Efficacy of Ballast Water Management Systems Operating within the Great Lakes and St. Lawrence River (2017 – 2022)

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ABSTRACT

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A science team from Fisheries and Oceans Canada has conducted ballast water sampling on ships in the Great Lakes and St. Lawrence River (GLSLR) to assess the effectiveness of ballast water management systems (BWMS) at reducing the number of organisms in ballast water. Three ballast water discharge-only samples and 11 paired ballast water uptake and discharge samples were collected from ships between 2017 and 2022. Ballast water samples were collected at 12 GLSLR ports on seven international ships and five Canadian domestic ships. Ten ships had ultraviolet BWMS, while two ships had chemical injection BWMS.

The results show that BWMS reduced the abundance of living organisms in ballast water by > 98% for both organism size classes specified by the International Maritime Organization's D-2 performance standard. Eight out of 14 discharge samples were below the limit of the D-2 standard for the ≥ 50 µm organism size class. All four tests with exceedances of the D-2 standard had loaded ballast water in Hamilton Harbour. All 14 discharge samples were below the limit of the D-2 standard for the ≥ 10 and < 50 µm organism size class.

Bi-weekly monitoring of water quality characteristics relevant to ballast water management was conducted in Hamilton Harbour throughout the shipping season in 2022. The results indicate that Hamilton Harbour has challenging water conditions for BWMS due to high zooplankton abundances during most of the shipping season.

RÉSUMÉ

Bailey, S. A., Casas-Monroy, O., Kydd, J., Ogilvie, D., Rozon, R. M., and Yardley, S. 2023. Efficacy of ballast water management systems operating within the Great Lakes and St. Lawrence River (2017 – 2022). Can. Data Rep. Fish. Aquat. Sci. 1376: vii + 24 p.

Afin d'évaluer l'efficacité des systèmes de gestion des eaux de ballast utilisés pour réduire le nombre d'organismes présents dans les réservoirs, une équipe scientifique de Pêches et Océans Canada a procédé à l'échantillonnage des eaux de ballast sur les navires traversant les Grands Lacs et le fleuve Saint-Laurent. Parmi l'ensemble des échantillons, trois correspondaient exclusivement au rejet des eaux de ballast tandis que onze échantillons correspondaient à la prise et au rejet des eaux de ballast, prélevés sur des navires ayant fait escale entre 2017 et 2022. Les échantillons d'eau de ballast ont été collectés dans douze ports du réseau des Grands Lacs à partir de sept navires internationaux et cinq navires domestiques. Parmi ces navires, dix étaient munis d'un système de gestion utilisant des rayonnements ultraviolets, tandis que deux utilisaient un système de gestion basé sur l'injection chimique.

Les résultats montrent que les systèmes de gestion des eaux de ballast peuvent réduire l'abondance d'organismes viables dans les eaux de ballast de plus de 98 % pour les deux classes de taille d'organismes spécifiées par la norme de performance D-2 de l'Organisation Maritime Internationale. Parmi les quatorze échantillons de rejet, huit étaient conformes à la limite de la norme D-2 pour la classe d'organismes de taille ≥ 50 µm. Parmi les échantillons excédant la norme D-2, quatre ont été collectés dans le port de Hamilton. En revanche, tous les quatorze échantillons de rejet étaient en dessous de la limite de la norme D-2 pour la classe d'organismes de taille ≥ 10 et < 50 µm.

Une surveillance de la qualité de l'eau, effectuée de manière bihebdomadaire dans le port de Hamilton pendant la saison de navigation de 2022, a permis d'obtenir des informations sur les caractéristiques environnementales en vue de la gestion des eaux de ballast. Les résultats révèlent que le port de Hamilton présente des conditions d'eau difficiles pour les systèmes de gestion des eaux de ballast, en raison de l'abondance élevée de zooplancton pendant la majeure partie de la saison de navigation.

INTRODUCTION

With the entry-into-force of the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 (hereafter referred to as the Convention; IMO 2004), many ships have begun to install and operate ballast water management systems (BWMS) to treat their ballast water. The Convention sets discharge standards for the commercial shipping industry to limit the abundance of organisms in ballast water in order to minimize the introduction and spread of potentially harmful aquatic organisms and pathogens. Specifically, Regulation D-2 of the Convention states that ballast water discharged into the environment shall contain < 10 viable organisms per m^3 ≥ 50 µm in minimum dimension (hereafter referred to as the ≥ 50 µm size class) and < 10 viable organisms per mL ≥ 10 µm and < 50 µm in minimum dimension (hereafter referred to as the 10 – 50 µm size class); Regulation D-2 also specifies limits for indicator microbes. The United States (U.S.) has the same numerical ballast water discharge standards for the two organism size classes. However, the discharge standard in the Convention is based on the number of viable organisms (organisms capable of reproduction) in ballast water, whereas the U.S. discharge standard is based on living organisms. Canada, a party to the Convention, updated its ballast water regulations requiring all (foreign and domestic) ships that are loading and discharging ballast water in Canadian waters to meet the D-2 standard (Canada Gazette 2021).

Ballast water operations of Great Lakes ships (hereafter referred to as Lakers) play a major role in the spread of nonindigenous species in the Great Lakes region (Bailey et al. 2012). At least seven species nonindigenous to the Great Lakes and 21 species with restricted distributions within the Great Lakes have been reported in ballast water samples destined for ports outside their historical distribution (Briski et al. 2012, Cangelosi et al. 2018). Furthermore, Lakers' ballast water can contain high abundances of nonindigenous organisms, and the organisms typically have high survival rates due to the relatively short transit times between Great Lakes ports (e.g. < 24 hours to 4 days; Rup et al. 2010, Briski et al. 2012, Adebayo et al. 2014). Lakers transport the vast majority of ballast water moved within the Great Lakes (95% and ~68 million tonnes per year), forming a highly interconnected network of ports that enables rapid dispersal of nonindigenous species over long distances to areas that they would otherwise be unlikely to reach naturally (Rup et al. 2010, Briski et al. 2012, DFO 2019).

Fisheries and Oceans Canada has conducted model-based analyses to estimate species establishment risk under various ballast water management scenarios for Lakers. The model results indicate that the use of BWMS by Lakers is expected to substantially reduce the establishment rate of nonindigenous zooplankton due to ballast water discharges (DFO 2020). Specifically, the management of all Lakers' ballast water to the D-2 standard is expected to reduce the establishment rate of nonindigenous zooplankton by 99%, while an 83% reduction in establishments is expected if only half of the treatment events successfully meet the D-2 standard (DFO 2020). These findings suggest that BWMS are beneficial even if ships cannot consistently meet the D-2 standard for all discharges. On the other hand, the results from an earlier model-based risk assessment by Casas-Monroy et al. (2014) suggest that even if all Lakers' ballast discharges met the D-2 standard, there would be little effect on the invasion risk of nonindigenous phytoplankton, since that risk was already low when ballast water was not managed. However, the risk of nonindigenous phytoplankton could be underestimated by that study since limited data from Laker ballast water samples were available for this taxonomic group. Furthermore, this study did not consider all pertinent phytoplankton taxa, such as harmful algal bloom-forming taxa, that may pose risk.

