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Inland Desalination: Potentials and Challenges

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1. Introduction

Groundwater is the main source of drinking water in many countries all over the world. In absence of surface water supply, the use of groundwater as the main water source for drinking, industrial, and agricultural use becomes essential especially in the case of rural communities. Underground reservoirs constitute a major source of fresh water, in terms of storage capacity; underground aquifers worldwide contain over 95% of the total fresh water available for human use. Typical groundwater supplies have low coliform counts and total bacterial counts, low turbidity, clear color, pleasant taste, and low odor. Accordingly, groundwater has higher quality than surface water, and the quality is quite uniform throughout the year that makes it easy to treat. A disadvantage of groundwater supplies is that many groundwater aquifers have moderate to high dissolved solids such as calcium, magnesium, iron, sulfate, sodium, chloride, and silica. The high concentration of dissolved solids particularly, sodium chloride, makes the water brackish and thus requires to be desalinated before its use for a certain purpose.

With the growth of membrane science, reverse osmosis RO overtook multi stage distillation MSF as the leading desalination technology. In the last two decades, RO processes have advanced significantly, allowing new brackish groundwater desalination facilities to use RO technology much more economically than distillation. RO treatment plants use semipermeable membranes and pressure to separate salts from water. These systems typically use less energy than thermal distillation, leading to a reduction in overall desalination costs.

The reverse osmosis process enables now the massive production of water with a moderate cost, providing flexible solutions to different necessities within the fields of population supply, industry and agriculture. The great development of reverse osmosis (RO) technology has been a consequence of several factors such as reduction in energy consumption and membrane cost. Nevertheless, the major problem of RO desalination

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plants is the generation of a concentrate effluent (brine) that must be properly managed. Disposal of such brines presents significant costs and challenges for the desalination industry due to high cost and environmental impact of brine disposal.

The reject brine from desalination plants not only contains various types of salts at higher concentration but also other types of wastes like pretreatment chemicals (antiscalents, antifouling,…etc). Also, if the feed water includes harmful chemicals such as heavy metals or others, these chemicals are concentrated in the reject brine. Improper disposal of reject brine from inland plants results in several environmental problems.

Although sea disposal of reject brine is a common practice for plants located in coastal areas, it would not be available for inland desalination. Deep well injection is prohibitly expensive and has its own problems such as the possibility of corrosion and subsequent leakage in the well casing, seismic activity which could cause damage to the well and subsequently result in ground water contamination, and uncertainty of the well life. Additionally, when a sewerage system is used for disposal of concentrate brine high in total dissolved solids (TDS) the treated municipal sewage effluent becomes unsuitable for reuse.

While operation and maintenance costs for evaporation ponds are minimal, large land areas are required, and pond construction costs are high. Even in arid climates ideally suited for evaporation, a typical design application rate is only 2 gpm per acre. The construction cost for an evaporation pond with a liner and monitoring system typically ranges between $100,000 and $200,000 per acre, exclusive of land cost. Thus a concentrate flow as small as 100 gpm would require a pond area of at least 50 acres and cost $10 to $20 million to construct. Consequently, evaporation ponds are often cost prohibitive and impractical for handling any significant concentrate flow. Furthermore, water evaporated from a pond is often a lost resource.

Therefore, the need to protect surface and groundwater resources may in many cases preclude concentrate disposal by the earlier three methods. The alternative is zero liquid discharge (ZLD). In ZLD, concentrate is treated to produce desalinated water and essentially dry salts. Consequently there is no discharge of liquid waste from the process. Most ZLD applications in operation today treat industrial wastewater or power plant cooling water using thermal crystallization, evaporation ponds, or a combination of these technologies. Thermal crystallization is energy-intensive with high capital and operating costs.

Given the need for ZLD and the disadvantages of existing ZLD methods, it is imperative to find alternative ZLD treatment technologies that provide more affordable concentrate management. This article reviews current trends and potential advancements of inland desalination and brine management alternatives.

2. Water and water resources

Water resources present naturally in the environment can be generally divided into freshwater and saline water according to the amount of dissolved solids it contains. Quality and quantity of different water resources are of high importance, many efforts are being made to have good estimates of water resources at both worldwide and country levels. In 1990s “The comprehensive assessment of the freshwater resources of the world” was launched to have estimates on worldwide water resources (United Nations [UN], 1997). The

AQUASTAT program (Food and Agriculture Organization [FAO]) was launched to form global information system on water and agriculture, the main objective of the program is to collect and analyze information on water resources, water uses, and agriculture water management within different countries. Information on the quantity of major water resources is present in table 2.1.

Water Resource	Volume, (1000 km^3)	Percent of total water	Percent of total fresh water
Saline water:			
Oceans/seas	1,338,000	96.54	-
Saline/brackish groundwater	12,870	0.93	-
Saltwater lakes	85	0.006	-
Freshwater:			
Glaciers and permanent snow covers	24,064	1.74	68.70
Fresh groundwater	10,530	0.76	30.06
Fresh lakes	91	0.007	0.26
Wetlands	11.5	0.001	0.03
Rivers	2.12	0.0001	0.006

Table 1. Estimates of major water resources on Earth (Gleick, 2001).

Freshwater is the water naturally found on Earth's surface and in underground aquifers such as surface water, fresh groundwater, and glaciers, and mainly characterized by its low content of dissolved solids. These water sources are considered to be renewable resource, by effect of natural water cycle. The quantity of freshwater present on Earth is around 2.5% only of the total water present on Earth.

Surface water is the water present in rivers, fresh lakes, and wetlands; the main source of surface water is by precipitation in the form of rain, snow….etc. Surface water is characterized by low content of dissolved salts generally below 500 mg/L. Surface water represents only around 0.3 % of the total freshwater present on Earth's surface. Fresh groundwater is the water located under the Earth's surface i.e. subsurface water which is mainly located in pores or spaces of soil and rocks, or in aquifers below the water table. It is mainly characterized by its low suspended solids. In many places groundwater contains high content of dissolved salts compared to that of surface water; with salinity level around 500-2,000 mg/L (Mickley, 2001). Groundwater represents around 0.76 % of the total water present on Earth, and around 30 % of the freshwater available on Earth.

Water or ice present in glaciers, icebergs, and icecaps represents the vast majority freshwater, this huge amount of water is currently unused and locked up in southern and northern poles. Up to date there is no efforts has been made to make use of such water resources due to the high cost associated with its processing as it is mainly present in very distant areas or at very high altitudes.

Brackish groundwater is the water located under the Earth's surface and it is characterized by its higher salinity than that of fresh groundwater with values of 2,000-10,000 mg/L

(Mickley, 2001). It is mainly present in aquifers that are much deeper than that of fresh groundwater. Brackish groundwater represents around 0.93 % of the total water present on Earth.

Saline or salty water is the water that contains considerable amount of salts and it is mainly found in oceans, seas, saline or brackish groundwater, and saltwater lakes. Saline water represents the majority of water resources in terms of quantity with around 97.5 % of the total water present on Earth. the salinity of seawater varying from one location to another, from around 21 g/L in the North Sea to 40 - 45 g/L in the Arabian Gulf and Red Sea, and even up to 300 g/L as in the Dead Sea (Gleick, 2006).

The majority of world population use surface water or groundwater as the main source for domestic, agriculture, and industrial water supplies. The most common surface water sources are rivers, and lakes. However, the most common groundwater sources are pumped wells or flowing artesian wells. In absence of surface water supply, it is clear that the use of groundwater becomes essential especially in the case of rural communities. Underground reservoirs constitute a major source of fresh water, in terms of storage capacity; underground aquifers worldwide contain over 95% of the total fresh water available for human use. In addition when looking to the map of worldwide water stress in figure 2.2, we find that areas that face water stresses are increasing with time with Middle East, North Africa, and Central Asia having the highest water stresses, while when looking to the worldwide groundwater resources map as shown in figure 2.3, we find that most of these areas have access to groundwater resources, which means that groundwater will present the relief to the faced water stress problems, and even can support the different developmental planes of these areas.

