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RESEARCH ARTICLE

Managing risk of non-indigenous species establishment associated with ballast water discharges from ships with bypassed or inoperable ballast water management systems

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Abstract

1. Ballast water is recognized as a leading pathway for the introduction of aquatic non-indigenous species which have caused substantial ecological damage globally.
2. Following international regulations, most international ships will install a ballast water management system (BWMS) by 2024 to limit the concentration of aquatic organisms in ballast water discharges; however, these new technologies may not operate as expected at global ports having variable water quality or may periodically malfunction.
3. Using simulations informed by empirical data, we investigated the risk of non-indigenous species establishment associated with BWMS inoperability and evaluated potential mitigation strategies. Scenarios considered included bypassed or inoperable BWMS achieving no reduction in organisms, and partially functioning BWMS with discharged organism concentrations exceeding permissible limits. These scenarios were contrasted to outcomes with fully functioning BWMS and to voyages where ballast water exchange (BWE) was used to mitigate risk.
4. Partially functioning BWMSs were nonetheless beneficial, reducing organism concentrations in ballast and thus establishment risk. When a BWMS is bypassed or partially functioning, BWE is a useful emergency mitigation measure, reducing establishment risks more than partial BMWS. However, the greatest risk reduction was achieved when partial BWMS and BWE were combined.
5. Voyage-specific characteristics such as concentration of organisms at uptake and destination port salinity can affect the optimal management strategy for voyages when the BWMS does not achieve compliant discharges.
6. *Synthesis and applications*. The risk of aquatic invasions and their associated ecological damages can be substantially reduced by using a ballast water management system (BWMS) and/or ballast water exchange (BWE). When a BWMS is inoperable, appropriate mitigation measures should be decided on a trip-by-trip basis considering voyage route and reason for BWMS inoperability (when

known). BWE is a useful strategy for reducing invasion risk, except when uptake concentrations are very low. Combining BWE and partial BWMS always reduced risk compared with BWE alone, but did not greatly reduce risk when uptake concentrations were high.

KEYWORDS
ballast water, D-2 standard, establishment risk, invasive, non-native, plankton, propagule pressure, shipping

1 | INTRODUCTION

Non-indigenous species (NIS) are a leading cause of biodiversity loss (Duenas et al., 2018), especially in aquatic ecosystems (Clavero & García-Berthou, 2005). NIS directly affect native species through predation (Albins & Hixon, 2013; Jänes et al., 2015; Pratchett et al., 2017), competitive displacement (Katsanevakis et al., 2014; Pyšek et al., 2017), parasitism (Costello et al., 2021; Dunn et al., 2012; Goedknegt et al., 2016) and complex ecosystem alterations (David et al., 2017; Kelly et al., 2010; Kotta et al., 2018; Zeug et al., 2014).

Ship-mediated transport is the main vector for aquatic NIS establishments (Bailey et al., 2020). Globally, ~3.1 billion tonnes of ballast water is discharged per year (David et al., 2015), contributing substantial ecological risk that was formally recognized on a global scale by the International Maritime Organization's (IMO) Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004 – globally ratified in 2017 and fully implemented by 2024 – that requires ships to limit the concentration of viable organisms in their ballast water discharges (IMO, 2004). Specifically, Regulation D-2 outlines the Ballast Water Performance Standard, requiring that ships discharge: (i) <10 viable organisms m^{-3} that are ≥50 μm in minimum dimension (typically zooplankton) and (ii) <10 viable organisms ml^{-1} that are ≥10 μm and <50 μm in minimum dimension (typically phytoplankton), in addition to numerical limits for three specific indicator microbes. The D-2 standards are intended to reduce community propagule pressure, which is the collective number of individuals introduced to a new location. Previous research has substantiated a strong link between species-based propagule pressure and establishment risk (Cassey et al., 2018; Lockwood et al., 2005; Stringham & Lockwood, 2021), with higher propagule pressure expected to help overcome demographic constraints (Lockwood et al., 2005) and increase genetic diversity in the new population (Roman & Darling, 2007). Untreated ballast water can contain organism concentrations up to four orders of magnitude higher than those allowable by D-2 standards (Briski et al., 2010; Briski, Drake, et al., 2014; Cabrini et al., 2019; DiBacco et al., 2012; Lawrence & Cordell, 2010; Paolucci et al., 2015), so the Convention is expected to mitigate risk associated with the introduction of NIS by this dominant transport pathway.

Prior to the implementation of the D-2 standards, ballast water exchange (BWE) was the predominant mechanism by which vessels sought to manage ballast water, by exchanging coastal-source ballast water with oceanic water having fewer NIS. Regulation D-2 will most often be achieved using a ballast water management system (BWMS). BWMSs generally pair a preliminary treatment consisting of a filter or hydrocyclone separator (Lakshmi et al., 2021) with a secondary treatment using either an inactive (e.g. UV, deoxygenation) or active (e.g. electrolysis, oxidation, ozonation) substance (Gerhard et al., 2019). Preliminary treatment reduces the abundance of organisms introduced into the ballast tank, thereby enhancing the efficacy of secondary treatment (Lakshmi et al., 2021; Sayinli et al., 2021). Filtration efficiency is affected by several variables, including salinity, temperature, and turbidity (Waite et al., 2003). Filters can clog if high concentrations of suspended solids are present during ballasting, reducing flow rates for ballast uptake owing to frequent backflushing by the BWMS; this may ultimately lead to complete shut-down of ballasting operations, with significant implications for cargo operations (Jang et al., 2020). Filter system efficacy can also be undermined by organic components, such as gelatinous phytoplankton or zooplankton that can rapidly clog filters (Briski, Linley, et al., 2014; Veldhuis et al., 2006).

