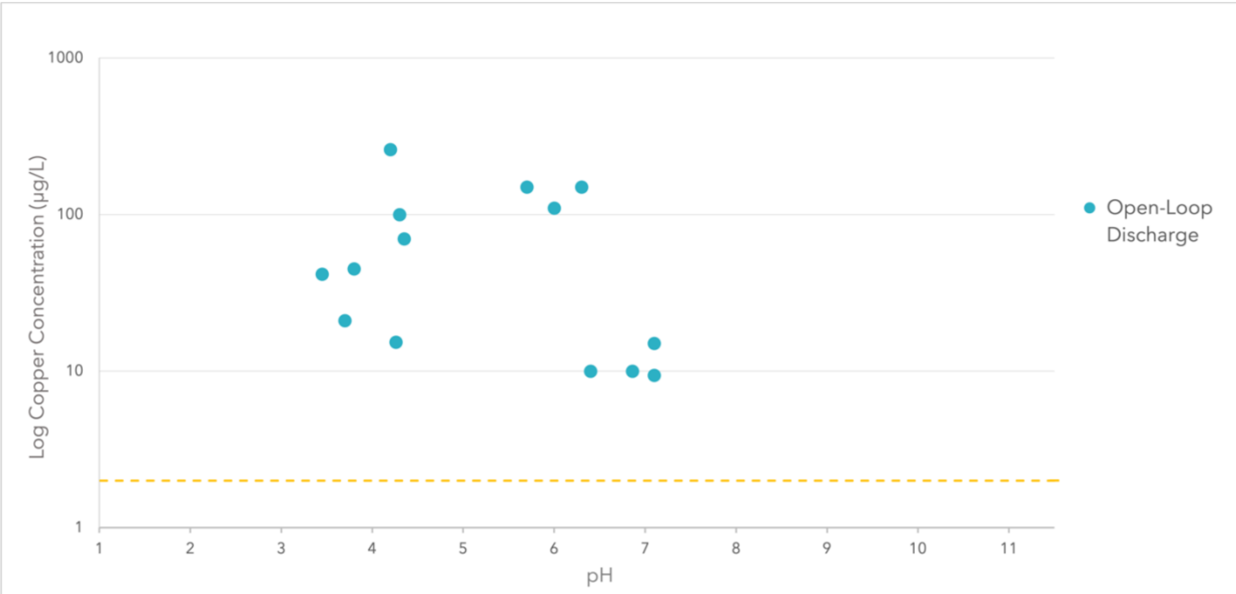


Figure 12. pH vs Copper results from combined analytical studies, compared to guideline B.C. WQG-Marine, Long-term guideline: 2 µg/L

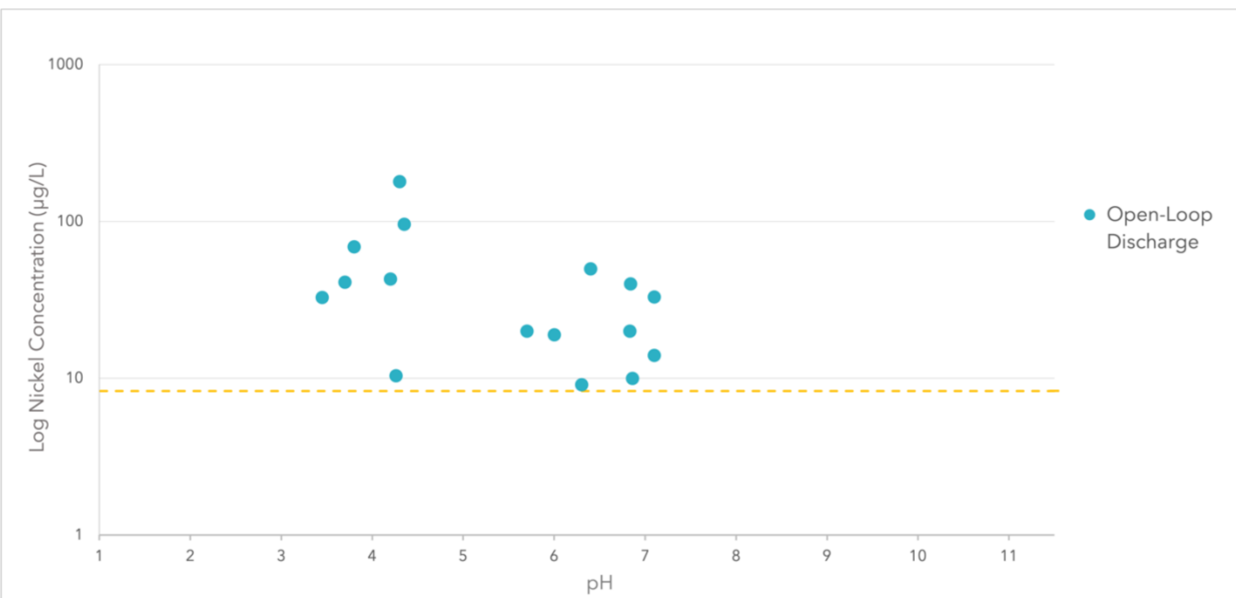


Figure 13. pH vs Nickel from combined analytical studies, compared to B.C. WQG Marine, Long-term guideline: 8.3 µg/L

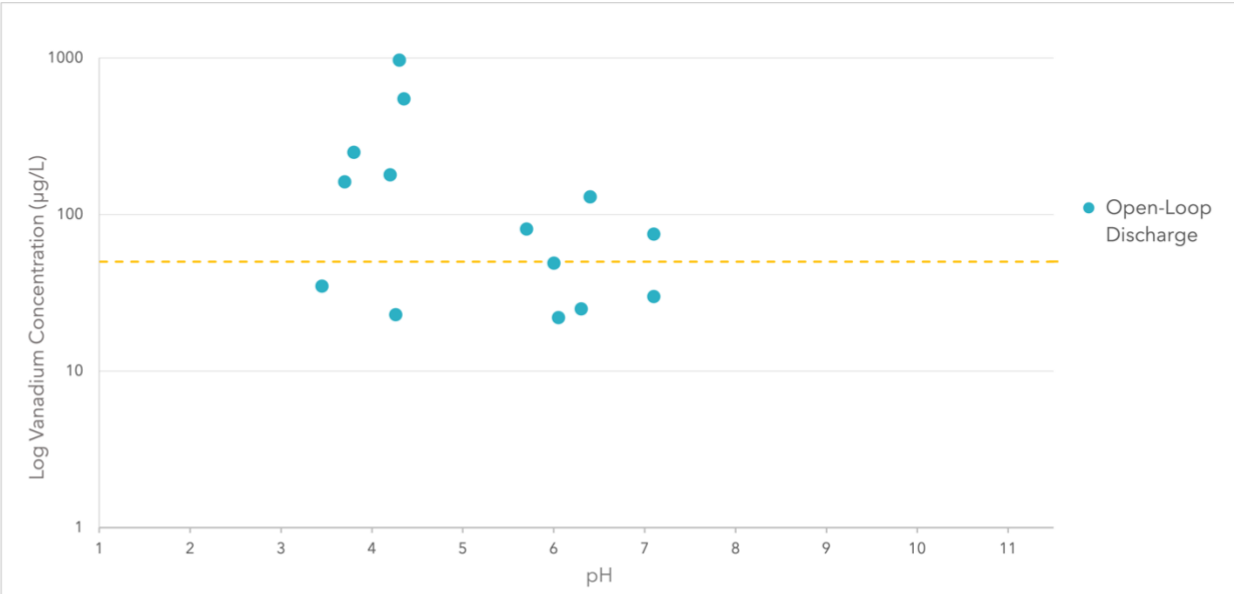


Figure 14. pH vs Vanadium from combined analytical studies, compared to B.C. WQG Marine, Long-term guideline: 50 μg/L

5.3. PAHs

PAHs are a concern and required for monitoring by the IMO guidelines. Observations from the meta-analysis for consideration when assessing PAH concentrations and discharge limits in scrubber effluent include:

5.3.1. Limitations of the IMO guideline for PAH

- The current IMO guidelines set a scrubber discharge water criterion for PAH in phenanthrene equivalents (PAH_{phe}) using an upper limit for PAH_{phe} as a maximum continuous PAH concentration in the discharge water above the inlet water PAH concentration. The IMO guidelines do not specifically address bleed-off water discharge during closed-loop operations.
- The IMO guidelines set the upper limit for PAH_{phe} at 50 μg/L normalized to a flow rate of 45 t/MWh (where the MW refers to 80% of the power rating of the fuel oil combustion unit), which is to be adjusted according to washwater flow rates. As noted above, only three of the ten analytical studies considered in this study, all of which report discharge water results for open-loop operations, provide sufficient data on washwater flow rates and engine power to assess PAH_{phe} concentrations to the IMO guidelines.
- Others have noted the potential weakness of using PAH_{phe}, including that the concept is unclear and its rationale not well established (Bartman, 2016; Comer et al., 2020; USEPA, 2011).
- The USEPA has noted that IMO guidelines may be unacceptably high and have observed that while median concentration of phenanthrene were well below the limit, concentrations of PAHs other than phenanthrene could pose a risk to the environment (USEPA, 2011). Comer et al. (2020) have noted

the original discharge limit proposed was 15 ppb, approximately equal to 15 µg/L of the sum total of the USEPA's 16 priority PAHs, with the actual guideline set well above that at 50 µg/L. Furthermore, it has been suggested that the USEPA's 16 PAHs may be insufficient and out of date – for instance, PAHs of higher toxicity than the traditional 16 that may not have been studied in sufficient detail to justify including them in routine analysis – and that the list could be revisited, as the state of knowledge and analytical capacity has advanced since this list was originally established in the 1970s (Andersson & Achten, 2015).

