Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.28558

257 (2022) 131–141
May

Environmental impact of Laayoune plant's desalination and brine management: challenges and mitigation measures

H. Elaouani[a,*], D. Beqqour[b], A. Taouallah[c], L. Salama[c], K. Abderrafi[d], K. Jaafari[a], S. Mailainine[e], K. Benkhouja[a], M. Ouammou[b], S. Alami Younssi[b]

[a]*Laboratory of Coordination and Analytical Chemistry, Department of Chemistry, Faculty of Sciences, Chouaib Doukkali University, El Jadida, Morocco, emails: helaouani@yahoo.fr (H. Elaouani), karimjaafari@yahoo.fr (K. Jaafari), benkhoujakhalil@yahoo.fr (K. Benkhouja)*
[b]*Laboratory of Materials, Membranes and Environment, Faculty of Sciences and Technologies Mohammedia, University Hassan II of Casablanca, Morocco, emails: dounia.beqqour-etu@etu.univh2c.ma (D. Beqqour), mouammou@yahoo.fr (M. Ouammou), alamiyounssisaad@yahoo.fr (S. Alami Younssi)*
[c]*Laboratory of Condensed Matter Physics, Department of physics, Faculty of Sciences Ben M'sick, Hassan II University of Casablanca, Morocco, emails: taoullah.amal2@gmail.com (A. Taouallah), salama.latifa0@gmail.com (L. Salama)*
[d]*Laboratory of Engineering and Materials, Faculty of Sciences Ben M'Sik, Hassan II University of Casablanca, Morocco, email: abderrafi@gmail.com (K. Abderrafi)*
[e]*National Institute of Halieutic Research – Laayoune Center, Morocco, email: eaudesyeux@yahoo.fr (S. Mailainine)*

Received 13 January 2022; Accepted 13 May 2022

ABSTRACT

The region of Moroccan Sahara Laayoune is characterized by an arid climate, where water is scarce and more in demand. In this case, the desalination process offers many advantages such as the preservation of current freshwater reserves and the use of seawater as an unlimited source. Unfortunately, by using this technology there are rising concerns about possible adverse environmental impacts. This work presents a qualitative study of marine waters desalination plants in the Moroccan Sahara in Laayoune. The different compositions of the brines and offshore marine were characterized and analyzed where they are discharged. Furthermore, the different aspects of the environmental impacts of desalination have been deducted comparing them to the literature. The studied desalination plants product permeates with 45% of total dissolved solids. A major issue of desalination in Moroccan Sahara Laayoune is the co-produced waste called 'brine' or 'reject' which has a high salinity along with chemical residuals and is discharged into the marine environment. Other issues include entrainment and entrapment of marine species, and heavy use of chemicals. The purpose of this study is to analyze the potential impacts of desalination, and brine treatment on the environment and suggest mitigation measures.

Keywords: Brine; Environmental impact; Desalination; Morocco

1. Introduction

Water is essential for life. It is one of the most important resources on earth, presenting three quarters of the planet's surface. In addition, about 97% of the earth's water is seawater in the oceans and 3% in the form of fresh water, groundwater, lakes and rivers. Nearly inexhaustible sources of water are the oceans and seas. Their main disadvantage is the high salinity. Therefore, it would be interesting to tackle

* Corresponding author.

Presented at the Second International Symposium on Nanomaterials and Membrane Science for Water, Energy and Environment (SNMS-2021), June 1–2, 2022, Tangier, Morocco

the problem of water scarcity with the desalination of this water [1,2].

Besides, the current water resources are inadequate and are depleting continuously due to rapid industrialization, overexploitation, population growth, and climate changes [3,4]. According to the United Nations, by 2050, around 7 billion in 60 countries will endure severe water scarcity [5–10]. Desalination of seawater is perceived as one of the most viable and oldest processes to encounter the mounting demand for high-quality water [11,12].

Desalination is now successfully practiced in more than 150 countries such as the Middle East, North Africa, southern and western US, and southern Europe to meet industrial and domestic water requirements according to the International Desalination Association [13]. Currently, the amount of water desalination has been reported to reach 95 million m^3/d, of which the Middle East and Africa region contributes to a 48% of water production.

Desalination is a multi-stage process and typically yields two products: (i) fresh water (water that meets quality for human use), and (ii) brine (water with high salinity and reject concentrate). In addition to its high salinity, reject brine is also chemically contaminated. A typical reverse osmosis (RO) brine consists of a total dissolved solids concentration of ~70.000 mg/L, which contains several chemical residues from pretreatment and cleaning processes, in addition to sodium chloride. Membrane processes are one of the conventional processes that are used for the pretreatment of raw seawater prior to RO desalination [14–16].

Chemicals such as NaOCl, $FeCl_3$, $AlCl_3$, H_2SO_4, HCl, and $NaHSO_3$ are typically applied at the pretreatment stage to aid in water treatment for minimizing algal growth, reducing corrosion, inhibiting scaling, adjusting the pH, and chlorinating the water. Brine also has a higher density than that of typical saltwater. Thus, brine disposal will contaminate the marine environment, causing a major concern for desalination around the world and therefore appropriate environmentally friendly brine management is essential [6]. There have been several methods implemented for brine disposal, including sea disposal, land disposal, evaporation, membrane distillation, forward osmosis, deep electrodialysis, capacitive deionization, well injection, and sewage disposal [7,8].

Firstly, the different compositions of the brines and offshore marine were characterized and analyzed where are discharged. In addition, the different aspects of desalination as well as the environmental impacts (EIs) were deduced and compared to the literature. On the other hand, various practices in brine management comprising treatment technologies and disposal methods have been evaluated and argued for developing zero liquid discharge (ZLD) systems for recovering freshwater and solid salts [13].

2. Materials and methods

2.1. Presentation of the study area and the Laayoune desalination plant

The bathymetry of the South Atlantic area shows the existence of two areas with a wide continental shelf, one is located north of Tarfaya (Cap Juby) and the other south of Boujdour (Cap Boujdour). The region of Laayoune, for its part, is located in a central area with a relatively narrow continental shelf between Tarfaya and Boujdour. It is in this part that the coastline of the study area is located.

Indeed, the distribution of isobaths, between the coast and the depths of 100 m, shows that the 100 m isobath is close to the coast between Tarfaya and Boujdour, and it gradually recedes offshore. It is a desert coastline, usually with long sandy beaches [17]. In the study area, the bathymetric line (–5 m) is located about 900 m from the shoreline, and the lines (–10 m) and (–20 m) at 1,700 and 3,800 m, respectively, which corresponds to an average slope of the very low fund, around 0.5% or (1/200).

The wave spectrum shows significant mean heights, between 0.5 and 3.5 m. The physical characteristics of the swell in the study area will strongly impact the coastal strip between the coastline and the 10 m isobaths [17,18].

The sea current is one of the important descriptive parameters of the environment. The surface currents observed in this area are those of the Canary Current, generally oriented in the North-South axis. The average current intensities observed in this zone are between 0.1 and 0.3 m/s. The maximums are of the order of 0.7–0.8 m/s [17].

At the coast, average wind speeds generally exceed 8 m/s. The frequency concentration in the N NE direction and more accentuated during the summer months (May to September). Also a negligible rainfall inputs (54.3 mm/y) according to the Department of National Meteorology-Delegation of Laayoune [19], as well as a high evaporation rate (158.99 mm) according to Sakia Hamra Oued Eddahab Hydraulic Basin Agency [20].