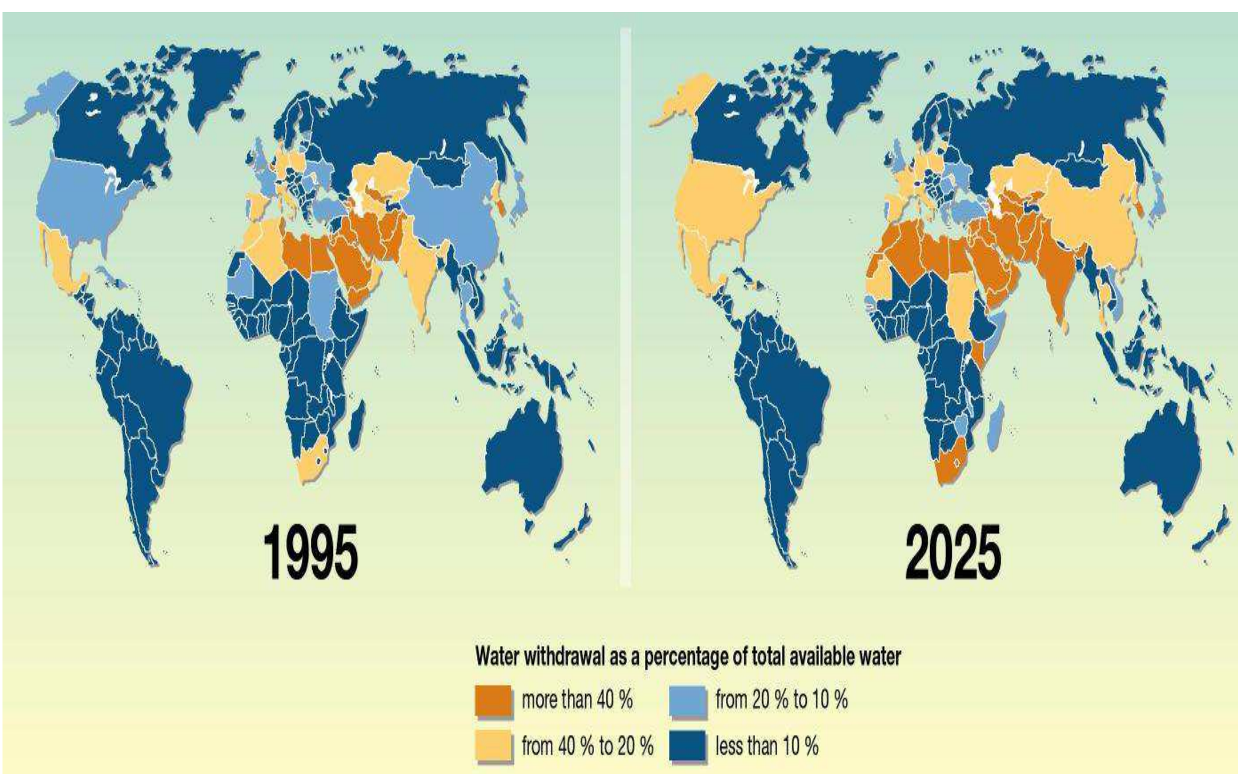

Fig. 1. Worldwide water stresses map (United nations Environmental Programme [UNEP]).

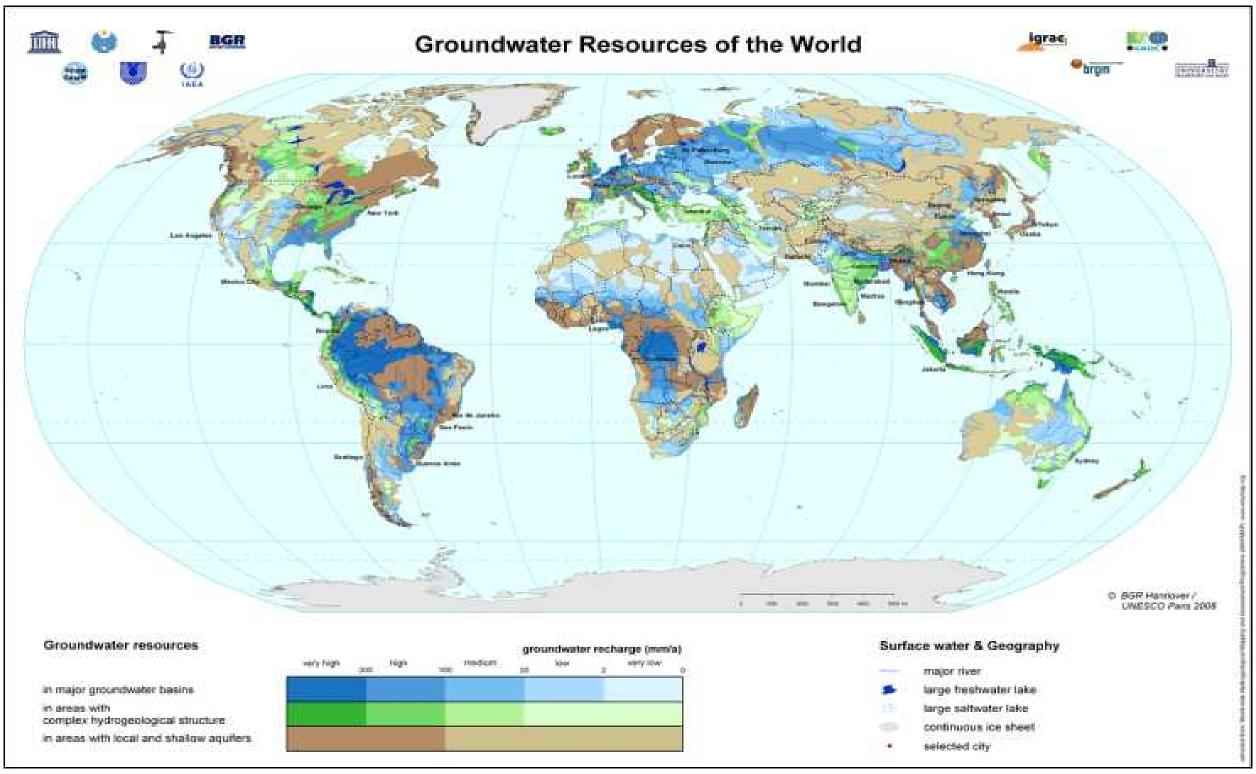

Fig. 2. Worldwide groundwater resources mapping (The Federal Institute for Geosciences and Natural Resources).

3. Groundwater quality

Pure water is a colorless, odorless, and tasteless liquid, water is polar and strong solvent capable of dissolving many natural and synthetic substances, many inorganic and organic compounds, in addition it is able to suspend many solids, and hence it is very hard to find pure water in nature.

The quality of groundwater is mainly determined by its content of dissolved solids and gases, presence of suspended solids, and bacteria present. Usually the nature and concentration of dissolved solids present in groundwater source will depend on characteristics of the aquifer and on travelling time or velocity of groundwater flow through the rock formation (Delleur, 2007).

The physical properties of water are mainly, the total, suspended, and dissolved solids, in addition to turbidity, temperature, color, odor and taste. Typical groundwaters, as they undergo natural filtration while passing through sand formations have very low suspended solids content, low turbidity, clear color, pleasant taste, and low odor. However, while water is travelling through the soil formations, groundwater may carry dissolved solids if the soil formations are relatively soluble. The type and concentration of dissolved solids released from soil to groundwater may vary based on the soil composition, travelling time and flow velocities.

Chemical characteristics are mainly concerned with pH value, cations and anions, alkalinity, acidity, hardness, dissolved gases, and other contaminants such as organic substances and heavy metals that might be present in water. Groundwaters in general have higher hardness when compared to surface waters; this is mainly due to the dissolution of limestone and dolomite formations which in turn increase the content of calcium ions and hence increasing the hardness of water.

Biological characteristics are concerned with the living organisms present in water, mainly bacteria, fungi, algae, and viruses. Microbes are generally absent from groundwater due to natural filtration, and hence groundwater has low coliform and total bacterial counts.

