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Assessment of cumulative chemical hazard from shipping to the marine environment of the North-East Atlantic (OSPAR)

Roland Pfeiffer [a,*], Erik Ytreberg [a,b], Anna Lunde Hermansson [a,c], Amanda Trygvesdotter Nylund [a,d], Jukka-Pekka Jalkanen [e], Tiia Grönholm [e], Ida-Maja Hassellöv [a]

[a] Department of Environmental and Energy Sciences, Chalmers University of Technology, SE-41296, Gothenburg, Sweden
[b] IVL Swedish Environmental Research Institute, P.O. Box 53021, 400 14, Gothenburg, Sweden
[c] RWTH Aachen University, 52056, Aachen, Germany
[d] Swedish Meteorological and Hydrological Institute (SMHI), Göteborgseskaderns Plats 3, SE 426 71, Västra Frölunda, Sweden
[e] Finnish Meteorological Institute (FMI), Erik Palménin aukio 1, FI-00560, Helsinki, Finland

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ABSTRACT

Shipping releases hazardous substances into marine environments through, e.g., scrubber effluents, bilge-, ballast-, and greywater, sewage, and biocides from antifouling paints. Effective regulation requires identifying these substances, their concentrations, source volumes, and resulting annual loads, to assess potential environmental hazards of individual waste streams relative to land-based sources. Focusing on the North-East Atlantic and the years 2018 and 2023, total loads of hazardous substances from shipping, and the cumulative hazard posed by individual waste streams were quantified. These ship-related sources were compared to inputs from rivers, and coastal industries and wastewater treatment. Substance-specific hazard was assessed by dividing waste-stream concentrations by each substance's environmental threshold value. Mixture toxicity was accounted for through concentration addition, using annual volumes to scale and comparing hazard indices (HI). Results show that all loads from shipping increased between 2018 and 2023. Copper and zinc from antifouling paints dominated total loads, with copper loads surpassing combined land-based copper inputs by 2023. HI from shipping increased even more than loads and shipping contributed more than half to the total HI by 2023 based on the available data. Antifouling paints and scrubbers dominated HI, marking them as the strongest contributors to hazard from shipping. Notably, scrubbers showed the highest relative increase in HI of all waste streams between 2018 and 2023. These findings highlight priority areas for regulation and monitoring within the OSPAR region. Targeted regulation on antifouling paints and scrubbers could substantially reduce the marine environmental impacts from shipping, improving the industry's environmental sustainability.

1. Introduction

The shipping industry is an important global sector, and more than 80% of transported goods have, at some point in their lifecycle, been transported via ship (UNCTAD, 2023). Port calls in Europe increased by 19% from 2.1 million in 2018 to 2.5 million in 2023 (UNCTAD, 2024a). The shipping sector is expected to continue to grow, with cargo being transported over increasingly longer distances as a result of geopolitical and safety-related factors (UNCTAD, 2024b). This increase in global ship traffic, distances, and volumes, has led to greater environmental pressures from the shipping industry, particularly through aquatic pollution, from emissions and discharges to the marine environment. These discharges originate from different waste streams, such as bilge water, ballast water, grey water, sewage, effluent from exhaust gas cleaning systems (EGCSs, also called “scrubbers”), and release of biocides from antifouling paints (Jalkanen et al., 2021). Each waste stream contains a mixture of substances with varying composition, including hazardous substances that can be harmful to the marine environment. In addition, many hazardous substances occur across multiple waste streams, yet past research (on risk assessment and/or composition of waste streams) often focused on single waste streams (Chan et al., 2015; García-Gómez et al., 2023; Mujingni et al., 2024; Ytreberg et al., 2020) and a similar

* Corresponding author at: Department of Environmental and Energy Sciences, Chalmers University of Technology, SE-41296, Gothenburg, Sweden.
E-mail address: roland.pfeiffer@chalmers.se (R. Pfeiffer).

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focus has characterized the regulation of these waste streams and the hazardous substances in them. For example, antifouling paints are regulated through the antifouling systems (AFS) convention (AFS/CONF/26, 2001) and the biocidal products regulation (BPR) (Regulation (EU) No 528/2012, 2012); ballast water is covered by the Ballast Water Management (BWM) convention (BWM/CONF.1/37, 2004) and atmospheric exhaust emissions from ships are regulated through MARPOL Annex IV (2005). Emissions of oil are covered in MARPOL Annex I (1983) while pollution from liquid substances transported in bulk or from sewage are regulated in MARPOL Annex II (1982) and MARPOL Annex IV (2003), respectively. Few studies have addressed the cumulative load of hazardous substances from ships by considering more than one waste stream and multiple hazardous substances (Jalkanen et al., 2021; Lunde Hermansson et al., 2023; Moldanová et al., 2022; Ytreberg et al., 2021a) or integrated this with conducting risk and hazard assessments (Lunde Hermansson et al., 2025a; Nys et al., 2017).

To regulate marine discharges from shipping effectively, policy decisions should prioritize substances and waste streams that pose the greatest environmental hazard—whether due to large discharge volumes, high toxicity, or both. This approach aligns with criteria such as 'intrinsic hazard' and 'potential for widespread contamination' used to define priority substances under Directive 2000/60/EC, commonly referred to as the Water Framework Directive (WFD), and its amendment in Decision No 2455/2001/EC. Intrinsic hazard refers to the inherent harmful properties of a hazardous substance, e.g., bioaccumulation potential, persistence, or endocrine-disrupting effects. The potential for widespread contamination depends on the total load of the hazardous substance released over a specific time period, the characteristics of the receiving environment, and the substance's chemical fate and behavior within that environment. In practice, however, prioritization is often driven by economic considerations: actions tend to be ranked by cost–benefit ratios, which may not correspond to the order of actual environmental risk (Nygård et al., 2016). There is a knowledge gap regarding the relative importance of shipping as a source of contaminants to the marine environment, both with respect to the contribution of the total load of hazardous substances, and the relative contribution from different on-board sources. Closing this gap would allow for a policy approach that considers the wider effects of (and links between) different sources of pollution. To identify waste streams and substances for regulatory prioritization, the first step is to quantify the contribution of hazardous substances from shipping relative to other natural and anthropogenic activities using a cumulative approach. In this study, cumulative hazard was determined based on substance concentrations in the waste streams, indicating a potential hazard. While efforts have been made to quantify the loads from ship activities, land-based sources and riverine input in the Baltic Sea area (Ytreberg et al., 2022), no previous studies have considered the combined load and hazard from all waste streams within the OSPAR maritime area in a cumulative way. This assessment of the cumulative potential hazard is an important second step, which is unique to the present study.

While regulation of coastal industries and riverine inputs usually cover entire sectors and a variety of human activities and environmental compartments as, e.g., the WFD, the Industrial Emissions Directive (Directive 2010/75/EU), or the Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC), discharges from shipping are regulated on a per-waste stream base, as mentioned above. For example, MARPOL Annex VI (2005) regulates sulfur emissions from ships by limiting the allowed sulfur content of marine fuels to 0.5% globally (and 0.1% in sulfur emission control areas (SECAs)). Ships may meet these criteria by either switching to low-sulfur fuels, or by continuing to use cheaper high-sulfur heavy-fuel oil (HFO) in combination with an exhaust gas cleaning system (scrubber) (Lunde Hermansson et al., 2024; MARPOL Annex VI, 2005). When in operation, scrubbers produce large amounts of acidic discharge water, particularly when operated in open-loop mode. This water contains a cocktail of hazardous substances removed from the exhaust gases, including polycyclic aromatic hydrocarbons (PAHs) and metals (García-Gómez et al., 2023; Lunde Hermansson et al., 2021), and is discharged into the marine environment. Due to environmental concerns several countries have responded by imposing bans: Denmark, Finland and Sweden prohibit open-loop scrubber discharges in their territorial waters since 1 July 2025 (BEK nr 539 af 21/05/2025, 2025; Laki 1116/2024, 2024; SFS 2025:23, 2025). This indicates that the original solution of internationally regulating a single emission type (atmospheric emissions, with a focus on sulfur) via MARPOL Annex VI (2005) was leading to sub-optimal outcomes by introducing pollution through other waste streams whose effects were insufficiently covered by that legislation. This created a different set of issues that then had to be addressed in subsequent national legislation, which could have been avoided with a more integrated initial assessment covering cumulative effects from different waste streams. When implementing legislation regulating waste streams from shipping it is therefore important to consider the other waste streams this regulation might affect to avoid simply moving pollution from one stream to another (as exemplified in the case of open-loop scrubbers). Similarly, when regulating one waste stream via legislation that concerns only that waste stream, the resulting changes might have effects that are covered by other regulations, or not regulated at all.

This requires a cumulative and cross-waste-stream approach when addressing marine pollution from ships and comparing waste streams. However, it is challenging to compare the potential hazards posed by the wide range of waste streams generated by shipping due to the large variety of substances and their contribution to the mixture in the waste stream. Yet without such knowledge, policymakers cannot effectively prioritize mitigation measures and take into account spillover effects from one area of legislation into another. In policy, chemicals have usually been assessed one-by-one, i.e. on a single-substance basis, where the measured environmental concentration is compared to a threshold value. For accounting for mixture toxicity, a commonly used first-tier method for predicting the toxicity of chemical mixtures is the concentration-addition (CA) approach, in which each substance's concentration is divided by a threshold value to obtain a hazard quotient; these quotients are then summed (Backhaus and Faust, 2012). This method applies to substances that share a similar toxic mode of action and is an improved approach to addressing mixture toxicity in regulatory contexts (Backhaus et al., 2013). CA has been recommended as a method for taking into account mixture toxicity as the additive nature of chemical toxicity has been widely observed, and CA is a common approach when more complex methods such as synergistic and/or antagonistic models are not available or not suitable (Cedergreen, 2014; Escher and Hermens, 2002). Since the shipping sector releases a wide number of hazardous substances through multiple waste streams, an integrated approach taking into account mixture toxicity is important in order to accurately estimate the cumulative potential hazard from shipping and limit negative environmental effects.

The necessity of measures to mitigate marine pollution (and of corresponding monitoring) is emphasized by the failure of some European marine regions in the North-East Atlantic, Baltic, and Mediterranean (Hassellöv et al., 2025; WISE Marine, 2025) to achieve good environmental status (GES) according to descriptor D8 (contaminants) defined in the MSFD, which aims to provide a policy framework for the protection of marine ecosystems and maintaining their productivity and biodiversity. EU member states determine whether they have reached GES based on the descriptors laid out in the MSFD, which defines GES as "*the environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable, thus safeguarding the potential for uses and activities by current and future generations*" (Directive 2008/56/EC). While previous analysis on pollution loads from shipping focused on e.g. the Baltic, the aim of the current study is an expansion of scope both in terms of spatial area but also the analytical approach. Hence, the focus of the current study is the entire area covered by the Convention for the

Protection of the Marine Environment of the North-East Atlantic (OSPAR) (Fig. 1). OSPAR is a regulatory mechanism by contracting parties to reduce marine pollution from maritime activities and land-based sources (OSPAR Convention, n.d.).