2.2. Presentation of Laayoune desalination plant

The desalination plant is located in the town of ElMarsa on the Atlantic coast, 28 km west of the town of Laayoune. The average latitude and longitude of the city are respectively: 13°25W and 27°06N. The plant is 800 m far from the coast and has a production capacity of 56.000 m^3/d as displayed in Fig. 1.

This plant has undergone several extensions since its construction in 1995, with a capacity of 6.000 m^3/d. The first was in 2005 to reach 13.000 m^3/d and the second in 2010 to achieve 26.000 m^3/d. The last extension brought the production capacity to 52.000 m^3/d [1].

The desalination process used comprises four main steps which are: (i) source water intake: The desalination plant uses subsurface intakes for seawater supply through 16 coastal boreholes. The raw water is stored in two tanks with a capacity each of 750 m^3/h, which ensures the continuous supply of the station. (ii) Pretreatment: the pre-treatment applied consists of filtration through sand filters in parallel, and acidification with concentrated sulfuric acid with an average treatment rate of 40.1 g/m^3. And injection of flocon 135 sequestering agent with an average treatment rate of 3.1 g/m^3 and microfiltration on parallel microfilter batteries with a differential pressure between upstream and downstream is 0.8–1 bar. (iii) RO: desalination of the pre-treated water is carried out by series modules and fitted with pressure exchangers of the ERI and DWEER type for energy recovery. (iv) Post processing: the RO water

Fig. 1. Geographical map of the situation of the desalination plant [18].

produced undergoes remineralization treatment. The objective is to comply with the requirements of the World Health Organization drinking water standards and for the protection of works downstream of the station and the distribution network. The osmosis water is remineralized by lime at the entrance to the treated water tank. Finally, the disinfection is carried out with gaseous chlorine with a treatment rate of around 0.6 to 1 mg/L.

2.3. Sampling

The sampling operation was carried out according to a schedule, by a specialized technician using a traditional fishing boat. The taking of samples includes the discharge of the desalination station (brine), nine points in the open sea and whose interdistance between them is 300 m as shown in Fig. 2. This operation was carried out monthly for a period of 21 months. The studied samples are stored in the dark at 4°C to prevent any possible degradation. All the rules of conservation of the samples were respected during their transport.

While specifying that the brine is discharged directly to the coast without any outlet reaching the Atlantic Ocean by crossing the sand of the coast.

The sampling points are given as follows:

- Position X: defines the point of discharge of the brine on the coast, before its contact with the ocean;
- The X_0 position: designates the point of contact with seawater, which is 300 m away from the X position;
- Points (X_1, X_1', X_2, X_3, X_3', X_4, X_5 and X_5') represent sampling stations at constant inter-distances of 300 m.

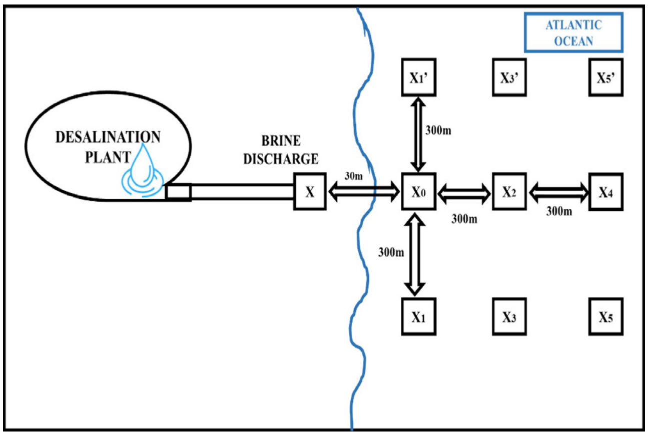

Fig. 2. Representation of the sampling points of marine water.

The choice of the location of the sampling points is guided by the desire to sweep a maximum and representative area. The aim of this work is to study the behavior of brine and the probable and possible changes in its physicochemical characteristics upon contact with seawater.

2.4. Characterization

A multitude of physicochemical parameters have been determined, such as temperature, pH, electrical conductivity (EC), turbidity, dissolved oxygen (DO), total phosphate (TP), total nitrogen (TN), as well as metals by Inductively coupled plasma mass spectrometry (ICP/MS), such as boron, plumb, total iron, and cadmium.

All these physicochemical parameters were analyzed according to the AFNOR [21], Standards in Public Laboratory for Tests and Studies (PLTS/LPEE).

3. Results and discussions

3.1. Results

As desalination activities intensify and the number of large installations around the world increases, concerns about the potentially adverse risks and EIs of desalination are still being assessed [23–30].

The main environmental concerns of desalination are classified into two categories: direct and indirect EIs. The direct impacts are mainly allied with the pollution associated with the brine, the emissions of air pollutants such as greenhouse gas emissions and intensification of energy use. Indirect impacts include noise pollution, land use and construction related impacts.

All seawater desalination processes, whether thermal or membrane, produce huge amounts of concentrate (brine). With a conversion rate of 45%, the Laayoune desalination plant rejects 68.500 m^3/d of brine. In general, these waste streams discharged directly to the sea and without an outfall, contain various heavy metals, by-products and residues of chemicals used in the desalination process such as the solvents used for anti-scaling, anti-foaming and anti-corrosion purposes. These discharges can have harmful effects abiotic and biotic impacts on marine life [31–36].

The abiotic impacts modify the physicochemical characteristics of the receiving environment, such as the chemical composition, temperature, salinity, turbidity and DO level. Biotic impacts directly affect living biota in terms of their abundance of diversity, metabolic rate and physiological state [37].

This study is interested in the environmental assessment of the direct discharge of brine to the ocean, through the space-time study of physicochemical parameters and some metal elements, over an area of 360.000 m^2, as explained in Fig. 2.

3.1.1. pH

The spatio-temporal variation in pH is displayed in Fig. 3. Firstly, the pH profile is almost identical, at all sampling stations, and oscillates between 7.2 and 7.5. Nevertheless, a slight increase for point X_1, with a value of 7.8 was noticed. Secondly, the pH value of the brine represented by the point X_0, does not vary, or varies slightly throughout its dispersion. The pH, therefore, remains in the range of neutrality, except that extreme values can constitute a danger for the fauna and the flora, as demonstrated by, Peres et al., that the fish are killed starting from a pH = 4.9 [38].

3.1.2. Temperature

Fig. 4 presents spatio-temporal temperature variation. It can be observed from this figure that the temperature of this zone varies between 19 and 23°C, with the minimum recorded at the level of X_2. In general, and according to these values, the temperature does not constitute thermal pollution for the aquatic environment. This is due to the use of RO seawater as a desalination technology.

It should be noted that the impacts of temperature are important when thermal processes which are mostly replaced by membrane desalination [39]. Indeed, the high temperature of the discharged brine can have several negative impacts on marine life, as the toxicity of chemicals and metals generally increases with temperature [40–42].

3.1.3. Dissolved oxygen

The spatio-temporal DO variation is depicted in Fig. 5. As can be seen, the DO levels are high and display values between 6 and 8.5 mg/L, this means that the study area benefits from good oxygenation in general. The spatiotemporal variation of DO is very important to take into account, since it is the essential element of life and governs the majority of biological processes in aquatic ecosystems.

The DO value in brine may be less than 1 mg/L, in certain desalination discharges [43], especially those using thermal processes. This low value is due to the high temperature.

