Discharges to the sea from Baltic Sea shipping in 2022

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Key Messages

1. **The total volume of discharge water from Exhaust Gas Cleaning Systems (EGCSs or scrubbers) was about 312 (2021:286) million cubic meters. This was almost completely (99.99%) from open loop scrubbers.** During the year 2022, there were 781 (2021:593; +32%) vessels operating the Baltic Sea area using scrubbers.

2. Bilge water releases from the Baltic Sea fleet were estimated as 505 000 cubic meters (-1.0%)

3. Estimated ballast water volume release to the Baltic Sea was 494 million tonnes (2021: 454 million tonnes; +8.8%). This volume contains both untreated and treated ballast water discharge.

4. **Sewage discharge to the sea was predicted as 0.5-1.4 million cubic meters (2021:+37%)**. Sewage volumes are lower than in 2019 (1.8 million m^3). Since June 2021, it is prohibited to release untreated sewage to the Baltic Sea from passenger ships, unless visiting St. Petersburg from outside the Baltic Sea area. No cruise ship traffic to Russian part of the Gulf of Finland was observed.

5. Grey water discharge was estimated to be 5.4 million cubic meters(2021:+47%), which is still less than in 2019, before the pandemic (2019: 6.9 million m^3). **Passenger ships are responsible for over 84% of grey water discharges.**

6. **The total amount of Phosphorus released to the sea was estimated as 179-188 tonnes. These were discharged as sewage (0-9 tonnes), food waste (110 tonnes) and grey water (68 tonnes).** Here, it was assumed that the phosphorus removal of wastewater treatment plants used in passenger ships was 98% and in constant use.

7. **Total Nitrogen discharge was estimated as 402-447 tonnes, which were from food waste (101 tonnes), sewage water (68-113 tonnes) and grey water (232 tonnes)**.

8. **Stern tube oil leakage was assumed to be about 4740 cubic meters**. This is an order of magnitude estimate because experimental data concerning leakages are scarce.

9. Release of six substances commonly used in anti-fouling paints were modeled. The wet surface area of large vessels is about 50 million square meters and the contribution of the 500 000 small boats around the Baltic Sea coastline is estimated at about 7 million square meters. **Over 569 tonnes of anti-fouling paint residues are released from ships' hulls to the sea**, which does not include the contribution from small boats. Of the estimated amount of antifouling paint released for ships, about 82% is Copper(II)oxide (CuO).

Harmful discharges from ships in the Baltic Sea area

This short summary includes a report of modeled discharges from Baltic Sea shipping during the year 2022 and their development over the period of 2006-2022. It should be noted that the modeling done for this report includes several updates to the STEAM model, which was used to predict the discharge streams. The totals reported here include the effects of sea currents, wind, waves, and sea ice. Additional resistance due to biofouling is treated with a simplistic manner, by adding 5% to vessel resistance (Munk et al., 2009).

Discharges from ships to water

The parameters used in modeling discharges from ships are listed in Table 1.

Table 1 The parameters used in discharge modelling of water pollutants

Modeled quantity	Main contribution	Quantity
Open loop scrubber discharge water	Used engine kWh, equipment type	Volume
Closed loop scrubber discharge water	Used engine kWh, equipment type	Volume
Bilge water release	Vessel type, engine kW, time	Volume
Ballast water	Vessel type, DWT	Volume
Sewage release	Vessel type, person days, capacity utilization, time	Volume
Black water Nitrogen	Vessel type, person days, capacity utilization, time	Mass
Black water Phosphorus	Vessel type, person days, capacity utilization, time	Mass
Grey water release	Vessel type, person days, capacity utilization, time	Volume
Food waste	Vessel type, person days, capacity utilization, time	Mass
Food waste Nitrogen	Vessel type, person days, capacity utilization, time	Mass
Food waste Phosphorus	Vessel type, person days, capacity utilization, time	Mass
Stern tube oil	Vessel type, time	Mass
Release of biocide(Cuprous Oxide)	Vessel wetted surface, operation area, paint type, time	Mass
Release of biocide (Copper Pyrithione)	Vessel wetted surface, operation area, paint type, time	Mass
Release of biocide (Zinc Oxide)	Vessel wetted surface, operation area, paint type, time	Mass
Release of biocide (Zinc pyrithione)	Vessel wetted surface, operation area, paint type, time	Mass
Release of biocide (DCOIT, 4,5-Dichloro-2-octyl-4-isothiazolin-3-one)	Vessel wetted surface, operation area, paint type, time	Mass
Release of biocide (ZINEB, zinc ethane-1,2-diylbis(dithiocarbamate))	Vessel wetted surface, operation area, paint type, time	Mass

Some of the discharged quantities are reported in volumes instead of mass. For example, determining the copper release from open loop scrubber discharge water to the sea requires water analysis results (copper concentration in effluent). Discharges of contaminants can be derived for dozens of different compounds this way, instead of generating a map for each of them. Summary of discharges from various kinds of ships is indicated in Table 2, and nutrients are listed in Table 3

Table 2. Discharged water pollutants and contaminants from ships during 2022 in the Baltic Sea area.

2022	Ballast [million m3]	STO* [m3]	Bilge [10^3 m3]	Scrubber (Open) [10^3 m3]	Scrubber (Closed) [10^3 m3]	Grey Water [10^3 m3]	sewage Water [10^3 m3]
RoPax_vessels	46.1	372.9	94.7	119919	26.9	3484.5	0-734.6
Vehicle_carriers	3.5	6.4	0.6	3981	0.0	3.4	77.9
RoRo_vessels	52.3	78.6	10.3	76913	1.9	107.9	2.4
Bulk_carriers	90.4	315.6	14.1	16228	0.0	113.7	82.0
General_cargo	52.0	1137.9	30.6	7827	5.3	204.3	147.5
Container_ships	53.2	118.2	9.5	20728	1.4	49.4	35.6
Reefers	1.6	22.6	1.6	1589	0.0	9.0	6.5
Tankers	169.9	366.5	23.3	31992	0.0	134.1	46.9
LNG_tankers	10.2	3.6	1.8	0	0.0	5.3	1.9
Gas_tankers	5.8	21.0	1.5	2101	0.1	8.5	3.0
Passenger_ships	0.0	249.6	43.5	0	0.0	112.6	23.7
Cruisers	9.1	9.6	13.2	30650	5.2	960.6	0-202.5
Fishing_vessels	0.0	256.5	16.3	0	0.0	36.4	3.6
Service_ships	0.0	67.9	10.0	0	0.0	13.8	5.6
Unknown	0.0	1318.9	174.5	0	0.0	87.5	35.4
Total	494.1	4736.1	505.1	312011	40.8	5399.5	500-1437

*STO = Stern Tube Oil

Table 3 Discharge of nutrients from ships ship to the Baltic Sea in 2022.

2022	Sewage Nitrogen [tonne]	Food Waste Nitrogen [tonne]	Grey Water Nitrogen [tonnes]	Sewage Phosphorus [tonnes]	Food Waste Phosphorus [tonnes]	Grey Water Phosporus [tonnes]
RoPax_vessels	0-35.5	35.5	143.0	1.0	86.5	61.8
Vehicle_carriers	0.5	0.0	0.1	0.1	0.0	0.1
RoRo_vessels	3.7	1.5	4.6	0.3	2.3	2.0
Bulk_carriers	15.3	1.5	4.5	1.6	0.5	0.1
General_cargo	27.1	2.7	1.9	2.9	0.9	0.1
Container_ships	6.6	0.7	0.7	0.7	0.2	0.1
Reefers	1.2	0.1	0.7	0.1	0.0	1.0
Tankers	8.6	2.0	1.0	1.0	0.3	0.2
LNG_tankers	0.8	0.1	8.0	0.1	0.0	0.2
Gas_tankers	1.3	0.1	33.1	0.1	0.0	0.6
Passenger_ships	0.0	1.1	0.5	0.0	0.0	1.2
Cruisers	0-9.8	53.2	0.1	0.2	19.3	0.7
Fishing_vessels	1.9	0.3	0.0	0.4	0.1	0.1
Service_ships	1.0	0.1	0.8	0.3	0.1	0.1
Unknown	0.1	0.9	31.9	0.0	0.0	0.0
Total	68-113	100.7	231.8	9.1	110.4	68.1

A. Scrubber discharge water

Three kinds of scrubbers (open, closed, hybrid loop) were included in the discharge water modeling, which was based on used engine power as a function of time. This allowed modeling of discharge water release based on engine kWh, on top of which additional power requirement (three percent for open loop, 0.5% for closed loop) of pumps was included. Hybrid scrubbers were run in open loop mode whenever possible considering the alkalinity of seawater and regional restrictions.

The link to IMO Global Integrated Shipping Information System (GISIS) was established in this work, to get insight on global EGCS installations. Previously, scrubber installations were collected from scattered online data sources and their numbers were underestimated. The IMO GISIS reports allow the determination of approval date and equipment type in a consistent manner. The data collected for the global fleet represents the situation of April 2023.

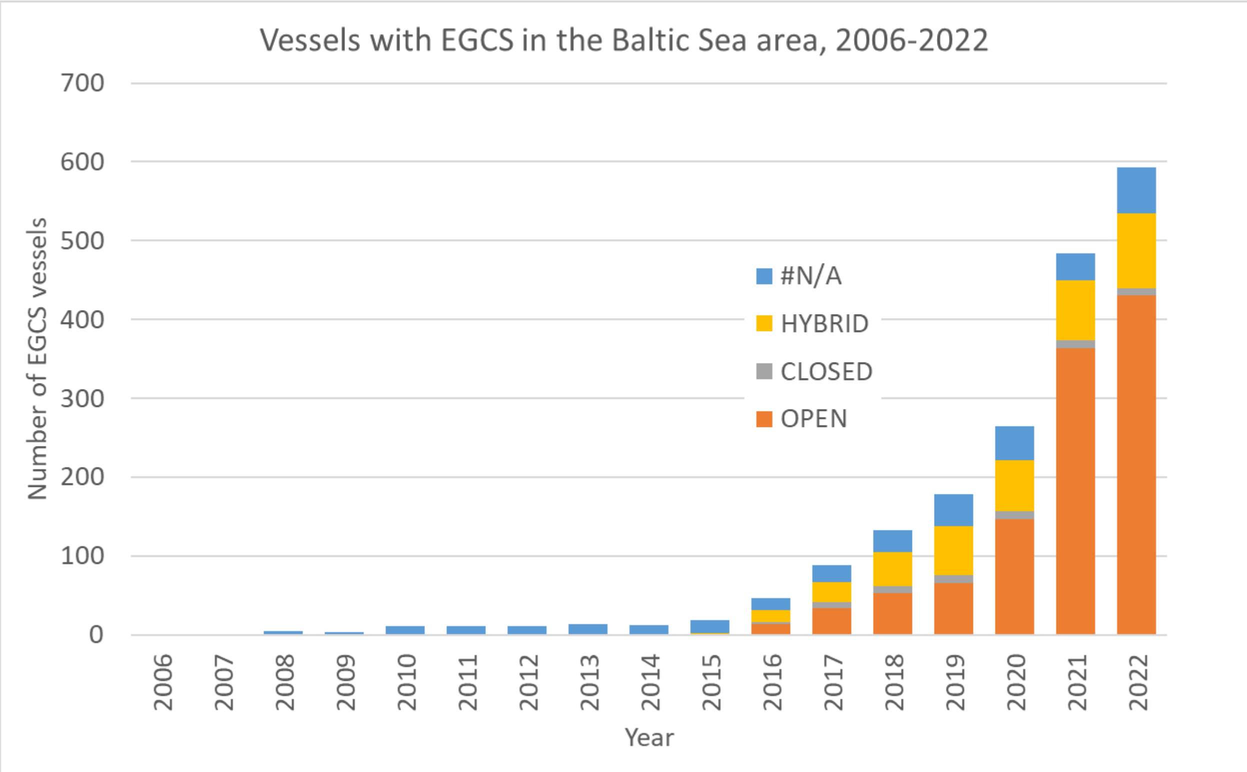


Figure 1 Development of the EGCS equipped fleet in the Baltic Sea area during 2006-2022. Unknown equipment type is indicated by #N/A entry, but for modeling purposes an Open Loop system is assumed for these cases.

