Management of Desalination Plant Concentrate

by

Nikolay Voutchkov, PE, BCEE

1. Introduction

Desalination of brackish water and seawater (collectively referred to as saline water) is becoming increasingly important method for production of fresh potable water in the US as many parts of the country, such as the arid southwest, Florida and Georgia, face limited availability of new low-cost fresh water resources traditionally used for municipal water supply. As compared to traditional water resources, such as groundwater aquifers, rivers, and lakes, desalination offers sustainable, reliable and drought-proof long term water supply alternative.

Concentrate (brine) is a byproduct from the desalination of brackish and seawater desalination plants which is generated as a result of the salt-separation process. This byproduct contains the minerals and other constituents which are removed from the saline source water. At present, the desalination technology most widely used in the US is reverse osmosis (RO) membrane separation. Therefore, this course encompasses only management of concentrate from RO membrane desalination plants.

Figure 1 shows the key waste streams generated by a typical desalination plant. Concentrate usually constitutes 90% to 95% of the total desalination plant discharge volume.

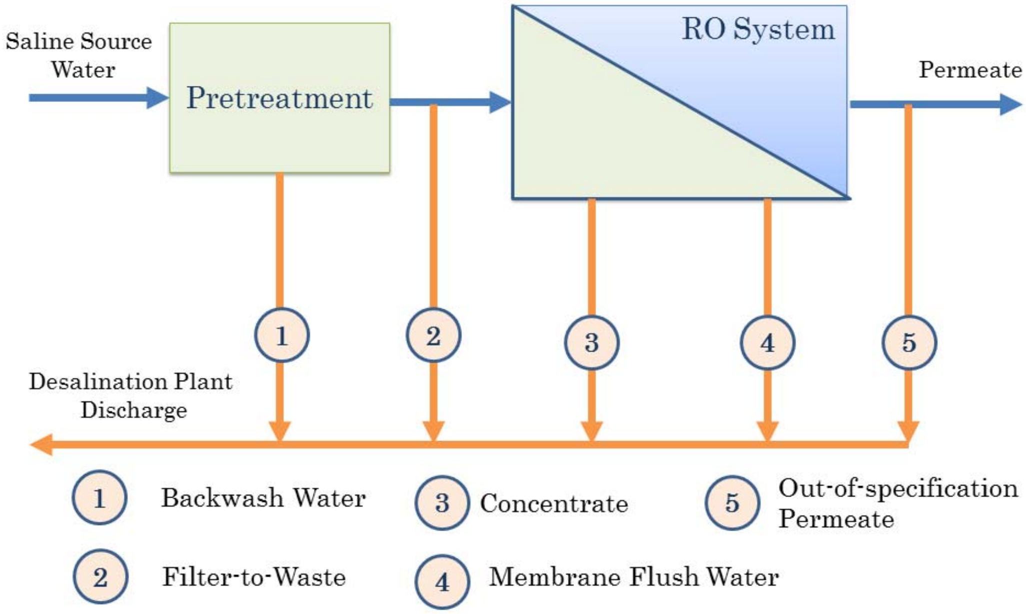


Figure 1 – Typical Discharge Components of Seawater Desalination Plant

Besides concentrate, desalination plant discharge may contain other waste streams including: backwash water generated by the pretreatment system; the filter-to-waste stream which is filtered water produced in the first 5 to 15 minutes (min) after pretreatment filter backwash which does not have adequate quality to be processed through the RO system; RO membrane flush water produced as a side-stream of periodic chemical cleaning of the membranes; and permeate which does not meet specifications in terms of conductivity or other product water quality parameters. Concentrate however, is the only continuously generated waste stream. All other waste discharges occur periodically with a frequency of once every several hours to one every several months. The type, volume and quality of concentrate depend on the source water origin, quality and the type of intake used to collect it.

2. Concentrate Quantity

The quantity of the concentrate generated by the desalination system is function of the plant size and the permeate recovery rate (P_r):

$$Q_c = Q_p \times (100/P_r - 1) \qquad (1)$$

Permeate recovery rate is defined as the portion of the saline source water flow converted into fresh water (permeate) flow (Q_f) and is measured as a percent of the saline feed flow (Q_f) – see Figure 2.

$$P_r = (Q_p/Q_f) \times 100\ \% \qquad (2)$$

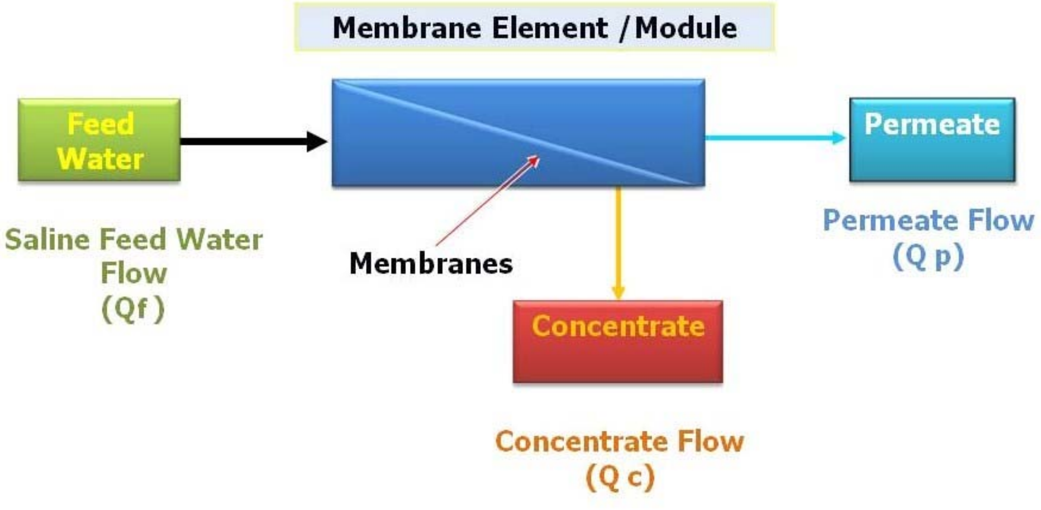


Figure 2 – General Schematic of RO System

Due to RO membrane mineral scaling, concentrate polarization, and standard equipment and facility constraints only a portion of the saline source water flow fed to the RO membrane system can be converted into fresh water. Permeate recovery rate for typical seawater reverse osmosis (SWRO) systems is 40% to 65%. Most SWRO plants are designed around 50% recovery, which means that it takes two gallons of seawater to produce one gallon of fresh water. Brackish water desalination plants are designed and operated at higher recoveries (usually 66 to 85%).

For example, if the permeate recovery rate for a SWRO desalination plant of production capacity (Q_p) of 1 million gallon per day (MGD)/3,785 m^3/day is 45% (i.e., $P_r = 45\%$), than according to Formula 1, the volume of concentrate generated by the referenced SWRO system is:

$$Q_c = 1 \text{ MGD} \times (100/45 - 1) = 1.22 \text{ MGD } (4{,}618 \text{ m}^3\text{/day})$$

Feed water flow of the RO system is a sum of concentrate and permeate flows:

$$Q_f = Q_p + Q_c \qquad (3)$$

For the example above, the source seawater flow needed to produce 1 MGD (3,785 m^3/day) of fresh water is:

$$Q_f = 1.00 \text{ MGD} + 1.22 \text{ MGD} = 2.22 \text{ MGD } (8{,}403 \text{ m}^3\text{/day})$$

Analysis of Formulas 1 and 2 indicates that designing plants for higher permeate recovery rates would result in smaller concentrate and intake volumes and vice versa. If the 1 MGD (3,785 m^3/day) desalination plant referenced in the example is designed for 50% instead of 45% recovery, the total volume of RO system concentrate will be reduced from 1.22 MGD (4,618 m^3/day) down to 1.00 MGD/3,785 m^3/day (i.e., by 22%). While designing plants around higher permeate recovery rate may be beneficial in terms concentrate volume, the salinity of the generated concentrate increases with recovery.

3. Concentrate Quality

The total dissolved solids concentration (TDS) of the concentrate (TDS_c) can be calculated based on the RO system permeate recovery rate P_r, in percent; the actual concentration of the permeate (TDS_p) and feed water TDS (TDS_f) using the following formula:

$$TDS_c = (TDS_f - P_r/100 \times TDS_p)/\ (1 - P_r/100) \qquad (4)$$

For the example SWRO system on Figure 3, the TDS of the concentrate, assuming recovery rate of 50% and permeate salinity of 200 mg/L, is calculated as follows:

$$TDS_c = (35{,}000 \text{ mg/L} - 50\%/100 \times 200 \text{ mg/L}) / (1-50\%/100) = 69{,}800 \text{ mg/L}$$

Formula 4 and the example above illustrate the fact that the salinity of the desalination plant concentrate increases with the increase in source water salinity, permeate recovery and permeate water quality.

The ratio between the salinity of the concentrate and the salinity of the source water is termed concentration factor – C_f. This parameter can be determined for the total dissolved solids in the source water and for individual mineral ions.

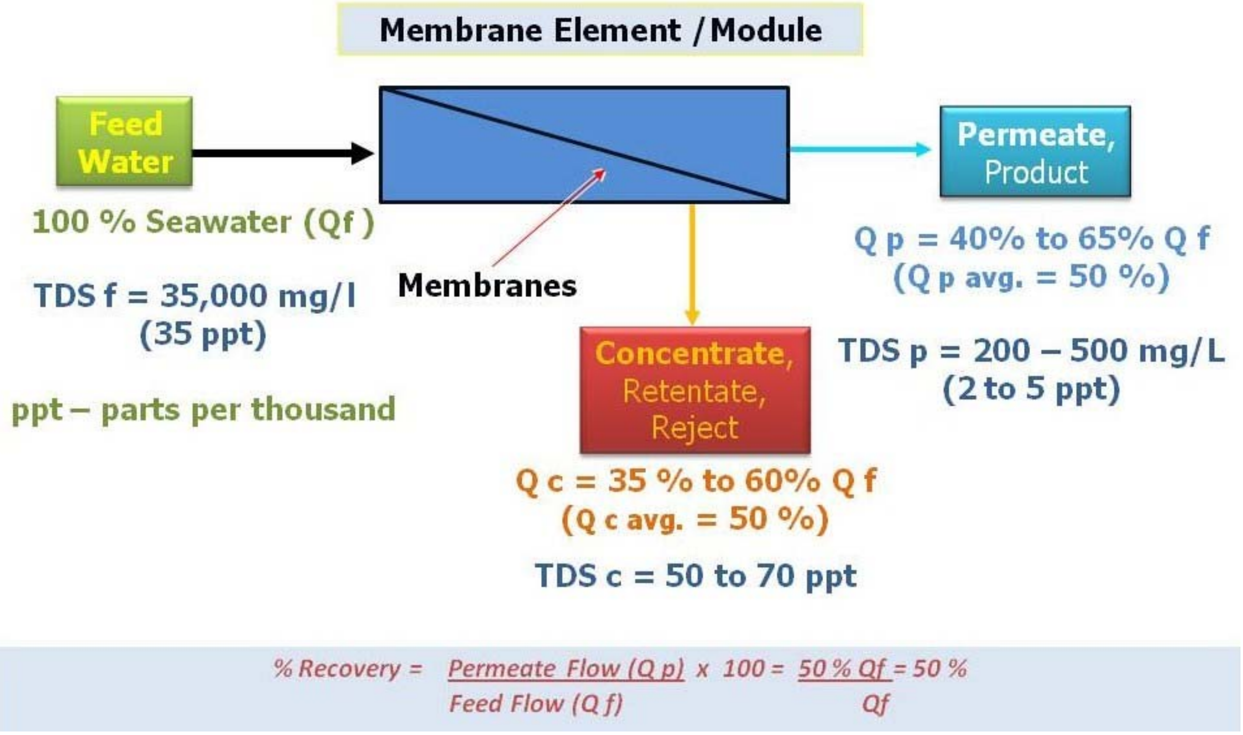


Figure 3 – Example RO System Flow and Salinity Balances

For RO plants, the concentration factor, C_f, assuming conservatively 100% salt rejection by the membranes, can be calculated from the following simplified equation:

$$C_f = 1 / (1 - P_r/100) \qquad (5)$$

In the example shown on Figure 3, the concentration factor of the SWRO system, which has 50% recovery is $C_f = 1/ (1 – 50\%/100) = 2$. If the actual RO membrane salt passage (S_p) is known, the concentration factor can be calculated more accurately using the formula below:

$$C_f = [1- (P_f/100 \text{ x } S_p /100)] / (1- P_f /100) \qquad (6)$$

Salt passage (S_p) of a membrane or RO system is defined as the ratio between the concentration of salt in the permeate (TDS_p) to that is the saline feed water (TDS_f) (see Figure 3) and is typically expressed in %. This parameter is indicative of the amount of salts that remain in RO permeate after desalination:

$$S_p = (TDS_p/TDS_f) \text{ x } 100 \qquad (7)$$

For the seawater desalination example shown on Figure 3, the salt passage of the SWRO system estimated for the high end of performance of the RO membrane (TDS_p = 200 mg/L) is S_p = (200 mg/L/35,000 mg/L) x 100% = 0.57%. Subsequently, for SWRO system with recovery of 50%, and salt passage of 0.57 %, the concentration factor C_f is:

$$C_f = [1 – (50\%/100 \text{ x } 0.57\%/100)]/[1-(50\%/100)] = 1.994$$

Since RO membranes reject some ions and chemicals better than others, variable concentration factors may apply for specific ions and chemicals. Exactly how the brine concentration factor impacts the disposal of concentrate depends mainly on the means of disposal. In some cases, volume minimization (high brine concentration factor) is preferred, whereas in cases where the concentrate is to be discharged to waterways, achieving lower TDS concentration is usually more important than low volume.