- It has also observed by others that onboard monitoring systems using PAH_{phe} are under reporting PAHs; for closed-loop scrubber systems in particular, measurements can be challenging due to concentration of water soluble chemicals during the washwater recycle, with the belief that analysis by UV absorption is not yet viable (Bartman, 2016). Authors of a closed-loop scrubber trial study from 2010 noted that continuous measurement of the PAH_{phe} in a reliable way is challenging using existing technology (Wärtsilä, 2010, as cited in USEPA (2011)).
- While the IMO guidelines provide an upper limit for PAH_{phe}, there is a need to better account for PAHs in scrubber effluent water, both as total PAHs (or the sum of the individual PAH concentrations) and by the individual PAHs and the risk of toxicity they pose to the aquatic environment.

5.3.2. Possible for total PAH concentrations in effluent to meet the IMO guideline

- Of the three studies (Kjølholt et al. (2012), EGCSA and Euroshore (2018), and Teuchies et al. (2020)) with sufficient information on engine load and flow discharge rate to normalize PAH concentrations to a washwater discharge rate of 45 t/MWh, all discharge water results were below the IMO guideline for PAH_{phe} (Figure 15).
- Separate to this study, PAHs exceeding the IMO guideline have been observed for four samples from open-loop system, as reported in Comer et al. (2020). These results were from a 2018 German study, the data from which were not included in this meta-analysis.
- Closed-loop discharge water samples perform better than open-loop samples for total PAHs normalized to flow (Figure 15), with concentrations that are well below the benchmark concentration range for the IMO guideline discharge limit calculated using the typical flow reported in the literature (Teuchies et al., 2020) (Figure 16). However, total PAHs from closed-loop systems should not be discounted due to limitations in the IMO guidelines or underreporting due to issues with the continuous monitoring approach specific to closed-loop operations, as discussed above.

5.3.3. IMO guideline may be ineffective for individual PAHs

- As described in Section 2.2, total PAHs concentrations were plotted relative to two benchmarks developed specifically for this study, the first using the IMO guideline for PAH_{phe} presented as a concentration at typical vessel and scrubber operations, and the second using an illustrative water quality guideline sample comprised of the sum of the best available CEQGs and B.C. WQGs (Figure 16).

- All except one of the 48 open-loop discharge water samples are below the total PAH concentration range for typical open-loop system flows loop (18.8 to 46.9 µg/L, for typical flow rates of 200-500 L s^{-1} for open-loop systems (Teuchies et al., 2020)). The one sample which does exceed the lower bound of the range, when adjusted for engine power and flow, is well below the IMO guideline (1,457,118 µg/MWh compared to 2,250,000 µg/MWh). This same sample is the only one of 48 open-loop samples that exceeds the illustrative WQG sample.
- All closed-loop discharge water samples are also all well below the total PAH concentration range for typical closed-loop system flows (given closed-loop systems are expected to release at very low flow rates, this allows for very high concentrations by the IMO guideline). However, two of the 14 closed-loop discharge water samples are above the illustrative WQG sample.
- While both open-loop and closed-loop results meet the IMO guideline, there is evidence that both types of scrubber systems release discharge water with concentrations that are of concern by at least one of the individual PAHs for which there is a Canadian or B.C. water quality guideline.
- A potential issue with current IMO guidelines is if the total PAH level is too high and masking contribution from a given PAHs. Looking at all PAHs in aggregate could under-represent issues with individual PAHs.

5.3.4. Individual PAHs need to be considered, not just total

- To further understand how well the IMO guideline for PAH_{phe} correlates to total PAHs or accounts for the potential contribution of individual PAHs, the breakdown of individual PAHs in a subset of eight samples (four closed-loop and four open-loop samples, selected from the 95th percentile of total PAHs and individual PAHs within the dataset) were compared to the illustrative WQG sample (Figure 17):
    - The sample that performs the worst by the IMO guidelines (highest result total PAH normalized to flow), is below the illustrative WQG sample for both open-loop and closed-loop discharge water samples (OL-1 and CL-1). However, the sample with the highest concentration of total PAHs (without normalizing for engine power and flow) is above the illustrative WQG sample, for both open-loop and closed-loop discharge water samples (OL-2 and CL-2). This same open-loop sample (OL-2) is below the IMO guideline. The same closed-loop (CL-2) does not report flow information so could not be compared to the IMO guideline, but would presumably be below the guideline if released within the very typical low flow range report for closed-loop systems. While none of these samples would have been triggered as exceeding the IMO guideline, at least one individual PAH would be above the Canadian or B.C. water quality guideline. The IMO guideline for PAH_{phe} normalized for flow would potentially not limit the release of individual PAHs at concentrations that are above Canadian or B.C. water quality guidelines. As noted previously, however, the water quality guideline used for comparison here are for assessing risk to biota and fish habitat function and are not designed for effluents.

- Furthermore, when examined on an individual PAH basis, many discharge water samples exceed the water quality guidelines for individual PAHs. The additional two open-loop and closed-loop samples (OL-3, OL-4, CL-3 and CL-4) further show the variation in breakdown of total PAH by the individual PAHs. While each of these samples are well below the illustrative WQG sample and IMO guideline, they each exceed for multiple of the individual PAHs.

- For the ten individual PAHs with corresponding water quality guidelines (Figure 18 to Figure 27), in both open-loop and closed-loop discharge water samples, concentrations in exceed the corresponding guideline for eight out of the ten individual PAHs (the exceptions being Acenaphthene (Figure 18) and Fluorene (Figure 24)). In the case of Anthracene (Figure 19) and Pyrene (Figure 27), the maximum concentration reported are 100 and 130 times the guideline, respectively.

5.3.5. Seawater source has a contribution; contamination in inlet water needs to be considered

- Similar to the metal results, elevated PAH concentrations are observed in the inlet samples, indicating that contribution of PAHs from the scrubber washwater source, which could contribute to the higher total PAH levels observed in open-loop than in closed-loop operations.
- A potential source is suspended sediments in the inlet water, related to the tendency of PAHs to bind to particulate matter and concentrate in sediments. "Sediments can be disturbed during the maneuvering of a ship in shallow water, and as a result may enter the washwater system. Since harbor sediments are often contaminated with PAHs, PAHs can enter the washwater system along with the sediment. The IMO therefore requires the background concentration of PAH at the washwater inlet be taken into account when measuring the PAH concentration at system discharge" (USEPA, 2011).
- Many inlet water samples exceed water quality guidelines for individual PAHs. For the ten individual PAHs which have corresponding water quality guidelines (Figure 18 to Figure 27), concentrations in inlet water samples exceed the corresponding guideline for seven out of the ten individual PAHs. In the case of Pyrene (Figure 27), the maximum concentration reported is over 40 times the guideline.
- The IMO guideline for PAH accounts for this by setting an upper limit for the maximum continuous concentration in effluent water above the inlet water PAH concentration. However, this is done using PAH_{phe} and not on an individual PAH basis.

5.3.6. Washwater treatment may remove certain PAHs

- Washwater treatment to remove particulate matter could improve PAHs. As PAHs are hydrophobic in nature, have low solubility and tend to absorb to organic matter, they bind to suspended particles in water and through treatment would be removed as sludge. The USEPA review of Hufnagl et al. (2005) reported higher PAH concentrations in the washwater treatment system, with most of the total PAHs bound to soot particles and reduced through multicyclone treatment, (USEPA, 2011), and noted that improving treatment efficiency could reduce particulate PAH concentrations in discharge water. And specifically, high PAH concentrations in scrubber discharge were predominantly made up of lower molecular weight PAHs, which are more soluble in water and presumed to be not as effectively removed by particle separation (USEPA, 2011).

