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DESALINATION BRINE DISPOSAL AND MANAGEMENT

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Abstract
Desalination plants impact environment in several ways, among these pollutants reject brine is the most hazardous output because of its voluminous and excessive salinity discharge. This study provides a brief review of desalination reject brine disposal methods and possible management. After a short technical introduction to the subject the identification of problem is presented. This followed by description of common methods used for reject brine disposal. From an environmental perspective the disposal methods divided in two main categories: into the sea and inland. The adverse effects on the environment, and relevant mitigation actions as well, of other methods have been discussed in some detail. Useful brine beneficiation and management are given in brief. It has concluded that the full evaporation is the best option to prevent environment degradation.
Keywords: Brine Disposal, Desalination, SWRO, BWRO, Evaporation, Solar, Ponds, Injection Wells

1.Introduction

Saline solutions can occur naturally (e.g. seawater, deep-water ocean pools, salt lakes, etc.), or they can result from industrial activity. Desalination plants turn salt water into potable water using two primary technologies: membrane-based Reverse Osmosis and Thermal Distillation. These systems address water scarcity by utilizing high pressure to filter salts or heat to evaporate water. Common types include RO (Reverse Osmosis), MSF (Multi-Stage Flash) and MED (Multi-Effect Distillation), often chosen based on water salinity and energy availability [1,2]. Brines produced as a byproduct of desalination plants are known as brine waste streams, they typically contain much higher concentrations of salt than natural brines like seawater [3,4].

However, in this text the term "brine" used to describe reject concentrate stream in both cases (reverse osmosis and thermal distillation). The relationship between salinity of feed water and that of generated brine depends on the design product recovery (R) and concentration factor (CF) as follows:

$$CF = 1 \div (1 - R) \quad (1)$$

where: R, recovery = (product rate, m^3/h ÷ (feed rate, m^3/h).

Note: this formula is conservative since it assumes 100% rejection, yet some ions will pass through the membrane into the product stream.

In equation (1) the product recovery is a decimal value (ex. R=0.4), but in practice, it is usually expressed as percentage to feed water volume (ex. 40%), which means that a volume of 40% is extracted as fresh water from the salty feed water and the rest (60%) is rejected as brine solution. When mass is considered (i.e. kilogram or ton) all numbers must be multiplied by the corresponding density at 25ºC. The CF is essential for predicting the brine salt content. For example, when TDS of the Red Sea feed water = 43196 mg/l, and projected fresh-water recovery = 40%, so:

- CF = 1 ÷ (1 – 0.4) = 1.67,
- Then, Brine TDS = 43196 X 1.67 = 72137 mg/l.

It is clear that the TDS of the product water (<500 mg/l) is neglected in these simple calculations. The CF is also used for estimating the individual ion concentration in the brine. For example, the Red Sea feed water may contain 11274 mg Na/l and 497 mg Ca/l, so it is possible to estimate the brine content by multiply each ion concentration value by the CF (1.67 in this example) and the result is: Na= 18828 mg/l and Ca= 830 mg/l. In reality, actual laboratory chemical analysis obtains similar results but not so identical. The reason for such minor discrepancy arises from the fact that some hard chemical species are usually separated from the system as fouling, scale, or colloid during thermal or membrane desalting process. This in addition to the expected difference, which comes from the pass of some ions to the product fresh water. Generally, the concentration factor (CF) is considered as a reliable method for process design.

RO-membrane technology offers wide range of fresh water recovery. BWRO desalting runs normally at 60% to 85% fresh water recovery (CF: 2.5– 6.67), this depends on salt concentration in the feed and the molar ratio (SO_4/HCO_3) that controlling the scaling potential on the membrane surface as reported by El-Manharawy et al. [5,6]. SWRO is more sensitive towards TDS and sulfate concentration in highly salty groundwaters that ranges from ocean water (~35500 mg/l) to the excessive salty water that may reach 50000 mg/l or higher as found somewhere on the Red Sea coast as reported by El-Manharawy et.al [7]. SWRO recovery could be as low as 30% (CF=1.43) and may rise to around 45% (CF=1.82) in some modern SWRO plants. Thermal desalination is generally lower in recovery of distilled water; for example, MSF plants are running at recovery ranges from 20% to 35% (CF: 1.25-1.54), this due to the effect of high temperature on

enhancing scaling potential over heat exchangers.

Reject brine usually contains various chemicals used in the pretreatment stage of the desalination process including:1) NaOCl or free chlorine, used for chlorination, preventing biological growth, 2) $FeCI_3$ or $AICl_3$, used for the flocculation and removal of suspended matter from the feed water, 3) H_2SO_4 or HCI, used for pH adjustment, 4) $(NaPO_3)_6$ and similar materials, which prevent scale formation on the pipes and on the membranes, 5) $NaHSO_3$, used to neutralize any remains of chlorine in the feed water, and 6)The periodical cleaning chemicals. Actually, most of these chemicals are usually added in minor quantities similar to those used in conventional water treatment plants for human drinking purpose. Therefore, there is no expected risk on the environment from the use of such chemicals. However, Xia Zhang et al. [8] reported that at some fragile ecosystem, such as marine coral reef, the recently developed organic-phosphate is preferred rather than inorganic salt.

RO-Membranes are usually cleaned four to six times a year. According to the quality of feed water either the acidic or alkaline cleaning can be applied. The chemicals used are mainly: acids, alkalis, EDTA, phosphates and detergents, which are used in mixtures for removal of fouling and deposits as reported Mohammed a et al. and Keith et al.[9,11]. These limited periodical chemicals, as well as its rinse, must not be considered as a part of the brine solution, and to be isolated, neutralized and disposed properly. Highly salty brines might increase the water turbidity especially in view of the fact that the highly sulfate-carbonate fouling potential could develop a fine white cloud in the brine solution. In addition, the added reagents, mostly those that contain iron salts those are dark black or red.

Heat evolved from the work of the high-pressure pumping on the RO-membrane surface may cause some raise in brine temperature that normally lies between +2ºC and +5ºC degrees above the ambient. In the case of thermal evaporation plants, a considerable thermal pollution is expected. The amount of residual heat depends on the efficiency of heat exchangers used for feed-water preheating and the climatic conditions as well. The rejected brine from thermal plants may acquire higher temperature up to +40ºC above the prevailing conditions [12]. In addition, some heavy metals (ex. Fe, Mn, Cu, Ni, Cr, Ti, V, Pb and Zn) are usually leaking into the hot reject brine from thermal distillation plants, which cause harmful effect on marine biota.

The present article provides a brief overview on desalination reject brine disposal methods and possible management [13-21]. After the given technical introduction to the subject the identification of problem is presented. This followed by a bibliometric analysis of Publication and Patents for Seawater Desalination and brine disposal, then description of common methods used for reject brine disposal. From an environmental perspective the disposal methods divided in two main categories: into the sea and inland. Among these methods we focused on natural evaporation and salt production as the best option to prevent environment degradation. The adverse effects on the environment, and relevant mitigation actions as well, of other methods have been discussed in some detail. Useful brine beneficiation and management are given in brief. Finally recommendations are concluded. More details are presented that illustrate many investigated cases and field visits conducted by the authors during the last 30 years.

2. Problem Identification

The above introductory background information describes the main characteristics of the generated brine, volumetrically and chemically, from desalination plants, so what is the problem? The problem is simply originating from the excessive salt content in the rejected brine and the higher heat evolves from thermal plants in addition. Due to recovery limitation the thermal plants discharging less salty hotter brine (<550000 mg/l) than that of the SWRO plants (>70000 mg/l) as described above. In both cases the impact of such excessive salinity on the environment is critical and hazardous. Water turbidity could be also additional source, beside salinity and heat, of contamination that known as “optical pollution”. In brief, the desalination reject brine causes mainly three types of serious environmental impacts: higher salinity, higher temperature and higher turbidity. The higher temperature pollution is only limited to thermal distillation plants.

3.Bibliometric analysis of Publication and Patents for Seawater Desalination

3.1 An AI-assisted bibliometric analysis during 2019–2024" was investigated by analyzes academic literature on desalination, highlighting a global capacity exceeding 80 million m^3/day. Published in Desalination and Water Treatment, provides a quantitative overview of research trends, technical focus areas, and sustainable strategies from 2019 to 2024 [22].