High concentrations of suspended solids can also hinder secondary treatment by reducing UV transmittance and oxidation potential affecting UV and electrolysis systems, respectively (MEP, 2016). This is concerning because most IMO-approved BWMSs use UV ($n = 30$ systems) or electrolysis ($n = 15$ systems) technology (Gerhard et al., 2019; Jang et al., 2020; Lakshmi et al., 2021; Sayinli et al., 2021; Vorkapić et al., 2018). Remote sensors measuring BWMS functionality are being developed to proactively inform stakeholders of BWMS issues such that actions can be taken to prevent discharges of non-compliant ballast water (Bakalar et al., 2012; Bakalar et al., 2017). Signatories to the Convention (89 countries representing ~91.2% of the world's gross tonnage as of May 2022, IMO, 2022) should plan for foreseeable implementation issues, such as the potential for a ship to arrive with non-compliant ballast water due to total or partial BWMS inoperability.

This study estimates risk from transits where BWMS do not achieve D-2 standards and evaluates strategies that can be employed before arrival to mitigate risk. We explore two scenarios of non-compliance: (i) the BWMS was bypassed or inoperable and no reduction in organisms was achieved or (ii) the BWMS was partially functioning but did not achieve discharge standards due to insufficient treatment and/or very high uptake concentrations. For each scenario, we forecasted the expected NIS establishment risk for a given trip with failed treatment and compared it with the risk for the same trip if discharge standards were met and when BWE was undertaken to mitigate risk. Since port state control may handle BWMS inoperability on a case-by-case basis, we also explored how transit-specific characteristics (i.e. high vs. low uptake organism concentration, destination port salinity) influence risk to inform decision-making.

2 | MATERIALS AND METHODS

We conducted agent-based simulations using R (R Core Team, 2021) to compare species establishments under six scenarios, including (i) functioning BWMS (discharge compliant with D-2 standards); (ii) partially functioning BWMS (reducing organism concentrations, but discharge non-compliant with D-2 standards, hereafter 'partial BWMS') and (iii) bypassed or inoperable BWMS (no organism reduction, discharge non-compliant with D-2 standards, hereafter 'bypassed BWMS'). We also modelled the addition of BWE in each of these scenarios: (iv) functioning BWMS + BWE, (v) partial BWMS + BWE and (vi) bypassed BWMS + BWE (Figure 1).

Owing to availability, we used Canadian ballast water data to parameterize our model (detailed below). While organism concentrations and establishment rates reported herein are directly applicable to Canada, we generalize our models such that the relative risks for each management strategy are expected to apply globally.

2.1 | Simulating transit and ballast data

Transit and ballast data were simulated following Bradie et al. (2020). Briefly, we generated 2,000,000 voyages using empirical data to select source port, destination port and ballast volume (Etemad et al., 2022). For each size class (i.e. zooplankton and phytoplankton), the overall concentration of organisms in ballast, concentration of harmful organisms in ballast, and their species' abundance distributions were simulated for each transit. Herein, 'harmful' propagules include zooplankton NIS and harmful phytoplankton (e.g. species toxic to humans) only, and no attempt was made to assess risk for indicator microbes. Full details for simulations are provided in Supporting Information (see Appendix S1).

2.2 | Ballast water management

Organism discharge concentrations were dependent on management scenario. A fully functioning BWMS was assumed to discharge <10 live (viable) individuals m^{-3} and ml^{-1} for zooplankton and phytoplankton, respectively, with actual concentrations estimated from successful treatment applications observed in field studies [Poisson distributions with mean 1.81 live zooplankton organisms m^{-3} (Bailey et al., 2022) and 1.38 live phytoplankton cells ml^{-1} (Casas-Monroy & Bailey, 2021)]. Partial BWMS concentrations were calculated by applying a 95% reduction to modelled uptake concentrations, matching reductions observed in limited field data (see '*Model sensitivity*') while not being so effective that most voyages became compliant. When this reduction caused the ballast discharge to become D-2-compliant, concentrations were set to 10 individuals m^{-3} or ml^{-1} for zooplankton and phytoplankton, respectively. Concentrations after BWMS bypass were assumed unchanged from uptake concentrations.

BWE was simulated by generating a new ballast concentration, a BWE location (based on mid-points of exchange for ships arriving to Canada), and a BWE method (empty-refill or flow-through,

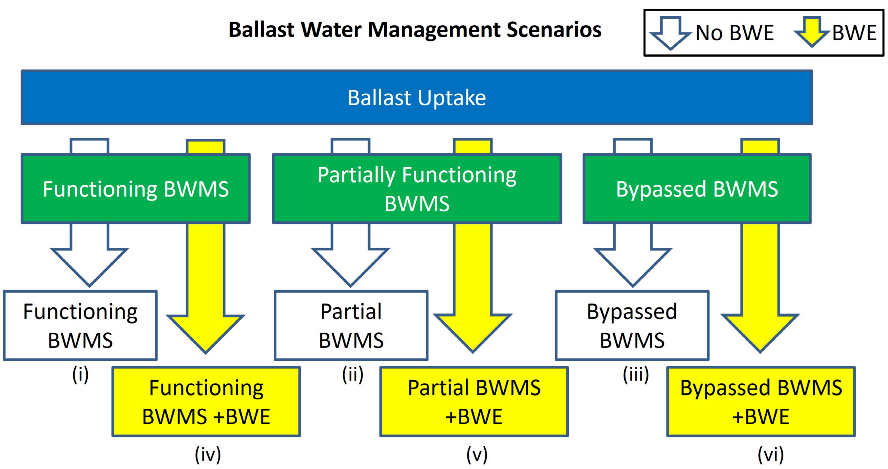

FIGURE 1 Ballast water management scenarios. Species establishments were predicted under six ballast water management scenarios. Modelled uptake concentrations (blue rectangle) were passed through a BWMS (green rectangles) that was either (i) functioning (discharge compliant with D-2 standards), (ii) partially functioning (modelled as 95% reduction of organisms achieved, but discharge is non-compliant with D-2 standards) or (iii) bypassed or inoperable (no organism reduction, discharge noncompliant with D-2 standards). The addition of BWE was also modelled (yellow arrows): (iv) functioning BWMS + BWE; or as an emergency measure for ships with unsuccessful treatment: (v) partial BWMS + BWE and (vi) bypassed BWMS + BWE.

