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Review of high recovery concentrate management options

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ABSTRACT

Current methods of inland concentrate disposal include surface water discharge, deep-well injection and evaporation ponds. These methods are unsustainable and are limited by high capital cost and non-ubiquitous applications. This paper gives an overview of potential alternatives and technologies available that can reduce the concentrate formed via reducing its volume or recycling. Potential alternatives explored have been electrodialysis, mechanical evaporation, Vibratory Shear-Enhanced Process (VSEP) and Wind-Aided Intensification of Evaporation. All technologies have potential for use in areas distant from the coast and have better performance than currents management techniques. This paper reviews multiple studies that have explored alternate technologies for concentrate disposal in terms of economics and feasibility. Of the five case studies presented, VSEP shows promise as a secondary system of treatment via enhancing percentage recovery; higher permeate flux and lower operational costs.

Keywords: Concentrate disposal; Volume reduction; VSEP; WAIV; Zero liquid discharge

1. Introduction

With the world population recently eclipsing 7 billion, the availability of clean drinking water is not meeting the demands of the population [1]. Whilst water conservation and dam constructions have provided temporary relief, there are still roughly 2.8 billion people worldwide that live in regions of water shortage [2]. The abundance of remaining brackish water found in the ocean, groundwater and estuaries has the potential for use as potable water [3]. In recent years, desalination has emerged as the headline technology in water reuse and sustainability for our resources over the coming generations.

Desalination is defined as a process which removes salt from water in order to produce fresh water. Standards for drinking water tend to vary between countries and even regions; though the World Health Organisation have applied a maximal threshold of 250 mg/L total dissolved solids (TDS) [4].

The application of desalination in industry has transcended beyond the treatment of salt water. Feed streams into desalination systems can range in levels of inorganic and organic materials. Constituents such as chemicals, salts and multivalent ions to microbes

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have the potential to be removed in desalination technologies [5]. Brackish water is the effluent commonly treated in waste water treatment plants. A common source of brackish water is groundwater from seawater intrusion or irrigation. A wide range of TDS (1,000–10,000 mg/L) can be observed in groundwater [6]. Brackish water consists of other contaminants ranging from organic carbon, colloids and components of boron and silica.

In the early twenty-first century, desalination trends showed significant jumps in continents such as Asia, North America and Europe [7]. However, in the 1980s, there was a large increase in the total world desalination capacity. As of 2013, the Middle East occupies up to 50% of the *world's production capacity* **[8].**

Desalination can be classed into two main categories being thermal- or membrane-based processes. Thermal processes cover distillation-based technologies such multi-effect distillation and multi-stage flash distillation [11]. Thermal-based desalination has been utilised for hundreds of years and the Middle East has adopted this form of desalination as the costs for energy requirements are significantly less in the region.

Membrane processes have focused primarily around reverse osmosis (RO), nanofiltration (NF) and electrodialysis (ED) with RO being the most widely used. In desalination plants, RO acts to remove molecules and ions by applying pressure over a solution allowing the solvent to pass through a selective membrane to other side [12]. RO differs from filtering technologies as it is dependent on solute concentration, applied pressure and water flux rate in comparison to size exclusion via pores [13].

Despite all the benefits of RO, there are multiple factors that have prevented membranes processes from being the sole solution for global freshwater shortage. Current RO units have a relatively large footprint, the overall production efficiency is significantly hindered according to the TDS content of the source and the post-treatment costs such as disposal are very expensive [14].

The hope to increase the performance of the membrane had to be delicately balanced by prevention of fouling and scaling at the surface [9]. Fouling and scaling from salt precipitation and biofilm formation affect the overall water flux at the membrane over long periods, resulting in the need for frequent cleaning and turnover of membrane sheets [15]. Furthermore, fouling leads to reduced productivity, lower permeate quality, higher energy requirements and treatment costs [16].

Anti-scalants introduced to effluents prior to membrane processes delay the precipitations of salts such as calcium carbonate and barium sulphate at the membrane [17]. However, the introduction of an anti-scalant results in an additional chemical that may need to be removed before the disposal of the final concentrate [18].

As climate change becomes more of an issue, the urgency to conserve drinkable water has motivated multiple industries to seek new desalination technologies in preference of traditional methods. Many of these technologies benefit from reduced footprints, lower costs, non-necessity of anti-scalant use, higher recovery percentages and low discharge rates. The ultimate goal in desalination is to achieve zero liquid discharge (ZLD) where almost no liquid is removed from the entire process resulting in significant reductions in disposal costs [19].

The following review delves into the current shortcomings of membrane technology and the current methods of concentrate management, and briefly touches on the regulatory issues linked to these management options. Furthermore, potential alternatives such as volume-reduction and ZLD systems ranging from Vibratory Shear-Enhanced Process (VSEP) to Wind-Aided Intensification of Evaporation (WAIV) are explored and assessed on the basis of feasibility, potential costs and management.