3.1.1 Academic literature publications

Song et al.[22] employed an AI assisted Bibliometric analysis to identify recent research hotspots and emerging trends in the seawater desalination. The data for academic literature were collected from the Science Citation Index Expanded (SCI-E) database of the Web of Science (WOS), the Conference Proceedings Citation Index-Science (CPCI-S) database, and the Social Sciences Citation Index (SSCI) database. A total of 6864 papers were retrieved in this study [Fig1,2]. China ranked first in the number of publications, with over 3400 papers, accounting for approximately 50 % of the total. Although China ranked first in publication volume, its average citation rate ranked only tenth among the top 20 publishing countries. The United States ranked second in publication volume, yet its papers achieved the third-highest average citation rate globally, demonstrating a strong academic influence. Saudi Arabia, the world's largest market for seawater desalination, ranked third in terms of publication numbers. Despite having a lower publication output, Singapore and the United Arab Emirates (UAE) ranked first and second globally in terms of average citation rates.

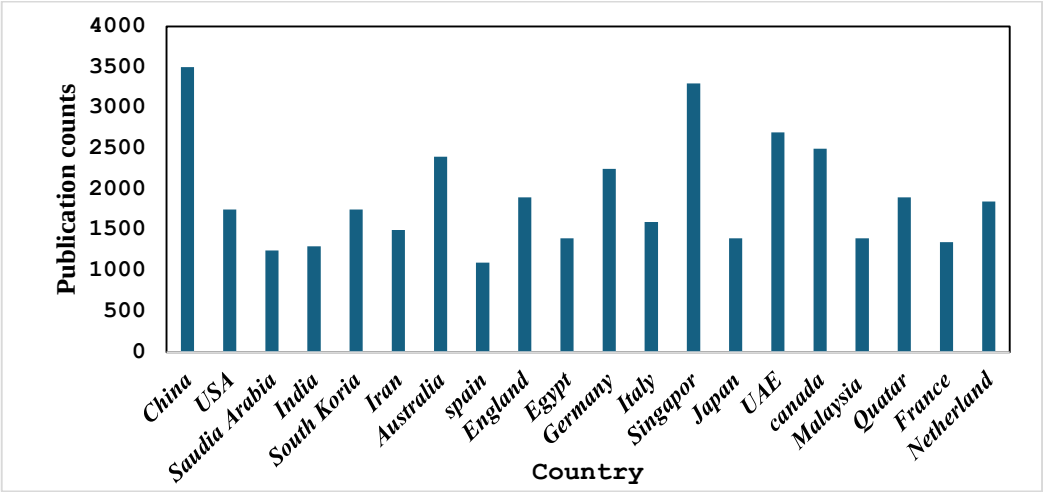

Fig. 1: The top 20 countries in academic literature publication on seawater desalination ("Publication count" refers to the number of academic papers published;[22]

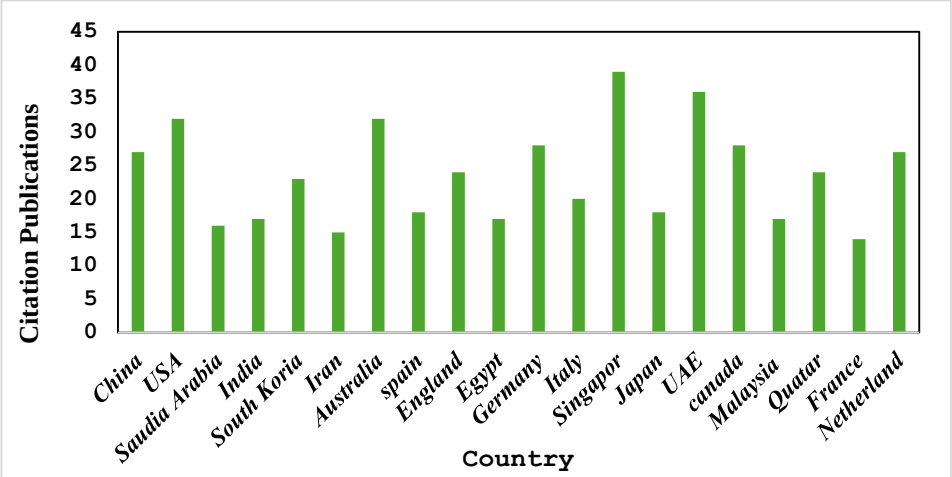

Fig.2: The top 20 countries versus Citation/Publications on seawater [22]

3.1.2.Patents

Since the early 1985s, the cumulative number of patents related to seawater desalination has steadily increased, reflecting ongoing technological advancements and the growing significance of this industry. By 2024, the total number of patents in the global seawater desalination sector surpassed 50,000. Among these patents, China held a dominant position, with over 20,000 patents as shown in Fig.3. Following China, the leading patent holders include the United States (US), Japan (JP), South Korea (KR), the European Patent Office (EP), Australia (AU), India (IN), Germany (DE), Canada (CA), Russia (RU), Singapore (SG), Brazil (BR), and Israel (IL) [22].

Patents in the seawater desalination sector are primarily distributed across the following areas: 1) Solar seawater desalination technology; 2) Reverse osmosis membrane technology; 3) Other membrane technologies, including ultrafiltration, nanofiltration and forward osmosis; 4) Energy and resource recovery, encompassing waste heat recovery, energy recovery equipment, humidification and dehumidification technologies, power recovery, and methods for extracting valuable chemicals from brine.

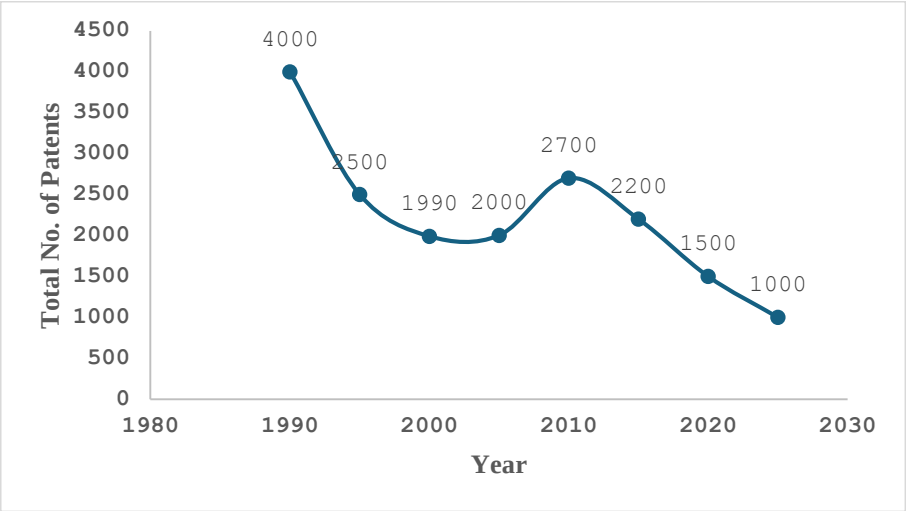

Fig.3: The cumulative patents of China during 1985-2025 [22]

3.2. A structured literature review framework to identify, screen, and synthesize research addressing the environmental impacts of brine discharge from desalination plants was investigated by Gupta et al. [23]. The review focused on peer-reviewed journal articles and authoritative reports published over the past 15 years (2010—2025) as shown in Fig.4.

