

## Article

# Using Onboard-Produced Drinking Water to Achieve Ballast-Free Management

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**Abstract:** Based on the International Convention for the Control and Management of Ships' Ballast Water and Sediments (the Ballast Water Management Convention, or BWM Convention) of the International Maritime Organization, from 8 September 2017, all ships must have an approved Ballast Water Management Treatment System (BWTS) to prevent the invasion of alien species through the discharge of ballast. Generally speaking, the need for an approved BWTS is limited to large vessels, as they are too large or too expensive for small vessels to install. This study aims to propose a simple ballast-free approach for small vessels (e.g., tugs, workboats, research vessels) that require ballast to compensate for the weight loss of fuel when sailing. Our approach involves refitting the dedicated ballast tank of these small vessels to be drinking water tanks and filling the tanks with onboard-generated distilled or reverse osmosis water to adjust the stability of the ships. We assessed our approach using three vessels. Two ships using our proposed method were certified by the American Bureau of Shipping as containing no ballast water tank, and not being subject to the BWM Convention. This study provides an environmentally harmless, easy to use, and economical approach for small vessels to comply with the BWM Convention.

**Keywords:** ballast; stability; BWM Convention; drinking water; distilled water; reverse osmosis; invasion; vessel; IMO



**Citation:** Lu, K.-T.; Lui, H.-K.; Chen, C.-T.A.; Liu, L.-L.; Yang, L.; Dong, C.-D.; Chen, C.-W. Using Onboard-Produced Drinking Water to Achieve Ballast-Free Management. *Sustainability* **2021**, *13*, 7648. <https://doi.org/10.3390/su13147648>

Academic Editors: Vincenzo Torretta, Eun-Sung Chung, António Dinis Ferreira, Peter Goethals and Jose Navarro Pedreño

Received: 6 May 2021

Accepted: 5 July 2021

Published: 8 July 2021

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## 1. Introduction

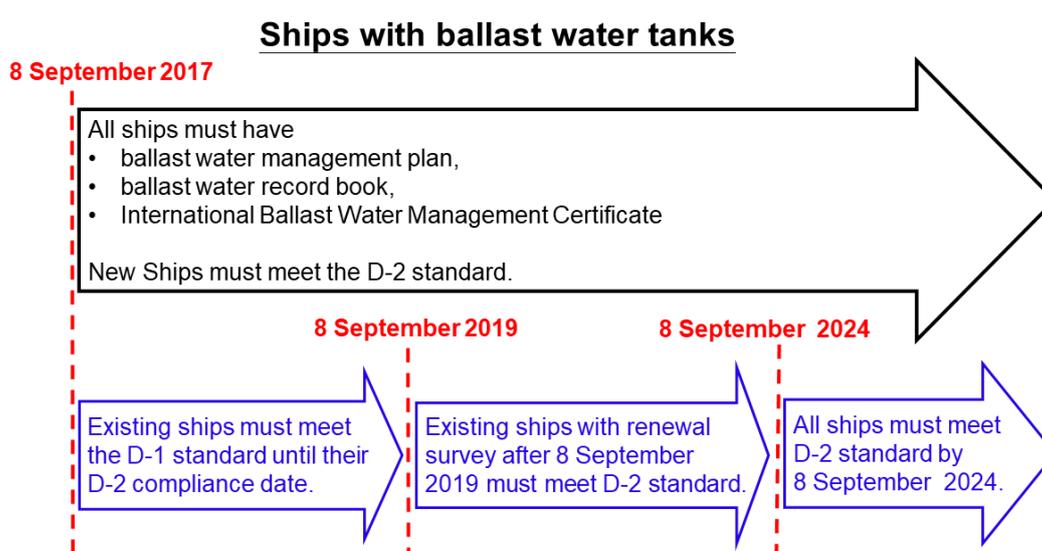
Ocean-going vessels have been built to transit cargoes safely between continents. The ballast is essential for a ship to trim the draft and maintain stability. The ballast is used to weigh down a vessel and to lower its center of gravity, to increase its draft to effectively improve propulsion and maneuverability, and to compensate for weight changes in cargo load levels or due to fuel and freshwater consumption. Generally speaking, the volume of the ballast water is almost one-third that of the ship's deadweight [1]. Insufficient ballast tends to tip or heel the vessel when heavy seas are encountered, and this may result in capsizing of the vessel.