2. Desalination and its waste

2.1. Scaling/fouling

A common phenomenon in desalination is membrane fouling due to adsorption of dissolved and suspended feed components at the membrane surface. Fouling of membranes is difficult to revert and often requires extensive cleansing [20].

The major types of fouling include [15]:

(1) Inorganic: inorganic deposits on the surface and within the pores;
(2) Organic: deposition of organic materials such as proteins, oils and humic acid;
(3) Colloidal & particulate: deposition of clay, silica and debris; and
(4) Microbiological: biofouling and formation of biofilms.

Colloids are defined as fine particles with a size characteristic of 1 nm–1 μm [21]. In most cases, colloids are more likely to cause fouling due to their size range. Smaller particles are able to diffuse away from membrane surfaces through diffusion. Larger particles can be removed from the surface via lateral migration [22].

Colloids can interact with membranes based on several properties. Properties such as size, shape and charge will all affect potential to foul a membrane [23]. Interactions between colloids and the membrane surface have been described by the Derjaguin–Landau–Verwey–Overbeek theory [24].

Looking particularly at RO and NF colloidal fouling, the key factors that affect the complexity can be classed into three groups.

(1) *Feedwater characteristics*: The types of foulants present in the feed and the concentration levels can drastically affect solution chemistry [25]. Surface charge on colloids is a function of solution pH and ionic strength. Ionic charges can be detrimental in cases of multivalent ions such as calcium which has potential to precipitate [26].
(2) *Membrane properties*: Apart from porosity, other key characteristics of membranes include surface roughness, charge and hydrophobicity [27].
(3) *Operating conditions*: Hydrodynamic conditions such as membrane flux, cross-flow velocity and transmembrane pressure (TMP) can affect the degree of fouling. In each case, critical flux and mass transfer can influence fouling [28].

Three possible approaches have been utilised for the control of membrane fouling [29]. Application of hydrophilic and charged functional groups on the membrane surface can modify the behaviour to retard micro-organisms and hydrophobic solutes. Additionally, chemical pre-treatment such as anti-scalants has been discussed earlier. Lastly, periodic treatment of membranes with suitable adsorbents keeps the surface clear of fouling.

Discharge of concentrate has potential to damage the environment, reduced public acceptance and also significant financial penalties if standards are not followed. Temperature, salinity and concentrate constituents are three important aspects to be considered prior to discharge [30]. Rises in either temperature or salinity may influence the oxygen level in the body of the receiving water leading to changes in microenvironment as well as introduce osmotic stresses and ion imbalance.

Desalination facilities situated nearby ocean or near coastal regions can often discharge concentrate wastes streams directly into surface waters. However, for plants located inland, there are limited environmentally sustainable surface discharge options.

2.2. Concentrate management practices for inland-/sea-based facilities

Current management practices for disposal of concentrates are largely dependent on two factors. These are the area required and the geography [31]. Larger volumes of concentrate can reduce the feasibility of existing disposal methods in terms of cost and convenience [32]. Furthermore, the geographic location of the proposed disposal site can limit the options of disposal [30]. Location can also contribute to conveyance costs including pipelines and right of way.

The following section explores current methods of concentrate disposal.

2.2.1. Surface water discharge

Discharging directly into surface waters is considered the easiest and cheapest method of disposal. However, the option is not always available. Prior to discharge, concentrate must undergo pre-treatment by pH adjustment and outfall. The feasibility of surface water discharge increases as the salinity of concentrate decreases [31].

In most countries, the TDS content in discharged concentrate must be less than that within the receiving water [4]. Mixing zones of local in-streams having increased levels of TDS are sometimes permitted as long as dilution of the receiving water meets the in-stream standards [33]. Similar to surface water discharge, direct disposal into sewers can also be applied. A fee is charged dependent on the perceived impact of the disposal.

2.2.2. Deep-well Injection

Deep-well injection (DWI) can be used to deal with waste streams of both higher contaminant and dissolved solid content. In the USA, wastes from drinking water plants are deemed as industrial wastes [32]. Industrial wastes require Class 1 well disposal [34]. Class 1 well disposal has aquifers that are isolated from overlying drinking water aquifers. The receiving water aquifer must have a TDS greater than 10,000 mg/L. The installation costs of injection wells can be considerably expensive due to the position of the aquifers, the tubing arrangement and the cement casing [18].

Determining the site for wells also contributes to front-end costs. Hydrogeological studies, drill testing holes, environmental overviews and many pilot tests all should be performed prior to the implementation [18]. The key advantage of DWI is its economy of scale, making it more feasible for desalination plants of larger capacity.