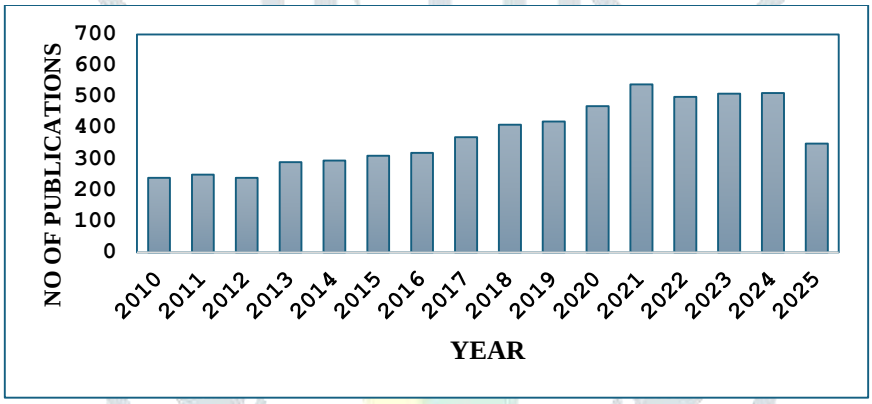

Fig. 4: Annual trend distribution of publications related to desalination and brine discharge [23].

4. Methods of Reject Brine Disposal and their Environmental Impacts

Desalination plants impact environment in several ways converting virgin locations like sea coast into real industrial zones which require lots of foundations, raw materials, equipment, installations, energy generators … etc. These intruded inputs discharging many hazardous materials, emissions, noise, and brine into the environment. Among these pollutants reject brine is the most hazardous output because of its voluminous and excessive salinity discharge. The "brine" term describes typically the concentrated reject from seawater (SW) desalination that has salts content higher than 70,000 mg/l. In brackish water (BW) desalination the reject concentrate is much lower in TDS than that of seawater desalination. When released, this dense, salty liquid sinks to the seafloor, forming a plume that can suppress oxygen levels and damage benthic marine life.

The UAE alone generates more than twice as much brine as potable water through seawater desalination processes, introducing concentrated discharges of NaCl, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and other ions into marine environments [24]. These discharges elevate salinity, reduce dissolved oxygen, disrupt osmotic balances, and threaten coral reefs, seagrasses, and coastal ecosystems. Conventional disposal practices such as open-sea discharge or deep-well injection pose ecological hazards and carry high energy and infrastructure costs [25,26].

Fig.4 depicts methods of reject brine disposal and described as follows:

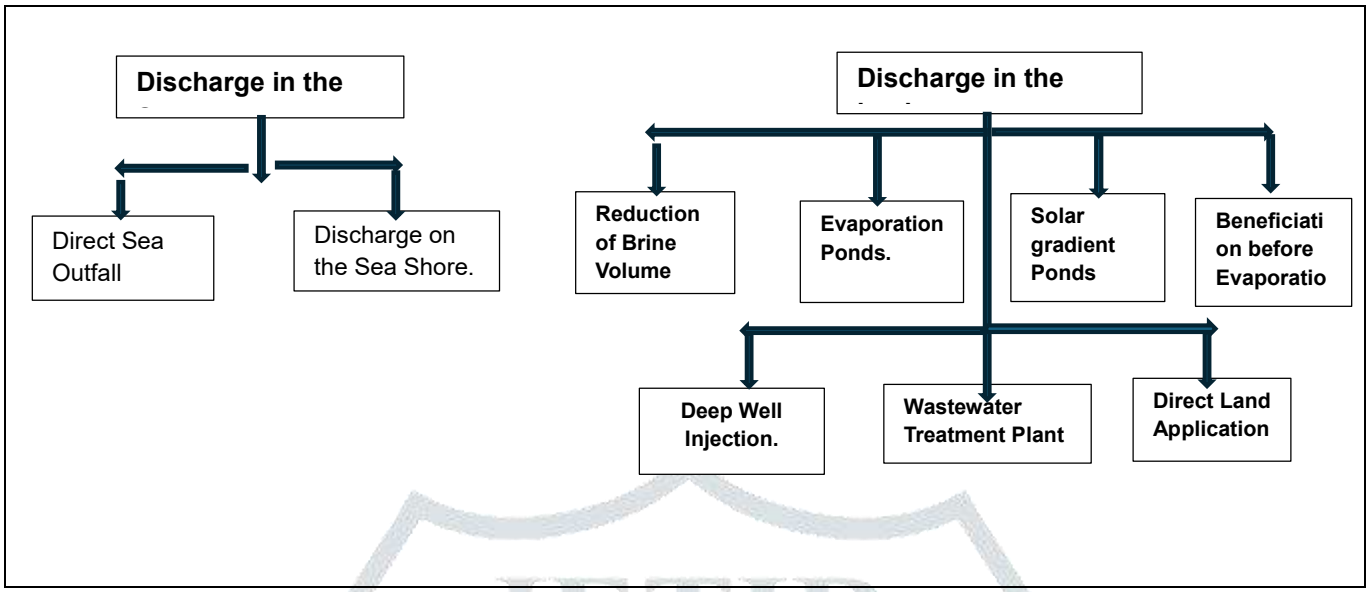

Fig.4. Methods of reject brine disposal

4.1 Discharge in the Sea:

4.1.1. Direct Sea Outfall:

Rejected brine from big seawater desalination plants is usually transported for some distance through an outfall pipe and discharged directly into the ocean, sea or estuary from the end of the pipe when natural mixing is available. When natural mixing is not sufficient enough to deal with the disposed brine volume it causes the denser brine to sink to the sea floor, as a plume of highly saline water creating a 'saline desert' in the vicinity of the discharge pipe. As this process of marine pollution by brines is usually continuous over long periods of time, it has a serious negative impact on the flora and fauna in the vicinity of the discharge pipe and may extend over a large sector from sea floor. The extent of the environmental damage is dependent on the prevailing sea conditions: bathymetry, currents, waves, depth, biota types and bio-diversity, as well as on the nature of the brine, e.g. concentration, turbidity, temperature, discharging rate, pressure at the point of discharge and the outfall pipes location and system design [27-29].

Application of vertical pressure diffusers that accelerate the diffusion and mixing processes are currently used now for this purpose. The big desalination plants in the eastern Mediterranean and the Arabian Gulf generally use this type of brine discharge. For example, at the SWRO Larnaca desalination plant (50000 m3/day), Cyprus, the outfall double-pipelines extending into the sea to about 1500 meter from the shore with a depth of about 20 m under sea level. These two pipelines equipped with vertical pressure diffusers to insure good mixing and dilution. Useful technical information about designing sea outfall and diffusers are given [30]. A numerical simulation to compare the performance of the Venturi diffuser and the current diffuser used in the Fouka desalination plant, west of Algiers (300,000 m3/day) was studied [31,32]. The study analyzed different scenarios for the dispersion of discharges in the marine environment. The Venturi diffuser was proposed as a more efficient technique for dispersing brine in the marine environment but required a high outlet velocity (> 5 m/s) to be more effective. The results showed a dilution rate of 74.97% of the current diffuser, compared to 93.14% for the Venturi diffuser at the point of impact. Current velocities (0.2, 0.4, 0.8 m/s) were studied in plume development, revealing that a velocity of 0.4 m/s improves dilution and salinity. The study concluded that the Venturi diffuser will be a practical solution for long-term sustainable desalination and prevent socio-environmental conflicts. Oceanographic surveys also were investigated before and after the diffuser installation (2006–2011), to quantify the effects of the diffuser on the behavior and dilution rate of the effluent. The results were also compared with simulations predicted by a numerical mixing model simulation (CORMIX 1), obtaining high concordance with field data. After the diffuser installation, both field data results and model simulations showed a strong increase in the dilution rate of the brine plume, and a significant reduction in the size of the affected area [33]. In addition ”The Oceanographic Impact of Desalination in the Arabian Gulf was recorded by Sterling etal.[34].

In essence, the main impact of discharging brine into the sea arises from its excessive salinity, which is composed of similar chemical species like seawater but at higher concentration. The logic solution is dilution, but for what extent? The US Environmental Protection Agency recommended that the diluted stream must has a salinity difference less than 1000 mg/l (<3%) from the normal seawater in site. It is recorded [35] that diluting reject brine with normal seawater is a common mitigation strategy used by desalination plants to minimize environmental impact. Because concentrated brine is denser and saltier than the ocean, it sinks and can harm marine ecosystems if not mixed. In addition dilution of reject brine that pumped from beach wells is costly, but it is a solution anyway [36].

