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Comparison of Environmental Impact of Seawater Desalination Between MSF and RO Methods A Literature Review

By

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Statement of Integrity

I hereby declare having conducted my thesis with integrity. I confirm that I have not used plagiarism or any form of falsification of results during the thesis elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of BIHE.

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Abstract

In this project a literature review was conducted to consider the latest process developments and operation of seawater desalination plants and their pollution potential, at a global level. Thermal desalination (MSF and MED), membrane separation (RO) and Chemical approaches were pointed out as three main desalination technologies. Two of the more advanced of such operations namely Reverse Osmosis (RO) and Multi-Stage Flash Desalination (MSF) were selected and were compared and contrasted. Then, their advantages and disadvantages were analysed and finally some recommendations were made to improve the operations and to reduce the pollution potential of such operations. Besides the main Seawater desalination technologies that are currently applied for mega-scale water production in Middle East were found as Reverse Osmosis (RO), Multi-Stage Flash (MSF) and Multi-Effect Desalination (MED).

Regarding advantages and disadvantages of the compared methods, RO plants demonstrated some positive and negative differences than the thermal plants such as lower overall energy consumption resulting in less atmospheric emission, higher concentration of the brine, lower increase in the temperature and etc. In general, it was found that with the development of today's technology, RO desalination has less environmental impacts than thermal desalination because of the possibility of using renewable energies in RO. Although thermal desalination plants have a great potential for reducing environmental effects, if integrated with other production process, both of the methods have their own advantage and disadvantages which should not be ignored.

To mitigate the environmental impacts of desalination, different methods were suggested in this thesis such as using a combination of varying decoy screens and a low velocity intake, pre-dilution of reject water with other reject streams, new technologies such as hybrid systems, using renewable energies and etc. amongst them, using renewable energies, as explained in the body of the thesis, seems to be the most efficient solution regarding environmental impacts mitigation.

Keywords: Reverse Osmosis (RO), Multi-Stage Flash Desalination (MSF), Mitigating Environmental Impact of Seawater Desalination, Hyper Saline, Warm Effluent, Greenhouse Gases.

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LIST OF ABBREVIATIONS

Abbreviation	Description
MED	Multi-Effect Desalination
MSF	Multi-Stage Flash Desalination
RO	Reverse Osmosis
VC	Vapor Compression
ED	Electro-Dialysis
FO	Forward Osmosis
MD	Membrane Desalination
CDI	Capacitance Deionization
GH	Gas Hydrates
HDH	Humidification De Humidification
UF	Ultra Filtration
NF	Nano Filtration
IF	Ionic Filtration
TBT	Top Brine Temperature Limitation
TDS	Total Dissolved Solids
GCC	Gulf Corporation Council
MIGD	Million Imperial Gallons Per Day
SWRO	Sea Water Reverse Osmosis
BWRO	Brackish Water Reverse Osmosis
EWRO	Effluent Water Reverse Osmosis
GHG	Greenhouse Gas
ZLD	Zero Liquid Discharge

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Chapter 1

Introduction

Ever-increasing population rate and as a result, the growing consumption are the main reason of pressure on natural resources [1]. It is estimated that 25 million m³/day of water is desalinated around the world [2]. Based on the research presented by Lattemann and Hopner (2008) around 50% of desalinated seawater is generated in Middle East due to the lack of potable water and access to cheap energy. Besides the Middle East, many countries including United States, China, Australia and Europe inclined to expand their desalinating capacity due to the following factors:

1. Rapid population growth;
2. Anticipated changes to precipitation patterns brought by climate Change;
3. Technological improvements in energy requirements;

For instants, twenty new desalination projects by total capacity of 2 million m³/day will be constructed by 2030 just in California [2].

1.1 Motivation

In this project a literature review would be conducted to consider the latest process developments and operation of seawater desalination plants and their pollution potential, at a

global level. Two of the more advanced of such operations would be selected and would be compared and contrasted. Besides, their advantages and disadvantages would be considered. Then, recommendations would be made to improve the operations and to reduce the pollution potential of such operations.

1.2 Objectives

The aim of this project is to conduct a literature review to determine the environmental impact of seawater desalination around the world. At the same time different desalination methods would be identified. In the next step two desalination methods of two such operations would be compared and contrasted and finally modifications that would improve and optimize their operation would be recommended.

1.3 Methodology

The core of this work is to conduct a literature review to consider the existing international research, development and operation of desalination plants, especially from water pollution control point of view. Also, advantages and disadvantages of the main processes of two such operations would be considered and recommendations would be made to improve their operation and reduce their pollution potential. For this aim over 100 scientific articles were studied amongst them 71 articles including conference papers, books and articles from scientific journals were cited in this research.

1.4 Outline of Thesis

This thesis is divided in 7 chapters. Chapter 1 presents an introduction to this research work, motivation and the objectives of current study as well as an overall view to the methods that have been applied herein. Chapter 2 is a state-of-the-art and presents relevant background information in the area of desalination. In chapter 3 the environmental impacts of seawater desalination were discussed. Chapter 4 includes the advantages and disadvantages of Multi-Stage flash desalination (MSF) and Reverse osmosis (RO) desalination methods. Chapter 5 explains the methods to

mitigate the impacts of seawater desalination. In chapter 6, the main conclusions of the current study are presented. Finally, the last chapter includes bibliography and references used in this thesis.

Chapter 2

Background and Overview of Different Desalination Methods

This chapter provides a review to seawater desalination methods worldwide and their related global capacity. In addition, this review includes desalination methods in Middle East.

2.1 Water desalination methods

Thermal desalination (MSF and MED), membrane separation (RO) and Chemical approaches are three main desalination technologies [3, 4]. Besides these three main methods, thermal and membrane technologies are integrated in some hybrids plants as well [5]. Two other commercial technologies are vapor compression (VC) and electro-dialysis (ED) that because of their small units' size and low salinity respectively have less application. Forward osmosis (FO), membrane desalination (MD), capacitance deionization (CDI), and gas hydrates (GH), freezing,

humidification dehumidification (HDH) and solar stills are evolving technologies those should be developed more for future. Ultra/nano/ionic filtration (UF/NF/IF respectively) are some supporting technologies beyond the aim of this research [6]. Different processes of the global desalination by capacity are depicted in **Figure 1**.

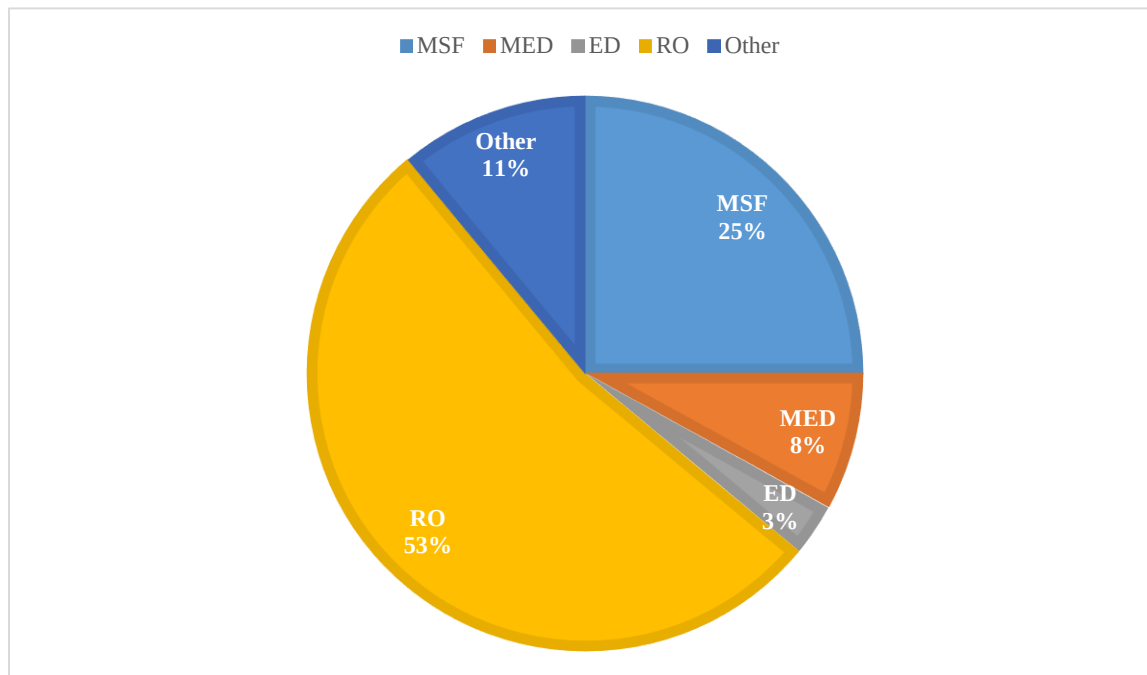


Figure 1. Global desalination capacity by process.