based on prevalence in 2018 data from Etemad et al., 2022). Thus, organism concentrations in ballast changed during BWE, but were not assumed to increase or decrease. This is consistent with evidence showing similar propagule concentrations with and without BWE (Chan, MacIsaac, & Bailey, 2015), inconsistent direction of change when differences are observed (Gray et al., 2007; Simard et al., 2011; Wonham et al., 2001) and high variability between voyages, especially in marine systems (Ruiz & Smith, 2005). Instead, the main modelled effect of BWE was to replace a portion of the ballast assemblage with a mid-ocean community dependent on efficacy of the BWE method used (97.9% for empty-refill exchange, 70.1% for flow through exchange (Ruiz & Smith, 2005)), which may alter survival and establishment probabilities for species resident in tanks.

2.3 | Organisms surviving release after discharge

The initial survival of released propagules was determined based on environmental distance from ballast source and/or exchange location to the discharge environment. Port environmental data were sourced from Keller et al. (2011), Locarnini et al. (2019), Zweng et al. (2019) and Bradie et al. (2020). Environmental distance was calculated as the Euclidean distance between standardized temperature variables (mean annual surface water temperature, mean surface water temperature in warmest month, mean surface water temperature in coldest month) for relevant locations. Using the relationship between environmental distance and survival probability for aquatic species published by Bradie et al. (2020), we calculated survival probability for each species depending on its source (i.e. uptake port or exchange location) and used a Bernoulli trial to determine survival.

2.4 | Estimating establishment

Species establishment probabilities (1 – probability of extinction) were estimated using the following equation adapted from Leung et al. (2004):

$$P_e = 1 - e^{-\alpha N^c},$$

where P_e is the probability of establishment, α is a shape coefficient equal to $-\ln(1-p)$, p is the probability that a single propagule will establish, N is discharge abundance, and c is a shape parameter to accommodate an Allee effect (where $c > 1$). The α parameter captures innate species characteristics that influence a species' establishment likelihood. There exists no accepted standard for α values, partly because the values are invariably linked to model assumptions and data sources. For example, previous studies have estimated p values for aquatic species ranging from 1.5×10^{-2} (Gertzen et al., 2011) to 7.0×10^{-4} (Bradie et al., 2013); the former derived from a highly invasive zooplankton in controlled mesocosms where healthy individuals with appropriate sex ratios were released into a hospitable environment, with the latter based on aquarium fishes with propagule loads estimated from national imports when only a fraction of individuals would be released live into suitable environments. Thus, it is good practice to ground-truth modelled establishment rates based on past establishment data to ensure appropriate α distributions were used for a given model. Our α value analysis and ground truthing (see Appendix S2) supported use of α values drawn from a beta distribution with shape parameters $\alpha = 5.0 \times 10^{-5}$, and $\beta = 5$ herein. α parameters were adjusted based on the salinity match between source and recipient region to account for physiological limitations wherein most species would experience highest establishment probability when recipient port salinity matched that in their native region (Kinne, 1971). Following Bradie et al. (2020), when the salinity difference between source and recipient environment was either marine-brackish or brackish-freshwater (or vice versa), the α value was halved. When the salinity difference was marine-freshwater (or vice versa), the α value was decreased 10-fold. Salinity could have instead been included in environmental distance, but we expect that it biologically acts as a categorical variable, since salinity differences are most important when transitioning between salinity categories (e.g. marine to freshwater).

Discharge abundances, N, were calculated by multiplying modelled ballast water concentrations by discharge volume. We assumed no Allee effect ($c = 1$), following Bradie et al. (2013) that showed $c = 1$ to be reasonable when modelling a heterogeneous group of species. Based on the establishment probability, a binary outcome of establishment (1) or extinction (0) was determined for each surviving species using a Bernoulli trial. The average probability of establishment under a given management scenario was determined by dividing the total number of transits where an establishment was expected by the total simulated transits.

2.5 | Model sensitivity

We examined the sensitivity of the model to chosen parameters and methodological assumptions. We evaluated increased and decreased percent reductions for partial BWMS at 99.5% and 90% (99.5% based on observed reduction in empirical zooplankton data from three before-after tests of BWMS with non-compliant outcomes; Bailey S. unpubl. data). Alternatively, we modelled partial BWMS discharge concentrations to match concentrations from limited non-compliance data, measured in field studies (zooplankton only, $n = 22$ trials between 2017–2019; Bailey et al., 2022). Alternative α distributions with higher per capita establishment probabilities were also evaluated (beta distributions with shape parameters $\alpha = 0.0005$ and $\beta = 5$, and $\alpha = 0.0001$ and $\beta = 5$). Finally, we examined the sensitivity of our assumed salinity effect by increasing or decreasing its magnitude (0.75x, 2x, 5x).

2.6 | Analysis

We present results using four metrics: (i) total concentration of individuals discharged; (ii) concentration of harmful individuals discharged; (iii) concentration of harmful individuals expected to survive introduction and (iv) probability of establishment for a single transit. Metrics (i) and (ii) inform on propagule pressure only, metric (iii) captures propagule pressure and environmental suitability and metric (iv) also includes species' innate establishment risk (captured by α parameter; see Bradie & Leung, 2015). The D-2 discharge standards regulate metric (i), but metric (iv) shows establishment risk, which is necessary to evaluate the benefits of the modelled mitigation measures. We estimated 95% bootstrapped confidence intervals by re-calculating metrics after resampling with replacement 1000 times. We present mean and median values; median values reflect 'typical' voyage concentrations, whereas mean values are influenced by rare voyages with very high propagule loads. 'Concentration' is used for organism concentrations in individuals m^{-3} for zooplankton or individuals ml^{-1} for phytoplankton, whereas 'abundance' is used for total discharges (i.e. concentration multiplied by discharge volume).