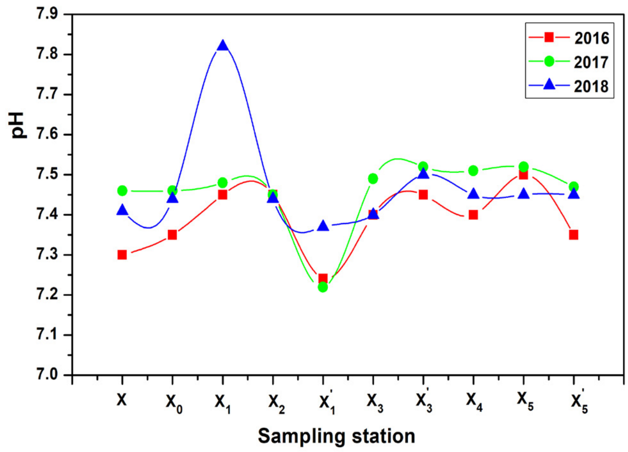

Fig. 3. Spatio-temporal variation in pH.

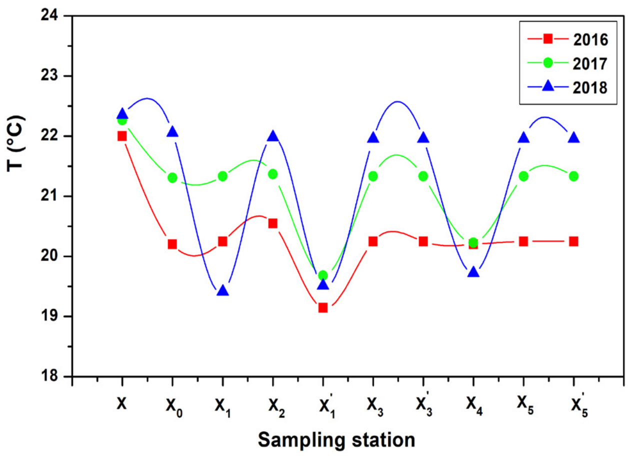

Fig. 4. Spatio-temporal temperature variation.

In this respect, a low level of DO affects marine life because even though adult fish can survive at reduced levels of DO, their reproductive capacities and the survival rate of juvenile fish decrease [44,45].

The reject stream may also contain residues of oxygen scavengers such as hydrazine (N_2H_4), hypochlorite ions (ClO^-) and sodium sulfite (Na_2SO_3) which are used to inhibit corrosion [46]. These chemicals can harm marine life if released into shallow water without treatment [47].

3.1.4. Electrical conductivity

Fig. 6 shows the spatio-temporal EC variation. It is clearly shown that the peak of the EC is reached, for the 3 y at the level of the point X_0, which is the brine. Degradation of these maximum values occurs as one moves away from the point of release. Thus, the EC varies between 63 mS/cm to more than 80 mS/cm. These values remain very high compared to that of seawater, which is in the order of 49 mS/cm. Similar EC values from brine discharges from Israeli desalination plants have resulted in adverse effects on benthic heterotrophic bacteria [48]. Likewise, a high salinity brine had negative impacts on photosynthesis and leaf growth of adult sea grass Posidonia australis [32].

The recorded results also reflect the high levels of salinity in the wastewater, affecting the habitats of marine species and therefore biodiversity [49]. This anthropogenic pollution, caused by this concentrate, can modify the local salinity regimes and its effect depends on the assimilation capacity of both the area and the species.

3.1.5. Turbidity

The spatio-temporal turbidity variation is presented in Fig. 7. According to this figure, the turbidity increases, from point X_0, which is also that of the brine, throughout the sampling stations, to reach a maximum of 8 NTU. This increase is due to the turbulence that characterizes the region. In addition, significantly higher values for the year 2016 was seen, which is probably because of the floods of Ouad Sakia Hamra that the region has experienced this year.

On top of that, the turbidity is responsible for the decrease in visibility which reduces the availability and reliability of visual cues for aquatic animals, limiting the private and social information available, reducing the distance at which animals can detect food, predators and congeners [50,51].

3.1.6. Total nitrogen and total phosphate

Figs. 8 and 9 display the spatio-temporal TN and TP variation, respectively. First, there is a discharge of brine with a TN rate which varies over the 3 y from 1.4 to 1.8 mg/L and continues to decrease or stabilize throughout the various sampling stations (Fig. 8). Then, and similarly, the TP profile is exposed, with a maximum of 2.7 mg/L (Fig. 9). The most remarkable thing is that these maxima coincide, always at point X_0. Admittedly, these values are much higher than those found during the characterization of seawater, which are in the order of 0.15 and 3.11 mg/L, for the TP and TN, respectively. In addition, it is well known that the excess of these two nutrients leads to the proliferation and excessive growth of fauna (algae and aquatic plants). It causes also hypoxia, which can change the balance of a specific ecosystem [52,53].

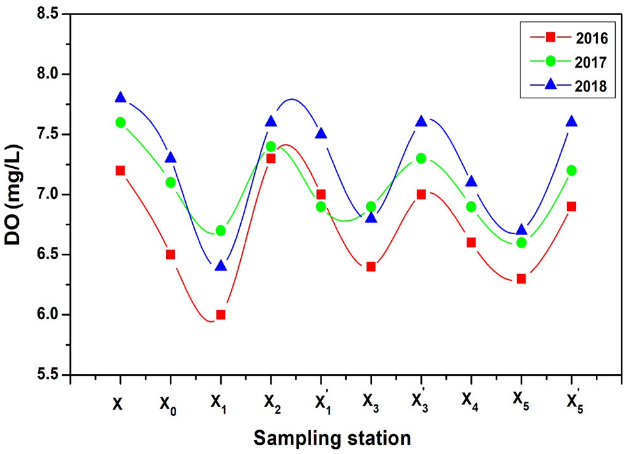

Fig. 5. Spatio-temporal DO variation.

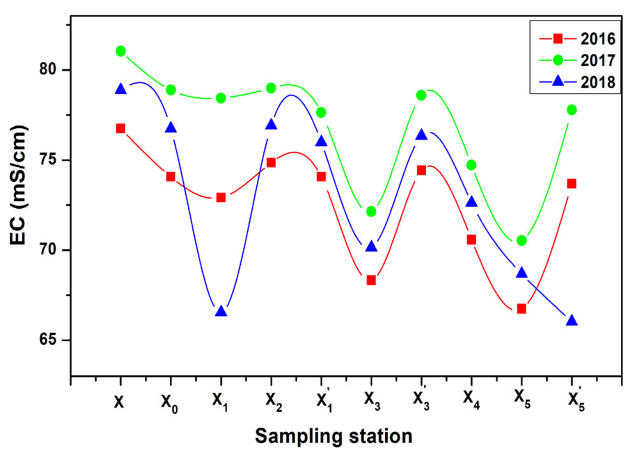

Fig. 6. Spatio-temporal EC variation.