Most ballast tanks are located under the seawater level, a location with an abundance of living microorganisms. According to the International Maritime Organization (IMO), there are about 7000 kinds of marine invasive species traveling around the world's oceans [2]. When a ship rolls and pitches, the water in the ballast tank intakes oxygen via the tank air vent. Therefore, some aquatic organisms are comfortably able to grow and reproduce. After the ship reaches the port of loading to load to its maximum cargo capacity, the seawater ballast is discharged. Some organisms, including bacteria,

viruses, microbes, small invertebrates, eggs, cysts, and other larvae, can survive in the new environment to become invasive, outcompeting native species and multiplying to pest proportions [3–7]. This becomes harmful to coastal and freshwater ecosystems [3–5]. This issue has been known for around a century. For instance, the Asian phytoplankton algae *Odontella* (*Biddulphia sinensis*) was introduced to the North Sea in 1903 [6]. According to the National Wildlife Federation, in the Great Lakes, more than 185 invasive aquatic organism species can be found, including zebra mussels and quagga mussels (<https://www.nwf.org/Our-Work/Environmental-Threats/Invasive-Species/Ballast-Water>, accessed on 1 May 2021). Based on the IMO, the ten most unwanted species in ballast water are Cholera (*Vibrio cholera*), Cladoceran Water Flea (*Cercopagis pengo*), Mitten Crab (*Eriocheir sinensis*), toxic algae, Round Goby (*Neogobius melanostomus*), Zebra Mussel (*Dreissena polymorpha*), North American Comb Jelly (*Mnemiopsis leidyi*), North Pacific Seastar (*Asterias amurensis*), European Green Crab (*Carcinus maenas*), and Asian Kelp (*Undaria pinnatifida*) [2,8].

To avoid the adverse impacts of the discharge of ballast on aquatic ecosystems, the IMO adopted the ‘International Convention for the Control and Management of Ships’ Ballast Water and Sediment’, the so-called BWM Convention, in 2014, which entered into force on 8 September 2017. As of 9 January 2020, 81 countries, representing 96.13% of the gross tonnage of the world’s merchant fleet, have signed the convention [9]. Accordingly, to the convention, the countries implementing it have the option to take additional measures, which are subject to criteria set out in the convention and the IMO guidelines.

After enforcement, all ships with ballast are required to have a ballast water plan, a ballast water record book, and an International Ballast Water Management Certificate [10]. The IMO has adopted two ballast water management standards: the D-1 and D-2 standards. Generally speaking, the D-1 standard requires ships to exchange their ballast water in open seas, at least 200 nautical miles from land and in water at least 300 m deep. The D-2 standard specifies the species of organisms and the maximum amount allowed to be discharged. From 8 September 2017, new ships must meet the D-2 standard, and existing ships must meet at least the D-1 standard. Existing ships undergoing a renewal survey linked to the International Oil Pollution Prevention Certificate after 8 September 2019, must meet the D-2 standard. We summarize the timeline of the requirements of the BWM Convention in Figure 1.

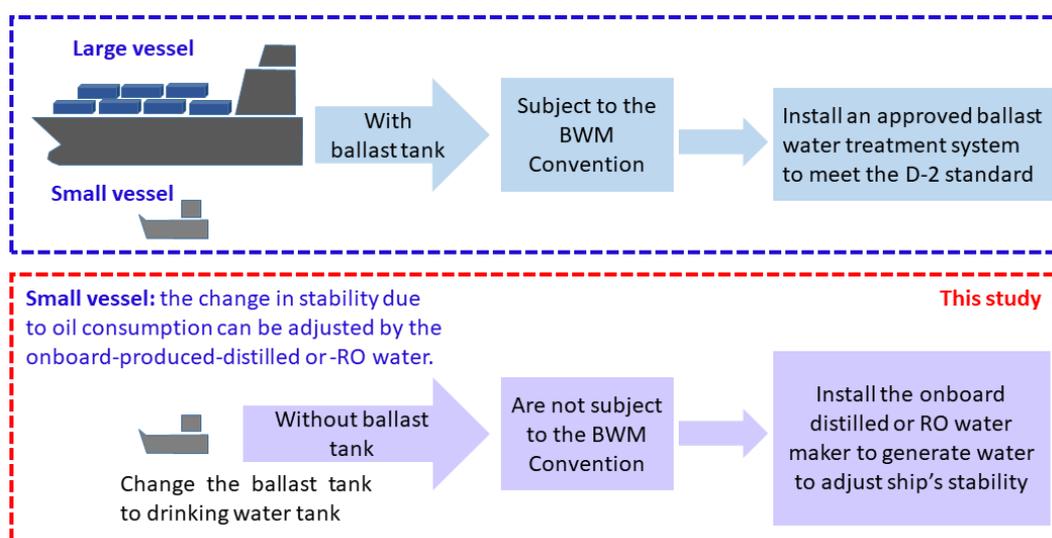


**Figure 1.** The timeline of the requirements of the BWM Convention at different phases.

To reach the D-2 standard, each ship requiring ballast needs to install a ballast water treatment system (BWTS). According to the IMO, 83 types of BWTS have been approved