Analyses considered results by salinity (marine vs. freshwater arrivals), size class (i.e. zooplankton and phytoplankton), and ballast uptake concentration, with 'high concentrations' and 'low concentrations' defined as trips with uptake concentrations in the top or bottom 10 percentile for that pathway. Since BWMS inoperability is expected to be associated with events where uptake concentrations are high or low (the latter due to association with high suspended solids; Bilotta & Brazier, 2008), we considered it important to examine risk at these ends of the spectrum. Differences in establishment rates between treatments were analysed using binomial repeated measures mixed models, with post hoc pairwise Tukey contrasts.

3 | RESULTS

Discharge concentrations, surviving concentrations, and establishment probabilities were highest when the BWMS was bypassed (Figures 2–4). The increased establishment risk caused by bypassing the BWMS was mitigated by conducting BWE to reduce survival and/or establishment or by using partial BWMS to reduce organism concentrations (Figures 2–5). Combining BWE and partial BWMS provided the greatest risk reduction, whereas BWE alone provided a better outcome than partial BWMS alone in nearly all scenarios, except when zooplankton uptake concentrations were low (Figures 4 and 5). On average, establishment rates were reduced 1.9x and 2.0x with the addition of BWE for zooplankton and phytoplankton, respectively, whereas lower reductions (1.4x and 1.1x, respectively) were observed for partial BWMS (Table 1). When both BWE and partial BWMS were used, expected establishment rates were reduced 2.7x and 2.3x for zooplankton and phytoplankton compared with bypassed BWMS alone (Table 1). The marginal benefit of combining BWE and partial BWMS (compared with BWE only) varied with ballast uptake concentration and transit pathway (Figure 5). Efficacy

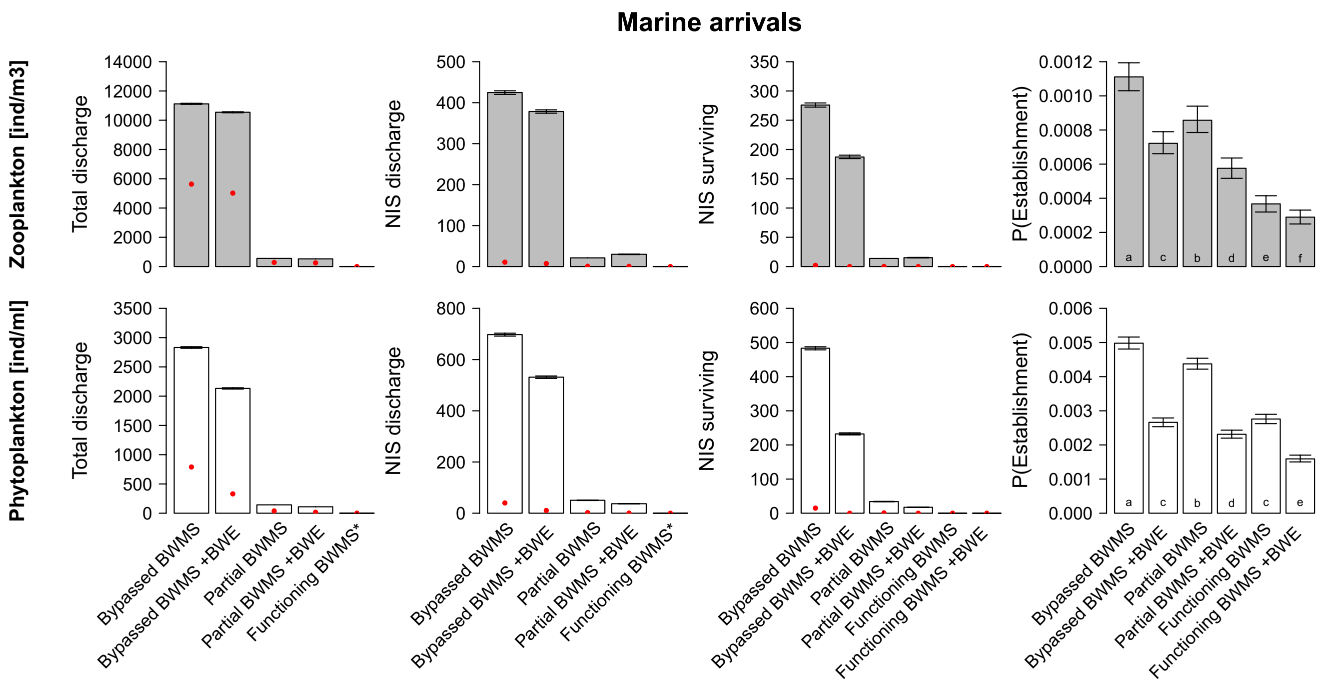

FIGURE 2 Mean (bars) and median (red dots) total discharge concentration, NIS discharge concentration, concentration of NIS surviving release at the destination port, and probability that at least one NIS establishment will occur with a single voyage to marine ports. Grey and white bars show zooplankton and phytoplankton data, respectively. Bars are labelled with mean (black) and median (red) values in individuals m^{-3} and error bars show ±95% CI for the mean. Ballast water management scenarios include bypassed BWMS, bypassed BWMS + BWE, partial BWMS, partial BWMS + BWE, functioning BWMS, and functioning BWMS + BWE. Functioning BWMS* indicates same result for functioning BWMS and functioning BWMS + BWE. Letters on bars indicate significant differences between treatments; bars with the same letter are not significantly different.