During 2022, 781 (2021: 593) vessels were installed with scrubbers in the Baltic Sea area (Figure 1 and Figure 2, Table 4). The share of closed/hybrid/open loop EGCS is similar to the global fleet (Figure 3). In the Baltic Sea region, 118 out of 781 (15%) are either closed or hybrid systems, whereas the share of open loop systems in the global fleet is 85%. In the Baltic Sea fleet, over two thirds of the open loop installations are in Oil Product tankers, Crude Oil Tanker and Bulk Cargo ships.

Table 4 EGCS equipment type in various vessel types. This data is for year 2022 only.

Type	Open	Closed	Hybrid	#N/A
Ropax	15	4	14	0
Roro cargo	18	0	20	7
Cruise vessel	19	4	12	5
Containership	48	4	26	1
Vehicle carrier	5	0	12	5
Crude oil tanker	131	0	5	32
Oil product tanker	62	0	10	21
Lpg tanker	11	0	11	4
General cargo ship	48	1	6	1
Bulk cargo ship	174	0	2	25
Refrigerated cargo ship	7	0	0	1
Chemical tanker	8	0	0	0
Total	546	13	118	102

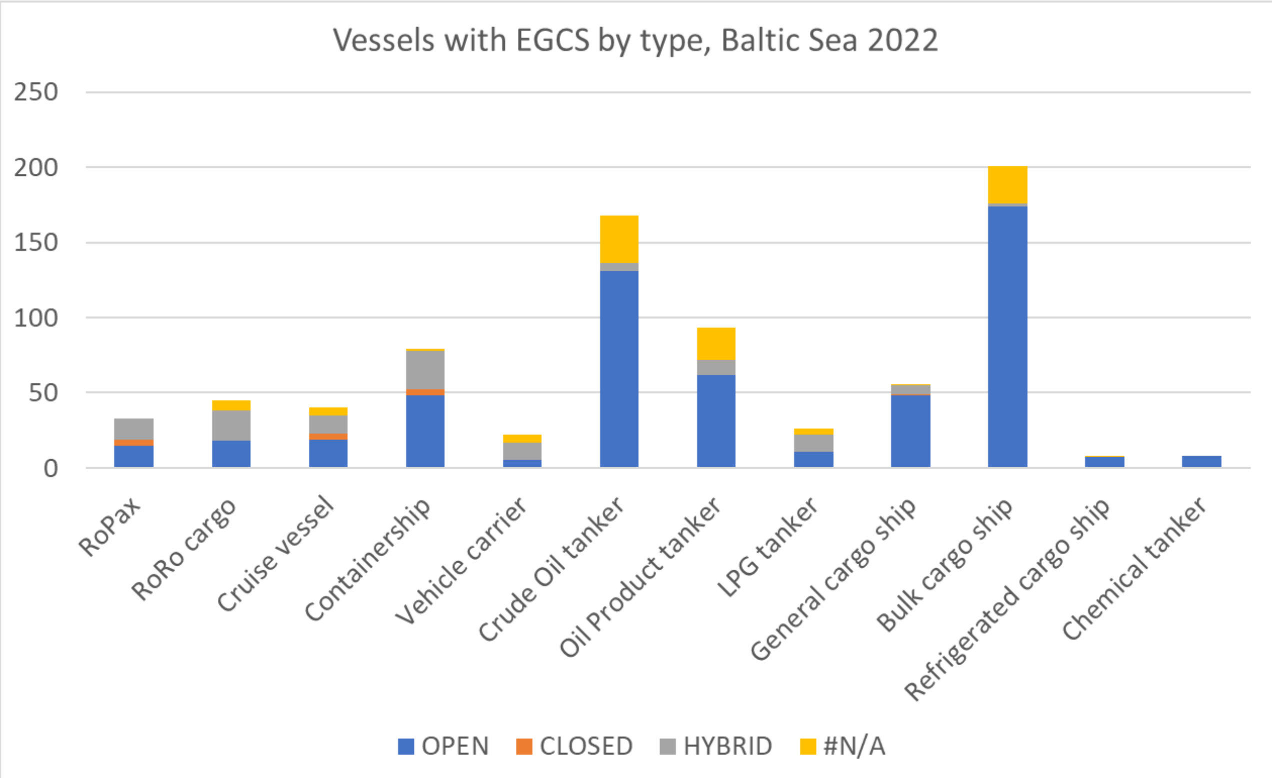


Figure 2 EGCS equipment type of various vessel types in the Baltic Sea area during year 2022. The N/A entry indicates a scrubber of unknown type, which is assumed to be Open Loop during STEAM runs.

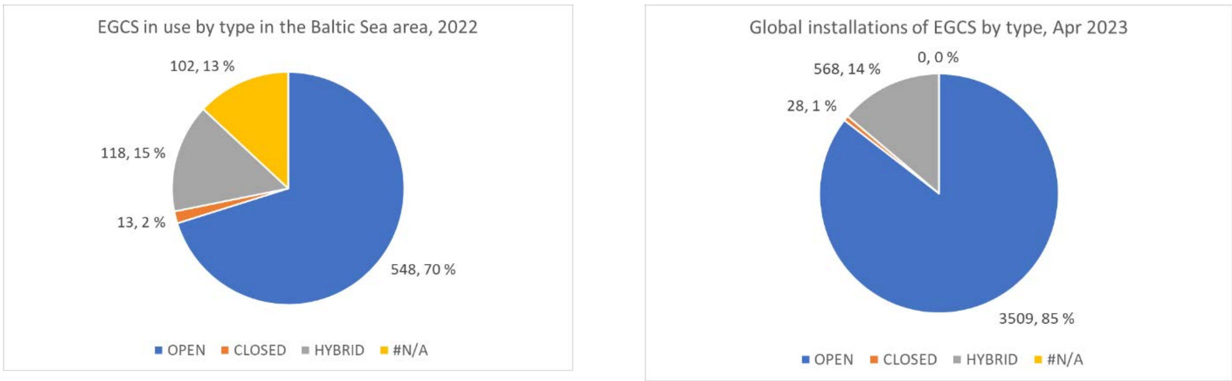


Figure 3 Equipment type of EGCS of the Baltic Sea in 2022(left) and the global (right) shipping fleet in April 2023.

The vessels equipped with EGCS operating in the Baltic Sea area released about 312 million cubic meters (2021: 286 million m^3) of discharge water into the sea. Over 99.99% of this release came from vessels using open loop scrubbers (Figure 4).

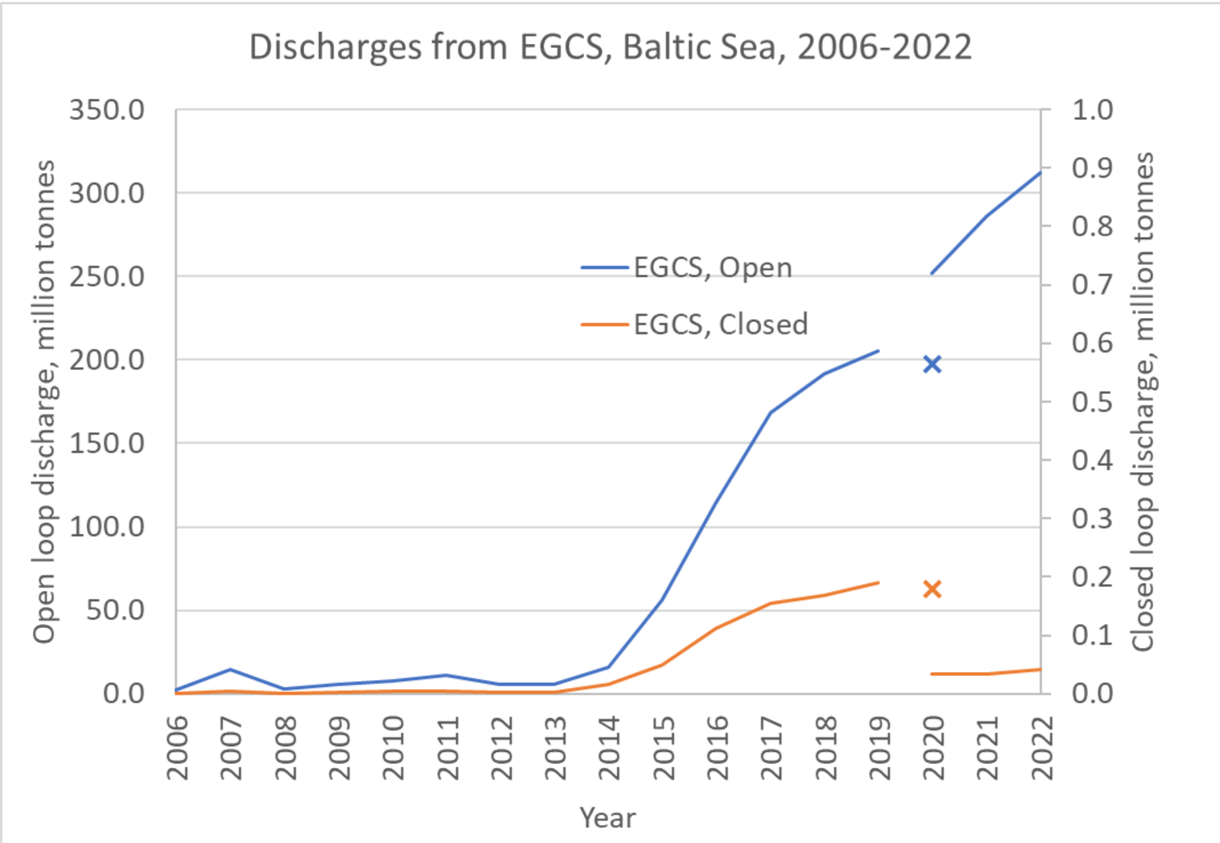


Figure 4 EGCS effluent discharges in the Baltic Sea area during 2006-2021. The blue line represents the Open loop discharge volumes (left vertical axis) and the orange line indicates the Closed loop effluent discharge volume (right side vertical axis). Note the difference of units between the axis. The blue and orange symbols indicate a result obtained with the old STEAM version for 2020. The trendline from 2006-2019 depicts the results obtained with the previous STEAM version, but the trendline 2020-2021 depicts the totals from the most recent version of STEAM.