to be used, as of December 2019. Treatments include filtration, UV radiation, electrolytic chlorination, deoxygenation, ozonation, chemical injection, heating, etc. All these methods have been used to kill, remove, or stop the reproduction of a majority of marine organisms in ballast waters [11,12]. It is worth mentioning that the capacities of the approved systems have a large range, from 12 to 34,000 m<sup>3</sup>/h. This is because large vessels, such as cargo vessels, have to discharge or reload the ballast within 24 h, which is the time it takes to load or discharge cargo. However, the approved BWTS are often either too large or too expensive for small vessels to install. The cost for installing a BWTS is estimated to be between US\$0.7 and US\$1.1 million [13]. The values estimated by tanker operators were about US\$1.8 million for the Euronav, and between US\$15 and US\$23 million for the Kuwait Oil Tanker Co. S.A.k. [14]. Generally, the cost increases with the ship's size, and varies with the ship's type. However, few BWTS have been designed specifically for small vessels, such as those using ultrasound-based techniques or onboard produced ballast [15,16].

For small vessels, such as tugboats, workboats, and research vessels, ballast is needed to adjust their stability when their weights are decreased due to oil consumption during sailing or operation. This study aimed to propose an environmentally friendly ballast-free method for these small vessels, by changing the existing ballast tanks to drinking water tanks, and then using the on-site produced drinking water to adjust the ship's stability. According to article 3.2 of the BWM Convention, these ships will not be subject to the BWM Convention as they contain no ballast water tank. We examined our approach with three vessels with different water makers installed. Figure 2 shows the conceptual framework of the traditional ballast water management, and our approach.



**Figure 2.** Conceptual framework for the (top) traditional ballast water management of large and small vessels, as well as (bottom) the approach this study proposed for small vessels.

## 2. Materials and Methods

To examine the (1) feasibility of using water generated by water makers to adjust a ship's stability and the differences in using a distilled water maker or RO water maker, and (2) the quality of the generated water, three vessels owned by Asian Marine Salvage Ltd. in Taiwan, with lengths and tonnages ranging from 65–68 m and 1714–2057 tons, respectively, were examined in this study (Figure 3, Table 1). Generally, the studied vessels were multi-purpose, but were mainly used for marine salvage and towage. The ballast tanks for these vessels were firstly refitted to be drinking water tanks, connected to a distilled or RO water maker. To examine if the distilled or RO water maker was able to produce sufficient water to meet the ballast need, one vessel, Salvage Titan, had a 10 m<sup>3</sup>/day Japan-made distilled water maker (the Sasakura Oasis Distilling Plant Type VA-100) installed which was able to

recycle waste heat from ship's main engine to generate distilled water. Later, the Salvage Champion had a China-made RO water maker, ZC-FSHB6, with a size of  $1.08 \times 0.44 \times 1.6$  m, installed. The RO water generator was expected to produce up to  $5 \text{ m}^3$  of RO water daily. The Salvage Ace had both the distilled water maker and the RO maker installed.



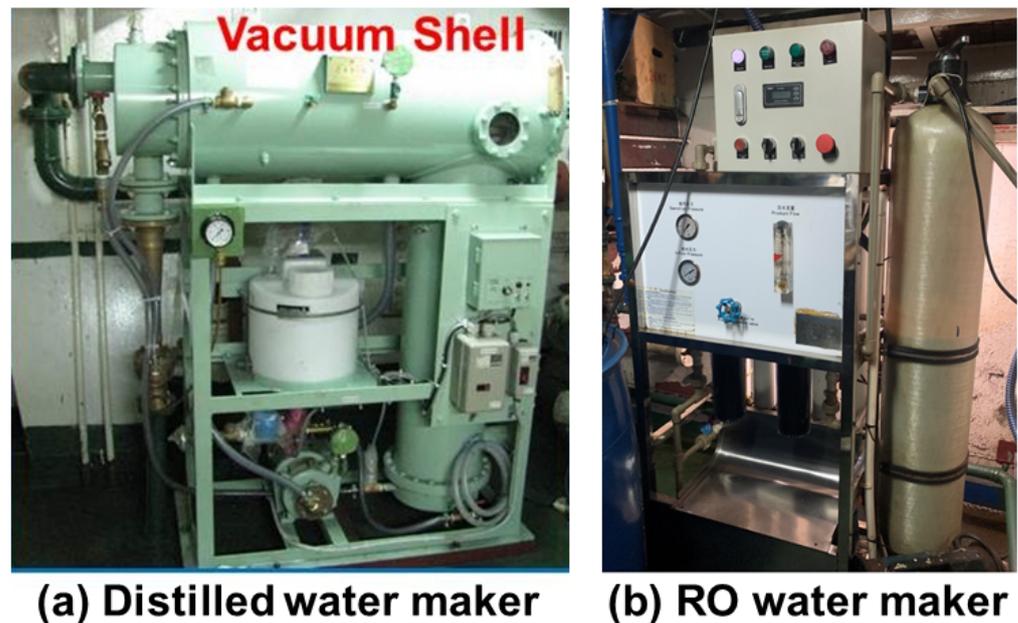
**Figure 3.** The vessels, (a) Salvage Ace, (b) Salvage Champion and (c) Salvage Titan, used in this study. Table 1 shows their information in detail.