In a shipboard study conducted on the Great Lakes to evaluate the effectiveness of ballast water filtration at reducing organism abundances in ballast water, three shipboard trials were conducted using a ballast water filtration unit with 40 µm steel candle filter elements (Briski et al. 2014). Before filtration, the abundance of organisms in the ballast water ranged from 72,478 – 868,791 organisms per m^3 for the ≥ 50 µm size class and from 88 – 531 organisms per mL for the 10 – 50 µm size class (Briski et al. 2014). After filtration, the abundance of organisms ranged from 17,101 – 787,518 organisms per m^3 and from 24 – 229 organisms per mL (Briski et al. 2014). The filtration system reduced organism abundances between 17 – 73% for the ≥ 50 µm size class and 26 – 62% for the 10 – 50 µm size class but did not meet the D-2 standard (Briski et al. 2014).

Transport Canada conducted a cost-benefit analysis for implementing ballast water regulations (capital and operational costs to Canadian ship owners and compliance and enforcement costs to the Canadian Government) against the benefits of reducing the number of nonindigenous harmful species introduced to and spread within Canadian waters due to the movement of ballast water (Canada Gazette 2021). The cost of harmful species was based on the cost of mitigating the impacts of Zebra Mussels (*Dreissena polymorpha*) in the Ontario Great Lakes. The cost-benefit analysis estimated a total net benefit of $701.38 million between 2021 and 2043, considering a present value total cost of $280.47 million and present value total benefit of $981.85 million (Canada Gazette 2021).

A science team from Fisheries and Oceans Canada has been sampling ships on the Great Lakes and St. Lawrence River (GLSLR) to determine the effectiveness of BWMS at reducing the abundance of organisms in ballast water. In 2017, ballast water samples were collected only during discharge. In 2019 and 2022, paired ballast water uptake and discharge samples were collected from ships to better understand the real-world effectiveness of BWMS and potential causes of ballast water samples failing to meet the D-2 standard. In addition, bi-weekly monitoring of water quality characteristics relevant to ballast water management were conducted in Hamilton Harbour throughout the shipping season in 2022.

The purpose of this report is to share data on BWMS effectiveness gathered to date from the GLSLR, which may be used to inform ongoing international rulemaking processes. Information shared includes the methods of collecting and analyzing samples, results observed, as well as issues (and potential solutions) encountered during sample collection and operation of BWMS. The focus of this report is on data sharing, with statistical analyses to be completed at a later date.

METHODS

Ballast Water Sample Collection

Ballast water samples were collected opportunistically from ships at 12 GLSLR ports between May and November in 2017, 2019 and 2022 (Table 1 and Figure 1). Ballast water sampling followed standard operating procedures that are consistent with international sampling guidance and protocols (ICES/IOC/IMO WGBOSV 2017). Ships' crews were sent a survey and/or interviewed in person prior to sampling to plan the sampling event(s) according to ship cargo operations.

Ballast water samples were collected during the ship's ballast operations from sample ports located either in the engine room, pump room or on deck (Table 2 and Figure 2). Untreated ballast water uptake samples were collected at the sample port located upstream (before) of the BWMS during uptake, while treated ballast water samples were collected from the sample port located near the overboard discharge (after the BWMS) during ballast water discharge.

For the ≥ 50 μm organism size class, an inline sample collection device was used to collect one cubic meter of ballast water for uptake samples and three cubic meters of ballast water for discharge samples (Figure 3); in-line sampling is conducted using a sample probe inserted into the main ballast pipe that directs a representative subsample of ballast water to a sample collection device. A smaller volume of ballast water was collected for uptake samples since untreated uptake water typically has higher organism abundances, therefore less sample volume is required to produce reliable abundance estimates. Ballast water samples were collected at flow rates below the isokinetic flow rate, which has a velocity that is identical to the main ballast pipe, aiming to minimize flow turbulence and injury to organisms (ICES/IOC/IMO WGBOSV 2017). Target flow rates were between 0.25 and 1.00 times the flow velocity in the main ballast pipe (Wier et al. 2015). Samples were collected continuously during the loading and unloading of the ballast tank(s) to obtain a representative sample; this was particularly important during discharge sampling since organism abundances in ballast tanks can be heterogenous due to in-tank stratification (Bailey and Rajakaruna 2017).

Simultaneously, a sample collection device was used to collect between 14 and 45 L of unconcentrated water over the sample duration for analysis of the 10 – 50 μm organism size class (Figure 3). A well-mixed unconcentrated 1 L subsample of water was taken to estimate live organisms in the 10 – 50 μm size class. The remaining volume was used to determine water quality parameters (ultraviolet transmittance, total residual oxidant and salinity), and concentrated for preservation and molecular analysis (results not presented here).

The concentration method for the ≥ 50 μm organism size class followed Bailey et al. (2022). Briefly, each sample was concentrated through a 35 μm mesh, 30 cm diameter net submerged in ambient ballast water in a 75 L plastic bin (Figure 3). The plastic bin has two discharge lines to direct the processed water into a suitable holding or disposal location as directed by the Chief Engineer. Once 1,000 L passed through the net, the outside of the net was rinsed with 10-μm filtered ballast water to wash the sample down into the codend, which was transferred into a 1 L Nalgene bottle; 10-μm filtered ballast water was prepared by filtering ambient ballast water from the plastic bin through a 7 μm mesh into a spray bottle. Ten-μm filtered ballast water was used as rinse water to minimize the mortality of organisms. For discharge samples, this was repeated up to three times, until a maximum of 3,000 L was collected. A YSI EXO multi-parameter water quality sonde (YSI Incorporated, Yellow Springs, OH) was submerged in the 75 L bin while collecting ballast samples to measure relevant water quality parameters (temperature, salinity, turbidity, fluorescent dissolved organic matter). Collected samples were wrapped in a thermal blanket or kept in a dark insulated cooler at or below ambient ballast water temperature.

Ambient port water samples were collected at the same time as uptake sampling on three trips. The water quality parameters measured from ambient port water include dissolved organic carbon, particulate organic carbon and total suspended solids. These water quality parameters were analyzed by Environment and Climate Change Canada’s National Laboratory for Environmental Testing in Burlington, Ontario. Additionally, organism abundances in ambient port water samples were estimated for both the ≥ 50 μm and 10 – 50 μm size classes (see below for counting methods).

Ballast Water Sample Analysis

Ballast water samples were transported off ship for analysis as soon as possible after collection; sample analysis was typically completed within six hours of the start of sampling to minimize mortality of organisms.

For the ≥ 50 µm organism size class, the concentrated net samples were first split for microscopy and molecular analysis (Figure 4). Samples were mixed by gentle inversion five times before splitting each sample. Two thirds of the sample was used for the microscopy counts (then preserved for taxonomy), while one third of the sample was used for molecular analysis. For microscopy counts, an initial 1 mL aliquot of the sample was examined to determine the concentration of organisms in the sample volume. Samples were condensed (using a 35 µm mesh) or diluted (using filtered ballast water) to achieve ~25 – 50 organisms per mL for analysis. Aliquots of up to 2.5 mL were transferred into single channels of a modified Bogorov counting chamber (Hydro-Bios Apparatebau GmbH, Germany) using an Eppendorf pipette with a wide-bore tip (Figure 4). A 10 µL aliquot of 50 µm beads was added to the counting chamber as a size reference. Each channel was assessed under a Nikon SMz800N Zoom stereoscope under 30 – 80x magnification (Figure 4). Both live (showing movement and response to stimuli techniques (NSF International 2010)) and total number of organisms (live and dead) were counted for uptake samples, while only live organisms were counted for discharge samples. Organisms in samples were counted for 60 to 90 minutes to minimize mortality due to handling/containment or until the entire sample was counted, whichever came first. The cumulative counts were converted to abundance per cubic meter based on volumes collected, sample concentration factor and fraction of sample counted. For discharge samples, the cumulative mean abundance of live organisms was calculated based on the total volume collected for the three net samples.

