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REVIEW

Environmental Impact Assessment of Water Desalinating Systems: Kuwait as a Case Study

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Abstract

The challenge of managing water resources is intensifying due to rapid urbanization, population expansion, and the growth of industry and agriculture. Furthermore, the looming threat of climate change significantly impacts both water resources and crop yields. In Kuwait, the majority of its potable water supply is dependent on seawater desalination. Specifically, multistage flash (MSF) desalination accounts for nearly 90% of the country's total desalination capacity, while the remaining 10% is generated using multi-effect distillation (MED) technology. Nevertheless, the environmental repercussions of desalination on Kuwait's ecosystem remain a subject of profound concern. This study employs a comprehensive approach, utilizing peer-reviewed journal articles in conjunction with data and reports from governmental and corporate institutions, to delve into the extensive ramifications of desalination in Kuwait. This exploration encompasses the scale of desalination operations, their impact on the coastal marine environment, and the resultant carbon footprint. Upon meticulous analysis of available data pertaining to desalinated water production and energy consumption, our findings indicate that Kuwait produced a staggering 740.10 million cubic meters of desalinated water per year as at the year 2022. Additionally, the research reveals that desalination in Kuwait contributes significantly to various environmental metrics, which bear direct relevance to understanding the impact of brine discharge on critical ecosystems, such as seagrass meadows, which are prevalent in the Mediterranean seabed. Furthermore, they provide valuable guidance for decision-makers as they endeavor to reduce net carbon emissions and navigate the complex landscape of environmental stewardship.

Keywords: Kuwait, Multistage flash distillation, Reverse osmosis, Environmental impact assessment (EIA), Seawater desalination

1. Introduction

The demand for freshwater resources has reached critical levels across the globe due to a combination of population growth, urbanization, and industrial expansion. As a result, many regions are facing acute water scarcity, necessitating the exploration of innovative solutions such as water desalination to address this pressing issue. A water desalination system is a crucial technology designed to address water scarcity by converting seawater (SW) or brackish water (BW) into freshwater suitable for various uses, such as drinking, irrigation, and industrial processes (Curto et al., 2021; Ungureanu et al., 2018). This process involves the removal of salts and impurities from the source water to make it safe and useable. Various desalination technologies are employed, including thermal methods like MSF distillation and multiple-effect distillation, as well as membrane-based processes like reverse osmosis (RO) (Curto et al., 2021; Jones et al., 2019; Islam et al., 2018). Among the countries most severely affected by water scarcity is Kuwait, a small, arid nation located in the

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Arabian Peninsula. Kuwait's geographical location, characterized by a desert climate and minimal annual rainfall, presents an acute scarcity of freshwater resources (Al-Zubari et al., 2017; Alhumoud et al., 2010; Uddin et al., 2011). This scarcity necessitates the utilization of desalination methods, mainly seawater desalination, to meet the water demands of its population and sustain its economic activities (Islam et al., 2018; Al-Zubari et al., 2017; Alhumoud et al., 2010; Uddin et al., 2011; Al-Dousari, 2009). The Gulf nation has embraced a paired approach, integrating expansive desalination facilities with power generation plants. These combined systems, situated along the coastline, draw substantial quantities of water for distillation and cooling purposes (Al-Zubari et al., 2017). However, the rapid expansion of desalination facilities has raised environmental alarms due to the potential adverse effects on marine ecosystems, energy consumption, and greenhouse gas emissions (Roberts et al., 2010; Lattemann and Höpner, 2008; Xevgenos et al., 2021; Ibrahim and Eltahir, 2019; Lattemann Sabine and Höpner, 2008). A significant volume of byproduct known as brine is generated from water desalination process, necessitating its discharge into the Gulf waters. Meanwhile, the effluent released from the desalination plant exhibits a notable rise in salinity levels and an increase in temperature. Moreover, this discharged wastewater contains significant concentrations of chemical contaminants. Notably, chloride, employed to manage biofouling within the plants, is present, along with anti-scalant agents used for scale inhibition. Additionally, heavy metals, stemming from corrosion processes, are also present in the wastewater (Altayaran and Madany, 1992; Al-Ghadban and Al-Ajmi, 1993; Alfadhli and Alhashemi, 2019). As the world grapples with the dual challenge of water scarcity and environmental preservation, conducting a comprehensive environmental impact assessment of water desalination systems becomes imperative. The primary objective of this study is to perform a detailed environmental impact assessment of water desalination systems in Kuwait, analyzing both the direct and indirect consequences on various ecological, social, and economic aspects. The study aims to identify potential negative impacts of certain elements of water desalination that affect the environment, including waste discharge from desalination facilities, water temperature pollution, salinity pollution, and greenhouse gas emissions. Desalination, particularly through thermal distillation and RO techniques, is notably energy-intensive. The substantial energy requirements of these processes often lead to increased greenhouse gas emissions, especially when powered by fossil fuels. Additionally, desalination generates a by-product known as brine, a highly concentrated saltwater solution. The disposal of brine into the ocean poses significant risks to marine ecosystems due to its elevated salinity and, occasionally, its chemical additives, which can disrupt marine life and alter the local marine habitat. The maintenance and operation of desalination plants involves the use of various chemicals, including anti-scalants and chlorine, which, without adequate treatment prior to discharge, pose a threat to marine organisms. Furthermore, certain desalination techniques discharge warm water into the sea, creating thermal pollution with potential adverse effects on temperature-sensitive marine species. After assessing the extent of their impacts, mitigation measures are proposed to guide sustainable decision-making in water resource management.

