INVASIVESNET

Management of Biological Invasions (2021) Volume 12, Issue 1: 108–124

Special Issue: Proceedings of the 21st International Conference on Aquatic Invasive Species
Guest editors: Sarah Bailey, Mattias Johansson, Brenda Koenig and Linda Shaw

Research Article

Scenario-based cost-effectiveness analysis of ballast water treatment strategies

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Co-Editors' Note: This study was contributed in relation to the 21st International Conference on Aquatic Invasive Species held in Montreal, Canada, October 27–31, 2019 (http://www.icais.org/html/previous21.html). This conference has provided a venue for the exchange of information on various aspects of aquatic invasive species since its inception in 1990. The conference continues to provide an opportunity for dialog between academia, industry and environmental regulators.

Citation: Wang Z, Corbett JJ (2021) Scenario-based cost-effectiveness analysis of ballast water treatment strategies. *Management of Biological Invasions* 12(1): 108–124, https://doi.org/10.3391/mbi.2021.12.1.08

Received: 13 September 2019
Accepted: 30 March 2020
Published: 10 May 2020

Handling editor: Mattias Johansson
Thematic editor: Sarah Bailey

Abstract

This work evaluates technological strategies that include conventional vessel-based and alternative barge-based technologies to meet various treatment standards and combinations. We construct a vessel-versus-barge compliance cost framework informed by California efforts to provide additional protection from ballast discharge invasive risk. The technology-policy goal is to achieve the regulatory standards with appropriate technology, and meanwhile, minimize the compliance cost to reduce the burden on the shipping industry. The results show that the required numeric standards matter a lot. If a single global standard is a weak standard, then adopting vessel-based compliant technology is less costly than centralized barge-based compliance. We consider these findings to apply generally beyond the California context. Specifically, if some region or all regions adopt standards different from current global standards (i.e., stricter), barge-based systems can be less costly than retrofitting world fleets. The findings reveal the potential role of barge-based treatment measure. The increased \$0.7 billion compliance cost for the U.S. to achieve stricter ballast water regulation per year may inform the relevant policymakers.

Key words: ballast water management, invasive species, technological strategy, port-based, vessel-based, policy scenario, ballast water treatment system

Introduction

Water was first used as ballast to maintain stability in navigation in the 19th century due to the invention of ballast tanks (Davidson et al. 2018), as a replacement for dry materials such as stones and sand. Water as ballast is free, abundant and can be easily handled by pumps among different tanks, compared to dry materials. However, ballast water is a major introduction vector of nonindigenous species and diseases (Carlton 1985; Drake et al. 2007), which may have negative impacts on health, biodiversity, and economics (Lodge et al. 2006; McGeoch et al. 2010; Pimentel et al. 2005; Ruiz et al. 2000; Wan et al. 2016). Regulations and technologies are available to reduce the invasion risk caused by ballast water discharge.

Regulations towards ballast water discharge

The concern regarding invasive species is manifest in legislative instruments at different levels (Pam et al. 2013). The International

Maritime Organization (IMO) primarily regulates ballast water management (BWM) at the international level and adopted the International Convention on the Control and Management of Ship's Ballast Water and Sediments (BWM Convention) in 2004. The BWM Convention came into force on September 8, 2017. As of January 2020, 81 states had ratified the Convention, accounting for 80.76% of the world tonnage (The IMO 2020). The BWM Convention includes two discharge standards: Ballast Water Exchange (D-1 Standard) and Ballast Water Performance Standard (D-2 Standard). D-1 Standard requires ships to exchange at least 95% of the ballast water within open ocean areas, and D-2 Standard specifies the maximum amounts of viable organisms allowed to be discharged, including specified indicator microbes harmful to human health.

Some regions have voluntary requirements, such as Mediterranean Sea (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea), North-East Atlantic and the Baltic Sea (OSPAR and Helsinki Convention members), and the Antarctic; some regions have mandatory requirements, such as Persian Gulf (Regional Organization for the Protection of the Marine Environment) and North Sea. Article 196 of United Nations Convention on the Law of the Sea (UNCLOS) addresses the obligations of states concerning the implementation of all measures necessary for the prevention, reduction, and control of environmental pollution from intentional and unintentional introductions of alien and new species which may lead to harmful changes (David et al. 2015).

Nationally, individual states also may establish regulations. The BWM Convention explicitly disavows preventing a State Party from taking, individually or jointly with other State Parties, more stringent measures with respect to the prevention, reduction or elimination of the transfer of Harmful Aquatic Organisms and Pathogens through ships' Ballast Water and Sediments, consistent with international law. Parties may also, consistent with international law, require ships to meet a specified standard or requirement for certain areas if necessary.