The maximum brine concentration is primarily limited by the increasing osmotic pressure of the generated concentrate. For reverse osmosis seawater desalination systems this limit is approximately 65,000 to 80,000 mg/L [65 to 80 parts per thousand (ppt)]. The combined effect of membrane rejection and source water concentration typically renders the optimum fractional recovery from a single pass SWRO system as low as 40-50% for seawater reverse osmosis plants. Therefore, concentration factors for single-pass seawater desalination processes are typically in a range of 1.7 to 2.0.

For example, the 38 MGD (140,000 m^3/day) Perth Seawater Desalination Plant in Australia is a two-pass RO plant operating with a first pass recovery of 45% and a second pass recovery of

90%. This corresponds to an overall recovery of 43% and brine concentration factor of approximately 1.75. Based on source water TDS of 33,000 to 37,000 mg/L the plant produces average RO concentrate TDS of approximately 65,000 mg/L.

For comparison, the considerably lower salt concentrations of brackish groundwater and municipal wastewater tend to allow for much greater fractional recoveries. Brackish groundwater RO plants typically operate at recoveries of 65 to 85%, corresponding to a concentration factor of 2.9 to 6.7.

The following rules can be used to predict concentrate quality based on source water characteristics:

- Most heavy metals are rejected by RO membranes in a similar ratio as calcium and magnesium.
- Organics are typically rejected in excess of 95% (except for low molecular-weight organics).
- Concentrate from brackish groundwater desalination plants will likely be anaerobic and may contain hydrogen sulfide.
- Concentrate pH is generally higher than the source water pH because of the greater concentration of alkalinity in the concentrate.

If pre-treatment is used, the feed water to the desalination membranes would have lower levels of certain constituents and particles. However, the source water pre-treatment may result in slight increase in inorganic ions, such as sulphate, chloride, and iron, if coagulants are used. Concentrate may also contain residual organics from polymer or sulphuric acid use.

Concentrate generated by nanofiltration systems differ somewhat from the brackish and seawater concentrate because the overall NF salt rejection is lower. Therefore, for a given feed and recovery, NF concentrate is less saline than the RO concentrate. Further, NF provides low rejection of monovalent ions (e.g., sodium and chloride) compared to multivalent ions (e.g., calcium and sulphate). Consequently, NF concentrate has a higher ratio of multivalent to monovalent ions than feed water. Lastly, since RO typically treats higher salinity waters, the TDS levels in the RO concentrate are much higher, especially for seawater.

Concentrate typically has low turbidity (usually < 2 NTU), low total suspended solids (TSS) and biological oxygen demand (BOD) levels (typically <5 mg/L), because most of the particulates contained in the source water are removed by the desalination plant pretreatment system or pre-filtered by the intake wells if subsurface intake is used. However, if plant pretreatment waste streams are discharged along with the concentrate, the blend may contain elevated turbidity, TSS and occasionally BOD. Acids and scale inhibitors added to the desalination plant source water are rejected by the seawater reverse osmosis membranes in the concentrate and also have impact on its overall mineral content and quality. Scale inhibitor levels in the concentrate are typically <20–30 mg/L and consist of phosphates or organic polymers (such as polyacrylates or dendrimers).

Concentrate from seawater desalination plants using open ocean intakes typically has the same color, odor, oxygen content and transparency as the source seawater from which the concentrate was produced. Therefore, concentrate discharge to surface water bodies (ocean, river, etc.) does not typically change its physical characteristics or aesthetic impact on the aquatic environment, except for its density.

When a coagulant such as ferric chloride or ferric sulfate is used for source water pretreatment, the spent pretreatment filter backwash will have a red color due to the high content of ferric hydroxide in the backwash water. If this backwash water is blended with the RO system concentrate, the concentrate and the entire desalination plant discharge will typically be visibly discolored.

In order to address this challenge, most recent desalination projects using open intakes, including the 25 MGD (95,000 m^3/day) seawater desalination plant in Tampa Bay, Florida, are equipped to remove the ferric hydroxide from the backwash water, dewater it and dispose of it to a landfill in a solid form. As a result, the visual appearance of the desalination plant discharge is the same as that of the ambient water – i.e., the concentrate is transparent and clear.

There is no relationship between the level of salinity and biological or chemical oxygen demand of the desalination plant concentrate – over 80% of the minerals that encompass concentrate salinity are sodium and chloride, and they are not food sources or nutrients for aquatic organisms. The dissolved solids in the concentrate discharged from seawater desalination plants are not of anthropogenic origin as compared to pollutants contained in discharges from industrial or municipal wastewater treatment plants.

4. Overview of Existing Concentrate Management Practices

The five most commonly used concentrate management alternatives in the US at present are: (1) surface water discharge; (2) sewer disposal; (3) deep-well injection; (4) land application, and (5) evaporation ponds (see Figure 4).

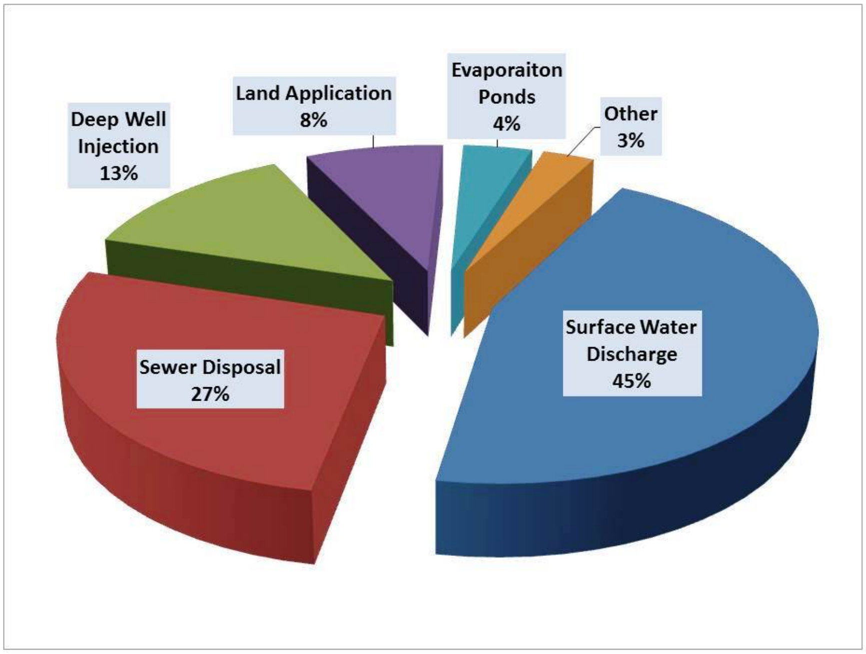


Figure 4 – Existing Concentrate Management Practices

Review of Figure 4 indicates that the most widely practiced method for concentrate disposal at present is its discharge to a surface water body (ocean, estuary, river, lake, etc.). This concentrate management practice is suitable for both seawater and brackish water desalination plants of all sizes. Sewer disposal is also a very commonly applied concentrate management alternative. However, because of the high salinity of the discharge it usually is viable for small plants only. Deep well injection is the most popular concentrate disposal practice for brackish seawater desalination facilities and usually is viable for both small and large plants. To date, land application and evaporation ponds have found practical application only for small brackish facilities in the US. The following sections provide overview of the concentrate management practices shown on Figure 4 and discuss key requirements, conditions, challenges and advantages associated with their practical application.

5. Concentrate Management Regulations in the US

At present, desalination plant discharges are classified by the United States Environmental Protection Agency (USEPA) as industrial waste despite the fact that these discharges are distinctively different from most industrial discharges. Regulatory programs in the US that address the disposal of desalination plant discharges include the Clean Water Act (CWA), the Underground Injection Control (UIC) Program, ordinances that protect groundwater, and the Resource Recovery and Conservation Act (RCRA) for any solid waste residuals. The key permitting requirements associated with the concentrate management alternatives depicted on Figure 4 are as follows:

- Concentrate disposal to surface waters is regulated by a National Pollutant Discharge Elimination System (NPDES) permit.

- Sewer discharge requires permit issued by the local sewer agency to meet its sewer ordinances and the CWA Industrial Pretreatment Program (IPP) requirements, as stipulated in the agency's wastewater treatment plant NPDES permit.

- Concentrate disposal by land application (percolation ponds, rapid infiltration basins, landscape and crop irrigation, etc.) must comply with federal and state regulations for protection of groundwater, public health, and crops/vegetation. Land application requires permit from state agencies.

- Concentrate disposal by deep well injection is regulated by the UIC program of the Safe Drinking Water Act. The related construction, monitoring, and other permits are issued and enforced by the USEPA region or state agency that has primacy.

RCRA regulates the disposal of solids, such as precipitated salts and sludge generated by desalination plants; if such solids contain arsenic or other toxin and do not pass the toxic characteristic leaching procedure (TCLP) test, they are considered a hazardous waste and must be handled accordingly.

The most important regulations pertaining to disposal of desalination plant discharges are those related to the CWA, including the NPDES program. Under the CWA, desalination plant discharges are regulated as industrial wastes because to date, the USEPA has not established specific regulations concerning the disposal of water treatment plant residuals, including desalination plant discharges.

For surface water discharge, NPDES permit is required pursuant to the CWA. CWA's anti-degradation policy prevents the relaxation of discharge limits for contaminants specified in a NPDES permit, particularly if the receiving water is designated as sensitive or impaired. If a water treatment plant currently has a salinity discharge limit, combining high salinity concentrate from the desalination plant's RO system with the existing discharge may not be allowed.

At present, there are no federal or state salinity surface water discharge limits in the US and worldwide. The pertinent federal and state laws in the US regulate salinity of desalination plant concentrate discharges by establishing project-specific acute and chronic WET objectives. WET is a more comprehensive measure of the environmental impact of concentrate than a salinity limit because WET water quality objectives also account for potential synergistic environmental impacts of concentrate with other constituents in the concentrate. Besides the effect of elevated mineral content of concentrate on the marine habitat in the area of the discharge, the potential environmental impacts of other dissolved solids contained in the concentrate (e.g., metals, organics, suspended solids) are considered alongside with other waste streams that may be contained in the desalination plant discharge (e.g., spent filter backwash, membrane flush water). In short, salinity is only a measure of the dissolved mineral (salt) content of the concentrate rather than the complex chemistry of the discharge in relationship to the receiving body of water.

According to current regulations in the US, if a desalination plant discharge meets all water quality objectives defined in the applicable federal state regulations as well as acute and chronic WET objectives, then the proposed discharge does not present a threat to aquatic life; regardless of what the actual salinity level of this discharge is or what increase above ambient salinity this discharge may cause because WET accounts for the salinity related environmental impacts of concentrate.

6. Surface Water Concentrate Disposal Alternatives

As indicated previously, surface water disposal is one of the most commonly practiced concentrate management methods. While in the US, rivers estuaries and lakes are used occasionally for discharge of concentrate from brackish water desalination plants, ocean discharge is the most popular surface water concentrate disposal method for both seawater and brackish water desalination facilities. Alternatives for discharging concentrate to surface waters include:

- Direct discharge through new outfalls;
- Discharge through existing wastewater treatment plant outfalls; and
- Discharge through existing power plant outfalls (collocation).

Discharge through New Outfalls

New plant outfalls are designed to dissipate desalination plant concentrate within a short time and distance from the point of its entrance into the surface water body in order to minimize environmental impacts. The two options available to accelerate and enhance the concentrate mixing process are to either rely on the naturally occurring mixing capacity of the near-shore zone of the surface water body (e.g., near-shore movement, near-shore currents, wind), or to discharge concentrate beyond the near-shore zone and to use diffusers which release concentrate at high velocity towards the surface of the water body in order to improve mixing.

The near-shore zone is usually a suitable location for concentrate discharge when it has adequate capacity to receive, mix and transport desalination plant discharge into the open ocean or river. This salinity threshold mixing/transport capacity of the near-shore zone can be determined using hydrodynamic modelling. If the salinity discharge load is lower than the near-shore zone threshold mixing/transport capacity, then concentrate discharge to this near-shore zone is significantly more environmentally compatible and cost effective than the use of constructing long, open outfalls equipped with diffuser systems.

For example, the sites of two of the largest operational seawater desalination plant in the world - the 85 MGD (320,000 m^3/day) Ashkelon Desalination Plant (Figure 5) was specifically selected for its vicinity to coastal locations with very intensive natural near-shore mixing, which eliminated the need for construction of lengthy outfalls and costly outfall diffuser structures.

Figure 5 – 85 MGD Ashkelon Desalination Plant Near-shore Discharge

Although near-shore zone of the receiving surface water body (i.e., ocean, river, bay) may have a significant amount of turbulent energy and often may provide better mixing than an end-of-pipe type diffuser outfall system, this zone has limited capacity to transport and dissipate the saline discharge load. If the mass of the saline discharge exceeds the threshold of the near-shore zone's salinity load mixing and transport capacity, the excess salinity would begin to accumulate in the near-shore zone and could ultimately result in a long-term salinity increment in this zone. For such conditions, the construction of a new outfall structure with diffusers is often the concentrate discharge system of choice. The diffuser system provides the mixing necessary to prevent the heavy saline discharge plume from accumulating at the bottom in the immediate vicinity of the discharge. The length, size and configuration of the outfall and diffuser structure are typically determined based on hydrodynamic modelling for the site-specific conditions of the discharge location.

Key advantages of constructing new discharge outfalls include accommodating practically any size desalination plant and providing for more freedom in selecting plant location, as compared to the other discharge alternatives which rely on the use of existing wastewater treatment plant or power plant outfalls. The key disadvantage is that it usually is the most costly alternative for disposal of concentrate from medium and large size desalination plants.