- The results presented in Sections 5.3.4 and 5.3.5 above for individual PAHs adds to the discussion on scrubbers as a potential mechanism for PAH removal; while the combined dataset does not allow for a direct comparison between scrubber washwater pre- and post-treatment, the individual PAH results are not inconsistent with earlier observations. Low molecular weight, or higher solubility PAHs, are observed to be more persistent in discharge water. For example, Naphthalene, the most water soluble of the set of PAHs assessed in this study (with a solubility of 31.6 mg/L at 25 °C), is observed at elevated levels and in a similar range in both open-loop and closed-loop discharge water samples (Figure 25), whereas the lower soluble Benzo(a)anthracene (with a solubility of 0.01 mg/L at 25 °C) (Figure 20) is lower in closed-loop samples.

Recommendations from PAHs Analysis

- This research highlights the importance of monitoring for individual PAH concentrations in scrubber discharge water, though limitations in comparing scrubber discharge to water quality guidelines are recognized. Better measuring and monitoring for PAHs is needed.
- Closed-loop scrubbers may have an advantage over low sulphur fuel in that washwater treatment to remove to particulate matter may also reduce the release of PAHs to the environment which would otherwise be released as exhaust gas emissions, at least for those PHAs with lower solubility in water.

Table 3. PAH Water Solubility (Monaco et al., 2017)

PAH	Water Solubility (mg/L at 25°C)	Number of Rings
Naphthalene	31.6	2
Acenaphthylene	16	3
Fluorene	1.8	3
Acenaphthene	4.5	3
Phenanthrene	1.3	3
Anthracene	0.07	3
Fluoranthene	0.24	4
Pyrene	0.14	4
Benzo(a)anthracene	0.01	4
Chrysene	0.003	4
Benzo(b)fluoranthene	<0.001	5
Benzo(k)fluoranthene	<0.001	5
Benzo(a)pyrene	<0.001	5
Dibenzo(a,h)anthracene	<0.001	5
Indeno(1,2,3-c,d)pyrene	<0.001	6
Benzo(g,h,i)perylene	<0.001	6

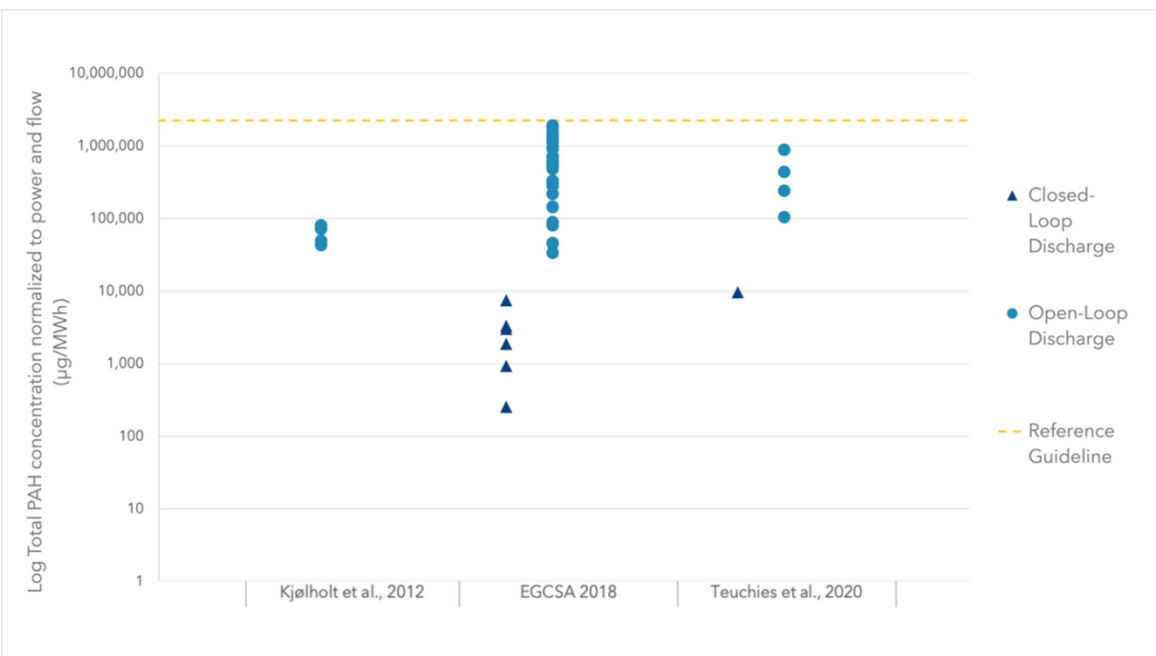


Figure 15. Total PAHs normalized to power and flow (µg/MWh), compared to IMO guideline for PAH_{phe} (2,250,000 µg/MWh)

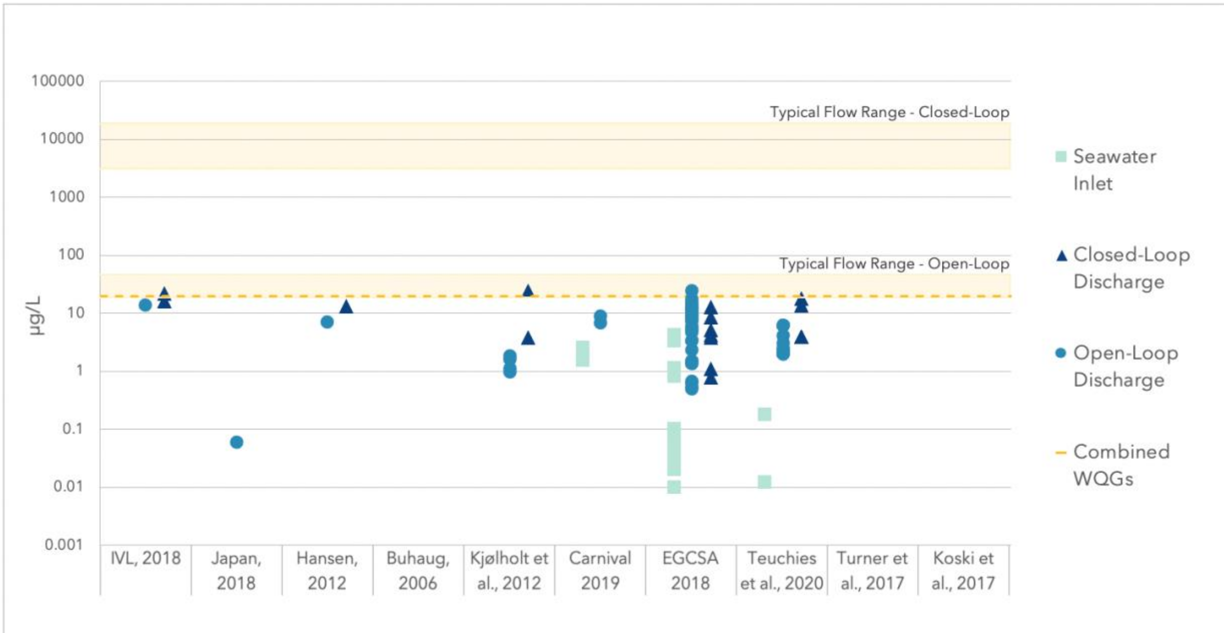
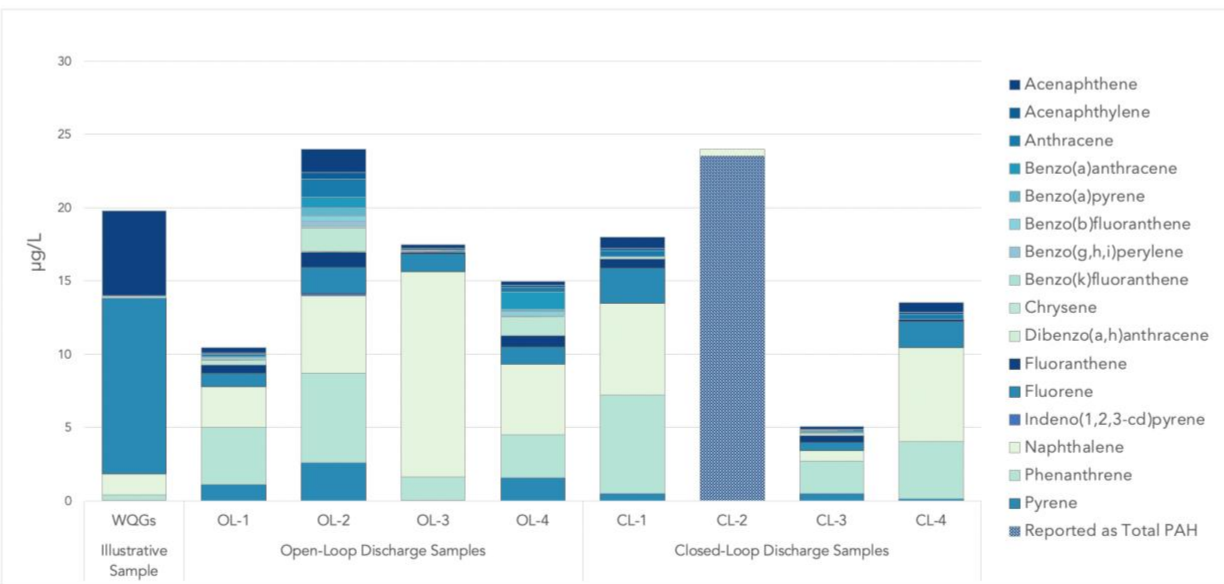