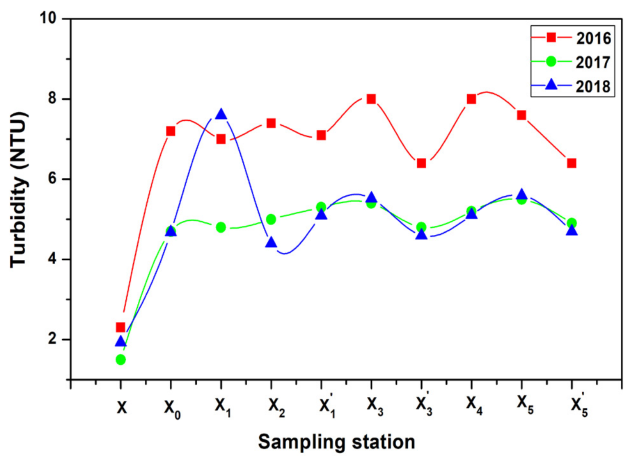

Fig. 7. Spatio-temporal turbidity variation.

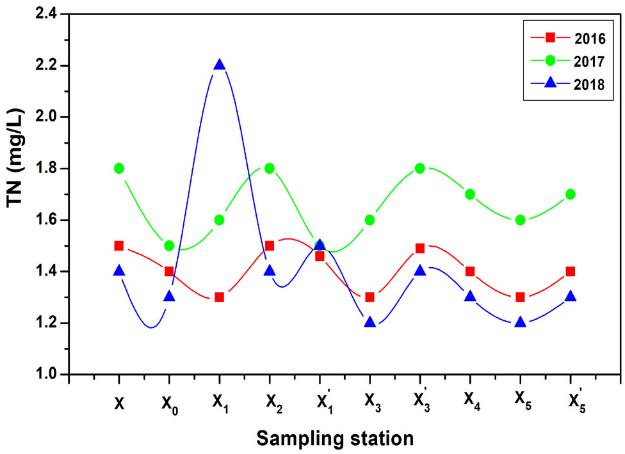

Fig. 8. Spatio-temporal TN variation.

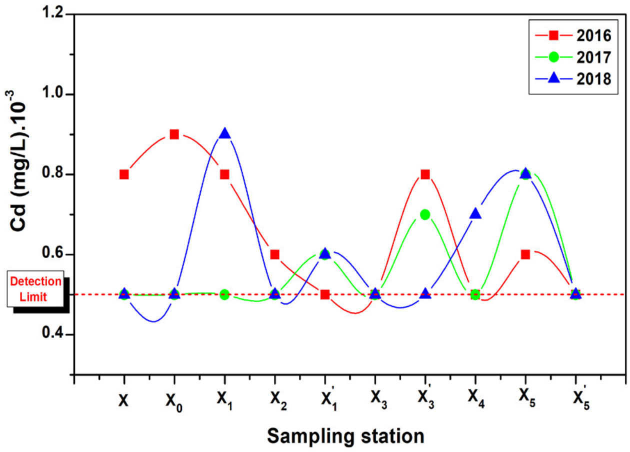

Fig. 10. Spatio-temporal Cd variation.

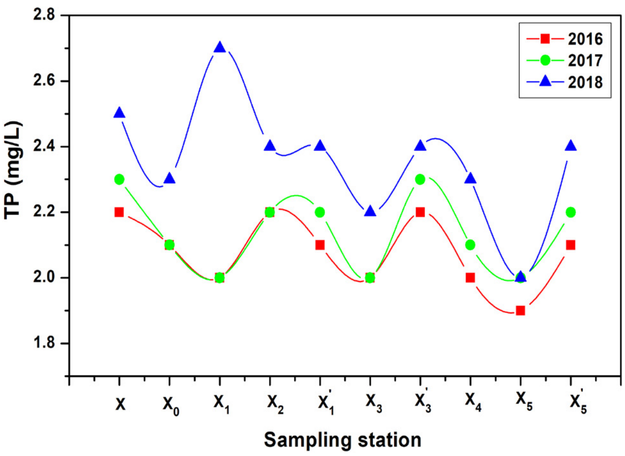

Fig. 9. Spatio-temporal TP variation.

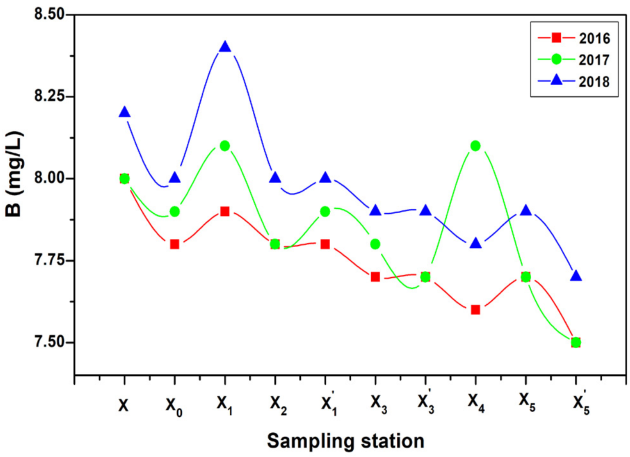

Fig. 11. Spatio-temporal B variation.

3.1.7. Cadmium

The spatio-temporal Cd variation is depicted in Fig. 10. It can be observed that the year 2016 was characterized by more levels above that of the detection limit, at 5 sampling points, with a maximum of $8.5\ 10^{-4}$ mg/L at X_0. The year 2018 comes later, with 4 points whose maximum value is at point X_1. All the values of X, which are the discharge point of the brine, are lower than the discharge standard prescribed by the Moroccan standard, the General limit value (GLV) of which is 0.2 mg/L [54,55].

3.1.8. Boron

Fig. 11 plots the variation of spatio-temporal B. As clearly shown in the figure, the rejected brine contains boron levels above 8 mg/L. This concentration decreases throughout the sampling points, except for station X_1, in the year 2018, where an increase to 8.57 mg/L was noticed. These rates remain quite high, and in the absence of GLV in the Moroccan legislation concerning boron, the limit required in the discharges is very variable, ranging from 1.5 mg/L in Israel, 5 mg/L in Brazil and Singapore, and 10 mg/L in Japan [56].

Several studies have shown that excessive consumption and exposure to boron is toxic to plants, animals and humans [57]. Common plant responses to high boron content include poor root development, impaired photosynthesis, and increased oxidative stress due to the generation of reactive oxygen species [58].

3.1.9. Lead

The spatio-temporal Pb variation is shown in Fig. 12. It can be seen that all the Pb values are below 0.0055 mg/L, except that an increase in the values compared to that recorded at point X was noticed, which is the rejection of the brine.

Lead accumulates in the bodies of aquatic organisms and in the soil, and consequently suffer from lead poisoning. In crustaceans, these effects are felt even though if very low levels of lead are present. The functions of phytoplankton can be disrupted in the presence of lead. It is worth to mention that, phytoplankton is an important source of

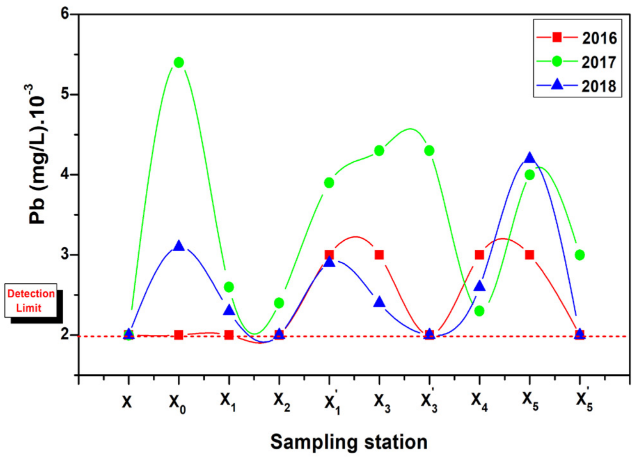

Fig. 12. Spatio-temporal Pb variation.