In general groundwater has higher quality than surface waters, and the quality is quite uniform throughout the year making it easy to treat. A disadvantage of groundwater is that many have moderate to high dissolved solids. The high concentration of dissolved solids, particularly sodium chloride, makes the water brackish. The removal of such dissolved solids requires use of desalination process to treat the water to a level of dissolved solids that makes it suitable for a certain use.

Technical and economical evaluations of desalinating groundwater has started early in 1960s. One of the first major brackish groundwater desalination plants was built in Florida, USA with capacity of 2.62 mgd, followed by another one using Reverse Osmosis RO in mid-1970s with capacity of 0.5 mgd (Bart Weiss, 2002). A combination of both field investigations and computer simulation modeling were used to assess the economic suitability of using highly brackish groundwater for large scale abstraction for feeding reverse osmosis desalination plant in many countries around the world (Brich et al., 1985; Hadi, 2002; Sherif et al., 2011; Zubari, 2003). The results from such technical and economical evaluations have shown that brackish groundwater can be considered as high quality source of feedwater for desalination plants, even at higher salinities, which still far below the salinity of seawater. However the evaluations also indicated that the groundwater quality is changing and not constant over long years with continuous increase in dissolved solids content, which should be considered during design stages of such desalination plants.

It was concluded that the major misconception of considering that the groundwater quality is relatively stable over time is very critical for design purposes. The groundwater quality tends to show increase in salinity with time, and hence the initial and future groundwater qualities should be considered (Missimer, 1994). The deteriorating quality of groundwater is becoming of high concern globally, mainly due to human activities such as over abstraction and seawater intrusion. The seawater intrusion is a very common problem worldwide especially, near coastal areas, it is a natural phenomenon in which saline water from sea or ocean moves into the fresh groundwater in coastal aquifers. This behavior is mainly attributed to the density difference and to tidal effects. Seawater intrusion was found to be the main source for the increased salinity of near-coast aquifers in many places worldwide (Amer et al., 2008; Zubari et al., 1994).

4. Inland desalination processes

Desalination is a water treatment process for removing total dissolved solids (TDS) from water. Desalination of seawater and brackish water has become a reliable method for water supply all-over the world and had been practiced successfully for many decades.

The worldwide desalination capacity increased dramatically from around 35 million m^3/d in 2005 (Gleick, 2006) to about 60 million m^3/d by 2009, with the largest desalination plant of 880,000 m^3/d at Shoaiba 3 project in Saudi Arabia (International Desalination Association [IDA], 2009). By 2009 there were 14,451 desalination plants online, with further 244 known to be on their way, being under contract or under construction, with an additional capacity of 9.1 million m^3/d in 130 countries around the world (IDA, 2009). Desalination in general can be mainly classified according to the feed water source into two main classes as seawater desalination and brackish groundwater desalination. In 2006 around 56 % of the world desalination capacity was for seawater desalination, and 24 % for brackish water, with Saudi Arabia KSA, Unite states US, United Arab Emirates UAE, Spain, Kuwait, and Japan having desalination capacity over 1 million m^3/d, with Middle East countries holding over 50 % of the worldwide desalination capacity (Gleick, 2006).

Desalination processes are many and can be generally classified according to the technology used and it mainly classified to thermal desalination, and membrane desalination, ion exchange, and electrodialysis. In addition, other new technologies are still under development. The common processes for desalination have been changed from expensive techniques with extensive energy requirements to a sustainable method for drinking water supply.

The selection of desalination process for a certain purpose depends on many factors such as energy cost, final water quality, fouling propensity, temperature, and overall process cost. Table 2 shows the worldwide, US, and Gulf Corporation Council GCC desalination capacity by processes.

Process Type	Worldwide	United States	GCC Countries
RO	46	69	28
MSF	36	1	54
ED	5	9	-
VC	5	3	-
MED	3	1	9
NF	-	15	-
Others	5	2	9

Table 2. Desalination capacity percentage distribution according to process type (Gleick, 2006).

The quality of desalinated water differs depending on the process used, with thermal desalination producing very high quality product water with salinity about 2-10 mg/L; which usually requires remineralization in the post treatment step (Gabbrielli, 1981). However for membrane process the quality of product water depends on many factors such as the quality of feedwater, design recovery, and membrane properties, but in general the product water will have higher salinity than that produced from thermal desalination.

The quality of the final water product mainly depends on the application in which it is to be used for, ranging from very high quality for process water to specified quality as per the regulation for drinking water, or to a certain quality suitable for agriculture. Most of the desalination plants worldwide are designed to be able to produce high quality water. Drinking water standards vary slightly from country to another. The most widely used is the United States Environmental Protection Agency US-EPA drinking water standards with

500 mg/L for total dissolved solids, and 250 mg/L for each of sulfate and chloride(US EPA, 2009). However the World Health Organization WHO guidelines for drinking water quality suggest that total dissolved solids value of 600-1,000 mg/L is generally acceptable (WHO, 2011). On the other hand the FAO suggests that a total dissolved solids up to 2,000 mg/L is acceptable for irrigation purposes (Ayers & Westcot, 1994).

4.1 Thermal desalination processes

In desalting operations, thermal technologies were the only viable option for long time, and Multi-Stage Flash Distillation (MSF) was established as the baseline technology; however Multiple-Effect Distillation (MED) is now the state-of-the-art thermal technology, but has not been widely implemented yet. Thermal desalination plants have provided the major portion of the world's desalination capacity, as the world's requirements for treated water increase. Thermal desalination is usually used for cases where high salinity feed waters are used i.e. seawater, high recoveries are required, high feedwater temperature, and low energy cost, however the main drawback is the extensive energy consumption (Greenlee et al., 2009).

Thermal desalination or some time called phase change desalination; is a very basic process in concept as it copies the natural process of water cycle, where energy in thermal form through the solar radiation evaporates the water into water vapor, which is condensed later and fall in the form of rains or snow (Gleick, 2001), so in thermal desalination thermal energy or heat is applied to the water present in boiler or evaporator to drive water evaporation, this water vapor is condensed later in condenser by exchanging heat, thus sometimes the process is called phase change desalination as water phase changes from liquid into vapor is encountered. Even though the basic concept is the same however there are many processes which utilize that concept in application today, the main thermal desalination technologies are Multi-Stage Flash Distillation (MSF), Multiple-Effect Distillation (MED), and Vapor Compression (VC).

4.2 Membrane desalination processes

With the growth of membrane science, RO overtook MSF as the leading desalination technology, membrane desalination processes in general and commercial RO processes in particular have been undergoing appreciable development. Important factors in the expansion of commercial RO applications are their favorably low power requirements and the realization of continuous technical improvements in membranes which are used in RO systems, RO was first applied to brackish groundwater with first large scale plants in late 1960s. A decade later RO membrane after further development was suitable for seawater desalination and become a strong competitive to conventional thermal desalination by the 1980s (Vandercaseele & Bruggen, 2002) and hence was able to expand the water sources used for desalination and utilize the brackish groundwater and dominate its market.

In the last two decades, RO processes have undergone major advancements significantly enabling now the massive production of water with a moderate cost, providing flexible solutions to different necessities within the fields of population supply, industry and agriculture. The great development of reverse osmosis (RO) technology has been a consequence of several factors such as energy consumption reduction, improvement of membrane material, and decrease in membrane cost.

Membrane processes are basic in principles, where semi-permeable membrane is used to allow the passage of water but not the salt to under certain driving forces. Different types of membrane processes include reverse osmosis RO, nanofiltration, and forward osmosis FO; the later is still under development mainly at laboratory and pilot scales.

4.2.1 Reverse osmosis RO membrane desalination

Osmosis is a natural physical process, where the solvent (i.e. water) moves through semi-permeable membrane (i.e. permeable to solvent and impermeable to solute) from low solute concentration to higher concentration creating differential pressure called osmotic pressure. The osmotic pressure depends mainly on the concentration difference, temperature, and nature of solute). The process continues till the hydraulic pressure difference due to the liquid column is equal to the osmotic pressure. In reverse osmosis RO, hydraulic pressure in value greater than the osmotic pressure is applied to the concentrated solution, results in reversing the osmosis process and in net solvent or water flow from the concentrate to the dilute solution (Fritzmann et al., 2007).