Figure 16. Total PAHs concentration (µg/L), compared to a) concentrations at typical flows for open-loop (18.8 to 46.9 µg/L) and closed-loop (3125 to 18,750 µg/L) systems and b) an illustrative WQG sample



Open-Loop Discharge Samples	**OL-1**	Maximum Flow Normalized Total PAHs
	OL-2	Maximum Total PAHs; 95th %tile Flow Normalized Total PAHs; Maximum Acenaphthene, Anthracene, Benzo(a)pyrene, Chrysene, Fluoranthene, Fluorene, Phenanthrene, Pyrene
	OL-3	Maximum Napthalene; 95 %tile Total PAHs
	OL-4	Maximum Benzo(a)anthracene; 95th %tile Flow Normalized Total PAHs, Chrysene, Fluoranthene,

Closed-Loop Discharge Samples	**CL-1**	Maximum Flow Normalized Total PAHs, Acenapthene, Anthracene, Chrysene, Fluorene, Phenanthrene, Pyrene
	CL-2	Maximum Total PAHs
	CL-3	Maximum Benxo(a)anthacene, Phenanthrene
	CL-4	Maximum Napthalene

Figure 17. Total PAH concentration for a subset of samples vs illustrative WQG sample

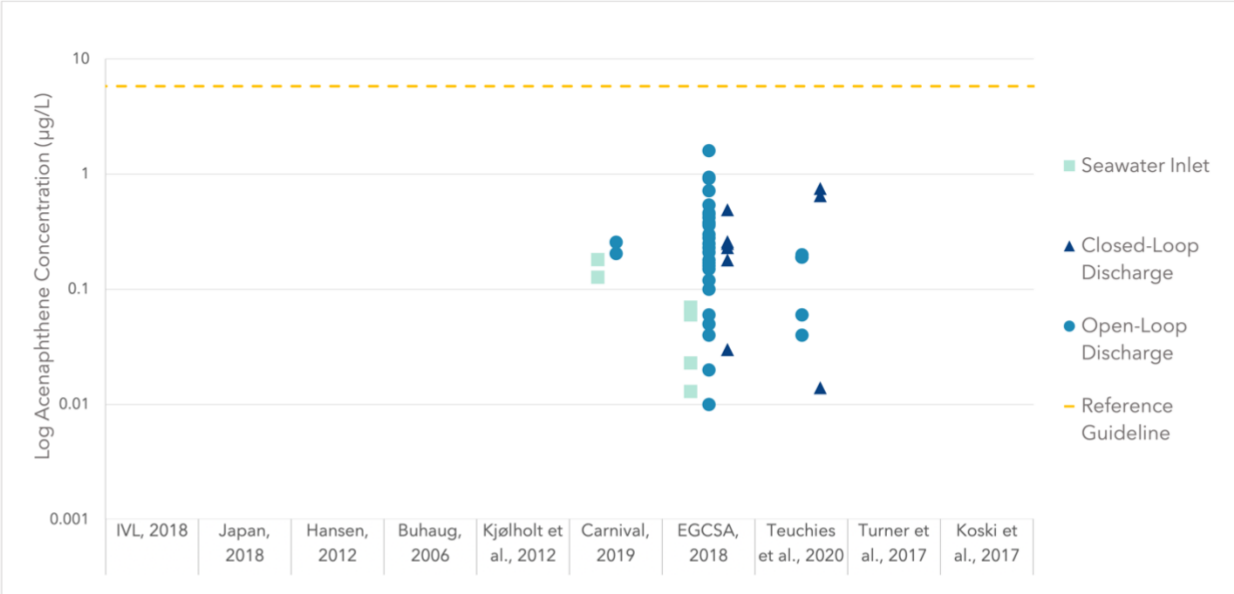


Figure 18. Acenaphthene results from combined analytical studies, compared to CCME CEQG Freshwater, Long-term guideline: 5.8 µg/L

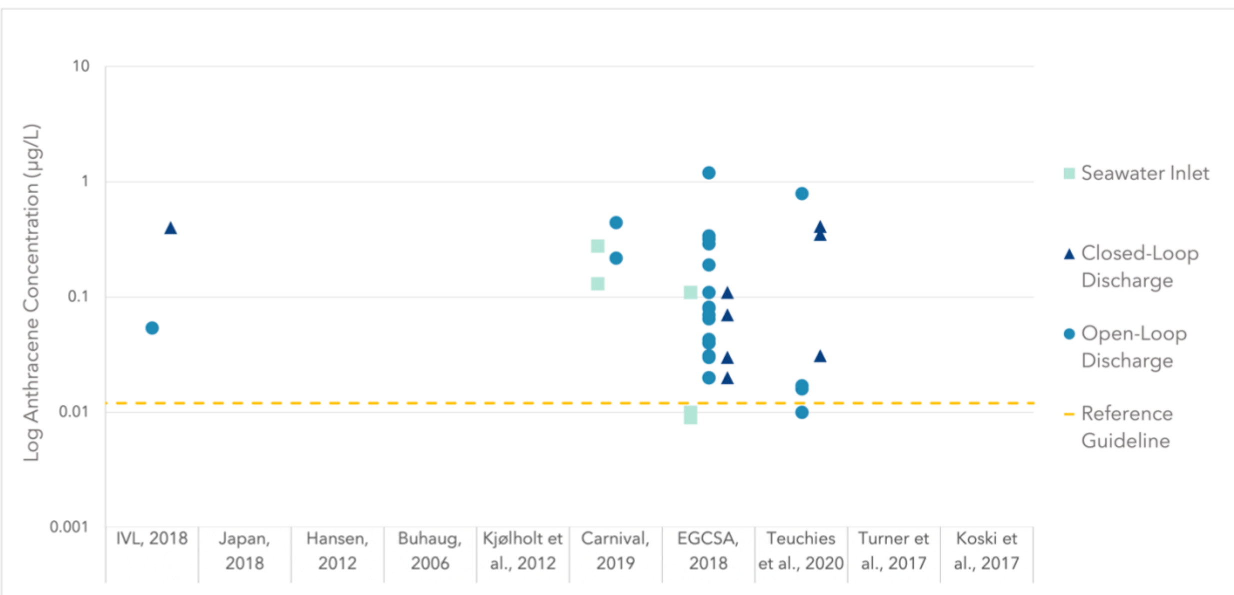


Figure 19. Anthracene results from combined analytical studies, compared to CCME CEQG Freshwater, Long-term guideline: 0.012 µg/L

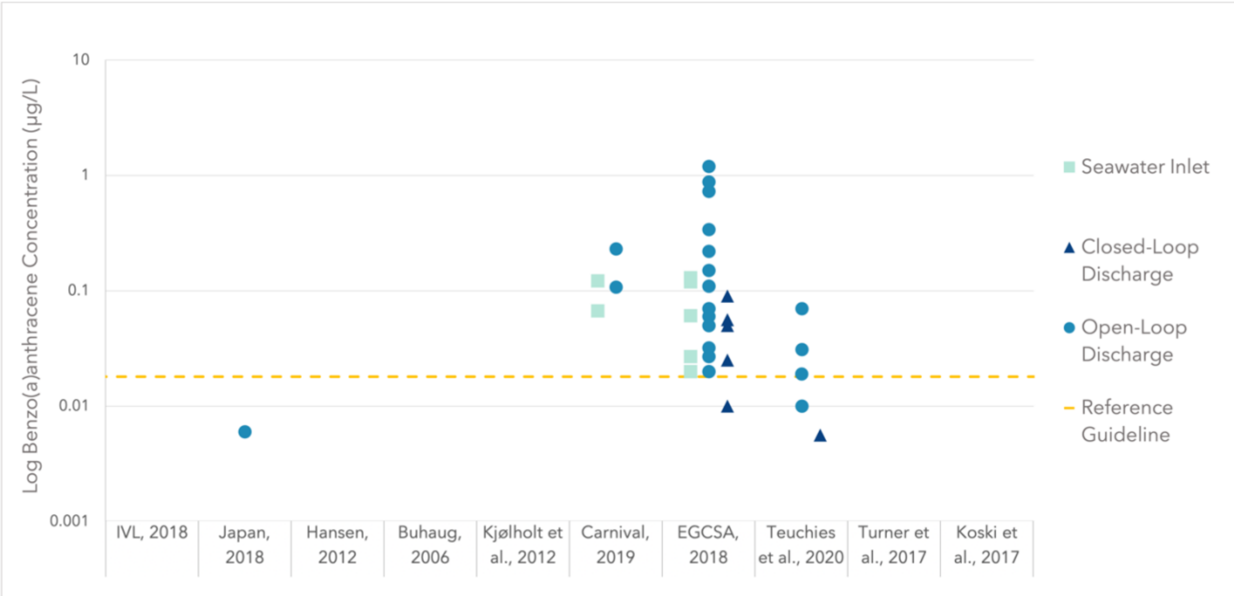


Figure 20. Benzo(a)anthracene results from combined analytical studies, compared to CCME CEQG Freshwater, Long-term guideline: 0.018 µg/L