The United States (U.S.) is not a party to the BWM Convention. Ballast water discharge was historically regulated by two authorities in the U.S. – the Coast Guard (USCG) under CFR 151, and the Environment Protection Agency (EPA) by 2013 Vessel General Permit (VGP). On December 4, 2018, the Vessel Incidental Discharge Act of 2018 (VIDA 2018) was signed into law establishing uniform national standards and requirements (Title IX of Frank LoBiondo Coast Guard Authorization Act of 2018). VIDA requires EPA to develop new national standards of performance for commercial vessel incidental discharges (including ballast water) and the USCG to develop corresponding implementing regulations. The existing 2013 VGP remains in full force and effect beyond its expiration date until such time that the EPA and the Coast Guard finalize and implement the new regulations that VIDA requires. VIDA preempts individual U.S. states from setting new standards other than those contained in national regulations, but it gives them the right to work together to develop a regional Great Lakes basin standard. In addition, the current standards of individual states will be valid until a new, region-wide standard for ballast water is fully implemented (MEP 2018). For example, California's interim and final performance standards, scheduled to be implemented by Jan 1st, 2030 and by Jan 1st, 2040, with different standards for organisms in different sizes, are stricter than the federal regulations (State of California 2020).

Ballast water treatment technologies

The BWM Convention requires all vessels to conform to the D-2 Standards by September 8, 2024. The D-2 standard involves installing a ballast water treatment system (BWTS). BWTS used to comply with the Convention must be type-approved by or on behalf of a Flag State Administration taking into account the Guidelines for approval of ballast water management systems (G8) (The IMO 2004). Even though some claim that nearly all of the tests conducted for compliance with the microbe standards have been defective (Cohen and Dobbs 2015), or some BWTS may fail to achieve the standards under certain conditions (Jing et al. 2012), approved BWTSs are the only choice for the shipping industry. BWTS may employ different treatment methods, including mechanical, physical and chemical treatment (Karahalios 2017; Tsolaki and Diamadopoulos 2010).

The USCG has different type approval requirements than the BWM Convention; 25 BWTS are approved by Marine Safety Center and 16 more were under review as of January 29, 2020 (U.S. Coast Guard 2020a). The USCG also approved 123 Alternative Management Systems (AMS) as of January 29, 2020 (U.S. Coast Guard 2020b).

Besides shipboard BWTS, port reception facilities are considered as an alternative, as stated in Regulation B-3.6 of BWM Convention and Guidelines for ballast water reception facilities (G5) (resolution MEPC.153(55)). Port-based treatment facilities have advantages of better monitoring, better control of treatment operation, more available treatment alternatives, higher safety for the crew, and economy of scale in construction and operation (Cohen and Foster 2000; Cohen and Weinstein 1998; Pereira et al. 2010). Disadvantages of port-based treatment include port congestion arising from ballast collection and storage, high cost of land acquisition, and demand of pipe connection between the treatment plants and all the berths (Gollasch et al. 2007; Pereira et al. 2010). However, Pereira et al. conclude that the port-based treatment does not impact the cargo capacity, occupation rate, or average queuing time at ports, even in those ports receiving high volumes of ballast water (Pereira et al. 2010).

Port-based reception facilities can be land- or barge-based (David et al. 2015; Maglić et al. 2015). Barge-based BWTS may offer advantages over land-based BWTS: they can be used at different locations, can use systems that are not viable on land, and do not need land-based pipelines (Maglić et al. 2015). A case study conducted in California justifies the focus on barge-based treatment and finds it significantly lower cost and provides more economic and more certainty than centralized land-based treatment (Glosten 2018b).

BWTS, no matter vessel- or port-based, approved by the IMO or the USCG can achieve the numeric standards required by the IMO (called "IMO-BWTS"). To achieve more stringent interim goals, California State Lands Commission funded a study to assess the feasibility of purpose-used barge-based treatment system (called "Stricter-BWTS") (California State Lands Commission 2018). The cost of one BWTS can range from $640,000 to $947,000, depending on different capacities, methods, and sizes (King et al. 2009). The cost of purpose-built barge-based BWTS by California is even higher (COWI A/S 2012; Glosten 2018a; Maglić et al. 2015). The regulatory compliance cost imposed on the shipping industry may decrease the shipping service or be passed through to final consumers (Schinas and Stefanakos 2012). Cost-effective treatment methods are needed to balance species invasion risk reduction and negative economic impacts.

Research question

Ballast water regulations are designed to protect regional ecosystems, while fleet managers seek compliance strategies that minimize cost across voyages to many ports (Firestone and Corbett 2005). The key question motiving this paper is: what are the cost-effective technological compliance strategies? Broad studies discuss vessel-based system selection given space and resources onboard, cost, effectiveness, size, installation space, power, the safety of the crew, etc. (Karahalios 2017; Ren 2018; Šateikienė et al. 2015; Satir 2014; Tsolaki and Diamadopoulos 2010). However, they do not consider the potential economic benefits of port-based treatment. To this end, this work considers the conventional onboard and alternative strategies for the world fleet. We want to know whether and when the port-based reception treatment could be a feasible alternative from an economic perspective. Due to the reviewed advantages of barge-based BWTS over shore-based BWTS, we use barge-based BWTS to represent port-based BWTS.

The key question motivating regional standards is whether cost-effective treatment strategies better address invasive risk complexity. As the asymmetric risk of invasive species introduction varies among ports, one treatment standard may be less efficient or less effective than variable (stricter) regional standards (Saebi et al. 2019). If more stringent regulation standards are proposed after vessels take actions to meet the current standards, vessels could need to change the treatment method, incurring cost and fleet availability time loss. Hence, a robust and sustainable compliance strategy is needed for the world fleet under different regulatory scenarios.