1.1. Desalination in Kuwait

Kuwait has a hot, arid climate with only 110 mm of annual rainfall on average. The Shatt Al–Arab River, which receives its water mostly from the Euphrates, Tigris, and Karun, is the only northern source of freshwater input into the Gulf. The volume of freshwater that enters the Arabian Gulf has significantly decreased as a result of hydrological interventions along these rivers in recent years. Groundwater, desalinated saltwater, brackish groundwater, and treated wastewater effluents are the only sources of fresh water (Aleisa and Alshayji, 2019; Abusam and Shahalam, 2013; AL-Jarallah, 2013). The distribution of water resources in Kuwait is presented in (Table 1). Kuwait has six million m^3 of annual conventional freshwater resources, but in the year 2000, the country's annual water consumption exceeded 350 million m^3. Only a little amount of fresh subterranean water, with an estimated natural reserve of roughly 180 million m^3 was found in two fields (Hamoda, 2001). The only natural water source in the nation is renewable water wells, which provide 60 m^3/yr per capita while requiring 307 m^3/y per capita in extraction (Darwish and Al-Najem, 2005). An integrated water resources management plan is crucial for

Table 1. Water resources distribution in Kuwait (World Bank, 2022).

Type of water resources	Distribution in percentages (%)
Desalination	61
Treated wastewater	20
Groundwater	19

sustainable development because of the diminishing availability of water resources and the enormous advantages that water has for society, the economy, and the environment. As water demand has increased, numerous solutions have been created in energy-rich nations like Kuwait. These plans call for the construction of saltwater desalination facilities utilizing one or more of the commercially available desalination technologies (Curto et al., 2021; Islam et al., 2018; Zheng et al., 2016). The statistic of the respective technologies is presented in Table 2 and Fig. 1.

Early in the 1950s, the State of Kuwait took the initiative to build thermal distillation units for saltwater desalination. In the previous four decades, MSF distillation plant building has increased freshwater output accounting for about 93% of the nation's fresh water supply (Islam et al., 2018). Continuous attempts were made to investigate additional desalination processes for the production of fresh water in Kuwait. RO has been shown to be a useful and vital non-thermal technology for converting saline water for desalination and purification of drinking water. The Sulaibiya water treatment and reclamation plant, initiated in 2005, stands as the world's largest facility using RO and ultrafiltration (UF) for membrane water treatment. It processes all sewage water from Kuwait City and Hawalli, treating about 64% of the nation's sewage (Hamoda, 2013). The plant consists of two main sections: the biological treatment plant and the reclamation plant. The process begins with prescreened effluent undergoing UF backwash. This is followed by distribution to nine aeration tanks, totaling a volume of 208,900 m^3. Afterward, the mixed liquor moves to a secondary clarifier, and then it's pumped to the UF plant. The UF-treated effluent is then sent to the RO section, equipped with 21,000 membranes, for filtration in three stages. Subsequently, 85% of the feed to the UF/RO is purified, and the remaining brine is discharged into the sea (Aleisa and Alshayji, 2019; Hamoda, 2013). A government organization, the Ministry of Energy: Electricity and Water, oversees saltwater desalination to ensure the safety of potable water. Six cogeneration desalting plants provide electricity and process heat (stream) for MSF seawater desalting facilities in Kuwait (Hamoda, 2001). The Map showing vocations of groundwater fields, water treatment plants, and desalination plants in Kuwait is presented in (Fig. 2).

1.2. Desalination facilities waste discharge

Desalination facilities have a large range of possible environmental effects, some of which are similar to other development initiatives in other areas including land usage. The impingement and entrainment of organisms caused by the intake of huge amounts of saltwater and the emission of air pollutants caused by the operations' high energy requirements are effects particularly, particular to desalination facilities (Roberts et al., 2010; Lattemann Sabine and Höpner, 2008). Desalination facilities discharge concentration and chemicals into the marine environment. These concentrates have a high salinity and may contain small amounts of chemicals like NaOCl or free chlorine to inhibit biological growth, $FeCl_3$ or $AlCl_3$ to flocculate and remove suspended matter, H_2SO_4 or HCl to change the pH of the water, and $NaHSO_3$ to neutralize chlorine residue in feed water. This invariably might have negative impacts on the quality of the water and sediment, harm marine life, and compromise the health and intactness of coastal ecosystems, are a major source of worry (Hamoda, 2001; Höpner and Lattemann, 2003).

The distribution of marine organisms is controlled by salinity and temperature; these species often reside in regions with ideal environmental conditions. The majority of organisms can adjust to small variations in ideal salinity and temperature conditions, and some could even withstand severe circumstances for a short period of time, but not long-term exposure to unfavorable conditions. This makes the continuous discharge of reject streams

Table 2. The state of the art of commercial desalination technologies.

Technology	Average capacity (10^3 m^3/day)	Input	Recovery ratio	Water quality (ppm)	Energy consumption Electrical (kWh/m^3)	Thermal (kJ/kg)	Water cost ($/$m^3$)
MED	0.6−30	SW	0.25	10	1.5−2.5	230−390	0.52−1.5
TVC	10−35	SW	0.25	10	1.5−2.5	145−390	0.87−0.95
MSF	50−70	SW	0.22	10	4−6	190−390	0.56−1.75
MVC	0.1−3	SW		10	6−12	No	2.0−2.6
SWRO	1−320	SW	0.42	400−500	3−6	No	0.45−1.72
BWRO	Up to 98	BW	0.65	200−500	1.5−2.5	No	0.26−1.33
ED	Up to 145	BW	0.9	150−500	2.64−5.5	No	0.6−1.05

Adapted with permission from Jones et al. (2019).

