Chapter 10
Ballast Water

Marlos De Souza

Abstract Ships are the transportation engines of the globalized world, responsible for moving around 90% of the global trade. Unfortunately, together with goods, food, and fuel, ships also transport uninvited aquatic organisms that can establish themselves in the receiving port with massive impact on the economy, public health, and the environment. With around 10 billion tons (10 km^3) of ballast water being discharged every year, a United Nations led International Convention on the Control and Management of Ships' Ballast Water and Sediments was adopted in 2004 and entered into force in 2017. The convention created regulatory framework to which the shipping industry and countries must comply. It means that all ships of 400 gross tonnage or more must manage their ballast water in a way that is approved under the convention. A great deal of work has been done by academic and industrial researchers to devise onboard ballast water treatment options based on various approaches. The regulations essentially have created a new unconventional water source based on treated ballast water. Two approaches are used for such treatments: onboard filtration (desalination) and onshore treatment (desalination). As desalinization is applied as a ballast-water treatment, the end-product (desalinated water) is free of invasive aquatic organisms and unhealthy chemical compounds and is usable for other economic activities such as public water supply and irrigation. Recent developments in desalinization processes have made membranes even more efficient, cost-effective, and compact, which is a perfect combination to be used onboard and onshore to produce a reusable, unconventional water from a ship's ballast.

Keywords Ballast-water · Desalination · Filtration · Water-reuse · Ships

10.1 Introduction

The shipping industry accounts for around 90% of the global trade of raw materials, consumer goods, and essential foodstuffs (IMO 2018). As some of these products

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can only be moved by ship, the recent years have experienced a considerable increase in the tonnage capacity in all segments, except general-cargo carriers, reaching in 2019 a carrying capacity of 1.98 billion deadweight tonnage (dwt), 52 million dwt more than the previous year.

Ships face several challenging operational conditions (i.e., rough weather), including safety issues that are crucial to improve the effectiveness of the transportation process (Krata 2013). A ship's stability against capsizing and excessive heeling is one of the most important topics, not only for naval architects but also for ship operators. Throughout history, the stability of ships has been achieved by placing and distributing extra heavy material (also called ballast) in the bottom section of the vessels. Apart from the cargo, the material was used to improve stability and the safe operation of ships by lowering the vessel's center of gravity.

In the early days of navigation, sand was widely used as ballast by ships. However, loading and downloading the sand to and from ships was time consuming and labor intensive. Therefore, other heavy and compact materials, such as roof tiles and rocks, rapidly replaced sand. Due to its easy availability, rocks became the preferred option. Areas around ports were created to extract rocky material, as well as to receive the discharged rocks from vessels during deballasting operations. In Australia, the ballast brought by the colliers and other ships around 1870 were used on the streets of the city of Wollongong (Gardiner-Garden 1975).

Everything changed in the mid-1850s after the coal shippers in England built bulk carriers using water as ballast instead of dry material, becoming the easiest and cheapest option for the shipping industry (Carlton 1985). It has significantly decreased operating time for loading solid materials and dangerous instabilities due to the movement of solid ballast during a voyage (National Research Council 1996). Nowadays, all ships are fitted with ballast tanks, which can be filled with saltwater, freshwater, or brackish water. Ballast water is also used for other purposes rather than stability, such as adjusting the ship's trim, improving maneuverability, increasing propulsion efficiency, reducing hull stress, raising the ship to pass over shallow areas (reducing draft), and lowering it to get under bridges or cranes (reducing air draft) (Cohen 1998).

Ballast-water operations recently discharge around 10 billion tons (10 km^3) of water every year in foreign waters (Yang 2011). The volume of ballast hold in vessels varies according to their size and purpose, ranging from several m^3 in sailing and fishing boats to hundreds of thousands of m^3 in large cargo carriers (i.e., over 200,000 m^3 in large tankers) (National Research Council 1996). Although the use of water as ballast has improved the operability and safety of ships, it has also created serious environmental problems, including the translocation of invasive and harmful aquatic species (marine or freshwater) and chemicals in marine environments. Alien and non-indigenous species have negatively affected countries globally, not only regarding the local ecological equilibrium but also the economy and human health due to passive importation of bacteria, disease agents, and toxic harmful algae through ballast water (Gollasch and David 2019).