Another question motivating this work is how much the ballast water management regulatory costs will add to the shipping costs for individual vessels. Each company faces challenges to navigate the way through environmental regulations. The cost of running a ship is one of key variables deciding financial performance for a shipping company (together with the revenue received from chartering/operating the ship and the method of financing the business) (Stopford 2009).

Materials and methods

The development and use of a set of scenarios is a strategy when facing uncertainty (Morgan 2017). Our work models three policy scenarios due to the uncertainty of future ballast water management regulation. Under each policy scenario, this work proposes different technological solutions composed of conventional onboard treatment systems and barge-based alternatives and then compares them using cost-effectiveness analysis (CEA).

Policy scenarios

Three policy scenarios are proposed with different ballast water discharge standards and geographical scopes. The first scenario is "Consistent IMO Regulation", where every port adopts the baseline BWM Convention standard. This is the current situation and practice of the industry.

The second one is "Inconsistent Regulation", where most ports in the world follow the BWM Convention, and some regions adopt independent stricter standards. The stricter standards refer to the interim standards proposed by California.

The third one is "Consistent Stricter Regulation", where all ports adopt the same stricter standards to the interim standards of California. It shows a boundary of the most stringent regulation by extending the scope of stricter standards to the whole world. This policy also applies to the situation where the precautionary principle is used in the policy-making process.

This work selects the U.S. as a representative for regional/national regulation to illustrate the range of our analysis. The method can be applied to other regions to examine different regulatory scenarios.

Compliance strategy alternatives for each policy

This work considers both the conventional onboard option and a barge-based alternative to comply with different BWM scenarios. Table 1 illustrates possible cost-effective compliance technological alternatives.

When the BWM regulation is uniform and consistent with IMO standards, the BWTS needed to meet the requirement is IMO-BWTS. The potential cost-effective strategies are to put the IMO-BWTS on all vessels or at all ports.

Under inconsistent regulation, Stricter-BWTS is required to achieve the standards at US Ports, so either US Ports need to install barge-based

Table 1. Possible cost-effective alternatives to comply with three policy scenarios.

Policy scenario	Compliance Strategy[1]	Description[2]
1. Consistent IMO regulation	Strategy 1.1	IMO-BWTS on all vessels
	Strategy 1.2	IMO-BWTS at all ports
2. Inconsistent regulation: The U.S. adopts stricter standards	Strategy 2.1	Stricter-BWTS on Vessel-may-US[3] IMO-BWTS on Vessel-never-US
	Strategy 2.2	Stricter-BWTS at US Ports IMO-BWTS at non-US Ports
	Strategy 2.3	Stricter-BWTS at US Ports IMO-BWTS on all vessels
	Strategy 2.4	Stricter-BWTS on Vessel-may-US[3] IMO-BWTS at non-US Ports
3. Consistent stricter regulation	Strategy 3.1	Stricter-BWTS on all vessels[3]
	Strategy 3.2	Stricter-BWTS at all ports

1: The set of combinations does not include more expensive options that we can easily tell. For example, Stricter-BWTS on all vessels to comply with the first and second regulation scenarios, but the costs are much higher than IMO-BWTS.
2: Figure S1 provides figure illustration for these strategies.
3: This work includes the case that Stricter-BWTS can be installed on vessels, even though the footprint of Stricter-BWTS may be too large for vessels. These potential strategies try to include future condition due to technological innovation.

Stricter-BWTS or vessels that have a possibility to call at US Ports need to install Stricter-BWTS onboard. At non-US Ports, IMO-BWTS is enough to meet the requirement. Especially, under Strategy 2.4, vessel-may-US have two options when they call at non-US ports: they can either use vessel-based Stricter-BWTS or use barge-based IMO-BWTS to meet the IMO standards of non-US ports.

When the uniform regulation adopts California's stricter standards, the world fleet can either install Stricter-BWTS onboard every vessel or use barge-based Stricter-BWTS at every port.

Cost-effectiveness analysis for the world fleet

CEA compares alternatives in terms of costs to meet a single quantified effectiveness measure. It works well when the policy impact is unable to be monetized or the considerations are about human or ecosystem health. It also can be transformed into a cost-minimization problem with fixed effectiveness if the strategies have the same efficiency (Boardman et al. 2018). This is the case in this work in that all compliance strategies are proposed to meet certain regulatory standards. Therefore, we only need to find compliance strategies with the lowest cost. To this end, this work establishes compliance cost models to compare technological strategies.

We establish a world fleet compliance cost model and estimate the costs of technological strategies for the world fleet. The fleet compliance cost is calculated on a yearly basis. The compliance cost is calculated with Equation 1. Treatment cost depends on the treatment numbers and ballast water discharge volume each year.

Table 2. World fleet cost model of compliance strategies.