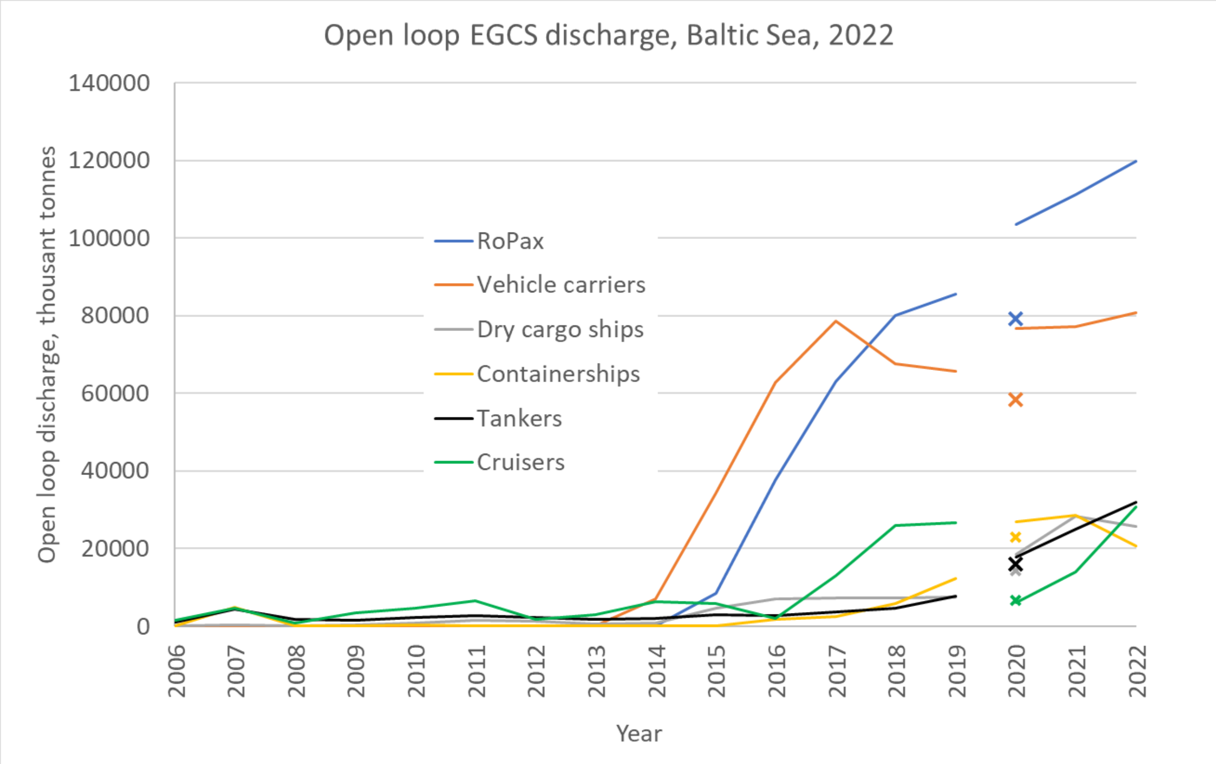
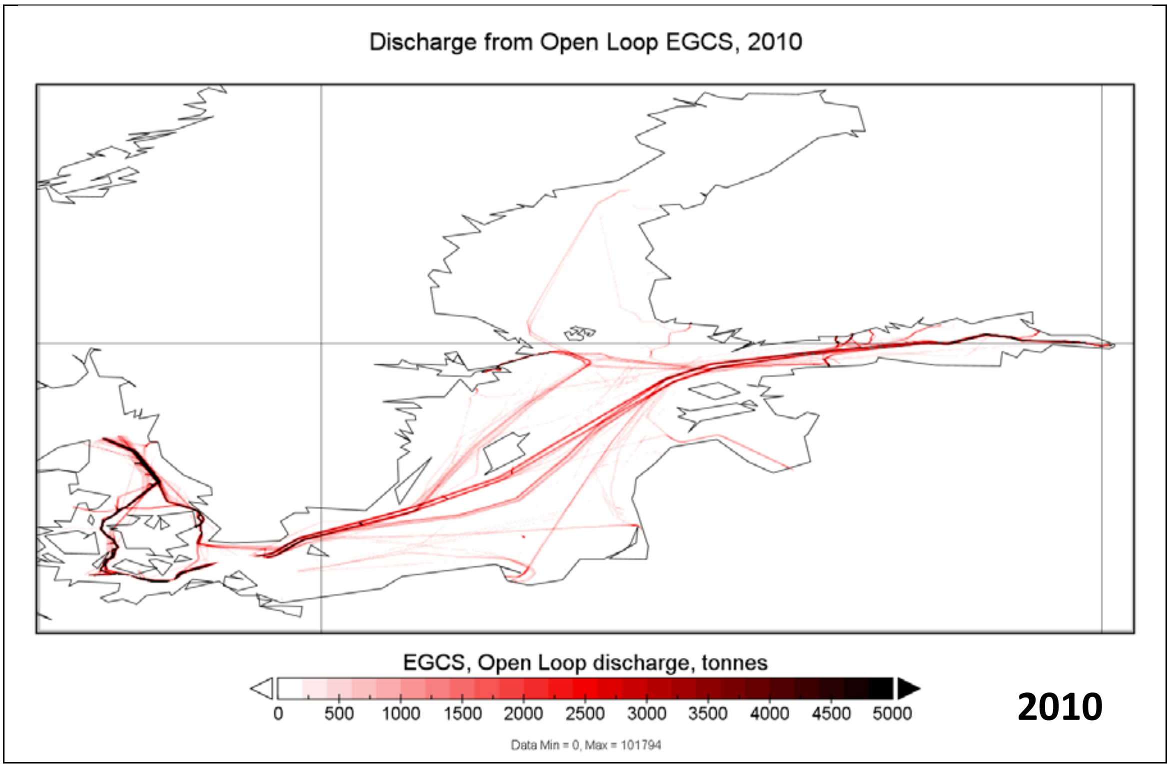


Figure 5 Effluent discharge from Open loop and Hybrid EGCS in the Baltic Sea area during 2006-2021. Largest releases come from EGCS in ro-ro cargo ships, ro-ro passenger ships and vehicle carrier types. Cruise passenger ship traffic in the area is still recovering from Covid19 pandemic and has not yet returned to pre-pandemic levels. Note that the trendline from 2006-2019 and the crosses indicate values obtained with the previous STEAM version, whereas the new trendlines in 2020-2021 indicate totals from the new model version.



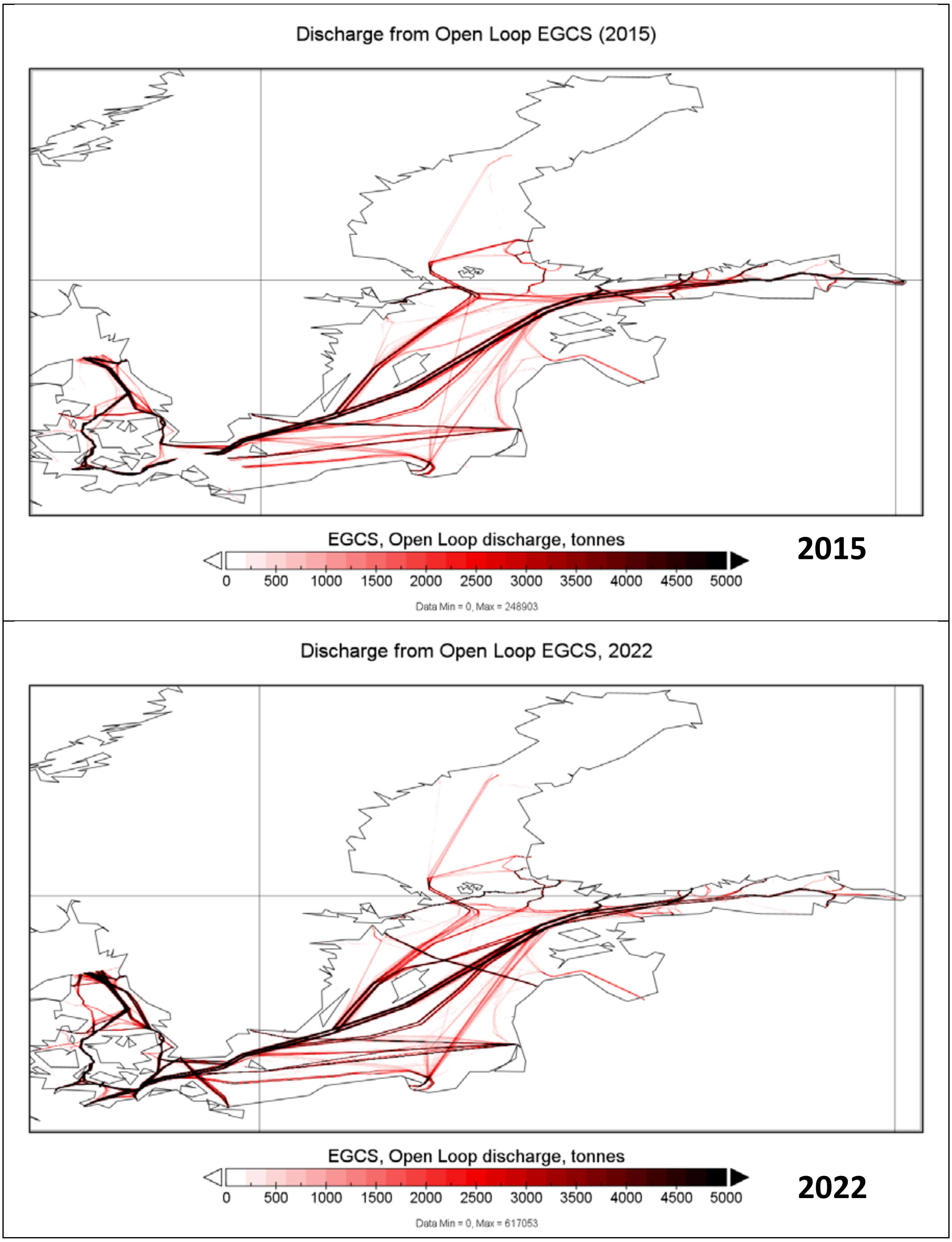


Figure 6 Discharge patterns of EGCS effluent release from Open loop systems in 2010, 2015 and 2022.Corresponding volumes were 8 million tonnes (2010), 56 million tonnes (2015) and 312 million tonnes (2022). Note, that allowed area for Open loop EGCS was changed to include German EEZ in 2021, in contrast to previous definitions (visible in 2015 and 2010 maps).