Apart from front-end costs, the overlying factor that determines DWI feasibility is the hydrogeological conditions. Apart from aquifer permeability, porosity of the subsurface can considerably affect the injection rate. Lower injection rates introduce the need for multiple wells with larger spacing [34]. A deep-well aquifer must have the capacity to receive concentrate over the life of the desalination plant.

2.2.3. Evaporation ponds

Evaporation Ponds (EPs) have potential in areas of hot climate where there are high evaporation rate and large expanses of unused land that is inexpensive [32]. Concentrate is pumped from the desalination plant into a pond where evaporation of the concentrate occurs leaving behind wet salts.

Operating and maintaining EP requires little labour and is cost-effective. However, the overall efficiency of the process is considerably low and its operation during colder seasons is limited. Furthermore, the capital cost for setting up the ponds can significant with values ranging from \$100,000 to \$400,000 per acre [18] (Fig. 1).

Other enhanced methods of EP have been explored as alternatives for concentrate disposal; these include wetlands and wind-aided intensified evaporation.

A study by Foldager estimated overall disposal costs via three disposal methods EP, deep-well injection and salinity-graded solar ponds (SGSPs) [35]. The calculations were based on low capacity treatment to high capacity treatment and used an updated formula to improve on the Esquivel data used previously [36]. Figs. 2 and 3 show that the disposal costs of DWI are highly uneconomic at low capacities but are the more feasible option in dealing with high capacities. The data show that solar-based ponds are highly uneconomic under both cases of low and high capacities and EPs have low capital costs for both low and high capacities. The study concluded that a 1 MGD facility would select EP over SGSP due to lower capital costs and Operating & Maintenance (O&M) costs. Furthermore, a 10 MGD SGSPs would have an excessively high initial capital cost to further proceed with the method.

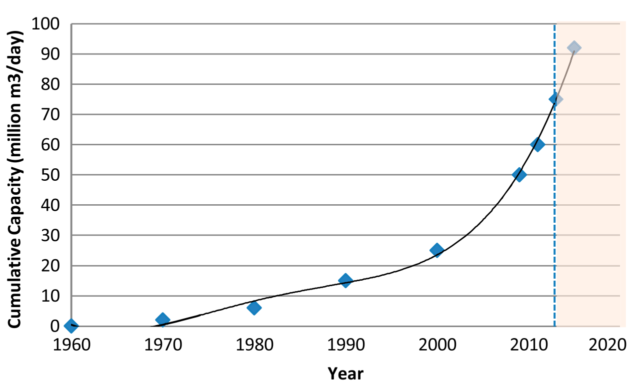

Fig. 1. Trend graph showing total world desalination capacity over the past 50 year (adapted from Lee & Shatat) [9,10].

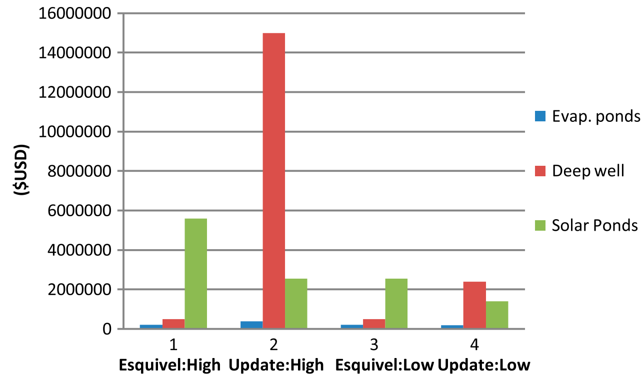

Fig. 2. The disposal costs of EP, deep-well injection and salinity gradient solar ponds under low capacity (1 MGD) adjusted for inflation as of 2013 [35].

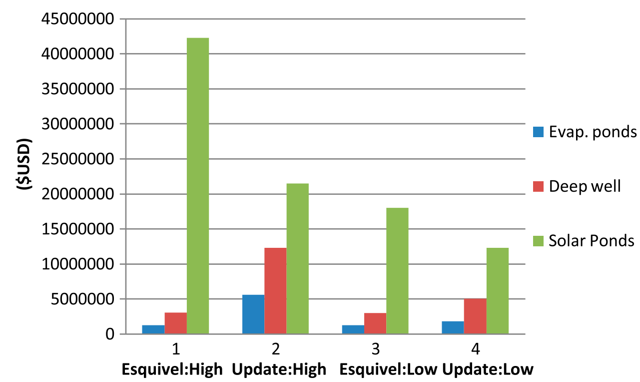

Fig. 3. The disposal costs of EP, deep-well injection and salinity gradient solar ponds under high capacity (10 MGD) adjusted for inflation as of 2013 [35].

A study by Mickley in 2004 compared the capital costs of certain concentrate disposal methods to the capacity of flow rate [37]. Fig. 4 shows the economy of scale of each process. EP has significantly poor economy of scales. Both discharge to surface water or sewage as well as deep-well injection present economically feasible options when dealing with increase in scale.