**Table 1.** Name, length, gross tonnage, maximum ballast water capacity, type of water maker used, Classification Society, ballast-free certification from ABS, and the navigation after installation of water maker of the three examined vessels.

Name	Length (m)	Gross Tonnage (Ton)	Ballast Capacity ( $\text{m}^3$ )	Type of Water Maker	Classification Society	Ballast-Free Certification by Class	Navigation after Installation till 1 January 2021 (Mile) <sup>2</sup>
Salvage Ace	65	1714	571 <sup>1</sup>	Distillation+ RO	ABS	✓	> 30,000
Salvage Champion	65	1830	610 <sup>1</sup>	RO	ABS	✓	> 30,000
Salvage Titan	68	2057	420	Distillation	CCS	-	> 10,000

<sup>1</sup> Estimated as 1/3 of the gross tonnage, <sup>2</sup> Installation for Salvage Titan was done in 2016, while the rest were between 2019 and 2020.

A nine-day continuous operation between the 3 and 13 June 2016 was carried out to examine the performance of the distilled water maker. To determine the water quality of the distilled water generated, water samples were taken from the Salvage Titan on 8 November 2016 and the Salvage Ace on 30 May 2019. The water quality of the distilled water sample taken from Salvage Titan was analyzed by the SGS Far East Ltd., Taiwan. We analyzed the water quality of the distilled water sample taken from Salvage Ace with analytical methods, following the Environmental Protection Administration of Taiwan guidelines. An additional RO water maker was installed in the Salvage Ace and will be discussed later. The distilled water maker installed in the Salvage Titan and the RO water maker installed in the Salvage Ace are shown in Figure 4.



**Figure 4.** The (a) distilled water maker installed in Salvage Titan and the (b) RO water maker installed in Salvage Ace.

### 3. Results and Discussion

#### 3.1. Drinking Water System and the Production Rate

To determine if the amount of drinking water produced onboard is sufficient to balance the weight reduction due to fuel consumption, the weight of loading (sum of fuel, diesel oil, and drinking water) of the vessels can be modeled as follows:

$$W_{loading} = W_{fuel+diesel\ oil} + W_{distilled/RO\ water} \quad (1)$$

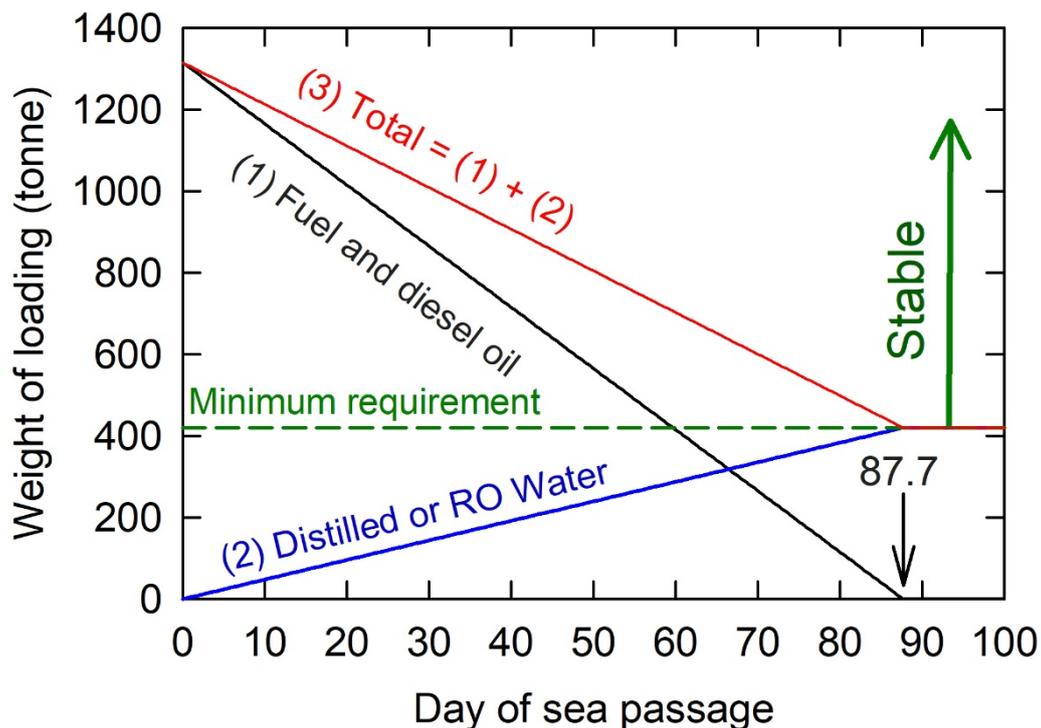
$$W_{fuel+distilled\ oil} = W_{initial\ fuel+distilled\ oil} - R_{fuel+diesel\ oil} \times t \quad (2)$$