Globally, a detailed assessment of the economic impacts of invasive aquatic species has not been systematically done. However, it has been estimated that the direct economic loss due to invasive species may be in the order of $100 billion a year (IMO 2018). Based on almost all the coastal countries of the world with records of invasive species, the economic impact is shared by all.

The International Maritime Organization of the United Nations (IMO) initiated negotiations to develop an internationally binding instrument addressing the translocation of harmful aquatic organisms and pathogens in ships' ballast water after the UN Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992. The International Convention for the Control and Management of Ships' Ballast Water and Sediments (the Convention) was finally adopted in 2004 and entered into force in 2017. The Convention aims to prevent, minimize, and ultimately eliminate the risks to the environment, human health, property, and resources arising from the transfer of harmful aquatic organisms in ships' ballast water (IMO 2018).

The convention has driven the shipping industry to look for new technologies to treat ballast water efficiently, in accordance with the introduced regulations. Several options have since been developed applying diverse approaches, such as the use of microfiltration, which is largely being used in desalination plants. Therefore, ships fitted with microfiltration technologies will also be able to produce desalinated water, which can be reused as an unconventional water source at the receiving port. For example, a supertanker fitted with desalination technology and carrying 200,000 m^3 of ballast water would be able to supply enough water to a city of 50,000 inhabitants in Brazil (daily average use of around 155 L/capita) for 25 days.

10.2 Technological Interventions

The Convention requires all ships of 400 gross tonnage and above to possess an approved International Ballast Water Management Certificate. There are several options available for ballast water management under the Convention that can be chosen by the ships (Fig. 10.1). The following are the standard regulations of the Convention (Section D) for Ballast Water Management:

Regulation D-1 Ballast Water Exchange Standard—Ships performing Ballast Water exchange shall do so with an efficiency of 95% volumetric exchange of Ballast Water. For ships exchanging ballast water by the pumping-through method, pumping through three times the volume of each ballast water tank shall be considered to meet the standard described. Pumping through less than three times the volume may be accepted provided the ship can demonstrate that at least 95 percent volumetric exchange is met.

All ships using ballast water exchange should conduct ballast water exchange at least 200 nautical miles from the nearest land and in water at least 200 m in depth.

Regulation D-2 Ballast Water Performance Standard—Ships conducting ballast water management shall discharge less than 10 viable organisms per m^3 greater than or equal to 50 μm in minimum dimension and less than 10 viable organisms per milliliter less than 50 μm in minimum dimension and greater than or equal to

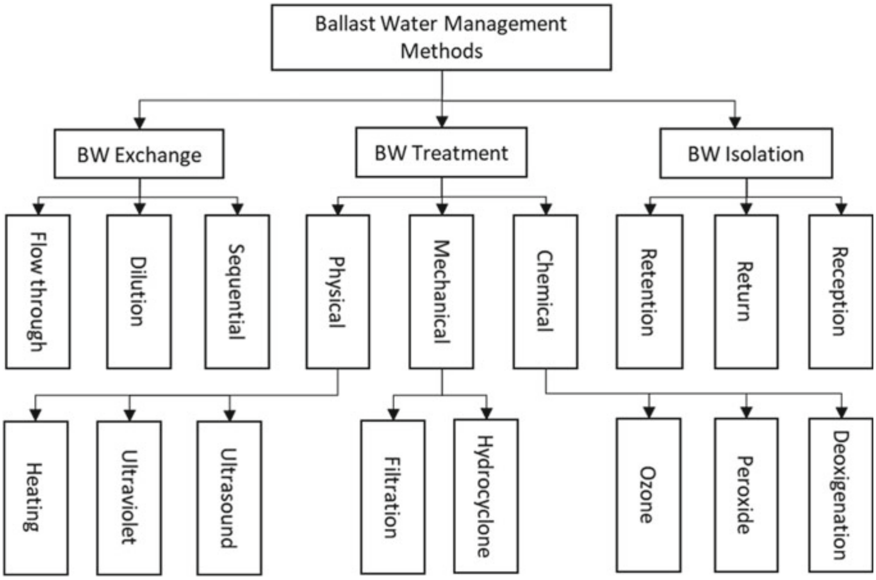

Fig. 10.1 Available options for onboard ballast water (BW) management (Modified from Yongming and Shuhong 2012)

10 μm in minimum dimension; and discharge of the indicator microbes shall not exceed the specified concentrations.