As can be seen in **Figure 1**, RO, MSF and MED share the highest capacities globally. Besides, as shown in **Figure 2** for the feed water quality, seawater, brackish and river are the most used waters respectively [7].

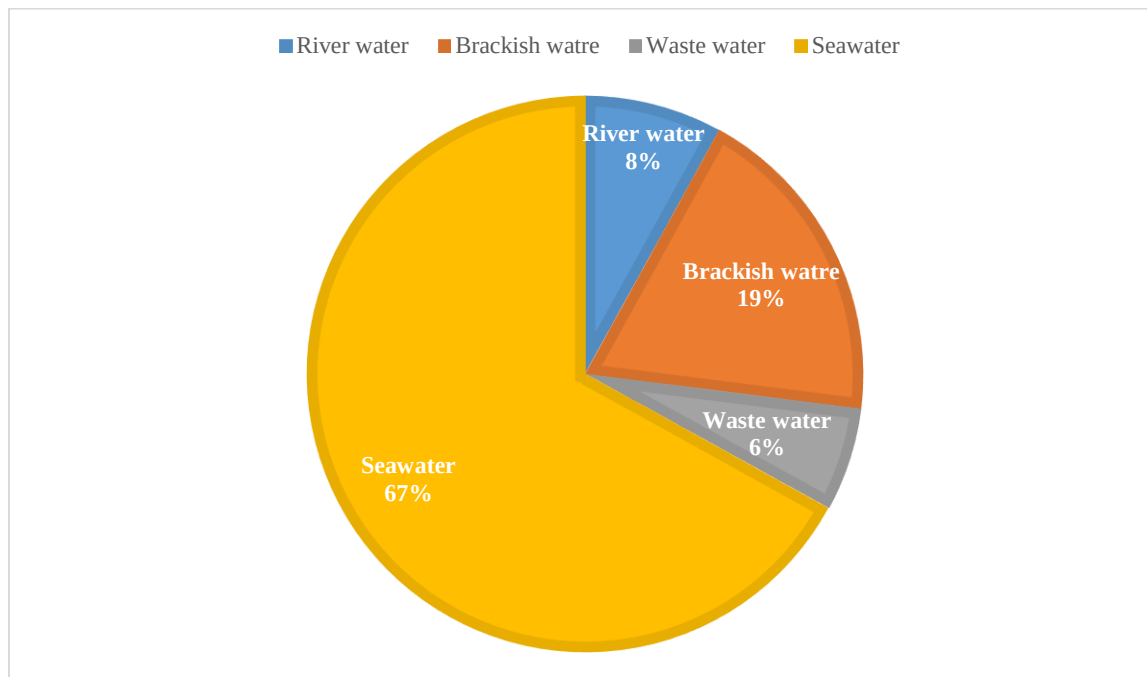


Figure 2. Worldwide feed water quality used in desalination [7].

2.1.1 Thermal technologies

A schematic principle of thermal desalination method is depicted in **Figure 3**. There are two major commercial thermal desalination methods including MSF and MED. In the Middle East due to the low energy cost and large scale plants, thermal technologies have been of special importance. Due to the fact that in thermal desalination methods natural water cycle of evaporation and condensation exists to produce high quality water, it suffers from formation of scales such as magnesium hydroxide, calcium carbonates and sulfates which finally leads to top brine temperature limits (TBT) [7, 8].

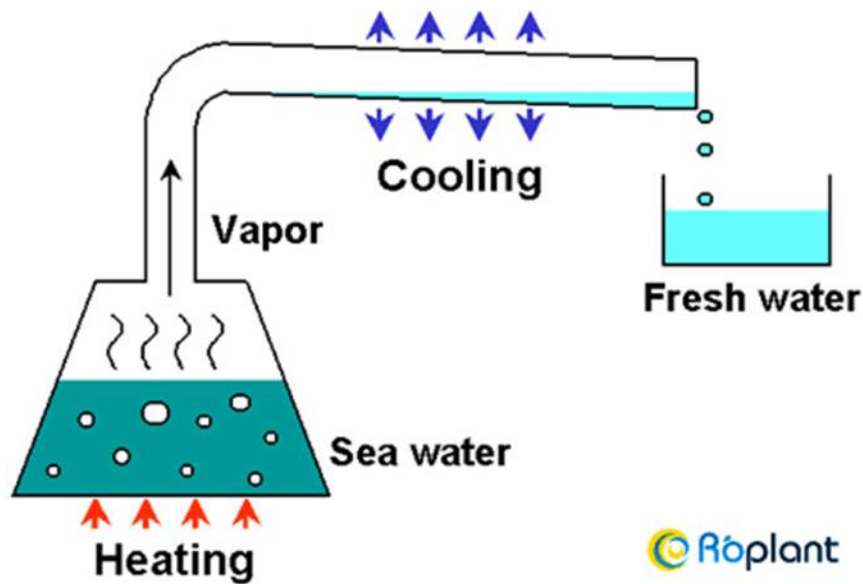


Figure 3. Schematic principle of Thermal desalination.

2.1.1.1 Multi-stage flash distillation

As can be seen in **Figure 4**, boiling and then condensing saline water is the main task in producing pure water in MSF. In other words, the saline feed water passes through a series of tubes. First, this would be essential to preheat the feed water before entering the brine heater. Then it is heated by any type of thermal energy. This heated water then is introduced into a vessel with an ambient pressure which is lower than the brine heater pressure. The main reason of the sudden boiling in this stage, called flashing, is this low pressure. The final result of this boiling is water vapors which is condensed on the tubes carrying input cold saline water and finally the distilled water is collected. This process would be repeated for the remaining water with an even lower pressure until the brine is cooled down and discharged. Usually MSF plants comprise of 18 to 25 stages [7, 8, 9].

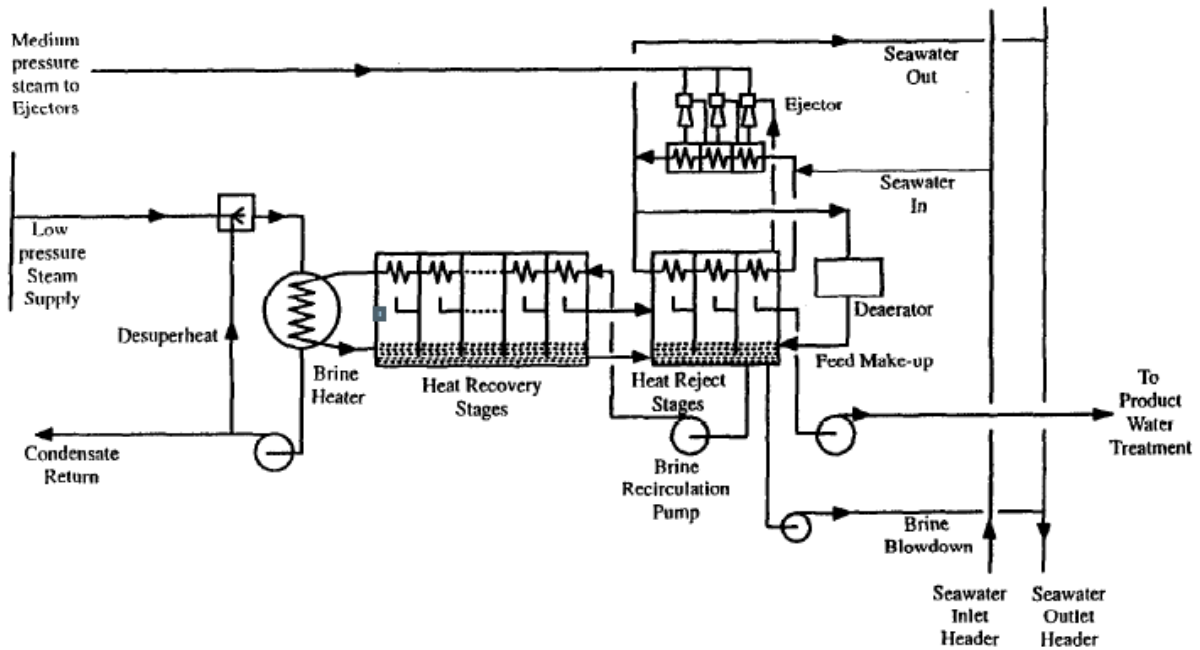


Figure 4. The MSF process with brine recirculation [9].