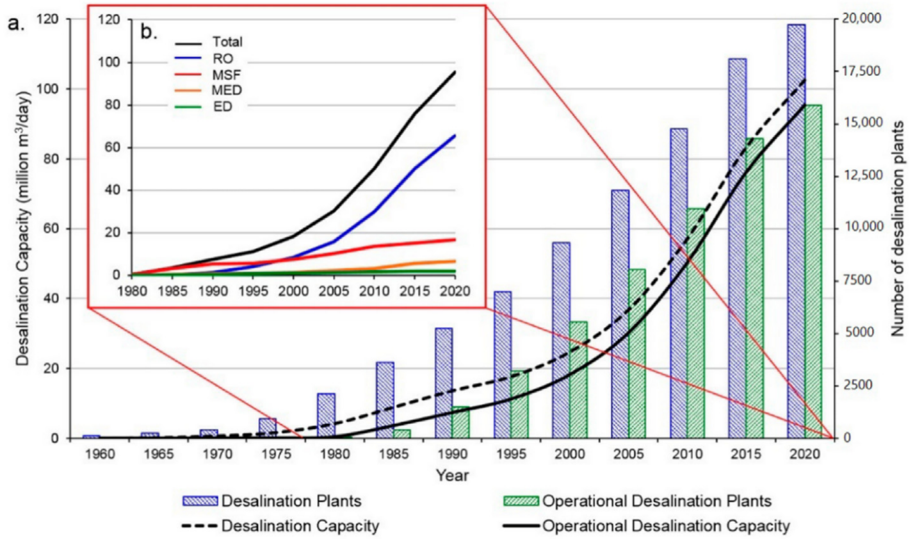

Fig. 1. Statistics of commercial desalination plants from 1960 to 2020. Adapted with permission from Jones et al. (Jones et al., 2019).

with high salt and temperature levels potentially lethal to marine life and capable of permanently altering the species composition and abundance in the discharge site. The altered habitat can attract or repel marine creatures, and those that are more adapted to it will eventually dominate the discharge site. Additionally, brine might sink toward the bottom due to its higher density than salt water, which could have a negative effect on the surrounding marine biota. The maritime environment will undoubtedly also be affected by other chemical treatments including antifoulants, antifoaming chemicals (such as polypropylene glycol), antiscalants (polycarbonic acids), and coagulants (such as ferric–III–chloride) (Hamoda, 2001; Höpner and Lattemann, 2003). In Kuwait, the marine and coastal environments are therefore expected to undergo significant changes as a result of development of eight dual-purpose sites for water production and power generation along a 120 km stretch of shoreline over the past forty years. World Health Organization (WHO) advice paper, and UNEP report provides a comprehensive review of the content and impacts of desalination waste discharges on the environment (WHO and World Health Organization, 2007; United Nations Environment Programme, 2003).

2. The MSF desalination process

The majority of desalinated municipal drinking water supplied worldwide is generated via MSF, which is predominantly used to desalt saltwater (Islam et al., 2018). Over 22% of the world's

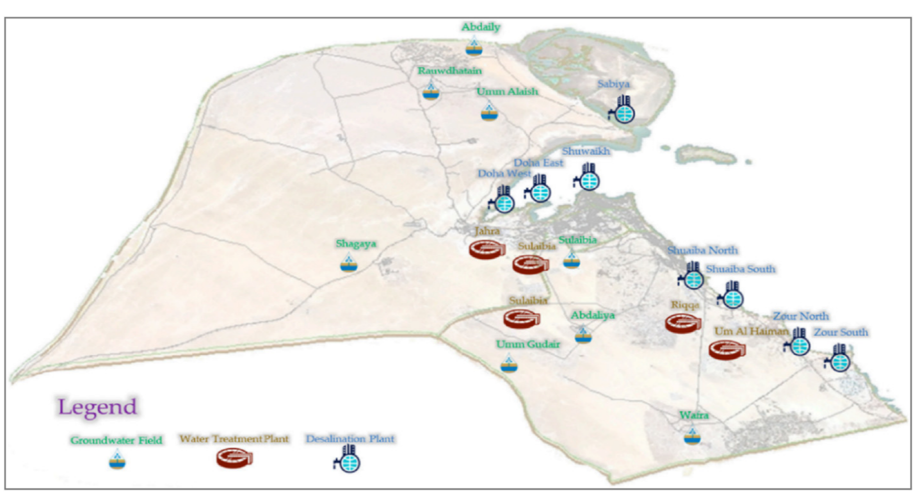

Fig. 2. Locations of Kuwait groundwater fields, water treatment and desalination plants (Tariq et al., 2022).

desalination capacity comes from MSF units, which are widely employed in the Middle East, especially in Saudi Arabia, the United Arab Emirates, and Kuwait (World Bank, 2022). A typical MSF distillation unit begins with a heater and ends with a condenser, as shown in (Fig. 3). A number of evaporator-heat exchanger subunits are located between the heater and the condenser, where the heat from the heater's external heat sources is continually recycled for distillation and the condenser's heat sink is made of cold saltwater. Two or three evaporation stages are often included in the condenser, also known as the heat rejection section. Starting with the last stage of the heat rejection section, which has the lowest absolute pressure and consequently the lowest temperature vapor, the cold saltwater flows within the heat exchanger tubes of the heat rejection section. Due to the many degrees of temperature difference, the vapor condenses on the exterior of the heat exchanger tubes and transfers its latent heat to the seawater stream (Alfadhli and Alhashemi, 2019).