In another approach, when a desalting plant is co-located or in close proximity to a coastal thermal power plant, the reject brine would be mixed with power plant cooling water within the outfall line prior to discharge into the open sea. Tampa Bay SWRO plant at Florida (~100000 m^3/d) uses this method effectively to lower salinity of reject brine being returned to the bay with a difference of about 3% (~1000 mg/l) higher than the background salinity in Tampa Bay plant [37]. The diluting factor is in the order of 1:74. In this case the local natural

mixing forces (i.e. by action of wind, waves and marine currents) are not of a great concern because of the availability of abundant cooling seawater from the close thermal power plant. At Ashkelon SWRO desalination plant (274000 m^3/d), in Israel on the Mediterranean, reject brine mixed with a limited coolant seawater amount from a nearby thermal power station before disposal into the sea This insure sufficient brine dilution so that the concentration of reject brine would be about 10% higher than the sea. This slight increase in concentration would be offset by a slight increase in temperature so that the specific gravity would remain the same as that of seawater, and the sinking of brines to the sea floor would be avoided [38]. Einave [39] draw our attention towards a new concept about the environmental benefit of associated heat with the power plant cooling water. As a marine biologist investigated this issue and concluded that the discharging of hot water-brine mixture would be useful for reducing the impact on the marine biota. This lies in the relatively lower density of hot water, which would partially offset the higher dense brine and would therefore reduce their tendency to sink to sea bottom. As a result, the probability of mixing and dilution would be much better. The negative effect on the marine creatures from such limited warming is less than the deadly impact of the salty plume. This important information must be greatly considered in the coastal desalination plant design. In addition Einav and Alshwafe et al. [39,40] reported that combined electric power production and seawater desalination would share same pumping intake system, preliminary filtration units and discharging facilities. The advantages are obvious: reduced impact on the marine environment at a reduced price Also a simulation case in Illinois, United States concluded that the environmental benefit of associated heat in power plant cooling water lies in energy conservation and emissions reduction, this research examines the reliability, economic, and environmental implications of cooling water shortages on power system operations. The results show that Illinois may experience 10–15% daily load curtailment and severe congestion between certain regions from the east to central during cooling water shortages, while once-through and wet-tower units experience a 52% and 17% reduction in power generation. Overall cooling water withdrawal decreases by 24–38% as severity intensifies [43][41]**.** Fore that it can be concluded that the combined electric power production and seawater desalination would share same pumping intake system, preliminary filtration units and discharging facilities [42]. Also Baraka [43] estimated that the combination of desalination plant and a coastal thermal power plant with seawater cooling would result in 8% -10% reduction of the total cost of the seawater supply systems and brine discharge. A study to see the effects of brine release from five desalination plants, located along the Israeli Mediterranean coastline was investigated by Julie et al. [44]. Premixing the brine with power plant cooling water compensates for the negative buoyancy and prevents their generation. The propagating density currents (DCs) can impact coastal water dynamics by increasing the velocities and transports in alongshore and downslope directions. The spreading and trajectories of the DCs was strongly influenced by seasonal stratification. In winter, due to a mixed water column, the DCs were relatively focused and propagate downslope. While in the summer they are confined to a narrow band along the coastline. A model results highlight the possibility that brine discharge might have a large scale, non-negligible effect on shelf circulation than previously considered. Amitochea etal. [45] studied the operation of the desalination unit at the thermal power plant of Cap Djinet (Eastern Algeria) and the management and characteristics of the brine. The desalination unit at the thermal power plant of Cap Djinet (Eastern Algeria) operates a multi-stage flash distillation (MSF). The desalinated water passes through a demineralization step to obtain water with characteristics according to a boiler feed water at high pressure. During rejection, the brine is subjected to dilution with cooling water. This causes a decrease in the brine water salinity from 70 to 40 g/l and conductivity of 85 to 56 ms/cm which is equal to the conductivity of seawater. For other parameters, the authors found the same results as seawater based on the results of various analyses, they stated that the rejection of brine diluted station Cap Djinet is similar to seawater as probably it does not affect the receiving marine environment.

In another dilution option for smaller desalination plants, reject brine might discharge to rivers or canals that immediately lead to the sea or other salt sink. In such case the seasonal volume changes as well as the mixing ratio should be evaluated carefully.

4.1.2 Discharge on the Sea Shore:

Small seawater desalting plants sometimes take advantage of the shore-mixing zone where reject brine being discharge directly over the shore or right at the surf zone where it mixes and diluted with normal seawater under natural strong turbulent conditions. SWRO plants on the islands of Malta and Santa Catalina are examples of this type of discharge where average annual current velocity exceeding 0.5 m/sec. as reported from Smart Water Magazine [46].

Different authors reported [47-49] that this discharging often causes ecological stress to shallow benthic habitats, localized water stagnation and poses severe risks to marine ecosystems, primarily through hyper salinity, oxygen depletion, and chemical pollution. In addition brine is denser than ambient seawater, it sinks and hugs the seafloor, smothering sensitive benthic organisms and disrupting nearby coastal habitats. Grammatiki et al.[50] also confirmed that small seawater desalting plants sometimes take advantage of the shore-mixing zone where reject brine being discharge directly over the shore or right at the surf zone where it mixes and diluted with normal seawater under natural strong turbulent conditions. On the shallow non-turbulent shores, where natural mixing is minimized, the impact of discharging reject brine on living organism is massive and could be deadly. Some authors stated that aggressive salinities (i.e. twice the ocean ambient) could impact ocean biota if they are exposed for extended time periods [51,52]. Suizu etal. [53]. carried out experiments on the incipient lethal high salinity reject brine on some stages of development such as fertilized eggs, larvae, juveniles and adults, of two species of fish and a bivalve. They found that the excessive salty brine caused serious delays in embryonic development. The environmental impact arisen from brine discharging directly on or near the ocean shoreline was also investigated by Hopner et al. [54]. They divided the marine habitats into 15 categories according to their sensitivities towards the effects of the undiluted brine. According to their hierarchy, the sites most suitable (i.e. lesser sensitive) for the construction of desalination plants are regions of highly energy oceanic coasts. On the other hand, the upper most sensitive regions are the calm coral reefs and the mangrove flats which are easily subjected to fast degradation under the negative impact of excessive salinity. Accordingly, the Red Sea and Sinai coasts, where the precious treasures of coral reefs and other beautifully living marine organisms, are classified as the most environmentally sensitive habitats towards the aggressive effect of the rejected brine. This beside two other important facts, the first fact is that the coral reefs are occupying the shoreline itself and extending to several hundred meters inside the sea with a shallow depth ranging between less than 1 meters and 5 m. The second fact is about the shore-mixing zone, which is characterizes with very slow coastal currents due to its shallow nature, and mostly activated with the seasonal winds rather than

the effective marine currents especially at the south of Sinai and the closed-end Gulf of Aqaba. Therefore, discharging of reject brine without sufficient dilution on the ecologically sensitive, shallow and low turbulent coral shore zones is not recommended and should be avoided.

4.2. Discharge In land:

4.2.1. Reduction of Brine Volume:

On the contrary of discharging brine after dilution into the sea, concentration of reject brine is the best starting action in inland disposals, why? This because it cuts handling and final disposal costs that reversibly proportional to brine volume. Reject brine volume decreases via increasing fresh water recovery as mentioned earlier. However, the reduction of brine volume is not so simple [55,56]. A developed hydration model published by the present authors [57] proved that the lower salinity brackish water (~1200 mg/l) may exhibit strong carbonate scaling problem at recovery 70% in such a way that the BWRO modules had totally blocked just during the first 3 days from start up, and the weight of these modules became 3 times heavier. In another case on the Red Sea, the SWRO that desalinate a 52000 mg/l groundwater at recovery 35% were totally blocked with dense big tabular gypsum crystals during the first month from start up. The authors recommended to keep the number of hard atoms in the 1mm x $1cm^2$ brine layer on the membrane surface to be lower than 2×10^{18} by using the proper pretreatment or/and lowering permeate recovery ratio. In other words, it is possible to increase fresh water recovery via lowering (or removing) the hardness ions. This is the key for reduction of reject brine volume. Removal of hardness ions (i.e. Ca, Mg, Ba, Sr, Fe, Mn, CO_3, SO_4, PO_4, SiO_3) from feed water can be achieved, partially or totally, via 1) Lime Softening,2) Resin Softening, 3)Nano-Filtration, and 4) Alkalization. Both softening processes (lime and resin) are highly efficient in removal of Ca and Mg ions from brackish feed water. After softening it is possible to increase recovery up to 85% or higher in some cases. The recently developed Nano-Filtration membranes allow the removal of most of the divalent hardness ions from brackish feed water as well as seawater effectively but the cost could be relatively high. On the other side, alkalization method of seawater was develop by the present authors and proved that it is more suitable and economic for removal of all hardness ions from seawater and higher salinity ground water. This method uses NaOH for alkalization to pH ~10 in order to precipitate all hardness ions including barium, strontium, iron, manganese, phosphate and silica quantitively. Sodium hydroxide could be self-generated directly by the electrolysis of seawater. The purified seawater allows higher desalination recovery up to 60% or higher.