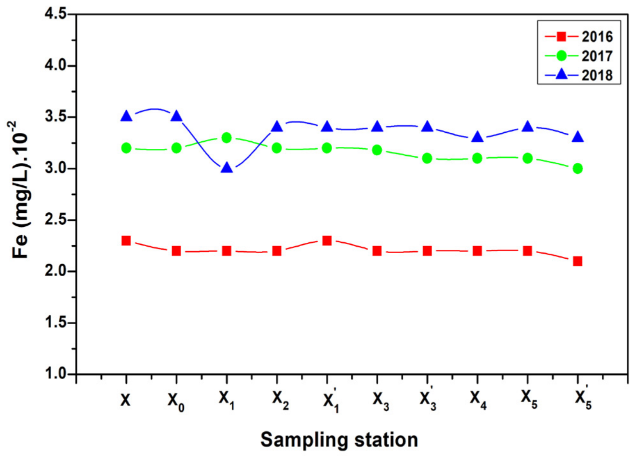

Fig. 13. Spatio-temporal Fe variation.

oxygen in the seas and many large marine animals feed on them [59–61].

3.1.10. Total iron

Fig. 13 presents the spatio-temporal Fe variation. According to this figure, obtained results during the year 2016, record the minimums for all the campaigns and stabilize around 0.023 mg/L. The years 2018 and 2017 present values oscillating between 0.03 and 0.035 mg/L, and are dispersed at the same rate, at all the sampling stations. The main source of iron is ferric chloride, which is a coagulant used in the desalination process [62,63]. In reality, the intake, which is done underground via coastal boreholes, coagulation is not used in the desalination process in Laayoune, because of the raw water which wonderfully reduces the turbidity content.

3.2. Discussion

Overall, it was noticed from the spatio-temporal distribution of all the parameters studied that:

- A clear variability of values over time, thus negating the prejudice or the hypothesis of accumulation in the same sampling station, throughout the years of study;
- A certain horizontal or/and vertical alignment of the values along the sampling stations;
- Peaks are often recorded in the sampling station X_1. This is perhaps due to the bathymetry and the residual current of the study area, which allows having a point of accumulation or stagnation due to oceanographic factors;
- The virtual stability of the values recorded in this study area, supported by minimal variation percentages, leads to the conclusion that there is no effective dilution of this discharge into the ocean. This means that the study area is at the heart of the brine plume.

Thus, and given the location of the brine discharge area, leading directly to the entrance to the port area, and bordering that of the discharge of industrial effluents, there could be an effect of accumulation of pollution in depth and in sediments. Without an outlet to ensure the dilution of the brine released, this area then constitutes a discharge of hypersaline concentrate, which can harm the receiving environment, this ecosystem known for its fishery resources. As a result, this can lead to the unemployment of local fishermen [64]. As a consequence of dehydration, there is a reduction in turgor pressure that could result in the long-term extinction of the marine species [65].

In the case of well-designed maritime infrastructure, as indicated in recent studies, more fish were found in the discard areas. In particular, Kelaher et al. [66], studied the effect of desalination reef fish abundance and diversity in the Sydney RO desalination plant (Australia). Researchers found that a rate of 279% increase in the number of fish in the exit sites obtained from before to after the start of the discharge.

4. Mitigations

The commonly used method for the efficient removal of brine adopted by the majority of plants is the discharge to surface water, especially the sea [12]. Brine treatment is considered one of the favorable options as it involves minimizing the volume of waste, reducing environmental pollution and recovering fresh water [12,67].

In this part, the main ways of mitigating the harmful impacts of brine discharge, through the bibliography were summarized. Several authors have raised this subject, approaching it from several angles [6,11,68].

Recently, researchers are focused to mitigate the harmful impacts of brine towards: (i) brine dilution multiport delivery systems which can be used for brine dispersion and to control the concentration and extent of the salinity plume [69], and far from productive and ecologically sensitive areas. (ii) Reduction of the amount of waste stream via a minimum liquid discharge or ZLD. However, further research needs to conduct in this direction to assess the feasibility of the ZLD system in practical applications [70,71]. (iii) The valorization from the rejected brine, which can be a precious and important source of water, by the recovery of minerals, salts and chemicals through processing, such as lithium recovery [72].

4.1. Water recovery

The desalination process generates huge volumes of wastewater with many retained materials. Effective brine treatment can result in the recovery of water from brine and a significant decrease for streams [73].

EIs can also be reduced using ZLD technologies to treat the desalination reject. ZLD has the advantage of recovering valuable salt and fresh water from the brine and minimizing the volume of concentrate. Several thermal and membrane technologies can be used to achieve ZLD, such as the brine concentrator and crystallizer [74]. Some methods are based on conventional and natural processes, while others are sophisticated and mechanical technologies. Processes, such as mechanical and thermal evaporative crystallizers, evaporation ponds, spray dryers, wind intensified evaporation, salt solidification and sequestration, slurry precipitation and recycling, RO and forced circulation crystallization can separate water and salts from the discharged brine. Although these technologies are currently not favorable due to their high cost, it is expected that more efficient ZLD techniques will be available in the future [12].

Evaporation ponds are most effective in arid or semiarid areas as they depend on solar energy to evaporate the water from the discharged brine and leave the salts to precipitate. This technique is simple and proven in industrial and wastewater treatment applications. However, this method has the disadvantages of high cost, and it contaminates groundwater and habitat due to the infiltration and accumulation of micropollutants.

4.2. Extraction of precious materials

Lately, special, and serious attention has been paid to recovering valuable elements from the discarded brine, as it contains most of the elements of the periodic table and it is concentrated there, so it considered co-products of the desalination process of seawater.

The idea of extracting valuable materials from discarded brine was proposed by Mero et al., [75]. The last few years have seen huge advances in the treatment and reuse of desalination brine. Historically, sodium chloride salt has recovered from seawater for the past few thousand years. Over the years, people have explored ways to extract other precious metals such as magnesium, gold, uranium, bromine, potassium, cesium, rubidium, and lithium from seawater [6,11,76].

A recent study shows great potential recovery lithium by membrane process, the preliminary economic analysis affirms that the process can be made profitable chlor-alkali industry [72]. In addition, other minerals and chemicals such as NaOH, Cl_2, H_2, MgO, $CaCO_3$, KCl, HCl, Na_2SO_4, $CaSO_4$, $CaCl_2$ and pure salts can be recovered from brine using various techniques [75,77].

The recovery of valuable materials from the brine not only minimizes its negative effects on the environment but also reduces the operational cost of desalination. In addition, it can increase the profitability of desalination plants if these constituents could be marketed. The extraction process, however, depends on feasibility, economics, energy considerations, and technical aspects of the technology [75].

4.3. Energy recovery

The reject can be used to recover energy from the salinity gradient, and theoretical calculations suggest that an amount of energy can be recovered. Because of that, the discharged brine has high osmotic pressure due to the high salinity; the brine can used as a salinity gradient energy source by mixing it with fresh water. Therefore, the discharged brine can be used for power generation and water harvesting simultaneously [77,78].

The recovered energy can be converted into electricity or mechanical energy by developing a suitable system. Likewise, delayed pressure osmosis and reverse electrodialysis can be used to recover energy from the reject stream [78].