$$W_{distilled/RO\ water} = W_{initial\ distilled/RO\ water} + R_{distilled/RO\ water} \times t \quad (3)$$

$$W_{distilled/RO\ water} \leq W_{water\ tank} \quad (4)$$

where  $W_{loading}$  is the weight of loading of a vessel,  $W_{fuel+diesel\ oil}$  is the weights of fuel and diesel oil,  $W_{distilled/RO\ water}$  is the weight of distilled or RO water,  $W_{initial\ fuel+distilled\ oil}$  is the initial weights of fuel and diesel oil when time ( $t$ ) is equal to zero,  $W_{initial\ distilled/RO\ water}$  is the initial weight of distilled or RO water when  $t$  is equal to zero,  $W_{water\ tank}$  is the maximum storage weight of the water tank,  $R_{fuel+diesel\ oil}$  is the consumption rate of fuel and diesel oil, and  $R_{distilled\ water/RO}$  is the production rate of distilled or RO water.

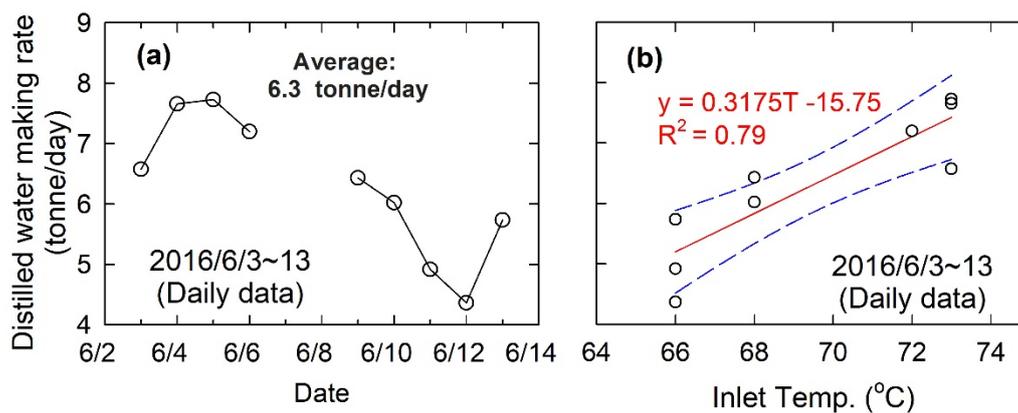
As an example, the Salvage Titan has fuel and diesel oil carrying capacities of 1100 M/t and 215 M/t, respectively. The fuel consumption is about 15 tonne/day, including 0.7 tonne/day consumption by the generator. Therefore, the total maximum duration for sea passage is about  $(1100 + 215)/15 = 87.7$  days without refilling. When the vessel has consumed all the fuel, a total of 420 tons of ballast water is needed for sailing to maintain reasonable stability. That is, the minimum distilled water generation rate is  $420/87.7 = 4.79$  tonne/day. The weight of loadings of the Salvage Titan, based on Equations (1)–(4), are shown in Figure 5.



**Figure 5.** The modeled weight of loading of the Salvage Titan vs. day of sea passage. The black line refers to the total weight of fuel and diesel oil. The blue line refers to the weight of water produced by the distilled or RO water maker at the minimum requirement rate of 4.79 tonne/day. The value is assumed to be zero when time is equal to zero. The red line refers to the total weight, while the green line is the minimum requirement weight for the ballast system.