RO membranes do not have a distinct pore that traverse the membrane; it consists of polymeric material forming a layered, web-like structure characterized by high rejection to most of the dissolved solids present in water, with typical salt rejection above 99 % (Lee et al., 2011). The driving force for RO process is the applied hydraulic pressure which varies considerably from 15-25 bar for brackish water, and 60-80 bar for seawater (Fritzmann et al., 2007).

4.2.2 Nanofiltration NF membrane desalination

The Nanofiltration NF term was first introduced by FilmTech in 1980s to describe RO membranes that allow selectively and purposely some ionic solutes to path through the membrane, the membrane's selectivity was towards solute of about 1 nm cutoff, and hence the term nano comes from (Wang, 2008). Nanofiltration is an intermediate between RO membranes which has a low Molecular Weight Cut Off MWCO of about 100 and ultrafiltration membranes which has MWCO of about 1000 (Eriksson, 1988).

NF membranes have higher permeability for monovalent ions such as Na, K, and Cl and very low permeability to multivalent ions such as Ca, Mg, SO_4 and organics with MWCO of around 300 (Rautenbach & Groschl, 1990), as a result NF membranes were used mainly for removal of hardness and natural organic matter, as pretreatment before RO and MSD for seawater desalination (Al-shammiri et al., 2004; Hassan et al., 1998), and for groundwater quality enhancement (Burggen & Vandercasteele, 2003; Gorenflo et al., 2002; Saitua et al., 2011; Tahaikt et al., 2007). Nanofiltration membranes operating in a similar fashion to that of RO membranes, except of lower driving pressure and hence lower energy requirements, higher flowrates, and lower product water quality (Schaep et al., 1998).

4.2.3 Electrodialysis/ electrodialysis reversal membrane desalination

Electrodialysis/Electrodialysis Reversal membrane desalination (ED/EDR) is one of the oldest tried desalination processes, with ED process since the 1950s. In ED/EDR electrochemical separation is the main phenomena takes place utilizing electrical power as driving force to separate ions through ion-exchange membranes (Gleick, 2001). In typical ED cell, a series of anion- and cation-exchange membranes are a arranged in alternating pattern between the two electrical electrodes, anode and cathode, and hence ion concentrations increase in alternating compartments, and decrease simultaneously in the other compartments (Walha et al., 2007), ED process has been applied successfully but on small scale for brackish water (Adhikary et al., 1991; Brown, 1981; Harkare et al., 1982), and seawater (Sadrzadeh & Mohammadi, 2008; Seto et al., 1978).

In the 1970s, electrodialysis reversal EDR has been introduced as an innovative modification to the conventional electrodialysis, EDR operates on the same principle as ED. However the polarities of the electrodes are reversed for short time at specified time intervals, so that the ions are attracted in the opposite direction, and hence the brine and product channels are switched (Katz, 1979). EDR process has several features that promoted its application such as ability to treat feedwater of different qualities i.e. higher content of dissolved and suspended solids, ability to operate with high salts saturation levels and hence higher scale resistance, chlorine tolerance, cleanability, higher recovery, un affected by non-ionic species such as silica, low chemical pretreatment, and durability (Buros, 1999; Fubao, 1985; Katz, 1979; Katz, 1982; Valcour, 2010). In addition ED/EDR have been integrated successfully with other desalination processes such as RO (Oren et al., 2010).

4.2.4 Forward osmosis FO membrane desalination

Although RO membrane desalination has the major share in membrane desalination plants, the energy and membrane replacement cost are of major concern, and hence there is a search for new low energy and low fouling membrane processes. Forward osmosis (FO) or called direct osmosis (DO), employs the natural physical osmosis process by increasing the osmotic pressure in the permeate side to balance the pressure in the opposite side.

The FO exploits this natural tendency of water to move through the semi-permeable membrane from the saline water to a more concentrated solution called draw solution, the draw solution has significantly higher pressure than the saline water. Draw solutions of different natures have been tested for FO operation. Volatile solutes or gases such as sulfur dioxide which can be stripped out later to have pure water, perceptible salts such as aluminum sulfate which can be treated by lime to precipitate aluminum hydroxide and calcium sulfate, a two-stage system with sulfur dioxide-potassium nitrate used as the draw solutions has been also evaluated (McCutcheon et al., 2005a).

However recently more attention has been given to ammonia-carbon dioxide system due to several advantages such as the high solubility of ammonia and carbon dioxide gasses in water and the solution of formed ammonium bicarbonate have a high osmotic pressure which in turn provide higher water flux and recovery, followed by ease separation of the gases by moderate heating, which will be recycled back to the process (McCutcheon et al., 2005b; McGinnis & Elimelech, 2007).

Unlike other membrane process, FO does not require any hydraulic pressure to be applied and hence less energy requirements, which in turn results in less capital and operating costs. Furthermore the process has much lower fouling propensity (McGinnis & Elimelech, 2007, Phillip et al., 2007). In addition FO has been integrated successfully with other desalination processes such as RO enabling increased recovery, lower energy consumption (Lee et al., 2009; Martinetti et al., 2009; Tang & Ng, 2008; Yangali et al., 2011).

4.3 Other desalination processes

There are many other desalination process that are available today, some of them still at research and development stages, however they did not reach the development level to be commercialized on large scale as the previous processes, although many of them have a very promising features over the now widely used desalination process such as less corrosion and scaling problems, less energy consumption, less need for pre and post treatment. These processes include solar, ion-exchange, freezing, and membrane distillation.

5. Developments in desalination processes

Desalination has been extensively used over the past decades; with the great developments in desalination industry that have led to a higher acceptance and growth worldwide, particularly in arid areas. Although different desalination processes are well established today, further development are needed to resolve its various technical and operational issues which represent the essential key for successful desalination, including feed characterization for fouling and scaling propensity, process development, energy requirements, desalination economics, and finally brine disposal which will be given more attention due to its high importance (Sheikholesami, 2009).

5.1 Scaling and fouling

Fouling is a phenomenon that plagues the operation of desalination units, the deposition of foulants on to the heat (in case of thermal desalination) and mass (in case of membrane desalination) transfer surface results in reducing water productivity and decrease product quality, therefore as the fouling deposit builds up the energy consumption increases to accommodate for the required product flow till the unit is cleaned (Hamrouni & Dhahbi, 2001; Sheikholesami, 2004).

Fouling of membrane surface can be caused by any of the rejected constitutes, and can be generally classified to chemical fouling or scaling caused by sparingly soluble inorganic salts exceeding their saturation level, physical or colloidal fouling caused by particulate matter, biological fouling or biofouling due to the formation of biofilms of microorganisms, and finally organic fouling caused by natural organic matter NOM (Fritzmann et al., 2007). The water recovery is mainly constrained by fouling, and hence it is paramount to mitigate fouling of desalination units (Semiat et al., 2004).

The general approach to avoid scaling and fouling by sparingly soluble salts, is to estimate the saturation level of these salts according to the feed water quality, design recovery, and operation conditions and try to operate below such saturation levels where the solution is stable (Sheikholesami, 2004). Extensive work has been done to study the fouling and to determine the saturation levels of common scale forming sparingly soluble salts at different conditions with focus on calcium, barium, and silica particularly calcium sulfate, barium sulfate, calcium carbonate, and silica.

In seawater desalination main types of fouling is scaling by calcium carbonate, calcium sulfate, and magnesium hydroxide in case of thermal desalination. For membrane desalination, the major fouling of concern is biofouling (Al-Ahmad & Abdil Aleem, 1993). Fouling caused by precipitation of sparingly soluble salts is less likely to occur mainly due to the relative lower recovery, higher ionic strength, and low bicarbonate and sulfate concentration (Reverter et al., 2001). The contribution of each type of fouling in typical seawater RO desalination are 48% for biofouling, 18% for inorganic colloids, 15% for organic matter, 13% for silicates, and only about 6% for mineral deposits (Shon et al., 2009). Hence one of the most important steps in seawater pretreatment for desalination is disinfection with optimized dose of biocide, usually chlorine, in order to reduce biofouling propensity (Fujiwara & Matsuyama, 2008).