Construction of new concentrate disposal outfalls with a diffuser structure is commonly used in the US. For example over 50% of the brackish water desalination plants in Texas and approximately 18% of the desalination facilities in Florida discharge their concentrate to surface waters. The 10 MGD (37,850 m^3/day) Taunton River desalination plant in Dighton, Massachusetts also uses surface water discharge with diffusers. Concentrate disposal outfalls are also used for all of the seawater desalination plants in Australia constructed to date (Perth I, Gold Coast and Sydney discharging over 140 MGD/530,000 m^3/day of concentrate), and the new the Australian plants under construction (Adelaide, Perth II and Melbourne – with total discharge volume of over 260 MGD/984,000 m^3/day), as well as at many plants in Spain, the Middle East, Africa, South America, and the Caribbean.

Discharge through Existing Wastewater Treatment Plant Outfalls

Two of the largest desalination plants in Florida [the 40 MGD (150,000 m^3/day) Boca Raton plant and the 4 MGD (15,000 m^3/day) Hollywood plant] co-discharge their concentrate with wastewater treatment plant (WWTP) effluent. A key feature of this combined discharge method is the benefit of accelerated mixing that stems from blending the heavier high-salinity concentrate with the lighter low-salinity wastewater discharge. Depending on the volume of the concentrate and how well the two waste streams are mixed prior to the point of discharge, the blending may allow for reducing the size of the wastewater discharge plume and diluting of some of its constituents. This approach was first permitted in California for the Santa Barbara Desalination Plant in 1994 and has been proposed for the Marina Coast desalination project on the Monterey Peninsula, as well as for the Santa Cruz and Dana Point desalination projects in California.

Similarly, a number of large desalination plants worldwide co-discharge their concentrate through existing wastewater treatment plant (WWTP) outfalls. For example, the concentrate from the 40 MGD (150,000 m^3/day) Beckton desalination plant in London, England is effectively blended with secondary effluent from the Beckton Wastewater Treatment Works at a dilution ratio of 1:50 and discharged to the Thames River.

The largest plant in operation at present which practices co-discharge of desalination plant concentrate and wastewater effluent is the 50 MGD (200,000 m^3/day) Barcelona SWRO facility in Spain. Co-disposal with WWTP effluent is also used at the 30 MGD (110,000 m^3/day) Fukuoka SWRO plant, which is the largest SWRO plant in Japan.

Key considerations related to the use of existing WWTP outfalls for direct seawater desalination plant concentrate discharge are: (1) the availability and cost of wastewater outfall capacity; (2) the need for modification of the outfall system of the existing wastewater treatment plant due to altered buoyancy of the concentrate-wastewater mix; and (3) the compatibility of the diurnal variation wastewater treatment plant discharge flows in relation to the discharge from the desalination plant.

The main advantage of wastewater treatment plant co-discharge is that it avoids substantial costs and environmental impacts associated with construction of a new outfall for the desalination plant. Mixing of the negatively buoyant wastewater discharge with the heavier than ocean water concentrate, promotes the accelerated dissipation of both the wastewater plume, which tends to float to the ocean surface, and the concentrate which tends to sink towards the ocean bottom. In addition, metals, organics and pathogens in seawater concentrate are typically at significantly lower levels than those in the wastewater discharge, which helps with reducing their discharge concentrations in the combined WWTP effluent.

Often, desalination plants are operated at a constant production rate and, as a result, they generate concentrate discharge with little or no diurnal flow variation. On the other hand, wastewater treatment plant availability for dilution of the desalination plant concentrate typically follows a distinctive diurnal or daily variation pattern. Since adequate protection of aquatic life typically requires a certain minimum concentrate dilution ratio to be maintained at all times, the amount of concentrate disposed by the desalination plant (and therefore, the plant production capacity) may be limited by the lack of adequate hydraulic capacity of wastewater plant effluent for blending during periods of low wastewater effluent flows (i.e., at night).

In order to address this concern, the desalination plant operational regime and capacity may need to be altered to match the WWTP effluent availability patterns or a diurnal concentrate storage/equalization facility may need to be constructed at the desalination plant. Alternatively, the desalination plant could collect additional saline source water to dilute the concentrate when needed.

Collocation with Existing Power Plants

Copyright© 2011 Nikolay Voutchkov

Collocation involves using the cooling water discharge of an existing power plant as both the source of saline water for production of fresh water and as dilution water for mixing with the desalination plant concentrate. For collocation to be viable, the power plant cooling water discharge flow must be greater than the proposed desalination plant intake flow, and the power plant outfall configuration must be adequate to avoid entrainment and recirculation of concentrate into the desalination plant intake. Special consideration must be given to the effect of the power plant operations on the cooling water quality, since this discharge is used as source water for the desalination plant.

Under a collocation configuration, the intake of the seawater desalination plant is connected to the discharge canal of the power plant to collect a portion of the cooling water of this plant for desalination (see Figure 6).

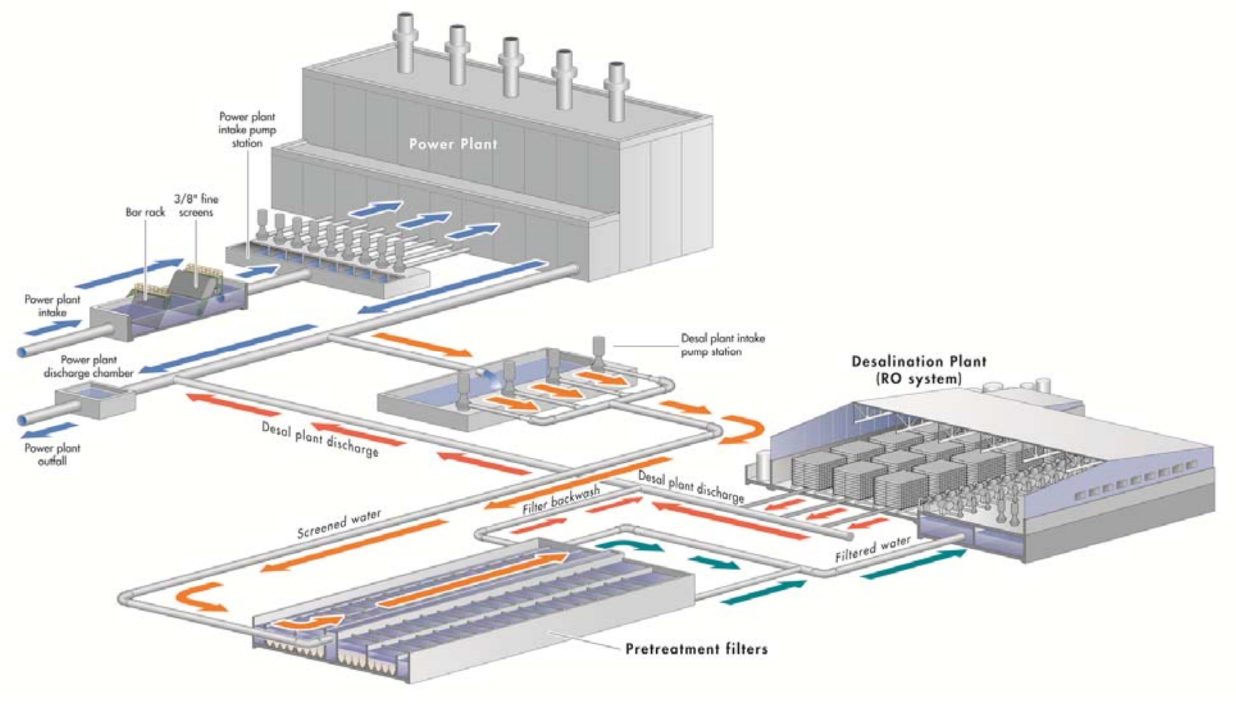


Figure 6 – Typical Configuration of Collocated Desalination Plant

After the saline source water is pre-treated, it is processed in a reverse osmosis membrane desalination system, which produces two key streams – low salinity permeate, which after conditioning is conveyed for potable water supply, and concentrate which is returned to the power plant discharge downstream of the point of cooling water intake. This configuration allows using the power plant cooling water both as source water for the seawater desalination plant and as a blending water to reduce the salinity of the desalination plant concentrate prior to its discharge to the ocean.

As shown on Figure 6, under typical operational conditions seawater enters the power plant intake facilities and after screening is pumped through the power plant condensers to cool them and thereby to remove the waste heat generated during the electricity generation process. The cooling water discharged from the condensers is typically 5 to 15^{0}C warmer than the saline source water which could be beneficial for the desalination process because warmer seawater has lower viscosity and therefore, lower osmotic pressure/energy for salt separation.

Collocation of SWRO desalination plants with existing once-trough cooling coastal power plants yields four key benefits: (1) the construction of a separate desalination plant outfall structure is avoided thereby reducing the overall cost of desalinated water; (2) the salinity of the desalination plant discharge is reduced as a result of the mixing and dilution of the membrane concentrate with the power plant discharge, which has ambient seawater salinity; (3) because a portion of the discharge water is converted into potable water, the power plant thermal discharge load is decreased, which in turn lessens the negative effect of the power plant thermal plume on the aquatic environment; (4) the blending of the desalination plant and the power plant discharges results in accelerated dissipation of both the salinity and the thermal discharges.

Usually, coastal power plants with once-trough cooling systems use large volumes of seawater. Because the power plant intake seawater has to pass through the small diameter tubes (typically 10-mm or less) of the plant condensers to cool them, the plant discharge cooling water is already screened through bar racks and fine screens similar to these used at surface water intake desalination plants. Therefore, a desalination plant which intake is connected to the discharge outfall of a power plant usually does not require the construction of a separate intake structure, intake pipeline and screening facilities (bar-racks and fine screens). Since the construction cost of a new surface water intake and discharge structures for a desalination plant is typically 15 to 40% of the total plant construction expenditure, power plant collocation could yield significant construction cost savings.

The need for installation of additional fine screening facilities for the desalination plant intake is driven by the screenings disposal practice adopted by the power plant and the type of desalination plant pretreatment system. As indicated previously, power plants typically remove the screenings retained at their bar racks and fine screens, and dispose these waste debris to a landfill or return them back to the ocean. However, in some power plants, the screenings collected at the power plant's mechanical screens are discharged into the cooling water downstream from the plant's condensers. In this case, the power plant discharge would contain screenings that need to be removed at the desalination plant intake.

As a result of the collocation the desalination plant unit power costs could be further decreased by avoiding the need for using the power grid and the associated fees for power transmission to the desalination plant. Typically, the electricity tariff (unit power cost) structure includes two components: fees for power production and for power grid transmission. Often, the power transmission grid portion of the tariff is 30 to 50% of the total unit power cost. By connecting the desalination plant directly to the power plant electricity generation equipment, the grid transmission portion of the power fees could be substantially reduced or completely avoided, thereby further reducing the overall seawater desalination cost.

The length and configuration of the desalination plant concentrate discharge outfall are closely related to the discharge salinity. Usually, the lower the discharge salinity, the shorter the outfall and the less sophisticated the discharge diffuser configuration needed to achieve environmentally safe concentrate discharge. Blending the desalination plant concentrate with the lower salinity power plant cooling water often allows reducing the overall salinity of the surface water discharge within the range of natural variability of the saline source water at the end of the discharge pipe, thereby completely alleviating the need for complex and costly discharge diffuser structures.

Collocation with a power station in a large scale was first proposed for the Tampa Bay Seawater Desalination Project in Florida. Since then, collocation has been considered for numerous plants in the US and worldwide. The intake and discharge of the Tampa Bay Seawater Desalination Plant are connected directly to the cooling water discharge outfalls of the Tampa Electric Company (TECO)'s Big Bend Power Station (Figure 7)**.**

The TECO power generation station discharges an average of 1.4 billion gallons (5.3 million m^3) of cooling water per day, of which the desalination plant takes an average of 44 MGD (166,000 m^3/day) to produce 25 MGD (95,000 m^3/day) of fresh drinking water. The 19 MGD (71,000 m^3/day) desalination plant concentrate is discharged to the same TECO cooling water outfalls downstream from the point of seawater desalination plant intake connection.

In this case, the source seawater is treated through fine screens, coagulation and flocculation chambers, a single stage of sand media followed by diatomaceous filters for polishing, and cartridge filters before the SWRO system with a partial second pass. The spent filter backwash water from the desalination plant is processed through lamella settlers and dewatered using belt filter presses. Treated backwash water and concentrate are blended and disposed through the power plant outfalls under a NPDES permit administered by the Florida Department of Environmental Protection.