Alternative	Annual capital, installation and operating cost	Annual treatment cost
Strategy 1.1	n_allvessel×(C_imo+O_imo)	V_allport×T_imo
Strategy 1.2	n_allport×(C_barge+C_imo+O_barge+O_imo)	V_allport×T_imo+T_tug×N_allport
Strategy 2.1	n_vmayus×(C_stricter+O_stricter) + n_vneverus×(C_imo+O_imo)	(V_vmayus_to_usport+V_vmayus_to_otherport)× T_stricter +V_vneverus_to_otherport×T_imo
Strategy 2.2	n_usport×(C_barge+C_stricter+O_barge+ O_stricter)+n_otherport×(C_barge+C_imo+ O_barge + O_imo)	V_usport×T_stricter+V_otherport×T_imo+ T_tug×N_allport
Strategy 2.3	n_allvessel×(C_imo+O_imo)+n_usport× (C_barge+C_stricter+O_barge+O_stricter)	V_usport×T_stricter+V_otherport×T_imo+ T_tug×N_usport
Strategy 2.4 (1) Use vessel-based BWTS when Vessel-may-US call non-US Ports	n_vmayus×(C_stricter+O_stricter)+ n_otherport×(C_barge+C_imo+O_barge+ O_imo)	V_usport×T_stricter+V_vmayus_to_otherport× T_stricter+T_tug×N_vneverus_to_otherport+ T_imo×V_vneverus_to_otherport
Strategy 2.4 (2) Use barge-based BWTS when Vessel-may-US call non-US Ports	Same to above	V_usport×T_stricter+V_otherport×T_imo +T_tug×N_otherport
Strategy 3.1	n_allvessel×(C_stricter+O_stricter)	V_allport×T_stricter
Strategy 3.2	n_allport×(C_barge+C_stricter+O_barge+ O_stricter)	V_allport×T_stricter +T_tug×N_allport

C_imo, C_stricter, C_barge: annual capital and installation cost of an IMO-BWTS/a Stricter-BWTS/a barge.
O_imo, O_stricter, O_barge: annual operation cost of an IMO-BWTS/a Stricter-BWTS/a barge.
T_imo, T_stricter: unit ballast water treatment cost of IMO-BWTS/Stricter-BWTS ($/ton).
T_tug: treatment cost of a tug ($/treatment; one treatment needs one tug) .
n_allvessel, n_vmayus, n_vneverus: number of the world fleet, Vessel-may-US, and Vessel-never-US.
n_allport, n_usport, n_otherport: number of world ports, US Port and non-US Ports.
V_allport, V_otherport, V_usport: annual ballast water treatment volume from vessels to all ports/non-US Ports/US Port. The ballast water discharge probability of each voyage of 0.5 is considered.
V_vmayus_to_usport: annual treatment ballast water volume from Vessel-may-US to US Port.
V_vmayus_to_otherport: annual treatment ballast water volume from Vessel-may-US to Other-Port.
V_vneverus_to_otherport: annual treatment ballast water volume from Vessel-never-US to Non-US Ports.
N_allport, N_usport, N_otherport: annual treatment/discharge times at all ports/US Port/Non-US Ports. The discharge probability of 0.5 is considered.
N_vneverus_to_otherport: annual treatment times of Vessel-never-US at Non-US Ports.

Fleet compliance cost = purchase + installation + operating + treatment cost (Equation 1).

If the BWTS is vessel-based, each item refers to the annual cost of BWTS. If the BWTS is barge-based, annualized purchase, installation, and operating cost also include those of barges, and treatment cost also includes cost of tugs because tugs control the movement of barges. Table 2 illustrates the detailed compliance cost model for each policy scenario.

Compliance cost model for individual vessels

Even though the cost-effective alternatives identified may be the optimal options for the world fleet, it cannot reveal the cost difference among individual vessels. Therefore, the work further establishes individual vessel cost models. With the individual vessel compliance cost model, we further estimate the impacts of compliance costs on shipping costs. Individual vessel compliance cost model is shown in Table 3. Since the cost of Strategy 2.4 (1)

Table 3. Cost model for individual vessels.

<table>
<tr><th rowspan="2">Strategy</th><th colspan="2">Annual capital, installation and operating cost</th><th colspan="2">Annual treatment cost</th></tr>
<tr><th>Vessel-may-US</th><th>Vessel-never-US</th><th>Vessel-may-US</th><th>Vessel-never-US</th></tr>
<tr><td>Strategy 1.1</td><td colspan="2">C_imo+O_imo</td><td colspan="2">V_v×T_imo</td></tr>
<tr><td>Strategy 1.2</td><td colspan="2">n_allport×(C_barge+C_imo+O_barge+O_imo)× V_v/V_allport</td><td colspan="2">V_v×T_imo+T_tug×N_v</td></tr>
<tr><td>Strategy 2.1</td><td>C_stricter+O_stricter</td><td>C_imo+O_imo</td><td>V_v*T_stricter</td><td>V_v*T_imo</td></tr>
<tr><td>Strategy 2.2</td><td>V_v_to_usport×n_usport× (C_barge+C_stricter+O_barge+ O_stricter) / V_vmayus_to_usport+ V_v_to_otherport×n_otherport× (C_barge+C_imo+O_barge+ O_imo) / V_otherport</td><td>V_v_to_otherport× n_otherport× (C_barge+C_imo+ O_barge+O_imo) / V_otherport</td><td>V_v_to_usport× T_stricter+ V_v_to_otherport× T_imo+T_tug×N_v</td><td>V_v_to_otherport× T_imo+T_tug×N_v</td></tr>
<tr><td>Strategy 2.3</td><td>(C_imo+O_imo)+ V_v_to_usport×n_usport× (C_barge+C_stricter+O_barge+ O_stricter) / V_vmayus_to_usport</td><td>C_imo+O_imo</td><td>V_v_to_usport× T_stricter+ V_v_to_otherport× T_imo+T_tug× N_v_to_usport</td><td>V_v×T_imo</td></tr>
<tr><td>Strategy 2.4 (1)</td><td>(C_stricter+O_stricter)+ V_v_to_otherport×n_otherport× (C_barge+C_imo+O_barge+ O_imo)/ V_otherport</td><td>V_v× n_otherport× (C_barge+C_imo+ O_barge+O_imo)/ V_otherport</td><td>V_v×T_stricter</td><td>V_v×T_imo+ T_tug×N_v</td></tr>
<tr><td>Strategy 3.1</td><td colspan="2">C_stricter+O_stricter</td><td colspan="2">V_v×T_stricter</td></tr>
<tr><td>Strategy 3.2</td><td colspan="2">n_allport×(C_barge+C_stricter+O_barge+O_stricter)× V_v/V_allport</td><td colspan="2">V_v×T_stricter+T_tug×N_v</td></tr>
</table>