The goal of the OSPAR convention is to prevent environmental degradation due to pollution, climate change, and loss of biodiversity, as outlined in OSPAR's North-East Atlantic Environment Strategy 2030 (OSPAR Decision 2025/01). In an effort to mitigate harmful effects from shipping activities, the OSPAR contracting parties have agreed to ban scrubber discharges in ports and inland waters, starting in 2027 for open loop systems and extending to also include close-loop discharges in 2029 (DNV, 2025). The state of the OSPAR area is regularly assessed in the OSPAR Quality Status Reports (QSRs). The latest QSR from 2023 identified downward trends in hazardous substance concentrations in most cases, but registered increasing overall pollution the southern North Sea, and no improvement in the North Sea, the English Channel and Bay of Biscay (OSPAR, 2023a). Similarly to OSPAR for the North-East Atlantic, the Helsinki Commission (HELCOM) is a body of contracting parties adjacent to the Baltic Sea (including the EU) that provides recommendations on environmental protection on the Baltic Sea and can make consensus-based decisions (HELCOM, n.d.). HELCOM's 3rd holistic assessment 2016–2021 (HOLAS3) also notices a lack of improvement across the entire Baltic region (HELCOM, 2023). As shipping is a major human activity in those regions (Andersen et al., 2013; HELCOM, 2023; OSPAR, 2023b), assessing the hazards associated with it is essential.

The aim of this paper is to:

- assess the contribution of liquid discharges from shipping to
  - o the load of hazardous substances
  - o the cumulative hazard posed by those substances
- identify the waste streams and hazardous substances with the largest impact
- outline an approach for a cumulative assessment of potential environmental hazard attributable to different sources and substances, which allows a more comprehensive assessment of the outcomes of specific policy decisions within the framework of national and international regulation

This has been conducted with the OSPAR region as a case study, and shipping defined as encompassing the activity of all vessels transmitting an AIS signal as outlined in the methods section. The waste streams which pose the highest environmental hazard have been identified, and shipping's contribution to those waste streams have, where possible, been put into relation to pollution sources originating from land (riverine inputs, and direct discharges such as industrial point sources or wastewater treatment plants). Lastly, in order to assess whether there is a monitoring effort that allows data to assess the success of regulation and mitigation efforts, it was investigated using the DOME database (ICES, n.d.) when and in what matrix the substances were last monitored in the OSPAR area. The results from this assessment are important for policymakers to make science-based decisions and implement measures and regulations that will have the strongest impact on a reduction of hazardous impacts from shipping in the OSPAR region, while also ensuring that secondary effects on other pollution sources can be considered.

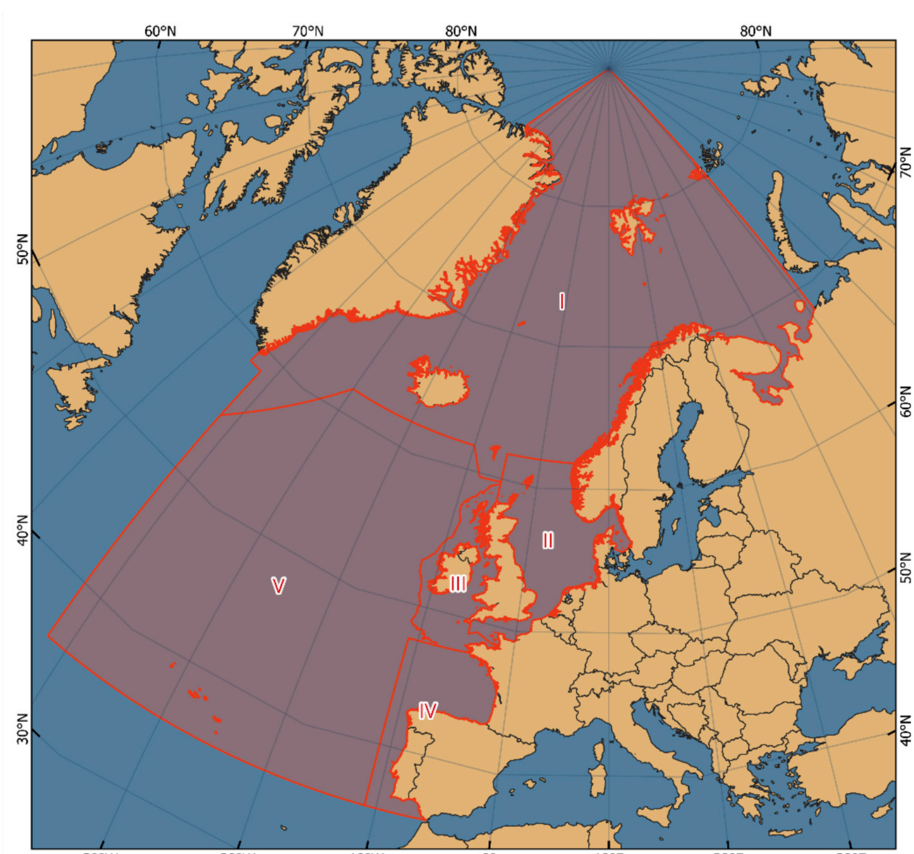

Fig. 1. OSPAR area and regions. OSPAR regions I to V (outlined in red): region I (Arctic Waters), region II (Greater North Sea), region III (Celtic Sea), region IV (Bay of Biscay), and region V (Wider Atlantic). OSPAR regions in the analysis were used as depicted in the figure, i.e. using the version prior to the expansion of OSPAR region V in 2025 (OSPAR 25/14/01, Annex 17). OSPAR shapefile retrieved from (ODIMS, 2024), countries shapefile obtained from the UN World Food Programme via opendatasoft (2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

Loads of hazardous substances from shipping were assessed for two different years (2018 and 2023) in the OSPAR area and per-region (Fig. 1), and the contribution of the shipping sector was compared to loads from riverine inputs and direct discharges (RID). Additionally, hazard quotients (HQs) and hazard index (HI) – calculated by summing HQs and multiplying by the total volume of each waste stream – were used to assess and compare the hazard potential across different waste streams (see following chapters for a detailed description). The years 2018 and 2023 were selected because the number of global scrubber installations showed a large increase between them (Fig. S1) (DNV, 2025), and 2023 was the latest year for which OSPAR data on riverine inputs and direct discharges was available (direct discharges being inputs from, e.g., coastal industries and waste-water-treatment plants).

Data on the discharge volumes of ship-generated waste streams were obtained from model predictions from the Ship Traffic Emission Assessment Model (STEAM), and concentrations of substances in the waste streams (necessary to calculate substance loads) were obtained from scientific literature (Lunde Hermansson et al., 2025b; Ytreberg et al., 2021b) (Fig. 2).

Annual substance loads from shipping were calculated by multiplying the spatially aggregated yearly waste stream volumes, estimated by STEAM predictions, with the corresponding substance concentrations obtained from literature reviews, as in Eq. (1), where $m_{i,j,y}$ is the load of substance i in waste stream j in year y, $c_{i,j}$ the concentration of the substance i in the waste stream j, and $V_{j,y}$ the volume of the waste stream j in year y.

$$m_{i,j,y} = c_{i,j} {}^* V_{j,y} \quad (1)$$

OSPAR data on annual metal loads from land-based sources was obtained from the OSPAR database on riverine inputs and direct discharges (RID) (Farkas, 2025). The annual loads were then divided by a threshold value T_i for substance i (environmental quality standards (EQS) or predicted no-effect concentration (PNEC) values) to obtain a relative hazard quotient $HQ_{i,j,y}$ for each substance i in each waste stream j (including riverine inputs and direct discharges) in year y, as in Eq. (2).

$$HQ_{i,j,y} = \frac{m_{i,j,y}}{T_i} \quad (2)$$

These $HQ_{i,j,y}$ were then summed across substances to obtain an overall $HI_{j,y}$ for each waste stream j in year y as in Eq. (3) where n_s is the number of included substances, m_w is the number of waste streams (Fig. 2). Annual total loads of hazardous substances entering the marine environment (both from shipping and land-based sources), along with the HI, were calculated for the whole OSPAR region and each of the five sub-regions (Fig. 1).

$$HI_{j,y} = \sum_{i=1,j=1}^{n_s,m_w} HQ_{i,j} {}^* V_{j,y} \quad (3)$$

Uncertainties in discharge volumes and substance concentrations were accounted for using a Monte-Carlo simulation with 10,000 iterations. Where no uncertainty estimate was available for a parameter, that parameter was repeatedly used across all iterations. Model convergence was monitored as a function of number of iterations, and 10,000 iterations were determined to be an acceptable tradeoff between computational requirements and model convergence (Figs. S2 and S3). A sensitivity analysis was conducted by assessing the effects of a ± 5% change in substance concentrations, waste stream volumes, and PNEC values on the total HI in 2023.

2.1. Shipping discharge volumes

Yearly discharge volumes to the OSPAR region from ship waste streams were obtained for two years (2018 and 2023) from STEAM (v.