As the saltwater moves from one stage to the next, its temperature rises by a few degrees. With a total temperature increase of 7–8 °C, the saltwater exits the first stage of the heat rejection section and divides into a makeup feed stream and a rejection stream. In a procedure known as stripping, the makeup supply water must travel through a column (or columns) known as a deaerator to remove the dissolved gases from the makeup water. After that, before the makeup water enters the final evaporation stage, chemicals including antifoaming and anticipant agents and sodium sulfite are introduced at the necessary dosage rates into the makeup water. The external low-pressure steam that provides heat for the operation enters the brine heater on the other side of the MSF distillation unit and condenses there. The top brine temperature (TBT), which ranges in value from 90 to 120 °C is reached when its latent heat is transferred to the warmed recycling brine (Altayaran and Madany, 1992).

The quality of the generated water, which contains less than 10 mg/l total dissolved solids (TDS) is one of the benefits of adopting MSF for desalination (WHO and World Health Organization, 2007). The technique and costs of MSF are not significantly impacted by the feed-water's salinity. It can be integrated with other procedures, for instance, by utilizing the heat energy from an electricity generating facility. Nevertheless, there are several drawbacks to adopting MSF for desalination, including the high degree of technical expertise and the expense of installation and operation. Because of the poor recovery ratio, more feed water is needed to generate the same quantity of product water (Alfadhli and Alhashemi, 2019). The structural elements used in MSF desalination technology also have a tendency to corrode, which makes it easy for saltwater to flow into the condenser pipe when corrosion failure occurs. The MSF system also requires a certain volume of seawater to circulate, which increases the pump's power consumption (United Nations Environment Programme, 2003).

3. Results and discussion

3.1. Production and uses of desalinated water in Kuwait

Desalination is the main method used to supply water to homes and businesses. Over 90% of the water used by the residential and service sectors is produced by desalination facilities. Additionally,

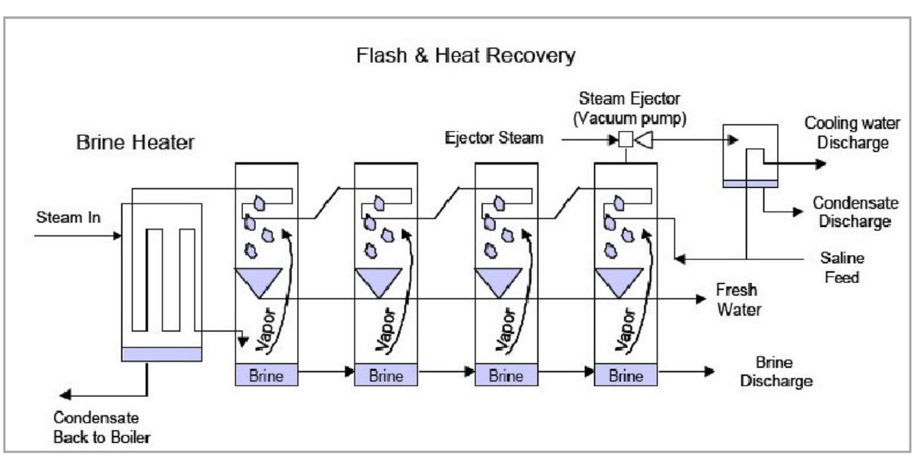

Fig. 3. MSF desalination process (WHO and World Health Organization, 2007).

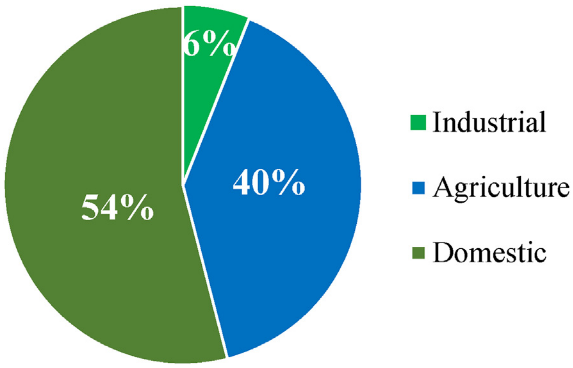

Fig. 4. Water consumption by sector in Kuwait (2022) (World Bank, 2022; Tariq et al., 2022).

they meet 60% of the water needs of the industrial sector. A pie chart showing the water consumption by sectors in Kuwait is depicted in Fig. 4.

Eight desalination facilities in Kuwait produced 747.76 million cubic meters (m^3) per day of desalinated water in the year 2022. Table 3 shows the production capacities of each of these facilities (K. Kuwait Institute for Scientific Research, 2019). About three-quarters of the desalinated water produced is generated using the desalination method. The sole desalination plant employing multi-effect distillation (MED) technology is the Sabiya desalination facility, which was commissioned in 2006 (Tariq et al., 2022). The gross production of each of the desalination plants in Kuwait from 1993 to 2022 is presented in (Fig. 5) (State of Kuwait, 2023a). Doha West and Az-Zour South stations, currently running on both MSF and RO, have had the highest production in the past five years. Fig. 6 illustrates the gross freshwater production, gross freshwater consumption, and the total installed desalination plant capacity. The figure indicates a continuous increase in installed desalination capacity and a corresponding increase in freshwater production. Similarly, it is observed that the production of fresh water in the country closely matches the consumption for the period reviewed in this study. The per capita consumption of fresh water by desalination is presented in Fig. 7.

3.2. Water temperature pollution

Rapid temperature changes in an untreated natural body of water are known as thermal or water temperature pollution. The majority of the time, hot discharge from an industrial site or another human activity is what causes this pollution. Industrial facilities, such as steel mills, pulp and paper mills, chemical plants, and petroleum refineries, contribute to thermal pollution in addition to power plants. Once-through cooling is the term for the industrial process of drawing water from a lake, ocean, or river, heating it, and then releasing it back to the source. It has long been recognized as having a negative impact on aquatic and marine habitats. Fish and larvae that are stuck against intake screens owing to once-through cooling are killed, and habitats are changed by the outflow of warmer, frequently contaminated water (K. Kuwait Institute for Scientific Research, 2019). In addition, the quality and length of life for underwater species suffer when oxygen levels in the water are changed. Therefore, this process may also destroy the streamside flora that depends on stable oxygen and temperature levels.