Our results showed that the RO water makers of Salvage Ace and Salvage Champion stably produced five tons of RO water daily. In contrast, the production rate of the distilled water maker varied with the performance of the vessel's engine. To understand the efficiency of the distilled water maker, we conducted a nine-day continuous operation between 3 and 13 June 2016, in the Salvage Titan. The results showed that the distilled water production rates reached as high as 7.7 tonne/day (average  $6.3 \pm 1.2$  tonne/day) in the 9-day sea trial (Figure 6a). Briefly, compared with the minimum requirement of 4.79 tonne/day, the distilled water produced was enough to meet the ballast need with about 31.5% extra in reserve. However, the rates were still 37% lower than the expected rate of 10 tonne/day under normal operation conditions. This was because the vessel was not fully operational, so the distilled water was produced at a reduced capacity.

The principles of the distilled water maker are as follows. The ambient seawater is first pumped into a vacuum shell. The engine's jacket cooling water, with the inlet temperature as high as 80 °C, is then transferred by a pipe, passing through a vacuum shell to heat the seawater. Then, a vacuum pump is used to lower the pressure and boil the seawater below 80 °C. Water vapor forms when the seawater temperature and the pressure are high and low enough, respectively, for boiling. Meanwhile, the water vapor condenses to distilled water, and is then collected and transferred to distilled water tanks, serving as the distilled water ballast system. Figure 6b shows the positive correlation between the distilled water production rates and the inlet water temperatures. That is, the higher the inlet water temperature, the higher the distilled water production rate. The regression in Figure 6b shows that when the inlet temperature was 80 °C, the distilled water production rate equaled 9.65 tonne/day, matching the claimed 10 tonne/day from the manufacturer.



**Figure 6.** Daily distilled water production rate vs. (a) time and (b) inlet temperature of the distilled water maker, in the nine-day sea trial between 3 and 13 June 2016. The red and the blue lines show the regression result and the 95% confidence interval of the daily averages, respectively.

Based on the water production rate of the distilled water maker varying with the performance of the vessel's engine, we installed the RO water maker on both the Salvage Ace and Salvage Champion. The distilled water maker was different from the RO water maker as the distilled water maker generated distilled water only when the vessel's engine was under operation. The distilled water production rate also was related to the performance of the vessel's engine (the waste heat production rate). In contrast, the RO water maker worked steadily, without being influenced by the inlet seawater temperature or the performance of the vessel's engine. In brief, the rate of distilled or RO water generated was sufficient to adjust the ships' stability during sailing. Furthermore, the RO water maker worked more reliably, with a steadier freshwater production rate than the distilled water maker.

### 3.2. Quality of the Distilled or RO Water

To examine the quality of the onboard-produced water, several parameters were analyzed (Table 2). The drinking water standards of the EU are shown for comparison. As expected, the examined items for the onboard drinking waters complied with the drinking water standards of the EU. That is to say, the onboard-produced distilled or RO water can be used to adjust the ship's stability, and for drinking. Additionally, the discharge of water from the drinking water tanks is equivalent to the discharge of drinking water into the ocean.

Since the distilled water was formed by condensed water vapor, it was expected to contain no marine organisms and minimal dissolved substances. We expected the RO process would be able to remove more than 99.9% of contaminants (depending on the quality of the filter used) which had larger molecular sizes than water molecules. Such contaminants included dissolved minerals. Filtration is a commonly used method in BWTS, as it can very effectively screen unwanted species from the ballast [17–19]. Generally speaking, a pore size of  $<10 \mu\text{m}$  meets the requirements of the D-2 standard [8,17,18]. It is worth mentioning that the pore size of the filter for the RO maker is far below that size, which meets the D-2 standard. That is, the discharge of the distilled water made onboard will not cause any environmental impacts due to the invasion of alien species. As mentioned above, ships that operate locally do not need to install any BWTS. It has been suggested that such an exemption may cause a secondary spread of invasive species [19,20], which could be avoided if these ships use the method we have proposed here.

We also needed to address the low pH and salinity of both the distilled and RO waters. Generally, surface oceans have a pH and salinity of about 8.0–8.2 and 34–35, respectively [21]. Based on our method, the place of discharge of the distilled water or RO water generally is in the harbor where the vessels are refueling. Therefore, the discharged

drinking water will float, mix with the ambient seawater, and spread on the sea surface. Indeed, because the ocean is absorbing an increasing amount of human-released CO<sub>2</sub>, seawater is acidifying [22,23]. Previous studies have found that a decrease of pH in the ocean reduces the calcification rate of marine organisms which use CaCO<sub>3</sub> to build their skeleton or shells [24,25]. Meanwhile, freshening of the surface seawater, and the consequence of the capping effect, may cause anoxic bottom water inside the harbor [26]. On the other hand, increased buoyancy may enhance productivity outside the harbor [27,28]. We expect that the freshening and acidifying effects would be minimal when the amount of discharge of distilled or RO water is small, or when the water exchange between the harbor and seawater outside is strong. Having high dissolved oxygen but low nutrient concentrations, distilled water or RO water also tends not to cause or enhance coastal eutrophication or hypoxia. Nevertheless, potential changes of marine ecosystems around harbors due to the discharge of the distilled or RO water deserve further investigation.