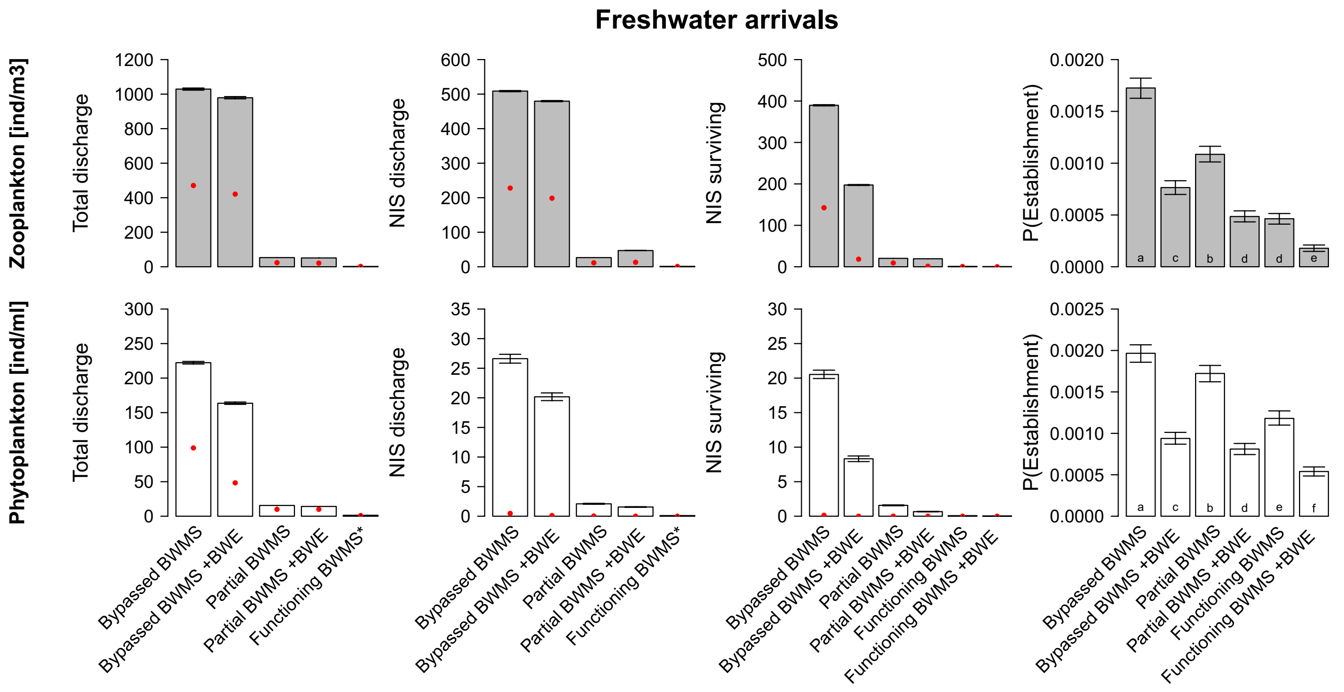

FIGURE 3 Mean (bars) and median (red dots) total discharge concentration, NIS discharge concentration, concentration of NIS surviving release at the destination port, and probability that at least one NIS establishment will occur with a single voyage to freshwater ports. Grey and white bars show zooplankton and phytoplankton data, respectively. Bars are labelled with mean (black) and median (red) values in individuals m^{-3} and error bars show ±95% CI for the mean. Ballast water management scenarios include bypassed BWMS, bypassed BWMS + BWE, partial BWMS, partial BWMS + BWE, functioning BWMS, and functioning BWMS + BWE. Functioning BWMS* indicates same result for functioning BWMS and functioning BWMS + BWE. Letters on bars indicate significant differences between treatments; bars with the same letter are not significantly different.