For the 10 – 50 µm organism size class, samples were examined by epifluorescence microscopy using fluorescein diacetate as a vital marker (Adams et al. 2014). A 5 mL subsample was removed from a well-mixed 1 L sample of unconcentrated ballast water, and 417 µL of fluorescein diacetate working solution was added to the subsample. The subsample was incubated in the dark for 10 minutes. Once the incubation was completed, 1 mL of the subsample was transferred to a Sedgewick-Rafter counting chamber (Wildlife Supply Company, Yulee, Florida, USA; Figure 5). A 1 µL aliquot of 10 µm and 50 µm fluorescent bead solution was added to the counting chamber as a size reference. Six 1 mL subsamples were examined using a Zeiss Axio Vert.A1 microscope (Carl Zeiss Canada, Ltd, Toronto, Ontario, Canada; Figure 5), equipped with a LED Module (470 nm) and filter for green fluorescent protein (filter set 38, excitation 495 nm, emission 517 nm). All fluorescing organisms were counted in the entire chamber within 20 minutes. The mean abundance of live organisms for the 10 – 50 µm size class was calculated from the six subsamples.

These methods produce estimates of living organisms in ballast water that are consistent with the U.S. discharge standard. Counting live organisms may provide a conservative estimate of viable organisms as specified in Regulation D-2 of the Convention.

Ninety percent confidence intervals were calculated assuming a Poisson distribution for both organism size classes (NSF International 2010). The confidence intervals were used to determine whether samples exceeded the D-2 standard; results where confidence intervals span above and below the D-2 standard were called ‘close to the limit’.

Quasi-Poisson generalized linear models were applied to examine the relationship between the abundance of organisms in discharge samples and factors that may influence the performance of BWMS (work to be presented elsewhere). The factors examined include BWMS type, BWMS filter size, ballast age, turbidity, fluorescent dissolved organic matter, ultraviolet transmittance and organism abundance in uptake samples.

Hamilton Harbour Bi-Weekly Monitoring

Port water samples were collected from Hamilton Harbour and analyzed to better understand the variability in relevant water quality conditions at a Great Lakes port in comparison to BWMS Type Approval test criteria (IMO 2018; NSF International 2010). Port water samples were collected every two weeks from a wharf in the south east corner of the harbour from April to December in 2022. Water samples were collected at five metres depth using a Van Dorn water sampler and Schindler-Patalas plankton trap. The water quality parameters measured were dissolved organic carbon, particulate organic carbon, total suspended solids and live organism abundances for both the ≥ 50 μm and 10 – 50 μm size classes (following the same methods described above for ambient port water samples).

RESULTS AND DISCUSSION

Sample, Ship and BWMS Characteristics

In total, three discharge-only samples and 11 pairs of uptake and discharge samples were collected from 12 unique ships having ballast sourced from freshwater ports within the GLSLR (Table 1 and Figure 1). Ballast water sources include ports on the St. Lawrence River (Levis, Sorel-Tracy, Montreal and Valleyfield in Quebec), Lake Ontario (Hamilton, Oakville, Oshawa and Toronto in Ontario) and Calumet River (Chicago, Illinois). Two ships were sampled on two different trips (having different ballast source ports). Seven international ships and five Canadian domestic ships were sampled, including seven geared bulkers (607 – 657 ft in length), four tankers (443 – 750 ft in length), and one barge (407 ft in length) that does not operate outside the GLSLR (Table 2). These results were intentionally anonymized to protect the identity of the ships.

The ships each had two ballast pumps with combined rated pump capacities ranging from 600 to 3,000 m^3 per hour (Table 2). Ship crews reported that expected pumping rates during normal ballast operations are typically below the rated capacity (median 600 m^3 per hour), due to operational factors such as head pressure, piped distance and BWMS effects; some ships also used only one pump during ballast operations. Observed pumping rates during sample collection were generally similar to the expected pumping rates (rates proposed by ships' Officers prior to sampling). The difference between expected and observed pumping rates ranged from 20 to 291 m^3 per hour on uptake and 23 to 386 m^3 per hour on discharge, excluding one ship (Ship 8) where the ballast pumping rate was intentionally reduced to allow for longer sample time to facilitate more representative sample collection. Ship crews kept the BWMS operating as planned during all sampling events — without any need to bypass BWMS due to low flow rates. Additional characteristics of the ships sampled, such as the number of ballast tanks and holds and sample port location are described in Table 2.

The majority of ships sampled used a BWMS with filtration plus ultraviolet (UV) irradiation (10 out of 12 ships), including systems manufactured by Alfa Laval (seven ships), Optimarin (two ships) and BioUV (one ship); two ships used a BWMS with filtration plus chemical injection (chlorination) by JFE (Table 3 and Figure 6). The mode of operation of the UV BWMS was selected by the ship crew for each test, with four tests conducted using U.S. Coast Guard mode (higher UV dosage) and seven tests conducted using International Maritime Organization (IMO) mode (aligning with Type Approval requirements set by the IMO); the mode was not recorded for one UV BWMS test.

Paired uptake and discharge samples were collected before and ≥ 24 hours after uptake (Table 1). Less than 3,000 L of ballast water was collected for one discharge sample due to insufficient ballast water volume in the tank.

Water Quality Parameters

The temperature of samples ranged from 9.9 to 24.8 °C (Tables 4 and 5). All ballast water samples had a salinity < 1.5 ppt (Tables 4 and 5). Turbidity ranged from 0.6 to 17.9 FNU on uptake and 0.0 to 76.0 FNU on discharge (Tables 4 and 5). Three discharge samples had higher turbidity compared to their paired uptake samples (a difference of > 41 FNU), likely due to sediment resuspension in the ballast tank during ballast discharge operations. The fluorescent dissolved organic matter readings ranged from 0.9 – 12.6 RFU on uptake and 0.4 – 10.5 RFU on discharge (Tables 4 and 5). The ultraviolet transmittance of samples was between 77.0 and 94.6% (Tables 4 and 5).

Two ambient port water samples were collected from Hamilton Harbour and one sample was collected from the Port of Oshawa in Ontario (Table 4). Hamilton Harbour had higher dissolved organic carbon, particulate organic carbon and organism abundances for both size classes than the Port of Oshawa. Relative to the Port of Oshawa, Hamilton Harbour's dissolved organic carbon was nearly twice as high, particulate organic carbon was nearly five times higher and organism abundances were 14 times higher for both size classes (Table 4). Total suspended solids were below the detection limit (5 mg/L) for all ambient port water samples (Table 4).

Flow Rates of Sample Collection Device

The flow rates through the sample collection device were within the target range for 16 out of 25 samples (Table 6). The flow rates for six samples were lower than the target range by 8 to 76 L per minute (Table 6). While not ideal, these six samples collected outside of the target range were considered valid because the risk of damaging cells was thought to be low at lower than target flow rates. Minimum target flow rates could not be calculated for three uptake samples because a sample probe was not installed on the ballast uptake sample port.

Results for the ≥ 50 µm and 10 – 50 µm Organism Size Classes

For the ≥ 50 µm organism size class, two out of the three treated discharge-only samples were below the limit of the D-2 standard (< 10 organisms per m^3), while one sample had an organism concentration two orders of magnitude higher than the limit of the D-2 standard (Figure 7). The uptake concentrations ranged from 2,168 to 107,577 organisms per m^3 for the 11 paired samples (Figure 7). Six of the paired treated discharge samples were below the limit of the D-2 standard, one was close to the limit (12 organisms per m^3) and four were above the limit of the D-2 standard (73 – 803 organisms per m^3; Table 7 and Figure 7). All five tests with exceedances of the D-2 standard had loaded ballast water in Hamilton Harbour. All treated discharge samples had > 99% reduction in organism abundances compared to their paired, untreated uptake sample for the ≥ 50 µm size class.