10.2.1 Ballast Water Isolation

Under the Convention, the principle behind the isolation method is that ships can manage their ballast water without deballasting directly into the waters of the destination port. The three accepted options are:

(a) Retention: ships do not need to deballast water as part of their normal operations; therefore, they can retain the water in the ballast tanks. Cruise ships are mainly in this segment because the change in their DWT is usually not very significant during operations so they can keep the same water for months or even years.
(b) Return: the ship is travelling back to its port of origin without deballasting at the destination port. Depending on its operationally, ship may transfer ballast water between its own tanks to allow them to travel back to its port of origin; and
(c) Reception: the receiving port has onshore ballast water-treatment facilities into which the water can be pumped without being discharged directly into the sea. The ballast water will then be treated under the applicable standards described

in the Convention before being either reused for other purposes or discharged back to the environment.

10.2.2 Ballast Water Exchange

Under the Convention (IMO 2018), the exchange method showed in Fig. 10.2 is based on the principle that organisms and pathogens contained in ballast water taken on board from coastal waters will not survive when discharged into deep oceans or open seas because these waters have different temperatures, salinity, and chemical composition. There are three methods stated under the convention for ballast-water exchange:

(a) Sequential Method: A process by which a ballast tank is first emptied and then refilled with replacement ballast water. According to the convention, efficiency is to be at least a 95% volumetric exchange.
(b) Flow-through Method: A process by which replacement ballast water is pumped into a ballast tank, allowing water to flow through overflow or other arrangements. At least three times the tank volume should be pumped through the tank.
(c) Dilution Method: A method by which replacement ballast water is filled through the top of the ballast tank with simultaneous discharge from the bottom at the same flow rate and maintaining a constant level in the tank throughout the ballast-exchange operation. At least three times the tank volume should be pumped through the tank.

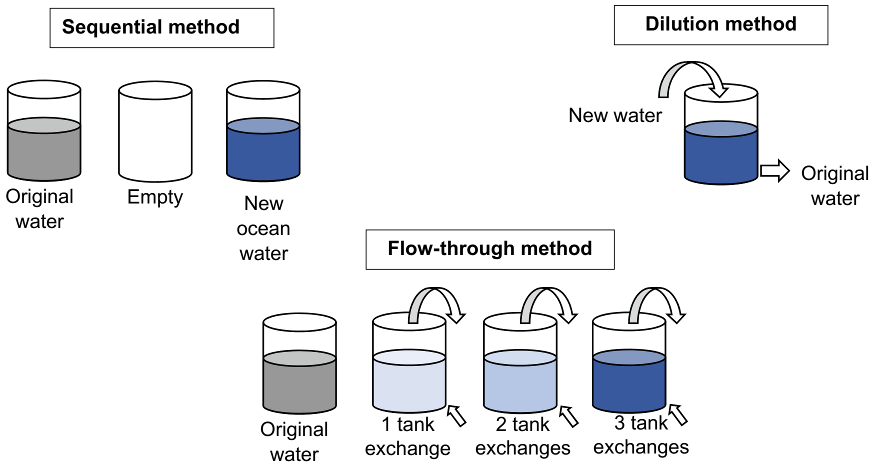

Fig. 10.2 Ballast-water exchange methods; Sequential, Flow-through, and Dilution method

Although these methods are very efficient when conducted properly, ballast-water exchange can be limited by weather conditions, ocean conditions, timing, and the distance to land, making it difficult to always perform.

10.2.3 Ballast Water Treatment Methods

Theoretically, all ships carrying ballast water can manage ballast according to the regulation D1 (ballast-water exchange). Adding to the distance of 200 nautical miles at 200-m deep, exchanging ballast water while enroute is a very complex operation with possibly disastrous consequences if not conducted properly (i.e., structural damages) (Endresen et al. 2004). Therefore, onboard treatment systems are better alternatives for the shipping industry to comply fully with the current regulations in place since they can operate independently of location (i.e., within 200 nautical miles) and some other limiting factors (i.e., time). Currently there are three methods of ballast water treatment: mechanical, chemical, and physical.

Mechanical: During the treatment process, the mechanical separation of aquatic organisms and sediments are divided based on their size (Szczepanek and Behrendt 2018).

