

Impacts of Seawater Desalination on Marine Ecosystems

Yinuo Zhang

High School Attached to Shandong
Normal University, Jinan, China
zhangyinuo joe@163.com

Abstract:

With the global freshwater scarcity, Seawater desalination particularly through reverse osmosis (RO), is a solution to address the problem. Nowadays, seawater desalination is used in various countries, like The United Arab Emirates (UAE), Africa and China, etc. However, despite its huge benefits, the technology is also accompanied by adverse environmental effects, like brine discharge which can lead to localized changes in salinity and subsequently affect the water quality and biodiversity of the area. Huge energy consumption is another issue, as most seawater desalination plants need the electrical energy to control the high-pressure pump which means the enormous energy requirement. Noise pollution, CO₂ emissions, biofouling and invasive species also impact on marine ecosystems. These effects can be minimized by innovative solution, such as improving RO membrane, zero liquid discharge technology, renewable energy technologies, energy recovery devices and continuous environmental monitoring and regulation. This paper investigates ecological consequences in seawater desalination processes, highlights the potential adverse effects, and discusses the mitigation measures.

Keywords: Seawater Desalination; Marine Ecosystems; Brine discharge; Energy Consumption; Marine Biodiversity.

1. Introduction.

Fresh water is scarce, and its global availability is decreasing. More than 2 billion people suffered by water stress and about 3.6 billion people undergoing water scarcity for at least one month per year. By 2050, the quantity of suffered people in the world is anticipated to about 5.7 billion. Desalination is gradually becoming an important method to solve this

problem. By 2022, global total daily seawater desalination capacity approximately exceeded 80 million cubic meters [1]. Despite its critical role in freshwater provision, the ecological impacts of desalination remain a major concern. This is primarily because most seawater desalination techniques, such as reverse osmosis, multi-stage flash desalination, and multi-effect distillation, can only acquire less than 50% of freshwater from the feed stream. The remain-

ing portion which contains most of the dissolved solids and pre-treatment additives, is managed as brine effluent. As byproducts of desalination plants, concentrated brine and carbon emissions lead to thermal pollution, effect the climate, and become a threat to the environment. This review provides a comprehensive analysis of the ecological implications of seawater desalination and explores mitigation measures.

2. Overview of Seawater Desalination Technologies

Seawater desalination technologies developed rapidly, primarily include thermal and membrane-based methods. The most widespread desalination technologies are reverse osmosis (RO) and multi-stage flash (MSF) but other technologies such as multi-effect distillation (MED), membrane distillation (MD) and Electrodialysis (ED) are currently being developed.

Reverse Osmosis (RO) is accounted as one of the essential methods for seawater desalination. RO is a procedure that use pressure push seawater through a semi-permeable membrane to separate pure water and salt solution. RO effectively removes most dissolved salts, microorganisms, and organic compounds from seawater [2]. MSF and MED are technologies intending to facilitate the recovery of condensation latent heat, and then can maintain low temperatures. By decreasing the vapor pressure, rapid water evaporation can be achieved in the upper space, and then removing water vapor from the device can decrease the energy consumption during operation. Membrane distillation (MD) means a groundbreaking approach to water separation. In this system, raw water is received to heating, making vapor to permeate through hydrophobic membrane materials which situated on one side. Consequently, the water vapor molecules undergo a phase transition on the opposite side of the membrane, and then transforms back into liquid water by the introduction of cold flow. Electrodialysis technique (ED) is a method that extracts salt from seawater through thin channels and uses ion-exchange membranes to exchange positive and negative ions. When seawater flows the membranes, an electrical current pushes the cations and anions exchange respectively, so contribute to high efficiency in seawater desalination [3].

3. Environmental Impacts of Seawater Desalination

Seawater Desalination may impact environment on many pathways: the occupancy land, the brine discharge, the

groundwater, the marine ecosystems, thermal pollution, and finally energy consumption.

3.1 Impact of land use and water Conservation

The seawater desalination plants, especially in coastal areas, convert a beautiful tourism into an industrial zone. If pipelines carrying seawater are put above the aquifer, in some case of sealing failures in valves and pipelines, the groundwater may be contaminated, leading to decreased groundwater quality, directly influencing human health.