It should be noticed that increasing SWRO-recovery requires higher mechanical pressure in order to overcome increasing of osmotic pressure as a function of increasing salinity. Fortunately, the newly development in the SWRO ultra-high pressure membrane technology (~120 bar) makes the recovery of 70% of fresh water from seawater is possible when it is free from hardness ions as mentioned above. The application of two or three phases RO-modules configuration is recommended in such cases. As a result of increasing fresh water recovery the volume of the rejected brine will be dropped automatically. This situation results in increasing brine salinity considerably, which allows a feasible evaporation process either naturally or on industrial scale. The evaporation and crystallization of the de-hardened seawater brine slurry will produce high quality salts of an attractive economic value. Even in the case of deep injection wells the less brine volume is beneficial. The reduction of brine volume should be considered greatly in designing of desalination plants as it has many economical and environmental benefits [58.59].

4.2.2. Evaporation Ponds:

Full evaporation is the best option for protecting environment from the adverse impacts of brine disposal. The most economic method for brine disposal is simply done by natural evaporation in evaporation ponds, i.e. by aid of the sun and wind. Reject brine, or its concentrated slurry, being discharge to shallow earth ponds and evaporated to dryness for final disposal. This is generally applicable in hot arid and semiarid environments. Evaporation ponds are usually isolated from underneath sub-surface water with clay lining. It is relatively easy to construct, while requiring low maintenance and little operator attention compared to other mechanical systems. The main obstacle of evaporation ponds is the substantial land area requirement. The efficiency and performance of evaporation ponds are very site-specific as the principal factor is the local net evaporation rate (NER), which is defined as:

NER = average annual evaporation – average annual precipitation (2)

The absorbed solar energy is to a great extent dependent upon the characteristics of the water body and climatic conditions (solar radiation, wind velocity, humidity, daily and seasonal variations). Evaporation from small shallow ponds is usually considered to be quite different than that of large lakes mainly due to differences in the rates of heating and cooling of the water bodies because of size and depth differences. Additionally, in semi-arid regions like Egypt, hot dry air moving from a land surface over a water body will result in higher evaporation rates for smaller water bodies. The evaporation rate of a solution will decrease as the dissolving salts increases. Decreases in evaporation rates compared to fresh water rates can seriously increase the failure potential of ponds designed on fresh water evaporation criteria.

Field determination of the net evaporation rate under variable climatic conditions is highly recommended. A field measurements to determine the evaporation rate on some SWRO reject brines by using the pan method and the modified Kohler-Nordenson-Fox equation found that the NER varies between 40 and 45 inch/year at Sharm El-Sheikh, south Sinai, and up to about 50 inch/year at Hurghada on the Red Sea coast where the average wind velocity is considerably high (>10 km/hr) most of the year, Therefore, evaporation ponds are generally designed as several connected or separate very shallow basins with a depth of less than 50 cm, typically 20 to 40 cm, over a vast surface area (~4000 m^2 each) in order to keep the inflow rate as low as possible as reported [60].

Fakir et al.[61]A study reported that the evaporation rates on saline solutions. They carried out field investigations to measure the evaporation rate of brine solutions and compare this against that of a standard water sample. Initial results indicated that stratification occurred in the evaporation pans, impacting on the results obtained. The experimental procedure was modified to include daily mixing in the pans. Armstrong et al. [62] introduces a novel approach for computing a normalized radiometric index from surface variables

that can be used to obtain more-realistic distributed estimates of actual evaporation. For demonstration purposes the Granger–Gray evaporation model was applied at a rolling prairie agricultural site in central Saskatchewan, Canada. Visible and thermal images and meteorological reference data required to parameterize the model were obtained at midday. Ratio metric indexes were computed for the key surface variables albedo and net radiation at midday. This allowed point observations of albedo and mean daily net radiation to be scaled across high-resolution images over a large study region. Albedo and net radiation estimates were within 5 %–10 % of measured values. A daily evaporation estimate for a grassed surface was 0.5 mm (23 %) larger than eddy covariance measurements. Spatial variations in key factors driving evaporation and their impacts on upscaled evaporation estimates are also discussed. The methods applied have two key advantages for estimating evaporation over previous remote-sensing approaches: (1) detailed daily estimates of actual evaporation can be directly obtained using a physically based evaporation model, and (2) analysis of more-detailed and more-reliable evaporation estimates may lead to improved methods for upscaling evaporative fluxes to larger areas. Also at 2021 "Evaporation in Brazilian dry land reservoirs: Spatial variability and impact of riparian vegetation" study demonstrates that marginal riparian vegetation reduces local water evaporation rates by 18% -31% to compared to the open-water average [63].

Some modern technologies have come up with a concept exploiting wind energy for operation of some devices, such as water turbines and evaporation towers, that break brine solution into spray-like in order to enhance evaporation rate by several fold. This takes advantage of the availability of wind in 24 hours/day and not just during daylight. Some companies claimed that the size of evaporation ponds could be cut by at least 50% by using wind evaporation. Therefore, these types of wind-enhanced evaporation ponds are recommended where land availability is limited.

4.2.3. Solar Gradient Ponds:

A solar gradient pond is a body of brine water that captures solar energy for either evaporation, such as in a salt concentration works, or to provide useful heat. There are several types of solar ponds, including evaporation ponds with covers, deep ponds with glass, plastic, or gel-filled plastic covers, and salt gradient solar ponds. Solar ponds have several advantages over other solar technologies. They have low cost per unit area of collector, inherent storage capacity; and are easily constructed over large areas. This big amount of stored solar heat is greatly utilized in the production of distilled water, electricity, space heating and commercial salts. Solar gradient pond is deeper (2-4 meter) than normal evaporation pond (<0.5 meter) and consists of three main water layers. The top layer is cold and has lower salt content. The bottom layer is hot (70°C - 95°C) and very salty. Separating these two layers is the important gradient zone, where salt content increases with depth. Water in the gradient zone cannot rise because the water above it is less saline, and is therefore lighter. Similarly, water cannot fall because the water below it has a higher salt content and is heavier. Thus, the stable gradient zone can act as a transparent Insulator, permitting sunlight to be trapped in the hot bottom layer from which useful heat is withdrawn. Most of solar gradient ponds are of square or rectangular in shape with a surface area ranges typically between 400 and 4000 m^2, nearly flat or very gently sloping bottoms, and have incorporated sloping walls. The quantity and quality of heat stored by a solar pond are influenced by pond depth and climatic conditions as well. The depth determines such factors as maximum pond temperature, heat losses to the surrounding soil and air, and temperature response time of the solar pond storage zone.

Salt is the major requirement for a solar pond. To function efficiently, the pond must have an adequate supply of salt in the storage zone. The seawater reject brine consists of several chemical species among of them some tend to precipitate at high concentration like calcium and magnesium sulfates and carbonates. Therefore, the net salt requirement should be estimated as pure sodium chloride. Generally, NaCl salt content varies between 400 and 600 kg NaCl per one square meter of surface area of 3-meter depth solar pond, depending on solar radiation and climatic conditions. Therefore, brackish reject brine is not typically suitable for solar gradient pond process unless cheap salt source is available, such as the concentrated brine slurry that disposed from a nearby seawater desalination plant or dried salt from evaporation ponds. Generally, the economics of evaporation ponds is much better than solar ponds as a disposal option for the brackish reject brine. Combining between the two methods could be feasible.