V_v: the annual discharged volume of vessel *v*, vessel *v* can be Vessel-may-US, or Vessel-never-US.
V_v_to_usport: the annual discharged volume at US Port of vessel *v*.
V_v_to_otherport: the annual discharged volume at non-US Port of vessel *v*.
N_v: the annual treatment times at all ports of vessel *v*.
N_v_to_usport: the annual treatment times at US Port of vessel *v*.

is lower than strategy 2.4 (2), the following work uses Strategy 2.4 (1) and compare it with others. For all vessels, the individual vessel cost comprises capital, installation, operating and treatment cost (the representative equation is the same to Equation (1). However, the details are different for Vessel-may-US and Vessel-never-US under the scenario of Inconsistent Regulation, so Table 3 shows different models for them.

Shipping costs are estimated for all container vessels, bulkers and tankers with shipping cost models (the database has 21,624 vessels of these three vessel types). Annual shipping cost for each vessel is estimated with daily shipping cost and voyage duration. Daily shipping cost is estimated with the method and data of Guide to Deep-Draft Vessel Operating Costs (US Army Corps of Engineers 2002).

Data

The models mainly use three types of data: the cost and performance of BWTS, shipping traffic, and the ballast water discharge profile.

Cost and performance of BWTS

The work of King and Hagan includes cost data for IMO-BWTS (King et al. 2009). The information comes from technology vendors whose systems had been approved by the IMO as of May 2009, other industry representatives, and ship engineers. They present the preliminary costs for a "typical" ship within each ship type/size category and include the cost variation caused by different BWTS treatment methods (i.e. chemical, physical and mechanical). The range of the IMO-BWTS purchase and installation costs is between $0.7 to $1.1 million. Some vessels need small BWTSs and some use large BWTSs, so we use the average of lower and upper boundaries to calculate the average fleet costs for available compliance strategies. Every vessel using the most expensive BWTS is the higher boundary and every vessel using the least expensive BWTS is the lower boundary.

The costs of some BWTS may decline due to technology advancement and large scale or production since more BWTS have obtained the type-approval certificate under the regulation of the IMO and the USCG. In considering whether to use 2009 ballast treatment cost data (King et al. 2009), we recognize that either costs may need upward adjustment to 2020 based on constant dollar differences or that fleet adoption experience over time may yield cost savings offsetting time-value increases. We interviewed a BWTS commissioning engineer from RMS Marine Service Company Ltd. about the lowest and highest market prices of a BWTS. We found the BWTS costs can be as low as $0.2 million, while they can still be high as $1.2 million for a VLCC (Y. Zheng 2020, January 10 *pers. comm.*). We include the possible lowest IMO-BWTS cost of $0.2 million and 1.5 times of the highest cost ($1.8 million) in our analysis as sensitivity analysis to show the robustness of cost-effective strategy facing technology uncertainty.

Delta Stewardship Council provides cost analysis for stricter-BWTS (Glosten 2018a), including cost estimation for barges and tugs. Their reports consider the cost variation due to different sizes and capacities of BWTS and barges, and our work uses the upper and lower bounds to consider the data uncertainty.

The reports include 16 ports in California, and these ports use 24 barges in total. That is about 1.5 barges per port. The barges in different sizes are arranged for each port zone according to BWTS treatment capacities and vessel treatment demands (Glosten 2018b). Capacities are measured in terms of ballast water discharge rate, i.e., 30,000MT discharged in 24 hours is similar to 15,000 MT discharged in 12 hours (Glosten 2018a). Our work uses the same method and adjusts the number of barges needed for each port within the U.S. The average ballast water discharge volume of U.S. ports is 14% of the California average, and the average ballast water discharge/treatment events of U.S. ports is 55% of the California average, so

Table 4. Cost components of IMO-BWTS[1].