(a) Filtration: In the early days of onboard treatment systems, simple filters placed on the ballast-water intake could not prevent small organisms and sediments from entering the ballast tanks (Fig. 10.3). Filters were required to be of a much finer pore size, which made filtration a pretreatment option to improve the performance of secondary treatment systems (Tsolaki and Diamadopoulos 2009).

(b) Hydrocyclone: The operation principle is based on the acceleration of particles and the separation of the light phase from the heavy phase due to different densities of existing materials. Although hydrocyclone has proved efficient to remove large particles, its efficiency was negligible in the elimination of organisms, especially bacteria (Kurtela and Komadina 2010)

Chemical: The principle of chemical treatment is to neutralize microbiological and biological contaminants (Fig. 10.4). Various chemical compounds and approaches are/have been used in isolation or combined with other treatment systems (i.e., filtration). The major disadvantages of the chemical treatments are the generation of

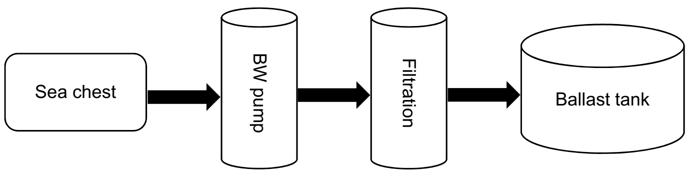

Fig. 10.3 Simple principal scheme for "filtration-only" treatment of ballast water (BW)

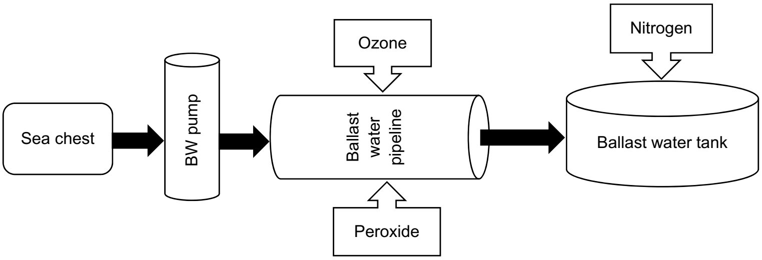

Fig. 10.4 Simple scheme for ballast water (BW) treatment principles for ozone, peroxide, and deoxygenation (by adding nitrogen)

disinfection by-products, the lifetime of the biocides used (i.e., not recommended for short routes), and the need to carry chemical products onboard.

(a) Ozone: It has been used for a long time as a disinfectant in water treatment plants, especially in Europe. Ozone is a very powerful agent to eliminate viruses and bacteria, including spores in freshwater. However, the presence of bromide ions in seawater has added a degree of challenge to achieve initially the same results (Tsolaki and Diamadopoulos 2009). Bromine compounds are the primary biocides generated by ozonation of seawater and are efficient in destroying aquatic organisms, but total residual oxidants can be long-lived in water tanks, making them unsuitable for discharge at ports (Wright et al. 2010).
(b) Peroxide: Hydrogen peroxide (H_2O_2) is an uncharged molecule, which can be used as a disinfectant, by diffusion passes easily through cell membranes. When inside the cells, the reactive and destructive hydroxyl radicals are liberated by H_2O_2 eliminating aquatic organisms (Smit et al. 2009).
(c) Deoxygenation: The principle of this method is based on reducing/removing oxygen from the ballast water tanks, leading to the elimination of aquatic organisms. It can be achieved by creating an anoxic environment by either adding nutrients to the ballast tanks to encourage the growth of bacteria or injecting an inert gas (i.e., nitrogen) to inhibit oxygen from entering (McCollin et al. 2007).

Physical: Physical disinfection is widely applied in freshwater treatment systems. It is based on the application of a variety of physical fields, such as ultraviolet rays and ultrasound for disinfection (Fig. 10.5). Also referred to as ‘reagent less’ technique, the physical disinfection acts directly on microorganisms without changing the properties and composition of the water or creating unwanted disinfection by-products (Biryukov et al. 2005). Although the physical methods have proved their efficiency in destroying aquatic organisms, usually they are combined with mechanical treatment (i.e., filtration or hydro cyclones) to increase effectiveness.