It should be noted that with emerging of new technologies such as RO and MED, MSF method follows a downward trend in the number of contracts as depicted in **Figure 5** with present 25% worldwide capacity share as can be seen in **Figure 1**. However, it has dominated the thermal desalination market during the 1980s and 1990s [7].

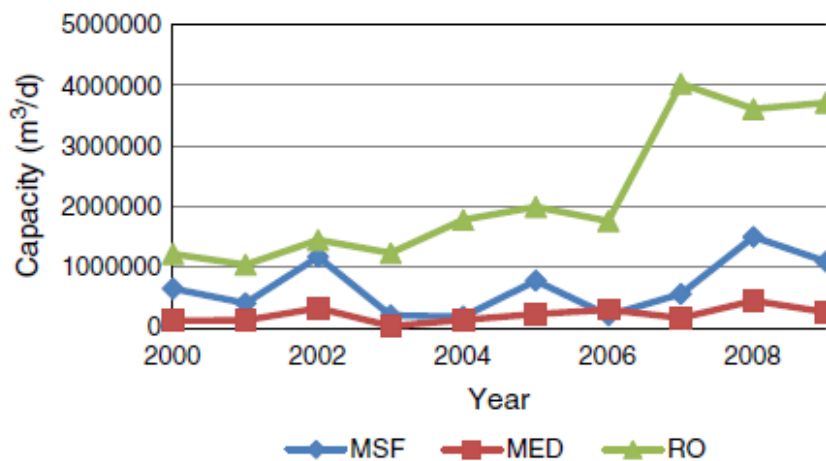


Figure 5. Capacity of desalination plants worldwide for different technologies by year [7].

It should be noticed that MSF still dominated in some part of the world especially in the Gulf region, in spite of the emerging growth of MED as shown in **Figure 6** for UAE. As an evidence, there are 45 MSF plants, 32 MED plants, and 41 RO plants in the Gulf region [10, 7, 11].

Despite RO's global dominance, RO is only now starting to gain foothold in the Persian Gulf due to its extensive pretreatment requirements to mitigate membrane fouling [11]. Despite SWRO's improvements over thermal techniques, it is still associated with a number of environmental issues, such as high energy demands, chemical dosing and concentrated brine disposal [13].

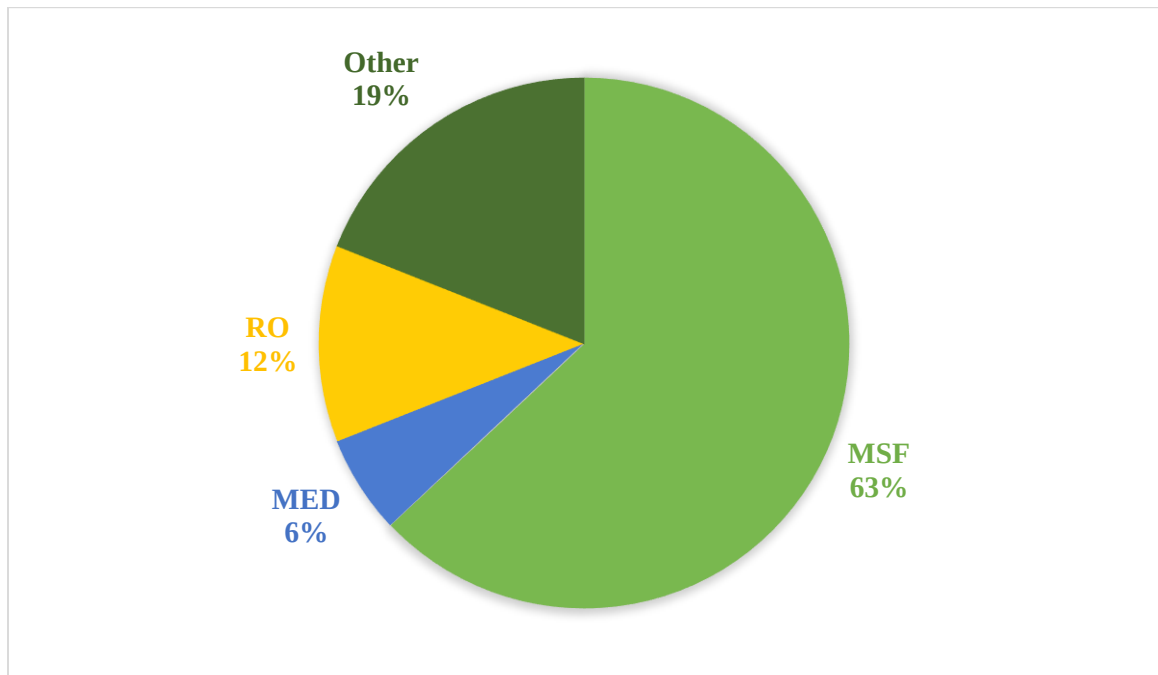


Figure 6. Distribution of desalination technologies used in UAE [7].

2.1.2 Membrane Technologies

In Membrane technology the passing of certain salt ions are prohibited or permitted. This method is used for both brackish and seawater desalination.

Membrane desalination (MD) was first introduced in the 1980s on a small scale combining the use of both thermal distillation and membranes. Generally in this method vapor is generated through thermal evaporation by using membranes to pass vapor, which is then condensed to produce fresh water. Due to the fact that MD requires more pumping energy per unit of fresh water produced, more space and more money are required compared with other approaches and hence its application has been limited. Since MD is a simple method and operates by small temperature differentials, it is probably best suited for industries or solar collectors with availability of inexpensive low-grade thermal energy [8].

2.1.2.1 Reverse osmosis

Reverse osmosis (RO) is a developing process in which an external pressure higher than the osmotic pressure on the seawater is required. Thus, after water flows in the reverse direction, dissolved salts are remained behind membranes with an increase in salt concentration into the brine stream. The advantage of this method is that no phase separation change or heating is necessary and just for the aim of pressurizing the seawater feed, energy is required.

Generally, RO process consists of four major steps [14, 15, 16, 17, 18]:

1. feed water pre-treatment;
2. high pressure pumping;
3. membrane separation;
4. Permeate post-treatment.

For a feed-water of a given salinity through applying higher pressure, flow of water through the membrane increases. Besides, for the higher salinity the greater pressure is required [9]. The flow diagram of a typical RO process is illustrated in **Figure 7**.

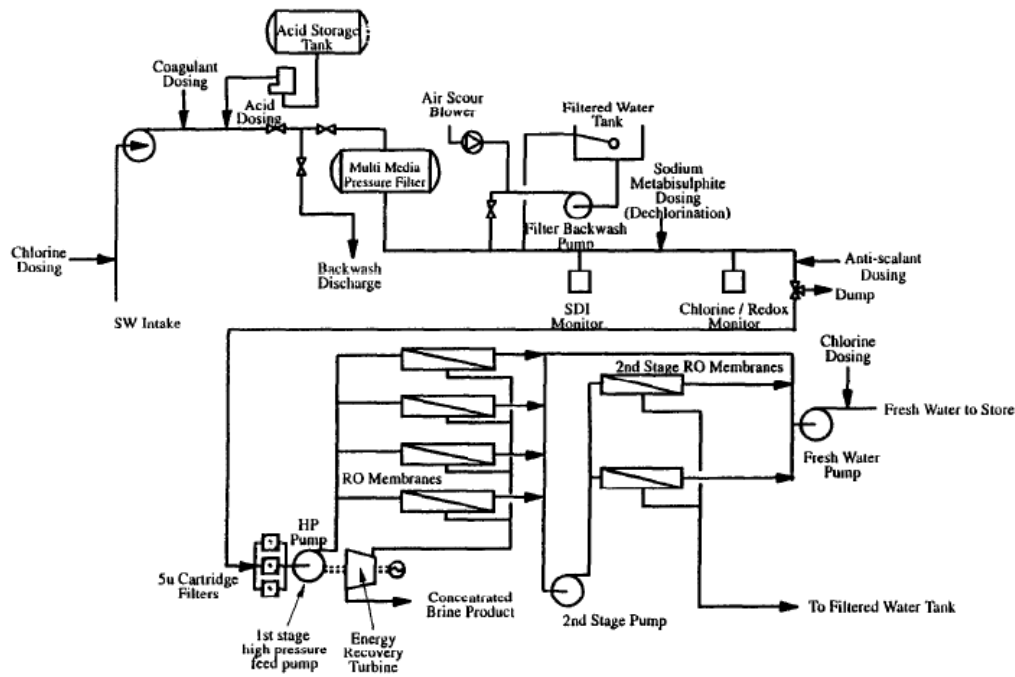


Figure 7. Typical flow sheet- Seawater RO [18].