2.2.4. Effluent mixing

Wastewater effluent mixing is a known method of concentrate management which involves the blending of RO concentrate with treated effluent to mitigate the

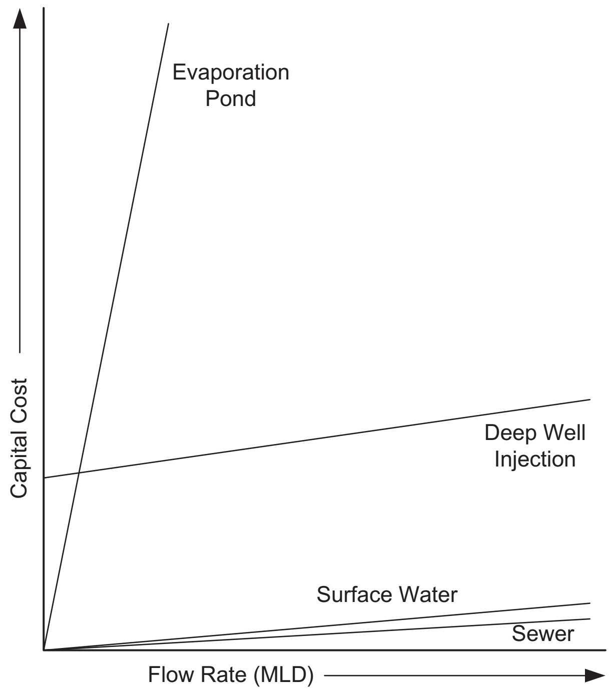

Fig. 4. The relationship between capital cost and flow capacity for several disposal methods (image adapted from Mickley) [37].

impact of high TDS RO concentrate prior to disposal [38]. The advantage of this form of disposal is its simplicity and low capital cost due to lack of new equipment required. The method is limited by the blending capacity of the concentrate and also the existing discharge limits being applied [33,39].

2.3. Regulatory issues

The principles of waste management are fairly consistent across countries. One must approach concentrate disposal in a hierarchy [33].

(1) Waste minimisation;
(2) recycling;
(3) reuse of concentrate;
(4) treatment to reduce its potential to harm; and
(5) discharge into the environment.

In order to preserve water quality, governments continue to implement policies that can command, control and monitor the concentrates being discharged into the environment. A key control mechanism is regulations. In Australia, regulation of water varies between states and territories [40]. Individual states are responsible for setting water quality goals, establishing clear grounds for stewarding of water resources and monitoring management practices and water quality, ensuring they meet the standards set. Discharge must comply with multiple regulations ranging from health, catchment and environmental discharge limits [33].

Sampling and monitoring programmes are incorporated at all treatment plants in order to predict concentrate quality and the potential for impact and to determine if standards are met.

Discharge limits are governed by individual state EPA. Samples are often collected to ensure compliance with the primary and secondary standards set up by the states. Some of the key concentrate constituents under analysis include aluminium, arsenic, calcium, chromium, copper, zinc, cyanide, silica, sulfate, colouring and TDS [31]. As discussed earlier, the quality of the effluent entering a membrane system has a significant effect on fouling. Effluents with high TDS concentrations not only cause higher fouling risk but are also more difficult to discharge directly. Non-constituent problems such as temperature and pH must be monitored carefully depending on the discharge point.

Apart from setting discharge limits, most EPA have implemented risk assessments to identify the interactions with environmental and public values, the key stressors which can cause non-compliance and how to manage situations which do not meet standards [41].

3. Concentrate management options

Current concentrate management practices (as discussed earlier) are highly limited by many uncontrollable factors such as geographical location, land availability and location of resources [42]. In order to meet the regulatory limits, reducing the overall amount of waste would be the ideal approach. Volume-reduction technologies aim to process wastes created by upstream processes and reduce their overall volume for more efficient and cost-effective disposal. Some of the key volume-reduction technologies will be discussed in the following section. The ultimate objective of each of these systems is to achieve ZLD. ZLD is achieved by maximising water recovery to the point where no effluent or liquid discharge is removed from the system via multiple stages of treatment [42].

Based upon Perez-Gonzalez et al., ZLD systems are classed into four schemes. Basic, Type A, Type B and Type C schemes can be observed in Fig. 5. In most cases, the basic set-up of a primary unit such as RO or magnetic ion exchange is followed up with a secondary unit which may be ED or vibratory shear enhance processing [42].

Basic ZLD schemes consist of just only primary and secondary treatment. Type A schemes employ intermediate treatment between the stages of primary and secondary treatment to reduce foulants and scalants entering the secondary unit. Type B systems consist of a primary and secondary unit followed by a post-treatment unit to further treat final concentrate. Type C ZLD schemes utilise both intermediate and post-treatment along with the conventional primary and secondary RO units.

