State-of-the-Art of Concentrate Management for Desalination Plants

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Here is a state-of-the-art overview of the alternatives for managing the concentrate generated by brackish water and seawater desalination plants.

Desalination plants generate discharge, containing treatment byproducts including concentrate, spent pretreatment filter backwash water, and membrane cleaning solutions. Concentrate is the desalination process byproduct of the largest volume and the greatest management challenges. The five most commonly used concentrate management alternatives are: (1) surface water discharge; (2) sewer disposal; (3) deep-well injection; (4) land application, and (5) evaporation ponds (see Figure 1).

Surface water discharge is the most common method for disposal of desalination plant waste streams because it is applicable for practically all sizes of desalination projects. Sewer (wastewater collection system) disposal is the most widely applied method for disposal of discharges from small desalination plants. Deep well injection has found application as one of the most suitable methods for disposal of concentrate from medium and large size inland brackish water desalination plants. Land application and evaporation ponds are concentrate management alternatives typically applied for small and medium size plants in areas where climate and soil conditions provide for high evaporation rates and year-around growth and harvesting of halophytic vegetation.

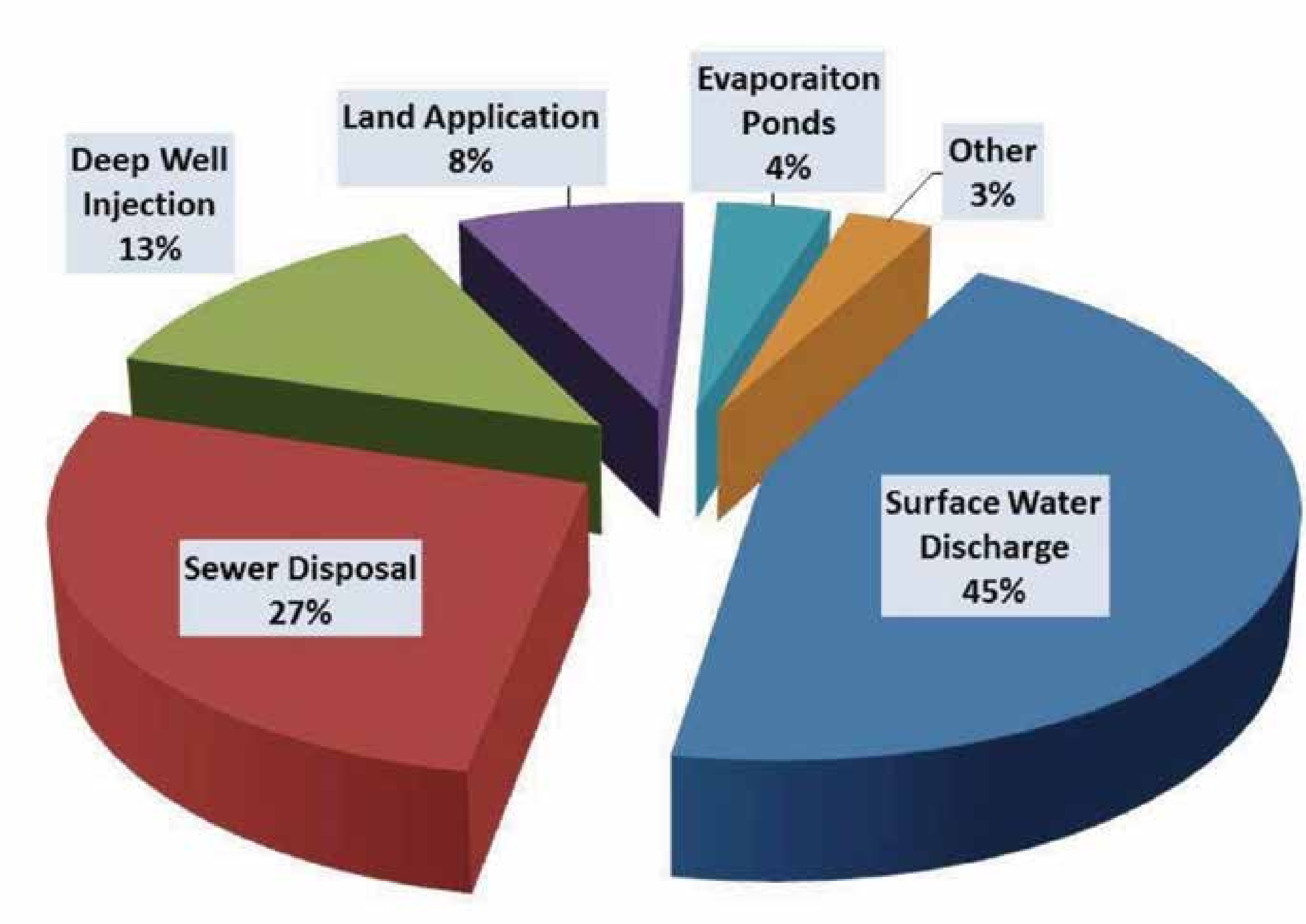

Figure 1. Current Concentrate Management Practices

None of the discharge management methods can be applied universally to every size and type of desalination project at every plant site. Therefore, selecting the most suitable and cost-effective method or combination of methods for management of plant discharge is one of the greatest implementation challenges for seawater desalination projects.

SURFACE WATER DISCHARGE OF CONCENTRATE

Surface water discharge involves disposal of concentrate from the desalination plant to an open water body such as a bay, tidal lake, brackish canal, or the ocean. The three most widely used alternatives are: (1) direct surface discharge (2) discharge through existing wastewater treatment plant outfall; and (3) co-disposal with cooling water of existing power plant. Each of these concentrate management alternatives has limitations and potential environmental impacts on aquatic environment.

New Surface Water Discharge

Discharge of concentrate and other desalination plant waste streams through a new surface water discharge system (near-shore discharge structure or off-shore outfall) is widely used for desalination projects of all sizes. Such discharges are more common for seawater rather than brackish water desalination plants.