Related to the brine discharge it should be noted that its concentration may range from 20% to 70% depending upon the salt content of the feed-water [7, 9].

Regarding the energy efficiency of RO method, it should be reminded that most modern reverse osmosis plants have an energy recovery system. In other words, the pressure energy in the brine, which is usually very high, is feed back to the feed-water using pressure exchangers. These exchanger systems has led to cost-efficiency of RO desalination methods [7].

As illustrated in **Figure 1**, RO is the world leading technology with a 53% world share in fresh water production [7].

There are three main types of desalination discharges in RO method including Seawater (SWRO), (2) Brackish water (BWRO) and (3) Effluent water (EWRO) [19].

The environmental characterizations of Seawater (SWRO) include the following items:

- "concentrated brine is approximately twice the concentration of ambient seawater;

- *additives such as antiscalants (polyphosphates, polymers), coagulants (ferric sulfate, ferric chloride) and membrane preservative (sodium bisulfite);*
- *Backwash water with concentrated wastes (suspended solids, turbidity, ferric);*
- *There is also brine with organic or inorganic cleaning solutions” [19].*

The potential environmental impacts of SWRO are:

- stratification as a result of salinity and density increase due to concentrated brine that accumulated at the bottom;
- eutrophication as the result of phosphate enrichment due to application of polyphosphates and if organic cleaning solutions are added to the brine;
- Discoloration as a result of some additives such as ferric, high-suspended solids and turbidity [19].

The environmental characterizations of Brackish water (BWRO) include:

- Salinity of the brine is about third to half of environmental seawater.
- There are additives like antiscalants such as polyphosphate and polymers, plus there is nitrogen enrichment.
- Decreasing in the Salinity and density.
- Eutrophication which happens as a result of the presence of Nitrogen, Silica and phosphate.

Changes in the chemistry of water might effect on the composition and variety of the ecosystem in the area [19].

2.2 Desalination methods in Middle East

Regarding the desalination of seawater in Middle East, it should be noted that this region and its three enclosed seas including the Red Sea, the Persian Gulf, and the Mediterranean alone account for nearly three-quarters of the global seawater desalination capacity, 45% of which is produced by desalination plants in the Gulf Cooperation Council (GCC) countries namely: Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates among them United Arab Emirates, Saudi Arabia and Kuwait are the largest producers, contributing to 26%, 23% and 7% of the global production, respectively. It is predicted that, due to continuous water demand as well as boosting national economies, the seawater desalination capacity will increase nearly 40%, from 4000 million imperial gallons per day to more than 5500 MIGD, by 2020 [20, 2].

As depicted in **Figure 8**, the main Seawater desalination technologies that are currently applied for mega-scale water production in Middle East are reverse osmosis (RO), multi-stage flash (MSF) and multi-effect desalination (MED).

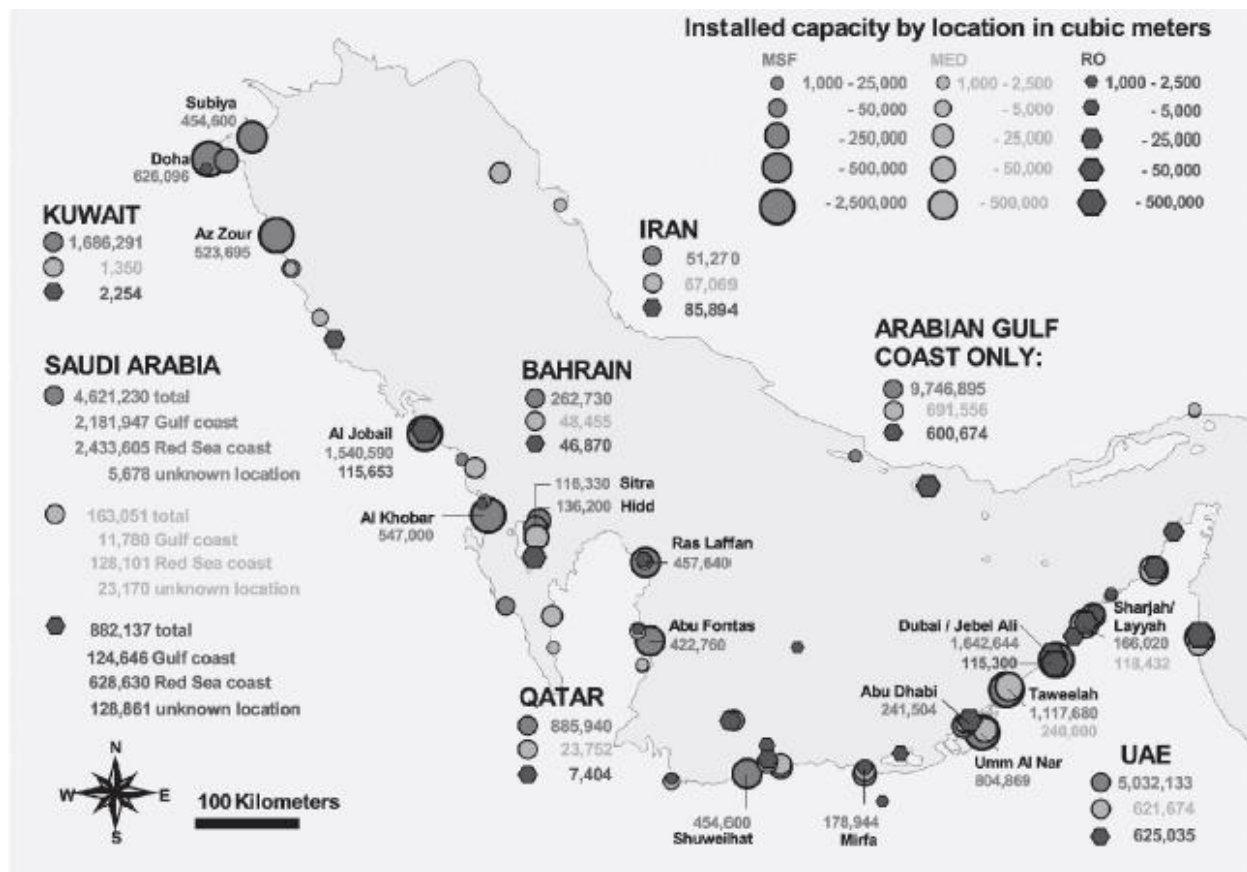


Figure 8. Seawater desalination capacity in the Arabian Gulf [2].

As a conclusion in this chapter and based on **Figure 1**, MSF and RO share the highest capacity globally and hence these two methods would be the analyzed, compared and contrasted more in the rest of this thesis.

Chapter 3

Environmental Impact of Seawater Desalination

This chapter deals with the main environmental impact of seawater desalination including abstracting feed water, the atmospheric impact and site selection effects particularly in MSF and RO methods. In general, the detrimental impact of seawater desalination is discussed in the second part and finally RO desalination types will be explained with respect to their environmental impact.

3.1 Seawater desalination factors affecting the Environment

All major industrial processes have some kind of environmental impact and desalination is no exception, so like any other environmental impact it should be understood and reduced. For instance, the effect of a long term construction that can be effective on the withdrawal of large volumes of seawater from ocean, brackish water from an aquifer or discharging large volumes of high concentration brine. Another thing to consider is the indirect impact of substantial use of energy. Every desalination facility is different in the context of plant design location and the environmental condition so each should be evaluated individually [8].

