

Abstract

This review paper on environmental concerns of desalination plants suggest that planning and monitoring stages are critical aspects of successful management and operation of plants. The site for the desalination plants should be selected carefully and should be away from residential areas particularly for forward planning for possible future expansions. The concerning issues identified are noise pollution, visual pollution, reduction in recreational fishing and swimming areas, emission of materials into the atmosphere, the brine discharge and types of disposal methods used are the main cause of pollution. The reverse osmosis (RO) method is the preferred option in modern times especially when fossil fuels are becoming expensive. The RO has other positives such as better efficiency (30-50%) when compared with distillation type plants (10-30%). However, the RO membranes are susceptible to fouling and scaling and as such they need to be cleaned with chemicals regularly that may be toxic to receiving waters. The input and output water in desalination plants have to be pre and post treated respectively. This involves treating for pH, coagulants, Cl, Cu, organics, CO₂, H₂S and hypoxia. The by product of the plant is mainly brine with concentration at times twice that of seawater. This discharge also includes traces of various chemicals used in cleaning including any anticorrosion products used in the plant and has to be treated to acceptable levels of each chemical before discharge but acceptable levels vary depending on receiving waters and state regulations. The discharge of the brine is usually done by a long pipe far into the sea or at the coastline. Either way the high density of the discharge reaches the bottom layers of receiving waters and thus may affect marine life particularly at the bottom layers or boundaries. The longer term effects of such discharge concentrate has not been documented but it is possible that small traces of toxic substances used in the cleaning of RO membranes may be harmful to marine life and ecosystem. The plants require saline water and thus the construction of input and discharge output piping is vital. The piping are often lengthy and underground as it is in Tugun (QLD, Australia), passing below the ground. Leakage of the concentrate via cracks in rocks to aquifers is a concern and therefore appropriate monitoring quality is needed. Leakage monitoring devices ought to be attached to such piping during installation. The initial environment impact assessment should identify key parameters for monitoring during discharge processes and should recommend ongoing monitoring with devices attached to structures installed during construction of plants.

Keywords:

Desalination plants, reverse osmosis, plant efficiency, environmental concerns

Environmental concerns of desalinating seawater using reverse osmosis

Gurudeo Anand Tularam¹ and Mahbub Ilahee²

¹Lecturer in Mathematics and Statistics, Griffith School of Environmental, Griffith University,
Australia

²Research Assistant, Faculty of Environmental Sciences (AES), Griffith University, Australia

1. Introduction

Almost all of the potable water required in the world today is supplied by surface water and groundwater resources (Semiati, 2000). Higher demands for potable water has led to excessive use and thus lowered the levels of surface water and ground water availability (Buros, 1999; Schiffler, 2004). Increasing population particularly in coastal regions in different countries around the world has lowered ground water table due to excessive pumping of ground water causing saline intrusion in countries such as Vietnam, Bangladesh, India and Florida state (US) (Bennett, Bredehoeft & Motz, 2002; El-Dessouky and Ettouney, 2002; Post, 2004; Tularam et al., 2006). Erratic weather patterns are linked to global climatic changes seems to have affected rainfall volume and pattern causing drought conditions in some parts of the world such as Australia. The extreme shortage of potable water has made countries rethink their potable water supply policies; for example, US and Australia are both considering alternatives of potable water supply (Winter et al., 2001, Pannell, 2001 and Nuclear desalination, 2006). A method exploited in many arid countries is desalination of seawater. Seawater is freely available and exists close to coastal lands where around 39% of the world's population reside, hence desalination of sea water can be an attractive and logical option for alternative potable water supply (El-Dessouky and Ettouney, 2002; Meerganz von Medeazza, 2004; Schiffler, 2004).

Many countries in the Middle East, North Africa and Central Asia rely almost entirely on desalination for their potable water needs (El-Dessouky and Ettouney, 2002; Gleick, 1998; Schiffler, 2004). Indeed, it is proven technology and helped alleviate freshwater scarcity in the Middle East for more than 20 years (Fririn and Al-Madhari, 1997; Semiati, 2000). Despite the high energy demands, capital costs and environmental concerns, desalination appears to be a saviour for low rainfall occurring countries such as Australia. Although the negative impacts has been reported at existing plants, equally positive aspects exist in that desalination aids and maintains industry, agricultural production, and helps preserve existing natural water resources. The pumping of seawater causes not only coning but also lowers close by seawater levels thus helping restrict saline intrusion into coastal aquifers (Schiffler, 2004). However, environmental concerns such as emission of pollutants into the atmosphere, noise, and pollution caused by discharge of concentrates are important considerations and should be investigated before desalination option is undertaken (Burashid and Hussain, 2004).

2. Australian context

In the past, Middle Eastern gulf countries rich in fossil fuels preferred to build distillation type evaporative methods for desalination but development of better technology has shifted the preference towards the relatively cleaner and cheaper option of RO. The RO process has been used in the past mostly in inland plants treating brackish water that has much lower total dissolved solids (1,000-10,000 ppm) than seawater (33000-35000 ppm). An RO plant has recently been built in Western Australia (WA) with a capacity of 130,000m³/d (130ML/d). A comparable USA plant is in Tampa (Florida) producing 1,000,00m³/d and a similar capacity Askleon plant is in Israel producing 120,000m³/d. Australia has a smaller plant in Bayswater, New South Wales with capacity of 35000m³/d. Presently, a new RO plant (1,250,000m³/d or 1250ML/d) is being built in Tugun (Queensland), Australia.