Once-through cooling is also used in desalination facilities. More than half of the salt water used for desalination is disposed of as effluent, sometimes at a high temperature, back into the ocean (Younos, 2009). Desalination plants are also mostly grouped together in various locations of the world, discharging enormous volumes of hot, salty wastewater into the shallow coastal areas. This has a substantial impact on the salinity and temperature of salt water (Darwish et al., 2008). With the basic goals of determining the temperature field in the Shuaiba offshore area, identifying potential recirculation patterns and temperature increases at the intakes, examining the flow and mixing

Table 3. Desalination plants with mounted capacities and gross production in 2022 (State of Kuwait, 2023a).

Plant references	Technology	Commissioning year	Installed capacity in million m^3/day	Gross production of distilled water in 2022 (million m^3)
Shuwaikh	MSF and RO	1982	0.22	42.33
Shuaiba North	MSF	2011	0.21	28.19
Shuaiba South	MSF	1971	0.14	38.93
Doha East	MSF	1978	0.19	50.34
Doha West	MSF and RO	1983	0.78	186.59
Zour South	MSF and RO	1988	0.64	109.55
Zour North	MSF and RO	2016	0.49	173.47
Sabiya	MED	2006	0.46	110.70
		Total capacity	**3.11**	**740.10**

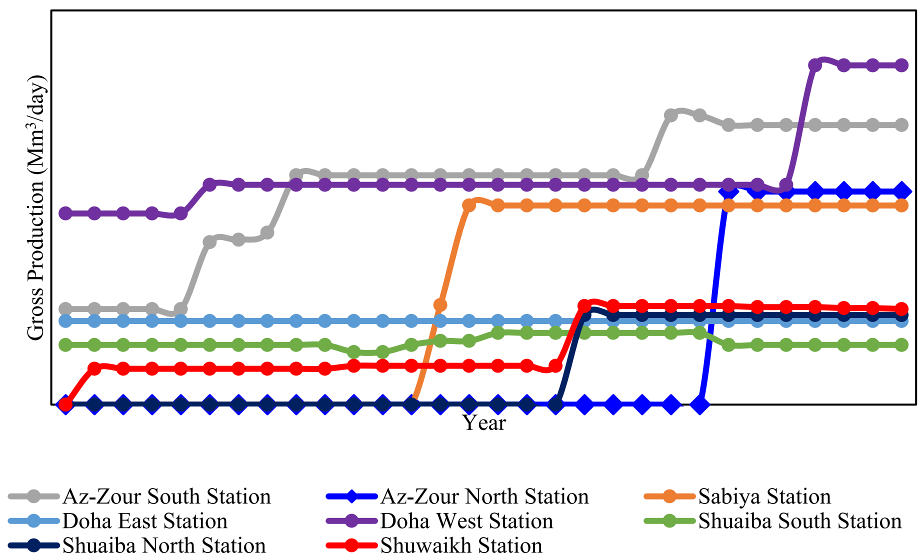

Fig. 5. Gross production of distilled water by desalination plants in Kuwait (State of Kuwait, 2023a).

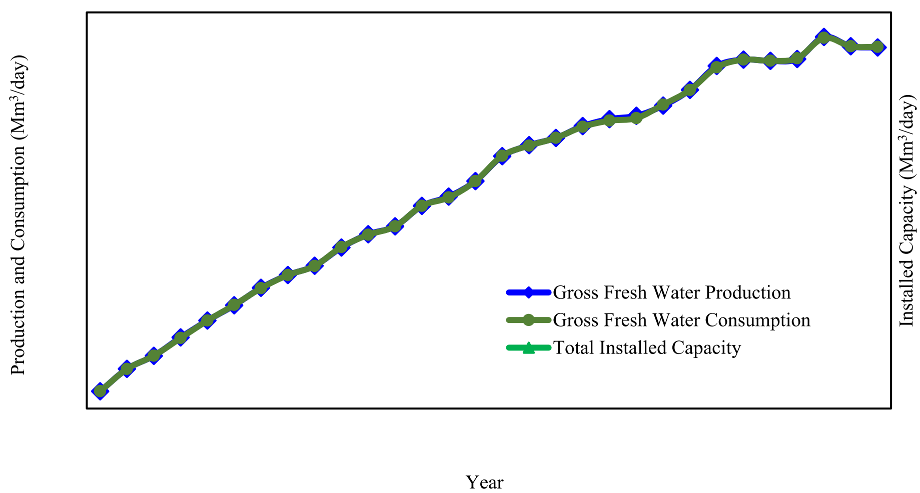

Fig. 6. Gross freshwater production, gross freshwater consumption and total installed desalination plant capacity in Kuwait (State of Kuwait, 2023a).