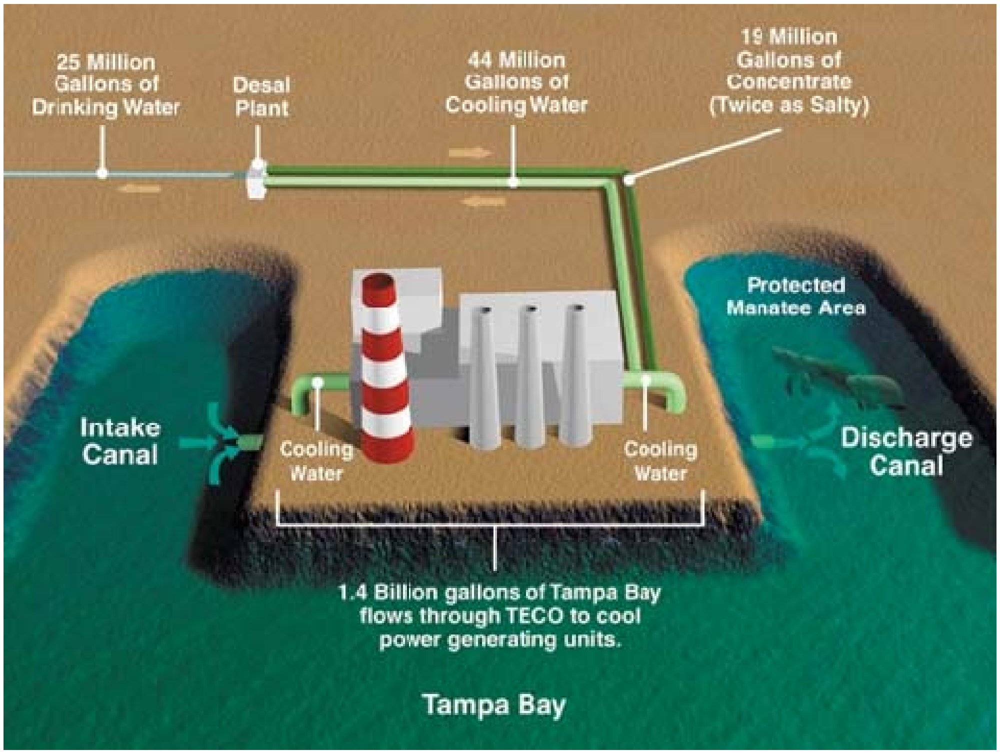


Figure 7 – Tampa Bay SWRO Plant Collocation Schematic

Surface Water Discharge Design Guidelines

<u>Outfall Pipeline</u>

The concentrate disposal site should be located as near to the desalination plant as practically possible. Concentrate discharge pipes should be made of corrosion- and crush-resistant material. At present, high density polyethylene (HDPE), glass-reinforced plastic (GRP) and polypropylene (PP) pipe materials are most commonly used for construction of outfalls of all sizes of desalination plants. Over the past 10 years, plastic piping has replaced traditional materials for construction of ocean outfall piping systems (concrete, steel, cast iron). Key advantages of plastic pipe materials include: higher corrosion resistance; chemical inertness; lighter weight; resistance to galvanic attack; and lower unit cost. In many cases, HDPE and GRP outfalls are less expensive than the use of traditional piping materials, such as concrete or steel pipe.

Usually, the GRP pipe is less costly than HDPE pipe, but this type of pipe is positively buoyant in water; fractures more easily; and is not resistant to negative pressure. If the outfall pipe is located in beach area exposed to accelerated erosion or wave action, GRP pipe has to be buried and installed in trench on special bedding, which often makes the use of GRP pipe more costly than the installation of HDPE, concrete or steel pipe on the ocean bottom. Low cost construction of outfalls encompasses the installation of plastic pipe directly on the ocean floor. The outfall pipe and secured to the bottom with concrete blocks (see Figure 8).

Figure 8 – Concentrate Discharge Pipe

Table 1 lists the type and maximum size of plastic pipes most commonly used in outfall construction.

Table 1 - Plastic Piping Materials Used for Outfalls

Plastic Material	**Typical Maximum Pipe Diameter, inches/mm**
High-density polyethylene (HDPE)	78 in/2000 mm
Glass Reinforced Plastic (GRP)	24 in/600 mm
Polypropylene (PP)	24 in/600 mm

While plastic pipe is typically preferred to concrete or steel pipe because of its lower cost, often for large and mega-size desalination plants with outfall located in area with strong underwater currents and environmentally sensitive marine habitats as well as at sites with active beach erosion or intense ship traffic, the construction of large-diameter reinforced concrete tunnels under the ocean bottom is the preferred outfall discharge alternative. Usually such concrete tunnel discharges are several times more costly to construct than to build a discharge outfall that consists of multiple plastic pipes. Therefore, construction of discharge tunnels is recommended to be avoided if site specific conditions are favorable for installation of plastic pipe outfalls.

Typically, outfall pipelines are designed to maintain velocity of 2 feet per second (fps) (7 m/s) or more in order to prevent formation of deposits and scale on the inner surface of the pipes. The maximum velocity/minimum pipe size is determined based on the total available discharge head and the goal to avoid pumping of concentrate into the discharge line, if possible.

Discharge outfall pipe is usually sized to convey the entire maximum design intake volume because during startup and commissioning, as well as after routine plant shutdowns, the pretreated seawater is often discharged back to the ocean until it reaches quality suitable to be directed to the RO membranes.

In addition, if source water is temporarily contaminated by accidental source (i.e., large oil spill or wastewater discharge) to a level that makes this water unsuitable for processing through the desalination plant, the contaminated source water that has entered the desalination plant intake can be returned directly back to the ocean without negatively impacting desalination plant operations.

In many cases, the discharge outfall pipe is designed to handle only concentrate, spent filter backwash water and membrane cleaning solutions, thereby reducing discharge facility size and costs. While this design approach decreases plant capital expenditures, it also reduces plant's operational flexibility, especially if the facility is planned to be operated intermittently.

Concentrate Conveyance

Concentrate typically exits the RO system at pressure ranging from ambient atmospheric pressure to 10 to 25 pounds per square inch (psi) (0.7 to 1.8 bars) depending on the type of energy recovery device and plant design. In most cases, the available concentrate head is sufficient to overcome frictional losses within the discharge piping system, allowing concentrate flow to be conveyed to the outfall diffusers without the need for additional pumping.

When pumping is necessary, energy use and maintenance associated with concentrate pump station and conveyance system become important cost factors. The need for surge control should also be considered in the outfall design.

Outfall Diffuser Design

Outfall pipes typically terminate with a multiport diffuser, a perforated discharge section or a simple open pipe end. A multiport diffuser is designed so that the end of the outfall pipe is capped and the last sections of this pipe contain small concentrate discharge ports (openings or diffuser nozzles around the circumference of the pipe). The main purpose of the diffusers is to provide a greater initial dilution of the concentrate as it enters the receiving water body.

Most small outfalls have simple open pipe end with perorations along the last 10 to 30% of the pipeline length. In recent years, multiport diffusers have become the accepted design norm for larger diameter outfalls. Simple open-end outfalls are recommended when the initial dilution that is achieved naturally at the point of exit is adequate to meet applicable discharge water quality standards. If concentrate dilution requirements are not met at the point of exit, installation of diffusers becomes necessary.

The most commonly used concentrate discharges have series of diffusers which are designed to direct the desalination plant concentrate towards the surface of the ocean and to release it with energy which is adequate to facilitate concentrate plume dissipation within a pre-determined distance from the point of discharge. The key parameters for desalination discharge outfalls which need to be determined during design include:

- Diameter and length of concentrate discharge pipe;
- Configuration of the diffuser system;
- Number of diffuser ports;
- Distance between ports;
- Port diameter;
- Port upward angle from pipeline center;
- Pipe and diffuser port material;
- Distance of diffuser system from shore;
- Diffuser submergence depth;
- Exit velocity of concentrate through the diffuser ports.

The optimum configuration and design of the outfall diffuser system listed above can be determined using hydrodynamic models such as CORMIX, EPA PLUMES (Visual Plumes) and others. Some key guidelines for diffuser system design are:

- Diffuser exit velocity - 6 to 12 fps (2 to 4 m/s). This velocity is determined by the force needed to eject the desalination concentrate near the surface of the ocean, which allows to maximize concentrate mixing/contact time with the ambient water column and to engage the largest possible volume of ambient water in the mixing process.

- Diffuser system orientation - perpendicular to the prevailing ocean current.

- Distance between ports - should be such that their individual discharge plumes do not overlap.

- Diffuser angle - 45 to 60 degrees from the horizontal outfall pipe;

- Diffuser port size distribution - Increase gradually diffuser port size towards the end of the pipe in order to maintain sufficient flow in each diffuser;

- Total diffuser port cross-section area – should be less than 70% of the cross-section of the outfall pipe;

- Minimum diffuser port opening – 3 inches (80 mm) to prevent the blockage from aquatic life growth.

7. Discharge to Sanitary Sewer

Discharge to the nearby wastewater collection system is one of the most widely used methods for disposal of concentrate from small brackish and seawater desalination plants in the US and worldwide. This indirect wastewater plant outfall discharge method however, is only suitable for disposal of very small volumes of concentrate into large-capacity wastewater treatment facilities mainly because of the potential negative impacts of the concentrate’s high salinity content on the operations of the receiving wastewater treatment plant.

Disposal of concentrate to the sanitary sewer in most countries is regulated by the requirements applicable to industrial wastewater discharges and limits for discharge volume, organic loads, suspended solids and salinity concentrations established by the utility/municipality which is responsible for wastewater collection system management/wastewater treatment.

Usually, concentrate water quality is compliant with typical requirements for discharging of industrial waste to sanitary sewer. Therefore, the application of this concentrate disposal method is not anticipated to have significant impacts on the sanitary sewer system, especially for concentrate discharges of 0.1 MGD (380 m^3/day) or less.

Feasibility of disposing desalination plant concentrate to the sanitary sewer is limited by the hydraulic capacity of the wastewater collection system and by the treatment capacity of the wastewater treatment plant receiving the discharge. Typically, wastewater treatment plants' biological treatment process is inhibited by high salinity when the plant influent TDS concentration exceeds 3,000 mg/L. Therefore, before directing desalination plant concentrate to the sanitary sewer the increase of wastewater treatment plant influent salinity must be assessed and its potential impact on the plant's biological treatment system should be investigated.

While low-salinity concentrate discharges to the sanitary sewer from brackish desalination plants are less likely to interfere with the WWTP plant operations, highly saline discharges from seawater desalination plants may pose a challenge. Taking under consideration that WWTP influent salinity concentration may be up to 1,000 mg/L in many facilities located along the ocean coast, and that typically seawater desalination plant concentrate salinity would be above 65,000 mg/L, the capacity of the wastewater treatment plant has to be at least 30 to 35 times higher than the daily volume of concentrate discharge in order to maintain the wastewater plant influent salinity concentration below 3,000 mg/L after blending the desalination plant discharge with the raw municipal wastewater. This means, that for example a 10 MGD (37,850 m^3/day) wastewater treatment plant would likely not be able to accept more than 0.25 MGD (1,000 m^3/day) of concentrate (i.e. serve a seawater desalination plant of capacity higher than 0.2 to 0.3 MGD/800 to 1,100 m^3/day).

If the effluent from the wastewater treatment plant is reclaimed for water reuse, the amount of concentrate that can be accepted by the wastewater treatment plant is limited not only by the concentrate salinity, but also by the content of sodium, chlorides, boron and bromides in the blend. All of these compounds could have a profound negative impact on the reclaimed water quality, especially if the effluent is used for irrigation. Treatment processes of a typical municipal wastewater treatment plant such as sedimentation, activated sludge treatment and sand filtration, do not remove a measurable amount of these concentrate constituents.

A number of crops and plants cannot tolerate irrigation water that contains over 1,000 mg/L of TDS. However, TDS is not the only water quality parameter of concern when the desalinated water is used for irrigation. High levels of chloride and sodium may also have significant negative impacts on the irrigated plants. Most plants cannot tolerate chloride levels above 250 mg/L. Typical wastewater plant effluent has chloride levels of 150 mg/L or less, while seawater treatment plant concentrate could have chloride concentration in excess of 40,000 mg/L. For example, using the chloride levels indicated above, a 10 MGD (37,500 m^3/day) wastewater treatment plant cannot accept more than 0.02 MGD (75 m^3/day) of seawater desalination concentrate, if the wastewater plant's effluent would be used for irrigation. This limitation would be even more stringent if the wastewater effluent is applied for irrigation of salinity-sensitive ornamental plants which often have tolerance threshold levels for sodium of ≤ 80 mg/L and chloride of ≤120 mg/L.

Design and Configuration Guidelines

Conveyance pipeline for this concentrate disposal alternative is designed similar to any other wastewater discharge pipeline. The pipeline material is usually HDPE, GRP of PVC. Because desalination plant concentrate is usually safe to dispose to the wastewater collection system, no specific concentrate treatment is typically needed.

If spent RO membrane cleaning solutions are planned to be discharged to the sanitary sewer, they will need to be pH adjusted to a range of 6 to 9 in order to protect the integrity of the wastewater collection system. If concentrate discharge volume is such that after blending with the WWTP effluent, the salinity of the blend exceeds 3,000 mg/L during the periods of daily low wastewater flows (off-peak hours) than this concentrate will need to be stored and equalized in order to prevent the excessive increase in the WWTP influent salinity. As indicated previously, influent salinity over 3,000 mg/L could inhibit the biological activated sludge wastewater treatment process.

8. Deep Well Injection

This disposal method is one of the most widely used alternatives for concentrate disposal from brackish water desalination plants in the US and involves injection of desalination plant concentrate into an acceptable confined deep underground aquifer adequately separated from freshwater or brackish water aquifers above it. The depth of such wells usually varies between 1,500 and 4,500 ft (500 to 1,500 m). Wells typically consist of three or more concentric layers of pipe: surface casing, long string casing, and injection tubing. Figure 9 depicts the key components of a typical concentrate deep injection well.