4.4. Carbon dioxide sequestration

Several researchers have studied and shown the CO_2 capture potential of the released brine and its storage [79–81]. This way of using brine not only contributes to the reduction of CO_2 emissions, but also decreases the salinity of the brine discharged [81].

Dindi et al., reported that brine was used for CO_2 absorption to precipitate $NaHCO_3$ which resulted in the removal of Na^+ from the brine, making them safer to release into the environment [81]. The adsorbent can be recycled and reused in many cycles for CO_2 absorption and chloride removal [83].

4.5. Other beneficial uses of brine

Spirulina cultivation, fish farming (for specific fish that adapt to saline waters), and irrigation of shrubs and fodder crops, are all potential applications of the brine released from desalination plants [83]. However, more researchers are needed in this direction to determine the suitability of the release flux for the applications and necessary pretreatments [84].

Another potential use for brines is hydrotherapy. Hypersaline swimming pools promote the exchange of mineral salts with the body, which is useful as a disinfectant and wound healing, for the treatment of health problems such as rheumatism and osteoarthritis, skin conditions involving acne or psoriasis, and finally flotation which is ideal for people with reduced mobility, being also an effective relaxant [85].

5. Conclusion

The Laayoune region in southern Morocco has experienced rapid socio-economic development, which has required a large mobilization of water resources. This demand will continue to grow in the future, given the ambitious projects already launched or under construction in several sectors (industry, energy, urbanization, agriculture, etc.). Desalination of seawater, therefore, remains the most reliable solution to meet this demand in this arid region.

However, desalination generates various EIs, mainly the rejection of brine and overconsumption of energy. This work aimed to study the potential impacts of desalination of brine discharges, and suggest mitigation measures. It has clearly shown that the brine does not undergo a dilution in the receiving marine ecosystem, where the physical and chemical properties of the brine do not or little change.

To remedy this situation, it is suggested to adopt mitigation measures such as dilution before discharge, the installation of diffusers ensuring better dispersion in the ocean and the treatment of brines according to the ZLD approach. The latter solution offers several advantages, such as increasing the rate of freshwater production, recovering valuable materials and producing salts. In addition, the region offers great opportunities that make desalination more environmentally friendly. It should be noted that several projects exploiting the inexhaustible source of solar and wind energy are installed in the region. Among the geomorphological characteristics of the region, the existence of large flat-bottomed depressions, in communication or not with the sea, called "sebkhas", offering prospects for aquaculture of species that adapt to the high level of salinity. In addition, environmental monitoring plans and brine dispersion modeling approaches to predict releases, brine diffusion and mixing behavior must be in place for the ongoing environmental assessment of the littoral.

Finally, there is no doubt that with technological progress, the use of renewable energies in desalination, and the exploitation of the local specificities, the objective of sustainable and ecological desalination can be achieved.

Acknowledgments

The authors thank OCP group for physicochemical analyses.

References

[1] H. Elaouani, K. Jaafari, K. Benkhouja, N. Elbada, H. Haffad, Industrial Fish Wastewater Treatment by Electrocoagulation Processes Powered by Solar Energy, 2018 Renewable Energies, Power Systems & Green Inclusive Economy (REPS-GIE), IEEE, Casablanca, Morocco, 2018, pp. 1–6.
[2] L. Salama, K. El Ghazaouy, M. Zaidi, O. Elhaitamy, S. Rochd, M. el Marsi, A. Dezairi, Simulation of NaCl separation from seawater in membrane contactor, J. Heat Mass Transfer, 21 (2020) 203–216.
[3] N.C. Darre, G.S. Toor, Desalination of water: a review, Curr. Pollut. Rep., 4 (2018) 104–111.
[4] Y.H. Teow, A.W. Mohammad, New generation nanomaterials for water desalination: a review, Desalination, 451 (2019) 2–17.
[5] P.S. Goh, A.F. Ismail, B.C. Ng, Carbon nanotubes for desalination: performance evaluation and current hurdles, Desalination, 308 (2013) 2–14.
[6] I. Ihsanullah, M.A. Atieh, M. Sajid, M.K. Nazal, Desalination and environment: a critical analysis of impacts, mitigation strategies, and greener desalination technologies, Sci. Total Environ., 780 (2021) 146585, doi: 10.1016/j.scitotenv.2021.146585.
[7] Ihsanullah, T. Laoui, A.M. Al-Amer, A.B. Khalil, A. Abbas, M. Khraisheh, M.A. Atieh, Novel anti-microbial membrane for desalination pretreatment: a silver nanoparticle-doped carbon nanotube membrane, Desalination, 376 (2015) 82–93.
[8] A. Ihsanullah, A.M. Al Amer, T. Laoui, A. Abbas, N. Al-Aqeeli, F. Patel, M. Khraisheh, M.A. Atieh, N. Hilal, Fabrication and antifouling behaviour of a carbon nanotube membrane, Mater. Des., 89 (2016) 549–558.
[9] S. Kar, R.C. Bindal, P.K. Tewari, Carbon nanotube membranes for desalination and water purification: challenges and opportunities, Nano Today, 7 (2012) 385–389.
[10] X. Qu, J. Brame, Q. Li, P.J.J. Alvarez, Nanotechnology for a safe and sustainable water supply: enabling integrated water treatment and reuse, Acc. Chem. Res., 46 (2013) 834–843.
[11] M.O. Mavukkandy, C.M. Chabib, I. Mustafa, A. Al Ghaferi, F. AlMarzooqi, Brine management in desalination industry: from waste to resources generation, Desalination, 472 (2019) 114187, doi: 10.1016/j.desal.2019.114187.
[12] A. Panagopoulos, K.-J. Haralambous, M. Loizidou, Desalination brine disposal methods and treatment technologies - a review, Sci. Total Environ., 693 (2019) 133545, doi: 10.1016/j.scitotenv.2019.07.351.
[13] A. Panagopoulos, K.-J. Haralambous, Minimal liquid discharge (MLD) and zero liquid discharge (ZLD) strategies for wastewater management and resource recovery – analysis, challenges and prospects, J. Environ. Chem. Eng., 8 (2020) 104418, doi: 10.1016/j.jece.2020.104418.
[14] D. Beqqour, B. Achiou, A. Bouazizi, H. Ouaddari, H. Elomari, M. Ouammou, J. Bennazha, S. Alami Younssi, Enhancement of microfiltration performances of pozzolan membrane by incorporation of micronized phosphate and its application for industrial wastewater treatment, J. Environ. Chem. Eng., 7 (2019) 102981, doi: 10.1016/j.jece.2019.102981.
[15] D. Beqqour, G. Derouich, W. Taanaoui, A. Essate, M. Ouammou, S. Allami Younssi, J. Bennazha, J.A. Cody, M. El Rhazi, Development of composite ultrafiltration membrane made of PmPD/PVA layer deposited on ceramic pozzolan/micronized phosphate support and its application for Congo red dye removal, Desal. Water Treat., 240 (2021) 152–164.
[16] D. Beqqour, W. Taanaoui, M. Ouammou, S. Allami Younssi, J. Bennazha, J.A. Cody, M. El Rhazi, Removal of Congo red dye by ultrafiltration composite membrane of PpPD/PVA on flat pozzolan/micronized phosphate ceramic support, Desal. Water Treat., 240 (2021) 165–176.
[17] A. Makaoui, M. Idrissi, A. Benazzouz, M.A. Laamel, A. Agouzouk, J. Larissi, K. Hilmi, Hydrological variability of the upwelling and the filament in Cape Juby (28°N) Morocco, Int. J. Adv. Res., 3 (2015) 9–26.
[18] K. Hilmi, I. Bessa, A. Aouni, A. Makaoui, O. Ettahiri, Un Demi Siècle D'évaluation De L'activité De L'upwelling De La Côte Atlantique Marocaine, Eur. Sci. J., 89 (2020) 16–21.
[19] Direction de la Météorologie Nationale.
[20] A. Agence du Bassin Hydraulique de Sakia Hamra Ouad Dahab, Projet de recharge artificielle de la nappe de Foum Elouad., 2005.
[21] https://www.google.com/maps/@27.1006504,-13.4121128,2421m/data=!3m1!1e3
[22] AFNOR, Recueil des normes françaises (Qualité des eaux), 3ème edition, 1996.
[23] R. Baten, K. Stummeyer, How sustainable can desalination be?, Desal. Water Treat., 51 (2013) 44–52.
[24] P.K. Cornejo, M.V.E. Santana, D.R. Hokanson, J.R. Mihelcic, Q. Zhang, Carbon footprint of water reuse and desalination: a review of greenhouse gas emissions and estimation tools, J. Water Reuse Desal., 4 (2014) 238–252.
[25] M. Esrafilian, R. Ahmadi, Energy, environmental and economic assessment of a polygeneration system of local desalination and CCHP, Desalination, 454 (2019) 20–37.
[26] A.G. (Tony) Fane, A grand challenge for membrane desalination: more water, less carbon, Desalination, 426 (2018) 155–163.
[27] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water sources, technology, and today's challenges, Water Res., 43 (2009) 2317–2348.
[28] K. Loganathan, H.A. Al-Sulaiti, S.J. Bukhari, A.K. Fard, Y.M. Manawi, M.A. Hussien, Distribution of salinity and trace elements in surface seawater of the Arabian Gulf surrounding the State of Qatar, Desal. Water Treat., 143 (2019) 102–110.