In El-Paso Solar Pond, the first integrated pilot-scale project executed by the University of Texas in 1987 has a surface area of about 3000 m^2 with a total depth of 4 meters: 1 m storage zone, 1.5 m gradient zone, 0.5 m surface zone and a 1 m freeboard in order to contain brine during wind. The operation temperature of the pond ranged from 70°C in winter to 90°C in early fall. The highest temperature observed at the El Paso Solar Pond was 93°C. This solar pond delivers about 300 kw/h thermal by using a low-enthalpy organic Rankine-cycle engine generator. In addition to the extracted heat and generated electricity, El-Paso solar pond project supplied with a small-scale brine concentrator and a salt crystallizer used for the production of high-quality commercially salts. This project has a positive impact on the environment for both the short term and long term. Actually, it is considered as a “zero discharge” project. Many similar projects are now under construction for full or partial handling of the rejected brine that generated from the small and medium desalination plants[64].

Hybrid solar pond systems have significantly improved thermal storage, energy conversion efficiency, and reduced losses. Studies indicate that these systems can achieve bottom temperatures of up to 90 °C, with energy and exergy efficiencies exceeding 50 %, and generate hybrid capacities of about 5 MW. Self-desalination units based on hybrid ponds have demonstrated exergy efficiencies of around 54 % with an annual output of approximately 2,381 m^3 of freshwater, equivalent to 73 % of their operational capacity. These results confirm the ability of these systems to combine electricity production with thermal energy storage, thereby supporting water desalination processes [65]. In 2025 Sengottaiyan et al. [66] examined a desalination pond that is experimental in size and uses solar energy for its heating. The results prove that the proposed solar-powered pond can be realistically executed. The proposed solar-powered pond to a standard solar-powered pond in terms of the rate at which it gains distilled water were compared. Universiti of Putra in Malaysia proposes an integrated technique using solar and evaporation ponds to filter valuable minerals from concentrated brine [67]. The results of this study demonstrate that the proposed technique can be effectively employed for this purpose. Furthermore, this helps

reduce desalination costs and complies with the notion of renewable energy production and eco-friendliness. In addition a paper provides a critical review of concentrate disposal technology using evaporation ponds. Relevant topics are also covered including chemistry of brine, brine disposal methods, use of evaporation ponds in agriculture, determination of evaporation rate, and evaporation enhancement methods [68].

4.2.4 Beneficiation before Evaporation:

Desalination reject brine has several beneficial uses before final disposal via full evaporation in either evaporation ponds or solar ponds. Actually, solar ponds present the perfect integrated beneficiation and evaporation system indeed. Some other potential uses of seawater reject brine can be applied before evaporation like uses in mineral processing and production of the brine shrimp.

Mineral processing usually consumes huge amounts of salty groundwater as well as seawater for washing and sorting of crushed raw minerals. Seawater reject brine has the advantage of higher density that serving the floatation of gangue materials effectively. Actually, where a single mineral processing plant is located nearby a middle-size desalination plant it will consume all of the reject brine and may need more, it is a matter of luck. A study proposes an integrated technique using solar and evaporation ponds to filter valuable minerals from concentrated brine. The results of this study helps reduce desalination costs and complies with the notion of renewable energy production and eco-friendliness [69]. Another study focuses on the design and simulation of a process for selective precipitation and mineral recovery from reverse osmosis brines. The process involves a two-step evaporative system followed by reactive crystallization of magnesium hydroxide. Laboratory tests and simulations using PHREEQC (pH-Redox Equilibrium C-program) were conducted to validate the thermodynamics of the process and forecast the optimal operative conditions[70]. Another review assesses the technical and economic prospects for utilization of commercially viable products from seawater was carried out [71]. The authors suggested the most promising separation technologies are those, such as nanofiltration, which separate brine into streams enriched/depleted in entire classes of constituents with minimal input of energy and reagents. Concentration is becoming more economic due to rapid advances in Osmotically-Assisted RO technology. Despite very active research on many aspects of desalination concentrate utilization, it is likely that commercial development of the non-NaCl components of desalination brine will depend on the available market for NaCl, as the challenges and costs of extracting the other mineral components from bitterns in which they are highly enriched and so much less than those faced in direct treatment of brines.

The other potential use of brine is the farming and production of brine shrimp. A key factor in the environment of brine shrimp is salt. They are adapted for life in a wide range of high salt concentrations (25000 to 120000 mg/l), but their optimum salt environment is between 50000 and 80000 mg/l. Brine shrimp usually kept in a primary evaporation pond before full evaporation of the concentrated brine is completed in a secondary pond. Sometimes this process is done in a single pond of larger area where most of the brine shrimp lives near the pond entrance and towards the middle zone. Brine shrimp is a valuable commodity and sold mainly to the high quality hotels. Brackish water reject brine (<20000 mg/l) has similar useful uses in farming and production of the less-salty fish and shrimp. The fish product usually has a good economic value, while the brackish shrimp, which is of inferior quality, is cheaper and has an attractive growing market in the fast & ready food industry. A Master's thesis at the American University in Cairo investigates the sustainable use of desalination brine wastewater to cultivate *Artemia* (brine shrimp). The study evaluates utilizing this hypersaline byproduct for aquaculture. The research suggests growing Artemia (brine shrimp) in evaporation ponds of desalination brine water to feed the marine fish larvae in aquaculture by exploring Artemia growth in brine water in the short and long term and its impact on the reproductive characteristics of Artemia. Thus, it can produce income for these ponds, invest time during evaporation, reduce environmental impacts, and enhance the aquaculture industry [72].

Banerjee et al. [73] investigated various uses for reject brine, such as concrete production, road construction, and ground stabilization. In addition, this review highlights the potential cost savings and resource efficiency resulting from the utilization of reject brine, as well as the mitigation of environmental impacts associated with traditional disposal methods. The study also highlights current research gaps that are still unaddressed, hindering the complete realization of the full potential of reject brine as a sustainable resource.

4.2.5 Deep Well Injection:

The US EPA [74] classified the injection wells into five classes:

(a) **Class-I:** are technologically sophisticated wells that inject hazardous industrial and municipal liquid wastes and chemicals below the lowermost underground source of drinking water. Injection occurs into deep, isolated rock formations that are separated from the lowermost by layers of impermeable clay and rock formations. The injection of the desalination reject brine belongs to this class because of possible degradation of fresh and brackish water resources nearby the point of injection.

(b) Class-II: Wells that inject fluids associated with oil and natural gas production for enhanced recovery of oil or natural gas; and/or storage of hydrocarbons which are liquid at standard temperature and pressure.

(c) Class-III: Wells that inject super-heated steam or other hot fluids into formations in order to extract minerals. The injected fluids are then pumped to the surface and the minerals in solution are extracted. Generally, the fluid is treated and re-injected into the same formation, such as underground mining of sulfur, potash and uranium deposits.

(d) Class-IV: Wells used of injection of radioactive liquid wastes into or above underground sources of drinking water. These wells are banned under the UIC program because they directly threaten public health.

(e) Class-V: Injection wells not included in Class I, II, III, or IV.

Injection of excessive salty reject brine can be considered safe if never migrates out of the injection zone or reacts with the formation rocks. However, there are at least five ways brine may migrate and contaminate less-saline groundwater sources that

considered as potential source for direct drinking and irrigating uses or indirectly via the less-costly desalting technologies, such as BWRO and ED. Brine solutions may:

a) Escape through the well bore into an underground less-saline water because of insufficient casing or failure of the injection well casing due to corrosion or excessive injection pressure,

b) Escape vertically outside of the well casing from the injection zone into an underground less-saline water aquifer,

c) Escape vertically from the injection zone through confining beds that are inadequate because of high primary permeability, solution channels, joints, faults, or induced fractures,

d) Escape vertically from the injection zone through nearby wells that are improperly cemented or plugged, or that have inadequate or leaky casing, and

e) Contaminate less-saline groundwater directly by lateral travel of the injected brine solutions.