For the 10 – 50 µm organism size class, the three treated discharge-only samples were below the limit of the D-2 standard (< 10 organisms per mL; Figure 8). For the paired samples, all treated discharge samples were below the limit of the D-2 standard — noting that on uptake, one sample was below the limit of the D-2 standard, while three were close to the limit (7 – 12 organisms per mL) and seven were above the limit of the D-2 standard (20 – 169 organisms per mL; Table 7 and Figure 8). All treated discharge samples had > 98% reduction in organism abundances compared to the paired, untreated uptake sample for the 10 – 50 µm size class.

The results to date do not indicate any trends according to the mode of UV BWMS operation, as exceedances of the D-2 limit were observed equally for samples treated using U.S. Coast Guard and IMO modes.

The results of the Quasi-Poisson generalized linear model indicate that BWMS filter size, ballast age (days) and organism abundance in uptake samples were statistically significant predictors of organism abundance in discharge samples for the ≥ 50 µm size class (work to be presented elsewhere). Ballast age was the only significant predictor for the 10 – 50 µm size class. Turbidity, fluorescent dissolved organic matter, ultraviolet transmittance and BWMS type (ultraviolet or chemical injection) were not significant predictors of organism abundance for both size classes.

Issues Encountered During Sample Collection and Operation of BWMS

The sample team monitored the BWMS control panel during sample collection, when possible (access to the control panel was not always feasible from the sample port location). Any alarms generated by the BWMS during sampling were recorded and investigated to determine the type and cause of the alarm. Alarms recorded during sampling included: 1) total residual oxidant alarm that may indicate potential for environmental impact at the location of discharge; and, 2) low treatment dosage alarm that may indicate insufficient treatment of ballast water being applied. Some issues associated with BWMS operation do not trigger alarms on the control unit.

Two of the ‘failed’ discharge samples are likely explained by insufficient treatment being applied. In one case, after sampling was completed and the results (exceedance of the D-2 limit) were shared with the shipowner, a root-cause analysis determined that the BWMS software was out of date. As a result, the chlorine treatment dosage applied prior to the discharge sampling was lower than that applied using later software versions. The shipowner therefore contacted the vendor to update the software to correct the issue.

In the second case, the sample team noted that the ship crew had lowered the intensity of the UV BWMS during uptake by operating a subset of available UV chambers. This can be a standard practice on some ships to reduce power consumption, although it also lowers the treatment capacity of the BWMS (lowers the maximum ballast flow rate that can be treated). While the average ballast loading rate was within the lowered capacity of the BWMS, the sample team observed fluctuation in the ship’s ballast pumping rate, which was periodically greater than the capacity of the BWMS (as operated by the crew that day), resulting in insufficient ballast water treatment.

Another issue was highlighted during a different test, where the sample team was advised that untreated water from the harbour was mixing with the discharge sample due to an incompletely closed valve. In this case, sampling was restarted after the valve was fully closed and time had passed to flush the ballast lines. Leaky or partially closed valves can cause contamination of samples from an untreated source (particularly on discharge) and may occur without the knowledge of the ship crew or sample team.

Results of Hamilton Harbour Bi-Weekly Monitoring

A total of 18 port water samples were collected from Hamilton Harbour between April and December in 2022. Bi-weekly monitoring of Hamilton Harbour indicated that the abundance of organisms in the ≥ 50 µm size class was at or above the BWMS type approval challenge level (100,000 organisms per m^3; IMO 2018, NSF International 2010) from the end of April to October; during these months, organism abundances ranged from 197,000 to 250,000 individuals per m^3 (Figure 9). Measured organism abundances were below the type approval challenge level for the ≥ 50 µm size class at the beginning of April as well as in November and December (Figure 9).

The measured abundance of organisms in the 10 – 50 µm size class was below the BWMS type approval challenge level (1,000 cells per mL; IMO 2018, NSF International 2010) throughout the period of observation. The abundance of cells was typically < 400 cells per mL, except in April which had up to 930 cells per mL (Figure 9).

The measured dissolved organic carbon level in Hamilton Harbour fluctuated around the IMO's BWMS type approval challenge level of 5 mg/L but was below the U.S. Environmental Protection Agency's challenge level of 6 mg/L throughout the period of observation, ranging from 4.1 to 5.8 mg/L between April to December (Figure 9).

Total suspended solids in Hamilton Harbour were generally < 16 mg/L, which is below the BWMS type approval challenge level set by the IMO (50 mg/L) and U.S. Environmental Protection Agency (24 mg/L; Figure 9). However, total suspended solids surpassed the U.S. Environmental Protection Agency's challenge level during two sampling events in April (30.4 mg/L) and December (29.5 mg/L; Figure 9). For the April occurrence, the sampling team observed turbid, well-mixed water due to strong winds and waves, while for the December occurrence, there was sediment in the water column corresponding to ship movement at a berth next to the sampling location.

Particulate organic carbon measurements from Hamilton Harbour varied throughout the shipping season, ranging from 0.7 to 3.2 mg/L (Figure 9). Particulate organic carbon measurements did not surpass the type approval challenge levels (IMO or U.S. Environmental Protection Agency) during the period of observation.

CONCLUSION

The results presented in this report show that although the limit of the D-2 standard was sometimes exceeded, the abundance of live organisms was reduced by > 98% with the use of BWMS. Therefore, the results indicate that BWMS can substantially reduced the risk of introducing and spreading harmful aquatic species due to the movement of ballast water. During the tests, the BWMS operated in water with relatively high zooplankton abundances, with two uptake samples exceeding the BWMS type approval challenge level for the ≥ 50 µm organism size class. However, there was no test that included water with high turbidity, which may affect the performance of BWMS filtration and UV treatment. Operational issues noted by the team indicate that greater rates of compliance may be achieved as shipowners and crews move beyond the steep learning curve associated with operation and maintenance of these new and complex technologies.

Differences between rated pump capacity, actual pumping rates and observed pumping rates were recorded under differing cargo and sampling conditions such that the influence of BWMS on pumping rates cannot be directly determined.

Based on the bi-weekly monitoring results, Hamilton Harbour may be considered as a port with challenging water conditions for BWMS due to the abundance of ≥ 50 µm organisms during most of the shipping season. Hamilton Harbour can also have periodic episodes of increased dissolved organic carbon and total suspended solids. Water quality conditions may be expected to vary throughout the year due to various factors, including but not limited to: spring runoff, storm events leading to combined sewage overflow events, waves, plankton blooms and anthropogenic disturbances to sediment (Old et al. 2003; Estepp and Reavie 2015; Marcarelli et al. 2019).

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TABLES

Table 1. Dates of sample collection, duration (days) between uptake and discharge events and duration of sample collection. Ships 3 and 4 were sampled on two different trips. Date of uptake is not provided for the three discharge-only samples.