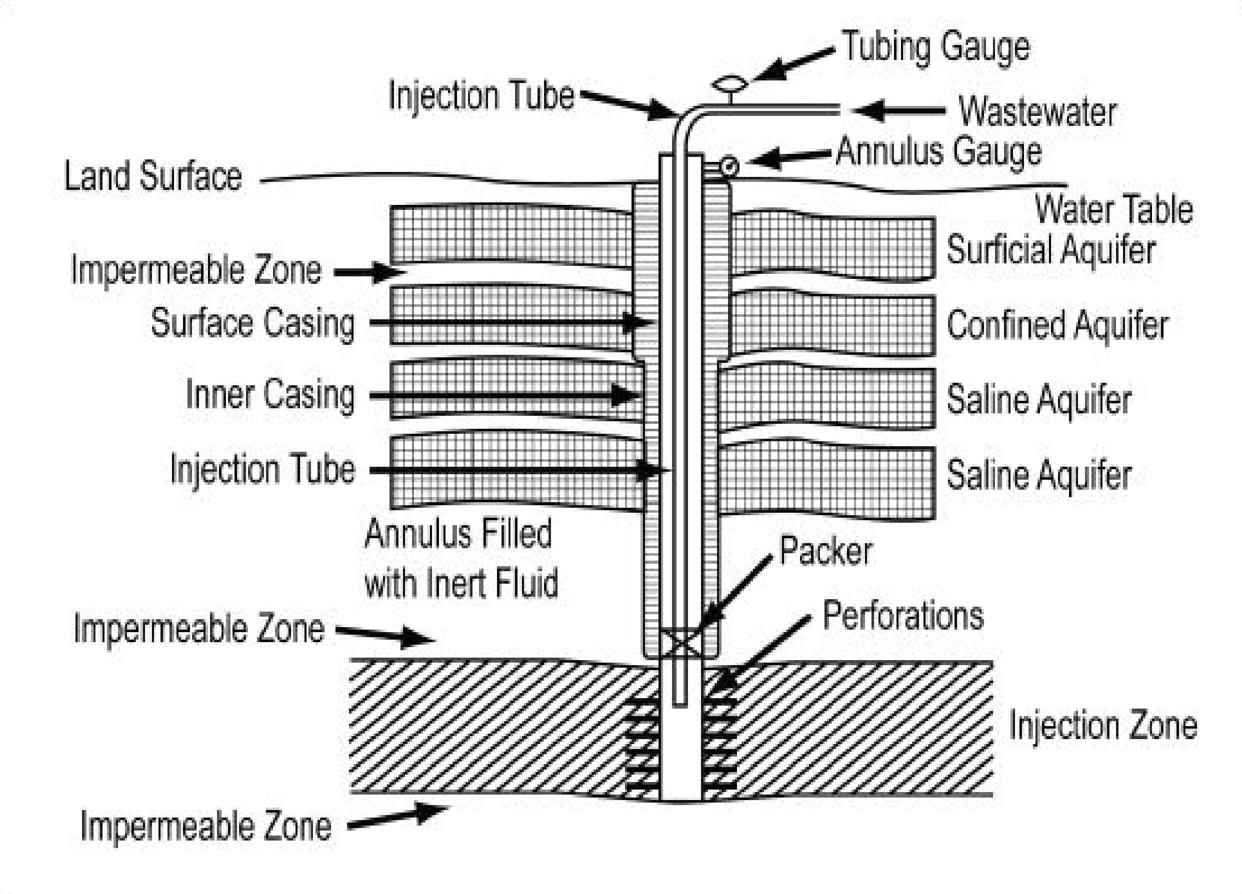


Figure 9 – Schematic of Deep Injection Well

A typical deep injection well consists of well head (equipped with pump, if needed) and a lined well shaft protected by multiple layers of casing and grouting.

Injection Well Shaft

The type of materials selected for well shaft construction should be compatible with desalination plant discharge water quality. Materials often used for the inner liner of a well shaft include fiberglass, plastic, stainless steel, and extra-thick steel pipe.

Injection wells are generally constructed by the same process used to construct extraction wells. Cable-tool and rotary drilling have been used successfully to construct deep wells. Completion of the well involves testing the casing and cement grouting to make sure they do not leak and can sustain design pressures.

Well Casing

Deep injection wells are multi-cased, with the innermost casing set at the top of the injection zone. Three to four casings are typically used. The depth of each casing depends on the geological environment surrounding the well. The main purpose of multiple staged casings is to protect the upper freshwater zones from deeper, brackish zones and to reduce the possibility of fluid exchange between the different aquifers.

Well's casting prevents the borehole from caving in and contains the tubing. Casting typically is constructed of a corrosion-resistant material such as steel or fiberglass-reinforced plastic (FRP). Surface casting is the outermost of the protective layers and it extends from the surface to below the lowermost underground source of drinking water (USDW) level. The long-string casting extends from the surface to or through the injection zone. This casing terminates in the injection zone with a screened, perforated, or open-hole completion, where injected concentrate exits the tubing and enters the receiving formation.

The well casing design and materials vary based on the physical and chemical nature of the concentrate and naturally occurring saline water in the rock formation, as well as the formation's characteristics. Concentrate must be compatible with the well materials that come into contact with it. Cement made of latex, mineral blends, or epoxy is used to seal and support the casing.

Well Grouting

The cement grouting surrounding each casing protects it from external corrosion, increases its strength, and prevents injected wastes from traveling to areas other than the designated injection zone. The type of cement and width of each cement layer surrounding a casing are typically regulated by the government agencies issuing permits (licenses) for well construction and operation.

Well Injection Zone

The characteristics of the receiving formation (injection zone) determine the appropriate well completion assembly — a perforated or screen assembly is suitable for unconsolidated formations such as sand and gravel, while an open-hole completion is used in wells that inject concentrate into consolidated sandstones or limestone.

The injection tubing, which is the innermost layer of the well, conveys concentrate from the surface to the injection zone. Because injection tubing is in continuous contact with concentrate, this tubing is constructed of corrosion-resistant material (e.g., fiberglass-reinforced plastic, coated or lined alloy stainless steel, or more exotic materials such as zirconium, tantalum, or titanium).

The annular space between the tubing and the long string casing, which is sealed at the bottom by a packer and at the top by the wellhead, isolates the casing from the injected concentrate and creates a fluid-tight seal. The packer is a mechanical device set immediately above the injection zone which seals the outside of the tubing to the inside of the long string casing. The packer may be a simple mechanically set rubber device or a complex concentric seal assembly. Constant pressure is maintained in the annular space. This pressure is continuously monitored to verify well's mechanical integrity and proper operational conditions.

Concentrate Pumping

Concentrate discharge pressure is usually adequate to convey concentrate to and down into the injection well. Many deep discharge wells operate at pressures of less than 14 psi (1 bar). However, depending on the geologic conditions and depth of the injection zone often the well feed pressure needed is in a range of 30 to 60 psi (2 to 4 bars). If the available concentrate head is insufficient, additional pumping will be needed.

The material of the injection well pump should be compatible with the physical and chemical properties of the injected concentrate. Past experiences with injection systems indicate that many difficulties are caused by improperly selected materials, resulting in corrosion of the injection pumps.

Concentrate Storage

Temporary storage of concentrate or an alternative method of disposal is needed to allow for maintenance and repairs of the injection well system. Additionally, the well system may be shut down if monitoring systems and monitoring wells indicate leakage. The type of storage facility or stand-by disposal method is highly dependent on the location of the well and the conditions surrounding the well site. If the injection well system is located near the coast, a discharge canal or pipeline can be used to temporarily discharge the concentrate flow to a saline water body. For example, a brackish desalination plant located in Englewood, Florida, is two miles from the Gulf of Mexico and has had an existing concentrate disposal pipeline available for use as a stand-by disposal system.

The deep well injection concentrate disposal system also includes a set of monitoring wells to confirm that the concentrate is not migrating into the adjacent aquifers. A variation of this disposal alternative is the injection of concentrate into existing oil and gas fields to aid field recovery. Deep well injection is frequently used for disposal of concentrate from all sizes of brackish water desalination plants.

Shallow beach well disposal is alternative to deep injection wells mainly used for seawater concentrate disposal. Compared to deep well injection, beach well disposal consists of concentrate discharge into a relatively shallow unconfined coastal aquifer that ultimately conveys this discharge into the open ocean through the bottom sediments. Discharge beach wells are typically used for small and medium-size seawater desalination plants only.

Design and Configuration Guidelines

Site Selection

Site selection is the first step of designing deep injection well system for concentrate disposal. Pertinent regulatory requirements in the US require injection wells to be sited in such fashion that they deliver concentrate into a formation which is beneath the lowermost aquifer used for drinking water supply which is located within ¼ mile (400 m) of the well site.

The location of a deep injection well is determined by the proximity of an acceptable injection zone. In order to avoid eventual plugging of the well, the water quality of the underground injection zone must be compatible to the water quality of the concentrate and the natural groundwater salinity of the injection zone aquifer receiving concentrate must be over 10,000 mg/L.

The geological formations of the injection zone should have high permeability and transmissivity, which are adequate to allow large volumes of concentrate to be injected without a significant pressure buildup. The injection zone should also be located away from abandoned wells, faults, or other hydrogeological short circuits.

The site selection for a discharge deep injection well system should begin with the evaluation of the condition, type, transmissivity of the geological formations and the salinity of the deep groundwater aquifers in the vicinity of the desalination plant site. In addition, the well designer will need to determine the location and depth of the shallow fresh water aquifers in the vicinity of the target well intake site as well as the current uses of these aquifers such as water supply, aquifer recharge, wastewater disposal, etc.

Deep injection wells should be located in geologically stable areas. The designer of a concentrate deep well injection system must install such system in area where there are no fractures or faults in the confining rock layer(s) through which injected concentrate could travel to drinking water sources.

Well designer must also ascertain that there are no wells or other artificial pathways between the injection zone and USDWs through which concentrate can travel. USEPA regulations prevent deep injection wells from being sited in seismically active areas because earthquakes could compromise the ability of the injection zone and confining zone to contain the injected concentrate.

Selection of Geological Formation

Deep injection wells should deliver concentrate into geological formations with the proper configuration to ensure that they can safely receive it. Extensive pre-siting geological investigations should be completed in order to confirm that the target injection zone is of sufficient lateral extent and thickness, and it is sufficiently porous and permeable so that the concentrate injected through the well can enter the rock formation without an excessive buildup of pressure and possible displacement of injected concentrate outside of the zone intended for its delivery. Typically, highly porous rock formations such as sandstone are very suitable for concentrate injection zones because they can retain large volumes of concentrate.

The injection zone should be overlain by one or more layers of relatively impermeable rock that can hold the injected concentrate in place and will not allow it to move vertically toward a USDW. This upper rock layer defines the confining zone which can be used for concentrate disposal. Confining zones are typically composed of shales or clays, which are “plastic” – i.e., they are less likely to be fractured than more brittle rocks, such as sandstones.

Deep wells typically are designed to inject concentrate into geologic formations thousands of feet below the land surface. In the US, the most suitable deep aquifers for concentrate disposal are located in the Gulf Coast, Texas, Great Lakes and Florida. In the Great Lakes region, injection well depths typically range from 1,500 to 5,500 ft (500 to 1,800 m); in the Gulf Coast, depths of geological formations suitable for concentrate disposal range from 1,800 ft to 10,000 ft (600 to 3,600 m) or more.

Florida has a distinctive underground environment that favors the use of deep injection wells. Five general injection zones exist within the state. The depths of these injection zones range from 600 ft to 7,500 ft (200 to 2,500 m) below land surface, with the most widely used zone being a unique underground discharge zone located in southeastern Florida, referred to as the Boulder Zone. The water quality of this zone is similar to seawater. Thick, compacted layers of dolomite and limestone separate the saline water injection zone from overlying freshwater aquifers. Such structure makes the Boulder Zone an ideal injection zone. Injection zone depths within the Boulder Zone range from 1,700 ft to 3,500 ft (550 to 1,200 m) whereas, injection zone depths along Florida's west coast range from 600 ft to 1,600 ft (200 to 500 m). Florida's deepest injection wells are found in the Panhandle, with average depths ranging from 6,000 to 8,000 ft (1,800 to 2,400 m). Concentrate at these depths move very slowly (on the order of a few meters per hundred or even thousand years) and therefore, when injected in these geological formations that concentrate subsurface is likely to remain confined for a long time.

It is important to determine the groundwater quality of the aquifer selected for deep well injection. The natural aquifer salinity of the injection zone should be higher or equal to the salinity of the concentrate being injected into it in order not to degrade aquifer quality. Usually, deep aquifers have very high salinity and meeting this requirement is not a challenge.

Sizing of Injection Wells

Well sizing involves the determination of well depth, diameter and number of wells.

Well Depth

This well parameter is determined by the depth of the injection zone to which the desalination plant concentrate is delivered. The injection zone depth in turn is established based on the available deep aquifers in the vicinity of the desalination plant site suitable for concentrate disposal. In the US, the deep confined aquifers are well studied and information of their capacity; size and location of other existing installations discharging to the same aquifers; and other data of the target hydrogeological formation are usually readily available from the state and/or local regulatory agencies responsible for groundwater resources oversight and management.