According to many of researches, in several arid areas of the world that rainfall is low and fresh water resources are very limited, desalination is the only means of producing drinking water. In the past, low population densities was likely to disperse around natural freshwater sources such as rivers and oasis. This life had an important effect on original flora and fauna and human population. Large fixed population, industrialization of cities and development of infrastructure to support this lifestyle are all the advent of desalination which its failure could lead to a human tragedy in these areas.

Based on the aforementioned introduction, general impact of desalination methods are due to the following factors:

3.1.1 Abstracting desalination plant feed-water and returning hyper-saline brine

It is clear that the worse side effect of seawater desalination is that the desalination plants extract high amount of seawater and return back hyper-saline brine into the main source of water which is harmful for environment [19]. The magnitude of the concentrated brine depends on environmental and hydro-geological characteristic of the receiving body including bathymetry, waves, currents, depth of the water column etc. And determining the extent of brines in different geographical areas [21].

3.1.2 The production of greenhouse-gases associated with the generation of steam and electricity

Due to the fact that Electricity and heat are the most commonly used energy sources for desalination, produced by burning fossil fuel, they have also great impact regarding production of green-house gasses however, new technologies such as hybrid systems utilize renewable energies, such as solar energy, to reduce the related environmental impact. It should be noted that, generally the desalination methods, such as RO, that require electricity are typically more energy efficient than thermal desalination. Solar electricity has been the most efficient type of renewable energy sources. Besides, it needs low maintenance which finally makes it suitable for any application.

3.1.3 Warm hyper saline water discharging to the marine environment

The increases in the temperature of the receiving environment take place when the volume of the cooling water discharges is high relative to its dissipative capacity. It should be noted that the waste heat discharged from thermal desalination plants is generally between 8 and 15°C above ambient seawater temperature which ultimately is dissipated in the marine environment [18, 22, 23, 24, 2].

This higher temperature would influence some properties of receiving body and would defect its quality. The main consequences are the following:

- With the increases of temperature the oxygen solubility decrease. At the same time the oxygen demand of biota rises at higher temperatures which all results in a serious threat for the receiving body particularly in summer.
- The Viscosity, density, the surface stress and the nitrogen solubility decrease as well resulting in:
 - ✓ “Density differences foster stratification of water bodies;
 - ✓ Viscosity leads to increased settling rates; thus, it influences sedimentation;
 - ✓ The reduction in the solubility of nitrogen can contribute, in return, with a deterioration of the primary production” [22].

Studies about the impact of brines on salinity shows different results about thermal impact. For instance, the monitoring studies and modelling in Western Australia shows that a hybrid power and desalination plant effluent stream could higher the temperature of intake waters by 0.1 to 0.5°C in a range of 7 kilometer area of the plant [26]. Other studies observed that the thermal impact in the vicinity streams is low despite the increase in the temperature of receiving water which is up to 15°C [27, 28].

MSF plants are typically associated with thermal impact, but it is generally dissipated rapidly with temperature decreasing in the receiving waters to the starting levels in tens of meters [27, 29]. Also the range of thermal effects is relative to the location of the plant discharge. When the effluent

water is in closed areas it has more thermal effects than when it is well distributed in the environment [30].

3.1.4 Site selection and environmental factors

The other significant issue regarding the environmental impact of desalination is Site selection and location of desalination plants. In other words, shallow and enclosed marine regions are more sensitive to desalination impact. By the same token, discharged brine will not be diffused well in the shallow water body besides, since it is denser than the seawater, it sinks to the sea floor. Hence, Site selection and location of desalination plants should be studied thoroughly to mitigate the impact on marine biodiversity [20].

3.2 Detrimental impact of seawater desalination

The desalination plants have detrimental impact from physicochemical and ecological point of view [31]. In fact, there are three main concerns regarding these detrimental factors. The first one, as mentioned above, as related to the hyper-saline brine and the second one is due to the toxic materials such as anti-foulants and anti-scalants for desalination plants maintenance [32]. The third concern is related to the potential thermal stress associated with the release of heated effluent [33].

- Physicochemical (related to the hyper-saline brine);
- Ecological (due to the toxic materials);
- Thermal stress

3.2.1 Physicochemical

Intensity and extent of brine plumes are two important issues regarding the salinity in receiving waters.

- Intensity
- extent of brine plumes

As can be seen in **Table 1**, there are different effects of desalination plants on receiving waters. The extension of plumes salinity differs from tens of meters [34] to several kilometers [35] due to the different capacity of the plants, the diffuser designs and hydrology of the environment or the sampling method for the study [36, 37, 38, 39, 21, 40, 41, 42].

Table 1. Extent and intensity of brine plumes in receiving waters surrounding desalination plant discharge outlets in shallow low-energy environments in the Mediterranean Sea [36].

Reference	Capacity ML/d	Discharge ML/d	Salinity of brine(PPt)	Location	habitat	Plume extension and intensity
[39]	92.4	NR	37.3	Muscat, Oman	Soft sediment	Returned to background levels within approximately 100m of outlet.
[39]	191	NR	40.11	Muscat, Oman	Soft sediment	Appeared to return to background levels 980m from outlet.
[28]	106	288	51	Sitra Island, Bahrain	Soft sediment	Salinity of receiving water reach 51ppt, relative to reference areas of 45 ppt, plums extended at least 160m from discharge. Temperature also affected, discharge at 10-15°C above ambient, receiving water up to 7°C above ambient.
[43]	9.1	22	40-55	Florida, USA	Artificial hard Substrata and Soft sediment	0.5 ppt above background levels within 10-20m outlet. Nevertheless, slight elevation was maintained for 600m within the harbor basin.
[42]	25	17	75.2	Canary Islands, Spain	Sub-tidal Rocky reef	2 ppt above background on the seabed and 1 ppt on the surface within the 20m of the outlet; Similar to background levels at 100m.
[21]	NR	NR	NR	Dhkelia, cyprus	NR	Above background 100-200m from outlet, occasionally as high as 60ppt.
[35]	50	75	68	Alicante, Spain	Sea grass and soft sediments	0.5 ppt above ambient for up to 4km from outlet along the seafloor.
[40]	28	NR	44	Javea, Spain	Sea grass and soft sediments	Slightly above background up to 300m from the outlet.
[37]	60	33	60	Blanes, Spain	Sea grass and soft sediments	At background levels within 10m of outlet, no apparent measurement or analysis of salinity.
[41]	50	65	68	Alicante, Spain	Soft sediment	2.6ppt above ambient within 300m ^b of outlet; 1ppt within 600m ^b ; similar to background at 1300m ^b .
[19]	274	600	42	Ashkelon, Israel	NR	Approximately 2ppt above ambient within 400m of outlet, <1ppm above ambient within 4000m of the outlet
[44]	25	NR	75	Canary, Islands, Spain	Soft sediment	75ppt effluent diluted to 38 ppt within 20m of outlet, no details given as to background salinity.
[34]	NR	2	60	Formentera, Balearic Islands, Spain	Sea grass and soft sediments	5.5ppt above background 10m from outlet; 2.5 ppt at 20m; 1ppt at 30m; not measured any further than this.

As mentioned above, the other important issue regarding the salinity is the intensity of the plume. With respect to most of the studies, the intensity of the plume is not a matter of concern. In other

words, within 20 meter of outlet, the intensity of the plumes is not more than 2 ppt and for hundreds of meters this value is less than 0.5 ppt [1].

Based on the aforementioned impact of desalination methods, the Existing desalination technologies could not be considered as environmental friendly or sustainable. On the other hand, they affect land, aquifer, air and marine environments. As noted before, the magnitude of this impact is dependent on the quantity, salinity, temperature and contents of the contaminants in the brine discharge as well as the sensitivity of the receiving water body such as the bathymetry, waves, currents and depth of the water column [44, 36].

On the other hand design and operation of the water intake has also ecological and environmental impact. As discussed before, during their operation, plants in coastal areas, take in large amounts of seawater. The California Energy Commission in their recent report on cooling-water intake structures of a power plant reported that: “seawater ... is not just water. It is habitat and contains an entire ecosystem of phytoplankton, fishes, and invertebrates” [8]. Large Marine organisms such as big fishes and birds get killed on the intake screen (impingement) and smaller ones like planktons they die in the operating system of desalination (entrainment). So these impinged and entrained organisms are out of the environment. The concentration of oxygen in the water is reduced then due to the decomposition of this organisms so the stress level in the marine environment is increased [8].