Scenarios[5]	Total capital and installation cost ($)	Annual capital and installation cost[2] ($)	Annual operating cost[3] ($)	Unit treatment cost[4] ($/MT)
Lower bound	658,000	35,776	9,000	0.02
Average cost	**901,000**	**48,989**	**13,500**	**0.135**
Upper bound	1,144,000	62,201	18,000	0.25

1: From (King et al. 2009).
2: Capital costs annualized: initial purchase and installation of a ballast water treatment system.
3: Fixed annual costs: does not vary with the volume of ballast water treated, including crew, consumables, parts, assistance, and technical support.
4: Variable annual costs: varies with the volume of ballast water treated, including crew, consumables, and fuel cost to run BWTS.
5: The lower and upper bound are the minimum and maximum costs of different treatment methods in the report.

Table 5. Cost components of Stricter-BWTS.

Scenarios[4]	Total capital and installation cost[1] ($)	Annual capital and installation cost ($)	Annual operating cost[2] ($)	Unit treatment cost[3] ($/MT)
Lower bound	4,600,000	250,108	326,000	0.27
Average cost	**7,000,000**	**380,599**	**502,000**	**0.48**
Upper bound	9,900,000	538,276	678,000	0.68

1: *Treatment Plant* from Table 6 in (Glosten 2018a).
2: *M&R of system* from Table 14 is the annual operating cost of all BWTS in each zone (Glosten 2018a). The cost for each BWTS is calculated with the number of barges in each zone (from Table 10).
3: *Operators* in Table 14 in (Glosten 2018a) is the total treatment cost of BWTS in each zone. The cost for average tonnage of discharged ballast water is calculated with the discharge volume in each zone (from Table 12).
4: The lower bound is when all BWTS used are in small size, the upper bound is when all BWTS are large.

Table 6. Extra Cost components if BWTS is installed on barges (the costs of barge and tug).

Scenarios[4]	Total capital and outfitting cost for one barge[1] ($)	Annual capital and outfitting cost for a barge ($)	Annual operating cost for a barge[2] ($)	Tug[3] ($/treatment)
Lower bound	6,300,000	342,540	231,000	11,400
Average cost	**10,100,000**	**549,150**	**231,000**	**11,400**
Upper bound	15,500,000	842,755	231,000	11,400

1: *Barge and Outfitting* in Table 9 (Glosten 2018a). The barge hull size is the smallest to not only provide enough deck space for the BWTS, but also enough tankage to provide adequate setting/flocculation of the ballast water prior to final treatment, so the cost of barges is assumed to be the same for IMO- and Stricter-IMO in this work.
2: The sum of *Barge berthing* and *Admin & Main Personnel* in Table 14 (Glosten 2018a) is the annual operating cost of barges in each zone. Divide it by the number of barges in each zone and get $231,000 for one barge.
3: *Tugboat* cost in Table 14 (Glosten 2018a) is the total tug cost to relocate barges at each zone. Divide it by total ballast water treatment times in each zone and then get the treatment cost for one tug.
4: The scenarios are determined in the same way to Table 5.

0.21 to 0.83 barge on average should be used in one U.S. port. We assume one barge per U.S. port if some fraction one barge is needed at a port. We include sensitivity analysis with 0.2 (several ports share one barge) to 3 barges per port (vessel arrival peak).

This work uses Delta Stewardship Council data to get annual costs: a BWTS lifetime of 30 years, a discount rate of 6%, and an annual inflation rate of 2.5%. Tables 4–6 summarizes the annual capital cost, operating cost, and unit treatment cost for BWTS, barges, and tugs.

Ship traffic and ballast water discharge profile

Table 7 provides the data of ship traffic and ballast water discharge profile. The port, vessel and voyage data are from 2012–2013 Lloyd's Vessels Database

Table 7. Ship traffic and ballast water discharge profile in year 2012–2013.

The number of ports		The number of unique vessels		The number of discharges/treatments[1]		Modeled Discharge volume (MT)	
U.S. Ports	257	Vessels may go U.S.	9088	Vessel-may-US to US-Port	18,555	Vessel-may-US to US-Port	35,165,961
non-US Ports	3164	Vessels never go to U.S.	32379	Vessel-may-US to non-US Ports	118,991	Vessel-may-US to non-US Ports	256,769,311
World Ports	3421	World Fleet	41467	Vessel-never-US to non-US Ports	535,540	Vessel-never-US to non-US Ports	622,544,170

1: The fraction of port arrivals without ballast water discharge varies from 42% to 88% for different vessel types. We assume the discharge probability is 0.5 for simplification.

and Moves Database. These numbers provide a preliminary description of the demand for BWTS. The work assumes all ports and vessels need BWTS, and no vessel or port has installed BWTS before. The domestic shipping moves within the same origin and destination country are removed because IMO requires ships in *international* traffic to manage ballast water. There are 41,467 unique ships left and 9,088 of them have at least one record of calling at a U.S. port.

While some ships may choose to avoid U.S. ports in the future to obviate the need to have more robust treatment, we assume that each of the 9,088 vessels calling on U.S. ports—creating an upper bound—will need to install a stricter BWTS onboard or use barge-based stricter BWTS at the 257 ports in the U.S. This work also assumes ballast water discharge may happen at every port, so all ports are included in the analysis.