(a) Ultrasound: Ultrasound generated by converting mechanical or electrical energy into high-frequency vibration causes the formation and collapse of

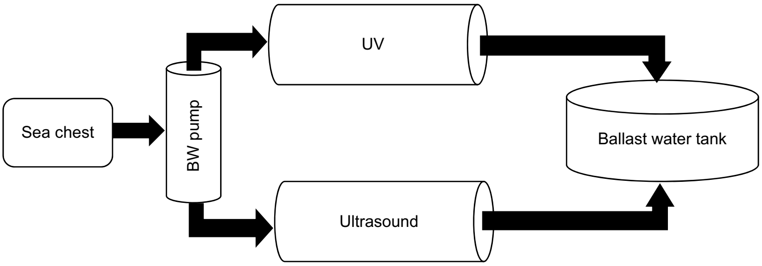

Fig. 10.5 Simple scheme for ballast water (BW) treatment principles using ultraviolet (UV) and ultrasound methods

microscopic gas bubbles in the incoming ballast water, leading to rupture of cell membranes and collisions with other aquatic organisms (Ta et al. 2005).

(b) Ultraviolet: The water-supply sector has been successfully using ultraviolet radiation (UV) for disinfection of drinking water and wastewater. Nucleic acids (DNA and RNA) and cell proteins of aquatic organisms are impacted by UV radiation through photochemical reactions leading to the inactivation of the organisms (Ta et al. 2005). Although UV treatment has been proven to be an effective bactericide and virucide, its effectiveness is related to the size and the morphology of organisms, as well as to the proper dosage application (Tsolaki and Diamadopoulos 2009).

(c) Heating: The heating treatment is based on the increase in the seawater temperature to a level that inactivates the aquatic organisms (Fig. 10.6). The method uses an existing heating system onboard (the engines), which would otherwise be heat that is lost (Mesbahi et al. 2007). Although a promising method, heating has not been a first option for the shipping industry unless used in combination with another method. This is due to the impracticality of heating huge ballast water volumes and the energy costs for heating at the effective temperature (~60–65 °C) and short port stays and voyage periods.

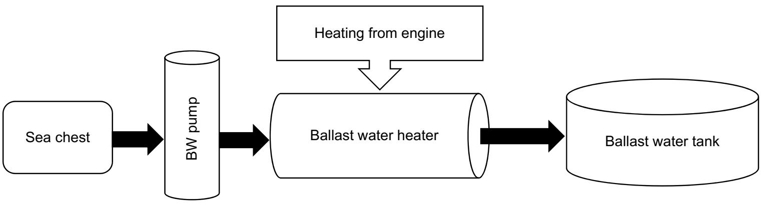

Fig. 10.6 Simple scheme for ballast water (BW) treatment principle using heating systems

10.3 History

Since Charles Darwin's memorable travel around the world on the HMS Beagle (1831–1836), several naturalists have also touched on the issue of invasive species. In 1936, the British ecologist Charles Elton reviewed Nicolaus Peter and Albert Panning monograph on the dispersion of the Chinese Mitten crab (*Eriocheir sinensis*) in Europe. The monograph linked the dispersion to ship's ballast water after two large crabs were found in the tanks of a Hamburg-American steamer in 1932 (Elton 1936). Later, in 1958, Charles Elton published the milestone book entitled *The Ecology of Invasions by Animals and Plants,* which is considered the foundation for all the following work in the field of invasive species (Kitching 2011). In his book, Elton emphasized that ships have been 'the greatest agency of all that spreads marine animals to new quarters of the world' (Fridley 2011).

10.3.1 Development

It was not until 1985, when James Carlton published the '*Transoceanic and interoceanic dispersal of coastal marine organisms: the biology of ballast water*', that addressed ballast-water ecology in detail. Carlton's publication brought light to the modern understanding of patterns and processes of ballast water as a vector of aquatic invasions globally (Davidson and Simkanin 2012). Consequent to this publication, the research field of ballast water as a vector has developed considerably, leading to the development of guidelines for ballast water management and finally the Convention (Fig. 10.7).