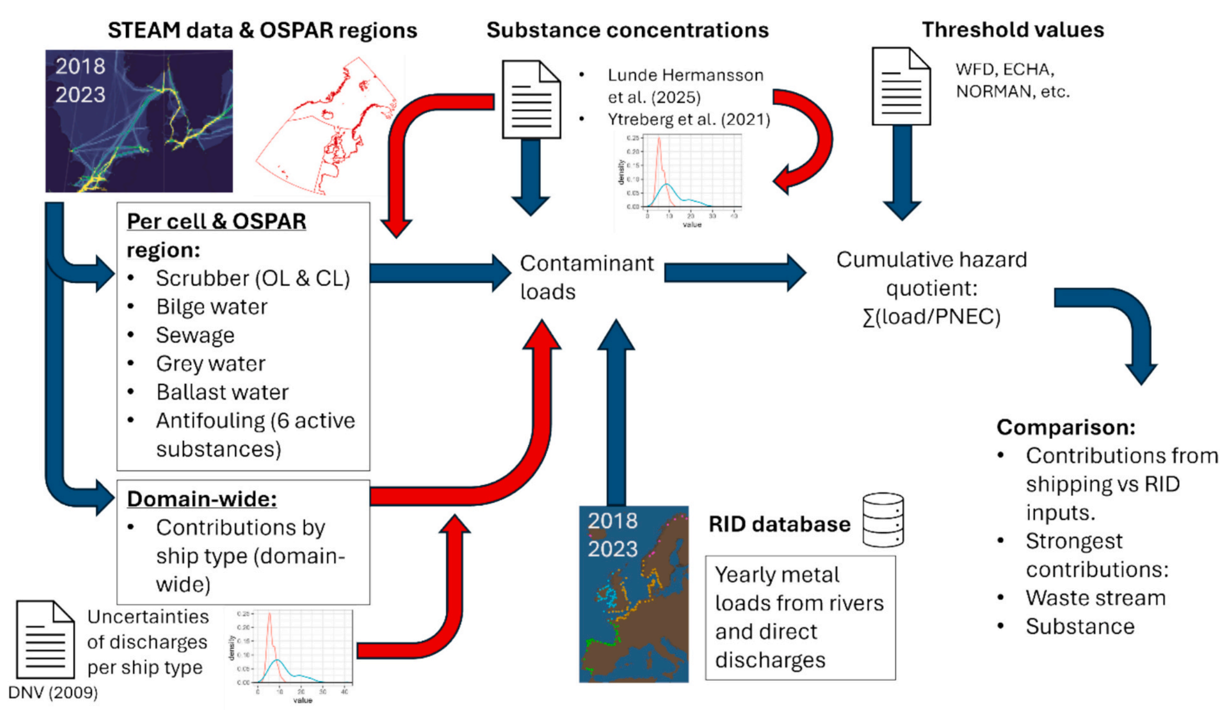

Fig. 2. Data sources and workflow. Blue arrows represent regular data flow, red arrows indicate uncertainty information used in the Monte Carlo simulation. Spatially resolved discharge volumes from shipping were obtained from the STEAM model and separated by OSPAR regions. Scrubber discharge water contains two separate waste streams: open-loop (OL) and closed-loop (CL) scrubber effluent. The proportional contributions of different ship types to each waste stream were also obtained from STEAM, on a domain-wide scale, and used to apply corresponding uncertainties to the Monte Carlo simulation. Concentrations, uncertainties and threshold values were obtained from literature (document symbols). Riverine inputs and direct discharges were obtained from the OSPAR riverine inputs and direct discharges (RID) database (containing loads of metals) (Farkas, 2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5.1.0), developed by the Finnish Meteorological Institute (FMI) (Jalkanen et al., 2009, 2012, 2021; Johansson et al., 2013, 2017). The modeling was based on a global automatic identification system (AIS) dataset from Orbcomm Ltd which includes both satellite and terrestrial AIS position reports which commercial ships are required to transmit regularly. Fleet technical data from S&P Global (2025) was used to describe the ship specifications. Ambient conditions from Copernicus Marine and Copernicus Atmospheres were used in the modeling (Hersbach et al., 2023; Le Galloudec et al., 2024), further details are available from Majamäki et al. (2025).

STEAM provides estimates for 60 parameters as a gridded output, including liquid discharges (bilge water, ballast water, scrubber effluent, etc.) and release of biocides from antifouling paints via leaching from the exposed wet hull surface. In STEAM, those parameters are cross-referenced with AIS data from commercial vessels (position, speed, heading, etc.) with static ship information (e.g., installed engine power, scrubber installations, hull type, size). The fleet used by STEAM comprises every vessel that is operating with an active AIS transponder. Besides regular commercial vessels such as cruise ships and different types of cargo- or other passenger vessels, this also includes (among others) supply vessels, fishing vessels, search and rescue vessels, research vessels, ice breakers, car ferries, etc. Equipment types and installation dates were also tracked using IMO Global Information System for International Shipping (GISIS) (IMO, 2025b). A more in-depth description of how different waste streams are handled in STEAM is provided in the supplementary material (Note S1). STEAM outputs were provided on a monthly resolution for a spatial domain ranging from 30°N to 90°N in latitude and 50°W to 60°E longitude, with a cell resolution of 0.2 degrees longitude and 0.09 degrees latitude (Fig. S4). These outputs were then manually aggregated per year and resolved on OSPAR region level (I-V) (Fig. 1). Because the STEAM model does not explicitly include OSPAR regions, annual emissions from individual vessels cannot be isolated solely to that area by the model directly. To address this limitation, the analysis considered vessels within this domain that had visited marine areas designated as part of OSPAR, while vessels operating exclusively in other regions, such as the Mediterranean or the Baltic Sea, were excluded from the assessment. The waste streams from shipping that were included in this study are exclusively discharging into the marine environment as liquid discharges, or in case of antifouling paint, as releases from the hull surface. The waste streams that were considered in this study were three types of ballast water (separated by treatment: chemical injection, electro-chlorination (EC), and UV treatment (UC)), bilge water, open- and closed-loop scrubber effluent, released substances from antifouling paint, greywater, and sewage. Atmospheric emissions were not included in this study (Fig. 2).

To account for uncertainties in the data on discharges and concentrations, a Monte Carlo simulation was conducted using uncertainties for those parameters where available. Uncertainties in discharge rates of sewage and grey water were obtained from DNV (2009), uncertainties of antifouling paint release rates were obtained from Ytreberg et al. (2021a), and for scrubber discharge volumes from Lunde Hermansson et al. (2025b). Where data on uncertainties was available, discharge volumes were assumed to follow a lognormal distribution in the Monte Carlo simulation, as discharges can be expected to follow a continuous, non-negative distribution. Where no distributional information/uncertainty was available, the volume obtained from STEAM was repeated across all iterations.

Ballast water discharge volumes, originally reported as one waste stream in STEAM, was separated into three different sub-categories based on the proportion of which the three systems electro-chlorination (EC, 45%), chemical injection and ozone treatment (CI, 5%), and UV treatment (UV, 50%) are being used (MEPC 78/4/1, 2022). The discharge volumes of each sub-category were calculated by multiplying total volume with the usage fraction of that category (e.g., total ballast volume * 0.45 for EC-treated ballast water), as in Eq. (4), where $V_{BW,i}$ is the volume of ballast water system type i, $V_{BW,tot}$ is the volume discharged from all ballast water systems combined, and f_i is the fraction of total ballast discharged generated by system i.

$$V_{BW,i} = V_{BW,tot} * f_i \tag{4}$$

No uncertainty estimate was available for ballast- and bilge water discharge volumes.

STEAM assumes that copper (Cu) and zinc (Zn) are the main active ingredients released from antifouling paints (Jalkanen et al., 2021) and provides an estimate of their loads directly (as opposed to other waste streams, where STEAM only provides the discharge volume, but not single-substance loads). Similarly, releases of copper pyrithione (CuPyr), zinc pyrithione (ZnPyr), dichlorooctylisothiazolinone (DCOIT) and Zineb are also predicted as substance loads from antifouling paints. CuPyr and ZnPyr are biocides used in antifouling paints whose environmental fate in aquatic systems is influenced by metal concentration and complex stability (Dahllöf et al., 2005). Due to similarities in fate and speciation, CuPyr and ZnPyr are frequently assessed together in risk evaluations and regulatory frameworks.

2.2. Concentrations of hazardous substances in ship waste streams

Concentrations of hazardous substances in various waste streams from ships have been documented in several EU projects, including the EU BONUS project SHEBA (Jalkanen et al., 2021) and the H2020 project EMERGE (García-Gómez et al., 2023, 2024). Data on concentrations in greywater, sewage, bilge water, treated ballast water was obtained from Ytreberg et al. (2021b), and in open- and closed-loop scrubber discharge water from Lunde Hermansson et al. (2025b). Only scrubber data from undiluted, unfiltered discharge samples from individual vessels (i.e., not averages of multiple vessels) were used, and data that was excluded from scrubber emission factor calculations in the original source was excluded in the present analysis as well.

For concentrations of hazardous substances in ballast water, each ballast water system (EC-, CI-, and UV) was treated as a separate waste stream. For each type of system, only substances previously measured in the specific system were assumed present in the modelled ballast discharge from that system.

All concentration estimates reported as 0 were not included in the analysis. Data reported as below limit of detection (LOD) was retained and imputed using regression on order statistics (ROS) (Helsel and Cohn, 1988). However, if all concentrations of a substance in a waste stream were reported as below LOD, it was considered absent in that waste stream. A detailed description of the handling of <LOD data and parameter selection is listed in the supplementary material (Note S2).

Substances for which only a single uncensored measurement value was available in a waste stream were excluded from distribution fitting for Monte Carlo simulations for that stream. For all other substances, lognormal distributions were fitted to the concentration data as is common for environmental pollutant concentrations (Gardner, 2014; Ott, 1990) and the concentration distribution was modelled using a Monte Carlo simulation with 10,000 iterations.

Detailed information on data selection and processing is provided in the supplementary material (Note S2), with a comprehensive list of included substances available in Tables S1 and S2.

2.3. Loads of hazardous substances from shipping

Absolute annual contaminant loads from shipping were obtained by multiplying the yearly discharge volume (from STEAM) of each waste stream with the stream-specific substance concentration. For antifouling paints, biocide loads were provided directly by STEAM. Further, substances were classified based on whether they have been designated as OSPAR Priority Substances (OSPAR, 2025a) and/or OSPAR Substances of Possible Concern (OSPAR, 2025b).

2.4. Calculation of loads from riverine input and direct discharges

Loads of hazardous substances from riverine inputs and direct discharges were obtained from the OSPAR Riverine Inputs and Direct Discharges (RID) database (Farkas, 2025), which (for the years 2018 and 2023) contains data from Belgium, France, Iceland, Ireland, The Netherlands, Norway, Portugal, Spain, Sweden, and the UK. The number of substances available in the RID database is limited and only includes information on eight metals. The raw data was extracted from the database, and the total substance loads were aggregated based on the OSPAR region in which they occurred. No uncertainties were available for the Monte Carlo simulations. In addition, not all countries report all (or the same set of) metals, and some countries report only loads from riverine discharges, but not from direct discharges (Fig. S5).

2.5. Hazard quotient calculation

A common way of assessing environmental hazard is comparing environmental concentrations with a threshold concentration. This threshold can be, e.g., an environmental quality standard (EQS), as provided in the WFD and Directive 2013/39/EU (the environmental quality standards (EQS) directive), or predicted no-effect concentration (PNEC) values, both obtained from ecotoxicological studies (van Leeuwen and Vermeire, 2007). The regulatory purpose of these thresholds is to obtain a concentration which can be considered safe, i.e. that the negative effects that occur at this level are acceptable or negligible (van Leeuwen and Vermeire, 2007).

The hazard quotient (HQ), i.e. the ratio of the measured concentration of an individual substance in a waste stream to the threshold value, as in Eq. (2) provides information as to whether the encountered concentration should be considered hazardous to marine organisms. If the HQ exceeds 1, the threshold value is exceeded, and exposure at that concentration may pose a risk to the environment. In environmental risk assessment, an HQ of >1 is commonly treated as an indicator of unacceptable risk. In the context of this work, HQ is assessed for the undiluted waste streams, i.e. if the HQ exceeds 1 there is an unacceptable risk to the environment if organisms are exposed to the corresponding undiluted discharge waste stream.