Impingement and entrainment is a new way that puts marine organisms in danger, this has broad effect on the lives of local fishes and invertebrates. In other words impingement and entrainment is effective on the lives of the fish and invertebrate so their population and breeding is reduced [45]. The amount of this effect varies with different factors such as:

The percentage of mortality in the vulnerable species,

The mortality rate of the organism relative to the natural mortality rate,

The standing stock in the area of the operation (Edinger and Kolluru 2000) [8].

3.2.2 Toxicity (Ecological);

Toxicity testing in laboratory in addition to field-based monitoring studies is used to measure the effect and constituent of the brine on marine organisms. These studies are based on single species [46, 47] and multi-species [48] tests and both fatal and sub-fatal effects [49, 48]. Many of the said experiments study the effects of the brine on seagrass (*P. oceanica*) and associated organisms. The results observed in laboratory experiments are reduction in growth, fatal wounds and premature senescence in seagrass at 39 ppt of salinity which is not that higher above the ambient salinity of the study environment [50].

40-45 ppt of salinity causes in numerous death of exposed plants, epifaunal mysida and echinoderms [50]. In an experiment [43] exposed echinoderms, ascidians and seagrass to dilute brines for 24- 96 h:

- Ascidians were the most sensitive and were 50% mortal following 96-h exposures to 5.8% brine dilutions.
- Echinoids showed similar levels of mortality in 96 h in 8.5% brine dilutions.
- Seagrass photosynthesis was lowered by 50% following 24-h exposures to 12% brine dilutions [43].

The result of experiments done on seagrass of hyper-saline environments is different. The pace of growth and leaf growing of seagrass that were based from Shark Bay, Western Australia (which in some places is as high as 70 ppt) were highest in the salinity range of 42.5 ppt [51]. Senescence and death happened at the salinity of 50 to 65 ppt [51]. So it's impossible to calculate a salinity value that is valid for saving all the seagrass around the world. Although laboratory experiments show that in the Mediterranean environment, desalination brine has a positive impact on the health and survival of the seagrass and invertebrate [50].

The salinity of 55, 60 and 70 ppt is extremely toxic for young clams, larval founder and clams. [48]. And pathological avoidance has been observed in the salinity of 45 ppt. In a 60 days exposure to the desalination discharge, reduction in the survival and impaired production in the oyster was observed in *Crassostrea Virginica* [47].

The dissolved copper that was present in the desalination discharge is responsible for these toxicological impact. In addition to that, the change in the physiochemical characteristics of the discharge water is effective on the rate of fungus infection in the exposed oyster [47].

Recent experiments show that the increased salinity and trace metal concentration of the desalination brine is extremely toxic to developing cuttlefish embryos. [52]. In laboratory experiments, fewer eggs of the giant Australian cuttlefish, *Sepia apama*, when exposed to the brine effluent with salinity greater than 45 ppt, developed to term. At these concentrations individual survival has shown pathological impact, like slower response to stimulation and less ink-jet defense responses [52]. When the concentration of the brine is higher than 45 ppt, exposed eggs have shown absolute mortality [46]. It is clear that brine discharges are often denser than seawater. In this regard plumes extend along the seafloor rather than at the surface [43, 53, 34, 54]. This phenomena causes exposure of benthic organisms to brine discharges in a laboratory, Sea grass have been exposed to conditions in order to simulate the brine exposure [50]. Regardless of exposure method, a significant effect was discovered between the sea grass survival and the brine discharge.

3.2.2.1 Ferric impact

Since the first and biggest desalination plant in Ashkelon Site has been operated in July 2005, some kind of a red brine phenomenon has been observed. This occurs every hour for 10 to 20 minutes when untreated discharge water, with high ferric concentration (up to 42 mg/L) is in the brine see **Figure 9**.

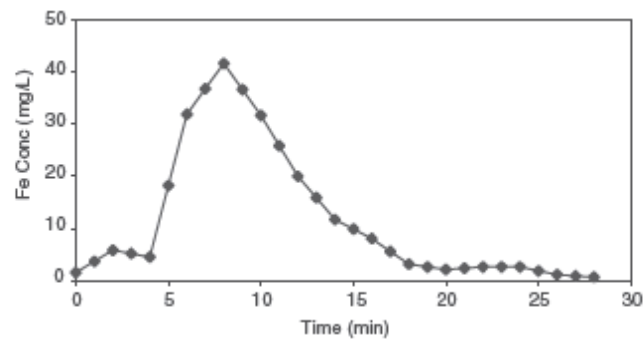


Figure 9. Ferric (Fe) concentration in the during sand-filter backwash [19]

This happens as a result of the usage of ferric sulfate as a coagulant additive and you may see the data in **Table 2**.

Table 2. Discharged SWRO ferric data

Year & status	Ferric load(Fe)(ton/y)	Fe concentration (mg/L)
Planned(2003)	265	0.48-1.6
Actual discharge,2005 (6 months)	320(annual basis)	1.2-3 daily average
Actual discharge ,2006	~500	3.5 daily average on annual basis, 5 daily average (occasionally),40-50 for intermittent peaks
Expected discharge, 2007	500-650	The same as 2006

Ferric is not a dangerous component for the marine life alone, but high concentrated ferric brines might affect the environment [54, 19].

The problem is whether the ferric component in the brine is only a matter of color or does it have an impact on the environment. When this effluent water is constantly adding to the sea, as a result

of an operational system, which is high in ferric concentration, it is obvious that some threats to the ecosystem is expected. Some of the environmental effects that are expected are:

1. High turbidity zone,
2. High-suspended solids zone
3. Decrease in light penetration and primary production rates, which is the result of the first two.
4. Sedimentation is also expected which may result in developing anoxic zones.

All said above are effective on ecosystem. For instance, high concentrations of Fe in filter feeders organisms and seabed ecosystems may cause algae bloom (some of which are toxic) changes in number and diversity, changes in variety of microbial organisms that are needed for decomposition and recycling which may result as a change in the food chain [19].

Chapter 4

Advantages and Disadvantages of RO and MSF Desalination

This chapter compare the RO and MSF desalination methods in order to select the best one regarding the environmental-friendliness criteria.

4.1 Advantages and disadvantages of RO and MSF desalination

In RO plants salinity of the discharge stream is higher, but in MSF plants the temperature of the effluent brine is higher. In RO on top of hyper salinity, the brine is also full of other chemicals that are used for the cleaning process, post and pretreatment. Chemicals such as chlorine and biocides (disinfectants), de-fouling and anti- scalant agents. The effluent brine may also contain metal ions on lower amounts as a result of corrosion metals like copper, chromium, nickel and iron. Cleaning plants with acid might increase the concentration of these metals [56]. In addition to that the desalination plants have effect in the reduction of the concentration of oxygen which is vital for the marine organisms [57].

MSF plants need high specific energy consumption when compared to other technologies such as MED and RO, plus they need both thermal and electrical energy as can be seen in **Table 3** [7].

Table 3. Desalination technologies matrix of major desalination processes. [7]

	MSF	RO
Energy requirement(kWh/m ³)	Electrical(SACG):3.5-5.0 kWh/m ³ SA:Thermal:69.44-83.33 kWh/m ³ CG: Thermal: 44.44-47.22 kWh/m ³	Seawater(SW):4-8 kWh/m ³ Brackish water(BW):2-3 kWh/m ³
Cost of water	0.9-1.5\$/m ³ ; the cost reduce with cogeneration and unit capacity	0.99\$/m ³ for seawater RO; 0.53\$/m ³ for Ashkelon 0.2-0.7\$/m ³ for brackish water
Technology growth trend	Moderate Is a mature technology	High, with membrane technology growth RO will become more and more economical
Environmental impact	Discharge is 10-15°C hotter than ambient, TDS increase of 15-20%	Brine discharge at ambient temperature TSD increase of 50-80%

However, it is claimed that the modified and combined cycle coupled with MSF desalination, demonstrates higher thermal efficiency and, therefore, lower environmental impact [7, 57].