Brackish groundwater however has higher quality as it is mainly characterized by low content of suspended solids, low bacterial count, and low content of organic matter; as a result the most found type of fouling is scaling by sparingly soluble inorganic salts such as calcium and barium salts and silica.

The dissolved solids present in groundwater results mainly from chemical weathering or dissolution of geological formations i.e. minerals which can be attributed to the direct contact of groundwater with the calcium carbonate, and calcium sulfate rocks forming the aquifer. In addition sulfate may result from biological oxidation of reduced sulfur species. As a result the different aspects of scaling by calcium sulfate and calcium carbonate has been intensively studied (Sheikholesami, 2003a; Sheikholesami, 2003b; Rahardianato et al., 2008).

Silica originates from the dissolution or chemical weathering of amorphous or crystalline SiO_2 and the major clay minerals (Faust & Aly, 1998). Crystalline silica has a very low solubility in water, however amorphous silica can have solubility up to 120 mg/L at pH 7 and the solubility increases with pH increase reaching around 889 mg/L at pH 10 (Hamrouni & Dhabi, 2001; Sheikholesami & Tan, 1999). Silica in water can be classified into two categories 1) soluble or dissolved silica which contains monomers, dimmers, and polymers of silicic acid, and 2) insoluble or colloidal silica, which results from high polymerization of silicic acid. Due to its severe effect on membrane desalination performance and lifetime of membranes, great attention has been paid to silica fouling (Al-Shammiri et al., 2000; Ning, 2002; Semiat et al., 2003; Sheikholesami et al., 2001,).

In any desalination process, there are three main factors for sustainable operation: 1) proper design, 2) proper pretreatment, and 3) proper operation and maintenance; with the proper pretreatment as the foundation for successful operation (Neofotistou & Demadis, 2004). The primary goal of pretreatment is to lower the fouling propensity during the desalination process, and the required pretreatments depend mainly on the characteristics of the water resource (Greenlee et al., 2009). Scale inhibitors or antiscalents are chemicals that are added to water during pretreatment to prevent scale formation and usually work synergically with dispersant polymers.

However most of traditional antiscalents are successful in scale control for crystalline mineral precipitates but not silica because it is amorphous (Freeman & Majerle, 1995), and hence control of silica scaling requires chemical pretreatment.

5.2 Process development

Desalination is a multi unit process, starting from water intake, pretreatment, desalination, and post-treatment. Desalination plants in the past used to contain one type of desalination processes in the past. However attention has been recently paid to hybridization of different desalination processes together, with main objective of maximizing overall recovery, minimizing energy requirements, and cost reduction. NF has been integrated successfully with RO process mainly as pretreatment step, which resulted in improving the RO performance (Al-Shammiri et al., 2004; Hassan et al., 1998), EDR with RO (Oren et al., 2010), FO with RO (Lee et al., 2009; Martinetti et al., 2009; Tang & Ng, 2008, Yangali et al., 2011) in case of membrane desalination processes, integration of VC with MSF and MED (El-Dessouky et al., 2000; Mabrouk et al., 2007), and even combination of thermal and membrane processes by integrating NF/RO/MSF together (Hamed et al., 2009), and FO and MD to RO (Martinetti et al., 2009).

In membrane processes, development of much better membrane material that can work for wider range of pH, chlorine resistant, high mechanical strength to withstand higher hydraulic pressures, better salt rejection, and scale resistant are considered to be the next breakthrough in membrane desalination development, enabling higher recoveries at lower cost (Sheikholesami, 2009).

5.3 Energy requirements

Desalination processes are known for their intensive energy consumption especially thermal desalination, and hence energy consumption make up the major part of operation cost of any desalination process, the energy consumption differs according to desalination process in use i.e. thermal or membrane, water source and quality i.e. seawater or brackish water, design recovery, system design, plant capacity, and utilization of energy recovery devices.

Energy requirement for desalination processes is generally reported as specific energy consumptions in kWh/m^3 of product water. There are a wide range of reported values for energy consumption in desalination with the most recent values of about 1.8 kWh/m^3 for seawater desalination using MED, 4 kWh/m^3 for MSF with heat recovery mechanism incorporated (Khawaji et al., 2008). However for seawater using RO it went down from 20 kWh/m^3 in early 1970s to 1.6-2 kWh/m^3 recently, and below 1 kWh/m^3 for brackish water with energy recovery devices (Fritzmann et al., 2007; Khawaji et al., 2008).

In RO operation, the main energy consumption is mainly for the high pressure pump to provide hydraulic pressure in excess to the osmotic pressure, most of this pressure is retained by the concentrate stream flowing out of the RO unit. Energy recovery devices ERD have been developed mainly for RO operation to recover some of the energy retained in the concentrate before disposal. There are two main classes of ERD, class I which transfer hydraulic energy from the concentrate stream to the feed stream in one step with net energy transfer of more than 95%. Class II transfer hydraulic energy of the concentrate to centrifugal mechanical energy and then to hydraulic energy in the feed in two steps process (Greenlee et al., 2009).

Integration of desalination plants with power plants or as called cogeneration, which refers to the use of single energy source for multiple needs; mainly encountered with thermal desalination offers better energy utilization. For example, power plants use high pressure steam for power generation by means of turbines, the steam comes out at low pressure which is very suitable for thermal desalination (Gleick, 2001). In addition there are efforts for implementing cogeneration in RO desalination process in order to address the water-electricity demand trade off (Altmann, 1997).

Use of renewable energy sources for driving the desalination process provide another development opportunity, specifically for membrane desalination where less energy is required and for rural communities in which desalination systems are generally small in size with usually non-continuous operation, and hence can be integrated to renewable energy sources. Considerable efforts has been made for integrating desalination processes with different renewable energy sources namely solar (photovoltaic and thermal), wind, and geothermal. The renewable energy can be used in one of two forms thermal or electrical, depending on which one that best match the desalination process (Al-karaghouli et al., 2009; Al-karaghouli et al., 2010; Forstmeier et al., 2007; Mathioulakis et al, 2007).

5.4 Desalination economics

Economics of any process represent the most crucial part for development and application, and hence economical feasibility is a very important factor when considering desalination processes. In desalination processes it is difficult to standardize the economics of process because it is case specific. There are several factors that affect desalination cost such as water source (brackish or seawater), desalination process used (thermal or membrane), energy source (traditional or renewable), and plant size (Dore, 2005; Karagiannis & Soldatos, 2008).

The source, and hence the quality of the feed water plays important rule for determination of both capital and operating cost, and the overall desalination cost. Brackish water has much low salt content and better water quality than seawater and therefore, it incorporates less capital and operating costs. The most recent data for average investment cost for brackish water was around \$200-450/ (m^3/d) with product water cost of \$0.25-0.75/m^3 for RO process which is the process dominating the brackish water desalination market (Vince et al., 2008; Yun et al, 2006).

The product water desalination cost varies significantly according to the salinity of the water sources. For example the product water cost for brackish water with salinity around 3,000 mg/L was found to be \$0.32/m^3. However, for water with salinity around 10,000 mg/L, the desalination cost was \$0.54 /m^3 (Karagiannis & Soldatos, 2008). The same trend was observed also for sea water desalination with desalination cost ranging from \$0.54 /m^3 for Mediterranean seawater to \$0.87/m^3 for Arabic Gulf seawater (Greenlee et al., 2009).

Capacity or size of desalination plant greatly affects the product water cost; table 3 shows the average desalination cost for brackish and seawater desalination plants of different production capacities.

Feed water	Plant size (m^3/ d)	Cost (\$ / m^3)
Brackish	≤ 1,000	0.78 – 1.33
	5,000 – 60,000	0.26 – 0.54
Seawater	< 1,000	2.2 – 11.25
	1,000 – 5,000	0.7 – 3.9
	12,000 – 60,000	0.44 – 1.62
	> 60,000	0.50 – 1.0

Table 3. Size of desalination plant and water production cost (Karagiannis & Soldatos, 2008).