The current modelling setup assumes that the effluent discharge from open loop is 90 m^3 kWh^{-1} and 0.45 m^3 kWh^{-1} from closed loop systems, in accordance with existing measurements for 48 scrubber systems (Kjølholt et al., 2012; Teuchies et al., 2020).

Majority of EGCS discharge comes from ships operating a regular schedule in the Baltic Sea area (Figure 5-Figure 6). In 2010, most of the discharge was from Cruise vessels, but current studies suggest about 40 times larger total releases than in 2010, mostly from ro-ro and ropax ship traffic.

B. Oily bilge water

According to the IMO MARPOL Annex I, the release of oily water to the sea requires meeting several criteria, for example vessel must be *en route* and the oil content must not exceed 15 ppm. Bilge water can practically contain any number of substances available onboard a vessel, which makes bilge water modeling very complicated if done on pollutant level. Further, the release of bilge water may be random discharge, depending on e.g. tank capacity. The approach of this report is to model the discharge as a continuous release instead, because actual areas of bilge water release could not be determined. The values reported here are bilge water release volumes, which need to be complemented with water analysis results to obtain final quantities of desired pollutants. Regional rules and restrictions have been applied and the modeled bilge water release follows the rules set in MARPOL Annex I and includes stricter rules in cases where national legislation (Finland, Act on Environmental Protection in Maritime Transport Chapter 2, §1) exceeds the IMO regulation (Figure 7). The total release of bilge water was estimated to be 0.51 million cubic meters.

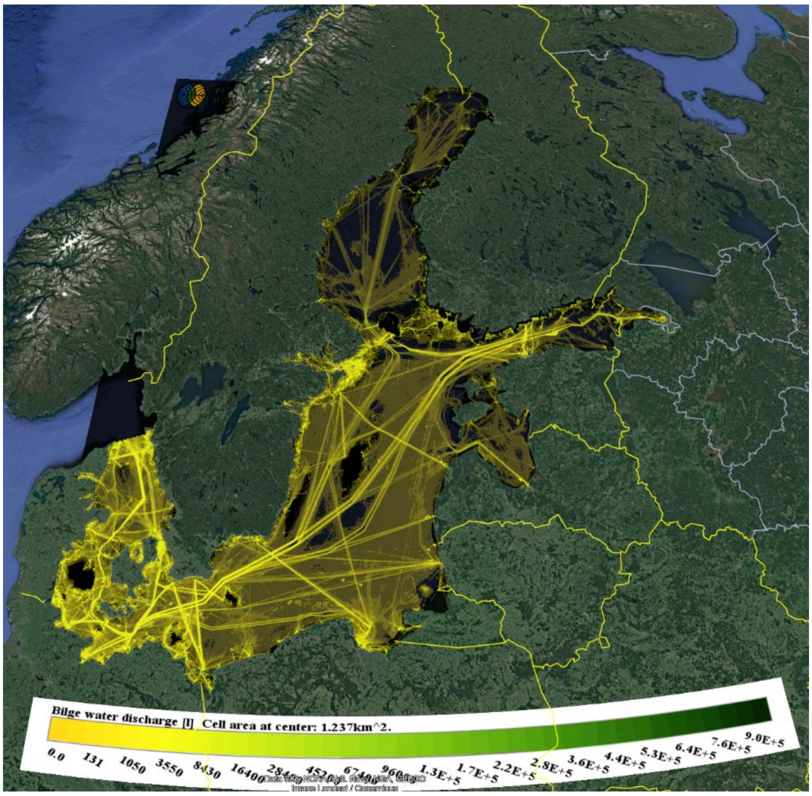


Figure 7 Estimated release of bilge water in the Baltic Sea during 2022. The release is reported in liters.

Bilge water releases were not affected by Covid19, because they do not depend on the number of people onboard the vessel.

C. Ballast water

As per April 2022, the IMO International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (BWMC) has been ratified by 91 out of 197 member states representing over 90% of the world's gross tonnage of ships. Regulation D-2 of the convention defines the necessary technological systems for effective treatment on board to minimise the spread of organisms within ballast water discharges. Even if a member state has not ratified the convention, it does not mean that it allows untreated ballast discharges. For example, the United States has not ratified the convention, but has its own regulation concerning ballast water and requires vessels to be equipped with US Coast Guard approved systems for ballast water treatment.

For accurate modelling of the volumes of treated and untreated ballast water discharges it is necessary to know which ships have D-2 approved systems installed and which have not. In the IHS database of ships used by STEAM, this information is available only for a fraction of the global fleet because the whole database is not updated every year. Thus, it is very probable that the amount of treated ballast water reported in this document is an underestimation and it will not include all the ships with ballast water treatment systems.

Regardless, an attempt was made to provide an estimate of the share of treated ballast water in the Baltic Sea area. This estimate is divided in two parts; the first describes the discharge volume of treated ballast water from vessels which are known to have treatment systems based on IHS data. The second part is based on an estimate of newbuilds and retrofits of existing vessels with treatment systems.

Total ballast water discharges

Total ballast water releases were estimated as 494 (2021:454) million tonnes (+8.8% when compared to 2021). Most of this is carried by tankers and bulk cargo ships, but also released from other vessels (Figure 8). The estimated ballast water discharge at global level is consistent with David and Gollasch (2015), but significantly higher than those estimated by (Endresen et al., 2004), which is in the range of Ballast Water/DWT ratio of previous work of others (David and Gollasch, 2015). Ballast water releases are geographically distributed to areas where cargo operations are conducted. Ballast water releases are modeled as a function of water mass carried and it highlights ports where liquid or dry bulk cargo is transferred. Assumptions which have been used in the activity-based modeling work do not take partial cargo deliveries into account, total discharge of all ballast water is assumed at each harbor, which may overestimate the released quantities. This leads to an order of magnitude estimate which is 494 million tonnes of ballast water for the Baltic Sea fleet during 2022.

Share of treated ballast water discharge, based on IHS data

The share of treated ballast water is also estimated in Figure 8 based on existing IHS entries of known ballast water management systems in STEAM data. In this estimate, tankers have the highest volume of treated ballast water discharge. However, it is likely that this estimate is too low since not all installations of treatment systems are known. For the Baltic Sea fleet, 588 entries specifically mentioned that a treatment system exists. Further, 91 entries indicated that ballast water will be exchanged during the voyage, but that is not allowed in the Baltic Sea region. In addition, 1068 ships were constructed after September 2017 and assumed to carry a treatment system.

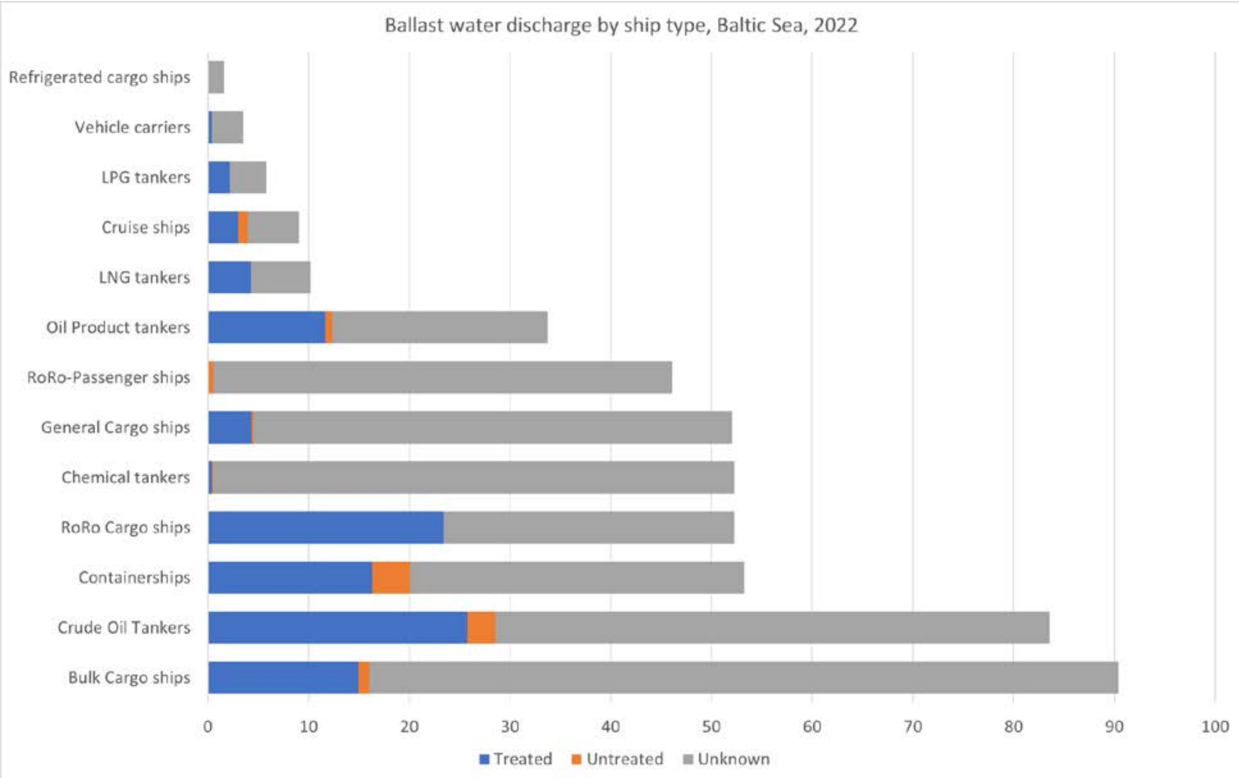


Figure 8 Estimated discharge of ballast water from different types of ships, Baltic Sea, 2021. The blue bars indicate the discharge of treated ballast water from ships, based on the data obtained from IHS database of known treatment system installations.

Based on the existing installations and the number of ships built since September 2017, about 20% of the ballast water is treated. However, the knowledge of retrofits of the existing fleet is incomplete.