[29] R. Semiat, Energy issues in desalination processes, Environ. Sci. Technol., 42 (2008) 8193–8201.
[30] G.A. Tularam, M. Ilahee, Environmental concerns of desalinating seawater using reverse osmosis, J. Environ. Monit., 9 (2007) 805–813.
[31] T. Alharbi, H. Alfaifi, S.A. Almadani, A. El-Sorogy, Spatial distribution and metal contamination in the coastal sediments of Al-Khafji area, Arabian Gulf, Saudi Arabia, Environ. Monit. Assess., 189 (2017) 634, doi: 10.1007/s10661-017-6352-1.
[32] M.L. Cambridge, A. Zavala-Perez, G.R. Cawthray, J. Statton, J. Mondon, G.A. Kendrick, Effects of desalination brine and seawater with the same elevated salinity on growth, physiology and seedling development of the seagrass *Posidonia australis*, Mar. Pollut. Bull., 140 (2019) 462–471.
[33] H. Frank, K.E. Fussmann, E. Rahav, E.B. Zeev, Chronic effects of brine discharge from large-scale seawater reverse osmosis desalination facilities on benthic bacteria, Water Res., 151 (2019) 478–487.
[34] E. Gacia, O. Invers, M. Manzanera, E. Ballesteros, J. Romero, Impact of the brine from a desalination plant on a shallow seagrass (*Posidonia oceanica*) meadow, Estuarine Coastal Shelf Sci., 72 (2007) 579–590.
[35] A. Garrote-Moreno, Y. Fernández-Torquemada, J.L. Sánchez-Lizaso, Salinity fluctuation of the brine discharge affects growth and survival of the seagrass *Cymodocea nodosa*, Mar. Pollut. Bull., 81 (2014) 61–68.
[36] M. Sadiq, Metal contamination in sediments from a desalination plant effluent outfall area, Sci. Total Environ., 287 (2002) 37–44.
[37] N. Kress, Chapter 6 – Actual Impacts of Seawater Desalination on the Marine Environment Reported Since 2001, in: Marine Impacts of Seawater Desalination: Science, Management, and Policy, Elsevier, 2019, pp. 81–133.
[38] J.M. Pèrés, La pollution des eaux marines, 1976.
[39] N. Voutchkov, G. Kaiser, R. Stover, J. Lienhart, L. Awerbuch, Sustainable Management of Desalination Plant Concentrate – Desalination Industry Position Paper – Energy and Environment Committee of the International Desalination Association (IDA) Presenter, Project: Concentrate Management, 2019 IDA World Congress, Dubai, 2019, pp. 1–32.
[40] N. Ahmad, R.E. Baddour, A review of sources, effects, disposal methods, and regulations of brine into marine environments, Ocean Coastal Manage., 87 (2014) 1–7.
[41] R.A. Browne, G. Wanigasekera, Combined effects of salinity and temperature on survival and reproduction of five species of *Artemia*, J. Exp. Mar. Biol. Ecol., 244 (2000) 29–44.
[42] T. Hoepner, A procedure for environmental impact assessments (EIA) for seawater desalination plants, Desalination, 124 (1999) 1–12.
[43] M. Sharifinia, Z. Afshari Bahmanbeigloo, W.O. Smith Jr., C.K. Yap, M. Keshavarzifard, Prevention is better than cure: Persian Gulf biodiversity vulnerability to the impacts of desalination plants, Global Change Biol., 25 (2019) 4022–4033.
[44] D. Vallero, Environmental Biotechnology: A Biosystems Approach, Academic Press, 2015.
[45] D.A. Vallero, Thermal Pollution, pp. 381–404.
[46] S.A. Umoren, M.M. Solomon, Chemical Additives for Corrosion Control in Desalination Plants, V.S. Saji, A.A. Meroufel, A.A. Sorour, Eds., Corrosion and Fouling Control in Desalination Industry, Springer, Cham, 2020, pp. 191–207.
[47] V.G. Gude, Desalination and sustainability – an appraisal and current perspective, Water Res., 89 (2016) 87–106.
[48] C. Kenigsberg, S. Abramovich, O. Hyams-Kaphzan, The effect of long-term brine discharge from desalination plants on benthic foraminifera, PloS One, 15 (2020) e0227589, doi: 10.1371/journal.pone.0227589.
[49] K. Smyth, M. Elliott, Effects of Changing Salinity on the Ecology of the Marine Environment, M. Solan, N. Whiteley, Eds., Stressors in the Marine Environment: Physiological and Ecological Responses; Societal Implications, 2016, pp. 161–174.
[50] A.C. Chamberlain, C.C. Ioannou, Turbidity increases risk perception but constrains collective behaviour during foraging by fish shoals, Animal Behav., 156 (2019) 129–138.
[51] A.C. Utne-Palm, Visual feeding of fish in a turbid environment: physical and behavioural aspects, Mar. Freshwater Behav. Physiol., 35 (2002) 111–128.
[52] T.J.R. Quimpo, C.A. Ligson, D.P. Manogan, J.N.C. Requilme, R.L. Albelda, C. Conaco, P.C. Cabaitan, Fish farm effluents alter reef benthic assemblages and reduce coral settlement, Mar. Pollut. Bull., 153 (2020) 111025, doi: 10.1016/j.marpolbul.2020.111025.
[53] M.S. Islam, S. Khan, M. Tanaka, Waste loading in shrimp and fish processing effluents: potential source of hazards to the coastal and nearshore environments, Mar. Pollut. Bull., 49 (2004) 103–110.
[54] Arrêté Interministériel 2942.13 du 07 Octobre 2013, Valeurs limites générales des rejets liquides, Ministere de la tarnsition energetique et du developpement durable, Département du developpement durable, 2013.
[55] Decret n°2.04.553 du 13 hija 1425 (24 janvier 2005) relatif aux deversements, ecoulements, rejets, depots directs ou indirects dans les eaux superficielles ou souterraines.
[56] J.-Y. Lin, N.N.N. Mahasti, Y.-H. Huang, Recent advances in adsorption and coagulation for boron removal from wastewater: a comprehensive review, J. Hazard. Mater., 407 (2021) 124401, doi: 10.1016/j.jhazmat.2020.124401.
[57] N. Hilal, G.J. Kim, C. Somerfield, Boron removal from saline water: a comprehensive review, Desalination, 273 (2011) 23–35.
[58] M. Landi, T. Margaritopoulou, I.E. Papadakis, F. Araniti, Boron toxicity in higher plants: an update, Planta, 250 (2019) 1011–1032.
[59] E. Canadian Council of Ministers of the, Canadian Soil Quality Guidelines for Carcinogenic and Other Polycyclic Aromatic Hydrocarbons (PAHS): Environmental and Human Health Effects: Scientific Supporting Document: Canadian Council of Ministers of the Environment, 2008.
[60] N. Mikac, M. Branicaa, R.M. Harrisonb, Total and organic lead distribution in water, sediment and organisms from the Eastern Adriatic coast, Chem. Speciation Bioavailability, 13 (2001) 121–128.
[61] Ecotoxicology Database, Version 4, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Mid-Continent Ecology Division, US Environmental Protection Agency, Washington (DC).
[62] S. Lattemann, T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination, 220 (2008) 1–15.
[63] K.L. Petersen, A. Paytan, E. Rahav, O. Levy, J. Silverman, O. Barzel, D. Potts, E. Bar-Zeev, Impact of brine and antiscalants on reef-building corals in the Gulf of Aqaba – potential effects from desalination plants, Water Res., 144 (2018) 183–191.
[64] H. Arafat, Desalination Sustainability: A Technical, Socioeconomic, and Environmental Approach, Elsevier, 2017.
[65] N. Belkin, E. Rahav, H. Elifantz, N. Kress, I. Berman-Frank, The effect of coagulants and antiscalants discharged with seawater desalination brines on coastal microbial communities: a laboratory and *in situ* study from the southeastern Mediterranean, Water Res., 110 (2017) 321–331.
[66] B.P. Kelaher, G.F. Clark, E.L. Johnston, M.A. Coleman, Effect of desalination discharge on the abundance and diversity of reef fishes, Environ. Sci. Technol., 54 (2019) 735–744.
[67] G. Ye, Z. Yu, Y. Li, L. Li, L. Song, L. Gu, X. Cao, Efficient treatment of brine wastewater through a flow-through technology integrating desalination and photocatalysis, Water Res., 157 (2019) 134–144.
[68] C.M. Papapostolou, E.M. Kondili, D.P. Zafirakis, G.T. Tzanes, Sustainable water supply systems for the islands: the integration with the energy problem, Renewable Energy, 146 (2020) 2577–2588.
[69] G. Amy, N. Ghaffour, Z. Li, L. Francis, R.V. Linares, T. Missimer, S. Lattemann, Membrane-based seawater desalination: Present and future prospects, Desalination, 401 (2017) 16–21.
[70] K.G. Nayar, J. Fernandes, R.K. McGovern, B.S. Al-Anzi, J.H. Lienhard V, Cost and energy needs of RO-ED-crystallizer systems for zero brine discharge seawater desalination, Desalination, 457 (2019) 115–132.