EQS values were obtained from the WFD and EQS directive and the Swedish Agency for Marine and Water Management (SwAM) (HVMFS 2019:25, 2020). PNEC values were collected from the European Chemicals Agency (ECHA) (ECHA, n.d.), and the NORMAN Ecotoxicological Database (NORMAN, 2025). Values obtained from QSAR models (instead of ecotoxicological experiments) were not included, and neither were values whose records had a Klimisch or Cred score other than 1 or 2. Lastly, the IMO GISIS database of chemicals in ballast water was also used to obtain PNEC values (IMO, 2025a).

For PNEC values of Zn and Cu, the ECHA guidance on biocidal products legislation and PNEC values from the corresponding emission scenarios documents (ECHA, 2017a, 2017b) were followed. When compared to the PNEC values obtained from ECHA directly, this led to more conservative PNEC values of 2.6 μg/L for Cu, and 3.4 μg/L for Zn. Similarly, the EQS for Cu set by the Swedish agency for Marine and Water Management (SwAM) is also 2.6 μg/L (HVMFS 2019:25, 2020). For other substances with ECHA-reported PNEC values based on an AF of 1, an AF of 2 was applied. This approach was followed for 1,2,4-trimethylbenzene and toluene. For Zn and Cu, the PNEC values of 3.4 and 2.6, respectively, were used, as recommended by ECHA under the Biocidal Product Regulation (ECHA, 2017a, 2017b). The PNEC value provided by the European Chemicals Agency (ECHA) for CuPyr used for the analysis (0.0176 μg/L) is representative of the toxicity of pyrithione (Pyr) in CuPyr; therefore the corresponding PNEC value for ZnPyr (0.0177 μg/L) was calculated based on the molecular weight of the two substances (ECHA, 2017a, 2017b). EQS and PNEC values used in the current study are shown in Table S1. A more detailed description of EQS and PNEC value derivation is provided in the supplementary material (Note S3).

In case of conflicting threshold values, the sources were prioritized as follows: WFD values were used where available, followed by SwAM values, ECHA's and BPR's emission scenario tool for antifouling products (ECHA, 2017a, 2017b), IMO values, ECHA values, and finally NORMAN values.

It should be noted that the calculation of HQ can only include substances for which both the concentration in the corresponding waste stream as well as a PNEC or EQS value are available. Therefore, the HQ calculations exclude substances for which no monitoring data in the waste streams was available, or for which no PNEC or EQS value was found. In addition, since data for riverine inputs and direct discharges only included a comparably small number of monitored metals, the resulting HQ of those sources will only represent those substances, although other substances might occur in those sources, albeit unmonitored.

2.6. Hazard comparison

The HQ is a useful metric for assessing the risk of a single substance in water. However, when addressing pollution from shipping and entire waste streams with a mixture of substances, it is important to also assess the discharge volume, as it varies considerably between waste streams (Figs. S6 and S7). This is especially relevant when comparing different waste streams with each other, as they do not only differ in the composition and concentration of hazardous substances, but also in discharge volumes.

To account for the contribution of the different waste streams and their mixture toxicity, the CA approach was used, based on Backhaus and Faust (2012) and the IMO recommendations for risk assessments for scrubber discharge water (MEPC.1-Circ.899, 2022). The CA approach predicts mixture toxicity well in the majority of cases, e.g. for mixtures of pesticides, metals, and antifoulants (Cedergreen, 2014). In accordance with the CA approach, $HQ_{i,j,y}$ was summed across substances. Assuming that the hazard scales in a linear fashion with the load of the substances included in the assessment, each summed quotient was then multiplied with the volume of the corresponding waste stream in the respective year and OSPAR region, resulting in the $Hi_{j,y}$, as in Eq. (3).

The $Hi_{j,y}$ is a screening-based, relative metric intended for prioritization across waste streams and substances. It does not represent ecological risk or predict biological effects in the receiving environment. Therefore, it is not a risk indicator in the commonly understood sense that defines risk as the product of the probability of occurrence and the potential damage incurred. Instead, it combines inherent toxicity (via EQS or PNEC values) with the waste streams discharge magnitude, assuming concentration addition among substances. $Hi_{j,y}$ values are therefore only interpretable relative to each other within the same assessment and are used here to compare the relative contribution of different waste streams, substances, regions, and years to the overall hazard.

Considering Eqs. (1) and (2), Eq. (3) can be rearranged as Eq. (5) by separating the $HQ_{i,j,y}$ into its own components of $c_{i,j}$, the measured concentration of substance i in waste stream j, and threshold value T_i for substance i.

$$HI_{j,y} = \sum\nolimits_{i=1,j=1}^{n_s,m_w} \frac{c_{i,j}}{T_i} * V_{j,y} \tag{5}$$

For hazardous substances released from antifouling paint, STEAM already quantifies the substance loads. Since the load is calculated as the product of the volume $V_{j,y}$ of waste stream j in year y with the measured concentration $c_{i,j}$ for substance i in waste stream j (Eq. (1)), the HI from antifouling substances ($HI_{AF,y}$) in year y can be calculated as in Eq. (6) where $m_{AF,i,y}$ is the load from antifouling of substance i in year y.

$$HI_{AF,y} = \sum\nolimits_{i=1,j=1}^{n_s,m_w} \frac{m_{AF,i,y}}{T_i} \tag{6}$$

Using Eqs. (5) and (6), it is possible to calculate the HI of any number and combination of substances and waste streams. Through HIs, it is possible to compare specific waste streams and/or hazardous substances, as the HI describes the waste streams' corresponding relative hazard (i.e., their contribution to the combined hazard can be computed). The HI for a specific region r and year y ($HI_{r,y}$) can be calculated using Eq. (7), where $V_{,r,y}$ is the volume of waste stream j in region r in year y:

$$HI_{r,y} = \sum_{i=1,j=1}^{n_s,m_w} \frac{c_{i,j}}{T_i} * V_{j,r,y} \tag{7}$$

In addition, the $HI_{i,y}$ for a single substance i in year y can be calculated using Eq. (8), which is similar to Eq. (5), but does not sum across substances.

$$HI_{i,y} = \sum_{j=1}^{m_w} \frac{c_{i,j}}{T_i} * V_{j,y} \tag{8}$$

For substances released from antifouling, for which loads are already provided from STEAM, $c_{,j}$ * $V_{j,y}$ in Eq. (8) should be replaced with the corresponding load (as illustrated by Eq. (6)).

HI was compared between regions and years and the relative contribution of different waste streams and substances to the overall hazard was assessed.

2.7. Assessment of monitoring coverage

Substances for which a HI had been calculated were looked up in the DOME database (ICES, n.d.), and their last monitoring year within the range of the years 2000 to 2024 (most recent available data in DOME) inside the OSPAR region was recorded for all three marine sampling matrices (sediment, biota, and water). Spatial and temporal coverage of the data were not assessed.

3. Results and discussion

3.1. Loads of hazardous substances

Rivers were the largest source of metals to the OSPAR region in both years with the exception of Cu where shipping emissions exceeded the load from rivers in 2023 (Fig. 3). While metal loads from shipping increased for all substances between 2018 and 2023, RID metal loads decreased between 2018 and 2023 across almost all included metals. The largest metal loads from shipping were Cu, Zn, and Nickel (Ni). Largest relative increases in metal loads from shipping were observed for Ni (420%), Chromium (Cr, 370%), arsenic (As, 346%), cadmium (Cd, 249%), and lead (Pb, 133%). Cu loads from shipping increased by 18% and in 2023 exceeded those from riverine inputs and direct discharges combined. Ni and Arsenic (As) loads from ships exceeded those from direct discharges, although not the loads from rivers (Fig. 3). The volumes of the different wase streams are visualized in Figs. S6 and S7.

The decrease in RID inputs was mainly attributable to lower reported inputs from Spain, the UK, Norway, and Ireland, and contracting parties report a general decrease in flow-normalized loads (Farkas and Skarbøvik, 2024b). However, it should be noted that OSPAR reporting is incomplete (Farkas and Skarbøvik, 2024a) and some countries did not report inputs due to limitations of the quality of available data. No data was available from Germany, and no direct discharges were reported from Belgium, France, Iceland, the Netherlands, and Portugal (Fig. S5) (Farkas, 2025). Therefore, it can be expected that the available RID discharge data represents an underestimate of the actual loads, both in terms of the substances that were reported by only some of the countries, and also in terms of substances that are not being monitored at all.

Overall, loads of all hazardous substances from shipping increased between 2018 and 2023, with Cu having the highest load, followed by Zn, isocyanuric acid, sodium thiosulphate, vanadium (V), and Ni (Fig. 4). The vast majority of Cu and Zn loads were released from antifouling paint. Similar patterns were observed by Ytreberg et al. (2022), who also found riverine inputs to be dominating the metal inputs to the Baltic Sea, although Cu loads from shipping were notably significant (37%). In contrast, the contribution from shipping to Cu loads in our data in the OSPAR region is more than 50% in 2023 (Fig. 5). Isocyanuric acid is a disinfectant byproduct from ballast water treatment systems with chemical injection (Fujiwara et al., 2014). Sodium thiosulphate (commonly added to ballast water to neutralize potentially remaining total residual oxidants) originates mainly from ballast water treated

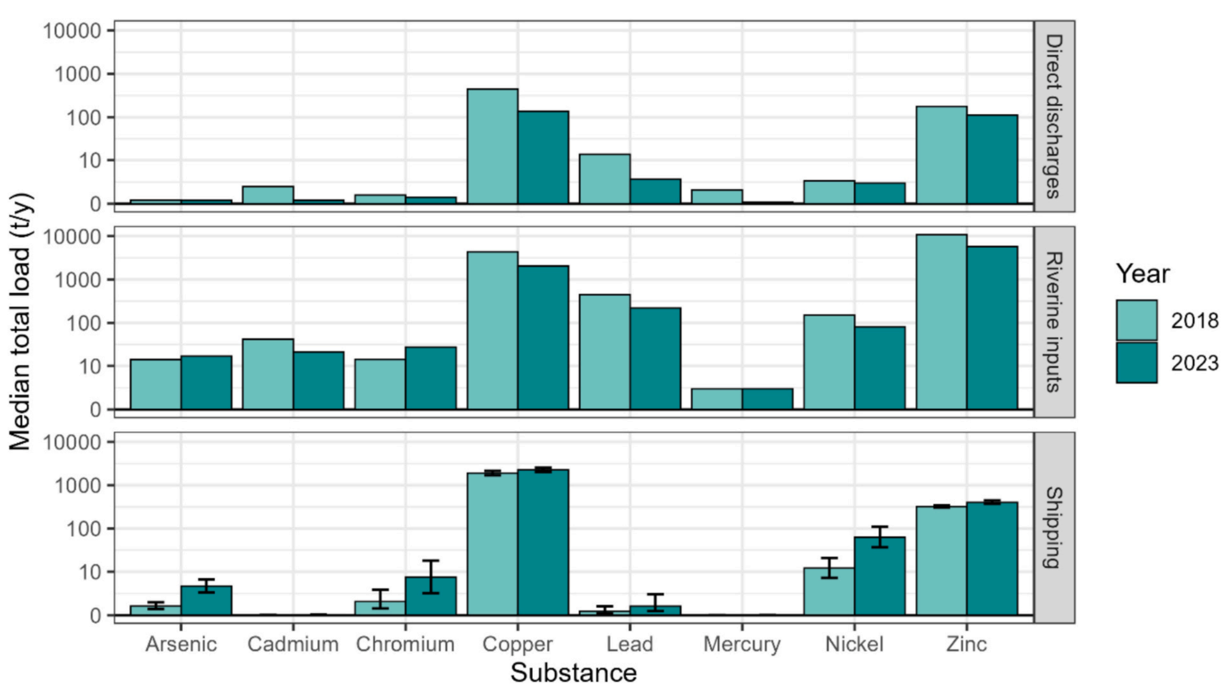

Fig. 3. Yearly metal loads. Comparison of metal loads from direct discharges, riverine inputs, and shipping in 2018 and 2023. Bars indicate the median total yearly load, error bars indicate the 25th and 75th percentile of the loads estimates from the Monte Carlo simulation for shipping loads (no uncertainty estimate was available for data on direct discharges and riverine inputs, which thus lack error bars). Note the logarithmic scale on the y-axis.