Treated ballast water discharge estimate based on build year and retrofits

The estimated share of treated ballast water in the Baltic Sea area is based on newbuilds, which have the D-2 approved systems (Ballast Water Management Convention, Regulation D-2) installed since start of operation and known cases of retrofitted systems. Newbuilds with the keel laying date later than the entry in force date of Sep 8th 2017 are assumed to discharge only treated ballast water, which is depicted in Figure 9. However, there are very likely retrofitted systems which are not currently included in the modelling because of the limitations concerning IHS data updates.

Currently known ballast water treatment system retrofits and newbuilds (after Sep 2017) are collected to Figure 9 by vessel type. As can be seen from Figure 9, significant share of the data is under the category Unknown. The estimate provided in this document, assuming known retrofits and build date after Sep 2017, leads to 24/76 split between treated and untreated discharge of ballast water (Figure 10).

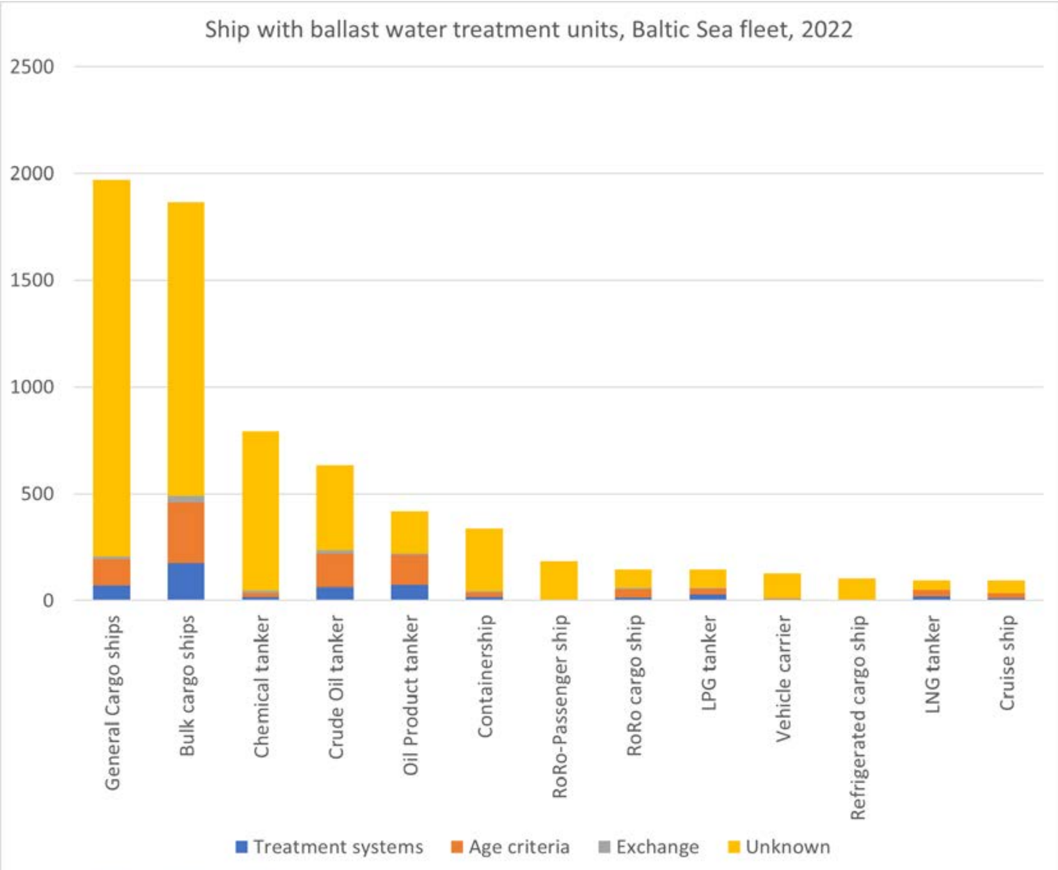


Figure 9 Number of ships which released treated and untreated ballast water in the Baltic Sea area during 2022. Treated discharge was assumed for ships which were built after Sep 2017 or had known installation of retrofitted treatment system.

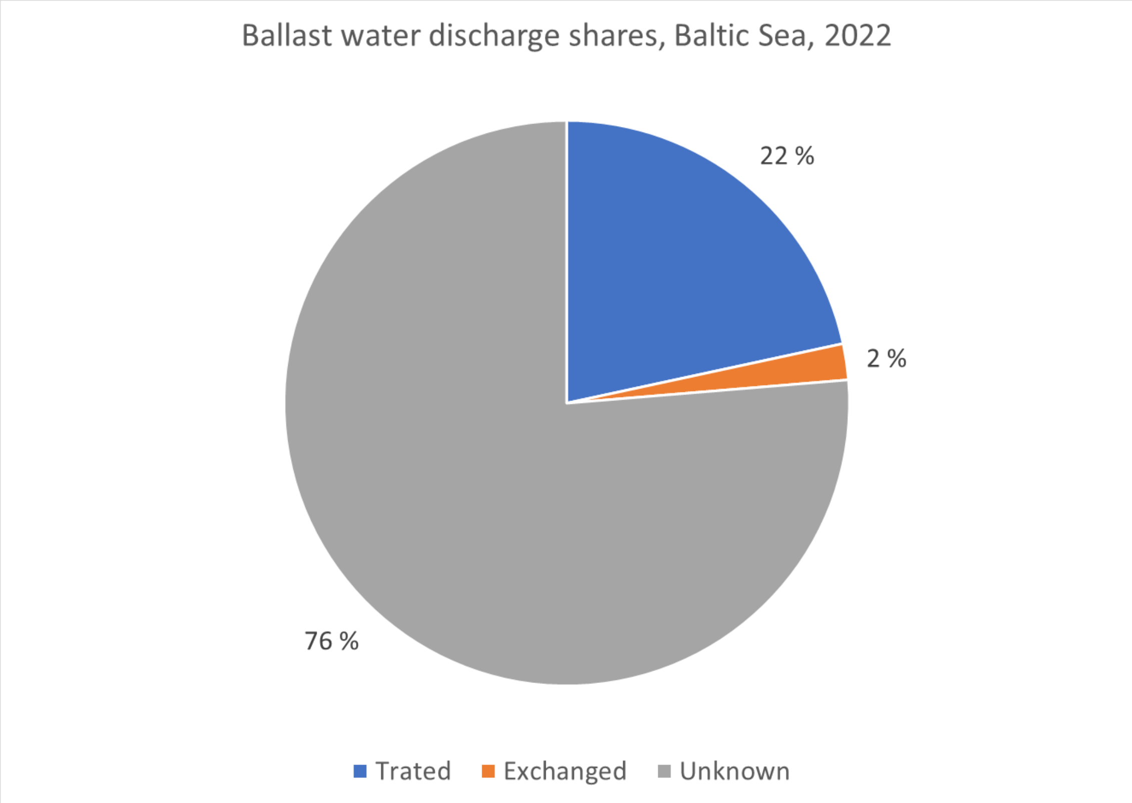


Figure 10 Estimated shares of treated and untreated ballast water discharges in the Baltic Sea area during 2021. The exchange of ballast water is prohibited in the Baltic Sea area, and is shown here only to indicate the share of Unknown ballast water treatment share correctly.

D. Sewage and grey water

The sewage release ban for discharge of untreated sewage from passenger ships sailing in the Baltic Sea, regulated by the MARPOL convention Annex IV, entered into force on 1st June 2019 for newbuilds, 1st June 2021 for existing vessels with an exemption granted until 1st June 2023 for single voyages from outside of the Baltic Sea to Russian territorial waters and back. Compliance can be achieved by either discharging sewage to Port Reception Facilities (PRF) or using a type approved sewage treatment plant (MEPC.227(64) including standards of section 4.2). During 2022, no international passenger traffic going/leaving St Petersburg was observed.

As per the regulation, passenger vessels that do not carry approved and certified treatment systems are required to discharge their sewage to PRFs. It is worth noting that the regulation only applies to sewage. Grey water, which is wastewater from showers, sinks and galleys, is not regulated and thus can be legally discharged into the Baltic Sea.

To accurately model the volumes of treated sewage discharges into the Baltic Sea, information on MEPC.227(64) specified approved sewage treatment systems installations onboard should be known. Unfortunately, this information is not available because the type of sewage treatment plant onboard cannot be determined based on the IHS vessel database used for STEAM.

Discharges of sewage and grey water are directly connected to number of people carried onboard (Figure 11). During the Covid19 pandemic, tight travel restrictions reduced the number of passengers carried significantly, and only a slow recovery of passenger traffic was observed in 2021. The current estimates of number of passengers carried is done by adjusting the passenger and crew capacity utilization. Passenger capacity utilization of pre-pandemic levels were used, 45% for RoPax traffic and 90% rate was used for cruise ships.

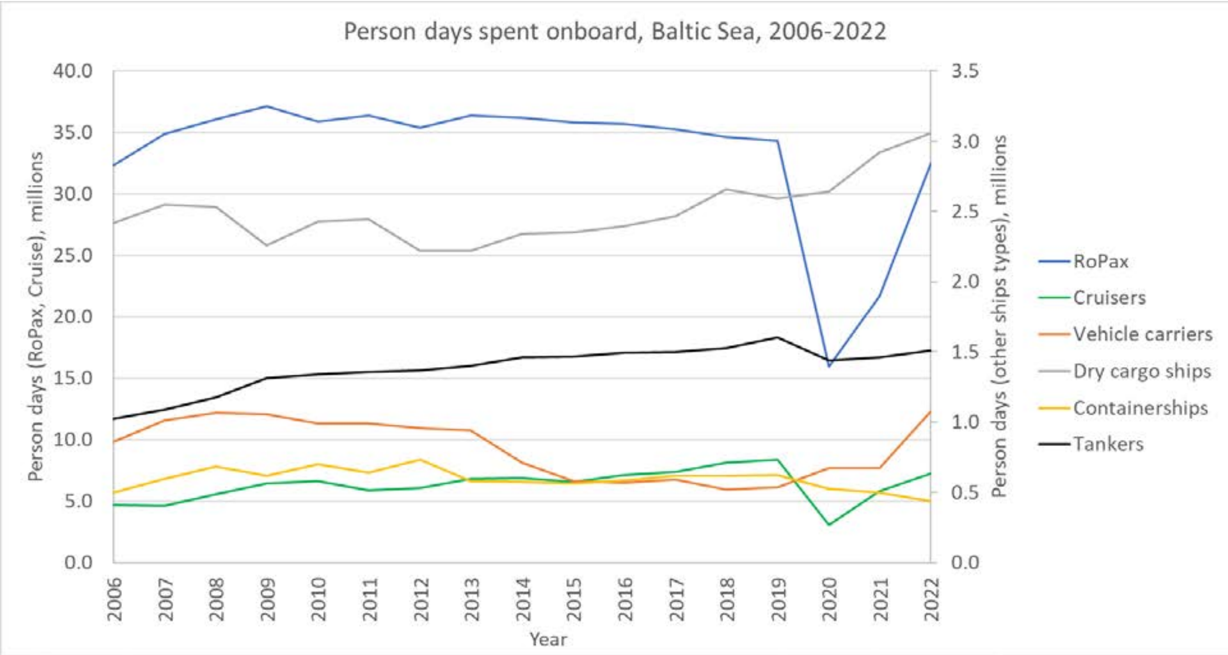


Figure 11 Estimated person days for each vessel type. Note, that both the number of passengers and crew size are affected included. Estimated person days are estimated based on the statistics of number of people carried (data from Finnish customs office).