These regulations require that all Class-I wells be cased and cemented properly to prevent the movement of fluids into or between underground potentially less-saline water sources. The casing and cement used in the construction of each well are to be designed for the life expectancy of the well. In determining and specifying casing and cementing requirements, the following factors should be considered; depth to the injection zone, Injection pressure, external pressure, internal pressure, and axial loading.

The geological, structural and hydrological properties at the point of injection are the most critical controlling factors affecting the fate of the injecting brine. Wells location must be free of faults, fissures, crakes and other adverse geological features. Some week structures like underground caves and soft sliding planes may cause local seismic activities. In all cases, rock formations should be chemically inactive against the injected wastes. The evolution of big amounts of reaction gases could be very dangerous.

Class-l injection wells are normally multi-cased. The use of more than one casing provides transition zones and isolates deep contaminated aquifers from the lesser saline water contained in shallower aquifers. The injection tube is run from the surface to the deep aquifer where the water will be injected. The tube is encased in cement at least 5 in. thick to comply with environmental regulations. Intermediate depths of casing are selected based on the geological conditions at each site. It should be noted that the grout surrounding the intermediate casing is always a minimum of 3 in. thick and may be as high as 10 in. The grouting thickness is dictated to some extent by the allowable standard casing sizes. Depths of the injection wells typically range from 300 to more than 1500 meter. Generally, injection wells should be at least 3 times deeper and 500 meter away from the nearest water productive well. However, subsurface structural geology and hydrology still the main controlling factors in this subject.

The brine solutions to be injected may require pretreatment in an above-surface facility to prevent plugging in the receiving rock formation. When significant suspended solids are present, such as when concentrate is mixed with membrane pre-filter backwash and periodic cleaning waste. The typical pretreatment consists of: pH adjustment, degassing then SS removal by 5-micron cartridge and in the same sequence.

Pumps are used in above-surface facilities to inject the treated brine concentrate. The flow and pressure requirements are site specific. The discharge head will vary depending upon the geologic conditions and depth of the injection zone. Some municipal disposal wells operate at pressures as low as 3 to 6 psig. More typical discharge pressures are in the range of 30 to 50 psig; however, much higher pressures are often required. Discharge as high as 2,000 to 5,000 psi can be encountered. To attain discharge pressures in this range, reciprocating pumps are typically used, and the pump cost increases drastically.

Before well compilation, systematic site tests are necessary in order to confirm drilling specifications as well as the suitability of the receiving formation. These may include the following tests and measurements: initial drilling and throughout sequence, water samples, core samples, setting casing, setting cement, caliper survey, geophysical logging, down-hole video survey, straddle packer pumping test, pressure test of final casing, hydrostatic pressure test on the annulus of tubing, flow test, final injection test, water samples from the injection zone, radioactive tracer survey, aquifer characteristics, … etc. To ensure compliance with environmental regulations the monitoring wells are required. From these wells periodic samples can be taken and analyzed to determine if there has been any leakage of the waste to the surrounding aquifers. In general the most critical areas are the upper less-saline aquifers [75].

A compilation of existing information on the Class I UIC injection program was studied. Much program data has been gathered on Class I hazardous and nonhazardous injection wells, and each type of well is regulated separately, but stringently. In APE study [76]. the hazardous and nonhazardous Class I requirements are presented together to give a complete picture of the UIC program. A calibrated transient model to assess the environmental impact of the abstraction operations from the groundwater in the Middle Miocene aquifer in the El-Dabaa area on the northern coast of Egypt and the effect of the rejected brine resulting from the desalination plant on groundwater where for three wells were tested are investigated by Embaby et al. [77] The forecasting scenario results indicate the decline of the aquifer's potentiometric surface to reach its maximum value of 1.4 m at well 3 within the study area by 2040. The radius of the affected area by drawdown is about 550 m, and the drawdown is generally decreased far away from the location of extraction wells (feeding wells). The salinity of the aquifer in the future scenario is affected by the rejected water inflow due to the high coefficient of permeability of the aquifer in the study area. The salinity increases to reach its maximum value of 40919 ppm at each reject well site and its maximum value of 37860 ppm at feed well 2 sites within the study area by the 2040 year. In contrast, most of the study area, mainly feed well 3, wasn't affected by rejected water. The radius of the affected area by salinity is about 700 m around the reject wells site by 2040. The effects of brine water injection in the Nile coastal aquifer, one of the largest underground freshwater reservoirs in the world, and to find a way to minimize and manage the environmental impact of the RO process was investigated by Abd-Elaty et al. [78]. In order to simulate the effects of the brackish water extraction and the brine deep-injection on the Nile coastal aquifer, a combined seawater intrusion, numerical

models for flow and salt transport model in aquifers and the solution-diffusion in RO practices were implemented. Different management scenarios were considered and their consequences on salt mass storage in the Nile coastal aquifer evaluated. According to the numerical results, the salinization of the coastal aquifer can be mitigated by reducing the concentration of the water feeding the reverse osmosis plant, i.e., mixing the extracted brackish water with a lower salinity water. Besides, low feed salinity leads to significant gains by decreasing the specific energy consumption of the desalination process. **Also** Ahmmad et al. [79] study aims to advance the current understanding and enhance the management of wellbore integrity issues in CO_2 injection wells. Accordingly, this review paper undertakes a thorough exploration of the primary factors influencing wellbore integrity in CO_2 injection wells. Furthermore, it delineates a pressing necessity for more exhaustive investigations regarding the influence of CO_2 injection rate, CO_2 purity, and wellbore geometry on wellbore integrity. Investigation of the hydrological and environmental impacts of well injection using groundwater flow and solute transport numerical models was studied [80], showing the fresh-saline water interface (FSI) response at different injection rates, depths, and distances from shore. Moreover, this study investigates the recovery evolution of the aquifer after injection stops. A hydrological response was analyzed when pumping saline groundwater (SGW) (for desalination) or freshwater (for water supply) simultaneously with brine injection. Results show that brine injection creates a high salinity plume that pushes the FSI landward and salinizes the aquifer. After 20 years of injecting 5 million $m^3\ y^{-1}$, 17 million m^3 of freshwater are lost due to salt contamination. It is also shown that by injecting further offshore and in shallower depths, the impact on the FSI and the aquifer is reduced. Furthermore, pumping SGW simultaneously with brine injection negates the brine plume effect on the FSI and results in a more stable interface. It is noted that aquifer recovery is a long process and even after 100 years of recovery, the aquifer is not fully rehabilitated. This paper shows for the first time the hydrological implications of brine injection into the saline part of the coastal aquifer and demonstrates its potential utility for desalination plants in protecting the environment. Another study [81] aims to bridge the knowledge gap by employing experimental (sand tank) and numerical modeling approaches. To accomplish this, five distinct scenarios were examined: (1) brine injection only; (2) saline groundwater (SGW) pumping only; (3) freshwater pumping only; (4) simultaneous brine injection and SGW pumping; and (5) simultaneous brine injection and fresh groundwater pumping. Results show that brine injection creates a high salinity plume that pushes the fresh-saline water interface (FSI) landward and salinizes the aquifer. Pumping SGW simultaneously with brine injection negates the injection effect on the FSI and results in a more stable interface. Conversely, pumping freshwater simultaneously with brine injection exacerbates seawater intrusion and causes faster salinization of the freshwater aquifer. In all injection scenarios, the brine plume propagation velocity decreases as injection continues. The analysis shows, for the first time, the hydrological implications of brine injection into the saline part of the coastal aquifer using controlled sand tank experiments and numerical modeling, and demonstrates its potential use for desalination plants in protecting the environment.