Ship	Date of uptake	Date of discharge	Duration between uptake and discharge (days)	Duration of uptake sampling (minutes)	Duration of discharge sampling (minutes)
Ship 1	--	July 24, 2017	1 day	--	37
Ship 2	--	August 31, 2017	1 day	--	48
Ship 3	May 17, 2019	May 22, 2019	5 days	38	48
Ship 3	May 23, 2019	May 28, 2019	5 days	39	48
Ship 4	June 16, 2019	June 18, 2019	2 days	53	57
Ship 4	--	June 19, 2019	5 days	--	57
Ship 5	September 17, 2019	September 18, 2019	1 day	11	53
Ship 6	September 21, 2019	September 24, 2019	3 days	16	54
Ship 7	October 19, 2019	October 22, 2019	3 days	15	65
Ship 8	June 6, 2022	June 8, 2022	2 days	21	69
Ship 9	July 8, 2022	July 9, 2022	1 day	14	49
Ship 10	August 15, 2022	August 18, 2022	3 days	28	95
Ship 11	August 30, 2022	September 1, 2022	2 days	29	88
Ship 12	October 28, 2022	November 6, 2022	9 days	21	86

Table 2. Characteristics of ships (n = 12) sampled within the Great Lakes and St. Lawrence River region. The ship, fleet, type and length are reported, as well as the number of ballast tanks and holds, ballast sample port location, number of ballast pumps, combined rated pump capacity, expected pumping rate during ballast operations as reported by the ship crew (not reported for ships 2 and 6) and average pumping rate observed during ballast water sampling on uptake and discharge. Ships 3 and 4 were sampled on two different trips. Uptake values were not available for the three discharge-only samples.

Ship	Fleet	Ship type	Ship length (ft)	Number of tanks + holds	Sample port location	Number of ballast pumps	Combined rated pump capacity (m^3/hour)	Expected pumping rate (m^3/hour)	Average observed pumping rate on uptake (m^3/hour)	Average observed pumping rate on discharge (m^3/hour)
Ship 1	Coastal	Tanker	443	17 + 0	Engine room	2	1,000	500*	--	556*
Ship 2	International	Bulker (geared)	656	16 + 1	Engine room	2	1,380	--	--	999
Ship 3	International	Bulker (geared)	656	17 + 1	Engine room	2	1,380	1,000	919; 980	957; 974
Ship 4	Laker	Purpose-build barge	407	9 + 0	Engine room	2	600	600	640; --	456; 368
Ship 5	International	Bulker (geared)	607	22 + 1	Engine room	2	1,200	600	646	755
Ship 6	International	Bulker (geared)	607	22 + 1	Engine room	2	1,200	--	872	896
Ship 7	Coastal	Tanker	443	15 + 0	Pump room	2	1,000	500*	475*	477*
Ship 8	International	Bulker (geared)	656	16 + 1	Engine room	2	1,380	800 – 1,000	320**	364**
Ship 9	International	Bulker (geared)	607	22 + 1	Engine room	2	1,200	500 – 600*	582*	520*
Ship 10	Coastal	Tanker	750	14 + 0	On deck	2	3,000	1,500*	1,209*	1,143*
Ship 11	International	Bulker (geared)	656	17 + 1	Engine room	2	1,380	800 – 900	666	464
Ship 12	Coastal	Tanker	492	15 + 0	Pump room	2	1,000	600	409	506

*Pumping rates based on one ballast pump, as required for cargo operations at the time or to facilitate ballast water sample collection.
**Ballast pumping rate intentionally reduced in order to collect a representative sample over a longer duration of time.

Table 3. Ballast water management systems used by ships (n = 12) sampled within the Great Lakes and St. Lawrence River region. Flow variant is the maximum flow rate for each variant of ballast water management system based on type approval by the United States (U.S.) Coast Guard. The flow variant of Alfa Laval systems were unknown, therefore, the range of flow variants are shown.

Manufacturer	Model	U.S. Coast Guard type approval certificate number	Treatment type	Flow variant (m^3/hour)	Number of ships
Alfa Laval	Pureballast 3.0	162.060/2/4	Ultraviolet	85 – 3,000	1
Alfa Laval	Pureballast 3.1	162.060/2/4	Ultraviolet	85 – 3,000	5
Alfa Laval	Pureballast 3.2 EX	162.060/19/3	Ultraviolet	85 – 3,000	1
BioUV	Bio-Sea B06-0750	162.060/9/2	Ultraviolet	750	1
JFE	BallastAce 1380	162.060/13/3	Chemical injection	1,380	1
JFE	BallastAce 1500	162.060/13/3	Chemical injection	1,500	1
Optimarin	BWTS 1000/1400 BK2	162.060/1/4	Ultraviolet	1,000 (uptake) 1,400 (discharge)	2

Table 4. Water quality parameters measured for each source port based on ballast water collected during uptake on ships (n = 11) and ambient port water collected at the same time as uptake sampling (n = 3). Water quality parameters measured from ballast water include temperature (temp), salinity (sal), turbidity (turb), fluorescent dissolved organic matter (fDOM) and ultraviolet transmittance (UVT). Water quality parameters measured from ambient port water include dissolved organic carbon (DOC), particulate organic carbon (POC), total suspended solids (TSS), organism counts for both the ≥ 50 µm (organisms/m³) and 10 – 50 µm (cells/mL) size classes and confidence intervals (CI) for the organism counts. The minimum detection limit for total suspended solids is 5.0 mg/L. Hamilton, ON, was a source port for sampled ballast water four times.

	Ballast water					Ambient port water								
Port	Temp (°C)	Sal (ppt)	Turb (FNU)	fDOM (RFU)	UVT (%)	DOC (mg/L)	POC (mg/L)	TSS (mg/L)	≥ 50 µm count (org./m³)	≥ 50 µm lower CI (org./m³)	≥ 50 µm upper CI (org./m³)	10 – 50 µm count (cells/mL)	10 – 50 µm lower CI (cells/mL)	10 – 50 µm upper CI (cells/mL)
Calumet River, IL	15.1	0.24	3.5	1.9	92.4	--	--	--	--	--	--	--	--	--
Hamilton, ON	11.5	0.36	3.1	12.6	77.4	--	--	--	--	--	--	--	--	--
Hamilton, ON	20.6	0.26	4.2	5.4	86.1	--	--	--	--	--	--	--	--	--
Hamilton, ON	16.1	0.35	2.2	9.1	85.7	5.3	1.1	< 5.0	363,158	336,863	391,031	148	129	170
Hamilton, ON	21.4	0.28	2.2	5.8	86.8	4.4	1.8	< 5.0	214,857	198,985	231,703	245	220	272
Levis, QC	24.8	0.12	5.3	7.6	77.4	--	--	--	--	--	--	--	--	--
Oakville, ON	13.9	0.14	0.6	0.9	93.9	--	--	--	--	--	--	--	--	--
Oshawa, ON	18.1	0.15	2.3	1.2	87.2	2.7	0.3	< 5.0	19,572	17,824	21,452	14	8	22
Sorel-Tracy, QC	11.9	0.14	2.2	2.3	91.1	--	--	--	--	--	--	--	--	--
Toronto, ON	17.8	0.17	1.7	3.7	90.6	--	--	--	--	--	--	--	--	--
Valleyfield, QC	14.7	0.14	17.9	1.5	89.8	--	--	--	--	--	--	--	--	--

Table 5. Water quality parameters of ballast water samples collected during discharge on ships, including temperature (°C), salinity (ppt), turbidity (FNU), fluorescent dissolved organic matter (fDOM) and ultraviolet transmittance (UVT).