The ballast water discharge volumes are estimated with a regression method using Deadweight Tonnage (DWT) and ballast water discharge reported in the National Ballast Information Clearinghouse Database (NBIC) (Seebens et al. 2013). DWT data are from Lloyd's dataset and the average discharge volume is used for those vessels with missing DWT data. NBIC receives ballast water discharge reports that are required under U.S. law (U.S. Coast Guard 2015). Furthermore, past reports on this database document compliance with reporting requirements are near or above 80% of all reportable discharges of ballast water (Miller et al. 2007, 2011). Based on this information, this work treats the reported discharge volumes as valid enough for our analysis. We report the confidence of the regression fit of discharge volume and DWT in Supplementary material Table S1.

Results and discussion

Cost-effective compliance strategies for the world fleet

Table 8 shows the annual fleet costs for each compliance strategy. The cost-effective strategies are marked in bold. We can see the identified cost-effective strategies remain the same under different cost scenarios, which reveals the robustness of the identified options.

Table 8. World fleet annual regulation compliance cost for each technological strategy.

Policy scenario	Strategy	Annual fleet cost (billion $)				
		Average	Lower bound	Higher bound	Lowest bound with the lowest IMO-BWTS capital cost	Highest bound with the highest IMO-BWTS capital cost
Consistent IMO regulation	**Strategy 1.1**	**2.7**	**1.9**	**3.6**	**0.8**	**5.0**
	Strategy 1.2	10.7	10.5	10.8	10.4	11.0
Inconsistent regulation: The U.S. adopts stricter standards	Strategy 2.1	10.3	6.8	14.0	6.0	15.2
	Strategy 2.2	10.9	10.6	11.2	10.5	11.3
	Strategy 2.3	**3.4**	**2.4**	**4.4**	**1.4**	**5.8**
	Strategy 2.4	17.0	14.0	20.2	13.9	20.3
Consistent stricter regulation	Strategy 3.1	37.0	24.1	51.1	24.1	51.1
	Strategy 3.2	**13.8**	**11.9**	**16.1**	**11.9**	**16.1**

Note: In the lower bound, all cost components, including capital, operating, and treatment costs of IMO-BWTS, stricter-BWTS, and barges use the minimum numbers in Tables 4, 5 and 6. In the lowest bound of the sensitivity analysis, only the capital cost of IMO-BWTS is $0.2 million to show the extreme limit, and other cost components are the same to the lower bound.

Consistent IMO regulation is the current ballast water regulation practice. The most cost-effective strategy is to use the vessel-based BWTS (Strategy 1.1). This optimal strategy verifies the current BWTS installation practice of the industry. In other words, this work confirms that the fleetwide vessel treatment is more cost-effective than port-based schemes to meet global treatment standards set by the IMO BWM Convention.

Under the policy scenario of inconsistent regulations when the U.S. adopts stricter regulations, the optimal compliance strategy is to install IMO-BWTS on all vessels and install Stricter-BWTS at US ports (Strategy 2.3). This result also suggests that regions can adopt stricter regulations than the BWM Convention without conflicting with current industry practice or requiring vessels to engage in retrofits on top of retrofits to come into compliance. Thus, these vessels will not be "grandfathered" at the expense of better environmental protection. Rather, the only update required will be a State's own ports to meet Stricter-BWTS. When vessels call at these ports, the ballast water will be treated by barge-based BWTS. When vessels call at non-US Ports, the onboard BWTS will be used. Such strategy also does not require other countries to cooperate.

If all ports require stricter regulations, the barge-based strategy (Strategy 3.2) is more cost-effective than the vessel-based strategy (Strategy 3.1). Even though the capital cost of barge-based BWTS is much higher than vessel-based BWTS, the economies of scale make barge-based BWTS economically feasible for the world fleet. The average estimate of $13.8 billion provides the highest boundary of stricter regulation worldwide.

The last two columns of Table 8 show the fleet annual cost considering the capital cost uncertainty of IMO-BWTS. When we change the minimum IMO-BWTS cost to $0.2 million, Strategy 1.1, 2.3 and 3.2 remain the most cost-effective strategies under all regulatory scenarios. The fleet costs of lower bound and lowest bound are the same for Strategy 3.1 and Strategy 3.2. This is because we only vary the capital cost of IMO-BWTS for the lowest

Table 9. The ranges of unit compliance costs of individual vessels of cost-effective strategies.

Strategy	Minimum unit compliance cost ($/MT)	Maximum unit compliance cost ($/MT)	Maximum unit cost (excluding passenger and service vessels) ($/MT)
Strategy 1.1	5	540,000	18,000
Strategy 2.3	5	1,200,000	18,000
Strategy 3.2	7	3,100,000	109,000

bound and keep other cost components (operating cost of IMO-BWTS, costs of stricter-BWTS and barges, and treatment costs) the same to the lower bound, and these two technological strategies do not include IMO-BWTS. The same reason applies to the observation that the higher bound and the highest bound have the same costs for these two technological Strategies 1 and 2. The table also shows that the difference in the fleet compliance costs between Strategy 1.1 and Strategy 1.2 becomes bigger than the lower bound and the Average case, due to the cost advantage of IMO-BWTS over stricter-BWTS. When we change the maximum IMO-BWTS cost to $1.8 million, the cost-effective strategies remain the same. These results indicate that the identified cost-effective compliance strategies are robust within the possible cost ranges.