A serious water crisis exists in Queensland with the state experiencing the lowest dam levels sufficient to supply the region possibly for another two years only. Extreme level 4 restrictions are presently in place to conserve water and help lower the 750 ML/d current demand. Conservation is an important strategy but there are longer timer issue facing Queensland; it is prone to long drought conditions and its population is rapidly increasing. All states in Australia are facing similar problems in that WA's population is predicted to double in 2020. Mostly the surface and groundwater resources supply the potable water in WA, now the groundwater is not appropriate for potable use. Given that groundwater may be taken as a finite source, it is vitally important that Australian states develop sustainable potable water supply programs (A state of Water Strategy for WA, 2003). The clear inability of cope with the present shortages has led both Queensland and WA to build large desalination plants even though they have opposed by environmental groups. The environmentalists argue that desalination is relatively expensive, pollutes the environment and long term impacts of the pollutants are yet unknown.

This paper reviews the RO process of desalination focusing on the environmental concerns and issues. The research completed on the existing plants are analysed and studied in terms of possible impacts on the environment. Possible consequences of pollutants in marine discharges and coastal groundwater pollution are examined in light of the Tugun 125 ML/d RO plant being built in coastal Queensland, Australia.

3. Desalination processes

Desalination is the process of removing dissolved salts from seawater, brackishwater, riverwater, or other water effluent. The process requires vast amount of energy and was considered less viable in 1970's when the energy consumption requirements were over 20kWh/m³ (20kWh to desalinate one cubic meter of water). The energy demands are much less today. Most plants require around 3-20 kWh/m³; when the minimum theoretical energy is required to convert seawater to potable water is 0.7 kWh/m³ (Schiffler, 2004). As mentioned earlier, the most widely applied technologies fall into two categories:

- Distillation based thermal (eg. Mutli-Stage Flash (MSF) / Multi-effect Distillation (MED), Mechanical Vapour Compression (MVC) and
- Membrane based methods (eg. Reverse Osmosis (RO), Electrodialysis and Nanofiltration).

The MSF thermal method involves water evaporation that leaves behind the salt as concentrated brine. This method is mostly employed where fossil fuels are cheaply or readily available such as in the Middle East but evaporative methods are being replaced steadily by membrane methods (Schiffler, 2004). The MED is a thermal method that takes place in a series of vessels or “effects” and reduces the ambient pressure in subsequent effects. The MSF, MED and MVC are thermal processes that produce distilled water. Typically this distillate is very pure with a TDS of 1 - 50 PPM.

The RO method involves the use of high pressure pumps in the order of 800psi - 1200 psi (5.51MPa – 8.27MPa) forcing the feed water, salts are rejected from the membrane, and hence the separation is accomplished. The membrane removes such impurities providing very low TDS potable water. Other commonly used membrane methods are Electrodialysis and Nanofiltration.

Electrodialysis is a method for desalination of sea water using a main electrochemical generator that has an anode compartment through which seawater is fed causing the formation in the solution of chlorates and per-chlorates; the removal of the latter being effected by a potassium salt such as potassium bicarbonate. This is an electro-membrane process in which the ions are transported through a membrane from one solution to another under the influence of an electrical potential. Electrodialysis technique (ED) can be utilised to perform several general types of separations such as separation and concentration of salts, acids and bases from aqueous solutions or the separation and concentration of monovalent ions from multiple charged components or the separation of ionic compounds from uncharged molecules.

Nanofiltration (NF) allows diffusion of organic compounds, and rejects some salts with low pressures being applied and is a process normally used for mildly salt tasting water, or as a water softening technique. The NF is a form of filtration that uses membranes to separate different fluids or ions. NF is typically referred to as "loose" RO due to its larger membrane pore structure when compared to the membranes used in RO, and allows more salt passage through the membrane.

Membranes used for NF are of cellulosic acetate and aromatic polyamide type having characteristics as salt rejections from 95% for divalent salts to 40% for monovalent salts and an approximate 300 molecular weight cut-off (MWCO) for organics (Srikanth, 1999).

In this paper, of most concern is the reverse osmosis method for desalination of seawater as it removes chloride salts, pathogens and other contaminants and provides better recovery rates but it is often compared with MSF.

Mutlistage flash (MSF) and Reverse osmosis (RO)

There are approximately 7,500 desalination plants in operation throughout the world and most of these (about 60%) are located in the Middle East (California coastal commission, 2003). About 12% of the world’s capacity is in America while the remaining plants are in Spain, India and a few other countries. In the Red Sea/ Gulf Region, there are 280 thermal desalination plants and about 112 RO plants with production capacity ranges from 425,000 to 6,800,000m³ freshwater per day. The Middle East is nevertheless still the largest user of RO desalination plants with capacities over 100,000 m³/d (300 ML/d). Increasing use is

noted in Europe, West Indies, Spain, North America and now Australia with plants of over 100,000 m³/d (100ML/d) capacity.

The thermal desalination (MSF) is high energy driven process supplied usually by auxiliary boilers that are turn responsible for discharging pollutants such as CO₂, NO_x, SO_x. MSF plants also discharges concentrated brine. The higher temperatures involved in distillation type techniques are responsible for the hotter discharge concentrates.

The Reverse osmosis (RO) plants do not require as high energy demands but can be noisy due to the use of high pressure pumps. These plants are also responsible for the discharge of concentrated brine together with sludge. While both plants discharge chemical agents needed for in the pre/post treatment of seawater and discharge respectively, the RO plants require careful attention due to membrane fouling. A number of chemicals are used to remove fouling in RO but their use is limited in quantity and can be treated before discharge. The RO plants have higher recovery rates of around 30-50% when compared to MSF, which is around 10-30%.