In **Table 4** the amount of carbon dioxide in different MSF plants that use natural gas is available, which is worse in the case of using oil instead of natural gas. The temperature of the discharge water from these plants is 7 to 15°C higher and the concentration of the brine is 15 to 20% higher in salt than feed water [58, 7].

Table 4. CO₂ emissions and their abatement cost for different desalination processes [7]

Configuration(Fuel)	MSF		MED		RO	
	Kg/CO ₂ /m ³	CO ₂ abatement(\$/m ³)	Kg/CO ₂ /m ³	CO ₂ abatement(\$/m ³)	Kg/CO ₂ /m ³	
Non- cogeneration, natural gas, NG	20.4-25	0.41-0.5	11.8-17.6	0.24-0.35	Steam cycle	2.79
Cogeneration, steam cycle, NG	13.9-15.6	0.28-0.31	8.2-8.9	0.16-0.18	Internal combustion engine	2.13
Cogeneration, combined cycle, NG	9.41	-	7.01	-	Combined cycle	1.75
Cogeneration, hybrid RO, steam cycle, NG	9.45	-	7.33	-		

Cogeneration, hybrid RO, combined cycle, NG	5.56	-	4.38	-
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Some authors believe that MSF has reached its highest maturity and there's no room for more improvement in the future, but if the top brine temperature and the stages are increased, the MSF performance and economy could be improved. If high TBT anti-scalant and NF is used in the pre-treatment, the result is an increase in the TBT and the system performance would be improved. Another way of improving is the partial recycle of the low pressure vapor that can result in reduction of thermal and electrical energies [7].

Persian Gulf has mainly large MSF desalination plants discharging waste water flow of more than 1,000 cubic meters per second with higher temperature and increased salinity, including chlorine and antiscalants, as well as corrosion products such as copper [10].

The energy required for RO unit, **Table 5**, depends mainly on water salinity however, it could be the lowest as compared to other technologies. Consequently, the greenhouse gas emissions of RO will be less than emissions by an MSF or MED [7].

Table 5. Methods of evaluation energy for desalination giving the following heat input, for typical plants, per kg of water produced [18].

Desalination process	MSF	MSF	RO
Associated power plant type	Gas turbines and heat recovery boilers	Combined cycle	Combined cycle
Heat consumption of desalination process. kJ/kg	282	282	-
Power consumption of desalination process. kWh/m³	3.6	3.6	7.5
Prime energy from fuel for water production. kJ/kg	213	149	75.0

As mentioned before, the cost-efficiency of RO has been increased over the years due to development of efficient membranes and pressure recovery devices such as Ashkelon at the Mediterranean with a reduction of 0.53\$/m³ [59]. However, in some Gulf sites, due to the need of

expensive pre-treatment system as the result of high water salinity, high turbidity, high feed water temperature, high marine life presence, the cost will be high and near to MSF and MED [7].

On the other hand, due to the higher recovery rate of about 30–50%, the waste discharge from RO could have high salinity. Besides, the total dissolved solids (TDS) in RO increases from 50% to 80% above feed water [58]. Moreover, the chemicals added for the pre-treatment increase the toxicity of the brine discharge [7].

In RO, the brine is discharged at ambient temperature. Hence, no thermal pollution exists as in the other thermal technologies. On the other hand, in RO, due to the employing large pumps for generating high pressures, noise pollution is generated [21, 7].

As depicted in **Figure 5**, RO has an increasing trend between years 2006 and 2009 particularly in the brackish water desalination and also towards the use of RO for seawater desalination. This trend depends on the growth in water demand besides the integration of nano-filtration (NF) for pretreatment, preheating of feed water, improvements of pressure recovery systems, and development of larger size and low pressure membranes [58, 7].

In conclusion, RO plants have some positive and negative differences than the thermal plants:

1. Depending on the technology, the overall energy consumption is half or even one third, which causes less atmospheric emission.
2. The conversion ratio is about 30 to 35% higher. Which means higher concentration in the brine, and attaining about 130% of the intake water. Plus the amount of the outlet water is less than that of a thermal plant.
3. RO plants do not need less chemicals in comparison to the volume of intake water, although as a result of the conversion ratio being higher, the emission load is lower, when compared to produce freshwater. Adding Sulfuric acid to the feed water makes a big difference: 30 rag/1.
4. The increase in the temperature is very low that can be neglected. Causes no thermal problems.

6. Technological problems of RO are not solved as good as in thermal plants, which is the main reason why thermal plants are more common.
7. RO plants make more solid waste in comparison to the thermal ones. There are also no solutions that can be used to dispose or reuse the membrane system.
8. Thermal plants are mostly used in countries that use more fossil energy, but RO plants are used more in the developed countries [24].

Chapter 5

Mitigating the Environmental Impact of Desalination

In this chapter some methods to mitigate the environmental impact of seawater desalination are proposed.

In recent decades, the desalination technologies have been developed by a high speed. In a research performed in 1991 it has been observed that more than 65% of desalination plants are MSF, which produces high temperature brine and causes more pollution in the atmosphere [60, 61]. MSF plants have been mostly used in Middle East, because they have access to rich sources of fossil fuels [62]. In other countries like Australia and the United States, these methods of desalination are quickly being replaced with methods that use membrane based desalination like RO plants that cause lesser thermal effects, though yields saltier brines [63, 62]. Using pressure exchange technologies, reduces the recovery rates so it might help in mitigating the salinity of RO brines [64, 30]. In general, mitigating the environmental impact of desalination could be discussed from different point of views as follows:

5.1 Source water intake

For reducing the effects of wide intakes, using a combination of varying decoy screens and a low velocity intake is key. This way impingement and entrainment of bigger organisms like fish or turtles can be minimized and by locating intakes away from productive areas of smaller plankton organisms, eggs and larvae, entrainment of these smaller organisms can be avoided. Likewise, by using beach wells only minimal or no chemical pretreatment is needed, because the intake water quality in these areas is often better in such locations than near shore or surface water. Although, the initial soil disturbance while construction in below ground or long pipelines can be higher, mostly while drilling or excavating. Well intakes can only be used by small or medium-sized plants, so co-locating of desalination and power plants if possible, can be considered. The amount of intake water can be reduced if the cooling water from the power plants would work as the feed-water of the desalination plant, this way the impact of entrainment and impingement, the usage of chemicals and land use and construction impact can be minimized [2].

5.2 Reject streams

There are so many ways in which the environmental impact of effluent water can be reduced. In order to cease the effects of high salinity, the discharge water from the desalination plants can be pre-diluted with other reject streams where there is one, like power plant cooling water. For avoiding the effects of high temperature, the waste water should lose its temperature to the atmosphere before entering the water body (like using cooling towers). Mixing and distributing the effluent water is one way that can be achieved through installing a diffuser system and locating the reject stream in the right oceanographic place that dissipates the heat and salinity rapidly. Hydrodynamic modeling is one way to analyze the reject stream of a specific project, the modeling contains environmental and operational conditions of the project, salinity and temperature for density calculations before the operation and while it is working [2]. The other method regarding mitigating the environmental impact is to use high-salinity reject water reservoir as a habitat for animals or plants specious.

5.3 Energy use

Energy use is one of the main factors in water desalination. Some innovations have helped some reductions in this area, like using equipment that helps with energy recovery or different frequency pumps in RO plants. By using an energy recovery system which is made out of a piston type accumulator and a low pressure pump [65], a seawater desalination plant has accomplished the very low specific energy of 2-2.3 kWh/m³. Also using renewable energy like solar, wind, biomass, etc. can help with minimizing the effects on the quality of air and climate change [2]. It should be noted that, generally the desalination methods, such as RO, that require electricity are typically more energy efficient than thermal desalination. Solar electricity has been the most efficient type of renewable energy sources. Besides, it needs low maintenance which finally makes it suitable for any application [20].

Due to the fact that electricity and heat are the most commonly used energy sources for desalination, produced by burning fossil fuel, they have also great impact regarding production of green-house gasses. However, new technologies such as hybrid systems utilize renewable energies, such as solar energy, to reduce the related environmental impact. For more clarification, it was reported that the annual CO₂ emission of MSF, RO, and hybrid MSF/RO plants was 250,470.9, 22,807.3, and 70,636.8 tons, respectively. Besides, the concentrated brine was discharged at a flow rate and salinity of 482.14 kg/s (61,149.88 ppm), 482.12 kg/s (69,031.75 ppm), and 472.2 kg/s (69,225.40 ppm) for MSF, RO, and MSF/RO, respectively. As a case study, the impact of hybrid method in Al Taweelah A2 MSF plant has resulted in 71.8% reduction of greenhouse gas emissions [66].