The discharge of untreated sewage to the Baltic Sea from all passenger ships will be stopped by June 2023 (MARPOL Annex IV). Overall sewage release volume (treated + untreated) from passenger ships to the sea was not changed, but sewage treatment plants were estimated to remove most nutrients (-90% nitrogen, -98% phosphorus) from the discharge. A range of values are provided to illustrate the uncertainty concerning whether all sewage is left in port reception facilities or treated onboard with advanced sewage treatment systems with significant nutrient removal.

In 2022, of 100 cruise vessels observed in the Baltic Sea area, 44 had “Advanced sewage treatment plant” in their description. Of these 44, only four vessels specifically mentioned “Baltic Sea standard” or MEPC.227(64) compliant device. Six vessels had entries of “Sewage treatment”, but no further knowledge was available, and for the remaining 50 no description of their wastewater treatment systems was found. The 100 cruise ships sailing in the Baltic Sea were estimated to produce 202,500 tonnes of sewage during normal operation during 2022. Similarly, RoPax vessels were estimated to produce 734,600 tonnes of sewage. Estimated total sewage release was 0.5-1.5 million tonnes and sewage nitrogen was 68-113 tonnes. It should be noted that significant uncertainty is involved in these estimates since it is not known which ships treat their sewage with nutrient removal and how much was left at ports.

If all passenger vessels treated their sewage onboard and then discharged the treated sewage to the sea, then 1.5 million tonnes of sewage would have been discharged during 2022. However, if all sewage from passenger traffic had been pumped to port reception facilities, this would have led to discharge of 0.5 million tonnes of sewage mainly from cargo traffic (show in Figure 13).

The estimates of sewage and grey water are based on vessel passenger counts, capacity utilization, crew size, time spent onboard, sewage plant treatment efficiency and share of sewage left in port reception facilities (Wilewska-Bien et al., 2019). It should be noted that the modeling approach chosen applies to all ships, not just passenger vessels, since it depends on the number of crew and passengers onboard.

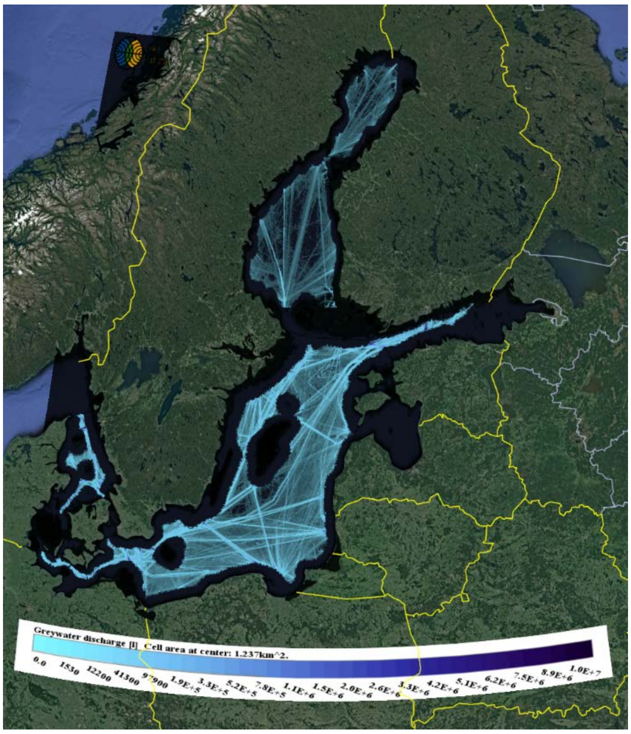


Figure 12. Estimated grey water discharges from ships sailing the Baltic Sea in 2022. Discharge volume is in liters per area of a map grid cell.

Discharge volumes of grey water were relatively stable during the period 2006-2019, but a sharp decline was predicted for 2020, which reflects the Covid19 effect on passenger traffic (Figure 11). Grey water releases were predicted as 5.4 (2021: 3.7) million tonnes, which is +46% more than in 2021. Estimates concerning the grey water release are based on similar methodology as the estimates of sewage, i.e. passenger counts, size of the crew and time spent onboard. Geographical distribution of estimated grey water discharge is depicted in Figure 12. Grey water releases are not currently regulated in the model. Bilge water releases were modeled to be 0.51 million tonnes, a decrease of -0.9% from previous year.

Figure 13 illustrates the trends for sewage, grey and bilge water releases during the period 2006-2022. It should be noted that the trend 2006-2019 depicts results of an earlier STEAM version, whereas the totals for 2020-2022 were obtained using the most recent model version. The symbols in Figure 13 indicate the 2020 results modeled with the earlier model version and are provided here for reference. A challenge for sewage and nutrient discharge modeling is the lack of data for advanced sewage treatment plant installations.

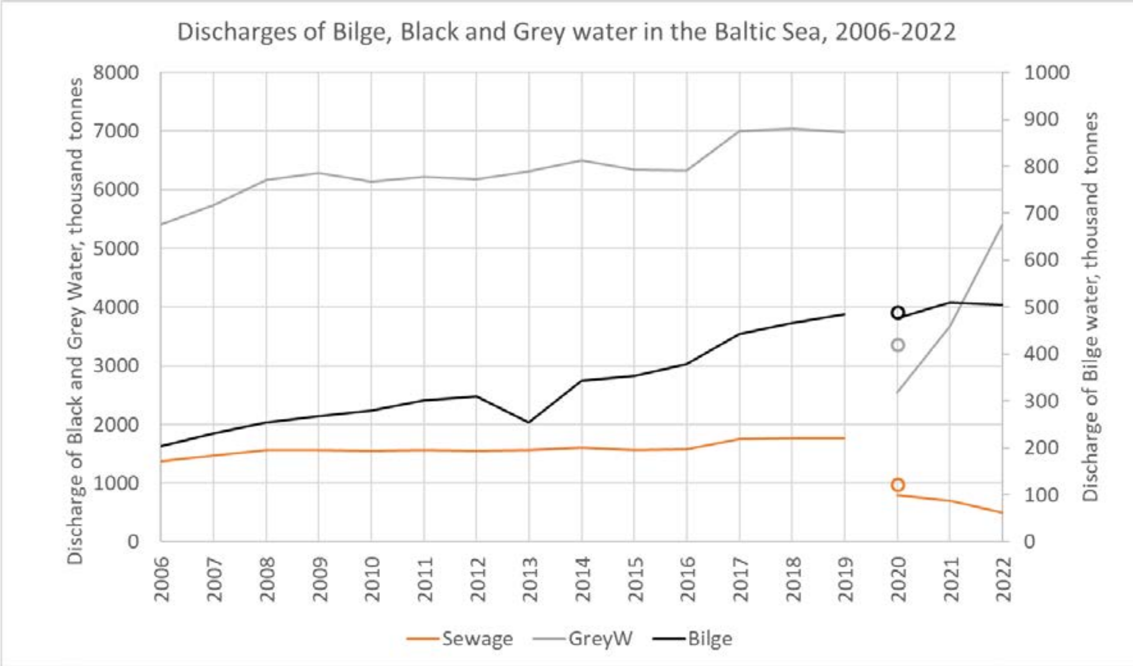


Figure 13 Sewage, bilge, and grey water releases during years 2006-2022 from Baltic Sea shipping. Estimated total sewage release was 0.69 million tonnes including 220 tonnes of nitrogen.

E. Food waste nitrogen

The nutrient release in comminuted food waste mainly comes from passenger traffic, due to many passengers and crew onboard. All ships were modeled in the food waste estimates, based on the size of crew and passengers onboard. According to the IMO MARPOL Annex V, 12 nautical mile distance is applied in special areas like the Baltic Sea. Total reduced nitrogen release to the Baltic Sea from food waste in 2022 was estimated as 101 (+53% increase from 2021 total) tonnes, but still less than the 2019 total of 132 tonnes (Figure 14).

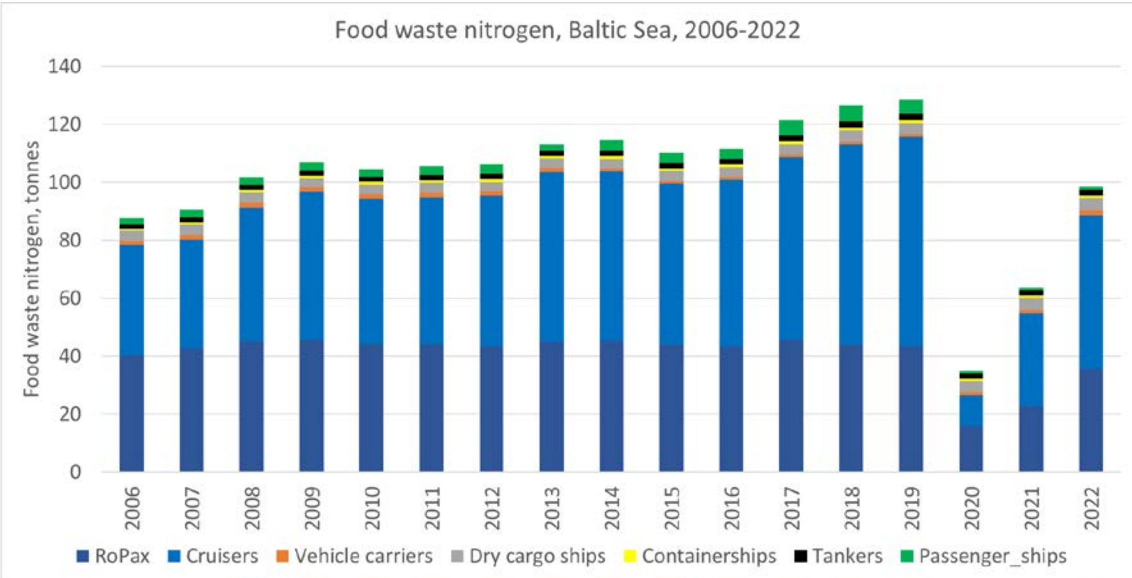


Figure 14 Estimated release of Nitrogen in food waste discharge in the Baltic Sea area during 2006-2021.