The nature of effluent discharged in the environment by desalination processes depend on the type of process involved. In this paper, the focus is on the RO plants and in particular the environmental impacts of the processes applied. However, aspects of MSF will be also discussed in the comparative analysis presented in the following. The RO method is particularly important to the Australian context since two large RO based plants will be fully operational by 2008.

4. RO treatment

Osmosis involves diffusion of solvent such as water through a semi-permeable membrane caused by a difference in chemical concentrations of solutions either side of the membrane. For example, salty water on one side has a greater chemical concentration than the fresh water on the other. The solutions equilibrate by allowing the solvent water molecules to pass through from the dilute side to the concentrated side. The diffusion of water continues until the solutions essentially equilibrate in concentration (allowing for resistance of the membrane) or when the salty water head starts exerting an opposite hydrostatic pressure large enough to limit further diffusion of water totally. A greater pressure than the sum of the osmotic pressure difference and the pressure loss of diffusion through the membrane can be applied to reverse the process and this is known as RO.

In the desalination plants, inlet seawater is treated and then pressurized (Figure 1). The water from a pressurized saline solution is separated from the dissolved salts by forcing its flow through a water-semi permeable membrane. The liquid that passes through the membrane is referred to as permeate. The flow is caused by the pressure differential created between the feedwater and the permeate water (Figure 1). Once water is separated, the remaining feedwater comes through as concentrate brine. Often a second or third stage treatment is included to capture lost water in this process. There is little heating or phase change is such a process and the major energy requirement is for the initial pressurization of the feedwater. For brackish water (1,000-10,000 mg/L of minerals) the RO operating pressures range from 250-400 psi (1.72 MPa – 2.75 MPa) while for seawater (10,000-37,000 ppm) desalination pressures required range from 800-1200 psi. (5.51MPa – 8.27MPa)

Figure 1 shows the feedwater being pumped into a closed container against the membrane to pressurize it. As the product water passes through the membrane, the remaining feedwater and brine solution becomes more concentrated. To reduce the concentration a portion of this concentrated feedwater-brine solution is withdrawn from the pressure vessel. For without this discharge, the concentration in the feedwater would continue to increase, requiring increasing energy inputs to overcome the naturally increased osmotic pressure.

In the main, the reverse osmosis system consists of four major components/processes (see Figure 1): pre-treatment, pressurization, membrane separation; and post-treatment.

Pretreatment: The feedwater is treated to be compatible before it goes to the membranes by removing suspended solids, adjusting the pH, and adding a threshold inhibitor to control scaling caused by constituents such as calcium sulphate.

Pressurization: The pump raises the pressure of the feedwater to an operating pressure, which is suitable for the membrane and the salinity of the feedwater.

Separation: The permeable membranes inhibit the passage of dissolved salts while permitting the desalinated product water to pass through. Since no membrane is perfect in its rejection of dissolved salts, a small percentage of salt passes through the membrane and remains in the product water (acceptable drinking water levels require less than 500 TDS). The smaller molecules such as CO₂ and H₂S may also pass through the membrane along with the product water. The RO membranes are available in a variety of configurations some spirally bound. The specific membrane and the nature and construction of the pressure vessel vary according to the different operating pressures used for the different types of feedwater (brackish or seawater).

Post- treatment stabilization: The product water from the membrane assembly usually requires pH adjustment and degasification before being transferred to the distribution system. In an aeration column, the pH of the product water is elevated from a value of approximately 5 to a value close to 7. In many cases, this water is discharged to storage for later use.

To determine efficiency, flow regime, solute concentrations and investigation of what if scenarios in RO process mathematical models may be developed. A simple model presented elucidates the underlying processes. After the treatment process, the feedwater is pumped at a particular pressure (Δp) through a channel with permeable membrane on one side and impermeable boundary on the other. A natural osmotic pressure exists due to the presence of the two sides of the membrane; and is dependent on the difference in chemical concentrations present. The osmotic pressure labelled $\Delta\pi$ is dependent on temperature, pressure and membrane's ability to reject salts. The pressure difference allows the "permeate" or water to flow through the membrane toward a region of lower pressure. There is some resistance to this flow due to the membrane itself and depending on its properties the ability of a particular liquid to flow through is labelled A . In this manner a flow equation through the channel may be written as:

$$J_w = A(\Delta p - \sigma\Delta\pi) \quad 1$$

where J_w is the flux of solvent through the membrane, A is the water permeability (this equation contains a negative sign, which is already included in water permeability A) and

σ the reflection coefficient, which is approximately one in the case of high rejection membranes (Gauwbergen and Baeyens, 2002). The solute flux (J_s) through the membrane is governed by the concentration difference between the membrane wall (C_M) from the feedwater and permeated product water that has passed through the membrane (C_P).

The solute flow can be written as

$$J_s = B(C_{s,M} - C_{s,P}) \quad 2$$

The above two equations describes the major processes of solvent flow and solute transport often referred to as the solution-diffusion model. The parameters A and B are the water and solute permeabilities respectively (Wijmans and Baker, 1995). Further manipulations of these models can lead to the efficiency or recovery rate of RO by comparing the amount of solute passes or diffuses through the membrane with the concentration of solute remaining in the feedwater. In this manner, the permeate flow velocity in the channel can also be determined. The above models may be used to predict brine and chemical discharge concentrations in plants and appropriate measures may be undertaken for better management. It is clear that stringent planning and monitoring is needed when considering the costly desalination option and mathematical models may be useful in determining critical loads and in the conduction of risk analysis. .