[71] G.U. Semblante, J.Z. Lee, L.Y. Lee, S.L. Ong, H.Y. Ng, Brine pre-treatment technologies for zero liquid discharge systems, Desalination, 441 (2018) 96–111.
[72] Z. Li, C. Li, X. Liu, L. Cao, P. Li, R. Wei, X. Li, D. Guo, K.-W. Huang, Z. Lai, Continuous electrical pumping membrane process for seawater lithium mining, Energy Environ. Sci., 14 (2021) 3152–3159.
[73] A. Giwa, V. Dufour, F. Al Marzooqi, M. Al Kaabi, S.W. Hasan, Brine management methods: recent innovations and current status, Desalination, 407 (2017) 1–23.
[74] M. Lee, C.-S. Fan, Y.-W. Chen, K.-C. Chang, P.-T. Chiueh, C.-H. Hou, Membrane capacitive deionization for low-salinity desalination in the reclamation of domestic wastewater effluents, Chemosphere, 235 (2019) 413–422.
[75] A. Shahmansouri, J. Min, L. Jin, C. Bellona, Feasibility of extracting valuable minerals from desalination concentrate: a comprehensive literature review, J. Cleaner Prod., 100 (2015) 4–16.
[76] Y. Aviezer, L. Birnhack, A. Leon, E. Aghion, O. Lahav, A new thermal-reduction-based approach for producing Mg from seawater, Hydrometallurgy, 169 (2017) 520–533.
[77] R.S. Kingsbury, F. Liu, S. Zhu, C. Boggs, M.D. Armstrong, D.F. Call, O. Coronell, Impact of natural organic matter and inorganic solutes on energy recovery from five real salinity gradients using reverse electrodialysis, J. Membr. Sci., 541 (2017) 621–632.
[78] S. Lee, J. Choi, Y.-G. Park, H. Shon, C.H. Ahn, S.-H. Kim, Hybrid desalination processes for beneficial use of reverse osmosis brine: current status and future prospects, Desalination, 454 (2019) 104–111.
[79] J.-H. Bang, S.C. Chae, S.-W. Lee, J.-W. Kim, K. Song, J. Kim, W. Kim, Sequential carbonate mineralization of desalination brine for CO_2 emission reduction, J. CO_2 Util., 33 (2019) 427–433.
[80] H.M. Breunig, J.T. Birkholzer, A. Borgia, C.M. Oldenburg, P.N. Price, T.E. McKone, Regional evaluation of brine management for geologic carbon sequestration, Int. J. Greenhouse Gas Control, 14 (2013) 39–48.
[81] J. Jeon, M.-J. Kim, CO_2 storage and $CaCO_3$ production using seawater and an alkali industrial by-product, Chem. Eng. J., 378 (2019) 122–180.
[82] A. Dindi, D.V. Quang, I. AlNashef, M.R.M. Abu-Zahra, A process for combined CO_2 utilization and treatment of desalination reject brine, Desalination, 442 (2018) 62–74.
[83] A.S. Sánchez, I.B.R. Nogueira, R.A. Kalid, Uses of the reject brine from inland desalination for fish farming, *Spirulina* cultivation, and irrigation of forage shrub and crops, Desalination, 364 (2015) 96–107.
[84] M.C. Hacıfazlıoğlu, H.R. Tomasini, L. Bertin, T. Pek, N. Kabay, Concentrate reduction in NF and RO desalination systems by membrane-in-series configurations-evaluation of product water for reuse in irrigation, Desalination, 466 (2019) 89–96.
[85] D. Zarzo, Chapter 11 – Beneficial Uses and Valorization of Reverse Osmosis Brines, V.G. Gude, Ed., Emerging Technologies for Sustainable Desalination Handbook, Elsevier, 2018, pp. 365–397.