Over 90% of the large seawater desalination plants worldwide dispose their concentrate through a new outfall specifically designed and build for that purpose. Examples are the 136,000 m^3/day Tuas Seawater Desalination Plant in Singapore; and the majority of large SWRO plants in Spain, and Australia.

The main purpose of outfalls is to discharge the plant concentrate to a surface water body in an environmentally safe manner, which in practical terms means to minimise the size of the zone of the discharge in which the salinity is elevated outside of the typical TDS range of tolerance of the aquatic organisms inhabiting the discharge area.

The two key options available to accelerate concentrate mixing with the water of the receiving water body is to either rely on the naturally occurring mixing capacity of the tidal zone or to discharge the concentrate beyond the tidal zone and to install diffusers at the end of the discharge outfall in order to improve mixing. Although open-ocean near-shore tidal zones usually carry a significant amount of turbulent energy and provide much better mixing than the end-of-pipe type diffuser outfall system, such zones have limited capacity to transport and dissipate the saline discharge load into the surface water body.

If the mass of the saline discharge exceeds the threshold of the tidal zone's salinity load transport capacity, the excess salinity would begin to accumulate in the tidal zone and could ultimately result in a long-term salinity increment in this zone beyond the level of tolerance of the aquatic life in the area of the discharge. Therefore, the tidal zone is usually a suitable location for salinity discharge only when it has adequate capacity to receive, mix and transport this discharge into the surface water body (oceans, rivers or bays). This can be determined using hydrodynamic modelling.

Examples of large desalination plant discharges in the tidal zone are the 360,000 m^3/day Ashkelon seawater desalination plant and the 274,000 m^3/day Hadera SWRO Plant in Israel and of the 170,000 m^3/day Fujairah SWRO plant in the UAE. For small desalination plants (1,000 m^3/day or less), the outfall is typically constructed as an open-ended (sometimes perforated) pipe that extends several hundred metres into the tidal (high mixing intensity) zone of the receiving water body. This relies on the mixing turbulence of the tidal zone to dissipate the concentrate and to reduce the discharge salinity to ambient conditions.

Most of the ocean outfalls for large seawater desalination plants extend beyond the tidal zone. Their design is usually based on hydrodynamic or physical modelling of the discharge diffuser structure for the site-specific conditions of the outfall location.