4.2.6 Wastewater Treatment Plant:

Direct discharge of rejected brine into sewage treatment plant is an attractive solution for the small seawater desalination plants as well as the brackish water ones in general. The idea based on that the fresh water (TDS<300 mg/l) is the main source of municipal sewage water, which has low TDS ranging between 400 and 600 mg/l. Therefore, the dilution of rejected brine with raw or treated sewage water to the upper limit of the biological process (~2500 mg/l) is practically accepted. The minor amounts of the pretreatment chemicals are not harmful to the active biomass; on the contrary, some phosphate, carbonate and sulfate could be useful indeed. Direct application of the mixed waters is quite suitable for irrigation of trees and other decorating plantation. This method allows the disposal of relatively small brine volumes without any pretreatment because that biological process is able to assimilate and clarify such mixed solutions effectively. It is noticed that in mixing industrial wastewater with sewage, the biological contact stabilization method, which runs at higher MLSS (>3000 mg/l), is much superior than the conventional extended aeration method (MLSS ~1500 mg/l) in handling additional highly polluted loads. In all cases, the valuable biomass must be protected from any unexpected shock.

Direct discharging reject brine into an industrial wastewater treatment plant is applicable and an economical disposal method, but it requires careful management. The high salinity and specific chemical composition of the brine can severely impact the biological and chemical processes of the treatment facility if not properly controlled. The advantage of discharging into these treatment plants is that the later are usually consume bigger volumes of industrial water that is capable to accept considerable amounts of the reject brine easily.

Iinvestigated the fate of brine water produced by the inland desalination units on the underlying aquifers using numerical modelling and field investigations was studied [82]. The methodology involved developing groundwater flow and solute transport models using Flex VMF-SEAWAT to simulate the movement of reject brine. The field investigations included collecting 150 water samples and conducting pumping tests on newly drilled wells. The results show that the RO reject brine will significantly increase groundwater salinity, exceeding 10,000 mg/L when accounting for advection, dispersion, and adsorption processes. The sustainable yield of the aquifer, with a salinity of <10,000 mg/L, averages 500 Mm^3 but is expected to be depleted within 16 years with the current extraction rate. The resulting hydraulic properties are favorable with K about 100 m/d, $T > 1000\ m^2$/day, and Sy just >0.1. The adopted values for dispersity and adsorption coefficients for chloride and sulphate salts in the aquifer were 10 m and $1 \times 10^{-7}\ [mg/l]^{-1}$ respectively. Chemical and numerical analyses indicate a mixing ratio between the reject brine and groundwater in the study area of approximately 10 %. Uncontrolled groundwater extraction, combined with the surface disposal of RO reject brine, has led to a significant decline in groundwater levels and an increase in the salinity. The adsorption ratio of simulated brine plume was 13 %. The authors recommend to dispose the RO reject water in a safe location or transfer it to the nearest wastewater treatment plant for proper treatment and reuse.

4.2.7 Direct Land Application:

In fundamental, treatment of wastewater by land application involves the use of plants, soil surface and soil matrix to remove many of the pollutants contained in the wastewater. The pollutants can be removed by: plant uptake, organic decomposition in the vegetation soil complex; and by absorptive, physical, chemical reactions with earth materials. The main processes are: slow rate (irrigation), rapid infiltration, reclamation of marginal land and overland flow to wetlands and salty marches. Accordingly, the choice of direct land

application for reject brine disposal is only limited for that generated from low brackish water desalting (<4000 mg/l) unless diluted with sewage water or similar sources. On the other hand, seawater reject brine cannot comply with the conditions of surface land application and should be avoided.

Impact of reject brine chemical composition on soils in Riyadh Saudi Arabia, was evaluated [83]. Soil samples at three depths along transect on both sides of the pond were taken, in addition to, water samples from feed, product, reject and pond. Results showed that, the salinity of the brine reached up to 5500 mg l^{-1}. The concentrations of soluble ions were exceeding the allowable limits in most water samples. The ratio of major ions and concentration factor was higher. The concentrations of heavy metals were in the allowable limits for drinking water standards especially, in the feed, and product waters. Results pertaining soil properties indicated that the soil pH, EC_e values and, the concentrations of soluble ions were higher in soils closed to the pond. Also, the concentrations of heavy metals were negatively correlated with $CaCO_3$ content and soil pH (expect for Pb; Zn; Cd and Cr), while it was highly correlated with clay content of the soil. Generally, higher ESP and EC_e values in the studied soils can lead to lower permeability, poor aeration and consequently soil deterioration

Potential impacts from using brackish reject brine with high salinity and SAR for normal irrigation causes serious reduction in plant yield as well as damaging the soil structure. The high salinity irrigation water cannot be used on clay soils or soils with poor drainage. It may be used occasionally on sandy soils with excellent drainage if considerable excess water is applied for leaching and if crops with high salt tolerance are grown. This water is not recommended for use under sprinkler application methods unless leaching is practiced. However, some field observations indicated that many economic plants, like the fig and olive trees in south Sinai, are irrigating with ~4000 mg/l groundwater successfully. Also, many golf courses there are covered with planted turfgrass that tolerates up to 3500 mg/l salinity water.

Modern scientific researches gained a reasonable success in high salinity acclamation of some crops, medical herbs, flowers and even vegetables. In addition they have achieved remarkable success in developing salt-tolerant (halophytic) or salt-acclimated plants. Through advanced plant breeding, genetic engineering, and specialized agricultural priming, scientists are unlocking the ability for crops, medical herbs, vegetables, and flowers to thrive in high-salinity conditions.

For example, a review examines the morpho-physiological, molecular, and genetic mechanisms underlying plant adaptation to soil salinity and drought stress. It highlights their impact on plant growth, productivity, and microbial diversity. Diverse methods are investigated to tackle soil salinity and drought stress, encompassing chemical, physical, and biological approaches [84. In addition another research described how they succeeded in plantation of spinach (Spinacia oleracea) in a 3500 mg/l NaCl water by adding supplementary potassium and phosphorus which reduced the adverse effects of high salinity on plant growth and physiological development. On the other side, many researches are underway in order to discover the natural mechanism of the mangrove trees that extract fresh water from seawater. This may solve saline irrigation problems in future[85].

In some limited cases the brackish reject brine used in fixing or killing the moving sand dunes around by planting some herbaceous plants and grasses. The disposed brine volume depends on the planted area, porosity and climatic conditions.

5. Conclusion and Recommendations

The present study reviews the brine disposal options in some details, however, full evaporation option still the most effective way to protect environment from disposed brine. Dilution option has the second priority after full evaporation, if done properly. All other disposal methods have its limitations and drawbacks. For example, the deep injection wells is an expensive alternative that transfer the problem from the surface and hides it in depth where we cannot be sure about its long-term sequences. Other inland disposal methods are actually a matter of redistributing salinity over wider surface area ignoring the serious effect of salt accumulation. Therefore, we may recommend the following:

1. Full evaporation of reject brine either via evaporation ponds or solar gradient ponds- should be greatly considered as a first priority in designing of desalination plants especially at the fragile ecosystem zones like the Red Sea and south of Sinai.
2. Beneficiation before brine full evaporation is economically recommended.
3. Dilution of sea water reject brine with normal seawater is recommended as a second priority when done properly in order to keep the difference between ambient seawater salinity and diluted brine less than 1000 mg/l (<3%). This cannot be practically achieved unless diluting each ton of sea water reject brine with about 40 tons of seawater regarding the difference in densities. At locations where marine currents are active enough (>0.5 m/sec) this difference could be higher up to 10%. Otherwise long-term disposal of poorly diluted brine will certainly impact marine environment not only locally but also regionally.
4. Direct brine disposal on fragile ecosystem shore zones like at the Red Sea and south Sinai, must be avoided. It should be clear that without healthy corals and colored fishes desalination plants will not be required any more at these locations.
5. Deep injection wells could be considered as a third priority when full evaporation and efficient dilution cannot be applied. In this case, an effective monitoring program must be executed under competent supervision.
6. Direct land application is not environment friendly solutions and should be avoided due to possible salts accumulation.
7. Fresh water conservation and good management of treated sewage water are highly recommended as it is the key for reducing all adverse effects arising from over sizing desalination plants.
8. Major existing desalination plants on the Red Sea must reconsider again the evaporation option to replace the existing direct sea outfalls which discharging around 3 million m^3/day of reject brines (thermal and SWRO) since about 30 years ago. The vast dry desert valleys and salt plains can accept all or part of the disposed brine.

6. Conflicts of interest

There are no conflicts to declare.

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