Discharge sample	Temperature (°C)	Salinity (ppt)	Turbidity (FNU)	fDOM (RFU)	UVT (%)
Discharge sample 1	23.6	0.45	0.0	2.8	83.6
Discharge sample 2	20.4	0.84	4.1	2.6	83.5
Discharge sample 3	10.5	0.46	7.4	10.5	77.0
Discharge sample 4	9.9	0.37	2.3	1.8	93.8
Discharge sample 5	14.8	0.14	59.7	1.8	89.7
Discharge sample 6	16.8	0.15	7.5	0.4	94.6
Discharge sample 7	18.6	0.23	9.2	2.1	91.4
Discharge sample 8	23.0	0.42	76.0	2.9	87.7
Discharge sample 9	14.1	0.53	2.5	1.1	94.2
Discharge sample 10	17.1	0.66	50.5	2.3	90.7
Discharge sample 11	19.2	0.30	0.4	1.0	93.0
Discharge sample 12	23.4	0.54	1.8	8.5	79.7
Discharge sample 13	22.4	1.49	1.0	6.0	87.6
Discharge sample 14	14.8	0.67	2.9	2.7	92.0

Table 6. Actual and target flow rates for the large volume sampling device. Minimum target flow rates could not be calculated for three uptake samples because a sample probe was not installed on the ballast uptake sample port. Ships 3 and 4 were sampled on two different trips.

Ship	Ballast operation	Average flow rate	Minimum target flow rate	Maximum target flow rate	Within range of target flow rate
Ship 1	Discharge	90	98	391	No
Ship 2	Discharge	63	28	111	Yes
Ship 3	Uptake	100	--	60	--
Ship 3	Discharge	63	16	62	Yes
Ship 3	Uptake	76	--	64	--
Ship 3	Discharge	63	16	65	Yes
Ship 4	Uptake	60	65	260	Yes
Ship 4	Discharge	54	45	183	Yes
Ship 4	Discharge	55	39	157	Yes
Ship 5	Uptake	100	42	170	Yes
Ship 5	Discharge	58	40	162	Yes
Ship 6	Uptake	63	44	175	Yes
Ship 6	Discharge	59	46	190	Yes
Ship 7	Uptake	70	124	495	No
Ship 7	Discharge	48	124	495	No
Ship 8	Uptake	40	12	48	Yes
Ship 8	Discharge	51	14	56	Yes
Ship 9	Uptake	81	52	206	Yes
Ship 9	Discharge	61	92	367	No
Ship 10	Uptake	36	--	38	--
Ship 10	Discharge	34	47	255	No
Ship 11	Uptake	35	11	45	Yes
Ship 11	Discharge	31	8	31	Yes
Ship 12	Uptake	53	35	142	Yes
Ship 12	Discharge	30	44	177	No

Table 7. Results for the paired uptake and discharge samples for both organism size classes (≥ 50 µm and 10 – 50 µm). 'Pass' indicates samples that had organism abundances below the limit of the D-2 standard, 'fail' indicates samples that were above the limit of the D-2 standard, and 'close to the limit' indicates samples where the 90% confidence intervals of the count span above and below the D-2 standard.

		≥ 50 µm organism size class			10 – 50 µm organism size class		
		Uptake			Uptake		
Ballast operation	Result	Pass	Fail	Close to limit	Pass	Fail	Close to limit
Discharge	Pass	0	6	0	1	7	3
	Fail	0	4	0	0	0	0
	Close to limit	0	1	0	0	0	0

FIGURES

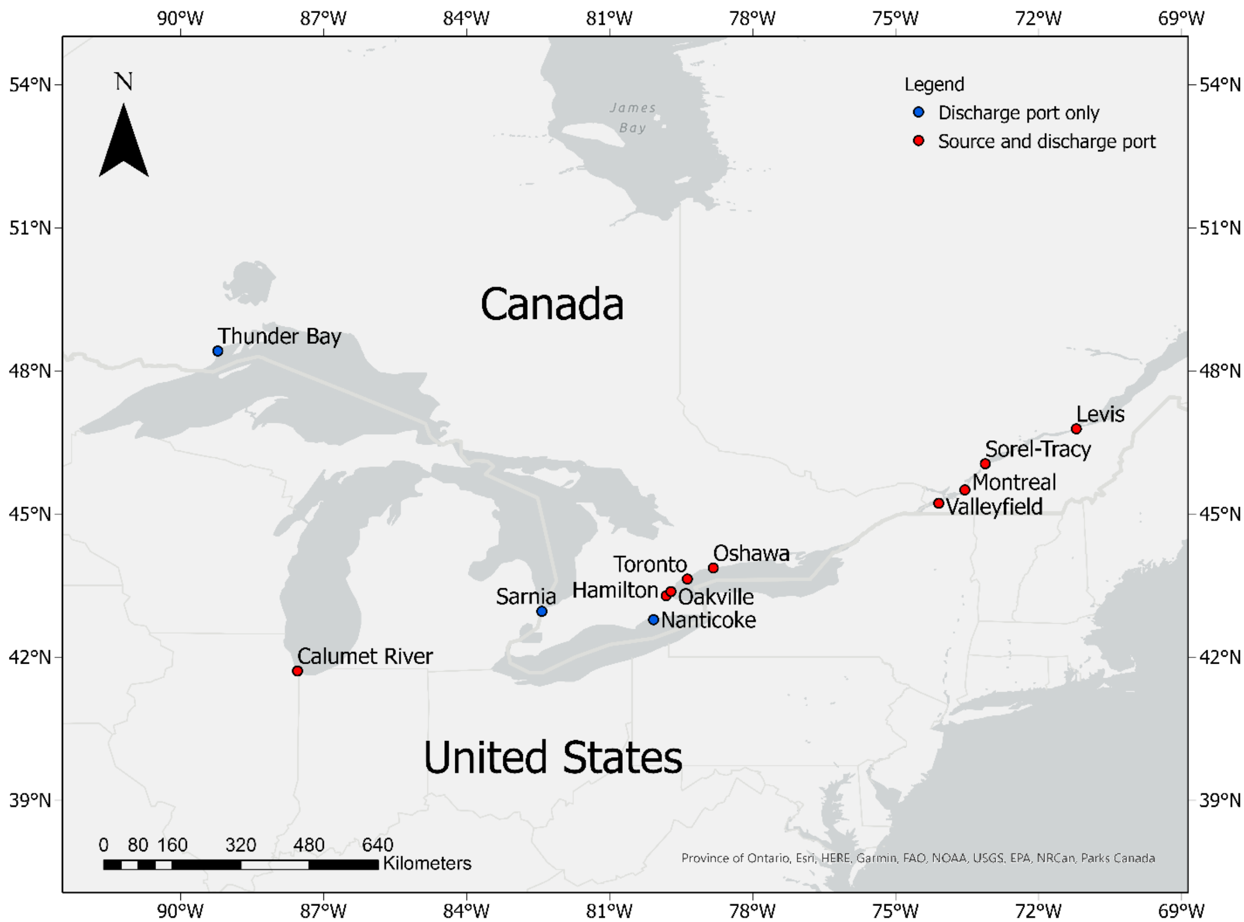

Figure 1. Ballast water source and discharge ports in the Great Lakes and St. Lawrence River region included in this report. Discharge ports were ports where ballast water discharge samples were collected, while source and discharge ports were ports where ballast water was also loaded on ships.

Figure 2. Ballast water sampling team boarding a ship (left) and sampling ballast water in a ship's engine room (right).

Figure 3. Collecting ballast water samples for the ≥ 50 µm (left) and 10 – 50 µm (right) organism size classes using the sample collection device, and a plankton net submerged in ambient ballast water in a plastic bin (center).

Figure 4. Preparing and analyzing samples for the ≥ 50 µm organism size class by splitting the sample for analysis by microscopy (left), transferring aliquots of the sample to a Modified Bogorov counting chamber (center), and counting organisms under a microscope.

Figure 5. Analyzing samples for the 10 – 50 µm organism size class (left) by counting six 1 mL subsamples on a Sedgewick-Rafter counting chamber under a microscope (right).