Although seawater desalination can provide large amounts of freshwater, its long-term operation may not effectively address the root causes of water scarcity. In some areas, desalination may be perceived as a substitute for traditional water management practices, thereby neglecting the importance of water conservation and sustainable water resource management. Over-reliance on desalination could exacerbate the over-extraction of natural water sources, thereby disrupting natural water cycles [4].

3.2 Impact of Brine Discharge on Marine Ecosystems

One of the by-products of both RO and thermal seawater desalination is brine, which is water with a much higher salinity than the original seawater. When directly discharged into the ocean, brine can lead to localized changes in salinity and subsequently affect the water quality and biodiversity of the area. The disposal of brine can cause a number of ecological problems.

Brine discharge from desalination plants contains salt concentrations several times higher than the natural seawater. The release of large quantities of brine into the ocean can change the salinity of surrounding water and the physical and chemical character of seawater. Marine organisms are highly sensitive to salinity fluctuations, especially those species with low tolerance to salt, such as certain fish, seaweed, and shellfish which may face growth and reproduction challenges. Changes in salinity caused by brine can interfere with spawning cycles, egg hatching rates, and survival rates of juveniles. Tay et al. [5] reported that changes in water quality due to brine discharge affected reproductive success in certain marine species. This disrupted the local populations of these species and altered the dynamics of the ecosystem. A case Study indicated that some desalination plants in the UAE have caused significant changes in salinity and temperature in surrounding marine areas, affecting local fisheries [6]. The ability of marine species to adapt to increased salinity is influenced by several factors, including species' natural tolerance limits, the duration of exposure, and the rate of salinity change. Species such as coral reefs, which have

narrow salinity tolerance ranges, may be particularly vulnerable to brine discharge. Lee et al. pointed out that brine discharge leads to an increasing salinity around the discharge area, and in extreme cases, this may force species that were once well-suited to the area to relocate or perish, disrupting the stability of the ecosystem [7].

3.3 Chemical Contaminants and Heavy Metal Pollution

Brine from desalination plants may carry chemical additives (such as disinfectants) and heavy metals (like lead, mercury, and arsenic) from seawater. These pollutants can be toxic to marine organisms, especially those higher up in the food chain. El-Baz et al. [8] observed that brine discharge containing heavy metals and chemicals poses long-term negative effects on marine ecosystems. Fish and shellfish in the brine discharge zone exhibited higher levels of toxic substances, which may eventually affect human food safety through bio-accumulation.

Chemical Persistence and Toxicity are important factors. Some of these chemicals, such as chlorine and anti-scalants, can persist in the environment and bio-accumulate in marine organisms. For example, chlorine is known to be highly toxic to marine life, causing gill damage, reduced growth, and mortality in fish and invertebrates. Additionally, many biocides and disinfectants used in desalination plants can disrupt the reproductive processes of marine species by acting as endocrine disruptors. Studies on the Long Beach desalination plant have demonstrated that chemical additives used during the desalination process can have lethal effects on marine organisms, particularly on larval fish [9]. Another study found that the anti-scalants used in reverse osmosis membranes contributed to the accumulation of toxic substances in surrounding coastal ecosystems [10].

Oxygen Depletion: Brine often contains lower levels of dissolved oxygen, and its discharge can reduce the oxygen content in the local water, which in turn threatens marine organisms, particularly those species that depend on high-oxygen environments.

3.4 Energy Consumption and Its Indirect Environmental Impact

Seawater desalination technologies are primarily classified into two categories: reverse osmosis (RO) and thermal distillation (such as multi-stage flash (MSF) and multi-effect distillation (MED)). The energy consumption varies significantly between these technologies, both of which require substantial energy input to drive the desalination process. In general, many parameters may affect energy use and the choice of technique for desalination [11]. The

heating requirements are electrical power for thermal desalination techniques, which range from 40 kWh/m³ to 80 kWh/m³. At the same time, for its auxiliary equipment, it uses 2.5 kWh/m³ to 5 kWh/m³ of power. The most commercially viable desalination plant uses an average of around 100 TWh of energy annually, which causes emissions of 60–100 Mt of CO₂ [12–13]. So each technology should have an efficient solution to minimize the energy consumption and reduce CO₂ emissions. According to International Energy Agency, facilities relying on conventional energy sources are important point contributors of CO₂ emissions in regions with limited renewable energy deployment [14].