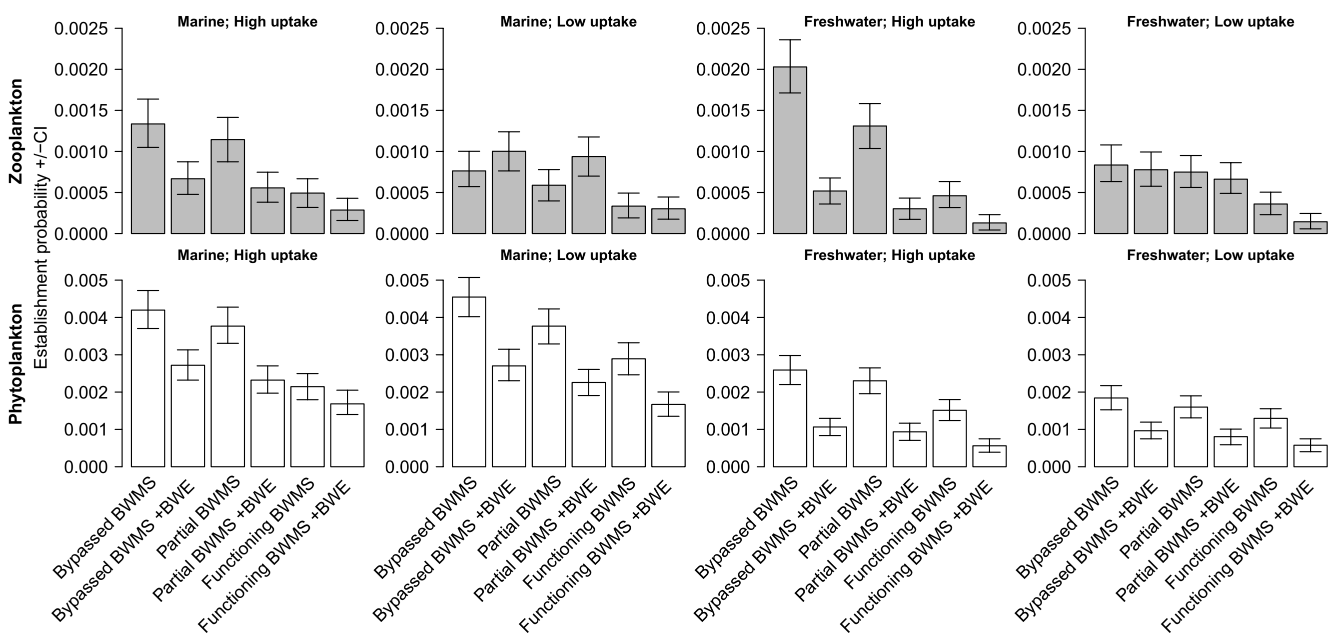

FIGURE 4 Mean probability that at least one establishment will occur after a single voyage ±95% CI for the mean under various scenarios. Grey and white bars show zooplankton and phytoplankton data, respectively; panels also distinguish between voyages where initial ballast uptake concentration was in the top or bottom 10 percentile of all transits for that route ('high uptake' and 'low uptake') and destination port salinity (marine or freshwater). Ballast water management scenarios include bypassed BWMS, bypassed BWMS + BWE, partial BWMS, partial BWMS + BWE, functioning BWMS, and functioning BWMS + BWE.

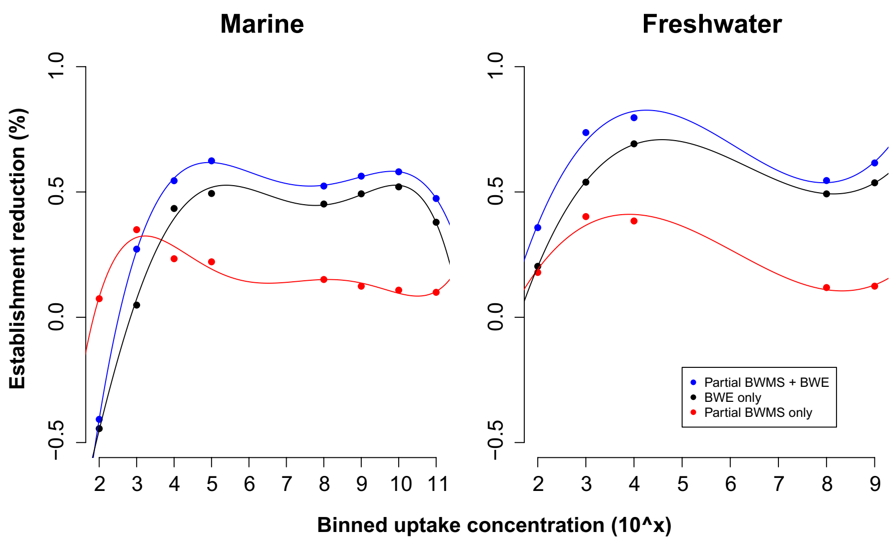

FIGURE 5 Establishment reduction achieved with partial BWMS only (red dots), BWE only (black dots) or partial BWMS and BWE (blue dots) relative to bypassed BWMS for both taxa with transits to marine or freshwater ports. Uptake concentrations were binned with maximum value shown on *x*-axis; bins containing <0.5% of simulated transits were dropped. Lines show best fit polynomial regression selected using adjusted *R*-squared.

TABLE 1 Mean probability ($\times10^{-3}$) of NIS establishment for zooplankton (ZP) and phytoplankton (Phyto) species ±95% CI for the mean across trips for arrivals to marine and freshwater ports. Ballast water management scenarios include bypassed BWMS, bypassed BWMS + BWE, partial BWMS, partial BWMS + BWE, functioning BWMS and functioning BWMS + BWE.

Destination port salinity	Taxa	Bypass	BWE only	Partial BWMS only	BWE and partial BWMS	Functioning BWMS	Functioning BWMS and BWE
Marine	ZP	1.11 (1.03–1.20)	0.72 (0.66–0.78)	0.85 (0.79–0.93)	0.58 (0.52–0.63)	0.37 (0.32–0.42)	0.29 (0.25–0.33)
Marine	Phyto	4.98 (4.80–5.15)	2.66 (2.54–2.79)	4.37 (4.22–4.54	2.31 (2.19–2.44)	2.76 (2.63–2.89)	1.59 (1.50–1.69)
Freshwater	ZP	1.73 (1.63–1.82)	0.76 (0.70–0.83)	1.09 (1.01–1.16)	0.49 (0.43–0.54)	0.46 (0.41–0.51)	0.18 (0.15–0.21)
Freshwater	Phyto	1.97 (1.86–2.07)	0.94 (0.87–1.01)	1.72 (1.64–1.82)	0.81 (0.75–0.88)	1.18 (1.10–1.26)	0.54 (0.49–0.60)

of BWE only was lowest at low uptake concentrations, whereas efficacy of partial BWMS only was lowest at high uptake concentrations (Figure 5). Generally, as uptake concentrations increased, the marginal benefit achieved by combining BWE and partial treatment decreased (Figure 5).

BWE decreases establishment risk by reducing the likelihood that introduced individuals can survive and establish, with its effects observable in surviving concentrations (temperature effect only) and establishment probabilities (both temperature and salinity effects; Figures 2 and 3). The use of BWE makes little difference in expected organism discharge concentrations, but a noticeable change in organism survival and species establishments (Figures 2 and 3). While the effect of BWE was most pronounced for transits to freshwater (risk reduced 2.3x and 2.1x compared with bypass for zooplankton and phytoplankton, respectively; Table 1), risk was also substantially reduced for transits to marine ports (risk reduced 1.5x and 1.9x compared with bypass for zooplankton and phytoplankton; Table 1). Further, since a very high abundance of phytoplankton can be released even with a functioning BWMS (i.e. average discharge of 13,000 m^3 for routes examined herein, equating to compliant discharge with up to 130 billion individuals [Casas-Monroy et al., 2014]), in some cases, the benefits of BWE alone surpassed that of functioning BWMS for phytoplankton since BWE could substantially decrease survival and establishment for these individuals (Figures 2–4).