F. Stern tube oil leaks

The propeller shaft connects the main engine to a propeller through a stern tube, which goes through the ship's hull. This connection uses white metal bearings which are lubricated either by sea water or, in most cases, by oil. Small amounts of oil leakage is allowed (six liters/day is normal according to Lloyds Register seal type approval) and up to 80 million liters/year is leaked to the sea globally (Sengottuvel and Jagadale, 2017). In the Baltic Sea area, the estimated stern tube oil leak is 4.7 (-1.9%) million liters (Figure 15).

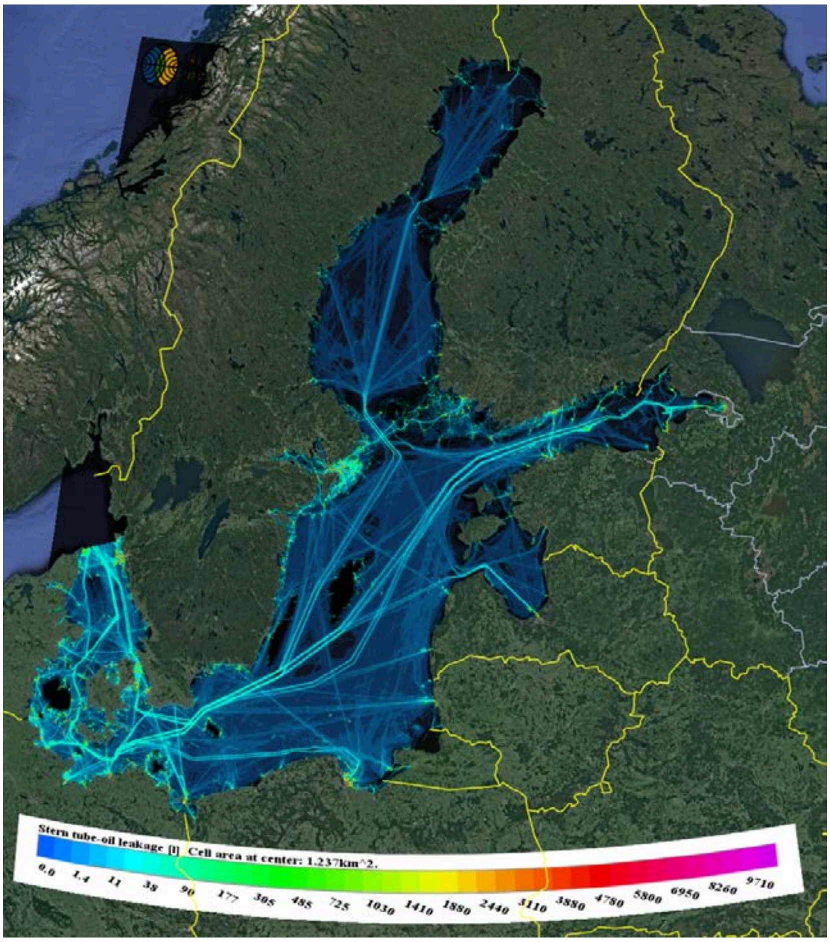


Figure 15 Estimated stern tube oil leakage during 2022 (in liters)

G. Anti-fouling paint release

The International Convention on the Control of Harmful Anti-Fouling Systems on Ships, 2001 (AFC) regulates the use and contents of hull paints used to protect underwater surfaces of ships from unwanted fouling. The modeling approach is based on the calculation of the wetted surface area of each vessel, considering the uptake of various paints in the different regions in the Baltic Sea. Specific leaching rates for different compounds are applied. Hull anti-fouling paint (AFP) coatings are not necessarily used in areas where vessels frequently navigate in ice conditions, because abrasion of ice may reduce the effectiveness of hull paints and frequent cleaning of hull is more effective. Vessels are tracked throughout the year and the highest leaching rate is selected based on where the ship has sailed. High AFP application is assumed for vessels which frequently operate outside the Baltic Sea area.

Six different biocides were considered, discharges and their temporal trends in 2006-2022 were estimated (Table 5- Table 6; Figure 16 - Figure 17).

Table 5 Biocides considered in this report. Molecular mass of each compound is indicated as well as the CAS registry number

Biocide	Molecular mass (g/mol)	CAS number
Cu(I)Oxide	143.09	1317-39-1
Cu Pyrithione	315.86	154592-20-8
Zinc Oxide	81.38	1314-13-2
Zinc Pyrithione	317.7	13463-41-7
DCOIT	282.2	64359-81-5
Zineb	275.8	12122-67-7

Table 6 Estimated biocide release from ship in the Baltic Sea during 2021. All discharges are given in tonnes of compound released. Values in parenthesis indicate the change (%) compared to previous year.

	CUO [TONNES]	CUPYR [TONNES]	ZNO [TONNES]	ZNPYR [TONNES]	DCOIT [TONNES]	ZINEB [TONNES]
TOTAL	418.2 (8.4%)	0.9 (9.2%)	83.5 (9.8%)	1.6 (10.%)	0.6 (9.8%)	1.6 (9.2%)
BALTIC PROPER	206. (14.7%)	0.4 (13.4%)	40.7 (12.5%)	0.8 (12.1%)	0.3 (12.5%)	0.8 (13.4%)
KATTEGAT	123.7 (9.1%)	0.3 (9.%)	25.2 (8.9%)	0.5 (8.9%)	0.2 (8.9%)	0.5 (9.%)
GULF OF FINLAND	104. (11.9%)	0.2 (11.6%)	19.7 (11.4%)	0.4 (11.3%)	0.1 (11.4%)	0.4 (11.6%)
GULF OF BOTHNIA	25.9 (6.6%)	0.1 (6.9%)	5.2 (6.8%)	0.1 (7.4%)	0. (7.3%)	0.1 (6.9%)
GULF OF RIGA	11.2 (40.3%)	0. (40.6%)	2.2 (41.%)	0. (41.2%)	0. (41.%)	0. (40.7%)
VESSEL TYPE						
ROPAX_VESSELS	14.2 (-6.%)	0. (-4.3%)	4. (-3.5%)	0.1 (-3.1%)	0. (-3.4%)	0.1 (-4.3%)
VEHICLE_CARRIERS	2.3 (-21.1%)	0. (-21.1%)	0.4 (-21.1%)	0. (-21.1%)	0. (-21.1%)	0. (-21.1%)
RORO_VESSELS	18.7 (23.7%)	0. (19.%)	3.7 (15.4%)	0.1 (13.9%)	0. (15.3%)	0.1 (18.6%)
BULK_CARRIERS	103.8 (29.4%)	0.2 (29.5%)	19. (29.6%)	0.4 (29.7%)	0.1 (29.6%)	0.4 (29.5%)
GENERAL_CARGO	79.3 (0.4%)	0.2 (1.2%)	15.3 (1.8%)	0.3 (2.%)	0.1 (1.8%)	0.3 (1.2%)
CONTAINER_SHIPS	33.7 (1.6%)	0.1 (-0.2%)	6.3 (-1.7%)	0.1 (-2.3%)	0. (-1.7%)	0.1 (-0.3%)
REEFERS	4.3 (13.3%)	0. (13.3%)	0.8 (13.2%)	0. (13.1%)	0. (13.2%)	0. (13.2%)
TANKERS	130. (16.5%)	0.3 (16.4%)	23.8 (16.4%)	0.5 (16.4%)	0.2 (16.4%)	0.5 (16.5%)
LNG_TANKERS	6.9 (73.%)	0. (62.7%)	1.3 (54.8%)	0. (51.6%)	0. (54.6%)	0. (62.%)
GAS_TANKERS	5.8 (75.%)	0. (75.1%)	1.1 (75.1%)	0. (75.1%)	0. (75.1%)	0. (75.1%)
PASSENGER_SHIPS	3.5 (27.%)	0. (35.4%)	1. (40.7%)	0. (43.4%)	0. (41.4%)	0. (36.%)
CRUISERS	6. (11.9%)	0. (10.1%)	1.2 (8.3%)	0. (8.1%)	0. (8.7%)	0. (9.9%)
FISHING_VESSELS	3.7 (-3.%)	0. (-1.6%)	0.8 (-0.5%)	0. (-0.2%)	0. (-0.6%)	0. (-1.5%)
SERVICE_SHIPS	3.6 (-27.8%)	0. (-27.8%)	0.8 (-27.9%)	0. (-28.%)	0. (-28.%)	0. (-27.9%)
UNKNOWN	32.5 (6.2%)	0.1 (6.3%)	8.6 (6.5%)	0.2 (6.6%)	0.1 (6.5%)	0.1 (6.4%)
MISC	22.5 (-0.2%)	0. (-1.1%)	5.1 (-1.8%)	0.1 (-2.%)	0. (-1.8%)	0.1 (-1.2%)

Largest AFP releases occur in the Baltic Proper, which is largest of the considered sub-regions. It should be noted that wetted surface area of IMO registered vessels is estimated to be about 85% of the total wet surface area of all waterborne vessels, the remaining 15% roughly represents the contribution from small boats. It is very likely that the quantities listed in Table 6 are underestimated, because small boat AFP releases are not included in these results. The unusually large shift in AFP release modeling between new and old

STEAM version arise from a programming error correction in STEAM code which overestimated the wet surface area.