6. Brine disposal from inland desalination

Brine, concentrate, or reject are different names for a stream that is commonly produced from any desalination process. In any desalination process, two streams are produced: 1) product water with high quality, 2) brine or concentrate stream that contains all the salts were originally present in the feed water in addition to the chemicals added in the pretreatment and during desalination such as antiscalents.

To reduce energy consumption, cleaning time and expenditure, loss of production during downtime, it is paramount to mitigate fouling. The general approach is to study the feed water characteristics and couple it with the expected recovery and operating conditions; and to operate at conditions where the solution is stable, hence scaling and fouling is minimized. However working at lower recoveries to avoid the fouling of membrane will increase the flow of brine stream generated, which present the main trade-off for desalination operation.

Brine stream does not contains only 2 or 4-5 folds the salinity of the feed water as in case of seawater, or brackish water respectively, but it contains all the chemicals that has been added to the desalination process during pretreatment. Moreover in case of thermal desalination it will be at high temperature, and hence more attention should be taken when considering the brine discharge method (Ahmed et al., 2002).

The problem of brine discharge is different in sea water and brackish water desalination. In the case of seawater desalination plants the problem is readily solved since these plants are usually placed near the coast, so the discharge method of choose is usually to discharge it back to the sea through brine pipes or submarine emissaries. Encouraging facts to utilize that option are, first the discharged brine is of similar chemistry, even being more concentrated but only by 50-100 %. Second is that the volume of brine stream relative to the water body being discharged to being very small, hence lower drawbacks are expected. However, there are many criteria to be considered such as having the discharge point far enough from intake at good mixing zone so it can be mixed with the main body of seawater.

However, the management of brine from brackish desalination plants i.e. inland desalination can be significant problem in case they are placed far from the coast (inland plants). Some of the conventional options for brine disposal from inland desalination plants are: 1) disposal into surface water bodies, 2) disposal to municipal sewers, 3) evaporation ponds, 4) deep well injection, and 5) irrigation of plants tolerant to high salinities (Ahuja & Howe, 2005). The main factors that influence the selection of a disposal method, among others, are: 1) volume or quantity of concentrate, 2) quality and constitutes present in the concentrate, 3) physical and geographical considerations, 4) capital and operational costs, 5) availability of receiving site, 6) permissibility of the option, facility future expansion plan, and 7) public acceptance. All of these factors together will affect the cost of brine disposal that can ranges from 5 -33 % of the total desalination cost (Ahmed et al, 2001).

Brine disposal method should be considered after the necessary studies and investigations have been performed in order to minimize the brine stream to be disposed off, and hence reduce the cost of subsequent disposal. This is mainly achieved by employing the proper feed water pretreatment, proper desalination process, maximizing the system recovery. However attention to the increased salinity and quality of brine should be considered.

6.1 Disposal to surface water bodies and sewers systems

Disposal of brine to surface water bodies if a available, present the first option to choose as it represent a ready and good solution to the challenge of brine disposal taking into account that the brine stream is diluted by mixing with the water body. However many consideration should be taken into account. The salinity if the receiving body might increase due to the disposal of the high salinity brine, and hence the self-purification capacity of the receiving water should be considered (Ahmed et al., 2000). As a result disposal to surface water should be permitted only if that will avoid dramatic impact on environment.

Another option is to dispose the brine to the local sewage system, which is usually employed by small membrane desalination plants. This option has many advantages such as use of the ready available and installed sewage system, lowering the BOD of the domestic sewage water. However that should be practiced carefully as the salinity of sewage water might increase which might affect the wastewater treatment facility especially biological treatment step. This might also render treated municipal sewage effluent unsuitable for agriculture use when disposing brines with high salinity (Ahmed et al., 2000).

6.2 Disposal to evaporation ponds

In evaporation bonds, the brine is discharged into a large surface area pond, where the water is naturally evaporated. Use of evaporation pond technology is practiced primarily in the arid and semi-arid areas, particularly in Middle East and Australia. Evaporation pond is probably the most widespread method for brine disposal from inland desalination plants.

Simple evaporation ponds have many advantages such as being easy to construct, low maintenance and operation cost, no equipment are needed specifically mechanical. Making it the most appropriate method with lower cost, especially in arid areas with high evaporation rates, low rainfall, and low land cost (Ahmed et al., 2000). Use of evaporation ponds for cultivation of brine shrimps has been studies as well, giving ideal place for brine-shrimp production as it present mono-culture environment under natural conditions with absence of any food competitors or predators (Ahmed et al., 2001).

The basic concern associated with use of evaporation pond for brine disposal is leakage of brine through soil. This may result in subsequent contamination and increasing salinity of the aquifer. Electrical conductivity and concentration of salts in the evaporation ponds can be used as indicators for leakage in the pond, where insignificant increase is a strong indication of brine leakage through the soil (Amed et al., 2001). Deterioration of soil and groundwater quality in areas nearby evaporation ponds used for brine disposal in KSA, UAE, and Oman was investigated and reported as one of the draw backs to use of evaporation bonds (Al-Faifi et al, 2010; Mohamed et al., 2005).

As a result most of the evaporation ponds installed recently are lined with polymeric sheets. Liner installation should be carried out carefully as joints sealing is very important for leakage prevention. Furthermore double lining is strongly recommended with proper monitoring for leakage.

In addition reduction in production from agricultural lands caused by deposition of airborne salts from dried concentrate of evaporation bonds, and formation of eyesores caused by improper disposal of concentrates on nearby land can be another disadvantage of brine disposal to evaporation ponds.

In conclusion, while operation and maintenance costs for evaporation ponds are minimal, large land areas are required which increases as the plant capacity increase, and pond construction costs are high due to lining and monitoring requirements. Consequently, proper evaporation ponds are often cost prohibitive and impractical for handling significant concentrate flow. Furthermore, water evaporated from a pond is often a lost resource.

6.3 Deep well injection

In deep well injection, the brine is injected back underground to depth ranges from few hundreds of meters to thousands of meters, depending on many factors which should be considered while designing, installing, and operating the system. Deep well injection for brine disposal includes permitting considerations, which look for identification of adequate geologic confining unit to prevent upward migration of effluent from the injection area. While design considerations focus generally on the tubing and packing installed inside the final cemented casing of the injection well, compatibility of the concentrate with the tubing material (to avoid corrosion), expected concentrate flow, and leak detection and monitoring systems (Skehan & Kwiatkowski, 2000).

One of the very attractive options with deep well injection is to use depleted oil and gas fields for brine disposal. This encounter many advantages such as making use of the readily available gas and oil wells, long experience encountered with the operation of such wells. However before applying this option the fields should be tested physically and chemically for accepting the brine stream [Mace et al., 2006; Nicot & Cjowdhury, 2005]

Generally site selection for installing of such deep well, is the most important step, and hence hydrological and geological conditions should be considered, as example the wells should never be installed in areas vulnerable to earthquakes (Ahmed et al., 2000). Although of availability of such option to many inland desalination plants, however many factors should be considered with deep well injection for brine disposal which can be summarized as follow (Mickley et al, 2006):

1. Site selection, which is performed through many geological and hydrological studies, to identify the proper area for installing the well,
2. High cost, associated with both capital and operational cost,
3. Possibility of corrosion and subsequent leakage in the well casing,
4. Seismic activity which could cause damage to the well and subsequently result in leakage,
5. Uncertainty of the well life,
6. Pollution of groundwater resources, which may result from high salinity and the presence of other harmful chemicals in the brine.

6.4 Land applications of brine

Land application such as use in irrigation systems that was originally developed for sewage effluents, can be used for brine disposal, and hence helps conserve natural resources. In areas where water conservation is of great importance, spray irrigation is especially attractive option. Concentrate can be applied to cropland or vegetation by sprinkling or surface techniques for water conservation when lawns, parks, or golf courses are irrigated and for preservation and enlargement of greenbelts and open spaces. Crops such as water-tolerant grasses with low potential for economic return but with high salinity tolerance are generally chosen for this type. However soil sanlinization and groundwater contamination should be carefully considered (Mickley et al, 2006).