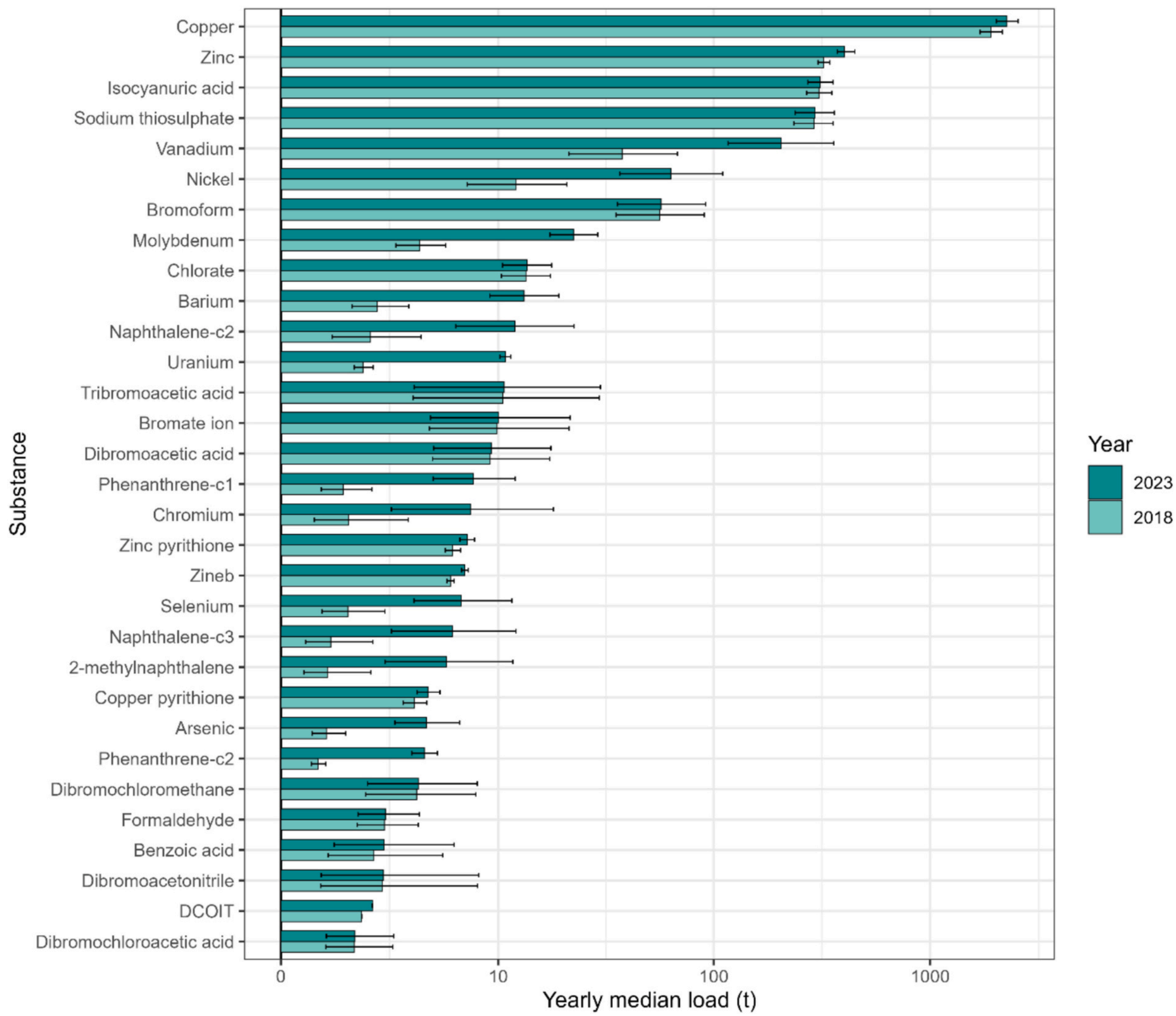

Fig. 4. Yearly substance loads from shipping. Loads of substances that were among the 25 highest loads from shipping in at least one of the two years 2018 (light teal bars) and 2023 (dark teal bars). Colored bars indicate the yearly median load; error bars give the range from the 25th to the 75th percentile of the results from the Monte Carlo simulation. Note the logarithmic scale on the x-axis. The full list of loads from all included substances and their change is available in table S3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with electro-chlorination and Ni mainly from open-loop scrubbers (Fig. 5).

Considering the released substances from antifouling paint, it should be noted that the STEAM model assumes that all vessels (outside of the Baltic Sea) use Cu-based coatings. While this represents a simplified assumption, it is supported by market data indicating that over 1000 mostly biocidal antifouling paint formulations are available globally (Paz-Villarraga et al., 2022), among which the majority contains inorganic copper compounds, with 76% formulated with cuprous oxide and 8.8% with cuprous thiocyanate. Therefore, it is reasonable to assume a widespread use of copper-based antifouling coatings among vessels operating in the OSPAR region. However, it is important to note that this proportion may be lower in certain subregions, particularly OSPAR region I, which is seasonally ice-covered. In such conditions, vessels are more likely to use hard, ice-resistant epoxy coatings, which typically do not contain any biocides. In the STEAM model, it is further assumed that 10% of antifouling coatings contain CuPyr and another 10% contain ZnPyr, totaling 20% with Pyr-based biocides. This may underestimate actual usage, as Paz-Villarraga et al. (2022) reported that 29% and 17% of biocidal antifouling products globally contain CuPyr and ZnPyr, respectively. Finally, the market share of alternative antifouling coatings is increasing (Ciriminna et al., 2015; Lagerström et al., 2022), possibly requiring updated model assumptions for antifouling coating types in the future. One alternative to copper-based antifouling coatings are biocide-free silicone-based foul-release paints, which, although also not suitable for ice conditions, providing one option of reducing the impacts of Cu (Lagerström et al., 2022), of which shipping is a major source.

The largest absolute increase in loads between 2018 and 2023 was observed in Cu, V, Zn, Ni, and Molybdenum (Mo) (Table S3, Fig. S8) in descending order. The increase in Cu was more than double that of V, which in turn increased by twice as much as Zn. Cu and Zn originated mostly from antifouling paints, while V and Ni stemmed mostly from open-loop scrubbers (Fig. 5).

An unexpected result of the analysis was the occurrence of uranium (U) (Fig. 4). U was reported in several measurements from one vessel (Lunde Hermansson et al., 2025b), but during the same measurement campaign described by Grigoriadis et al. (2022) and hence treated as an emission for all vessels. It was not found in any other vessels/campaigns in the available dataset, but is consistent with findings by Celo et al. (2015). While the origin of the measured U is unclear, it is known that chemical waste products are occasionally added to marine fuel oils (Broekman and Bakker, 2016; Human Environment and Transport Inspectorate, 2018), which might be a reason for the presence of U in the

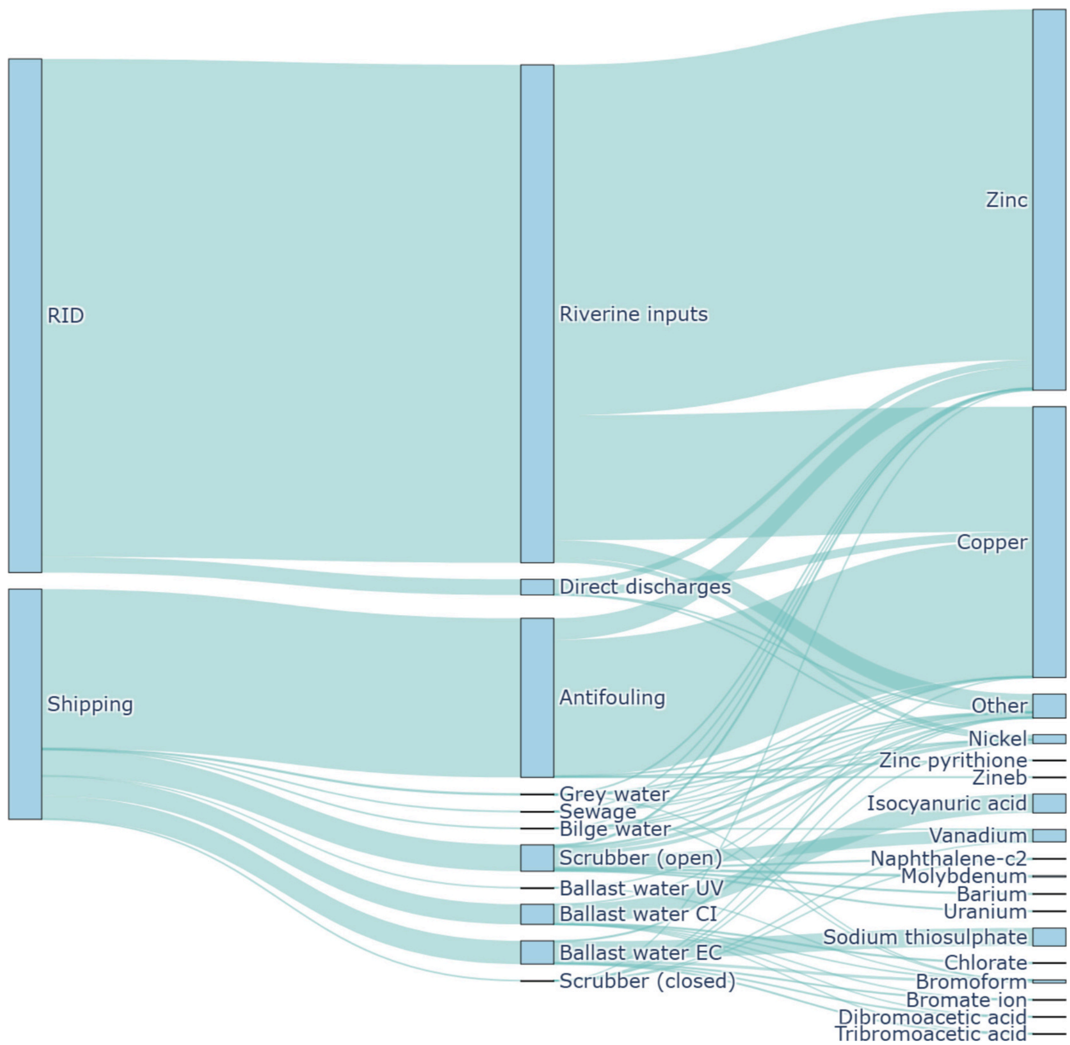

Fig. 5. Contributions to loads. Contribution of different sources (left) and waste streams (middle) to substance loads (right) in 2023. Loads of substances that were among the 15 highest loads from shipping in at least one of the two years 2018 and 2023 are listed individually, all other substances are grouped into "Other".

fuel. Since U was measured in more than one sample, albeit from the same measurement campaign and vessel, it is unlikely that the detection was due to sample contamination, but rather from impurities in the fuel batch.