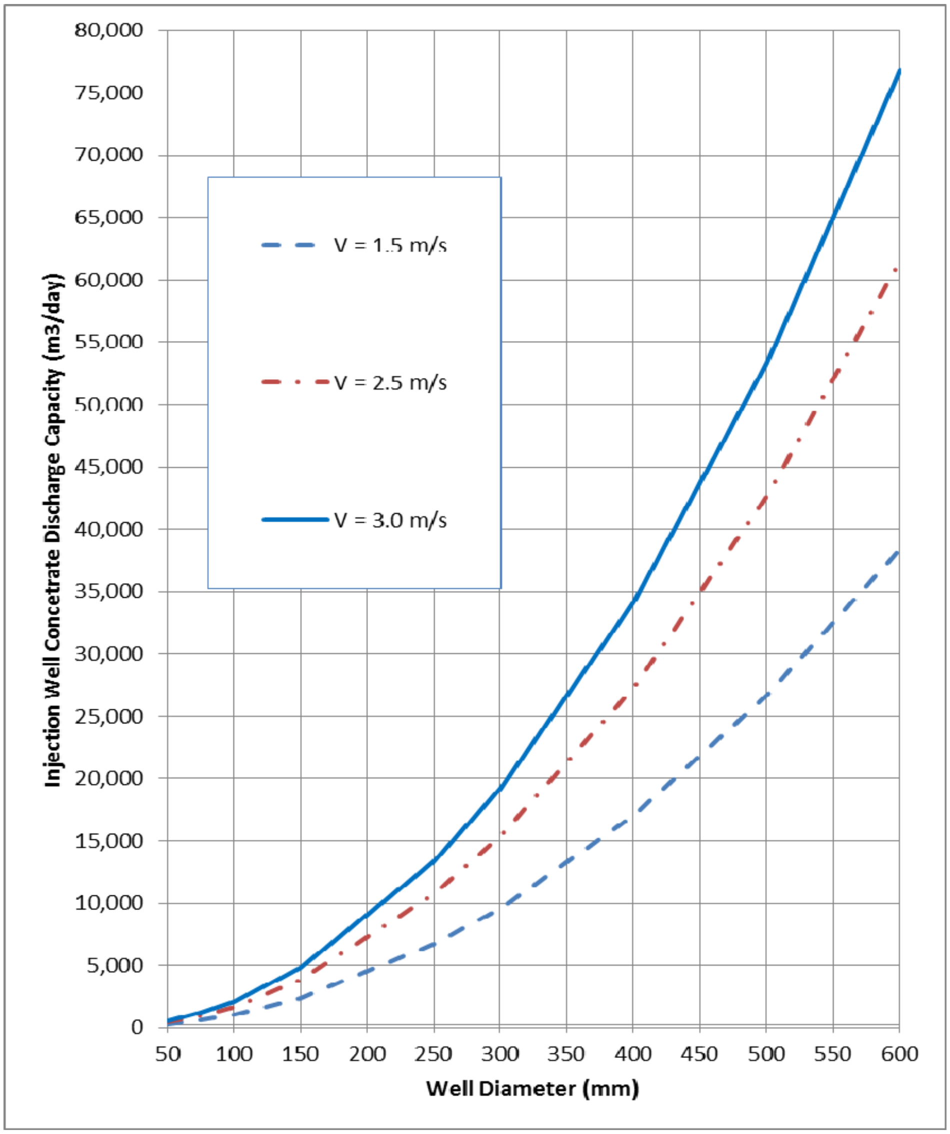
If such information is not readily available for a given project location, then the design engineer will need to complete site-specific hydrogeological investigation in order to determine the depth and capacity of the deep confined aquifer/s to which desalination plant discharge could be discharged. As indicated previously, injection well depth can vary from several hundred to several thousand feet.

Well Diameter and Number

Well diameter and number are established based on the maximum and average volumes of concentrate planned to be discharged. The number of wells is typically determined as a function of on the desalination plant annual operation pattern and the RO system configuration. Typically, the total number of duty discharge wells is designed to match the number of RO trains of the desalination plant, if possible. In addition, a number of standby wells of discharge capacity of 20 to 30% are constructed to accommodate periodic well maintenance and inspection as well as potential decrease in well capacity over time.

Well diameter is typically determined based on a maximum well tubing velocity of 10 fps (3 m/s), the total maximum concentrate discharge flow rate; and the total number of duty wells. The maximum design well velocity of 10 fps (3 m/s) is established based on good engineering practices and the regulatory requirements of some states (i.e., State of Florida in the US). The average well tube velocity should be in a range of 5 to 10 fps (1.5 to 3 m/s). Figure 10 presents injection well discharge capacity as a function of well diameter and tubular velocity. This graph can be used for determining the size of individual injection wells.

For example, a brackish desalination plant with fresh water production capacity of 10. 6 MGD (40,000 m^3/day) designed at 80% permeate recovery will generate 2.6 MGD (10,000 m^3/day) of concentrate. It is assumed that the BWRO plant has four 2.6 MGD (10,000 m^3/day) RO trains and should be designed to operate at a minimum capacity of 25% of the total plant production capacity with one RO train in service. The desalination plant concentrate is planned to be disposed using deep injection wells which will deliver the concentrate to a confined aquifer at a depth of 2,600 ft (800 m).



Note: 1 MGD = 3,785 m^3/day

Figure 10 – Injection Well Discahrge Capacity as a Function of Diameter

The example below presents the estimate of the number and size of concentrate injection wells needed for this project. The number of wells will be selected to be the same as the number of RO trains (i.e., 4) so at minimum production capacity the plant will have one RO train and one discharge well in operation. As a result, the unit capacity that a single duty well has to be designed to discharge is 2.6 MGD/4 = 0.65 MGD (2,500 m^3/day) per well.

Using Figure 10, for this size injection well and well velocity of 8 fps (2.5 m/s), the well diameter is selected to be 150 mm (6-inches). At average velocity of 8 fps (2.5 m/s) this well can discharge 1.03 MGD (3,900 m^3/day), which is well above its average design capacity of 0.65 MGD (2,500 m^3/day). At maximum discharge velocity of 10 fps (3.0 m/s) the well can safely dispose up to 1.32 MGD (5,000 m^3/day) of concentrate. Because of the large installed maximum discharge capacity of the four duty 6-inch (150-mm) diameter wells, the desalination plant does not require additional standby wells. Depending on the discharge water quality however, it may be prudent to install one standby well, especially if the scaling potential of the source brackish water and the water quality of the receiving aquifer are not well known.

In summary, for the example presented above a conservatively designed injection well system for concentrate disposal of the reference 10.6 MGD (40,000 m^3/day) desalination plant will have four duty and one standby wells of 6-inch (150-mm) diameter and 2,600 ft (800 m) depth, each.

Concentrate pretreatment

Concentrate pretreatment prior to deep well injection is typically needed when the receiving geological formation may be plugged by the concentrate discharge as a result of chemical incompatibility. Typical pretreatment includes removal of total suspended solids from the desalination plant discharge which may be accomplished using cartridge or bag filters or more sophisticated solids removal system, such as contact clarifiers or lamella settlers.

Another type of pretreatment that may be needed is the reduction of the concentrate pH in order to prevent scale formation along the well walls and in the injection zone. Typically, scaling compounds which may create disposal challenges are: sulfates of calcium, barium and strontium, calcium fluoride, as well as salts of iron, manganese and aluminum.

Environmental monitoring well system

In order to ascertain the proper performance of the deep well injection system for concentrate disposal, this system will need to incorporate one or more monitoring wells. Typically a deep and shallow monitoring wells or dual zone well are installed in the vicinity of the concentrate discharge system.

9. Land Application

Land application is concentrate disposal alternative which involves: (1) spray irrigation of concentrate on salt-tolerant plants; or (2) infiltration of concentrate through earthen rapid infiltration basins (RIBs). Land application is typically used for small volumes of brackish water concentrate only and its full-scale application is limited by climate conditions, seasonal application; and by availability of suitable land and groundwater conditions.

Key feasibility factors associated with the use of land application for concentrate disposal include: climate; availability and cost of land; percolation rate; irrigation needs; water-quality of the underlying groundwater aquifers; salinity tolerance to of the irrigated vegetation; and the ability of the land application system operation to comply with pertinent regulatory requirements and groundwater quality standards.

Successful multi-year use of such concentrate disposal by land application is contingent upon availability of: site with relatively low ground water level; warm, dry climate as well as large amount of low-cost land in the vicinity of the desalination project generating concentrate for disposal. Year-around conditions for land application of concentrate usually exist in inland desert-like environments. In colder climate conditions and for specific vegetation, storage facilities may be needed to retain concentrate during the period when it cannot be land applied (typically two to six months). Alternatively, a backup concentrate disposal option should be considered for periods of the year when land application is not possible.

Concentrate salinity is a key limiting factor for the feasibility of land application. As concentrate salinity increases, the feasibility of this scenario decreases. In many cases, concentrate has to be diluted prior to application in order to meet applicable groundwater quality constraints and/or vegetation salinity tolerance limits. Often treated wastewater effluent or low-salinity water extracted from shallow aquifers near the land application site is used to dilute the concentrate prior to land application.

Soil type is of critical importance for the feasibility of land application. Typically, loamy and sandy soils are suitable for this concentrate disposal method. Neutral and alkaline soils are preferable because they would minimize trace metal leaching. Sites with groundwater level lower than 6 ft (2 m) from the ground surface are preferred. If site groundwater level is less than 10 ft (3 m) from the surface, installation of drainage system would be needed. Typically, sites with slopes of up to 20% are suitable for land application. Sites with higher slopes would need to be levelled.

Irrigation of Salt-tolerant Vegetation with Concentrate

Irrigation with concentrate involves its application to vegetative surface and collection of the residual drainage water by a runoff control system, if needed. The concentrate stream is applied to a vegetative area by distribution system. There are three broad categories of concentrate distribution systems: (1) sprinkler or spray systems, (2) surface systems, and (3) drip irrigation systems. Sprinkler systems are most commonly used for concentrate disposal.

Spray irrigation systems cannot be used on variable soils, shallow soil profiles, rolling terrain, erosion-prone soils, and areas where high water tables exist. Disadvantages of sprinkler systems include their higher initial capital cost, higher energy costs, mechanical failures, wind drift problems, and excessive evaporation losses. Also, crops irrigated with sprinklers are subject to injury not only from the salts in the soil but also from the salts directly adsorbed on the wetted leaf surfaces. In general, plants with waxy leafs are less susceptible to injury from contact with concentrate that others.

Slowly rotating sprinklers that allow drying between spray cycles should be avoided since this irrigation pattern increases the wetting-drying frequency. Sprinkling should be completed at night or in the early morning when evaporation rate is lower. Surface systems use narrow-graded (less than 16 ft/5 m) and wide-graded (100 ft/30 m or greater) borders or furrows for irrigation water distribution. In general, surface irrigation systems are more suitable for irrigation with higher salinity concentrate than sprinklers. Drip systems have the greatest advantages when saline water is sprayed but they have found limited application because the system emitters clog easily. Drip irrigation avoids wetting the leaves with saline water.

The volume of runoff generated by an irrigation process depends on the type of irrigation system used. Spray distribution systems do not generally cause surface runoff, whereas surface systems produce some runoff. Ditches or drainage canals can be constructed to retain runoff, or tailwater return systems can be used instead. A tailwater return system consists of: sump or reservoir; pump station; and return pipeline. The pumps servicing these systems are typically sized for 25% of the distribution system.

The predominant type of sprinkler systems is solid-set. A solid-set system consists of mainline and lateral pipes that cover the irrigation field with the sprinklers spaced along each lateral. Pumping is usually needed to deliver the concentrate to the lateral pipelines and sprinkler heads. Solid-set systems remain in one position during concentrate application. The major advantages of these sprinkler irrigation systems are their low labor requirements and maintenance costs. The main disadvantage is their high installation cost.

Storage facilities are typically needed to retain concentrate during heavy rainfalls or periods when concentrate cannot be applied on the vegetation. Storage is usually provided in earthen holding tanks lined concrete or in steel structures with protective coating. Sometimes, temporary concentrate storage is provided in percolation ponds or earthen storage lagoons which allow to reduce concentrate volume.

Irrigation systems located in areas with high water table [i.e., water levels located 10 ft (3 m) or less from the ground surface] are often designed with subsurface drainage to provide a root zone area conducive to good vegetative growth. The proximity of the irrigation site to canals, rivers, and other bodies of water should be considered when the irrigation site is chosen because seepage from other water bodies can contribute to subsurface drainage problems.

Subsurface drainage systems consist of a network of buried perforated drainage pipes that designed to collect concentrate that has not been retained in the irrigated upper soil layer and vegetation. The collected concentrate is conveyed to a basin and either reused for irrigation or discharged into a surface water body.

Feasibility Factors

Concentrate salinity and levels of other contaminants determine whether or not irrigation is a viable option. An assessment of the compatibility with target vegetation should be conducted, including review of the acceptable maximum sodium adsorption ratio (SAR); trace metals uptake; and other vegetative and percolation factors. When salinity level of the concentrate is higher than 2,000 mg/L, special salt-tolerant species (halophytes) could be considered for irrigation.

Spray irrigation may be viable land application alternative when the desalination plant which is the source of concentrate is located in the vicinity of an agricultural area where salt-tolerant crops are grown year-around. While in most cases, concentrate cannot be applied directly for the irrigation of lawns, golf courses, and public parks due to its high salinity/sodium content, after blending and dilution with reclaimed water or other low-salinity water source down to less than 1,000 mg/L of TDS, such application may become feasible.

Sodium adsorption ratio (SAR). Parameter referred to as sodium adsorption ratio (SAR) is typically used to determine the maximum level of sodium in the concentrate that could be safely applied to the soil without an adverse long-term effect on soil structure and permeability. SAR is defined by the following formula:

$$\mathrm{SAR} = \mathrm{Na}/\ [(\mathrm{Ca} + \mathrm{Mg})]/2]^{1/2} \qquad (8)$$

Where, Na = sodium concentration in milliequivalent per liter (meq/L);
Ca = calcium concentration (meq/L);
Mg = magnesium concentration in (meq/L).

Usually, SAR higher than 9 may have an adverse impact on soils and is not recommended. In the case of land application to low-salinity tolerance crops and plants, SAR often will have to be maintained below 6.

TDS. Salinity decreases the water intake of plants by lowering the osmotic potential of the soil. The presence of salts in the soil reduces the rate at which water moves into the soil and also diminishes soil aeration. As a result, increase in salinity of the irrigation water results in decrease in the plant productivity.

Practically all plants can tolerate TDS lower than 500 mg/L. Salinity-sensitive species such as beans, strawberries, almonds, carrots, onions, avocado, and most golf-course grasses are affected by concentrate with TDS level higher than 1,000 mg/L. Some crops (i.e., sugar beet, sugar cane, dates, cotton, and barley) are tolerant to salinities of 2,000 mg/L or more.

Typically, only high-salinity tolerance plants (halophytes) can be irrigated with concentrate of salinity higher than 2,000 mg/L. Halophytes usually grow in the world's salt marshes and deserts. These plants can not only tolerate high salinity levels, but can also extract salt from the water and store it in the plant tissue. Since most desalination plant concentrates have salinities higher than 2,000 mg/L, spray irrigation typically can be applied only in limited number of occasions. Table 2 provides guideline for the TDS threshold of various salt-tolerant crops. The salinity thresholds presented in this table should be considered as guidelines only. Actual crops tolerance would also vary depending on the site-specific climate and soil conditions. As indicated in Table 2, rye and rapeseed could be successfully cultivated using concentrate of 6,000 to 7,000 mg/L of TDS. Date palms which are commonly cultivated in the Middle East and other arid parts of the world, could tolerate salinity of up to 2,550 mg/L.