Environmental impact of direct surface discharge

The main challenges associated with selecting the most appropriate location for desalination plant's outfall discharge are: finding an area devoid of endangered species and stressed aquatic habitats; identifying a location with strong underwater currents that allows quick and effective dissipation of the concentrate discharge; avoiding areas with frequent naval vessel traffic which could damage the outfall facility and change mixing patterns; and identifying a discharge location in relatively shallow waters, that at the same time is close to the shoreline, in order to minimise outfall construction expenditures. Attention has to be given to: salinity tolerance of aquatic species inhabiting the discharge area; concentration of some source water constituents to harmful levels; and discharge discolouration and low oxygen content.

Usually, concentrate from seawater desalination plants has ion composition very similar to the ambient seawater and therefore, its direct ocean discharge does not pose ion-imbalance driven toxicity challenges. Therefore, typically seawater concentrate can be discharged to the ocean without additional treatment, especially if the source seawater is collected by an open ocean intake.

But, if subsurface (well) intake is used to collect source seawater, the plant concentrate may be discolored due to elevated concentration of iron; may have very low oxygen concentration or may contain other contaminants that may trigger the need for additional source water or concentrate treatment.

Often, source seawater collected from alluvial coastal aquifers by beach wells may contain high levels of iron and manganese in reduced form. In many applications, such source seawater is processed through the desalination plant pretreatment and RO facilities without exposure to air/oxygen, which keeps iron and manganese in dissolved reduced form in which form they are colourless. Because iron and manganese are easily removed by the RO membranes, after membrane separation they are retained in the concentrate. If this concentrate is exposed to air, iron will convert from reduced form (typically ferric sulphide) to oxidised form (ferric hydroxide). Since ferric hydroxide is red in colour, it would discolour the concentrate, which degrades the visual appearance of the discharge area. Therefore, the iron in the source seawater would need to be oxidised and removed in the pretreatment system, or concentrate would need to be treated by sedimentation to remove ferric hydroxide.

If a large desalination plant delivers low-DO concentrate to the surface water body, this discharge could cause oxygen depletion and stress to aquatic life. Therefore, this concentrate has to be re-aerated before discharge.

Potential sources of pollution of source water supply aquifers or surface water bodies are existing landfills, septic tank leachate fields, industrial and military installations and cemeteries. Intakes and therefore, discharges from such desalination plants would contain elevated content of these contaminants. The compounds of concern could be treated by a number of available technologies, including activated carbon filtration, UV irradiation, hydrogen peroxide oxidation, and ozonation. However, this may increase the overall costs.

CO-DISPOSAL WITH WASTEWATER EFFLUENT

This surface water discharge alternative has the benefit of accelerated mixing that stems from blending the heavier than ocean water concentrate with the lighter wastewater effluent. Depending on the volume and mixing of the two waste streams prior to the discharge, the blending may allow to reduce the size of the wastewater discharge plume and to dilute some of its constituents. Co-discharge with the lighter-than-seawater wastewater effluent would also accelerate the dissipation of the saline plume by floating this plume upwards and expanding the volume of the ocean water with which it mixes.

This alternative also avoids costs and environmental impacts associated with the construction of 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, often concentrate contains metals, organics and pathogens which are of an order of magnitude lower levels than these in the wastewater discharge, which helps reducing the overall waste discharge load of the mix.

Environmental impacts of co-disposal with wastewater effluent

Seawater concentrate may trigger ion imbalance-based toxicity when blended with wastewater and discharged to a surface water body with significantly different ion composition of the receiving water. This impact is site-specific and will need to be investigated on a case-by-case basis.

Bioassay tests completed on blends of desalination plant concentrate and wastewater effluent from the El Estero wastewater treatment in Santa Barbara, California indicate that this blend can exhibit toxicity on fertilised sea urchin eggs. Parallel tests on desalination plant concentrate diluted to similar TDS concentration with seawater rather than wastewater effluent did not show such toxicity effects. Long-term exposure of red sea urchins on the blend of concentrate from the Carlsbad seawater desalination demonstration plant and ambient seawater discharged by the adjacent Encina power plant confirm the fact that sea urchins can survive elevated salinity conditions when the discharge is void of wastewater.

The most likely factor causing the toxicity effect on the sensitive marine species is the difference in ratios between major ions (calcium, magnesium, sodium, chloride and sulphate) and TDS that occur in the wastewater effluent-concentrate blend as compared to the blend of concentrate and ambient ocean water.