3.1. Types of technologies (volume-reduction & ZLD)

3.1.1. Electrodialysis Reversal (EDR)

In the past, ED has been applied across many industries ranging from the desalination to food processing to glycol desalting [43], [44]. The process of ED involves the application of an electrical current over a solution containing salts. Salts within the solution will dissociate based on their positive and negative charge. Positively charged cations will migrate through a cation-specific transfer membrane towards the negatively charged cathode and negatively charged anions migrate through an anion-specific transfer membrane towards the positively charged anode. ED works to remove salts and demineralise the product stream [38].

Based on the principles of ED, a technology tailored towards prevention of scaling has been developed. The method known as EDR maintains the desalting function of the original ED, in addition to controlling membrane fouling and high feedwater recovery [46]. Fig. 6 shows the EDR process and the direction of cation and anion flow. During operation, the cathode and anode positions are reversed at fixed times during the course of each hour. The periodic polarity change assists the total scale build-up on the membrane surface and the frequency of cleaning.

A design study by GE ionics used WATSYS performance software to develop an EDR system design suitable for brackish water. An estimated water recovery of 79% was determined with a reduction of RO concentrate flow of up to 4-fold [38].

The current method of EDR is limited by the membrane design despite many efforts to improve membrane properties [47–49]. The anion and cation transfer membranes are highly specific to charge and consequently, poorly ionised solutes, non-charged particulates and pathogens are unable to be removed by ED/EDR [50].

3.1.2. Enhanced membrane systems

Enhanced membrane systems (EMSs) are still fairly underexposed in applications. EMS operates via non-conventional RO system. An example of a known EMS is the high efficiency reverse osmosis (HERO) system. This particular process has been applied in industry to treat cooling tower blowdown [42].

HERO, an example of a type C ZLD scheme, first involves ion exchange softening to RO concentrate in order to reduce the overall scaling potential entering the next stage and is followed by high pH operation under a three-stage RO system consisting of spiral wound elements [51]. High pH provided by caustic soda can prevent silica scaling and the formation of biofilms.

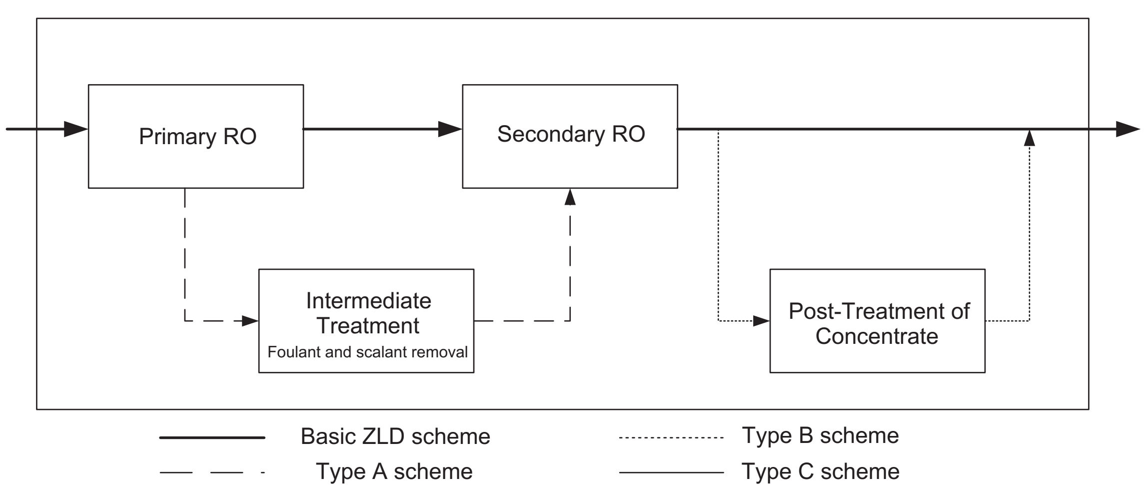

Fig. 5. The ZLD classification scheme (adapted from Perez-Gonzalez et al.) [42].