5. Planning and monitoring of plants

Some studies in the literature have attributed difficulties to inappropriate planning (Burashid and Hussain, 2004). Before the construction begins an appropriate feasibility study ought to be conducted to choose a suitable site (Hoepner, 1999). If the site chosen is close to residential areas, the visual and noise pollution may be a problem. Reports suggest that suggest that noise levels can be high due to the use of variable pressure pumps. The site chosen should then be away from residential regions whenever possible. Moreover, most desalination plant sites are constructed close to coastal areas and therefore would diminish any visual and architectural beauty related to the area. Recreational activities such as fishing and boating are further restricted around the inlet/outlet areas.

Devising a monitoring plan for plants appear critical but it is often considered after the actual completion of plant (Burashid and Hussain, 2004). A number of monitoring devices often have to be installed in subsurface piping or attached structurally to inlet and outlet structures underground and such installations are only possible during construction of the desalination plants. Planners need to think about developing an environmental monitoring program much earlier in the process. In the main, the monitoring should address critical parameters or issues identified in the environmental impact study (EIS) such as temperature, density, hypoxia, chlorine and copper levels for example. The monitoring should include the measurement of the important parameters making certain they meet established guidelines. Essentially, environmental management plans are necessary during the plant's operation to ensure the plant is operating within set environmental standards (Everest and Murphree, 1995). Inadequate planning and or monitoring can lead to a number of problems that are difficult to solve later such as re-drilling to install sensors and other monitoring equipment.

Desalination plants require water intake structures and pipelines that can carry feedwater and discharge concentrate to and from sea respectively. The Tugun plant piping is proposed to be built 50m below ground level and material may leak through to the aquifer. As such, the coastal groundwater aquifers may be contaminated through leakage in the long inlet/outlet pipes. The outlet pipes contain discharge sludge that is usually highly concentrated brine but may also contain low concentrations of chemicals sometimes at elevated temperatures. Therefore, careful monitoring of the piping as well as flow processes is needed. Appropriate monitoring devices may be attached to fixed structures to ensure failsafe subsurface flow processes and thus should be considered before construction is completed.

Another aspect of the pollution is the disposal of brine to seawaters such as the ocean. If such discharge products are released into surface seawater, the properties of the concentrated discharge products including chemicals that are not treated may cause problems for the marine habitats and receiving water environments. This is mainly due to the higher density of concentrate discharge compared to seawater that generally sinks to the bottom layers.

Desalination projects require an environmental impact assessment (EIA) study and the EIA should identify all critical environmental parameters and evaluate potential impacts to air, land, and marine environments. There are five aspects to the impact of desalination plants on the environment.

- Adverse effect on land use: Seashores serve as the sites for industrial plants and for pumping stations rather than for recreation and tourism.
- Impact on the aquifer: Leakage from the pipes may result in penetration of salt water and therefore presents a danger to the aquifer.
- Impact on the marine environment: As a result of returning the concentrated brine to the sea.
- Impact of noise: Desalination plants require high pressure pumps and turbines, which produces noise.
- Intensive use of energy: An indirect impact on the environment due to increase production of electricity.

The duty of environmental impact services (EIS) is to propose mitigation measures to reduce environmental impacts to safe levels but also discuss benefits the facility may offer to the community. A well designed mitigation measures will reduce possible problems associated with the facility in the future (Bene et al., 1994).

6. By-products of desalination plants

As noted earlier, desalination plants generate two products; clean water and concentrate brine (that is, the reject or residual stream). It is important to realize that cost-effectiveness and concentrate brine discharge are obstacles in the widespread use of desalination. Clearly, appropriate brine disposal methods incorporated in the plant's design can reduce the concentrate's impact on the receiving waters and coastal groundwater aquifers.

6.1 Brine characteristics

The main by product of desalination plants is brine referred to as the concentrate. This concentrate is made up of liquid substances containing up to 20% of the treated water. TDS (total dissolved solids), temperature, and specific weight (density) are the key parameters of the concentrate. The TDS of brine concentrate is usually greater than 36,000 mg/L (sometimes greater than 40,000 mg/L in many states in the Middle East). At 50% recovery 70,000 mg/l TDS are produced. The concentrate may also contain some chemicals that are used in pre/post-treatment usually in cleaning processes. Characteristics of the generated concentrate depend on the type of desalination technology used. Table 1 shows characteristics of concentrates from various desalination plant types (Meerganz von Medeazza, 2005; Mickley, 2001).

The amount of concentrate produced from a desalination plant is a factor of the desalination recovery rate (that is, product water/feedwater). Usually the RO membrane based plants have a higher recovery rate than distillation plants resulting in higher salt concentration amounts in the concentrate. Table 1 shows that the concentrate produced from seawater reverse osmosis (SWRO) plants have up to two times more salt concentration than the receiving water, while the concentrate produced from a distillation process may only have 10 percent higher. In distillation processes, the system mixes the concentrate with (once-through) cooling water to dilute the salt concentration. Table 1 also shows that the concentrate from distillation processes tend to be typically warmer, 10-15°F above the ambient water temperature. Concentrate temperature from the reverse osmosis process often remains at the ambient water temperature. (Meerganz von Medeazza., 2005)

As noted earlier, specific weight (or density) is a critical concentrate parameter and compared to freshwater, the concentrate has a higher density. When disposed into waters of lower salinity (lower density) the concentrate usually sinks to the bottom layers (Einav et al., 2002). In contrast, typical discharge from wastewater treatment plants will float as the discharge density is normally less than the receiving water. The tendency of the concentrate to sink when interacting with the receiving water introduces problems for the marine environment in that the discharge may be hypoxic or contain traces of damaging chemicals. In some cases, desalination plants dilute the concentrate to reduce density before release. Blending is a process that mixes the concentrate with cooling water, feedwater, or other low TDS waters before disposal

6.2. Pre/post treatment

Pre-treatment can include chlorination, clarification, coagulation, acidification, and degasification. Pre-treatment is applied to feedwater to minimize algae growth, scaling, and corrosion of the plant generally. The chemical agents used in the process are important and should be monitored since some remain in the concentrate before disposal. Typical pre-treatment chemicals used in desalination plants are:

- NaOCl or free chlorine - prevents biological growth;
- FeCl₃ or AlCl₃ - flocculation and removal of suspended matter from water;
- H₂SO₄ or HCl - pH adjustment;
- NaHSO₃ – neutralizes chlorine remains in feedwater; and
- Various scale inhibitors – prevents scale formation on the pipes and membranes.