The SWRO membranes reject all key seawater mineral ions at approximately the same level. As a result, the ratios between the concentrations of the individual key mineral ions that contribute to the seawater salinity and the TDS of the concentrate are approximately the same as these ratios in ambient seawater. Therefore, marine organisms are not exposed to conditions of ion-ratio imbalance, if this concentrate is directly disposed to the ocean.

Also, the high salinity may cause wastewater contaminants to aggregate in particles of different sizes than they would otherwise, resulting in enhanced sedimentation that could impact benthic organisms and phytoplankton in the vicinity of the existing discharge.

Although the use of existing WWTP outfalls may seem attractive, this disposal method has to be evaluated for its site-specific challenges. Due to potential toxicity effects, this may be limited to relatively small flows. For this option to be feasible, there has to be an existing WWTP in the vicinity of the desalination plant with extra capacity and reasonable fees for using it.

Other considerations are: (1) the potential need for modification of the outfall diffuser system of the existing seawater desalination plant due to altered buoyancy of the concentrate-wastewater mix; and (2) the compatibility of the diurnal fluctuation of the secondary effluent flow with that of the concentrate discharge flow. Often, seawater desalination plants are operated at a constant rate with little or no diurnal flow variation in concentrate discharge. But, WWTP effluent availability for dilution of the desalination plant concentrate typically follows a distinctive diurnal variation pattern.

Adequate protection of marine life requires a certain minimum concentrate dilution ratio. However, during periods of low wastewater effluent flows, the amount of concentrate disposed by the desalination plant may be limited by the lack of secondary effluent for blending. In order to address this concern, the desalination plant operational regime and capacity may need to be altered in order to match the wastewater effluent availability patterns, or diurnal concentrate storage facility may need to be constructed at the desalination plant.

CO-DISPOSAL WITH POWER PLANT COOLING WATER

At present, co-disposal of desalination plant power plant cooling discharges is mainly practiced for seawater desalination plants co-sited with large coastal power plants with open intakes. Under typical operational conditions, saline water 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. Typically the cooling water discharged from the condensers is 5 to 10 0C warmer than the source ocean water which could be beneficial for the desalination process because warmer saline water has lower viscosity and therefore, lower osmotic pressure/energy for salt separation.

Co-location of SWRO desalination plants with existing once-through cooling coastal power plants yields four key benefits: (1) A separate desalination plant outfall structure is avoided thereby reducing costs; (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.

As a result of the co-location, the desalination plant's power costs could be further decreased by avoiding the use of the power grid. Under a typical co-location configuration, the desalination plant uses the power plant discharge water both as source water for the desalination as well as dilution water for the concentrate. An example is the 120,000 m^3/day Carboneras desalination plant in Spain. The need for new intake and outfall construction in the ocean is avoided. The construction of a separate new open intake structure and pipeline could cause a disturbance of the benthic marine organisms.

Another clear environmental benefit of the co-location is the overall reduction of entrainment, impingement and entrapment of marine organisms as compared to the construction of two separate open intake structures for the power plant and desalination plant. By using the same intake seawater twice (once for cooling and then for desalination) the net intake inflow of marine organisms is minimised.

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 ocean discharge within the natural range, thereby completely alleviating the need for discharge diffuser structures.

The power plant thermal discharge is lighter than the ambient ocean water because of its elevated temperature and tends to float. The heavier saline discharge from the desalination plant draws the lighter cooling water downwards, thus reducing the time for dissipation of both discharges.

Environmental impacts of co-disposal with power plant cooling water

The potential environmental impacts associated with co-located desalination facilities are similar to these of open ocean outfalls. Depending on the site-specific missing conditions, for power plant outfalls equipped with diffusers, the plant outfall diffuser structure may need to be modified in order to accommodate the heavier concentrate discharge.

The environmental impacts of desalination plant operations may increase if the power plant operation is discontinued because the desalination plant cannot benefit from the mixing effect of its concentrate and warm and buoyant power plant cooling water. As a result, more source seawater may need to be collected in order to provide pre-dilution of the concentrate to environmentally safe salinity level prior to its discharge. Collection of dilution water may result in additional impingement and entrainment of marine organisms.