By examining the cost-effective strategies for each policy scenario, the vessel-based treatment method works well under current regulation, while the barge-based alternative is economically feasible if some regions adopt stricter regulation. Also, if the U.S. adopts stricter regulation in all the ports, the total cost will increase by $0.7 billion ($3.4 billion minus $2.7 billion from Column 3 of Table 8). The strategies proposed in Section 2.2 include the vessel-based Stricter-BWTS even though the footprint of Stricter-BWTS may be too large for vessels. We include this option to consider the future situation with technological innovation. The identified strategies under Policy 2 and 3 show that the Stricter-BWTS can be cost-effective when they are barge-based.

This work also considers the possible BWTS demand uncertainty due to the number of barges needed at the port and the fleet number. (1) By varying the number of barges used at one port, this work shows the same strategy selection results and reveals the robustness of the identified cost-effective strategies. The potential need for three barges per port demonstrates that the barge-based strategies remain feasible and preferred. (2) By varying the fleet number, we find that the demand for BWTS is inelastic. The compliance cost may be high enough to phase out some kinds of vessels, like small vessels operating in short-haul voyages, but the technological strategy selection will remain the same.

The compliance cost of individual vessels

Table 9 shows the cost difference of individual vessels for the identified cost-effective strategies. The unit ballast water treatment costs of individual

Table 10. The average proportions of compliance cost to shipping cost for individual vessels.

Strategy	The average proportion of compliance cost
Strategy 1.1	4.6%
Strategy 2.3	4.9%
Strategy 3.2	7.9%

vessels vary substantially. The ranges are from several dollars to several million dollars per ton of treated ballast water (Columns 2 and 3). The very high unit treatment costs are due to very little ballast water discharge volume from passenger and service vessels. When these vessels are removed, the highest unit treatment costs become much lower (Column 4). The maximum unit costs of Strategy 1.1 and 2.3 are the same if passenger and service vessels are excluded.

The proportions of compliance cost to total shipping cost for different vessels vary a lot. The vessels with very high percentages of compliance cost tend to be small or old vessels and tend to discharge less ballast water. Table 10 shows the average proportions of the compliance cost to the total shipping cost for individual vessels. The total shipping cost is composed of operating cost (14%), periodic maintenance (4%), voyage cost (40%), and capital cost (42%) (Stopford 2009). The average ballast water management compliance cost is higher than the periodic maintenance cost.

Under Strategy 1.1, the compliance cost accounts for 4.6% of total shipping cost on average under the current international ballast water discharge regulation, and the percentage under the stricter U.S. regulation becomes 4.9% under Strategy 2.3. The difference is 0.3%, which is very small. This suggests that the stricter regulation (adopted by the U.S. in our scenarios) will not increase the proportion of compliance costs a lot compared to current IMO standards. As for the vessels with very high compliance costs, their firms may choose to speed up phasing out such vessels or improve their business strategies to satisfy their economic goals. Policymakers need to consider mechanisms to enhance the compliance of these vessels. For example, treatment methods other than using BWTS, such as using fresh water as ballast water, may be good solutions for these vessels. Otherwise, a more careful cost allocation mechanism might be helpful to lower their compliance cost.

Conclusion

This analysis evaluates the cost-effectiveness of the vessel- and barge-based BWTS under three policy scenarios. The analysis shows that the vessel-based system is more cost-effective under current regulation, and the barge-based system is cost-effective when some ports or all ports worldwide adopt a more stringent ballast water discharge regulation. Depending on the global traffic pattern and which ports/regions may require better protection from the stricter treatment of ballast water, barge-based BWTS could be used without updating otherwise BWM-compliant vessel-based BWTS.

Since barge-based BWTS is shown to be cost effective in some situations, future study can be done to examine the cost-sharing issue of barge-based BWTS. The systems are used by vessels but are purchased and installed by ports or private operators. Ports can consider charging ballast water treatment fees or increasing port dues according to the treated volume. Also, the strategy design and cost models can be applied to other regional regulatory scenarios. For example, with species invasion risk assessment models, hotspot ports can be identified and set as protection zones with higher regulatory standards.

Acknowledgements

We thank the anonymous reviewers for valuable comments and suggestions. We thank Mr. Kevin J. Reynolds of Glosten and Mr. Yang Zheng of RMS Marine Service Company Ltd. for assistance with understanding the cost data, ballast water treatment systems, and ballast tanks. We thank Chris Scianni for assistance with understanding the regulations of California. We thank all collaborators, and Dr. Erin Grey who provided help in estimating the volume of ballast water discharge. We thank Dr. Jeremy Firestone for revision suggestions.

Funding Declaration

The work is based on the NSF Coastal SEES project [grant number 1748389]. We thank NSF Coastal SEES for funding this work.

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Supplementary material

The following supplementary material is available for this article:

Figure S1. Illustration of compliance strategies.

Table S1. Ballast water discharge volume estimation. The regression relationship of ballast water discharge volume and DWT.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2021/Supplements/MBI_2021_Wang_Corbett_SupplementaryMaterial.pdf