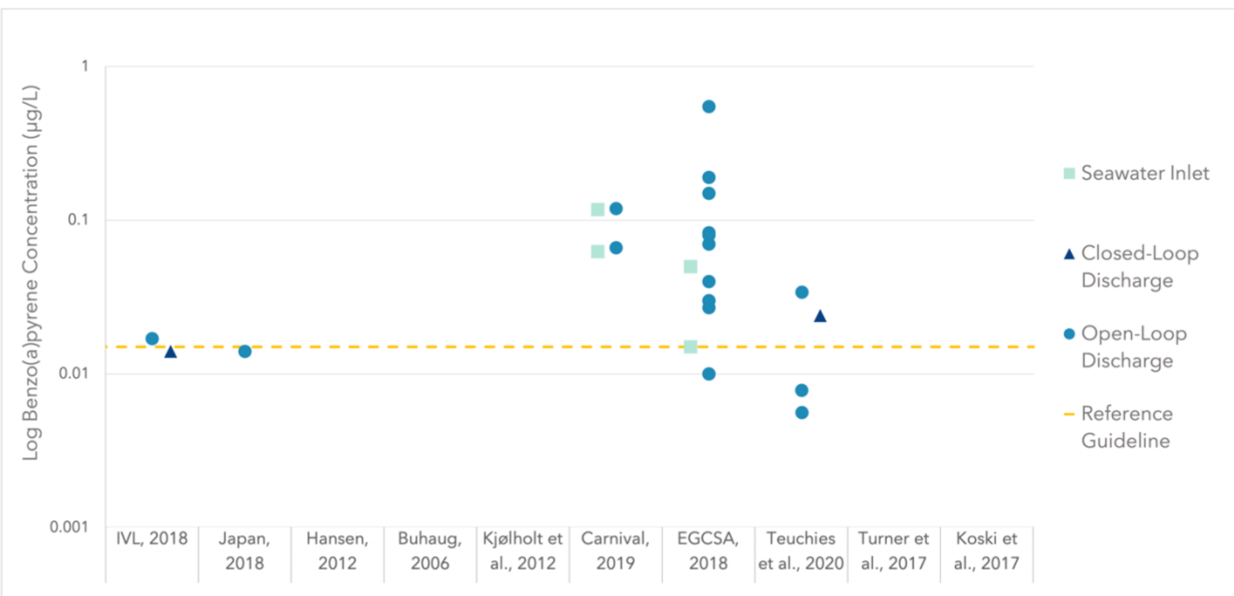


Figure 21. Benzo(a)pyrene results from combined analytical studies, compared to B.C. WQG Marine, Long-term guideline: 0.01 µg/L

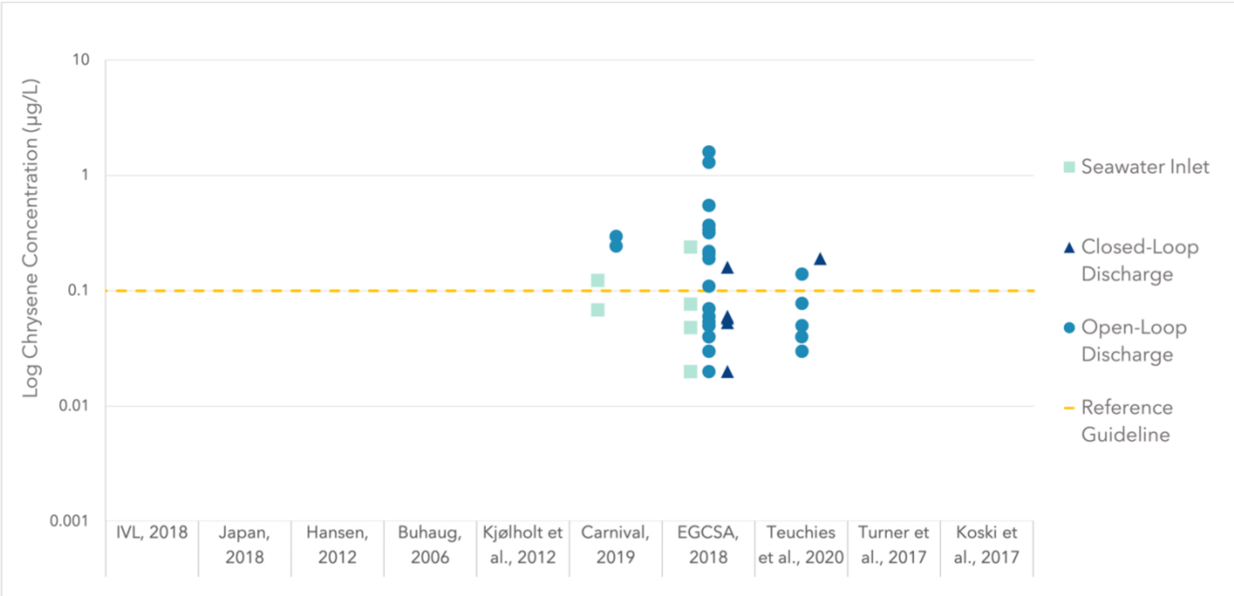


Figure 22. Chrysene results from combined analytical studies, compared to B.C. WQG Marine, Long-term guideline: 0.1 µg/L

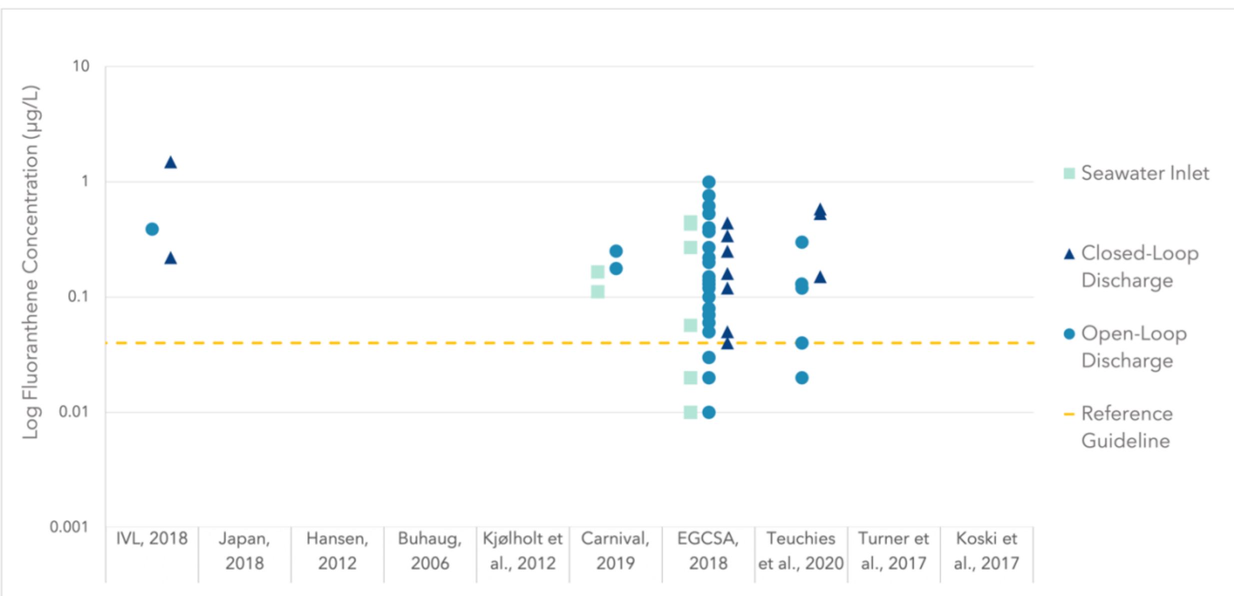


Figure 23. Fluoranthene results from combined analytical studies, compared to CCME CEQG Freshwater, Long-term guideline: 0.04 µg/L