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 worldwide. This however, is only suitable for very small volumes of concentrate into large-capacity wastewater treatment facilities mainly because of the potential negative impacts of concentrate's high TDS content on the operations of the receiving wastewater treatment plant. Discharging concentrate to the sanitary sewer in most countries is regulated by the requirements applicable to industrial discharges of the utility/municipality, which is responsible for wastewater collection system management.

The feasibility of this concentrate disposal method 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, WWTPs' 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 in the wastewater treatment plant influent salinity must be assessed and its effect on the plant's biological treatment system should be investigated.

Taking under consideration that wastewater treatment plant influent TDS may be up to 1,000 mg/L in many facilities located along the ocean coast, and that the seawater desalination plant concentrate TDS level 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 TDS concentration below 3,000 mg/L. This means, that for example a 40,000 m^3/day wastewater treatment plant would likely not be able to accept more than 1,000 m^3/day of concentrate.

If the effluent from the WWTP is used for water reuse, the amount of concentrate that can be accepted by the WWTP is limited not only by the concentrate salinity, but also by the content of sodium, chlorides, and boron 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.

Environmental impacts of discharge to sanitary sewer

Desalination plant discharge to sanitary sewer could potentially have environmental impacts very similar to these of co-discharge of concentrate and WWTP effluent. Usually, concentrate water quality is compliant with typical requirements for discharging wastewater to sanitary sewer. Therefore, the application of this concentrate disposal method is not anticipated to have significant impacts on the sanitary sewer system.

WELL INJECTION

This disposal method involves injection of desalination plant concentrate into an acceptable confined deep aquifer adequately separated from freshwater or brackish water aquifers above it. The depth of such wells usually varies between 500 and 1,500 m. 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 but so far no known plants exist that use deep well injection for seawater concentrate disposal.

This disposal method is fairly reliable and has a low probability of negative environmental impacts. However, there are circumstances under which concentrate could migrate upwards and could potentially contaminate shallow aquifers above it.

Well injection systems for concentrate disposal are only viable for confined aquifers of large storage capacity which have good soil transmissivity. They are not feasible for areas of elevated seismic activity or sites near geologic faults.

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. While conventional evaporation ponds are primarily designed for concentrate disposal, the main function of solar ponds is to generate electricity from solar energy.

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. While conventional evaporation ponds are configured to maximise heat convection and evaporation, solar ponds are deeper lagoons designed to retain heat and therefore, have lower evaporation rate. Therefore, solar ponds are often considered a system for beneficial use of concentrate (generation of electricity) rather than an efficient concentrate disposal method.

Solar ponds have been successfully tested in El Paso, Texas and in Victoria, Australia. A 10,000 m^2 solar pond in Australia was reported to produce electricity of 200,000 kWh/yr. Another 5,000 m^2 solar pond system in Australia has been documented to produce electricity of 130,000 kWh/yr at power generation cost of US$0.12/kWh. Solar evaporation is feasible 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 1.0 m/year and annual rainfall rate higher than 0.3 m/yr. Factors affecting evaporation rate are: humidity; temperature; solar irradiation intensity; wind; rainfall; and 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 that could fill the ponds during sand storms. Significant rainfall reduces evaporation rates.

Environmental impacts of evaporation ponds

Groundwater quality regulations in the US require evaporation ponds to be constructed with impervious lining for protection of underlying aquifers. Typically, a single layer liner is adequate. However, if concentrate is contaminated (contains high levels of trace metals), then double-lined pond may need to be constructed. Evaporation pond systems, especially these using geo-membrane liners, should be equipped with underground leak-detection systems that lie beneath the liner.

Zero Liquid Discharge concentrate disposal systems

Zero-liquid discharge (ZLD) technologies, such as brine concentrators, and crystallisers convert concentrate by thermal evaporation into highly purified water and solid dry product suitable for landfill disposal or for recovery of useful salts.

These systems typically consist of concentrate conveyance pipelines to and from the equipment; concentrator and or crystalliser towers; heat exchangers; de-aerators; seed slurry storage and delivery system; and vapour compressors and recirculation pumps. If crystallizer system is included, this system also has concentrate slurry dewatering equipment. Evaporator/crystalliser systems are the most commonly used zero-liquid discharge technologies.