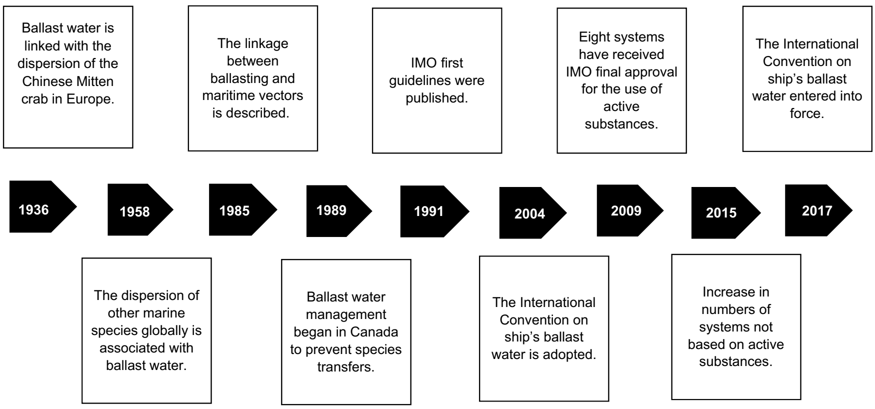

Fig. 10.7 History line of major developments in ballast water management

10.3.2 Progress

As the science behind ballast water as a vector bridged the knowledge gap, researchers began to explore avoiding the translocation of aquatic organisms in ballast tanks. In the beginning, exchanging ballast water at open sea was considered the most practical and feasible way of eliminating invasive species. Unfortunately, ballast water operations at open sea is not an easy task, as discussed previously. Therefore, other practical ways of avoiding the translocation of aquatic organisms were needed.

The first approaches were based on the use of active substances (biocides) that have been used in other sectors to eliminate unwanted organisms (i.e., in water supplies). Although very efficient in killing noxious organisms, active substances also have their own challenges when used onboard a ship, including:

(a) Chemical compounds must be stored onboard and handled by the ship crew.
(b) Possible corrosion of ballast water tanks.
(c) All active substances have a certain lifetime for their capacity to destroy noxious organisms, and the lifetime differs from one substance to another. It is important to note that in short journeys between ports in neighboring countries, the ships using biocides to treat ballast water may be deballasting substances that are still active at the receiving port. This means that the active substance being discharged could also target the local aquatic community.

Such challenges have driven the development of more environmentally friendly treatment systems not based on active substances. The last decade has experienced the development of other options free of active substances that applicable to be used on onboard and onshore.

10.4 State-of-the-Art

Initial developments in ballast water treatment systems were only focused on efficiently deactivating aquatic organisms as requested by the Convention. In this regard, several methods were developed to help the shipping industry to comply with the internationally agreed regulations. In a study made by the IMO in 2015 on the treatment systems approved and commercially accessible for the shipping industry, filtration systems were the most common method and used by 80% of the ships evaluated. This was followed by electrolytic disinfection systems (~40%), ultraviolet irradiation (32%), and the use of chemical biocides with almost 17% (Batista et al. 2017).

10.4.1 Onboard Treatment

Although it is the preferred option for most ships, filtration is usually used as a pretreatment to remove larger-sized classes of organisms and organic particles due to the pore size of filters. This is because the initial filtration technology used onboard to treat ballast water could not successfully deactivate small aquatic organisms (Werschkun et al. 2012) without affecting the ship's operation. The time needed to cope with the large volume of ballast water and the blockage of filters with smaller pore sizes were the principal issues.

The last decades have experienced a rapid development of new filtration technologies, especially microfiltration and reverse osmosis (RO). The RO is the most-used technology for desalination worldwide. The semipermeability of polymers is the basis of the RO process since polymers are highly permeable to water with a relatively lower permeability for dissolved substances producing a high-quality product (Ehteram et al. 2020). However, without pretreatment, RO membranes can be impacted by biofouling that results in membrane deterioration and high-energy costs (Ibrahim et al. 2020). In this regard, microfiltration membranes have proven to be an effective pretreatment to deliver high-quality water for the RO process. Microfiltration membranes separate large molecular weight suspended or colloidal compounds from dissolved solids (Maddah et al. 2018). Guilbaud et al. (2015) assessed the potential of microfiltration membrane treatment for cruise ships and liquid natural gas (LNG) carriers. The study proved the potential of using microfiltration membrane to deactivate aquatic organisms in compliance with current regulations. Although the study also concluded that the microfiltration process is more effective for cruise ships in terms of size and capital cost than for LNG carriers, it highlighted that the situation will change rapidly as manufacturers develop increasingly compact membrane systems.