Overall, the loads of 52 substances increased by more than 400%, many of which principally originate from scrubber effluent (both open- and closed loop) (Figs. 5, 6, and Table S3). In addition, the substances with the largest relative increases are all observed in scrubber effluent (Fig. 6, Tables S1 and S3).

In 2018, the largest modelled substance loads from shipping occurred in OSPAR region II – the majority originating from released substance from antifouling coatings (Fig. S9). For riverine input, loads were highest in region IV and direct discharge loads were highest in region I (Fig. S10). In 2023, the contribution of shipping had increased compared to 2018, while the region that received the largest loads from the respective pollution sources and waste streams remained the same (Fig. S10).

3.2. Hazard assessment

Since the HI scales with the loads from shipping, HI similarly increased across all substances between 2018 and 2023, and decreased with the decreasing load of most substances in the RID dataset (Fig. 7). Since the data from RID only contain 8 metals, the HI values presented here for riverine inputs and direct discharges are likely to be an underestimate.

In 2018, while the largest proportion of the HI originated from RID inputs (Fig. S11), the largest contributing waste streams from shipping were antifouling and open-loop scrubbers, despite the fact that scrubbers were not as common in 2018 as they are in recent years (Fig. S1) (globally, the number of scrubber-equipped vessels increased by 672%, from 693 in 2018 to 5353 in 2023 (DNV, 2025)). Within the OSPAR region and its adjacent areas, the number of vessels employing scrubbers increased by a factor of ten between 2018 and 2023 according to the modeling results. In 2018, water discharges were generated by approximately 210 vessels equipped with open-loop scrubbers, 10 with closed-loop systems, and 50 with hybrid systems capable of operating in either open- or closed-loop mode. By 2023, these figures had risen markedly to about 2300, 20, and 360 vessels, respectively. It is important to note that the model assumes that whenever a vessel is equipped with a scrubber, the system is operated upon entering areas where sulfur emissions are restricted. The framework does not account for the alternative compliance option of fuel switching.

In 2023, the overall HI from shipping exceeded the HI from RID inputs, increasing from 24% to 52% (Table 1, Fig. 8). However, as only metal loads were available from riverine inputs and direct discharges, the contribution of those sources in terms of other hazardous substances will be an underestimation. The comparison will be skewed, since a

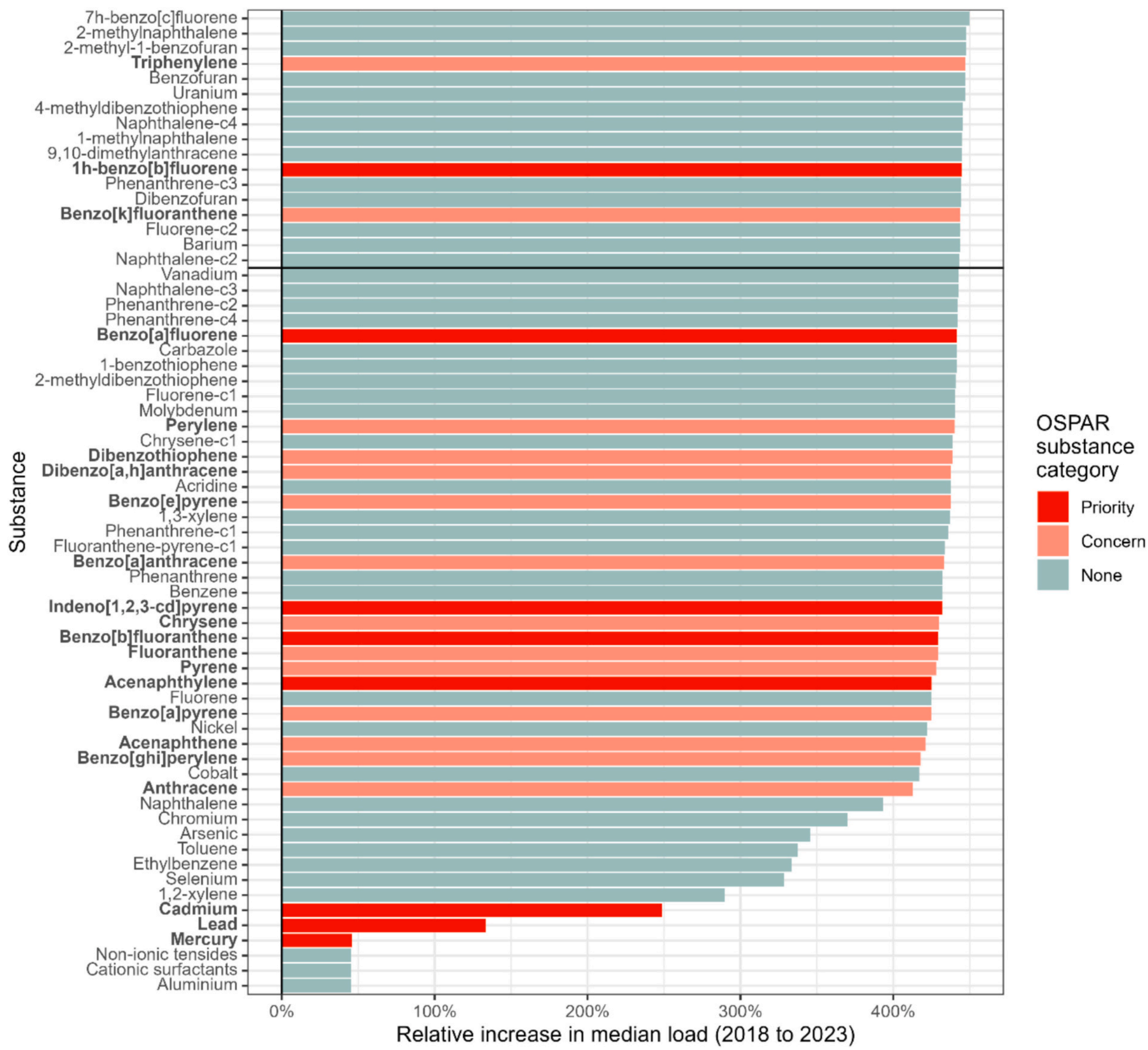

Fig. 6. Substances exhibiting the largest relative increase. 65 substances with the largest relative increase between 2018 and 2023 in loads released from shipping. Colors indicate whether the substances are OSPAR priority substances ("Priority", dark red, bold on the Y-axis), OSPAR substances of possible concern ("Concern", faint red, bold on the Y-axis), or neither ("None", light teal). All substances above vanadium (indicated by the black horizontal line) were exclusively found in scrubber effluent, except for benzo[*k*]fluoranthene, which was also found in bilge water in one instance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

higher number of substances has been used in the generation of the HI from shipping. However, when considering only substances that are shared between RID inputs and shipping, shipping still doubled its contribution between 2018 and 2023, increasing from 13% to 26% of the overall HI (Fig. S12).

The main drivers of the HI from shipping were antifouling and open-loop scrubbers. The relative contribution from other waste streams from shipping had not grown at the same proportion as the contribution from scrubbers. In addition, the increase in HI from shipping was disproportionate to its increase in loads. The substances contributing most to the HI in 2023 from shipping were Cu, CuPyr and ZnPyr from antifouling, and indeno[1,2,3-*cd*]pyrene, benzo[*k*]fluoranthene, benzo[*b*]fluoranthene from open-loop scrubbers (Fig. 8). While previous studies have also identified strong toxic effects of scrubber effluent (Hassellöv et al., 2020 and references therein; Picone et al., 2023; Thor et al., 2021), the growing awareness of the toxicity of scrubber effluent is also represented in the decision by various European countries (Finland, Denmark, Sweden) to ban scrubber discharges in their territorial waters (instead of only in ports and inland waters) (BEK nr 539 af 21/05/2025, 2025; Laki 1116/2024, 2024; SFS 2025:23, 2025), which will reduce the amount of scrubber discharge water introduced to those areas. Similarly, a reduction of substances released from antifouling paints could be achieved by applying different types of paint, such as biocide-free foul-release paints (Ciriminna et al., 2015). While they also exhibit some detrimental environmental effects (especially shortly after application), they show much lower toxicity than copper-based paints (Lagerström et al., 2022 and references therein). Regulation of antifouling coatings in the OSPAR region might prove difficult however, since vessels that operate in the region apply their coating in various places worldwide, and while e.g. hybrid scrubbers allow switching to closed-loop mode in areas where discharge of open-loop effluent is prohibited, vessels cannot dynamically adjust to local regulations regarding paint type. The STEAM model, as applied in the current study, assumes that all vessels in the OSPAR region are coated with copper-based antifouling paints. In addition, it should be noted that the assumption of universal copper-based coating coverage likely leads to an overestimation of biocide loads in the OSPAR region. Available industry data suggest a non-negligible and growing share of FRC usage: BIMCO (2024) survey data indicate that biocidal