Since we assumed that BWE did not have a directional effect on organism concentrations, BWE tended to maintain, on average, approximately the same discharge concentrations as voyages without BWE. However, when data were analysed by uptake concentration, BWE tended to increase discharge concentrations for low uptake transits and decrease discharge concentrations for high uptake transits (Figure 4), since the concentration after BWE was usually less extreme. Thus, in respect to propagule pressure, BWE was beneficial for transits with high uptake organism concentrations and detrimental for transits with low uptake concentrations. This effect diminished as propagules progressed through the invasion pathway (Figures 2 and 3). Indeed, the benefits achieved by BWE increasing environmental mismatch were outweighed by the drawbacks caused by increasing propagule pressure for low uptake voyages in all cases, except for zooplankton arriving to marine ports (Figures 4 and 5).

3.1 | Pathway-specific results

For transits to marine ports, BWE improved outcomes more than partial treatment (Figure 4), except for zooplankton with low uptake concentrations, where partial BWMS treatment was more effective (Figure 4). Generally, partial BWMS combined with BWE reduced risk to levels comparable with that achieved with a functioning BWMS alone (Figure 4) or, in some cases, beyond it owing to the greater risk reduction achieved using BWE as opposed to BWMS for phytoplankton (Figure 4).

For voyages to freshwater ports, we observed a strong reduction in establishment risk with the use of BWE only, which achieved a similar risk to that of a functioning BWMS (Figures 3 and 4), except for zooplankton when uptake concentrations were low (Figure 4). Even with low concentration uptake events, BWE decreased overall establishment risk despite increasing discharge concentrations (Figure 4).

3.2 | Sensitivity analysis

The relative performance of BWE and partial treatment varied with the magnitude of organism reduction applied. While BWE alone remained more effective than partial BWMS alone across this range (90%–99.5%) of reduction values, the relative performance of partial BWMS increased as a greater proportion of the species assemblage was eliminated (see Figure S3.1, Appendix S3).

When partial BWMS outcomes were based on data from sampled non-compliant events rather than a percent reduction, similar results were obtained to our main analyses and, most importantly, the relative performance of BWE vs. partial BWMS was maintained (see Table S3.2, Appendix S3).

For both alternate α distributions examined, we observed a marked increase in establishments. These values were unrealistic given observed historical invasion rates (see Appendix S2). Regardless, changing the α distribution did not change the relative performance of management options (see Table S3.3, Appendix S3).

Altering the magnitude of the salinity effect resulted in moderate changes to overall establishment rates but did not alter the relative performance of management options (see Table S3.4, Appendix S3).

4 | DISCUSSION

BWMS were developed to reduce propagule pressure and consequently reduce invasion risk (Albert et al., 2013). Thus, BWMS bypass or inoperability increases NIS establishment risk. We demonstrate the benefit of using BWE to mitigate risks associated with bypassed or inoperable BWMS, concordant with prior studies showing that BWE reduces invasion risk (Briski et al., 2015; DiBacco et al., 2012; Paolucci et al., 2015; Ricciardi & MacIsaac, 2022). Likewise, our results support the use of BWMS even when compliant organism concentrations are not achieved, aligning with propagule pressure theory. Generally, any reduction in propagule pressure will decrease establishment risk, although the benefit is limited if the discharge concentration was already so low that establishment was unlikely or so high that establishment remains likely even after propagule reduction. Indeed, the benefit of partial BWMS was related to discharge abundance owing to the sigmoid-shape of the propagule pressure-establishment curve, which is unique for each species and determined by their respective α values. Simply, each species has three regions along its propagule pressure-establishment curve: (i) a range of low propagule pressure, where establishment is very unlikely; (ii) a range of intermediate propagule pressure, where increases in propagule pressure result in proportionally higher establishment likelihood and (iii) a threshold propagule pressure above which establishment likelihood approaches one and further increases yield only marginal or no effect on establishment outcome. As such, partial BWMS is most effective when propagule pressure is in the intermediate range where decreases in propagule pressure result in establishment reductions (Figure 5). Interestingly, while BWMS are recognized to be more efficient than BWE in reducing organism concentrations (Briski et al., 2015; Gollasch et al., 2007), in some cases, when total discharge abundances were very high (i.e. for phytoplankton species), the establishment risk for transits using only BWE were even lower than those associated with a functioning BWMS (Figure 4).

BWE alone reduced establishment risk more than partial treatment alone, but the relative difference was dependent on the reduction in ballast concentrations achieved by using partial treatment. Owing to limited data on true reduction rates, the relative efficacy of BWE versus partial treatment should be interpreted with the understanding that it may vary based on transit circumstances. However, given that large discharge volumes can lead to large discharge abundances even when organism concentrations are low, we expect that BWE will generally be superior to partial treatment since it can reduce survival and establishment probabilities regardless of discharge abundances. Furthermore, since BWE must occur 200 nautical miles from land in water ≥200 m deep (IMO, 2004), it is expected that organisms ballasted during BWE will be less ecologically suitable for coastal environments (Gollasch et al., 2007). For this reason, BWE may reduce invasion risk more effectively than a partially functioning BWMS.