Table 2 – Guideline for Salinity Tolerance of Common Crops

Crops	**TDS Threshold (mg/L)**	**TDS at Which Yield Declines with 25% (mg/L)**
Rye	7,300	8,800
Rapeseed (Brass. Napus)	7,000	8,250

Barley(1)	5,100	8,300
Guayule	5,000	6,500
Cotton	4,900	8,000
Sugar Beet(2)	4,500	7,200
Sorghum	4,350	5,350
Triticale	3,900	10,300
Date Palm	2,550	7,000

Notes: (1) Sensitive during seeding stage – max salinity 2,600 mg/L; (2) Less tolerant during germination (max salinity 2,000 mg/L)

While, the plants presented on Table 2 have salinity tolerance in a range of 2,550 to 7,300 mg/L, other halophytes can tolerate salinities of up to 40,000 mg/L.

Trace Metals. In addition to the effects of total salinity on vegetative growth and soil, individual ions can cause a reduction in plant growth as well. Toxicity caused by a specific ion occurs when that ion is taken up and accumulated by the plants. The recommended long-term and short-term use limits of key trace metals in the concentrate applied for irrigation are shown in the Table 3 (adapted from USEPA).

Table 3 – Recommended Limits for Trace Metal Constituents

Constituent	Long-term Use (mg/L)	Short-term Use (mg/L)	Notes
Aluminum	5.0	2.0	Can cause non-productivity in acid soils.
Arsenic	0.1	2.0	Toxicity threshold varies – Sudan grass limit = 12 mg/L.
Beryllium	0.1	0.5	Toxicity threshold varies – kale limit = 5 mg/L.
Boron	0.75	2.0	Most grasses tolerant at 2 to 10 mg/L.
Cadmium	0.01	0.05	Toxic to beans and beets at 0.1 mg/L.
Cobalt	0.05	5.00	Toxicity inactivated in neutral and alkaline soils.

Copper	0.2	5.0	Toxic to a number of plants at 0.1 to 1.0 mg/L.
Iron	5.0	20.0	Could contribute to soil acidification & loss of Phosphorus.
Lead & Manganese	5.0	10.0	Can inhibit plant growth.
Nickel	0.2	2.0	Reduced toxicity in neutral and alkaline soils.
Selenium	0.02	0.02	Toxic to many plants at relatively low concentrations.
Vanadium	0.1	1.0	Toxic to many plants at relatively low concentrations.
Zinc	2.0	10.0	Reduced toxicity in soils with pH above 6.

Salt is continually added to the soil with each irrigation water application, a practice that would eventually harm vegetation. The rate of saline accumulation depends on the quantity of salt applied and the rate at which it is removed from the soil by leaching. Adequate subsurface drainage is also necessary to avoid shallow water tables, which become an additional source of salts.

pH. The pH of the concentrate typically has indirect effect on the soils mainly by leaching trace metals at low pH. The minimum pH threshold of the concentrate is recommended at 6.

Other Factors. Other conditions must also be met before irrigation with concentrate can be considered a practical disposal option. First, there must be a need for irrigation water within the vicinity of the desalination plant. Second, a backup disposal or storage method must be available during periods of heavy rainfall. Third, nearby surface waters have to be protected from the runoff generated from the irrigation site. The soil must also be able to support a vegetative surface. The need to prepare irrigation land by clearing or grubbing adds to overall disposal site costs and should be considered in selecting potential irrigation sites.

Concentrate Disposal by Rapid Infiltration Basins

Rapid infiltration basins (RIBs) typically are series of earthen basins with highly permeable soil bottoms which allow for high-rate percolation and infiltration of the concentrate into the ground. Concentrate is delivered to the individual infiltration basins via conveyance pipeline, enters the basins, quickly infiltrates through the porous surface soil, and then rapidly percolates into the underlying soils. In addition to the basins, the RIB system includes dikes, access ramps, inlet structures, outlet structures, flow control devices and depth measurement devices.

Uniform application of the desalination plant discharge on the basin surface is necessary to avoid erosion. A simple splash block at the point of discharge may be used for small basins, whereas larger basins typically have a concentrate distribution system.

Site Selection

Selecting suitable site for the RIB system is of critical importance for the successful use of this concentrate disposal method. Potential RIB sites should be characterized in terms of topography; soil classification to 10 ft (3 m) below the bottom of the RIB, lithology of the vadose zone; aquifer quality and gradient; existing vegetation; and distance to nearest seeps and surface waters. The site hydrogeological conditions will need to be investigated based on information from several boreholes extending to depth of the groundwater surface or maximum of 165 ft (50 m). Infiltration and permeability of the site soils will need to be tested at the bottom of the basin, 6 ft (2 m) and 12 ft (4 m) below the bottom of the RIBs in order to identify the most suitable depth of concentrate delivery.

RIB Area

The total area of a rapid infiltration basin system is determined by the amount of land needed for transmission pipe easement, infiltration basins, access roads, pumping, buffer zones, maintenance building, and future expansion. The active concentrate application surface area of the RIBs is calculated based on a hydraulic surface loading rate which in turns depends on the effective conductivity of the soils.

A typical cycle for a mix of concentrate and pretreatment backwash water during the summer period will be two (2) days of concentrate application followed by seven (7) days of drying [i.e., total cycle length of nine (9) days]. In the winter, the typical application schedule is 2 days of concentrate feed followed by 12 days of infiltration (i.e., total cycle length of 14 days).

The design loading rate must be based on the least permeable soil layer in the soil profile and on expected worst-case weather conditions. Concentrate discharge into the RIBs should be intermittent to maintain the design loading rate and soil capacity. The RIB system should be designed to comply with the following key design recommendations:

- Minimum Number of RIBs = 3;
- Minimum Basin Depth = 5 ft (1.5 m);
- Minimum Distance from RIBs to Site Boundary = 500 ft (150 m);

- Minimum Basin Bottom Permeability at 1 ft (30 cm) = 0.6 in/sec (1.4 cm/sec);
- Maximum Depth of Ground Water Below Basin Bottom = 10 ft (3 m);
- Minimum Depth of Impermeable Layer Below Basin Bottom = 30 ft (10 m);
- Minimum Distance from Water Supply Wells = 1,000 ft (300 m);
- Minimum Number of Monitoring Wells = 3 (one up-gradient and one down-gradient of the RIB).

Typically, the number of RIBs varies between 3 and 17 and individual basins can range from 0.2 to 2.0 ha for small and medium size applications and 2.0 to 5.0 ha for large projects. RIBs are recommended to be located perpendicular to the groundwater flow direction in order to reduce groundwater mounding.

The dikes for the RIBs have to be at least 1.5 ft (0.5 m) deeper than the maximum design water depth. Most dikes are 3 to 5 ft (1.0 to 1.5 m) deep and in some cases they are shallower. Higher dikes are not beneficial and contribute to operation problems through due to the extra runoff and potential for erosion of soil fines. The dikes should be compacted to prevent seepage through them. The top of the dikes is usually deigned for a vehicular access and should be at least 20 ft (6.0 m) wide. Use of silt fence or similar porous barrier at the tow of the dikes is recommended to protect against washout of soil fines.

Similar to irrigation systems, as a minimum 2 to 5 days of operational storage is recommended to be provided for RIB facilities. Depending on the local climate conditions, larger storage volume may be needed.

10. Evaporation Ponds

Evaporation ponds are shallow lined earthen basins in which concentrate evaporates naturally as a result of solar irradiation. As fresh water evaporates from the ponds, the minerals in the concentrate are precipitated in salt crystals, which are harvested periodically and disposed offsite. Evaporation ponds could be classified in two main groups: (1) conventional evaporation ponds; and (2) salinity gradient solar ponds. The fundamental difference of the two types of ponds is that while conventional evaporation ponds are primarily designed for concentrate disposal, the main function of solar ponds is to generate electricity from solar energy.

Conventional Evaporation Ponds

Conventional evaporation ponds consist of series of lined or unlined earthen or concrete structures designed to maximize water evaporation. They operate using natural solar evaporation of concentrate periodically fed to man-made lined earthen basins. Holding ponds are needed for concentrate storage while the evaporation pond reaches the high salinity needed for normal pond operations. The ponds should be fenced to prevent entrance and potential harm of people and animals in the area.

While evaporation ponds are typically designed to accommodate concentrate for the projected life of the desalination facility, precipitation of salts must be incorporated into the depth requirements of the pond or provisions must be made for periodic removal and disposal or beneficial use of the precipitated salts. The salts accumulated at the bottom of the ponds are typically disposed to a suitable landfill.

Solar Ponds

Solar ponds are deep lined earthen lagoons containing high-salinity water which are designed and operated to collect solar energy and convert it into electricity. It should be pointed out that while conventional evaporation ponds are configured to maximize heat convection and evaporation, solar ponds are deeper lagoons designed to retain heat and therefore, have lower evaporation rate. For this reason, solar ponds are often considered a system for beneficial use of concentrate (i.e., generation of electricity) rather than as an efficient concentrate disposal method.

Three layers of different salinity water naturally form in solar ponds (from top to bottom) - surface zone, gradient zone and lower zone. The surface zone is also referred to as an upper convective zone and is comprised of cool water of low salt content. This zone is typically 1 to 1.5 ft (0.3 to 0.5 m) deep.

The lower (salt-gradient) layer is a homogeneous, concentrated salt solution that is typically salinity and temperature stratified. The temperature and salinity of the concentrate in this layer increase from top to bottom. The thickness of this layer is typically 1.5 to 5.0 ft (0.5 to 1.5 m).

The bottom (high-salt content) layer contains concentrate with salinity near saturation level (TDS of 250,000 to 260,000 mg/L). If the salinity gradient in the salt-gradient layer is large enough, there is no convection in the gradient zone even when heat is absorbed in the lower zone and on the bottom, because the hotter, saltier water at the bottom of the gradient remains denser than the colder, less salty water above it.

As water is transparent to visible light but opaque to infrared radiation, the energy in the form of sunlight that reaches the lower zone and is absorbed there can escape only via conduction. Because the heat conductivity of concentrate is very low, the salt-gradient layer above the lower level works as an insulation which retains the heat accumulated in the bottom layer. As the temperature of this layer reaches 85 ^{0}C, the hot concentrate can be used to generate thermal electricity. Solar ponds have been successfully tested in El Paso, Texas and in Victoria, Australia.

Feasibility and Design Considerations

Groundwater quality regulations in the US require evaporation ponds to be constructed with impervious lining for protection of underlying aquifers. Typically, concentrate is not contaminated with hazardous materials and a single layer liner is adequate for groundwater protection. However, if concentrate is contaminated (i.e., contains high levels of trace metals), then double-lined pond may need to be constructed.

If the ponds are not lined or point liner is damaged, a portion of the concentrate may percolate to the water aquifer beneath the pond and deteriorate its water quality. Therefore, evaporation pond systems, especially these using geo-membrane liners, should be equipped with underground leak-detection systems that lie beneath the liner. Alternatively, pond leakage can be monitored via groundwater monitoring well system with at least three monitoring wells: one installed up-gradient to the groundwater flow; one down-gradient and one in the middle of the pond system. Monitoring must be conducted monthly.

Solar evaporation is feasible concentrate disposal alternative only in relatively warm, dry climates with high evaporation rates; low precipitation rates and humidity; flat terrain; and low land cost. Typically, evaporation ponds are not feasible for regions with annual evaporation rate lower than 3.3 ft/yr (1.0 m/year) and annual rainfall rate higher than 1.0 ft (0.3 m/yr).

Factors affecting evaporation rate are:

- Humidity;
- Temperature;
- Solar Irradiation Intensity;
- Wind;
- Rainfall;
- Concentrate Salinity.

Humidity has a significant impact on pond evaporation rate – the higher the humidity the lower the evaporation rate. Usually when the average annual humidity of a given location exceeds 60% the use of evaporation ponds is not likely to be a viable concentrate disposal option.

- Evaporation ponds are very climate dependent. The higher the temperature and solar irradiation intensity the more viable this option is. Dry equatorial and sub-equatorial regions of the world would be very suitable for such concentrate disposal alternative.

- Wind speed and duration have a significant impact on evaporation rate – windier locations are more suitable for installation of evaporation ponds. However, wind often carries solids (sand and dust) that could fill the ponds during sand storms.

- Significant rainfall reduces evaporation rates. In high-rainfall portions of the world, the actual annual rainfall rate should be subtracted from the annual evaporation rate, when determining the actual design pond evaporation rate. The difference between the standard annual evaporation rate and rainfall is referred to as evapotranspiration potential.

- For example, in Southern Florida the standard evaporation rate is between 3 and 6 ft/yr (1.0 and 2.0 m/yr). However, when corrected for the rainfall impact, the actual pond design evaporation rate has to be is reduced down to 2 ft/yr (0.6 m/yr). This rate corresponds to a land requirement of over 110 acres/MGD (70 ha/1,000 m^3/day) of concentrate.

- Evaporation rate decreases as solids and salinity levels in the ponds increase. However, typically it is less costly to evaporate higher salinity concentrate of smaller volume, than lower salinity concentrate of larger volume – i.e., minimization of concentrate volume is beneficial if this concentrate will be disposed using evaporation ponds.

Design and Configuration Guidelines

The disposal capacity of conventional evaporation ponds is a function of concentrate flow; evaporation rate at the location of the ponds; and average annual rainfall. Evaporation ponds are typically sized to ensure the containment of the maximum operating volume of concentrate and an inflow from a 100-year, 24-hour storm event under which conditions the ponds should have a minimum of 2 ft (0.6 m) freeboard.