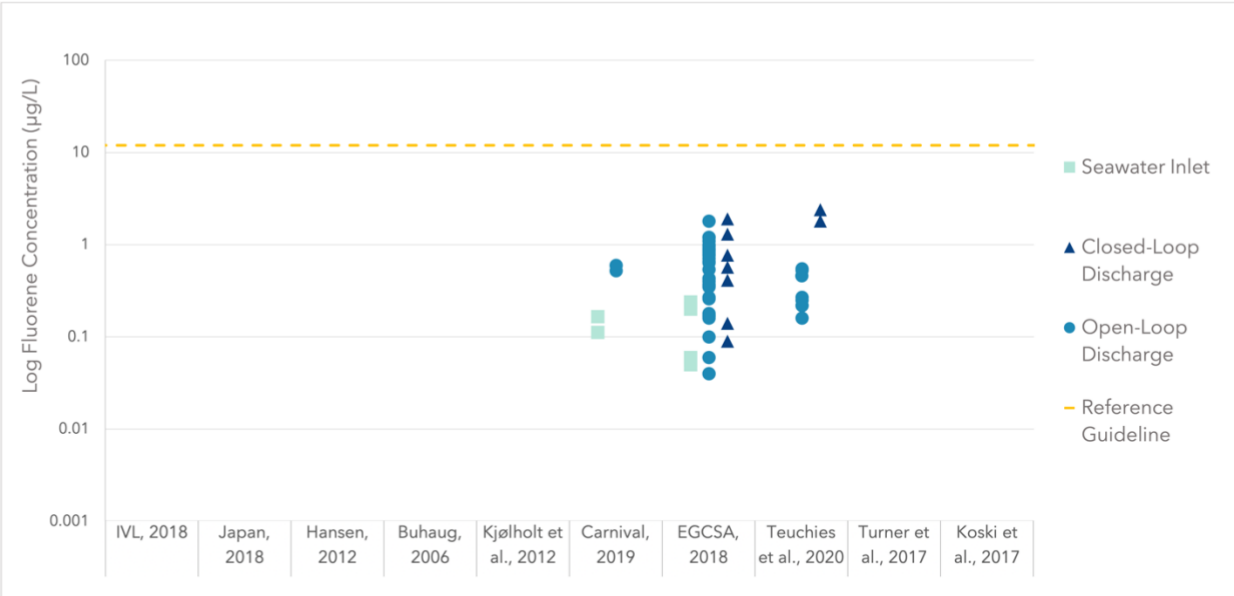


Figure 24. Fluorene results from combined analytical studies, compared to B.C. WQG Marine, Long-term guideline: 12 µg/L

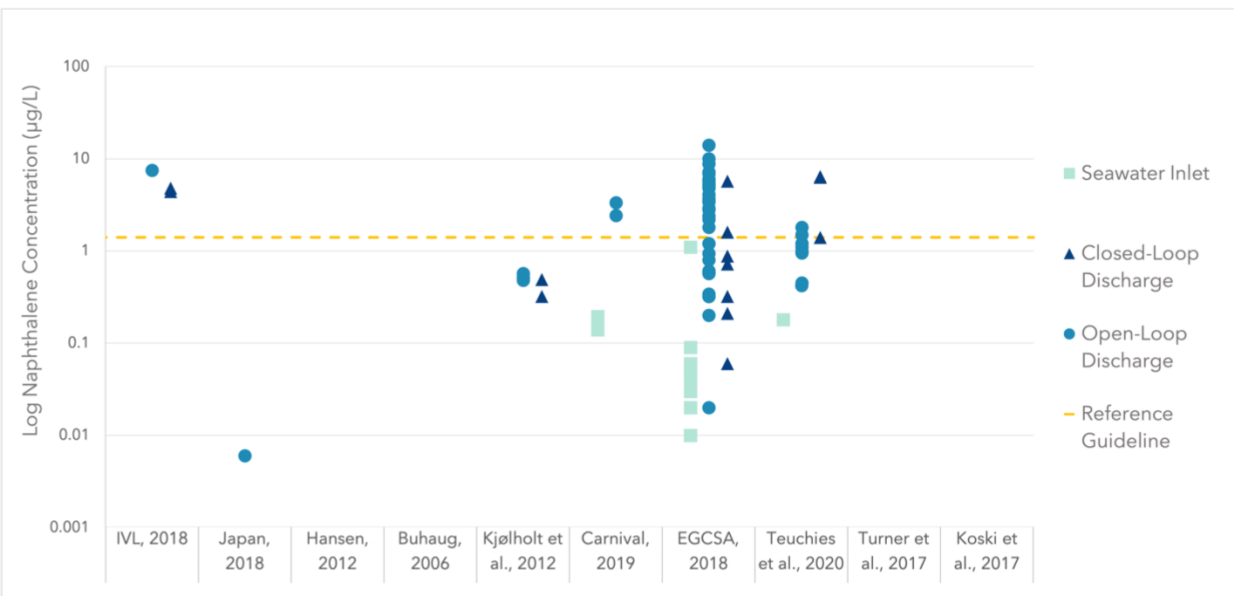


Figure 25. Naphthalene results from combined analytical studies, compared to CCME CEQG Marine, Long-term guideline: 1.4 µg/L

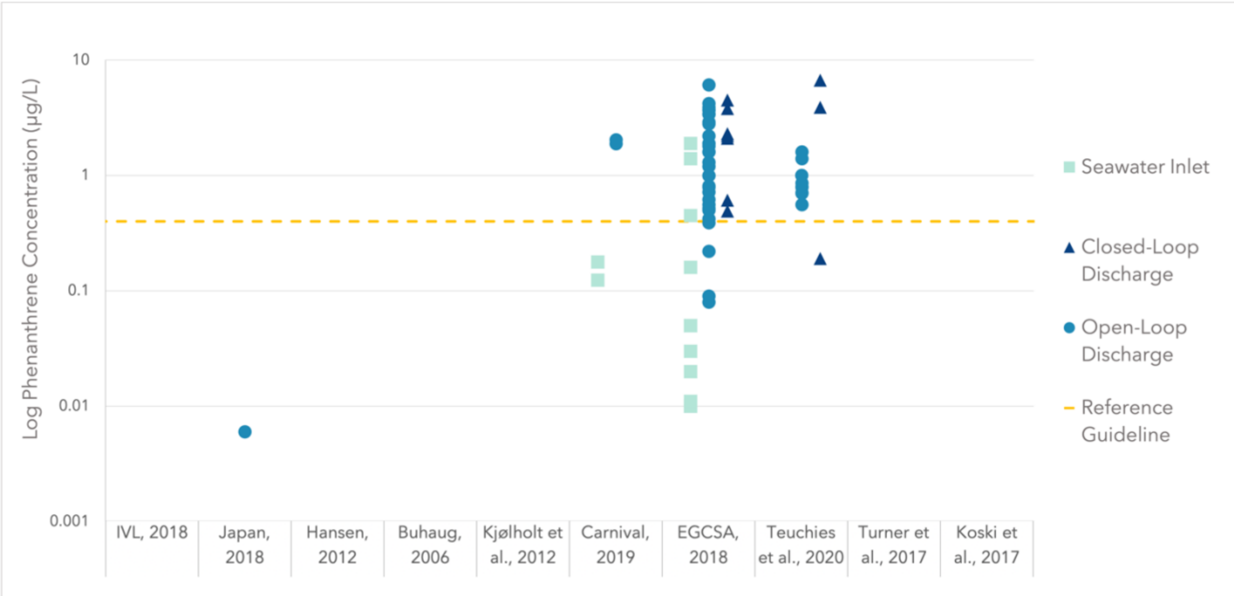


Figure 26. Phenanthrene results from combined analytical studies, compared to CCME CEQG Freshwater, Long-term guideline: 0.4 µg/L