7. Inland desalination with zero liquid discharge

In many cases of brackish water desalination, brine management is critical and of high concern, and hence the need for affordable inland desalination has become critical in many regions of the world where communities strive to meet rapidly growing water demands with limited freshwater resources.

Where brine disposal and management is a problem, given the disadvantages of existing brine disposal and management methods, it is imperative to find alternative Zero Liquid Discharge ZLD technologies that provide more affordable concentrate management. In ZLD, brine is treated to produce desalinated water and essentially dry salts; therefore there is no discharge of liquid waste from the site. Most ZLD applications in operation today treat industrial wastewater using thermal or membrane separation processes, or a combination of these technologies.

Thermal desalination is a mature technology that has been practiced for long time especially where energy is relatively inexpensive, while it is a proven process that generates high quality product water, thermal desalination is energy-intensive and its capital and operating costs are high. Membrane processes has been proved to provide high quality water, but also has some limitation concerning scaling and maximum hydraulic pressure and cannot alone provide ZLD solution. Advancement of ZLD science and associated reduction of ZLD costs will be of tremendous benefit and will alleviate the water supply challenges faced by many communities worldwide.

ZLD desalination present the perfect solution for the brine disposal and management problem usually encountered with inland desalination plants. In addition applying inland desalination with ZLD provide several advantages, the main advantages can summarized as below:

- Maximize Water Recovery: with ZLD systems approaches 100 % recovery, when compared to the conventional Inland desalination system with regular recovery of about 70-85%. ZLD systems should be able to provide more product water or less plant size by 15-30 %.
- Preserving Natural Resources: for inland desalination with ZLD systems, the natural resources, which are mainly groundwater and land, are preserved both quantitatively and qualitatively, by avoiding the different problems associated with conventional brine disposal methods.
- Byproduct salts: the ZLD system results into two stream, product water, and dry salts, these salts can be treated as added value product rather than solid waste, finding a lot of applications and beneficial uses.
- Integerability and applicability: ZLD system can be integrated to any existing inland desalination plant of any size and location. This is mainly because the system operates

on treat the brine resulted from the existing desalination plants, and hence it can be integrated at any stage from design to operation stages.

There have been many attempts to achieve a successful inland desalination with ZLD, however more attention and further research work and process developments are needed in order develop a full economic-technical feasible ZLD desalination. In the following sections the current efforts for providing a ZLD system, as well as further developments and research needs will be discussed.

7.1 Current zero liquid discharge schemes for inland desalination

Little literature work is available on ZLD systems for inland desalination; however three main schemes can be concluded and summarized as follow:

- Applying thermal processes directly to the brine generated from the primary desalination process, usually RO, followed by thermal processes for brine concentration, then crystallization or drying for final salt production (Mickley et al, 2006).
- Applying chemical treatment to the brine stream, followed by further membrane desalination, brine concentration, and finally crystallization or drying for final salt production (Bond & Veerapaneni, 2008; Mohammadesmaeili et al., 2010).
- Applying ED/EDR process to the brine stream making use of higher recovery encountered with such units, followed by crystallization or drying for final salt production (Greenlee et al., 2009, Oren et al., 2010).

Similarities between schemes are clear, especially for brine concentration and final salt production, with the difference mainly in brine treatment and further desalination. However brine treatment and further desalination results in significant reduction in the volume of brine to undergo the brine concentration and final drying/crystallization. Options for integrating different units in different setups can be investigated with an overall objective of ZLD desalination and production of salts can be generated, and should be evaluated for process optimization (Kim, 2011).

Conventional inland desalination system usually achieve 70-85 % recovery of the feed water, which is the largest recovery increment in single step, the recovery mainly depend on the quality of the feed water. However this recovery is usually limited due to scaling by sparingly soluble salts, typically calcium salts such as calcium sulfate and carbonate, in addition to silica (Freeman & Majerle, 1995; Rhardianato et al., 2008; Sheikholesami, 2003a; Sheikholesami, 2004). With this recovery range, about 15-30 % of the feed stream will be rejected as brine which should be disposed off.

In the first ZLD scheme this 15-30 % is fed to thermal processes using single or multiple effect evaporators or vapor compression evaporators for brine concentration which to be followed by crystallization or drying to obtain final dry salts. In the second scheme the brine is treated chemically to remove most of scale forming constitutes, achieving high removal of such constitutes rendering the treated brine suitable for further membrane separation to recover more water. With the two membrane desalination process with the intermediate brine treatment step recovery up to 95% can be achieved, moreover making use of membrane desalination reduces the cost, and minimizes the energy requirements. Moreover reduces the volume of brine to be handled by final evaporation step which results in lowering the energy requirements and hence the overall process cost. In the last scheme ED/EDR unit are employed, which can operate at high saturation levels of sparingly soluble salts as in the case of brine streams, and where high recovery up to 97% can be achieved.

7.2 Precipitation softening for brine treatment in zero liquid discharge systems

Intermediate brine treatment step as employed in the second ZLD scheme is the one receiving large attention recently. The main objective of this step to remove most of the scale forming constitutes typically calcium, magnesium, carbonate, sulfate, and silica. It is hard to find a chemical treatment process that is able to efficiently remove all of these constitutes. Furthermore most of the tested chemical treatment processes were not able to completely remove such constitutes. However the achieved removal efficiency was good enough to prevent such constitutes from limiting the recovery in the secondary membrane desalination process.

Precipitation softening is one of the widely used processes for reduction of hardness (calcium and magnesium) and alkalinity (mainly bicarbonate) in water treatment plants. The reduction of hardness is mainly achieved by removal of calcium as calcium carbonate $CaCO_3$ and magnesium as magnesium hydroxide $Mg(OH)_2$. This is usually achieved by addition of alkali usually lime, calcium hydroxide $Ca(OH)_2$ in lime softening or sodium hydroxide, NaOH in caustic softening and sodium carbonate Na_2CO_3 depending on the quality of water to be treated (Reynolds & Richards, 1996). Removal of calcium and magnesium present one of the major targets for brine chemical treatment, particularly calcium, as magnesium cause scaling problems only at high pH values forming insoluble magnesium hydroxide $Mg(OH)_2$. However at the normal pH values found in brine streams it will be mainly saturated by calcium sulfate and carbonate (Sheikholesami, 2003a; Sheikholesami, 2004; Rharadianato et al., 2008).

Silica removal during the precipitation softening was extensively studied, and it was found that silica is removal could be by co-precipitation with metal hydroxides, specifically iron, manganese, and magnesium hydroxides, or could be by precipitation as magnesium and calcium silicate (Sheikholesami & Bright, 2002). Furthermore caustic softening using only sodium hydroxide was found to be more effective and more viable in removal of silica over lime-soda softening using lime and soda ash (Al-Rehaili, 2003; Sheikholesami & Bright, 2003). Addition of sodium aluminate and aluminum sulfate was found to enhance the removal of silica during the softening process by co-precipitation with aluminum hydroxide (Cheng et al., 2009; Lindsay & Ryznar, 1939). Conventional softening process is slow, requires extensive space, and generates large volume of sludge which will need dewatering and further treatment later on (Kadem & Zalmon, 1997). As a result a more advanced process designated Compact Accelerated Precipitation Softening CAPS was developed to enhance the performance of the precipitation softening process. In CAPS process the saturated solution is passed through cake of calcium carbonate to enhance crystallization and approach equilibrium rapidly, the process has been found to overcome the different disadvantages encountered in conventional softening process (Gilron et al., 2005; Masarawa et al., 1997; Oren et al., 2001).

Although different precipitation softening processes have been applied basically for surface water treatment and as a pretreatment for membrane processes, specifically NF and RO (Al-

Rehaili, 2003; Cheng et al, 2009; Gilron et al., 2005; Kadem & Zalmon, 1997; Masarawa et al., 1997; Oren et al., 2001; Sheikholeslami & Bright, 2002) showing high efficiency in removal of calcium, magnesium, silica, and heavy metals. However such softening processes were found to be very effective and promising when applied for brine treatment where high calcium, magnesium, and silica removals from brine streams has been achived enabling higher recovery in the subsequent membrane desalination, facilitate reaching zero liquid discharge desalination [Comstock et al., 2011; Gabelich et al., 2007; Ning et al., 2006; Ning & Tryoer, 2009; Rahardianto et al., 2007].