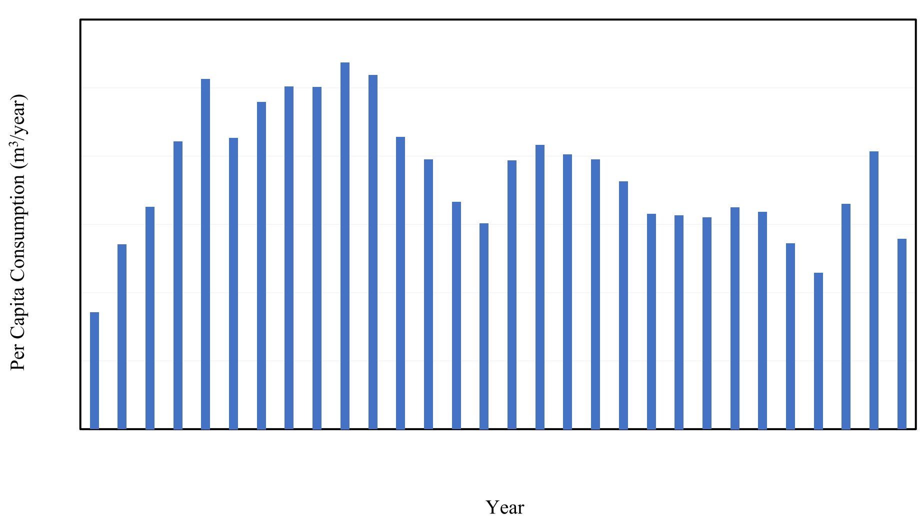

Fig. 7. Per capita consumption of fresh water in Kuwait (State of Kuwait, 2023a).

characteristics of chemical effluents discharged, and researching alternative corrective measures, Lo and Esen (1987) built an undistorted physical model with a scale of 1:50 that was constructed and tested. According to the model test findings and the field testing, the sea water temperature at the intakes was 1.7–2.5 °C higher than the surrounding air. The temperature increase at the intakes was kept to 0.8–1 °C. when heated water from the larger outlets was allowed to discharge into a channel that ran parallel to the shoreline and curved to remain parallel to the outside of the Shuaiba harbor's southern breakwater. Tests also revealed that the concentration of conservative chemical pollutants at the intakes was reduced by about 50% (Al-Said et al., 2017). Based on the analysis of water and particle samples collected from three locations spanning an area of 100 m to 10,600 m offshore within Kuwait Bay, between January and September 2017, including the discarded brine from the Doha East Desalination Plant Site. Alfadhli and Alhashemi (2019) determined that brine disposal increased the water bay temperature by 14 °C at the disposal point. This gradually decreased to the normal temperature at distance, which varied with the climatic conditions and incoming water from Khor Sabyiah and ranged from 300 m maximum in winter season to coverage of the entire bay in the summer season (Alfadhli and Alhashemi, 2019).

3.3. Salinity pollution

Concentrated brine outflow, a consequence of desalination, is a significant environmental issue as well. Concentrates are typically liquid substances with a TDS concentration of more than 36,000 mg/l (Younos, 2009). Concentrates may comprise up to 20% of the treated water. TDS, temperature (7° above ambient seawater temperature), and specific weight (density) are crucial concentration characteristics. Concentrates may have low concentrations of chemicals such as NaOCl or free chlorine to inhibit biological growth, $FeCl_3$ or $AlCl_3$ to flocculate and remove suspended matter, H_2SO_4 or HCl to change the pH of the water, and $NaHSO_3$ to neutralize chlorine residue in feed water. Concentrates are also high in salinity. The marine ecosystems and receiving water environments may be threatened by these concentration qualities. There might be negative consequences on marine resources depending on variables including the overall volume of brine discharged, its components, and the amount of dilution before release. Organisms close to the outfall may be impacted by the discharge water's high salt content and salinity variations. Additionally, brine has a higher density than seawater and may sink to the seafloor, having a negative effect on the surrounding marine biota (Darwish et al., 2008). As opposed to 95 million cubic meters of fresh water produced daily, desalination facilities generate 141.5 million cubic meters of brine daily, according to research (Darwish et al., 2008).

Alfadhli and Alhashemi (2019) study of the Kuwait bay region showed that the water salinity varied with the climatic conditions and the incoming water from Khor Sabyiah from 550 m maximum in winter season to about 3300 m. Half of the bay is covered during summer season as pollution inside the bay increased from 22 ppt at the source point 1 near the DEPS outlet and decreased gradually as the pollution motion decreased. They further forcasted that the continued discharge of brine into the bay will raise the water's temperature and salinity by 8% every three years, which might result in a very obvious alteration to the bay's ecosystem and environment in the years to come (Abusam and Shahalam, 2013).

Lattemann and Höpner (2008) in their work compared the saline output from the MSF and the RO (reversed osmosis) technologies. While the former typically released about 50,000 mg/l of brine into the surrounding marine environment, it is still more preferred to RO which has a contribution ranging between 65,000 and 85,000 mg/l (Lattemann and Höpner, 2008).

Al-Said *et al*.analysis of hydrological data showed that salinity in Kuwait Bay (time series station K6) and an offshore southern site (station 18) increased dramatically by 6 units between 2000 and 2013 (Al-Said et al., 2017).

3.4. Greenhouse gas emissions generated from the Kuwait seawater desalination sector

Numerous sources claim that many areas of Kuwait may become uninhabitable in the future decades as the country's average temperatures climb faster than the world average. The Environment Public Authority predicts that temperatures in some parts of Kuwait might rise by up to 4.5 °C above average, making a sizable chunk of the nation unfit for habitation (Darwish and Al-Najem, 2005). Fossil fuels are mostly used in power plants to supply this high electrical demand, which has a considerable impact on carbon emissions (Ritchie et al., 2020). Sixty one percent of Kuwait's water is produced through energy-intensive desalination procedures, which release greenhouse gases into the environment and contribute to the country's high water consumption rate. Gaseous emissions such as carbon dioxide (CO_2), nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) are produced when fossil fuels are used to create electricity and desalt water in amounts that are closely correlated to the amount of fuel energy used for each desalting operation. As greenhouse gases, these substances trap solar heat, accelerating global warming. Kuwait was among the nations with the greatest carbon emissions per person in 2021 with per-capita CO_2 emissions of 22.49 tons. Kuwait is now ranked sixth for air quality, making it one of the most polluted nations in the world (K. Kuwait Institute for Scientific Research, 2019).