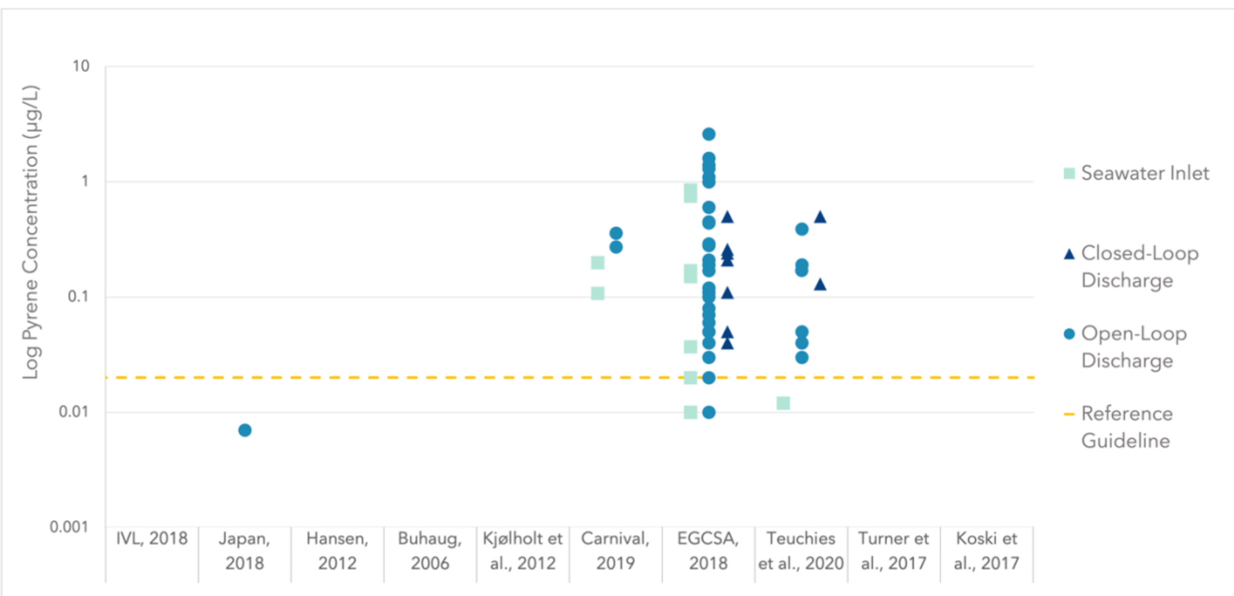


Figure 27. Pyrene results from combined analytical studies, compared to B.C. WQG Marine, Short-term guideline: 0.02 µg/L

6.0 Summary Recommendations

The objectives of this study were to better understand how pollutant concentrations in scrubber discharge water vary by scrubber type and operations. Scrubber discharge water quality was assessed relative to reference criteria including IMO guidelines and relevant Canadian water quality guidelines, to account for gaps in the current IMO guidelines which do not specify discharge limits for metals and individual PAHs. These criteria were used as a benchmark for comparison between different analytical studies and in reference to environmental quality guidelines set for the protection of aquatic life to help characterize the pollution levels in scrubber discharge water.

Key findings and recommendations from this assessment include:

- There is a lack of consistent reporting across studies, including supporting data on operational parameters, presents challenges. The use of standardized sampling methods and analytical protocols and analytical methods at a level of sensitivity that match that of concentration levels of concern would enable improved understanding on how pollutants vary by scrubber type and operations and inform their regulation.
- Discharge of low pH in scrubber water can be managed at the point of discharge or by relying on dilution in the receiving waters, however the contribution to ocean acidification remains a point of concern.
- Local contamination in the inlet waters results in elevated levels in the scrubber discharge water samples. It is important to account for the contribution from contaminants present in inlet water when net increase contributed from scrubbers.
- Closed-loop scrubbers may not provide a better alternative to open-loop scrubbers when it comes to concerns about metals contaminating local environments due to concentration in recirculated washwater released as concentrated bleed-off discharge water. While concerns about scrubbers have been focused on open-loop scrubber systems, the intermittent release of the concentrated bleed-off water from closed-loop systems are also of concern.
- This research provides further evidence supporting the hypothesis that low pH conditions cause leaching of metals components in the scrubber system itself (pipes and fittings). Better scrubber design standards using materials resistant to corrosion are needed to prevent potential leaching.
- Weaknesses have been noted in the current IMO guideline for PAHs, which set an upper limit for PAHs using phenanthrene equivalents (PAH_{phe}) through ultraviolet light (UV) and florescence detection method. Better measuring and monitoring for PAHs that accounts for individual PAH concentrations in scrubber discharge water is needed.
- Discharge water treatment to remove particulate matter may also remove particulate-bound PAHs, with these pollutants captured and disposed of as sludge. As a result, closed-loop scrubbers with discharge water treatment systems may have an advantage over low sulphur fuel in that these PAHs would have otherwise been released as exhaust gas emissions. However low sulphur fuels typically

have lower levels of PAHs than conventional heavy fuel oil, so for this effect to be beneficial, the PAH reduction from closed-loop scrubbers would have to be larger than the effect of switching to low-sulphur fuels.

The comparison of scrubber discharge to water quality guidelines in this study is done for general purposes only does not constitute an assessment of the resulting environmental impacts of scrubber discharge in Canadian waters. Area for future research studies include an assessment of environmental impacts using the guidelines, accounting for dilution in the receiving water and the total load of contaminants reaching the marine environment, including factors such as the number of vessels operating scrubber, and the frequency and flow rates of scrubber discharges waters.

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Appendix A – Summary of Studies Included in Meta-Analysis

Table A-1: Study Comparison Table

	IVL, 2018	Japan, 2018	Hansen, 2012	Buhaug, 2006	Kjølholt et al., 2012	Carnival 2019	EGCSA and Euroshore 2018	Teuchies et al., 2020[1]	Turner et al., 2017	Koski et al., 2017
Scrubber (EGCS), Ship and Engine Details										
Scrubber Type	2 CL 1 OL	1 Hybrid	1 Hybrid	1 OL	1 Hybrid	OL (all)	16 Hybrid 5 OL 1 CL	2 Hybrid 3 OL	OL	OL
Ship Details	3 ferries (Stena Britannica, Stena Transporter, Stena Forerunner)	None – Experimental diesel engine, results extrapolated to full-scale ship conditions	1 RoRo ferry (Ficaria Seaways)	1 tanker (Fjordshell)	1 RoRo ferry (Ficaria Seaways)	53 Cruise ships	22 vessels: 11 RoRo/RoPax 3 cruise ship 3 oil tankers 2 vehicle carriers 1 multi-purpose 1 RoRo container 1 container ship	5 vessels	1 RoRo ferry (Magnolia Seaways)	1 RoRo ferry (Magnolia Seaways)
Geographic Scope	North Sea and Baltic Sea	Japanese coastal areas, including Tokyo Bay, Ise Bay and the Seto Inland Sea	Vessel operating between Sweden, Norway and the UK (North Sea and the Skagerrak)	Norway	Vessel operating between Sweden, Norway and the UK (North Sea and the Skagerrak)	Not specified. Destinations include Australia, Alaska, Bahamas, Bermuda, Canada & New England, Caribbean, Europe, Hawaii, Mexico, Transatlantic and Panama Canal.[2]	North Sea and Baltic Sea ECAs (20 ships); Mediterranean Sea (2 ships)	Belgium (port of Antwerp, Scheldt estuary) and North Sea	North Sea	Copenhagen harbor
Engine Details (Power)	Not specified	Experimental diesel engine (4-stroke 257kW, medium-speed)	MAN 21 MW 2-stroke engine	Sulzer 6RND76, 10400 kW (2 stroke)	21 MW engine	Not specified	Varies by ship	Engine details for 2 of 5 ships, range from 0.442 to 11.72 MWh	N/A	N/A

[1] Only study included this meta-analysis which provided analytical results for bleed off water.
[2] Carnival Cruise Lines (n.d.). Retrieved from https://www.carnival.com/

	IVL, 2018	Japan, 2018	Hansen, 2012	Buhaug, 2006	Kjølholt et al., 2012	Carnival 2019	EGCSA and Euroshore 2018	Teuchies et al., 20201	Turner et al., 2017	Koski et al., 2017
Engine Load	One engine load only (70-75%)	Varies: 25%, 30%, 50%, 80%	High load - 85% MCR	High load (90% MCR) Low load (30% MCR)	High load (85-90%) Low load (40-45%)	Not specified	Varies by ship: range from 10% to 92% (max. continuous rating)	Not specified	Not specified	Not specified
Fuel Type	HFO	Type C Heavy Oil	HFO	HFO	Not specified	Not specified	IF380 Residual	Not specified	Not specified	Not specified
% Sulphur Content	Not specified	2.24%	2.2%	2.7%	2.2% and 1.0%	Not specified	Varies by ship: range from 0.96% to 3.14%	Varies: 1.13%, 1.49% and 1.75%, N/A (2)	Not specified	Not specified
Scrubber Discharge Water – Sampling Details										
Scrubber Mode of Operations	OL and CL	OL	OL and CL	OL	OL and CL	OL	OL and CL	OL and CL	OL	OL
Open-Loop Mode	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Closed-Loop Mode	Yes	No	Yes	No	Yes	No	Yes	Yes	No	No
Inlet / Seawater (Baseline)	No	No - Metals Yes - PAHs	Yes	No	Yes[3]	Yes	Yes (21 of 22 ships)	Yes	No	Yes
Flow Rate	Varies: 0.0028 m^3/s (2) and 0.097 m^3/s (1)	6 m^3/h	OL mode: 50 (no units provided) CL: N/A	50 and 150 (no units provided)	Hybrid in OL mode: 1,000 m^3/hr	Not specified	Varies by ship: range from 163 to 1332; "not recorded"	Varies: ranges from 0.536 to 146.18; N/A	Not specified	Not specified
Analyses[4]	Metals, PAHs, pH, Turbidity, Toxicity testing	Metals, PAHs, Toxicity testing	Metals, Total PAHs, Total Nitrogen	pH, THCs,[5] Total PAHs, PCDDs,[6] PCDFs[7]	Metals, PAHs, THCs, Nitrogen, Sulphur, pH, SS[8], COD[9]	Metals (total and dissolved), PAHs	Metals, PAHs, BTEX[10], Nitrate, Nitrite	pH, Metals, PAHs	Metals	pH, Metals