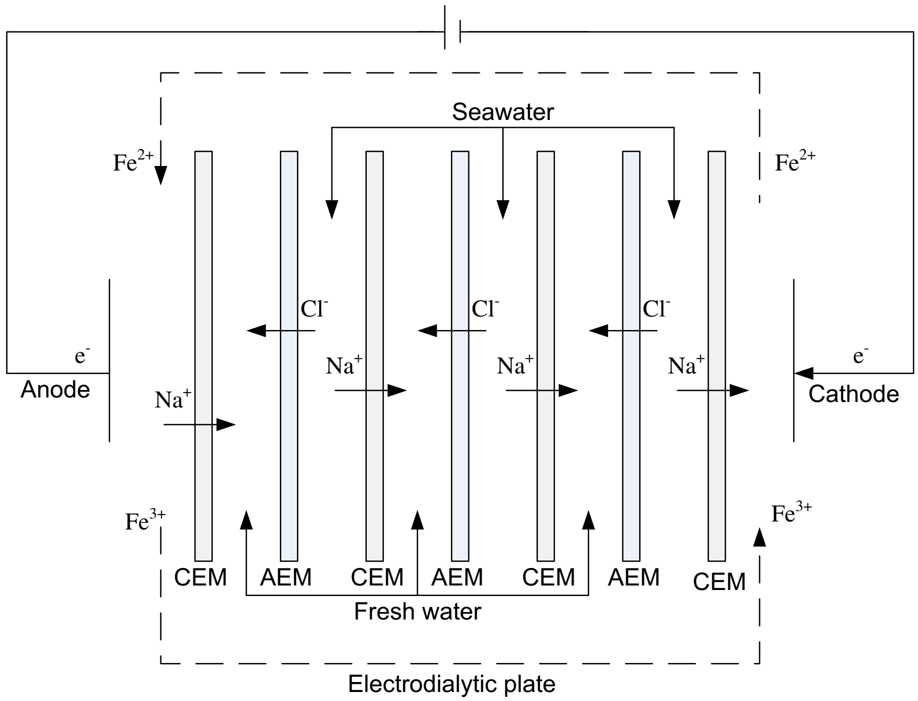

Fig. 6. Removal of charged ions in a reverse electrodialysis set-up (image adapted from Fernando) [45].

Although high recovery percentages and high flux can be obtained, the drawback of EMS is the complexity of its operation. The process involves chemical addition, ion exchange, pH adjustment as well as a RO system [38]. The cumulative results of capital and operating costs in addition to the energy requirements limit the applications of this technology.

3.1.3. Mechanical evaporation

The use of this technology enables the water component of the concentrate stream to be condensed into water vapour, leaving behind wet salt that can directly disposed. The two most common forms of mechanical evaporation (ME) are vertical tube falling film concentrators and forced circulation crystallisers.

Conventional evaporators are limited by high TDS and low solubility of scaling salts such as silica and calcium sulphate [38]. The use of the brine evaporator applies a seeded slurry to overcome these problems. During this process, a slurry of calcium sulphate seed crystals within the brine causes preferential precipitation of silica and calcium sulphate on the crystals rather than the tubes [52]. Across the concentrator, water recovery has reached levels of between 95 and 99%.

Brine evaporators can be operated in series with brine crystallisers. Outlet brine discharge from the brine evaporator is fed into the forced circulation crystalliser. The unit aims to precipitate and grow crystals as water continues to be evaporated [53]. Brine enters and is heated with steam to above its boiling temperature. Following heating, the concentrate is sent to the flash tank operating at a lower pressure and causing flash evaporation of water and crystallisation of salts [54]. The process requires high recirculation rates to maintain velocity high, prevent scaling and induce high transfer efficiency at the heated surface [38]. Slurry produced from the crystalliser is dewatered and the liquid portion can be recirculated to further increase recovery percentage.

Although brine concentrators can achieve near ZLD, the method is the least cost-effective concentrate disposal method due to the high dependence of equipment such as evaporators, and crystalliser. Energy costs associated with the evaporation process contribute most significantly.

3.1.4. Wind-aided intensification of evaporation

WAIV is a method that exploits wind energy to evaporate wet surfaces packed in high density sheets. WAIV has been considered as a suitable alternative in concentrate treatment in particular for cases where facilities are located inland. Water is pumped onto sheets ranging from geotextile to netting fabrics to increase the surface area of evaporation [55]. The fabric is installed laterally, stretching between the head tank where the concentrate wets the fabric to the collection tank and positioned parallel to the wind. The surface of the fabric is cooled to near wet bulb temperature. The temperature difference between the cooled surface and the warm air promotes heat flux to the wetted surface. Evaporation mass transfer from the surface occurs due to the vapour pressure gradient [56]. Concentrate can reach the collection tank via capillary action or gravity. Both involve falling films on vertical hydrophilic surfaces with gravity being the preferred option. Final solid waste remaining on the surface can be directly disposed and the evaporated liquid undergoes condensation for reuse or discharge [57].

The operation of WAIV requires constant wetting of the material. A study by Gilron et al. demonstrated that dried-out fabrics had increased salt deposition that significantly impeded water flow and corresponded to a reduced efficiency of the process [57]. Rinsing with water and citric acid every two months resulted in less residual salts and prevented the fabric from drying out.

Although the unit operates at minimal energy consumption and a small footprint, the overall productivity of the process is low ($4\,L/m^2d$) due to the reliance on natural evaporation [58]. As an example of the footprint savings potential at Sabha seawater RO plant, up to $5,000\,m^3$ of concentrate is sent to EP covering $700,000\,m^2$ each day. It has been estimated that implementation of WAIV plant could reduce the total land requirements by 10-fold [56].