3.5 Noise Pollution and Its Ecological Impact

Noise generated by desalination infrastructure is another ecological stressor. High-pressure pumps, motors, ventilation systems, and brine discharge operations all produce mechanical and underwater noise. These disturbances can affect marine species that rely on echolocation, such as whales and dolphins, by interfering with navigation and communication. Prolonged exposure to underwater noise has also been shown to reduce reproductive success and alter the behavior of fish and invertebrates [15,16]. In ecologically sensitive or protected areas, continuous noise emissions may disrupt food webs and force species to abandon critical habitats [17].

3.6 Biofouling and invasive species

Biofouling and invasive species present additional risks. Reverse osmosis membranes are prone to microbial adhesion and biofilm formation, which degrade system performance and can facilitate the transfer of microorganisms into the marine environment. Certain pathogenic microorganisms, including *Escherichia coli* and *Vibrio cholerae*, have been detected in poorly managed desalination systems. Even highly efficient membranes may fail to completely remove small viruses under conditions of aging or damage, allowing pathogens such as norovirus to contaminate treated water [18–20]. Leakage risks, including microcracks in membranes or sealing failures in pipelines and valves, may also lead to cross-contamination between seawater and product water, complicating quality control and increasing ecological risks [21].

3.7 Impacts on Marine Biodiversity

The discharge of brine and the associated chemicals can change the physical and chemical characters of marine ecosystems. These sudden changes in environmental conditions can stress marine organisms, particularly plankton and benthic species, leading to a loss of biodiversity.

Several studies have indicated that elevated salinity and the presence of toxic chemicals can disrupt reproductive cycles, growth, and survival of marine species, particularly in sensitive habitats such as coral reefs and seagrass meadows. Abdelrhman et al. [22] found that prolonged brine discharge led to significant changes in the species communities in the surrounding areas. Some species disappeared or diminished, and were replaced by those more tolerant to high salinity environments.

3.8 Thermal Pollution

Thermal pollution is another significant concern, especially for thermal desalination plants. The release of heated seawater into the environment can raise the temperature of local marine ecosystems, disrupting the delicate balance of marine life. Some species are particularly sensitive to temperature changes, and the increased water temperature can lead to changes in species composition, reduced biodiversity, and increased mortality rates among temperature-sensitive organisms.

4. Mitigation Measures for Environmental Impacts

There are several strategies to minimize brine disposal. Discharging brine into deep-sea areas, where salinity changes are less disruptive and biological activity is lower, can reduce the local ecological impact. While mixing and Dilution Technologies, such as ocean currents or air bubbles can dilute the brine, reduce its salinity increases. More advanced approaches, including zero liquid discharge (ZLD), aim to recover nearly all pure water from brine and leave solid residues for safer disposal or industrial reuse. In some cases, concentrated brine can be repurposed for salt production or other industrial processes, thereby reducing direct release into marine environments. Energy consumption is another pressing concern. The implementation of renewable energy technologies is the main purpose of research. The integration of solar energy, geothermal, and umidification–dehumidification systems into desalination plants has already shown success in regions such as the United Arab Emirates (UAE), where solar-powered reverse osmosis facilities have achieved lower carbon footprints and reduced operating costs [13]. Waste heat recovery and advanced energy recovery devices provide additional opportunities for reducing fossil fuel dependence and greenhouse gas emissions, ensuring a more sustainable operation of desalination facilities. Technological innovation is also vital for reducing ecological pressures. The development of low-impact desalination technologies, including high-efficiency reverse osmosis

membranes, anti-fouling coatings, and hybrid systems, can significantly reduce both energy demand and brine-related impacts [23]. Water recycling initiatives, where treated seawater is reused in industrial or agricultural applications, further enhance resource efficiency and alleviate environmental burdens. Finally, Strategies and policies need to be considered to protect the environment when making the planning, establishment, and operation on desalination facilities.

5. Conclusion

Seawater desalination is known as a vital strategy to solve the freshwater shortage. The potential negative effects of desalination, such as brine discharge, energy consumption, noise pollution, chemical contamination, and thermal pollution require careful management and technological innovation to minimize ecological harm. Future research and technological advancements should focus on advancing innovative membrane technologies to enhance efficiency, zero liquid discharge (ZLD) technologies, advantageous uses and final disposal options for the concentrate generated during desalination, further integrating renewable energy sources to power desalination plants, and the application of artificial intelligence (AI) to improve system function and maintenance. Furthermore, effective policy and ecological monitoring will be essential to achieve a long-term sustainable desalination operation.

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