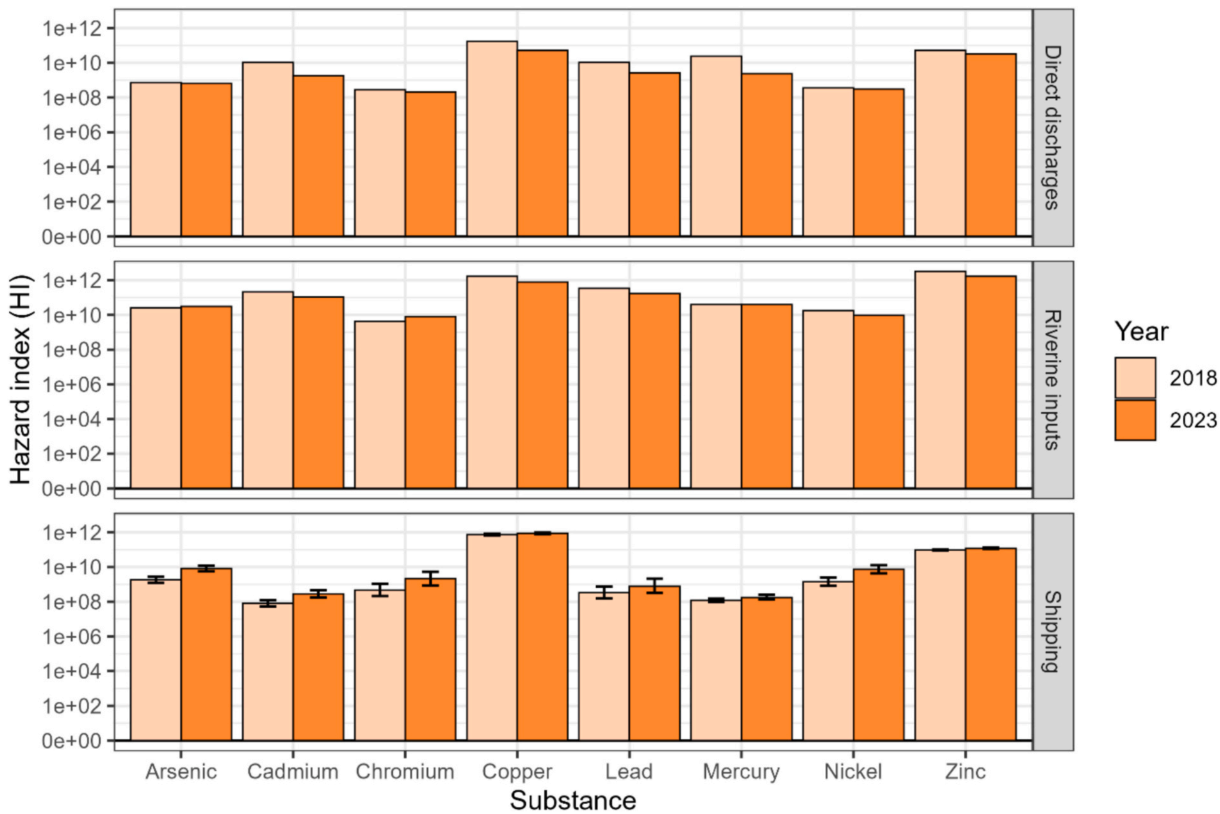

Fig. 7. Median hazard index (HI). Median HI from direct discharges, riverine inputs, and shipping in 2018 (light bars) and 2023 (dark bars). Error bars indicate 25th and 75th quantile of results from the Monte Carlo simulation (no uncertainty estimate was available for data on direct discharges and riverine inputs, which thus lack error bars). Note the log scale on the y-axis.

Table 1
Contribution to total hazard index (HI) per source and year. Note that riverine inputs and direct discharges only take into account eight metals, while the HI of shipping is based on a much larger variety and number of substances, which might lead to an underestimation of the hazard contribution stemming from rivers and direct discharges.

Source	Percentage of yearly total HI 2018	Percentage of yearly total HI 2023
Direct discharges	3.5%	1.5%
Riverine inputs	72.3%	46.1%
Shipping	24.2%	52.4%

FRCs and biocide-free FRCs account for approximately 20% and 13% of vessels respectively, while DNV (DNV, 2022) estimates that self-polishing antifouling paints remain the dominant technology used by approximately 90% of ships globally. Neither dataset provides OSPAR-specific resolution, and the extent to which FRCs are used in the OSPAR region remains insufficiently characterized.

Nonetheless, the cumulative hazard assessment approach presented in the current study extends the knowledge from information on specific waste streams to a per-substance scale and provides data on the contribution of specific substances to the overall hazard. This information can be used for prioritizing the substances within a policy context, or for further study regarding their environmental effects.

The contribution to HI is driven by the combination of substance concentration and toxicity, as well as waste stream volume. For antifouling, the loads result in a high HI although only the substances Cu, Zn, CuPyr and ZnPyr are included in the assessment. The HI of open-loop scrubber discharge was based on a much larger number of substances, and it was also the waste stream with the largest liquid volume in each region in 2023, as open-loop scrubber discharge volume had strongly increased between 2018 and 2023 (by 447%, from 294 mio. m^3 to 1610 mio. m^3 in the entire OSPAR area (Table S4)). Furthermore, the PNEC values for substances in scrubber discharge and bilge water were noticeably lower than for the other waste streams, highlighting the toxic potential of those waste streams (Fig. S13).

The sensitivity analysis resulted in similar conclusions, highlighting the strong effect of antifouling paints and open-loop scrubbers (Table S5). In terms of waste streams, the released loads from antifouling paint were the parameter with the single largest influence on overall HI, followed by the volume of open-loop scrubbers. When considering single substances, Cu had the largest effects, followed by ZnPyr, and indeno [1,2,3-*cd*]pyrene. The PNEC values with the largest influence were, similarly, those for Cu, ZnPyr, and indeno[1,2,3-*cd*]pyrene.

In this study, a linear relationship between HI and discharge volume and concentration was assumed (as in Eq. (5)). More complex interactions and potential non-linear scaling effects were outside of the scope of the present study, but an investigation of these dynamics might lead to an improved understanding of the hazard of mixtures of dynamic volumes. In addition, PNEC and EQS values are inherently designed to be protective and, in common risk assessment approaches, delineate between acceptable and inacceptable risk of environmental concentrations (van Leeuwen and Vermeire, 2007). As such, their exceedance does not imply an immediate effect, but indicates that the threshold of acceptable risk has been exceeded.

Many of the substances that were contributing the most to the HI from shipping are on the ECHA candidate list of substances of very high concern which lists dangerous substances for which a replacement should be found, or on the list of substances restricted under REACH (Table S6). The high toxicity of these streams can also be observed when normalizing the HI of the waste streams by their volume, i.e. transforming the HI into a HI per 1 L of waste stream (or 1 cm^2/day, in case of

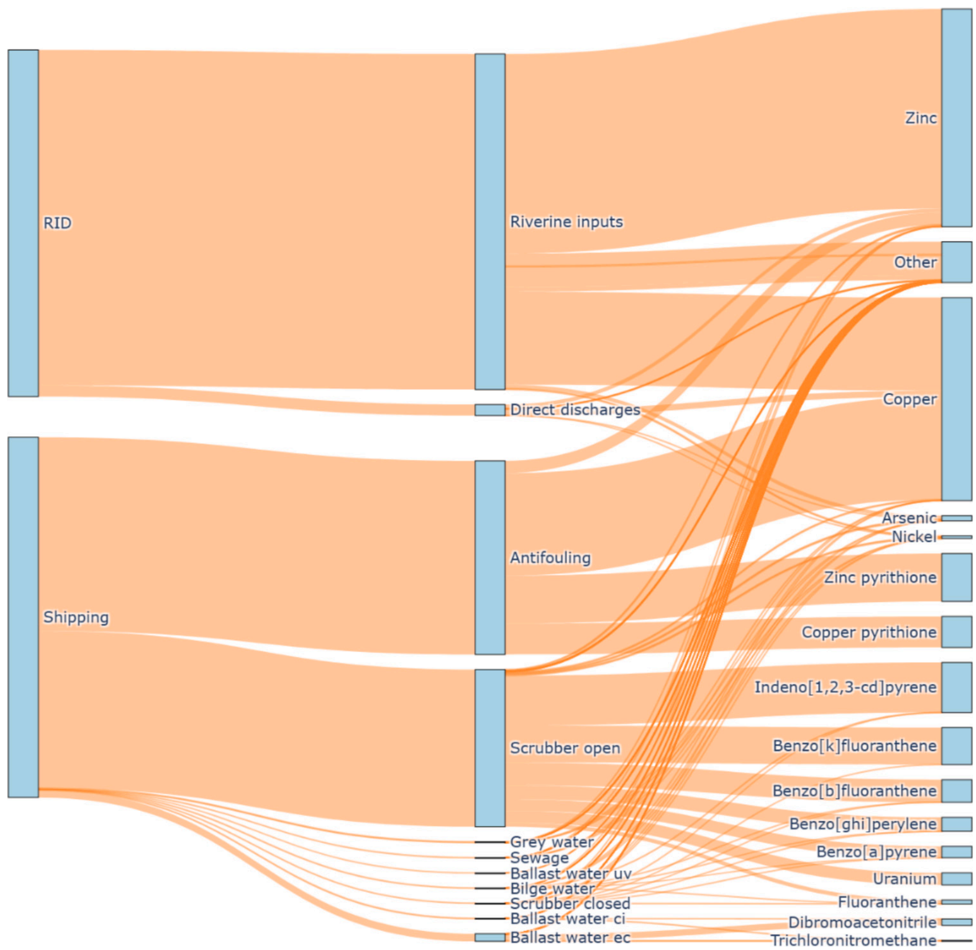

Fig. 8. Contribution of shipping to the hazard index (HI) in 2023. Relative median contribution of shipping and RID as well as the hazardous substances therein to the overall HI in 2023. The contribution of shipping, and especially open-loop scrubber discharges is disproportionate to their proportion in the loads (Fig. 5).

antifouling paint surface, which, however, is not directly comparable to the liquid streams). After this normalization, scrubber and bilge water occurred as the liquid waste streams with the largest normalized HI (Fig. 9). Other research also confirmed the toxicity of scrubber effluent (Hassellöv et al., 2020; Koski et al., 2017; Picone et al., 2023) and bilge water (Tiselius and Magnusson, 2017), the latter often varying in chemical composition between vessels (Magnusson et al., 2018).

The spatial distribution of the HI contributions in different OSPAR regions remained similar between 2018 and 2023, with RID contributing most to the HI in OSPAR region IV, while the largest effect of shipping was on region II (Fig. 10). Shipping's large contributions in region II can be explained by the high amount of traffic to large ports such as Rotterdam, Antwerp/Brugges, Hamburg, as well as transit traffic to/from the Baltic. This is especially relevant since a lot of economic activities (shipping, fisheries, aquaculture, oil and gas installations and -pipelines) overlap with ecologically (and, by extension, economically) relevant habitats and marine protection efforts in the area (Andersen et al., 2013), which these activities may threaten. When considering shipping emissions in marine spatial planning, the overlap of shipping activities with other areas of interest (e.g. sensitive ecosystems, Natura2000 areas) and activities needs to be taken into account. Additionally, the dilution and dispersion of shipping-related waste streams must be considered to assess the effect on water bodies on a more local scale. Such an assessment, however, falls outside the scope of this study.