[3] Seawater reference result from Kjolholt et al. (2012) provided a mean of two samples taken on two different days.
[4] Analytical results for the Carnival 2019 study are provided as an average of all ships/samples (mean, trimmed mean excluding statistical outliers). Results for all other studies are provided as unique analytical results for each individual sample.
[5] THCs - Total Hydrocarbons
[6] PCDD - Polychlorinated dibenzodioxins (Dioxins)
[7] PCDF - Polychlorinated Dibenzofuranes (Furanes)
[8] SS – Suspended Solids
[9] COD – Chemical Oxygen Demand
[10] BTEX – Benzene, Toluene, Ethylbenzene and Xylene

	IVL, 2018	Japan, 2018	Hansen, 2012	Buhaug, 2006	Kjølholt et al., 2012	Carnival 2019	EGCSA and Euroshore 2018	Teuchies et al., 20201	Turner et al., 2017	Koski et al., 2017
Available Analytical Data	Provided as unique analytical results for each ship	Provided as unique analytical results for different engine loads	Provided as unique analytical results for each ship	Provided as unique analytical results for different engine loads	Provided as a unique analytical result	Provided as an average of all samples collected from multiple ships	Provided as unique analytical result for each ship and by operational conditions (41 discharge results and 36 inlet seawater results)	Provided as unique analytical result for each ship and by operational conditions (41 discharge results and 36 inlet seawater results)	Provided as a unique analytical result	Provided as a unique analytical result
Application of Analytical Data in Original Study	Compared chemical analyses as predicted concentrations in the mixing zone after dilution to water quality criteria	Compared analytical results directly to IMO guidelines and water quality criteria	Compared analytical results directly to IMO guidelines	Provides background information supporting proposed discharge criteria developed and submitted as a proposition to IMO MEPC 55	Compared analytical results directly to water quality standards (no adjustment for reference seawater or flowrate)	Compared "net post-EGCS" (adjusted for concentrations in inlet seawater) to water quality standards. Uses results for dissolved metals	Compared normalized results for each ship (to a 45m^3/MWh washwater flowrate) to water quality standards	Assessed the impact of scrubber effluent on water quality using different treatment and discharge concentration scenarios for closed-loop and open-loop modes	Assessed the discharge of copper, zinc and vanadium to surface waters	Assessed the biological effects of contaminants present in scrubber effluent on marine plankton
Guidelines used in Study										
IMO Guidelines for Exhaust Gas Cleaning Systems – discharge criteria	IMO Resolution MEPC.259(68), 2015 Guidelines	IMO Resolution MEPC.259(68), 2015 Guidelines	IMO Resolutions MEPC.170(57) and MEPC.184(59), 2008 and 2009 Guidelines	IMO Resolution MEPC.130(53) – *specific criteria for washwater discharges cited in development*	IMO Resolution MEPC.184(59), 2009 Guidelines	IMO MEPC.259(68), 2015 Guidelines	IMO Resolution MEPC.259(68), 2015 Guidelines	n/a	n/a	n/a
Environmental quality	Environmental Quality Standards (EQS) for priority pollutants in the EU Water Framework Directive (2000/60/EC)	Japanese 'Basic Environment Act' - Environmental water quality standards	n/a	US EPA Water Quality Standards (WQS); EU Environmental Quality Standards (EQS)	Environmental Quality standards (EQS), EU Water Framework Directive (2008/105/EC); Danish national quality standards (Statutory Order No. 1022)	Surface Water Standards, EU Water Framework Directive (2013/39/EU)	n/a	Water Quality Standards (WQS), EU Water Framework Directive (2013/39/EU)	Predicted No-Effect Concentration values used in risk assessments in the EU (for copper and zinc)	*References EU Environmental Quality standards (2008) in conclusion but does not provide a direct comparison*

	IVL, 2018	Japan, 2018	Hansen, 2012	Buhaug, 2006	Kjølholt et al., 2012	Carnival 2019	EGCSA and Euroshore 2018	Teuchies et al., 20201	Turner et al., 2017	Koski et al., 2017
Drinking Water Quality	n/a	n/a	n/a	n/a	n/a	EU Drinking Water Standards (Council Directive 98/83/EC); US EPA Drinking Water Standards (2016) WHO Guidelines for Drinking-Water Quality (2018)	WHO Guidelines for drinking water quality (2017)	n/a	n/a	n/a
Industry Effluent	n/a	n/a	n/a	n/a	n/a	EU Industrial Emissions Directive, standards for incineration plant waste gas cleaning wastewater (2018); German Wastewater Ordinance, land-based point source wastewater limitations from biological waste treatment (2016)	Directive 2010/75/EU - European Union limits for discharges of wastewater from the cleaning of waste gases from incineration plant (metals).	n/a	n/a	n/a
Sludge quality	n/a	n/a	n/a	n/a	Danish (Statutory Order No. 1650) and German quality standards for application of sludge on agricultural soils	n/a	n/a	n/a	n/a	n/a

	IVL, 2018	Japan, 2018	Hansen, 2012	Buhaug, 2006	Kjølholt et al., 2012	Carnival 2019	EGCSA and Euroshore 2018	Teuchies et al., 20201	Turner et al., 2017	Koski et al., 2017
Study Conclusions *Overall assessment of scrubber discharge water impacts to marine environment* *Notable findings on variations in discharge water quality*	Effluents from both open- and closed-loop scrubbers found to cause risks to the marine environment. Risk from open-loop were concluded to be significantly higher. As pH and alkalinity did not differ from the clean seawater, effects were concluded to be primarily caused effluent water toxicity rather than by acidification.	Discharge from the scrubbers will not introduce an adverse effect on the stipulated environmental standards of pH, total nitrogen, total phosphorous and chemical oxygen demand (COD). Risks from scrubbers to the marine environment and marine aquatic organisms are in acceptable or negligible from both short-term and long-term perspectives. Higher levels of iron and zinc were assumed leached from steel pipes in discharge lines due to low pH of the washwater.	Discharge water is in compliance with IMO's guidelines for a hybrid scrubber operating in both in open-loop and closed-loop mode.	Note that there are few criteria/ standards of direct relevance to scrubber discharge from ships. Propose wastewater discharge criteria values. Mentions the scrubber itself as a possible source of elevated metals scrubber effluent water.	Hazardous substances were below EQS standards and not of ecological concern in three modelling scenarios. Scrubber washwater concluded to have negligible to marginal effects on ocean acidification and the buffering capacity of seawater. High levels of copper and zinc are unexpected based on the fuel used, suggested contamination from an unidentified source.	Pollutants present in washwater are well within the range specified by various water quality standards. Concludes that use of scrubbers are a safe and effective way to meet the IMO 2020 sulphur cap requirements. Washwater quality appears to be further improved by enhanced system filtration, however this observation is based on a small number of samples and is not a definitive conclusion. Areas for further study include to quantify the accumulation of washwater parameters entering seawater and to determine potential impacts on marine life.	Washwater discharge from various ships meet criteria of MARPOL, WHO and EU water directive. Recommends that any future programs and protocols are designed with both best practices and practicality/cost effectives in mind (including use of specialized equipment, lab and test methodologies, and shelf life of samples).	Concentrations of most PAHs and all metals in closed-loop bleed-off largely exceeded WQS and are expected to be acutely toxic for most aquatic organisms. However, when accounting for dilution, almost no compounds will exceed their WQS, whereby no acute toxicity is expected. The use of open-loop scrubbers as an abatement technology will not reduce the contribution of exhaust gas emissions from marine transportation to ocean acidification.	Concentrations of both copper and zinc in open-loop scrubber effluent are well above the Predicted No-Effect Concentration values for use in risk assessments in the EU (2.5 and 21 times higher than the releases from antifouling paint, respectively). Effluent discharge is not adequately handled in terms of harmonization with EU's Marine Strategy Framework Directive (MSFD) or subject to the Environmental Risk Assessment that is normally required for potentially polluting discharges within the European Union.	Observed detrimental effects of scrubber discharge water on plankton. Effects were linked to dilution suggesting that rapid dilution of scrubber effluents could ensure impacts are minimal and comparable to that from atmospheric deposition.