If an RO membrane becomes fouled or scaling occurs, the materials have to be removed and this is done via chemical cleaning with the use of various detergents. The type of chemicals used for cleaning depends on the type of membrane and for RO systems, chemical cleaning agents fall into the following categories (American Water Works Association 1999):

- Enzymes to break down bacterial slimes;
- Detergents and surfactants to resuspend particulate material and dissolve organic material;
- Biocides to kill bacteria;
- Chelators to remove scale;
- Acids to dissolve in-organics.
- Caustics to dissolve organic substances and silica.

The major pollutant of distillation processes is chlorine, which is added to prevent bio-fouling on heat exchanger surfaces. The two major pollutants in RO processes are Chlorine and Copper.

Chlorine

In RO plants, chlorine is also a common biocide. Most modern plants operate on polyamide membranes, which are sensitive to oxidizing chemicals such as chlorine. Treatment is typically required before the feedwater enters the RO unit. Chlorine is a strong oxidant and highly effective biocide and residual levels in the discharge may be toxic to marine life close to the discharge site. Following discharge, self-degradation and dilution lowers the environmental chlorine levels to lower concentrations but even such low concentrations are adverse to aquatic life (California coastal commission, 2003). Chlorine reacts with organic compounds in seawater forming a large number of chlorinated and halogenated organic by-products. Studies show that many of these compounds are carcinogenic or otherwise harmful to aquatic life (California coastal commission, 2003).

Chlorine is classified as a pollutant in the US and concentration limits are recommended by the Environmental Protection Agency (EPA) to avoid toxic conditions. For example, in saltwater, 0.013 ppm is allowed for the short term while 0.0075 ppm is considered safe for the longer term (Hoepner, T. and Lattemann, S., 2002). These restrictions can be met, for example, by limiting discharge concentrations to the same level. In some US states more stringent criteria have been established (California) such as zero tolerance; that is, the residual levels have to be totally treated (Hoepner and Lattemann, 2002).

Due to environmental and health problems caused by residual chlorine and disinfection by-products, several alternative pre-treatment methods have been considered to replace chlorine in desalination plants. Ozone and monochloramine are some alternatives while ultraviolet light may be used instead of biocides to eliminate micro-organisms.

Copper

In most RO processes, non-metal equipment and stainless steels items are used. The discharge levels in RO usually refer to the brine not the total effluent, which is about one third brine and two thirds cooling water discharged. It is likely that the cooling water is contaminated but it is not included in copper load calculation generally. The copper load is based on brine contamination only thus resulting in a conservative estimate of copper. In contrast to chlorine loads, where the product/effluent ratio (1:9) is used since both the

cooling water and desalination feed water are chlorinated, in the case of copper product/brine ratio of 1:2 is assumed. As before, a standard ratio between product capacity and chemical load is formed. Based on 30 g/d copper output per 1,000m³/d, the daily discharge amounts to 36 kg in the area studied (Hoepner and Lattemann, 2002).

It is well known that copper is not the only corrosion product released in that nickel, chromium, molybdenum and iron are also important to consider. It should be noted that the mere presence of copper does not imply an adverse affect on the environment since copper is an essential micronutrient for many organisms but copper becomes toxic whenever excess amounts of it become biologically available. A low brine of approximately 15 ppb appears to reduce the risk of toxic conditions for aquatic life with dispersion further decreasing the dissolved copper levels (Shi et al., 2006).

Clearly, pre and post treatments are required in RO processes, and in particular, the post treatment is needed to treat excess carbon dioxide and oxygenate to compensate the lack of oxygen in the discharge concentrate (Shi et al., 2006). The degasification of CO₂ is also an issue since CO₂ aids global warming. The foul smell is at times noted in product water and this is due to hydrogen sulphide which removed through aeration (Mickley, 2001). Oxygen is added to treat hypoxic conditions. Table 2 outlines the processes involved in pre-treatment and post-treatment of desalination plants.

In USA the National Pollutant Discharge Elimination System (NPDES) program regulates concentrate discharge to surface waters. The NPDES requires Whole Effluent Toxicity (WET) testing of concentrate to determine potential impacts on aquatic species. When tested, several utilities in Florida that use membrane technologies failed WET tests for unknown reasons. Research to determine causes of failure by examining concentrate characteristics from nine utilities in Florida (Mickley, 2001) showed the presence of excessive ions. Calcium and fluoride levels in concentrate were the major contributors (Mickley, 2001). In coastal areas, due to the dynamic nature of fresh water and saltwater interaction, the composition of brackish groundwater is not uniform or chemically balanced; while in these waters, calcium carbonate and calcium sulphate were dominant over sodium chloride.