To mitigate the environmental impact of desalination, using high-pressure reject water, wind and sea-water wave energy to produce electricity in power plant generators could be suggested.

5.4 Site selection

Selecting the right site for desalination plant is a big help on lowering the impact of environment, and also the effects of environment on the plant. For reducing the effects on the desalination process, site should be on a place with good and reliable water quality, and seasonal

variations should be considered. The intake water should be far from discharge waters of municipal, industrial, shipping and other pollutions. Locations with poor water quality should be also avoided, like places with particulate and dissolved organic compounds, high biological actions, and algal bloom toxic contaminations. If the intake water is far from shore and located in deep layers of water and far from pollutions of the land, the water quality is more stable and reliable. In site selecting it is also important to consider the risk of oil pollution that can cause serious damage inside the desalination plant and effect on the water quality [2].

Finally, according to of Life cycle assessment of MSF and RO desalination technologies followings are some other useful ways to lower the environmental impact of desalination plants:

- (a) Marine outfall design and construction for best dilution and for minimizing disturbances to marine environment and to sediment movement.
- (b) Polyphosphates replacement by friendly environment antiscalants and other friendly additives.
- (c) Removal of ferric, not only for the discoloration and aesthetic matter, but also for the preventing of a potential risk for the marine environment due to the high loads and accumulation with time.
- (d) For brackish water, pretreatment for nitrogen removal need to be considered, to prevent nutrient enrichment, eutrication and potential decrease in water quality.
- (e) Avoiding discharge of cleaning organic solutions.
- (f) “Expanding hydrodynamic model’s application by ecological modules such as sedimentation, biological degradation, assimilation and transformation processes” [66].
- (g) Since RO systems require pretreatment in order to prevent fouling of the membranes, using subsurface intakes, rather than open water intakes, has been one method for pretreatment requirements reduction. It utilizes the ocean floor where geological formations and sand provide filtration. It finally results in high-quality feed water, reducing the number of solids and organic carbon that is suspended in seawater [11]. Consequently, this can reduce the operations and maintenance costs needed in the desalination process [67].

Some other techniques to reduce the desalination impact are summarized in **Table 6**.

Table 6. Surface Water Disposal Problems and Mitigation. [70, 71]

Environmental Concern	process	Mitigation Method
From raw water...		
Contaminants present in raw water	Brackish-RO	Limit degree of concentration, blending, mixing zones, post treatment
Imbalance in essential ions (some groundwater)	Brackish-RO	Diffusers, blending, mixing zones
Low dissolved oxygen, high H ₂ S, etc. (some groundwater)	Brackish-RO	Aerate, degasify, or otherwise treat prior to discharge
From pretreatment...		
Toxicity of additives	All	Use non-toxic additives
Low pH (due to acid addition)	RO	Raise pH prior to discharge
From the concentration salinity...		
Different salinity than receiving water	RO more than thermal	Diffuser, blending, mixing zone, ZLD ¹

- 1- “Zero liquid discharge (ZLD) techniques use a type of mechanism (evaporator) to convert a liquid concentrate into a dry solid. Therefore, instead of concentrate disposal, this option deals with solid waste disposal” [70].

Chapter 6

Conclusions and Recommendations

In this thesis, two general methods of seawater desalination namely thermal and membrane methods were discussed. In the next step MSF and RO methods were analyzed as two most applied techniques of thermal and membrane methods respectively worldwide. It was concluded that with the development of today's technology, RO desalination has less environmental impact than thermal desalination. It is because of the possibility of using renewable energies in RO. Although thermal desalination plants have a great potential for reducing environmental effects, if integrated with other production process, both of the methods have their own advantage and disadvantages which should not be ignored and some of them are listed as following:

- The energy required for RO, depends mainly on water salinity however, it could be the lowest as compared to MSF;
- Consequently, the greenhouse gas emissions of RO will be less than emissions by MSF.
- In RO plants the salinity of the discharge stream is higher.
- Besides, the brine is also full of other chemicals that are used for the cleaning process, post and pretreatment. Chemicals such as chlorine and biocides (disinfectants), de-fouling and

anti-scalant agents. The effluent brine may also contain metal ions on lower amounts as a result of corrosion metals like copper, chromium, nickel and iron. Cleaning plants with acid might increase the concentration of these metals.

- Cost-efficiency of RO has been increased over the years due to development of efficient membranes and pressure recovery devices. However, in some Gulf sites, due to the need of expensive pre-treatment system as the result of high water salinity, high turbidity, high feed water temperature, high marine life presence, the cost will be high and near to MSF.
- In RO, the brine is discharged at ambient temperature while, In MSF plants the temperature of the effluent brine is higher.
- In RO no thermal pollution exists as in the other thermal technologies. On the other hand, in RO, due to the employing large pumps for generating high pressures, noise pollution is generated.
- RO plants make more solid waste in comparison to the thermal ones. There are also no solutions that can be used to dispose or reuse the membrane system.
- RO plants are used more in the developed countries while thermal plants are mostly used in countries that use more fossil energy.
- MSF needs high specific energy consumption when compared to other technologies. Plus, it needs both thermal and electrical energy.

To mitigate the environmental impact of desalination, the following methods are being suggested:

- Combination of varying decoy screens and a low velocity intake to minimize impingement and entrainment of seawater specious;
- Using beach wells for the aim of minimal or no chemical pretreatment because the intake water quality in these areas is often better than near shore or surface water.
- The amount of intake water can be reduced if the cooling water from the power plants would work as the feed-water of the desalination plant, this way the impact of entrainment and impingement, the usage of chemicals and land use and construction impact can be minimized.
- In order to cease the effects of high salinity, the discharge water from the desalination

plants can be pre-diluted with other reject streams where there is one, like power plant cooling water.

- For avoiding the effects of high temperature, the waste water should lose its temperature to the atmosphere before entering the water body (like using cooling towers).
- Mixing and distributing the effluent water is one way that can be achieved through installing a diffuser system and locating the reject stream in the right oceanographic place that dissipates the heat and salinity rapidly.
- The other method regarding mitigating the environmental impact is to use high-salinity reject water reservoir as a habitat for animals or plants specious.
- Using an energy recovery system which is made out of a piston type accumulator and a low pressure pump for the aim of very low specific energy.
- Using renewable energy like solar, wind, biomass, sea-water wave energy, etc. to minimize the effects on the quality of air and climate change. Solar electricity has been the most efficient type of renewable energy sources. Besides, it needs low maintenance which finally makes it suitable for any application.
- New technologies such as hybrid systems
- Using high-pressure reject water to produce electricity in power plant generators.
- Site should be on a place with good and reliable water quality, and seasonal variations should be considered.
- The intake water should be far from discharge waters of municipal, industrial, shipping and other pollutions. Locations with poor water quality should be also avoided, like places with particulate and dissolved organic compounds, high biological actions, and algal bloom toxic contaminations.
- Marine outfall design and construction for best dilution and for minimizing disturbances to marine environment and to sediment movement.
- Polyphosphates replacement by friendly environment antiscalants and other friendly

additives.

- Removal of ferric, not only for the discoloration and aesthetic matter, but also for the preventing of a potential risk for the marine environment due to the high loads and accumulation with time.
- For brackish water, pretreatment for nitrogen removal need to be considered, to prevent nutrient enrichment, eutrofication and potential decrease in water quality.
- Avoiding discharge of cleaning organic solutions.
- Expanding hydrodynamic model's application by ecological modules.
- Limiting the degree of concentration of contaminants in Brackish-RO, blending, mixing zones, Diffusers, Aerating, degasifying, and post treatment.
- Raising pH prior to discharge in RO method.

As described in the body of this thesis, although the desalination technologies are mature enough to be a reliable source of fresh water, active research and development work is still required to be performed in collaboration with the governments, industries, universities, and research institutions. Besides, to improve the sustainability of hybrid desalination systems, with important advantages such as their flexibility in operation, low energy consumption, low construction cost, high plant availability, and better power and water matching, innovation in membrane technologies and increasing the use of renewable energy will still need intensive future research to reach the desired level of sustainability.

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