A greater risk reduction was achieved by combining partial treatment and BWE than by using either measure alone (Figure 5). This is concordant with empirical and theoretical studies that have demonstrated that combining BWE and treatment reduces invasion risk (Bradie et al., 2020; Briski et al., 2015; Paolucci et al., 2017). However, this may not be possible in certain situations. For example, use of BWMS in waters with high suspended solids can cause operational issues due to slowed ballast uptake (e.g. Canada, 2017; Liberia et al., 2021; Republic of Korea, 2017), possibly leading to complete BWMS shutdown requiring filter disassembly and cleaning. If the BWMS cannot be brought back online quickly, it may not be possible to conduct combined BWE and BWMS on the next voyage. Further, a reduced benefit of partial BWMS (and therefore reduced marginal benefit of combined BWE and partial BWMS) is expected at high organism uptake concentrations (Figure 5). In these cases, BWE alone may be preferable to reduce risk. The Ballast Water Equipment Manufacturers Association (BEMA) has stated that mitigation should be case-specific (BEMA, 2021), a view consistent with our results indicating that transit-specific risk characteristics should be considered because the best treatment option varies depending on destination salinity (Figures 4 and 5). It may also be prudent to weigh the benefit of partial treatment against transit-specific risk if there is a risk of rendering the BWMS inoperable for an extended period of time.

4.1 | Model assumptions and limitations

Our modelled uptake concentrations were based on arrival concentrations of exchanged tanks. In reality, uptake concentrations could differ from arrival concentrations due to reproduction, death or BWE. Increasing salinity and tank temperature generally cause zooplankton and phytoplankton concentrations to decline with holding time (Gollasch & David, 2021). However, some species can reproduce in tanks (e.g. Bailey et al., 2005; Carney et al., 2017; Gollasch et al., 2000), and egg-carrying copepods (Gollasch & David, 2021) and juvenile zooplankton (Cabrini et al., 2019) have been observed in ballast samples. Thus, it is likely that population growth and decline both occur during the voyage, with the outcome being voyage-specific (Chan, Bradie, et al., 2015; Gray et al., 2007; Simard et al., 2011). Lacking data on uptake concentrations and evidence to support a directional change in concentrations between uptake and arrival, we propose that arrival concentrations of organisms are a reasonable surrogate for uptake concentrations.

Similarly, lacking consensus data to indicate that BWE either increases or decreases species concentrations in ballast consistently, we assumed no effect herein. Since our data were based on exchanged tanks, any differences would be expected to influence results for treatment options without BWE. If BWE decreased the number of individuals in tanks, discharge concentrations and establishment probabilities would be relatively higher for bypassed BWMS and partial BWMS than bypassed BWMS+BWE and partial BWMS+ BWE. Thus, the benefit of BWE to mitigate bypassed BWMS and partial BWMS would be higher than shown herein. Compliant discharges would not be affected since those outcomes are independent of uptake concentrations.

Our analysis assumed the same α distribution for zooplankton and phytoplankton species following previous work and lacking data to inform unique α distributions. However, predictions may be more accurate if these values were modelled separately according to each group's establishment likelihood. Future studies should focus on expanding knowledge on per capita establishment risk likelihood to ensure optimal predictions.

Finally, our analysis did not consider any risk associated with ballast sediments. Ballast sediments can provide habitat for active aquatic organisms and dormant stages (Gollasch et al., 2019), including zooplankton (Bailey et al., 2003; Briski et al., 2011; Gray & MacIsaac, 2010), phytoplankton (Bailey et al., 2007; Duggan et al., 2005), bacteria (Lv et al., 2017) and macroinvertebrates (Briski et al., 2012). During normal BWMS operation, water usually passes through 40- or 50-μm filters, as the lowest feasible mesh size at operational ballast flow rates (e.g. 500 $m^3 h^{-1}$). This prevents uptake of large particles like sand (63 μm–2 mm), but allows uptake of smaller particles such as clay (≤2 μm) and silt (2–63 μm; Maglić et al., 2019). If bypass was performed, larger sediment loads could be ballasted, potentially providing additional habitat for organisms and resting stages inside ballast tanks. Alternatively, high concentrations of organisms could be ballasted, which could seek refuge in sediments and potentially emerge and be discharged later. However, organisms in sediment often possess adaptations to hide in or attach to sediments and have a lower likelihood of release during deballasting than planktonic species (Duggan et al., 2005). Furthermore, sediments are largely unaffected during deballasting, remaining in tanks until periodic dry docking (Prange & Pereira, 2013). Thus, we do not expect that sediment substantially changes the establishment risk during BWMS bypass events.

5 | CONCLUSIONS

BWE and partial BWMS both mitigate risk of establishment of aquatic NIS after a BWMS bypass or malfunction. BWE mainly reduced organism survival and establishment risks, whereas partial BWMS reduced propagule pressure. BWE alone was able to outperform partial BWMS because organisms ballasted during BWE are less likely to survive coastal conditions. In contrast, while partial BWMS can reduce organism concentrations, the organisms introduced are relatively more likely to be able to survive in the discharge port. Our analyses highlight that BWE was generally superior to partial BWMS, but that the greatest risk reduction was achieved by combining the strategies. Given transit-specific information, it would be prudent to employ risk mitigation measures on a case-by-case basis. Tailored management strategies depending on the departure-port water quality and sediment concentration may be a feasible step forward for additional protection against invasion risk.

AUTHOR CONTRIBUTIONS

Johanna Bradie, Matteo Rolla, Sarah Bailey, and Hugh MacIsaac conceived the ideas and designed methodology; Johanna Bradie conducted the simulations, analysis and led the writing of the manuscript. Matteo Rolla conducted literature review and contributed to writing the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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CONFLICT OF INTEREST

The authors have no competing financial interests.

DATA AVAILABILITY STATEMENT

R code for simulations and analysis is available via the Zenodo Digital Repository https://doi.org/10.5281/zenodo.7221898 (Bradie, 2022).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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