Brine concentrators are single-effect thermal evaporator systems, which convert concentrate from liquid phase into dense slurry by boiling it in a tall packed tower. In these systems, the vapour produced from boiling of concentrate is pressurized by compressor and is then re-circulated for more vapour production. The high-salinity slurry generated in the brine evaporator could be either solidified in evaporation ponds or crystallised by mechanical drying equipment and disposed of to a landfill.

Usually, existing concentrator technology can evaporate 90 to 98% of the concentrate. As a result, TDS content of the high-salinity concentrate produced by these systems can reach 20,000 to 100,000 mg/L. The concentrated stream can be further dewatered and disposed to a landfill as a solid waste. Ultimately, the concentrated salt product could be designated for commercial applications.

Crystallisers precipitate highly soluble salts from concentrate such as sodium carbonate, sodium sulphate and sodium chloride into solid residuals. This technology applies vacuum compression and produces salt crystals and distilled water by forced circulation of slurry or dense concentrate in tall cylindrical reactors (crystallization vessels). The low salinity water separated from the concentrate is collected as distillate at the condenser. The filtrate from the filter press or centrate from the dewatering centrifuge is typically blended with the RO feed or permeate. The recovery of salts and reuse of the liquid separated from the concentrate is practically 100%.

Often brine concentrator and crystalliser systems are combined into one evaporator-crystalliser system. Usually, ZLD systems are used when other options for concentrate management are not feasible mainly because of their high construction and O&M costs. Since concentrate is very corrosive, all equipment used in this type of systems is built from corrosion resistant materials such as titanium, molybdenum and super duplex stainless steel. This makes zero-liquid discharge systems quite costly.

The generation of steam for the concentrate evaporation process could also add significant expense to the ZLD system operation. Therefore, most exiting evaporator-crystalliser systems are operated using waste steam from a nearby power plant or industrial facility that generates steam as a site product (oil refineries).

While zero liquid discharge has received a significant attention over the past ten years, its cost challenges have not been successfully solved to date.

Environmental impacts of ZLD

The evaporator-crystalliser system for zero liquid discharge management of concentrate is the highest energy use and carbon footprint type of all concentrate management alternatives and often exceeds the total power demand for production of desalinated water by the plant generating concentrate.

Beneficial Use of Concentrate

Concentrate from desalination plants contains large quantities of minerals that may have commercial value when extracted. The most valuable minerals are: magnesium, calcium and sodium chlorides, and bromine. Magnesium compounds in seawater have agricultural, nutritional, chemical, construction and industrial applications. Calcium sulphate (gypsum) could be used as a construction material for wallboard, plaster, building cement, and road building and repair. Sodium chloride can be applied for production of chlorine and caustic soda, highway de-icing, and food products.

Technologies for beneficial recovery of minerals from concentrate can be used for management of concentrate from both inland brackish water desalination plants and coastal seawater desalination plants. These technologies have the potential to decrease the volume and cost of transporting concentrate as well.

Use of concentrate for cooling of the condensers of power generation plants is typically practiced for small facilities with limited cooling needs and cooling towers that can withstand the highly corrosive concentrate. A key concern is the high scaling potential of the concentrate. Only a small portion of the concentrate is actually converted into vapour and disposed to the air. The rest would ultimately need to be discharged.

Small volumes of concentrate have been used occasionally for dust suppression, roadbed stabilization, soil remediation, and de-icing. In some US states (Texas, Utah, Arizona, Kanas, New Mexico, and Utah) there are inactive salt mines, which unless refilled, could collapse and cause damage of buildings in the vicinity. Such salt mines could be filled up with solidified concentrate to provide structural integrity of the mine caverns. These site-specific applications can only be used as supplemental concentrate disposal alternatives.

The key challenges of current technologies for beneficial reuse of concentrate are the large capital costs, energy, and chemical expenditures needed to reduce concentrate volume and to extract valuable minerals from it. Therefore, while environmentally attractive, the large-scale beneficial reuse of minerals produced form desalination plant concentrate is highly unlikely to gain significant grounds in the near future. As the costs of construction materials and other products that can be generated from concentrate increase in the long-term, and more cost competitive technologies for their production are developed, the beneficial reuse of concentrate may become viable. **AW**

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