The basic design recommendations for conventional evaporation ponds are as follows:

- Minimum of Two (2) Ponds;
- Dikes Constructed of Impervious Material and Compacted to At Least 90% of Its Maximum Dry Proctor Density;
- Minimum Depth = 8 ft (2.5 m);
- Minimum Freeboard at Average Annual Flow = 3 ft (1 m);
- Removal of Salt Deposits Every Two (2) Years;

Most ponds are designed in square or rectangular shape. Usually it is more beneficial to construct larger number of smaller size ponds than to have one or two large evaporation ponds because the smaller size pond configuration allows minimizing wind-triggered wave damage on the pond dikes.

Sizing of Conventional Evaporation Ponds

Pond Depth

As indicated previously, shallower ponds result in increased evaporation rate. However, the lower the pond depth the larger evaporation area is needed, which in turn translates to higher concentrate disposal costs. Taking into consideration that increase of pond depth from 0.3 ft (0.1 m) to 8 ft (2.5 m) would result in only 4% reduction in evaporation rate deeper ponds are overall more cost effective.

Optimum pond depth in terms of evaporation rate is approximately 2 ft (0.5 m), but often deeper 8 to 16 ft (2.5 to 5.0 m) ponds are used in order to reduce their construction costs and to accommodate salt accumulation at the bottom of the ponds, as well as to provide for accumulation of water from precipitation and for contingency water storage.

Pond Dikes

The perimeter of the evaporation ponds is surrounded by earthen dikes. The dikes are typically compacted earthen structures with slope of 2:1 to 4:1 and 12 to 20 ft (4 to 6 m) wide road on the top. Dike height usually varies between 5 to 12 ft (1.5 m and 4 m).

Pond Liner

Typically, concentrate evaporation ponds are lined with clay, clay/bentonite mix; or plastic (PVC, HDPE and Hypalon) liners. Liners should be designed to cover pond bottom, dikes and 2 to 3 m of additional area between the dike walls and the road (see Figure 11).

Evaporation pond liner should be designed to have very low hydraulic conductivity ($< 10^{-7}$ cm/sec) and seepage rate (< 5 mm/day); and at least 20-year durability on exposure to high salinity concentrations and ultraviolet (UV) light. Suitable liners are:

- In-Situ Clay with Thickness of 3 ft (1 m) or More;
- Compacted Clay of Thickness of 1.5 ft (0.5 m) or More;
- Soil and Bentonite Mix of Minimum Thickness of 0.3 ft (0.10 m).
- Geo-Membrane Liner with Thickness of 30-mil or More. If HDPE Liner is used the Minimum Liner Thickness Should be at Least 1.5 mm (60 mil).

Figure 11 – Geo-membrane Evaporation Pond Liner

The clay (in-situ or compacted) used as pond liner must comply with the following requirements: (1) more than 30% of the material passing the #200 sieve (0.074 mm); (2) liquid limit of 30 % or more; and (3) plasticity index higher or equal to 15%.

In addition, the clay liner must be applied in at least four (4) successive layers ("lifts") of not more than 20 cm in thickness (un-compacted) each; which should be compacted to 95% of its standard Proctor maximum dry density to meet the maximum hydraulic conductivity requirement of 10^{-7} cm/sec (minimum compacted thickness of 6 in (15 cm). Most pond liners have pH tolerance range of 6 to 9, and if the pH of the concentrate is outside of this range, it has to be properly adjusted before its application.

<u>Pond Area</u>

The evaporation pond surface area is primarily function of the evaporation rate, which in turn is determined by local climate conditions. It should be pointed out that standard evaporation rate is typically presented in m/yr and is measured for fresh water (1 m/yr = 27.4 m^3/day.ha).

Figure 12 shows typical evaporation rates for locations in the US most favorable for the construction of evaporation ponds - Southern Arizona (S. AZ), Western Texas (W. TX) and

Southern California (S. CA). As shown on this figure, the average annual evaporation rates vary between 0.7 and 1.5 m/yr (19.8 and 40.7 m^3/day.ha). For comparison, the evaporation rate is Aswan, Egypt is 5.0 m/yr.

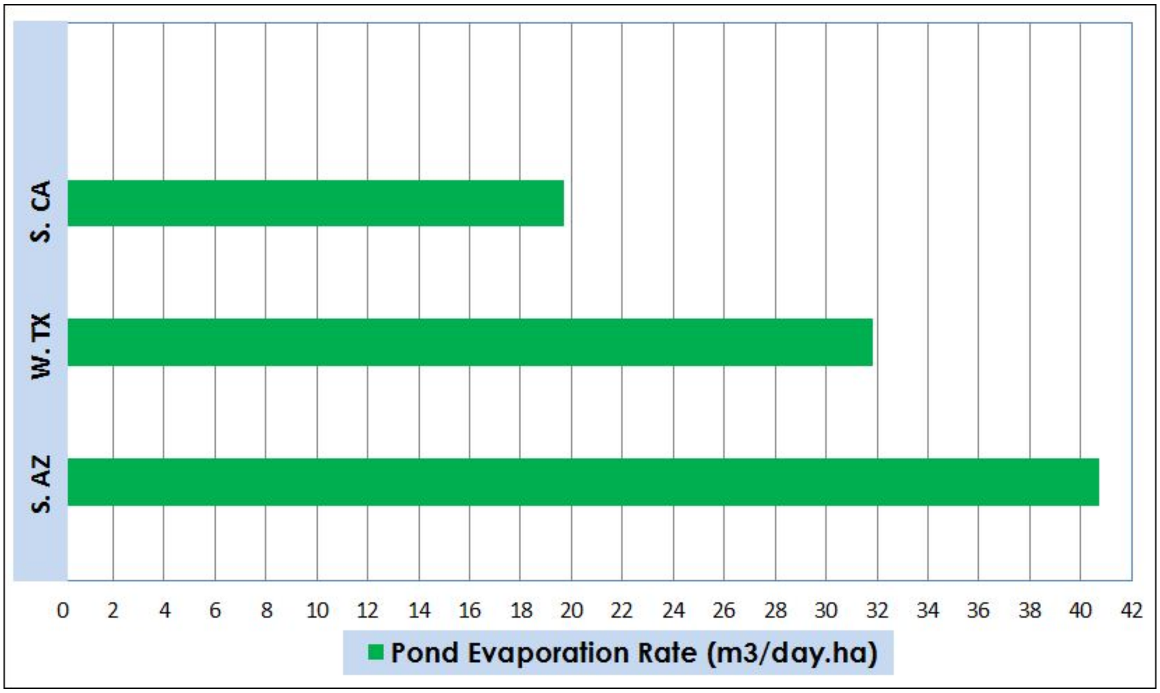


Figure 12 – Evaporation Rates in the Three Arid US Regions

It should be pointed out that standard evaporation rates readily available in the technical literature are determined for fresh water. Since evaporation rate decreases with salinity concentration, such "fresh water" evaporation rates should be reduced when applied to concentrate. The reduction ratio/actual evaporation rate will be very site-specific and therefore, it is recommended to be determined through pilot-testing.

If no specific data are available, concentrate evaporation rate can be assumed to be 70 % of the fresh water evaporation rate for a given location. While 70 % is a conservative estimate, and for low-salinity brackish SWRO plants this ratio could be significantly lower (80 to 90%). Often an additional 20 to 25 % of contingency is added to the capacity of the ponds to accommodate rain events and varying concentrate production and water quality over the useful life of the project. In summary, the total pond surface area as a function of the fresh water evaporation rate is expressed as follows:

$$A_p = (Q_{conc} \text{ x } S_F)/ (C_F \text{ x } SER)$$

where:

A_p = active evaporative pond area, ha; Q_{conc} is concentrate flowrate in m^3/day; SER – standard evaporation rate for fresh water, m^3/day.ha; C_F – contingency factor; S_F – factor for conversion of fresh water evaporation rate to concentrate evaporation rate. As indicated previously, unless the specific C_F is determined based on pilot testing, a conservative value of $C_F = 0.70$ (i.e., 70 %) should be used for pond sizing. The S_F typically has a value of 1.2 to 1.3.

11. Selection of Concentrate Management Approach

Key advantages and disadvantages of the most commonly used concentrate management alternatives presented in the previous sections of this book are summarized in Table 4.

Table 4 – Comparison of Concentrate Management Alternatives

Concentrate Management Alternative	**Key Advantages**	**Key Disadvantages and Challenges**
Surface Water Discharge	• Can be Used for All Sizes Plants • Cost Effective for Medium and Large Projects	• Concentrate May Impact Marine Habitat • Complex and Costly to Permit
Sanitary Sewer Discharge	• Low Construction and Operation Costs • Easiest to Implement • Low Energy Use	• Applicability Limited to Small Size Plants • Potential Negative Impact on WWTP Operations
Deep Well Injection	• Suitable for Inland Desalination Plants • Moderate Costs • Low Energy Use	• Only Feasible If Deep Confined Saline Aquifers are Available • Potential for Groundwater Contamination
Land Application	• Relatively Easy to Implement and Operate • Beneficial Use of Concentrate	• Seasonal and Climate Dependent • Limited to Small Plants • Potential for Groundwater Contamination
Evaporation Ponds	• Easy to Implement and Operate • Can Be Applied for Both Inland & Coastal Projects	• Very Large Footprint and High Costs • Climate Dependent • Limited to Small Plants

A general decision tree for selection of desalination plant discharge management alternatives is presented on Figure 13.

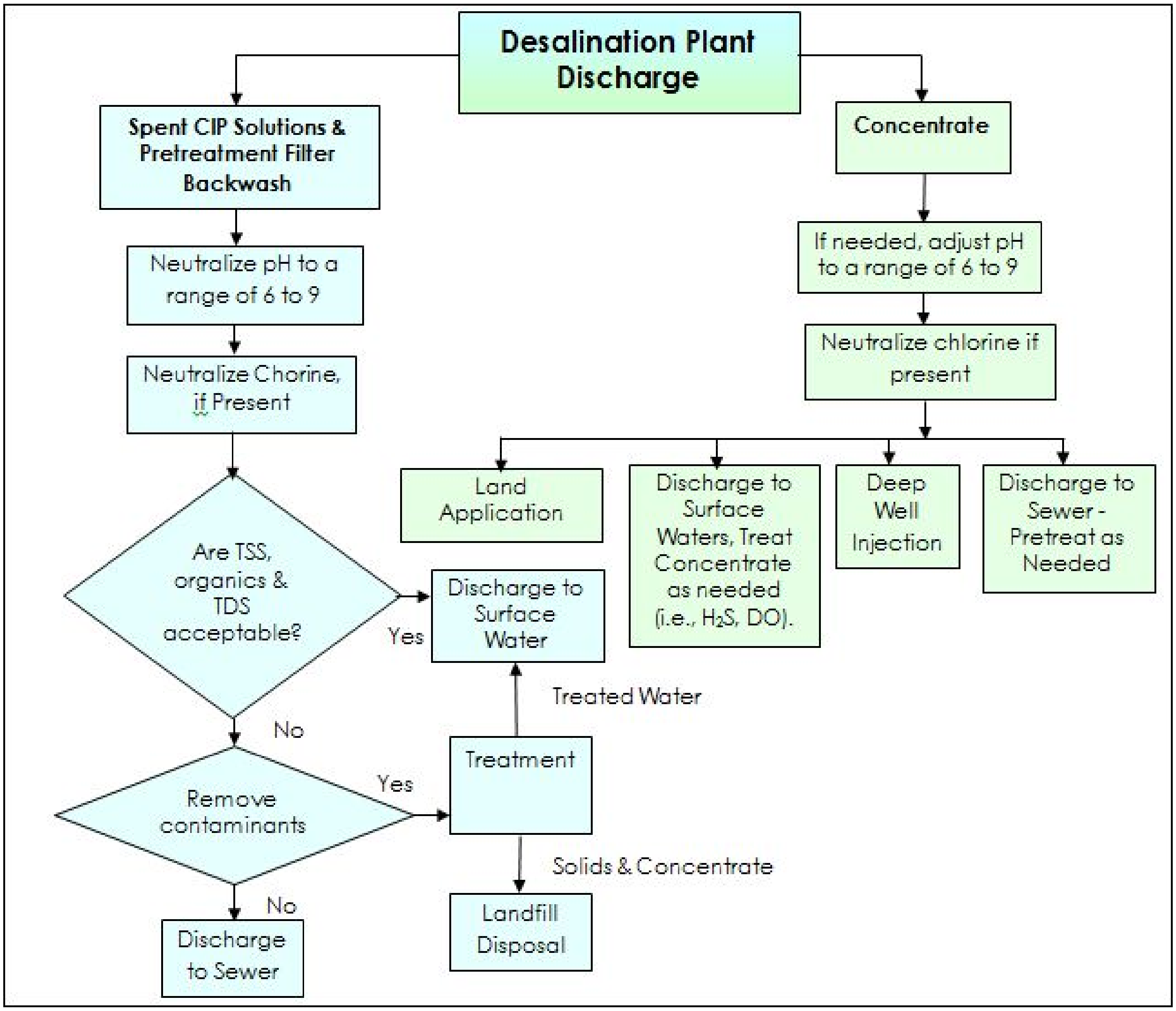


Figure 13 - Decision Tree for Desalination Plant Discharge Management

Key criteria for selection of the most viable alternative or combination of alternatives for concentrate management are: costs; environmental impacts; regulatory acceptance; ease of implementation; site footprint; reliability and operational constraints; and energy use. While concentrate water quality is of key importance in the selection process, the criterion of highest significance which is most widely applied for selection of the most viable concentrate management alternative is the lifecycle project cost.