Pre-treatment prior to disposal consists of aeration, i.e., adding oxygen to the concentrate, and degasification to remove hydrogen sulphide from the concentrate (Hoepner and Lattemann, 2002). Using non-toxic additives and dechlorination techniques limits the toxic chemical concentrations that enter the environment. The need for these techniques is site-specific depending on the maximum concentrations of the additives and chlorine allowed in the discharge.

Antiscalants

Antiscalants are products used to prevent fouling of membranes and need to be present in both MSF and RO plants (Hoepner and Lattemann, 2002). In the main, the outputs involve organics, carboxylic rich polymers such as polyacrylic acid and polymeric acid. It is usually assumed that about 2ppm enters the receiving waters. The load from an RO is typically 6kg/d per 1,000m³/d, a total of around 2257 kg/d (Hoepner and Lattemann, 2002). While a daily loads up to 9.4 tonnes of antiscalants by RO plants appears high the environmental risk of these substances is low when compared to chlorine and copper. Generally, the antiscalants are of low toxicity and their environmental fate involves significant dilution thus reducing possible ill effects. However, poor degradability is a major drawback in that

polymaleic acid biodegrades slowly while polyacrylic acid is three times faster. Nonetheless, the antiscalants may limit availability of important trace metal ions in receiving waters.

6.3 By product management options-brine disposal

At present, approximately 48% of desalination facilities in the U.S. and most others including many of the Middle East states dispose their concentrates to surface waters (Hoepner and Lattemann 2002). Other concentrate disposal options include deep well injection, land application, evaporation ponds, brine concentrators, and zero liquid discharge (ZLD) technologies ((Einav et al., 2002). Only surface water type, deep injection and waste water treatment disposal methods are analysed here and considered important in the Australian context. In order to choose a method among those mentioned, a number of factors need consideration including volume or quantity of concentrate, quality of concentrate, location of desalination plant, and environmental regulations. Other factors that could be critical are public acceptance, total costs of operation, and future plant expansion.

Surface Water Disposal

The surface disposal methods include the surface water disposal and submerged disposal (California coastal commission, 2003). The most common way to dispose the desalination plant concentrates is to dump them into the surface waters such as freshwater lakes or ponds, tidal streams and rivers, oceans, bays and estuaries. Clearly, the concentrate would somewhat pollute the disposed area often creating a plume in the waters (California coastal commission, 2003). The density of the concentrate would determine whether the plume caused by disposal sinks, floats, or stabilizes in surroundings waters. The waves, tides, bathymetry, currents, water depth determines whether dilution and general mixing occur but often the diluted plume may exist for a number of days possibly harming the ecosystem (Mickley, 2001).

Most countries have limits placed on such disposal into surface waters. For example, in USA, Florida has placed its mixing zone limitations at 2625 ft for canals, rivers, and streams; and 31 acres for lakes, estuaries, bays, lagoons, and bayous; including 124 acres for oceans (Truesdall et al., 1995). The WET test is used and if natural dilution is not appropriate for proper diffusion the special artificial ponds needs to be created for dilution. Clearly, the concentrate may be treated before discharge in that it can be diluted through blending or with the help of diffusers, within the standard mixing zones. Diffusers are jets that dilute the concentrate at the concentrate disposal outlet for maximum mixing. In case of diffusers, the factors include the difference in densities between the concentrate and the receiving waters, momentum and velocity of the water at the outlet. Small-scale desalination plants studied in Florida, which dispose directly into the sea or use a short discharge pipe, showed no environmental impact on the animal and plant life near the outlet pipes (Mickley, 2001).

Submerged Disposal

Submerged disposal is defined as the disposing of concentrate underwater, rather than disposing on the surface. Similar to surface disposals submerged disposal also occurs in tidal or estuarine environments. Disposal is done through the use of pipes far into the ocean in contrast with surface disposal that usually occurs closer to the coastline. Country regulations usually define certain zones in open oceans usually labelled the “allocated impact zones” and the water quality limits can be exceeded in such zones for non-toxic pollutants (Kimes, 1995). As noted earlier, the concentrate being of higher density usually

sinks to the bottom of the ocean and creates a quantitative boundary where the salinity limits may be exceeded regulated limits. In this case the dilution zone is understood to be the various vertical layers through which the concentrate passes through to reach to bottom (Kimes, 1995). Being at the bottom of the ocean the benthic marine organisms living at the sea bottom are clearly at risk mainly due to high salinity and low dissolved oxygen levels. Mickley (2001) noted that long abdomen invertebrates are more sensitive to high salinities than short abdomen invertebrates in the bottom ocean conditions.

Clearly a number of factors need to be considered before deciding on the discharge method. For example, if the area is highly populated, coastline disposal may be a problem, because of the interference of the mixing zone with recreation close to the beach. This is especially noticeable on days when the sea is calm when little to no natural dilution occurs. Although models have been developed for US conditions, similar models for the Queensland of shore conditions particularly for the Tugun plant should be developed for investigate possible outcomes of such disposal methods (Kimes, 1995). Computer programs will allow prediction at different dilution/dispersion rates under local conditions and moreover suggest possible environmental effects of concentrate disposal.

Disposal to Front of Wastewater Treatment Plant

The other most common option is to dispose of the concentrate into existing wastewater treatment plants (Benzaoui and Bouabdallah, 2004). The concentrate is dumped in the “front” or head works of a wastewater treatment plant or publicly owned treatment works (Mickley, 2001). There are however a number of concerns with this method such as the effect of very high salinity levels on the performance of the biological treatment especially when the concentrate volume is large; and the output of high TDS processed waste water in the plant effluent. In the end, these may lead to a reduction of plant treatment capacity as a whole but this option requires further research.