Being a busy port and located in a water-scarce region, the Emirates are extremely dependent on desalinated water for its economic activities and public supply. Wang and Tsai (2014) investigated the cost and benefits associated with supplying onboard desalinated ballast water brought in by oil tankers and LNG carriers to Abu Dhabi, using waste heat recovered from propulsion. At the receiving port, the desalinated water is transferred to an onshore plant for final processing before it is sold to the end users. Based on three scenarios (high, most likely, and low water demand), the study concluded that the onboard ballast water desalination system generates a saving of $772 million, $718 million, and $602 million when combined with conventional desalination plants. The study showed that integrating desalinated water from ballast operations in Abu Dhabi is economically feasible.

10.4.2 Onshore Treatment Facilities

Ballast water operations bring dissolved and particulate material into the ships. Particulate material is then deposited on the bottom of the ballast tanks during the ship's journey and are not usually discharged during deballasting operations. When sediments accumulate in the tanks to a level that impact the normal operation of a ship, then the sediments must be removed and managed properly in a receiving sediment-management facility during maintenance operations in shipyards (GloBallast 2017). Different from the port facilities specialized in managing sediments, the "reception" facilities are onshore treatment systems designed to treat ballast water from incoming ships before its disposal. Initial developments in onshore facilities were done to address ships unable to be retrofitted to accommodate ballast water treatment systems and/or to attend to ships experiencing failure of their onboard systems.

Although onshore treatment is not new, the concept of treating ballast water at the destination port has not received much attention, especially due to possible high investment in ports' infrastructure. Onshore facilities have several advantages over onboard systems, including (Donner 2010):

(a) Economy of scale: Onshore facilities can operate uninterrupted by serving a multitude of ships, which is more economically rationale rather than running a system onboard only during ballast-water operations;
(b) Ships' crew: Officers and crews of merchant ships may work on several ships from the same company. Although training is provided to them to operate onboard ballast water treatment systems, different ships may operate different systems causing possible mismanagement. The crew members are also not experts in the fields of marine biology or the physical, chemical, or biological processes to treat ballast water that my exist on different ships; and
(c) Monitoring: Onshore facilities can be monitored easily by local regulators making sure that the treatment is achieving the levels of protection required under the current regulations (Pereira and Brinati 2012).

Currently, with the latest technological developments on treatment systems and mobile facilities, onshore systems are getting more attention as an economically viable option and a business opportunity for port operators. Probably the only modification needed for small/medium-sized conventional desalination plants to treat ballast water onshore is the proper management of aquatic organisms as biological waste. As discussed previously in this chapter, the desalination process can deliver not only a water biologically free of aquatic invaders but also a new product (freshwater) that can be sold for other economic activities.

The quantity, timing, and type of ships entering or leaving the port area would define the size of the treatment facility (Tsolaki and Diamadopoulos 2009). Retrofitting a port to install the necessary infrastructure to receive, treat, and finally deliver desalinated ballast water to end users can be an expensive exercise. In this regard, compact filtration treatment systems, which might be seen as too bulky to be placed on ship, can be the solution as mobile onshore treatment facilities. Containerized desalination systems can be placed on barges, making the service mobile and capable of storing the desalinated water to be later transferred to a receiving facility for distribution.

10.5 Major Barriers and Response Options

The ballast water treatment systems were originally projected with the objective of deactivating aquatic organisms that otherwise could become biological invaders at the destination port. Under such an approach, several methods that are not applicable to produce desalinated water have been developed (i.e., ultrasound) as a viable solution. The latest technological developments in seawater treatment (i.e., microfiltration) have been reformulating the prospects for using ballast water as an unconventional water source to supply water for onshore economic activities, especially in regions where water is a scarce commodity. Table 10.1 presents major barriers and respective response options for using ballast water when considered as an unconventional water source.

10.6 Conclusions

The considerable amount of water moved globally by the shipping industry each year as ballast should not be neglected, not only due to its negative impacts but also because of its potential as an unconventional water resource. The impacts on the environment, economy, and public health have been extensively assessed and described by the international literature. As a result, the International Convention for the Control and Management of Ships' Ballast Water and Sediments was developed and is now in force. As defined under the Convention, all ships must manage their ballast water in a way that avoids negative impacts. However, the opportunities for reusing treated ballast water for other means (i.e., irrigation) have been overlooked until recent years.