Sulfate usually present in the brine streams in high concentrations, relative to those of calcium, magnesium, carbonate, and silica. However in presence of calcium, saturation and hence scaling due to calcium sulfate is very likely to happen (Rahardianato et al., 2008; Sheikholesami, 2003a; Sheikholesami, 2004). Precipitative softening processes were found to be very effective in removal of calcium, magnesium, carbonate, and silica. However such process had no success for removal of sulfate, even though removal of calcium from brine stream reduces the scaling potential of calcium sulfate. However it will be paramount to remove sulfate completely or partially, converting the brine chemistry typically to monovalent ions i.e. sodium, potassium, and chloride which has no scaling potential at the normal membrane desalination operating conditions.

Several works has been performed on removal of sulfate from industrial wastewater streams such as paper mills, mining, and fertilizers, and several attempts have been performed to reach zero discharge with such streams using membrane and thermal separation processes (Ericsson & Hallmans, 1996). However many attempts has been worked to employ precipitation and crystallization removal of sulfate as calcium sulfate, gypsum, by addition of calcium mainly as calcium hydroxide, lime (Tait et al., 2009), or as calcium chloride (Benatti et al., 2009), which was found to be very effective in removal of sulfate. Removal of sulfate as calcium sulfate below 1300 mg/L was found to be very hard due to solubility limits. However addition of aluminum as aluminum sulfate or alum, aluminum chloride, aluminum nitrate (Christoe, 1976), and sodium aluminate (Batchelor et al, 1985) was found to enhance the removal of sulfate far below this value by formation of more complex solids (Batchelor et al, 1985; Christoe, 1976) which has much lower solubility compared to that of calcium sulfate precipitated by lime addition only.

7.3 Secondary brine concentration and final salt production

The treated brine after being further concentrated in secondary membrane desalination has to be further concentrated reaching zero liquid. Zero liquid and dry salts cannot be produced by membrane desalination such as RO or NF, and hence the concentrated brine has to be subjected to thermal process such as brine concentration followed by crystallization or drying to produce dry salts.

Thermal processes such as single and multi stage evaporators, or vapor compression evaporators are usually employed for further brine concentration. Such units have dual purpose objectives which are further recovery of water with very high quality with salinity about 10 mg/L, and brine concentration up to 250,000 mg/L, with recovery above 90%. Final salt production can be achieved after brine concentration which usually performed in crystallizers or dryers (Mickley, 2006).

In addition to the salts produced from final crystallizer/dryer that can be assumed as byproducts from ZLD desalination, the precipitated solids from brine chemical treatment can be considered as another byproduct or added value product. This precipitate is rich in calcium as calcium carbonate, magnesium as magnesium hydroxide, and silicate of calcium and magnesium, in addition to gypsum or calcium sulfoaluminate in case of sulfate removal, such mixture can find a wide range of applications such as road pavement, cement industry, and any other applications where there is a need for mixture of similar composition.

7.4 Cost associated with zero liquid discharge systems

Reaching inland desalination with zero liquid discharge has to be considered on both scales, technically and economically, while technical ZLD system can be successfully achieved through the different ZLD schemes. However the costs associated with each proposed ZLD system should be carefully considered. It easily noticeable that employing a secondary membrane desalination step is of high importance for reduction of both capital and operating costs over the conventional thermal ZLD systems due to the reduced volume of brine stream to be thermally treated.

A cost comparison for standard bench mark brine treatment by brine concentration and evaporation to advanced brine treatment using secondary RO desalination and final brine concentration and drying for brine of different qualities has been performed. The study showed that a cost reduction ranging from 48-67%, with reduction in energy requirement of 58 - 72% using the advanced ZLD system (Bond & Veerapaneni, 2008) can be achieved. However it worth to mention that the comparison was for the brine management only, not the whole inland desalination system, as the primary RO desalination is a kind of standard step employed for all ZLD schemes.

Inland desalination with zero liquid discharge usually has higher product water cost when compared to conventional inland desalination systems with no brine disposal is employed, but becomes very economically attractive when compared to the different brine disposal methods. The high cost mainly due to the fact that several units such as chemical treatment, secondary membrane desalination, brine concentration, and crystallization/drying are employed to recover only 15-30%. Which increase both capital and operating cost increasing the average product cost compared to single step desalination unit recovering 70-85 % (Greenlee et al., 2009). However due to the different strict regulation on brine disposal using the conventional methods, and the efforts for preserving the groundwater resources, more driving force for advancement of ZLD systems are encouraged (Mickley, 2006).

7.5 Developments and research needs for zero liquid discharge desalination

Desalination with zero liquid discharge is the ultimate achievement for any inland desalination process. This will help to overcome the brine disposal limitations currently faced for applying inland desalination. Although different zero liquid discharge schemes are currently developed or under development, however further development are needed to resolve its various technical, operational, and economical issues. The essential key for successful ZLD inland desalination are brine treatment, process development, energy requirements, and process economics, which should be given more attention and further research and development efforts.

Precipitative softening processes have been widely used for treatment of primary brine stream, however softening process improvements through chemical doses optimization, testing different chemical reagents aiming at high efficiency in removal of scale forming constitutes should help improving the overall process performance. Furthermore other chemical treatment processes should be investigated which can result in better performance.

ZLD system usually employs different units with different nature, such as membrane and thermal process, liquid and solids handling. Process development should look at the different viable and optimum units arrangement and operation conditions with the objective reducing energy requirements and cost.

Thermal processes are usually employed in ZLD systems for further brine concentration up to level that can be handled by crystallizer or dryer. Such processes are known to be energy extensive, and hence reduction in energy requirements and utilization of renewable energy should help in reducing overall energy requirements.

Economics of ZLD process is very important factor in employing the ZLD for inland desalination. Reaching competitive overall cost for inland desalination with ZLD to that of conventional desalination should help in wider application of the process for inland desalination systems.

8. Conclusions

In conclusion, as groundwater presents the main source of potable water to communities that do not have access to surface water, the deterioration of groundwater quality, specifically salinity is of high concern, which leads to the use of desalination techniques to overcome such problem. The use of membrane desalination systems in general and reverse osmosis in particular is very beneficial due to capacity flexibility, lower energy requirements, and in turn lower cost for brackish groundwater desalination. However the generation of brine stream is the main problem facing such systems, and which should be managed properly, there are different ways for brine disposal. However each one has certain advantages and disadvantages that are a matter of question. Approaching inland desalination with zero liquid discharge presents the solution for having a perfect inland desalination system. Given such need it is imperative to find a zero liquid discharge treatment technologies that provide more affordable concentrate management at reasonable cost, and hence a very active area of research is going on to provide such solution.

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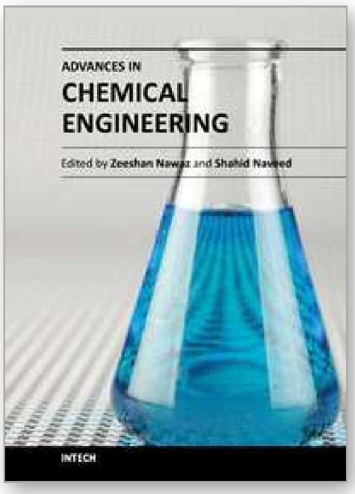

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Chemical engineering applications have been a source of challenging optimization problems in terms of economics and technology. The goal of this book is to enable the reader to get instant information on fundamentals and advancements in chemical engineering. This book addresses ongoing evolutions of chemical engineering and provides overview to the sate of the art advancements. Molecular perspective is increasingly important in the refinement of kinetic and thermodynamic molding. As a result, much of the material was revised on industrial problems and their sophisticated solutions from known scientists around the world. These issues were divided in to two sections, fundamental advances and catalysis and reaction engineering. A distinct feature of this text continues to be the emphasis on molecular chemistry, reaction engineering and modeling to achieve rational and robust industrial design. Our perspective is that this background must be made available to undergraduate, graduate and professionals in an integrated manner.

How to reference

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