7. Summary and conclusions

The various studies and general literature reviewed suggests stringent planning and monitoring is a critical aspect for the successful management of desalination plants. The site for the desalination plants should be selected carefully and should be away from residential areas particularly for forward planning for possible future expansions. Difficulties experienced by existing plants were often attributed to inadequate planning or less detailed environmental impact studies. A feasibility study together with environmental impact assessments should be conducted by appropriate authorities in relation to the proposed desalination plant and site. The concerning issues identified from existing plants are noise pollution, visual pollution, reduction in recreational fishing and swimming areas, emission of materials into the atmosphere, and most importantly pollution caused by product discharge and types of disposal methods used. The RO method is the preferred option in modern times especially when fossil fuels are becoming expensive. The RO has other positives such as better efficiency (30-50%) when compared with distillation type plants (10-30%). However, the membranes in RO are susceptible to fouling and scaling and as such they need to be cleaned with chemicals regularly that may be toxic to receiving waters. Complex RO models exist that can predict concentrations, velocity and membrane adsorption and should be used to complement risk assessments in membrane based desalination plants. The input and output water has to desalination plants have to be pre and post treated respectively. This involves treating for pH, coagulants, Cl, Cu, organics, CO₂, H₂S and hypoxia. The by product is usually termed the concentrate containing mainly of

brine with concentration at times twice that of seawater. This discharge also includes traces of various chemicals used in cleaning including any anticorrosion products used in the plant. This discharge concentrate has to be treated to acceptable levels of each chemical before discharge but acceptable levels may vary depending on receiving waters and state regulations. The disposal is usually done on surface waters some times through surface piping while other times subsurface piping. Either way the high density of the discharge reaches the bottom layers of receiving waters and thus may affect marine life particularly at the bottom layers or boundaries. The longer term effects of such discharge concentrate has not been documented but it is possible that even small traces of toxic substances used in the cleaning of RO membranes may be harmful to marine life and ecosystem generally. The plants require saline water input and discharge output piping. Such pipes are often lengthy and underground as it is in Tugun (QLD), more often than not passing below the existing coastal aquifers. Leakage of the concentrate via cracks in rocks to aquifers is a concern and therefore appropriate monitoring of the piping and aquifer water quality is needed. Importantly, leakage monitoring devices ought to be attached to such piping during installation. The initial environment impact assessment should be critical enough to identify key parameters for monitoring during discharge processes and should recommend ongoing monitoring with devices attached to structures installed during construction of plants.

In conclusion:

- The decision of when, how and which plant to build should be based on both environmental and socio-economical concerns;
- The sustainability of the plant must be considered in light of global climatic changes, sea level rise and possible expansion due to water demands;
- Discharge concentrate products should be critically monitored but sediment disturbance at the bottom of receiving waters tend to in oceans and thus should also need to be investigated;
- Damage by chlorine and copper appear to exist around outlets and later processes such as dilution, self-decomposition of chlorine and transport of copper into sediments appear to facilitate their fate; and
- Possible changes in flow and currents caused by concentration differences of discharge concentrates that are of much higher density should also be investigated

The environmental lessons learned from longer term existing plants is useful guide and is discussed here but much is still unknown about the longer term effect of the costs, energy use, emissions and discharges from such plants.

8. References

American Water Works Association, (1999). Reverse Osmosis and Nanofiltration. AWWA, M46, 173.

Bennett, G., Bredehoeft, J. and Motz, L. H., (2002). Salt water intrusion and the minimum aquifer level in the southern water use caution area: Hydrologic Evaluation Section, Southwest Florida Water Management District, August.

- Benne, J. V., Jirka, D. G. and Largier, J., (1994). Ocean Brine Disposal, *Desalination*, 97, 365–372.
- Benzaoui, A. and Bouabdallah, A., (2004). Desalination and biological wastewater treatment process, *Desalination*, 165, 105–110.
- Buros, O. K., (1999). The ABCs of desalting, International Desalination Association, Massachusetts, USA.
- Burashid, K. and Hussain, A. R., (2004). Seawater RO plant operation and maintenance experience: Addur desalination plant operation assessment. *Desalination*, 165, 11-22.
- California coastal commission., (2003). *Seawater Desalination in California*, University of California Press.
- Einav, R., Harussi, K. and Perry, D., (2002). The footprint of the desalination processes on the environment, *desalination*, 152, 141-154.
- EL-Dessouky, H. and Ettouney, H., (2002). Teaching Desalination -A Multidiscipline Engineering Science, Department of Chemical Engineering, College of Engineering and Petroleum, Kuwait University, Safat, Kuwait.
- Everest, W. R. and T Murphree, T., (1995). Desalting residuals: A problem or a beneficial resource? *Desalination*, 102(1), 107-117.
- Fkirin, M. A. and Al-Madhari, A. F., (1997). Prediction of time-varying dynamic processes, *International Journal of Quality and Reliability Management*, 14(5), 505-511.
- Gauwbergen. D. V. and Baeyens. J., (2002). Modeling and Scaleup of Reverse Osmosis separation, *Environmental Engineering Science*, 19(1), 37- 45.
- Gleick, P. H., (1998). *The Worlds water: the biennial report of Fresh water resources 1998-1999*, Island Press, USA.
- Hoepner, T., (1999). A procedure for environmental impact assessments (EIA) for seawater desalination plants, *Desalination*, 124, 1–12.
- Hoepner, T. and Lattemann, S., (2002). Chemical impacts from seawater desalination plants – a case study of the northern Red Sea, *Desalination*, 152, 133 – 140.
- Kimes, J. K., (1995). The Regulation of Concentrate Disposal in Florida, *Desalination*, vol 102, 87-92.
- Meerganz von Medeazza, G.L., (2005). Direct and socially-induced environmental impacts of desalination, *Desalination*, 185, 57-70.
- Meerganz von Medeazza, G.L., (2004). Desalination as a sustainable alternative to inter-basin water transfers?, Paper presented at the IV Congreso Ibérico del Agua, Tortosa, Spain, 8–12.