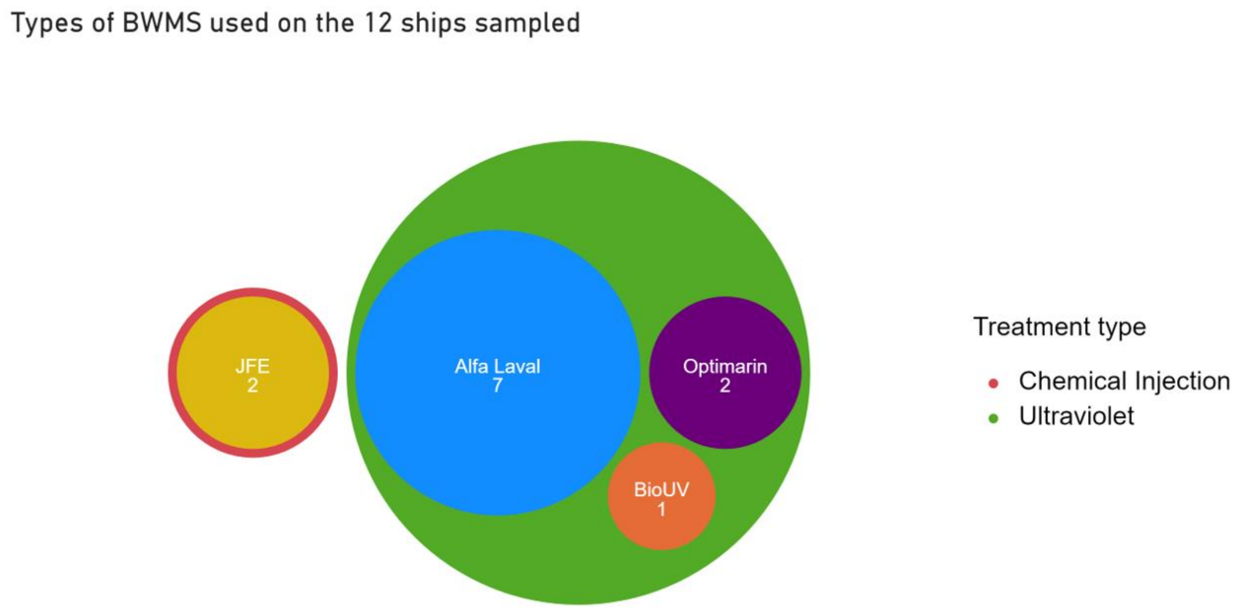

Figure 6. The types of ballast water management systems (BWMS) used on ships (n = 12) sampled in the Great Lakes and St. Lawrence River region, by BWMS manufacturer and treatment type. The values show the number of ships using each BWMS.

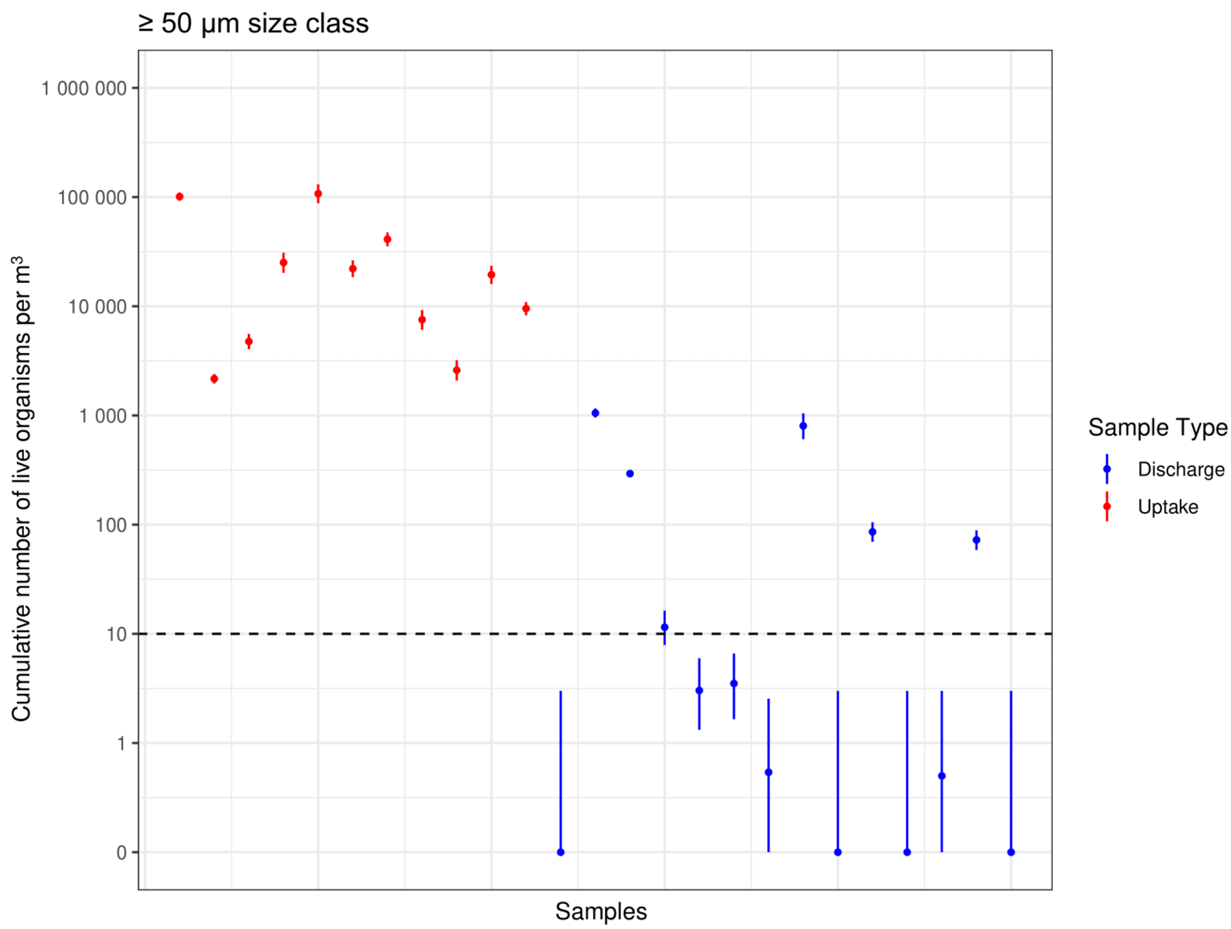

Figure 7. Cumulative number of live organisms per m³ in ballast water uptake (n = 11) and discharge (n = 14) samples for the ≥ 50 µm size class. Samples were collected from ships in the Great Lakes and St. Lawrence River region. The error bars represent 90% confidence intervals that were calculated based on a Poisson distribution. The y-axis is on a logarithmic scale. The markers represent the cumulative sample counts.