Al-Shayji and Aleisa (2018) in their report offers a thorough, quantitative baseline for Kuwait's desalination's environmental consequences. All nine desalination plants in the nation that use the Multistage Flash Desalination (MSF) and RO technologies are modeled using Life Cycle Assessment (LCA) at two scales: per one ton and on annual production. To determine which types of fossil fuels are considerably increasing the environmental burden of desalination. The analysis of variance (ANOVA) was utilized for the evaluation. The findings show that even if crude oil is used to provide 12.2% of Kuwait's electrical energy, crude oil still accounts for 63% of the global warming. The results also show that desalination in Kuwait contributes 7.89×10^8 kg Sb eq. to abiotic depletion, 1.15×10^8kg SO_2 eq. to acidification, 1.91×10^7kg PO_4 eq. to eutrophication, 2.71×10^{10} kg CO_2 eq. to global warming, 2.47×10^4kg CFC-11 eq. to ozone layer depletion, 6.45×10^9 kg 1,4-DB eq. to human toxicity, 6.03×10^{12}kg 1,4-DB eq. to marine aquatic ecotoxicity, and 7.53×10^6 kg C_2H_4 eq. to photochemical oxidation (Al-Shayji and Aleisa, 2018). Based on the research of Becker *et al*. (Becker et al., 2010), and Raluy *et al*. (Raluy et al., 2005), it can be seen that desalination technology has a significant impact on energy needs as well as the quantity of GHG emissions. They are higher for thermal desalination, hence a decrease in energy use directly affects a decrease in these related GHG emissions. Additionally, the research shown that using waste heat to partially or fully supply thermal energy for thermal desalination processes has a significant influence on lowering emissions of CO_2, NO_x, and SO_x by 91−94%, 85−89%, and 39−47%, respectively. Table 4 presents data from the electrical energy statistical yearbook 2022 on the energy demand, energy source, and total CO_2 emissions for each desalination plant for the years 2016 and 2022. The table indicates an average 5% increase in CO_2 emissions for each plant during the aforementioned period. Although daily and annual desalination water production has significantly increased during this time, the rise in CO_2 emissions has been mitigated by the recent introduction of renewable energy sources as auxiliary power in some of the power plants (State of Kuwait, 2023b).

3.5. Marine environmental impact of desalination plants

Roberts *et al*. (Roberts et al., 2010) submitted that the selection of the discharge site is the key element that defines the degree of ecological consequences of desalination facilities, in their review of several published studies. When discharges are discharged into weakly flushed settings, ecological monitoring studies have identified a range of consequences, from no substantial impacts to benthic organisms to broad disruptions to community structure in seagrass, coral reef, and soft-sediment ecosystems. The majority of the time, environmental effects seem to be restricted to areas 10 m or less from outfalls. However, they highlighted that a significant percentage of the literature is descriptive and offers little quantitative information that we could independently evaluate (Roberts et al., 2010).

Al-Said *et al*. also investigated if the features of the phytoplankton population in these semiarid waters were altered by increasing salinity. According to phytoplankton figures, the number of component

Table 4. Desalination plants in Kuwait, their energy type and total CO_2 emission ($MtCO_2$) (State of Kuwait, 2023b).

Name	Power (MW)	Natural gas quantities in (Bscf)	Heavy fuel oil quantities (bbl)	Crude oil quantities (bbl)	Gas Oil quantities (bbl)	CO_2 emissions 2016 ($MtCO_2$)	CO_2 emissions 2022 ($MtCO_2$)
Az-Zour South	5806	103.1	17458.5	213.0	1061.0	14.54	15.70
Az-Zour North 1	1531	49.3	0.0	0.0	118.8	2.95	3.01
Sabiya	5367	105.1	11921.9	97.1	4074.2	13.34	13.74
Shuwaikh	252	9.7	0.0	0.0	0.0	0.59	0.62
Shuaiba North	876	38.0	0.0	0.0	333.0	2.44	2.61
Doha West	2541	21.4	16227.5	331.6	15.2	8.53	9.21
Doha East	1158	15.3	2852.4	3416.2	0.4	3.72	3.79
Shuaiba South	720	36.7	0.0	0.0	129.2	2.53	2.66
Total	**18259**	**528**	**378.5**	**48460.3**	**4057.9**	**48.63**	**51.07**

species decreased from 353 to 159 in Kuwait Bay and from 164 to 156 in the offshore area over the past ten years. Their biomass changed as a result of a decline in the number of diatom species from 243 to 92 in the coastal waters and from 108 to 83 in the offshore regions, along with an accompanying rise in the number of smaller algae. Further analyses on phytoplankton data at various taxonomic levels, multivariate agglomerative hierarchical cluster analysis, non-metric multi-dimensional scaling, and one-way analysis of similarity studies indicated significant changes in their community organization on a decadal scale (Al-Said et al., 2017).

Desalination facilities release a major portion of the chemical compounds they use into the ocean, which might have a negative effect on the sediment, marine environment, and coastal water habitat (Alharbi et al., 2012). However, the desalination plant's operation and the quality of the water it produces depend on these chemicals. According to Al-Handhaly *et al*., residual biocides, anti-scalants, antifoaming agents, metals, and corrosion inhibitors are the most common chemical residues found in the MSF plants' output stream. Chlorine was the best option from a disinfection standpoint because it is a very effective biocide and has a reasonable price (Al-Handhaly et al., 2003). However, the results of various toxicological research demonstrated its toxicity. Some studies indicated that the chlorine fraction of 0.5 ppm at the disposing site was reduced to 0.05 ppm at 1 km away (Al-Ghadban and Al-Ajmi, 1993). There have been several other pretreatment techniques and materials put forth, but none have been shown to be superior to chlorination (Khordagui, 1992).