Recent technological developments in microfiltration have brought a new perspective on the reuse of treated ballast water for other economic activities. The applicability of using seawater-desalination technology as an option for ballast-water treatment onboard and onshore is making ship's ballast water a feasible source of unconventional water. Port cities located in water-scarce countries would benefit greatly by receiving desalinated water from ships and/or onshore treatment facilities to augment their water supply. Ships fitted with desalination systems would be able to offset some of their running costs by selling desalinated water to receiving cities. Ports with onshore ballast water-treatment facilities running desalination systems will also be able to sell the treated ballast for reuse in port cities. Such an approach will give them another revenue opportunity to defray the rates paid by ships to treat their ballast water.

Unfortunately, the onshore treatment of ballast water through desalination processes is still in its infancy, with mainly desktop simulations done in the last decade to demonstrate its economic and technical viability (Donner 2010; Wang and Tsai 2014; Pereira and Brinati 2012 and Pereira et al. 2017). These studies have shown that not only is desalination treatment for ballast water (especially onshore)

Table 10.1 Major barriers and response options for using ballast water (BW) as an unconventional water source

Major barriers	Response options
Onboard treatment	
The primary objective of BW treatment systems was not to produce desalinated water	Current perspectives of desalinated water reuse in port cities under water stress can drive the shipping industry to adapt their ships' treatment systems to also making profit by producing and selling reusable desalinated water
Old filtration technology (mesh size) was not suitable for coping with the volume of ballast water and removing dissolved and particulate salts. For this reason, it was mainly used as a pretreatment option to remove larger particles	New technological developments in microfiltration, which is widely used in modern desalinations plants, are now capable of removing aquatic organisms and dissolved and particulate salts from ballast water
Microfiltration consumes considerable energy to push water against the membranes. It also needs extra room onboard to be able to filter the volume of ballast water entering the BW tanks	Energy recovered from the ship (i.e., waste-heat energy from cooling the engines) can be used to provide the required energy. Nowadays, compact 'containerized' desalination units can be easily fitted onboard
Infrastructure needed to make treatment facilities able to receive and treat BW efficiently and in a timely manner (i.e., connections between the treatment stations and all berths)	Mobile treatment units (i.e., on trucks or barges) with storage capacity could reduce the necessity of major updates in ports' structure. New or renovated ports could include BW treatment facilities as part of the planned infrastructure
Capacity of the treatment system to cope with high volumes of BW in busy ports, which can cause delays in port operations	Busy ports might invest in a more substantial infrastructure to cope with high volumes of BW if selling treated water (desalinated) becomes a business opportunity. In busy ports it would be available only to older ships that cannot be retrofitted with a BW treatment system or to service ships on which the onboard treatment system has failed during the journey. Less busy ports can be a more feasible option as they receive fewer ships
Water authorities	
Lack of knowledge of the potential that BW has as an unconventional water source	Raising awareness of the huge potential of using ballast water as an unconventional water source, especially for port cities located in water-scarce regions
No clear water-management policies that consider unconventional water sources (i.e., ballast water) as an integrated part of the water cycle	Development of new policies integrating unconventional water sources (i.e., ballast water) as a feasible and viable option for water–scarce countries and cities

(continued)

Table 10.1 (continued)

Major barriers	Response options
Urban planning approaches do not consider sourcing water from unconventional sources (i.e., ballast water), especially in port cities located in water-scarce regions	Integration of BW as an unconventional water source at the urban planning level for port cities, especially those in water-scarce regions

a secure and viable option to prevent marine invasions, and they also provided an economic analysis of the investments needed and the financial returns.

Key recommendations/considerations:

- Port cities in water-scarce countries/regions would benefit most if desalinated ballast water from treatment facilities (onboard and onshore) were made available. However, a global–cost benefit analysis overlaying water availability and needs, and the traffic of ships at a port is yet to be done. Such a study would indicate the economically feasible port cities to receive investments in the necessary infrastructure;
- Public policies designed to create/develop a market to desalinate ballast water for reuse in other economic activities (i.e., irrigation) are still missing, including the regulatory frameworks.
- Establishment of financing mechanisms for the private sector to invest in onshore treatment and/or receiving facilities, as well as for the associated infrastructure for treated water distribution, would facilitate the development of the field.
- Mainstreaming the work on unconventional water within the shipping industry (including port operations) will certainly open new business opportunities for ship owners (i.e., recovering costs by selling desalinated water), port operators (i.e., treating and selling desalinated water), and city water managers (i.e., augmenting the water supply portfolio).

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