3.1.5. Wetlands

Constructed wetlands have not been utilised to the same extent as other technologies in methods of RO concentrate [18]. Marshes have been created in Oxnard, USA to reduce the volume of concentrate via evapotranspiration [59]. If chemical constituents of membrane are reduced to a threshold, the concentrate can be disposed to that of levels safe for biota within the wetland. The method of disposal has the additional benefit of providing salt-tolerant plants with valuable nutrient which can be removed in the roots of the plant.

Although a similar technology to EP, wetlands are more attractive, provide additional treatment via evapotranspiration, require less surface area and have less accumulation of material due to plant uptake [38].

The widespread use of wetlands has been limited due to federal regulations. In the USA, there is a minimal law of a secondary treatment of concentrate prior to discharge into natural wetlands [60].

Whilst providing significant benefits, constructed wetlands have not shown potential in achieving zero liquid discharge when dealing with concentrates of high TDS.

3.1.6. Vibratory shear-enhanced process

The use of membranes with high shear has been recognised as efficient in increasing permeate flux. High shear rates at the membrane surface were utilised to generate a axial pressure gradient via applying high feed flow rate tangential to the membrane surface [61]. Conventional shear-enhanced filtration designs required significant energy to drive feed flow rate but also decreased TMP leading to less than optimal utilisation.

Developed in 1987, the VSEP system was designed to overcome the problems related to scaling on the membrane surface. The VSEP, as its name suggests, uses vibration to generate shear waves along the membrane surface. High shear at the membrane interface causes solids and foulants to lift off the membrane and be transported away along with the bulk material flow [62]. The high shear generated ensures that membrane pores remain exposed allowing for high solute fluxes across the membrane. This differs to conventional cross-flow membranes where considerable plugging of membrane pores by the suspended colloids can occur due to fouling at the boundary layer (see Fig. 7).

By combining the appropriate membrane and materials, VSEP has been proven to be very successful in increasing flux rates. Membranes ranging from microfiltration, ultrafiltration and NF have all been considered in VSEP use. Pilot testing is often required to determine which membrane is suitable to achieve the maximum stable flux. Typical VSEP systems are arranged in a plate and frame configuration. The form of configuration selected ensures that shear is applied specifically at the thin zone near the filter corresponding to lower power consumptions and higher energy conversions [62]. A study by Culkin et al. determined that VSEP units converted up to 99% of total energy into shear that worked at the membrane[63]. This was significantly higher than conventional cross-flow filtration systems that convert roughly 10% of the provided energy into shear and the remainder to maintain flow.

Suspended colloids are washed away by cross-flow at the same rate as new particles arrive, hence keeping the washing process at equilibrium. The thickness of the suspension layer will be dependent on the

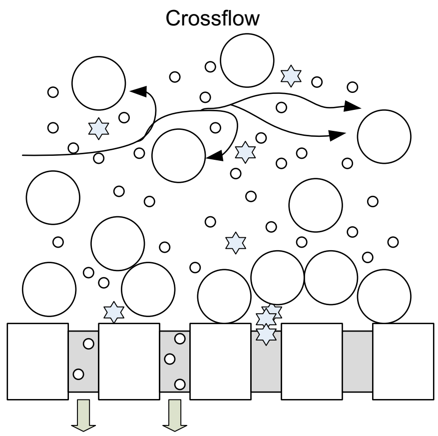

Fig. 7. The difference in colloid aggregation in cross-flow filtration and VSEP (image adapted from Johnson) [31].

pressure applied and the filtration rate [31]. The boundary layer acts as the nucleation site for scaling, however unique to VSEP, no matter how many colloids arrive at the surface, the equal amount is removed. To understand the shear flow created at the membrane surface, Fig. 8 shows that the highest shear is achieved at the fluid to membrane interface.

Originally created to separate plasma cells from blood, VSEP continues to be applied to wider industries. VSEP has been explored in latex concentrating, acid clarification, mineral clay dewatering, catalyst washing and pigment washing [64]. Several trials incorporating VSEP into local municipal water applications have been implemented to reduce organic levels via treatment of RO concentrates.

The most basic set-up of a VSEP system is depicted in Fig. 9. The filter pack unit consists of two moving components; the torsion spring and the bearings. Both operate using power with no need for manual operation. Frequency of oscillations is generally set at 50–60 Hz [65]. Shear rates up to 150,000 s^{-1} can be generated at 60 Hz which is 3–5 times greater than other cross-flow systems. The total footprint of a simple system is 1.85 square metres of floor space and is capable of accommodating up to 185 square feet of membrane area. Furthermore, the system can be integrated with existing processes and other VSEP units.