Lattemann and Höpner (2003) have provided a thorough analysis of the types and quantities of chemical pollution connected to desalination facilities in the Gulf area. In terms of their combined loads and possible harm to marine ecosystems, they determined that copper and chlorine were the two contaminants of greatest concern. The Doha West Power-Desalination Plant, which has an outfall on the Sulaibekhat Bay intertidal flat, is one illustration used in their study. The Doha West facility receives roughly 10.5 million m^3 of saltwater each day, which is treated with about 26,000 kg of chlorine. In the outflow to Sulaibekhat Bay, around 10% of this chlorine (2500 kg/d) is still present.

This is enough residual chlorine to pose a serious threat to marine life, even though it is rapidly degraded in the environment by sunlight (90% degradation in 45 min), especially during incoming tides that lengthen the residence times of pollutants in the Bay. Doha West treats the saltwater intake feedwater to keep the level of chlorine at roughly 2.5 mg/l. The residual concentration is approximately 0.25 mg/l, assuming that only 10% of this chlorine is still present in the outfall water. This exceeds the established hazardous amounts of chlorine by a significant margin. Such chlorine levels are expected to change the species makeup of the water as well as reduce phytoplankton growth. Even worse environmental consequences are predicted when chlorine concentrations are higher during shock and cleaning procedures. Small planktonic creatures cannot avoid chlorine exposure if they drift into the area around the outfall, whereas fish species can smell chlorine and react by swimming to chlorine-free waters (Lattemann and Höpner, 2008; Altayaran and Madany, 1992; Höpner and Lattemann, 2003).

4. Proposed solution strategies

Addressing the environmental impacts associated with water desalination is crucial for the sustainability of this vital water supply method. As the demand for freshwater grows, so does the importance of minimizing the ecological footprint of desalination processes. This section of the study outlines comprehensive strategies to mitigate the environmental challenges posed by desalination, specifically as regards waste discharge from desalination facilities, water temperature pollution, salinity pollution, and greenhouse gas emissions, ensuring its role as a sustainable water resource.

4.1. Renewable energy integration

The high energy demand of desalination, particularly in thermal distillation and RO processes, is a primary concern due to associated greenhouse gas emissions from fossil fuel consumption. A pivotal strategy is the integration of renewable energy sources, such as solar, wind, and geothermal energy, into desalination operations. This shift not only reduces carbon emissions but also aligns with global sustainability goals.

4.2. Energy recovery and efficiency

Implementing advanced energy recovery technologies can significantly enhance the energy efficiency of RO plants. These systems capture and reuse energy from the brine stream, reducing overall energy consumption and operational costs.

4.3. Brine management

The disposal of brine, a by-product with high salinity and sometimes chemical content, poses risks to marine ecosystems. Strategies such as brine dilution, which involves mixing brine with seawater or treated wastewater, and brine valorization, the extraction of valuable minerals for commercial use, can mitigate these risks. Moreover, adopting Zero Liquid Discharge (ZLD) systems can eliminate liquid waste, leaving only solid waste that can be handled more sustainably.

4.4. Chemical usage reduction

The use of harmful chemicals in desalination for equipment cleaning and maintenance presents risks to marine life. Developing and employing environmentally friendly antiscalants and biofouling preventatives, alongside advanced treatment systems for chemical neutralization, can substantially reduce these impacts.

4.5. Mitigating thermal pollution

Thermal pollution from desalination plants can disrupt local marine ecosystems. Implementing cooling systems to reduce the temperature of waste streams before ocean discharge and utilizing excess heat through Combined Heat and Power (CHP) systems can effectively minimize thermal impacts.

4.6. Protecting marine life

The intake and discharge systems of desalination plants can harm marine organisms. Installing fine mesh screens and regulating water velocities can prevent marine life from being drawn into these systems. Continuous ecological monitoring is essential to assess and adapt operations to protect marine biodiversity.

Implementing these solution strategies necessitates a collaborative and multidisciplinary approach. By combining engineering innovations with environmental science and policy reforms, desalination can evolve into a more sustainable practice. Success in these endeavors requires the concerted effort of industry stakeholders, government bodies, and research institutions, all working towards the common goal of sustainable water resource management.

4.7. Conclusion

In Kuwait, brackish groundwater and seawater are both regarded as alternative water sources. Currently, the MSF distillation method used for saltwater desalination satisfies around 90% of the Kuwait's freshwater needs. However, as the population grows and the industrial sector develops, including desalination and the oil production industry, the environmental issues caused using fossil fuels and the discharge of concentrates of brine from desalination plants might get worse. Since brines are concentrated flows, they should be viewed as valuable sources of materials rather than as waste that needs to be disposed of, necessitating the use of innovative methods. With improvements in RO technology and declining capital and operation and maintenance costs, brackish groundwater may be a viable prospective water supply to meet the nation's need for potable water. Complete wastewater reuse will eventually become competitive due to escalating environmental regulations, shifting public perceptions, expanding wastewater generation, and the development of water technologies, taking into account the increased water source and the favorable effects on the environment.

Author credit statement

Eissa S. Al-Mutairi, I. G. Rashed, M.M. El-Halwany, and Mohamed Mosaad contributed equally to this work. Eissa S. Al-Mutairi did the research, performed formal analysis and curated the data. I. G. Rashed contributed to the conceptualization and writing of the original draft. M.M. El-Halwany contributed to the data analysis, interpretation, and visualization, as well as the writing of the manuscript. Mohamed Mosaad assisted with data collection and analysis, and also contributed to the writing of the original draft.

Conflicts of interest

There is no conflict of interest.

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