Local considerations are also important because discharges from shipping do not exhibit a uniform spatial distribution, but can cluster in specific areas (e.g. ballast water discharges in port), happen continuously (open-loop scrubber discharge in ship lanes, releases from antifouling paint) or happen intermittently (such as discharges of sewage and grey water, although they are modelled as continuous discharges in STEAM) (Jalkanen et al., 2021). Due to this, the selection of the study area will also influence the predominance of the waste streams and their contribution to HI, especially when using smaller study areas: If the study area is mainly a port, the contribution of ballast water will be higher than when the study area mostly covers open sea.

It should be noted that not all substances were monitored in all waste streams, and their presence might therefore have been missed in some of the waste streams where they were treated as absent in the present study, or their contribution to HI could not be assessed because not all substances had an associated PNEC value, EQS value, or similar. Another reason for not covering the same set of substances in all waste streams is that screening efforts commonly focus on hazardous substances that are expected to occur in the specific waste stream, but there is a lack of knowledge regarding the chemical composition of grey water and sewage and therefore a lack of standard screening candidates (Mujingni et al., 2024).

3.3. Monitoring coverage

Environmental monitoring data of most of the substances that contribute most to the HI from shipping is available in the DOME database, from different relevant environmental compartments (sediment, biota, water) (Table S6). The last sampling year varied with substance and compartment, but most high-HI substances were monitored up until the last available year in the database (2024) (Table S6). While this indicates that data available in the DOME database might be a

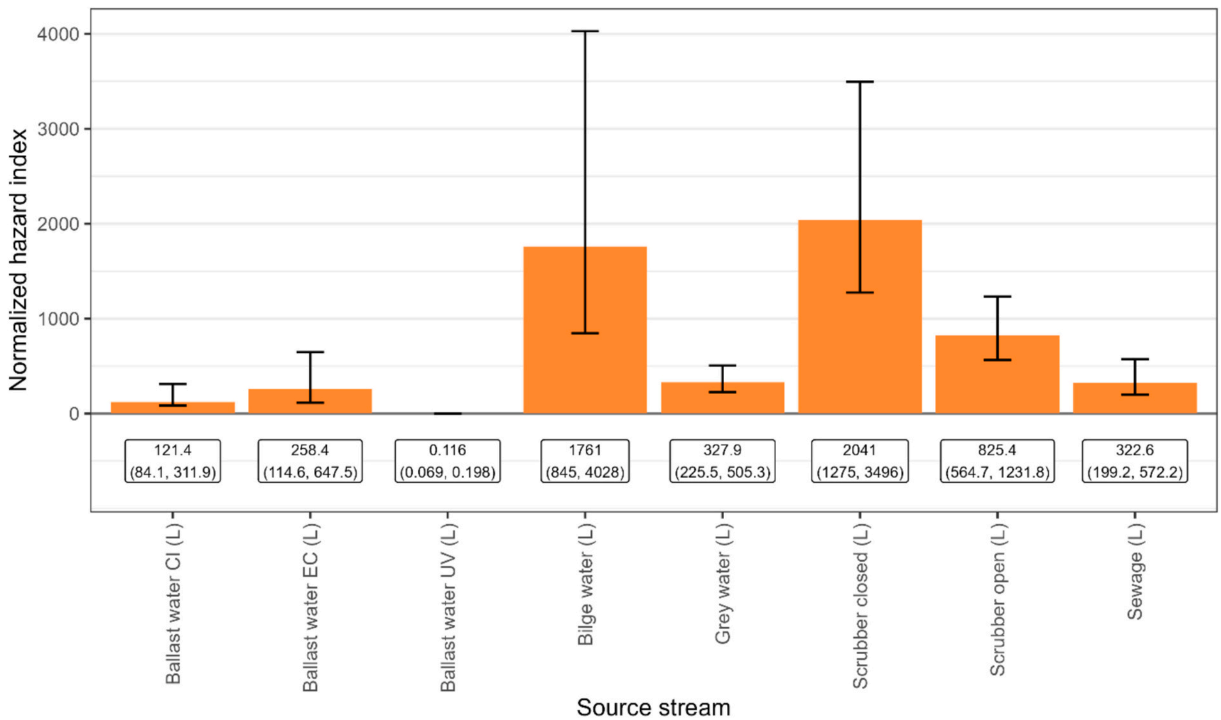

Fig. 9. Normalized hazard index (HI). Median HI for the different liquid waste streams in 2023, normalized to 1 L. Releases from antifouling have been omitted in this figure, as they can not be expressed in units of liters. Labels at the bottom indicate summary of the Monte-Carlo simulation results: median (25th percentile, 75th percentile), and 25th and 75th percentile are also depicted by the error bars in the figure. Highest normalized HI were observed for closed-loop scrubber effluent, bilge water, and open-loop scrubber effluent. Note the logarithmic scale on the y-axis.

good way of assessing regulatory success, a more in-depth analysis of the spatiotemporal distribution of available sampling data is required, which falls outside the scope of this study.

Together with the results from the HI comparison, the cumulative approach presented in this study can also contribute to an assessment of the success of the implementation of OSPAR's goals towards reducing marine pollution, e.g. via the North-East Atlantic Environment Strategy 2030 (NEAES 2030), especially with regards to the objective of preventing pollution by hazardous substances (OSPAR Agreement 2021-01). The OSPAR NEAES 2013 strategy also aligns with the requirements outlined in European legislation, e.g. the MSFD. Our findings identify antifouling paints and scrubber effluents as the dominant contributors to cumulative hazard in 2023. For several of the key drivers of HI, such as Cu, Zn, indeno[1,2,3-*cd*]pyrene, benzo[*k*]fluorene, monitoring data exist, but spatial coverage is patchy across the OSPAR area, and not all are included in assessments of good environmental status or coordinated monitoring. Strengthening monitoring for high-HI substances and in regions where shipping contributes substantially to the overall hazard would support more effective implementation of OSPAR's 2030 goals and related EU policy frameworks, including the MSFD.

4. Conclusion

The loads as well as the HI from shipping increased across all substances between 2018 and 2023, while loads and HI from RID decreased. The increase in HI attributable to shipping was larger than the increase in loads from shipping, indicating a comparatively high hazard potential of some substances in shipping (mainly in open-loop scrubber effluent). The increase in the HI and thereby the potential hazard was driven mostly by an increased loads from open-loop scrubbers and releases from antifouling paints (the latter being the largest source of Cu, exceeding inputs from direct discharges and rivers combined in 2023). In addition, the contribution of open-loop scrubbers relative to the other shipping waste streams increased markedly between 2018 and 2023.

The observed overall increase in HI from shipping was attributable to an increase in shipping activity, but also an increased open-loop scrubber adoption rate. It is noteworthy that the increase in hazard potential was of a larger magnitude than the increase in load, underlining the high toxic potential of some of the substances found in waste streams from shipping. The results show that pollution from shipping in the OSPAR region is increasing and also its contribution compared to other sources, which underlines the importance of making the sector more sustainable.

CRediT authorship contribution statement

Roland Pfeiffer: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Erik Ytreberg:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Anna Lunde Hermansson:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amanda Trygvesdotter Nylund:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Jukka-Pekka Jalkanen:** Writing – review & editing, Data curation. **Tiia Grönholm:** Writing – review & editing, Data curation. **Ida-Maja Hassellöv:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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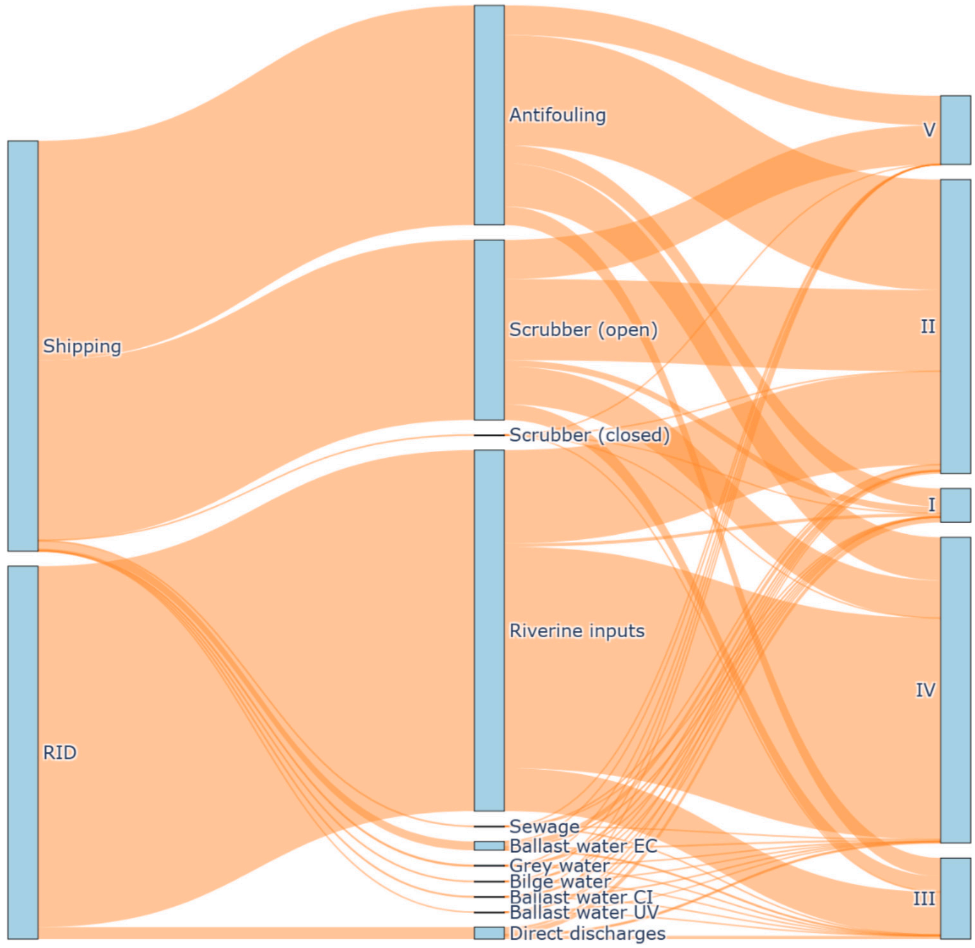

Fig. 10. Hazard index (HI) per region. Contribution of the different waste streams to the HI in the different OSPAR areas.

Water Management (Havs- och vattenmyndigheten) (project *Förbättrad kunskap om utsläpp av farliga ämnen från sjöfarten i Ospar-regionen (Nordostatlanten)* ("Improved knowledge about emissions of hazardous substances from shipping in the OSPAR region (North-East Atlantic)"), grant number Dnr 2024-001031). The modeling domain provided by Finnish Meterological Institute can be found in Fig. S4.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2026.119787.

Data availability

Data will be made available on request.

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