Mickley, M. C., (2001). Major ion Toxicity in Membrane concentrates, AWWA Research foundation project # 290.

Nuclear desalination, (2006). UIC Nuclear Issues Briefing Paper # 74, October 2006.

Pannell. D. J., (2001). Dryland Salinity: Economic, Scientific, Social and policy Dimension, Australian Journal of Agricultural and Resources Economics, 45(4), 517-546.

Post, V., (2004). Groundwater salinization processes in the coastal area of the Netherlands due to transgressions during the Holocene. : Vincent Eduard Alexander Post.

Einav, R., Harussi, K. and Perry, D., (2002). The footprint of the desalination process on the environment, Desalination, 152, 141-154.

Semiati, R., (2000). Desalination: Present and future, International Water Resources Association, Water International, vol 25(1), 54-65. March.

Schiffler, M., (2004). Perspectives and challenges for desalination in the 21st century, Desalination, 165,1-9.

Shi, B., Weizhong Xiao, W. and James S. Taylor, J. S., (2006). Influences of Water Treatment Process on Iron and Copper Release in Distribution System, Journal of Environmental Science and Health, 41(8), 1667 – 1683.

Srikanth, G., (1999). Membrane Separation Processes - Technology and Business Opportunities, Chemical Engineering World, 34(5), 55-66.

Truesdall, J., Mickley, M. and Hamilton, R., (1995). Survey of Membrane Drinking water plant Disposal Methods, Desalination, 102, 93-105.

Tularam, G. A., Surawski, N., and Braddock, R., (2006). Capabilities of Saltflow and Pde2d in modelling saltwater intrusion in coastal Australian lowlands. Australian Geomechanics Journal, 41(1), 73-78.

Wijmans, J.G., and Baker, R.W., (1995). The solution–diffusion model: A review. Journal of Membr. Sci., 107, 1–21.

Winter. T., Pannell. D. J. and McCann. L., (2001). The Economics of Desalination and its Potential Application in Australia, Agricultural and Resources Economics, University of Western Australia, Perth, WA 6009, Australia.

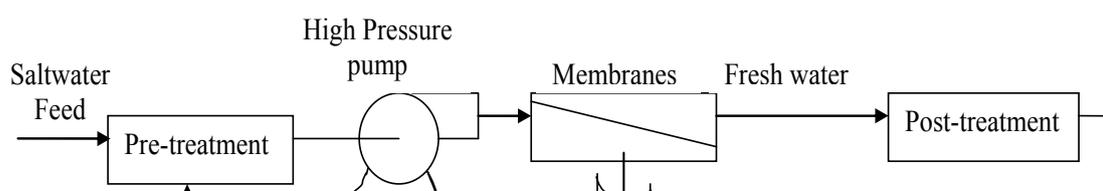


Figure 1: Schematic diagram of an RO desalination treatment Plant.

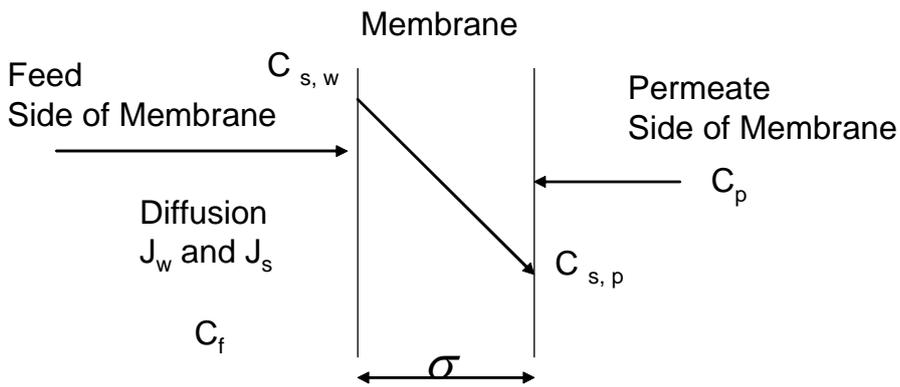


Figure 2: Mathematical modelling of a RO membrane.

Table 1: Concentrate characteristics in desalination technologies (Adapted from Younos, 2005)

	Plant Type	B-RO	S-RO	MSF/MED
Feedwater	(input)	Brackish (B)	Seawater (S)	Seawater (S)

Recovery	(output)	60-85%	30-50%	15-50%
Temperature	output	Ambient	Ambient	15-50% above ambient
Concentrate Dilution/Blending	(Output)	Possible, not typical	Possible, not typical	Typical, with cooling water
Final Ratio-Concentration	(In/output)	2.5-6.7	1.25-2.0	<1.15

BRO = Brackish water reverse osmosis, SRO = Seawater reverse osmosis, MSF = Multistage flash evaporation, MED = Multiple effect distillation

Table 2: Pre-treatment and post-treatment processes

Step No	Pre-treatment	Post-treatment
1	Chlorination where biological growth may be present	Degasification for CO ₂
2	Polymer additives used for scale control	Aeration to remove H ₂ S, adding O ₂
3	For RO sometimes acid is used in addition to additives	For RO, pH adjustment required for corrosion protection
4	Dechlorination for some membrane processes where chlorination is used	