**Table 2.** Water quality of the onboard-produced distilled and RO waters. The drinking water standards of the EU are shown for reference.

Test Item	Drinking Water Standards of EU [29]	Distilled Water Sample	
		Salvage Titan	Salvage Ace
Temperature (°C)		36	31.2
Salinity (psu)		0.0	0.1
pH	6.5–9.5	6.7 at 23.5 °C	7.41
<i>E. coli</i>	0 CFU/250 mL		<10 CFU/100 mL
Phytoplankton			48 cells/L
Zooplankton			ND (individual/L)
		-----mg/L-----	
Dissolved O <sub>2</sub>		6.9	6.96
Biological oxygen demand			1.4
Chemical oxygen demand			1.6
Total organic carbon			0.60
Mineral grease			0.5
Total phenols			0.01
Chlorophyll-a			ND (<0.0003)
Cadmium	0.005	ND (<0.002)	ND (<0.0001)
Chromium	0.05	ND (<0.004)	0.0003
Copper	2	0.207	0.0123
Mercury	0.001	ND (<0.0004)	ND (<0.0001)
Zinc		2.05	0.156
Lead	0.01	0.00263	0.0029
Nickle	0.02		0.0417
Manganese	0.05		0.0078
Arsenic	0.01		ND (<0.0005)
Ammonia-N	0.5	0.08	0.46
Nitrite-N	0.5	ND < 0.002	0.011
Nitrate-N	50	ND < 0.01	0.128
Phosphate		<0.0005	0.015

The low salinity of distilled or RO water has additional advantages to vessels. Rusting in the ballast tank is one of the most significant problems related to ballast, representing a costly maintenance requirement. Since the corrosion rate of ballast tanks filled with distilled or RO water is much lower than those filled with seawater, the service life of ships could be extended further when our proposed distilled or RO water is used. Furthermore, by adding an appropriate amount of minerals, the distilled or RO water could be a very reliable source of drinking water for crews.

### 3.3. Cost

As mentioned above, the cost of installing the approved BWTS is estimated to be US\$0.7–US\$1.1 million or even higher [13,14]. Such costs are too high for small vessels, such as tugs. In European seas, the operational cost of treatments for the non-indigenous species has been estimated to be between 1.6 and 4% of the annual operation cost for a ship [30]. In addition, a training course for the crew for operating the system is essential. Here, we calculate the cost of our approach as follows.

In this study, the costs of installing the distilled water maker and the RO water maker for the studied vessels were around US\$30,000 and US\$10,000, respectively. This was about 3–4%, or lower, of the cost for large vessels [13,14]. Each of the studied vessels was equipped with 2 to 3 sets of diesel generators. Each of the generators was capable of generating 320–416 kW. Normally, only one generator set is required for operation, and practically, only 25% of the generator capacity was utilized. Table 3 shows this information in detail. The generator of the vessels consumed diesel at rates between 0.70 and 0.91 tonne/day among the studied vessels, including 24 kg/day for the RO water maker and 72 kg/day for the distilled water maker. This is equivalent to the prices of US\$13.2 per day for the RO water maker or US\$39.6 per day for the distilled water maker, when US\$550 per tonne for the diesel is taken into account. The cost for replacing the filter for the RO water maker was about US\$0.07/tonne of RO water made.

**Table 3.** The power, diesel consumption rate, and cost of the vessel's electronic generator and the distilled or RO water maker.

Name	Power of Vessel's Generator (kW)		Power of Water Maker (kW)	Practical Diesel Consumption (tonne/day)		Cost (US\$/day) <sup>3</sup>	
	Maximum	Practical Use <sup>1</sup>		Generator <sup>2</sup>	Water Maker	Generator	Water Maker
Salvage ACE	320	80	2.75	0.70	0.024	385	13.2
Salvage Champion	320	80	2.75	0.70	0.024	385	13.2
Salvage Titan	416	104	8.25	0.91	0.072	500.5	39.6

<sup>1</sup> Assume the power generated is 25% of the maximum capacity of the generator. <sup>2</sup> Calculated assuming that generating 320 kW consumed 0.7 tonne daily. <sup>3</sup> Calculated assuming the price for the diesel as US\$550/ tonne.