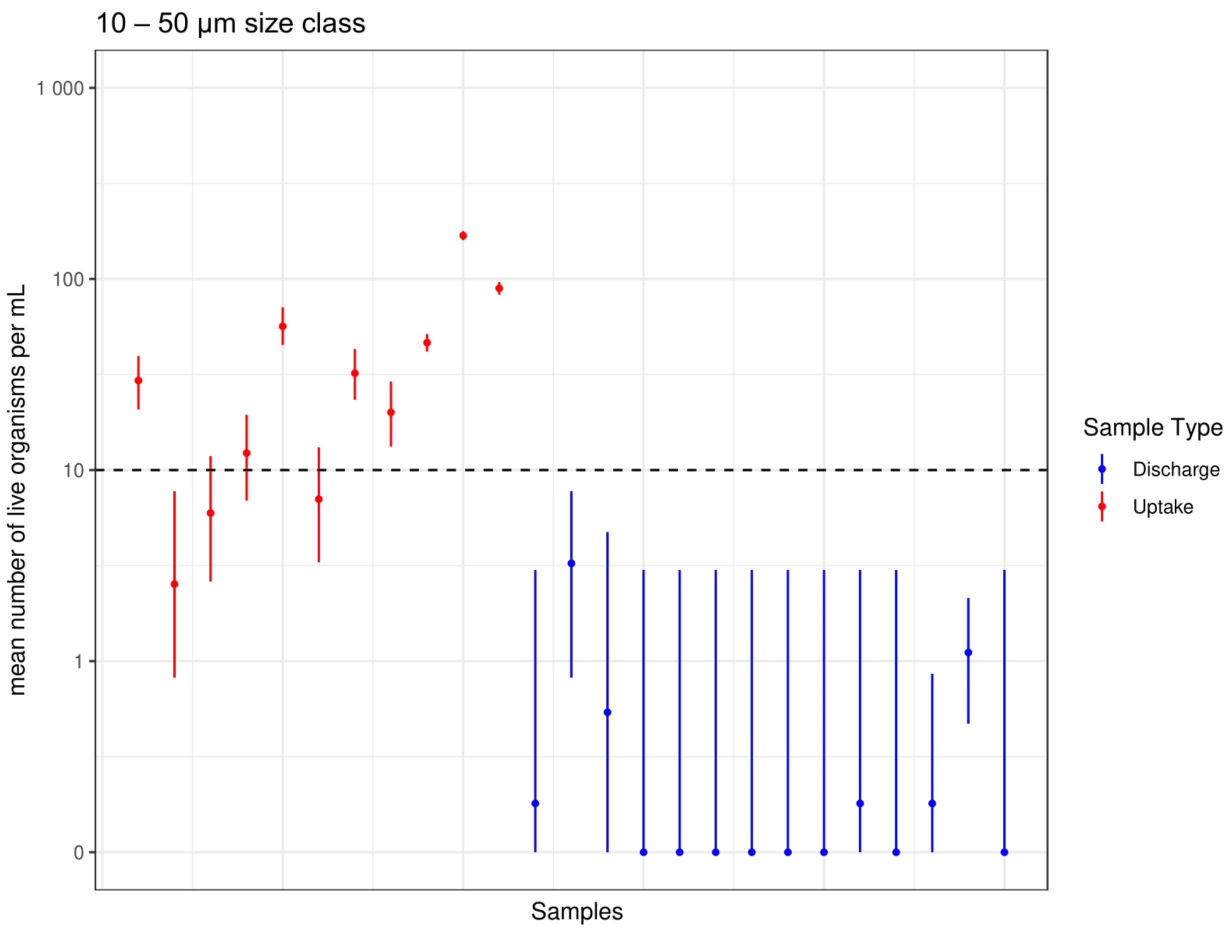

Figure 8. Mean number of live organisms per mL in ballast water uptake (n = 11) and discharge (n = 14) samples for the 10 – 50 µm size class. Samples were collected from ships in the Great Lakes and St. Lawrence River region. The error bars represent 90% confidence intervals that were calculated based on a Poisson distribution. The y-axis is on a logarithmic scale. The markers represent the mean sample counts.

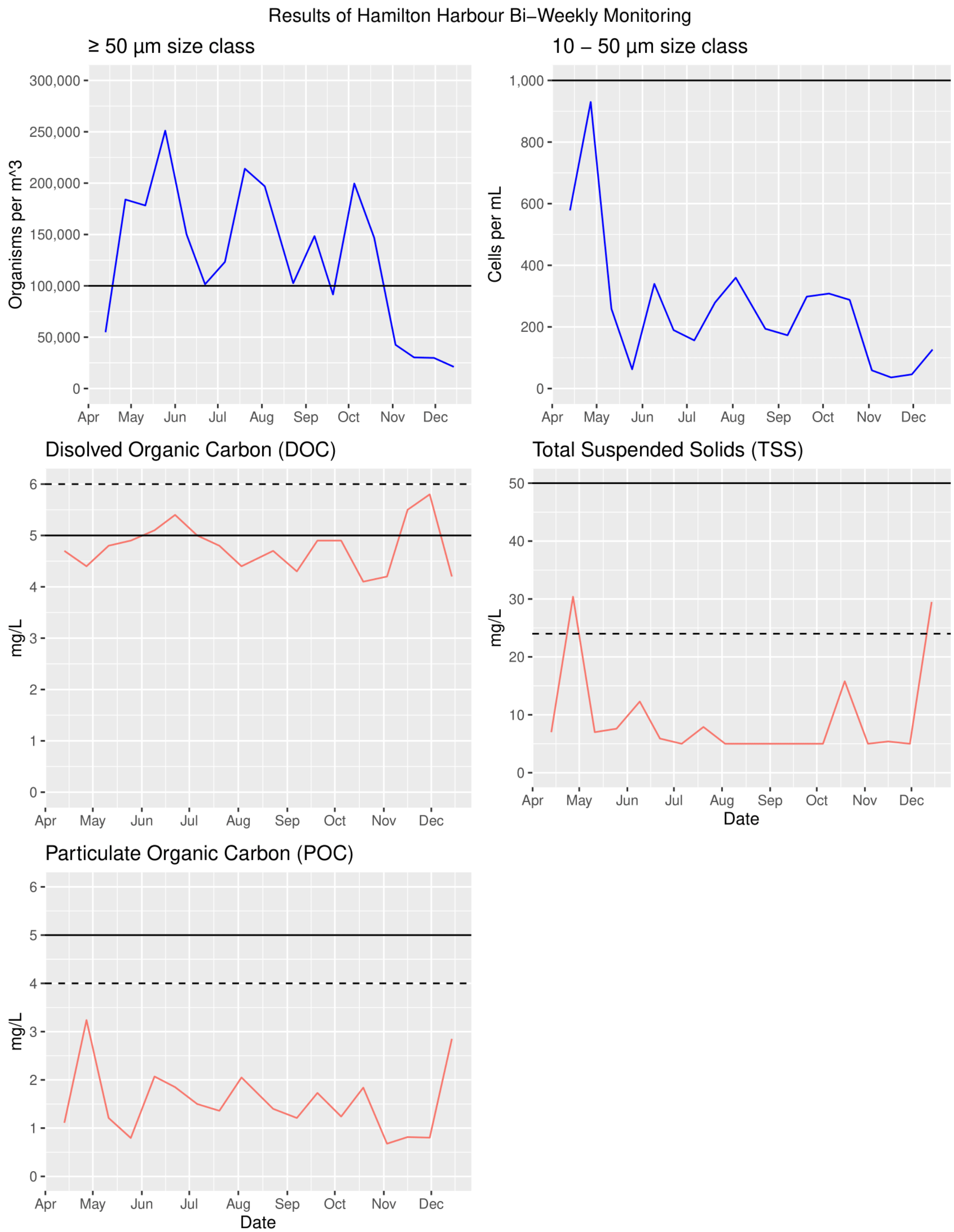

Figure 9. Results of bi-weekly monitoring in Hamilton Harbour from April to December in 2022. The minimum detection limit for total suspended solids is 5.0 mg/L. The dashed black lines show the minimum type approval challenge levels set by the United States Environmental Protection Agency (NSF International 2010), while the solid black solid lines show the type approval challenge levels set by the International Maritime Organization (IMO 2018). The challenge levels for the ≥ 50 µm and 10 – 50 µm organism size classes are identical for both organizations.