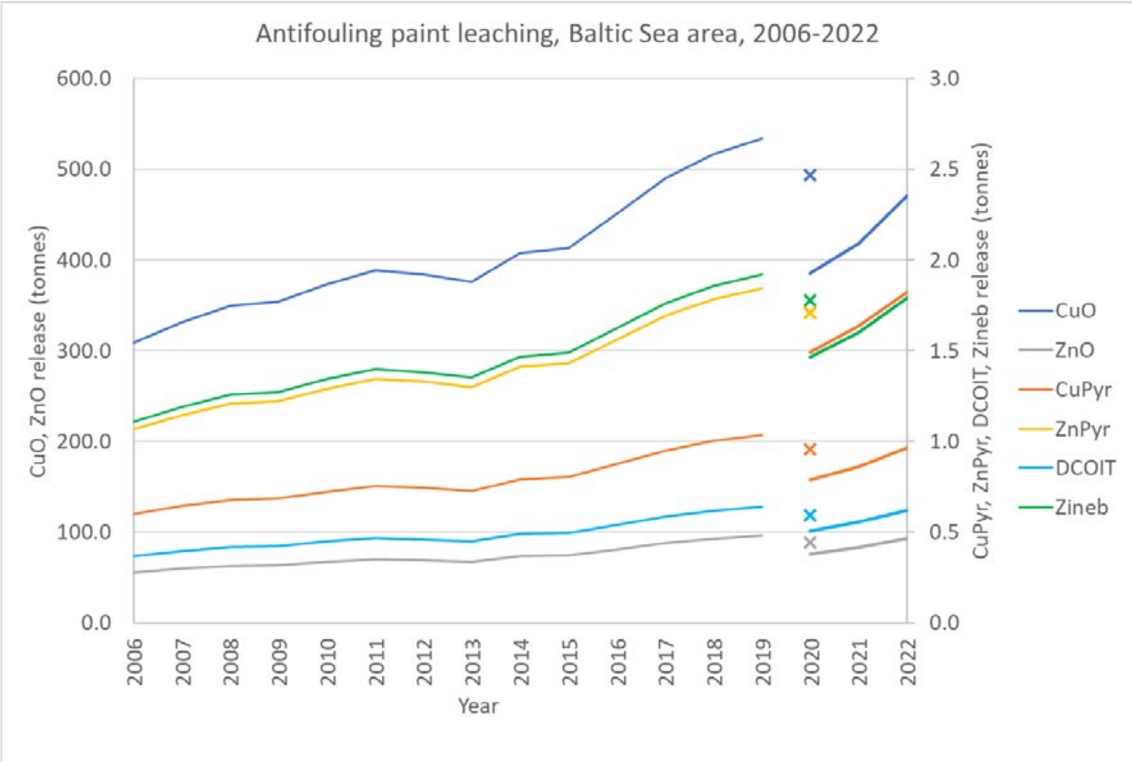


Figure 16 Biocide release from ships in the Baltic Sea area during 2006-2022. Six compounds are reported; Cu(II)Oxide, (Dark Blue), Zn Oxide (Grey), Cu-Pyrithione (Orange), Zn-Pyrithione (Yellow), DCOIT (Light Blue), Zineb(Green). Numerical values for releases of CuO and ZnO are given in left axis, for other releases see the right axis. Continuous lines indicate the timeseries for 2006-2019 (old model version), 2020-2022 (new STEAM version), symbols represent data points for 2020 (old STEAM version). The large difference between model versions was observed for 2020, and this was because of a programming error correction in STEAM code.

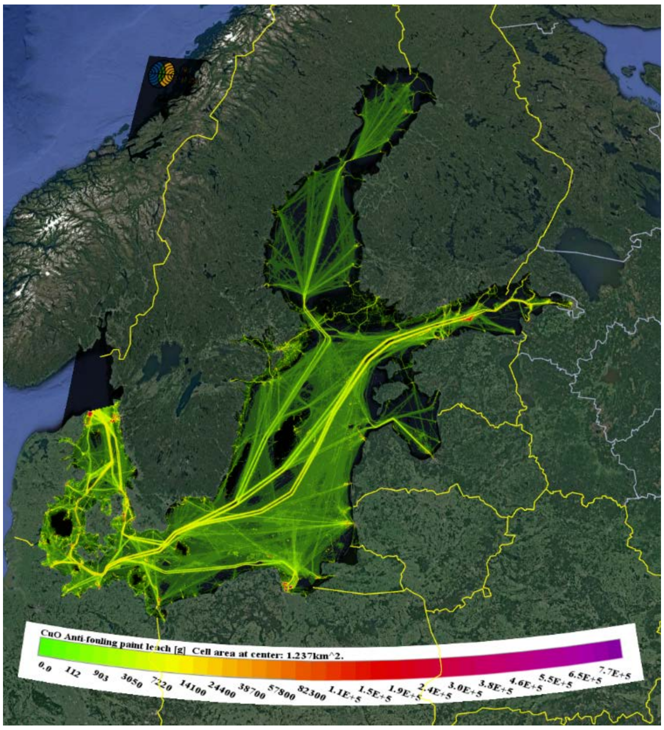


Figure 17 Biocide releases from the Baltic Sea fleet in 2022. Only CuO is presented here, but similar maps are available for other antifouling releases, too. Unit is mass in grams per grid cell area.

The estimated wetted surface area of all AIS equipped vessels was about 50.4 million square meters. This mostly describes large ships, for which AIS is mandatory. This estimate, however, does not include contribution from small boats, the number of which exceeds half a million around the Baltic Sea coastline. The estimated surface area of small boat fleet is about 7.1 million square meters, considering the number of boats of each type and their average size (Johansson et al., 2020). The boating contribution to overall wet surface is around 12%, considering the length of boating season, which mainly concerns May-September period of each year, the contribution of small boats to antifouling releases was estimated as 106 tonnes of Zn and Cu. Antifouling release from points has a very different spatial pattern than that of ships (ships: Figure 17, boats: Figure 18).

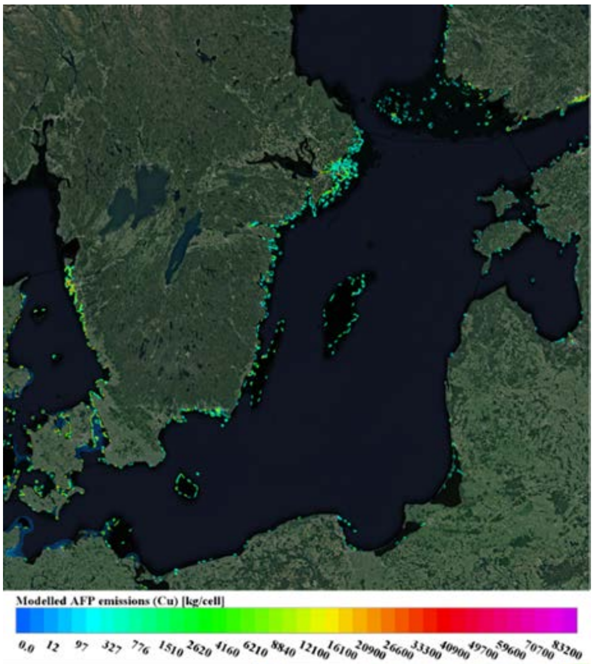


Figure 18. Release of Copper from antifouling paints used in boats in the Baltic Sea area. Image from (Johansson et al., 2020).

Large ships travel along the shipping lanes, whereas small boat traffic occurs close to the shore, extending tens of kilometers to the open sea, but no further.

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Data

The discharge estimates for the year 2022 are based on over 882 million AIS-messages sent by 37144 different ships, of which 9240 had an IMO registry number indicating commercial marine traffic. The AIS position reports were received by terrestrial base stations in the Baltic Sea countries and collected to regional HELCOM AIS data server. Discharges are generated using the Ship Traffic Emission Assessment Model (STEAM; (Jalkanen et al., 2009, 2012, 2021; Johansson et al., 2013, 2017).

For 2022, the temporal coverage of HELCOM AIS was 100% which is better than during the previous year (2021: 99.7%) (Figure 19). This is the first year of HELCOM AIS operation with a perfect service record. For the year 2022, the average data flow was around 100 000 messages per hour.

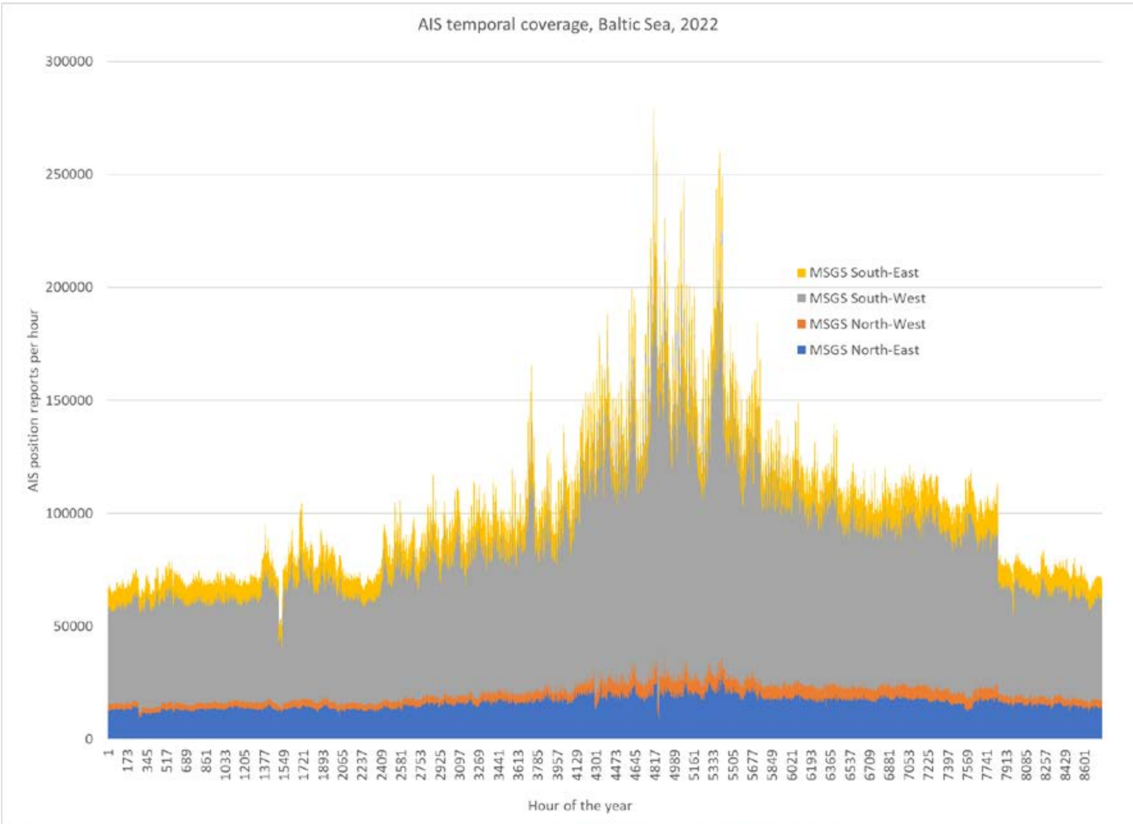

Figure 19 AIS-data hourly coverage in different parts of the modelling region for 2021.

Metadata

The STEAM model was updated to version 4.3.1 for this work, some of the changes made are listed below:

a) Added the NH_3 and N_2O pollutant species. This enabled modeling of ammonia slip from SCR units. It also enables modeling of ammonia/diesel mixtures as ship fuel.
b) Added variables "Fuel in ice" and "Travel in ice" variables to all statistics. This enables tracking of winter navigation effects throughout the global fleet at ship level.

It should be noted that current estimates do not include contributions from vessels without active AIS equipment.

All calculations were made including the effects of sea currents, winds, waves, and ice cover thickness. Impact of biofouling to vessel resistance was modeled with a simplified scaling approach, and impact of squat was neglected entirely.