### 3.4. Nil Ballast Statement from the Ship's Classification Society

According to the BWM Convention, since the studied research vessels contain only drinking water tanks and no ballast tank, they would not be subject to the BWM Convention. Indeed, the classification society of each vessel takes responsibility for official approval. Normally, each vessel has a class. The 12 members (each refers to an individual class) of the International Association of Classification Societies (IACS) covers 90% of the cargo vessels worldwide, including the American Bureau of Shipping (ABS), Korean Register (KR), Bureau Veritas (BV), Lloyd's Register (LR), China Classification Society (CCS), Nippon Kaiji Kyokai (NK), Croatian Register of Shipping (CRS), Polish Register of Shipping (PRS), DNV GL AS (DNV GL), RINA, Indian Register of Shipping (IRS), and Russian Maritime Register of Shipping (RS). In this study, the classes of Salvage Ace and Salvage Champion were ABS, and the Salvage Titan belonged to CCS (Table 1). Of note is that the Salvage Ace and Salvage Champion, using our proposed method, were certificated by the ABS as containing no ballast water tank, and were therefore not subject to the BWM Convention. Figure 7 shows the statement from the ABS for the Salvage Champion. The Salvage Ace and Salvage Champion provide an example of how the water maker can be used to achieve ballast-free management. It is important to state that the classification society of each vessel has the right to certify that there is no ballast tank onboard the vessel.

Document No 7625299-3343114-001



## American Bureau of Shipping

ABS Plaza 16855 Northchase Dr.  
Houston, TX 77060

### SALVAGE CHAMPION

Class No 7625299

Report No.: KS3343114

Date 12 June 2017

#### Statement of Fact - Nil Ballast Water Tanks Onboard

THIS IS TO REPORT that according to the survey status of M.V. "SALVAGE CHAMPION" of Kingstown, Saint Vincent and The Grenadines, Call Letters: J8B2604, IMO No.: 7530444, it was noted that M.V. "SALVAGE CHAMPION" has none of ballast water tanks onboard, and therefore the BWM 2004 Convention shall not apply to M.V. "SALVAGE CHAMPION" in accordance with BWM 2004 Convention / Article 3.2 This Convention shall not apply to: (a) ships not designed or constructed to carry Ballast Water.

Pan, Ho-Chun, Kaohsiung Port  
Surveyor

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**Figure 7.** The scanned statement of the ABS, stating that the Salvage Champion has no ballast water tanks onboard, and therefore the BWM 2004 Convention shall not apply to the Salvage Champion in accordance with BWM 2004 Convention/Article 3.2.

#### 4. Conclusions

Using three vessels as examples, this study proposed an easy and economical ballast-free management option for small vessels, by refitting the ballast tanks to be drinking water tanks. Drinking water is generated onboard and fills the tanks to compensate for the vessel's weight loss due to fuel consumption. The cost of installing the onboard water maker is just 3–4%, or even lower, of the cost of the BWTS for large vessels. Our results suggest that, practically, the RO water maker has a steadier water production rate and lower cost than the distilled water maker. Using our approach, two vessels were certificated by the ABS, stating that since there was no ballast tank on board, the vessels would not be subject to the BWM 2004 Convention. Vessels with similar existing seawater ballast systems or under construction could be modified with our proposed method to meet the requirements of the BWM Convention. It is important to note that this method is suitable for

vessels that undergo stability changes due to oil consumption, which can be compensated for by distilled or RO water generated onboard. Additionally, the classification society of the vessel has the right to certify whether the vessel contains a ballast tank.

**Author Contributions:** Conceptualization, K.-T.L., C.-T.A.C. and H.-K.L.; methodology, K.-T.L., H.-K.L., C.-T.A.C. and L.-L.L.; validation, K.-T.L., H.-K.L. and C.-T.A.C.; investigation, K.-T.L., H.-K.L. and C.-T.A.C.; resources, K.-T.L., H.-K.L., C.-T.A.C., C.-D.D. and C.-W.C.; writing—original draft preparation, K.-T.L., H.-K.L. and C.-T.A.C.; writing—review and editing, C.-T.A.C. and H.-K.L.; supervision, H.-K.L., C.-T.A.C., L.-L.L. and L.Y.; funding acquisition, H.-K.L. and C.-T.A.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Ministry of Science and Technology of Taiwan, under the following contract numbers: MOST 107-2611-M-110-026-; MOST 108-2611-M-110-025-; MOST 109-2611-M-110-016; MOST 109-2611-M-110-010.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data are available on request from the corresponding authors.

**Acknowledgments:** We acknowledge the captain and crew of the studied vessels. Two reviewers provided detailed and constructive comments, which helped to strengthen the manuscript.

**Conflicts of Interest:** The authors declare no conflict of interest.

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