In many cases, VSEP complements an existing treatment system. Systems such as reverse osmotic membranes, spiral systems, EDR and ion exchange membranes amongst others have been explored with VSEP in various case studies which will be discussed later. VSEP is not cost-competitive for the first stage of desalination due to other RO systems having higher recovery percentages. However, the implementation of VSEP at the second stage can prevent the need for chemical treatment and additional concentrate processing [66]. In multi-stage systems, filtered concentrate is often sent back to the feed tank at the beginning of the process for recycle and increased recovery.

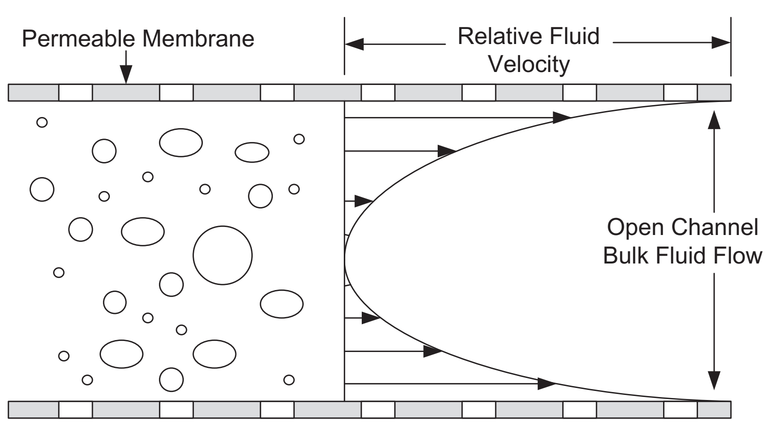

Fig. 8. The flow pattern in VSEP (image adapted from Johnson) [31].

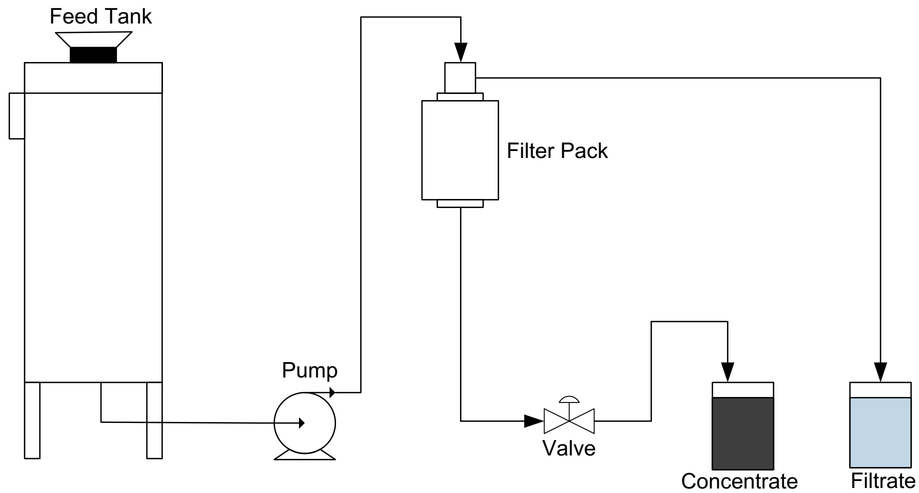

Fig. 9. The basic VSEP system set-up (image adapted from Culkin) [63].

Despite being energy efficient, VSEP is not ideal for all separation processes. Applications that involve low volumes (less than 5 gpm) are not recommended to be undertaken with VSEP as the system uses the same mechanism regardless of the size of the filter pack. Hence, a significant amount of energy is applied in excess [66].

Concentrate disposal management of ZLD technologies is considerably more cost-effective and much less complex compared to current disposal methods. A perfect ZLD system finishes with an end product with no effluent. Ultimately, concentrate will be in the form of wetted salts or solids. In many cases, wetted solids can be disposed by landfill or through natural evaporation via the sun.

Shi et al. explored the role of foulants in shear-based membranes such as VSEP [66]. The experiment measured the resistance at the membrane interface when VSEP is in operation. Two scenarios were tested; lack of vibration and vibration. Results showed that resistance due to fouling significantly decreased in the case of vibration, whilst resistance contributed by hydrostatic pressure and the membrane remained reasonably consistent between the two cases. Another study also performed by Shi et al. used SEM (see Fig. 10) to identify the differences in crystal structure of layers formed in both cases [67]. Notably, whilst both cases observed uniform layer morphology, the case of vibration consisted of a smooth, continuous and perforated layer. In comparison, the non-vibration layer had distinct needle-like particles. Shi hypothesised that vibration reduces the concentration gradient and the diffusive limitation on the growth rate. With vibration, particle growth out competes particle formation coalescing into a continuous smooth layer. The opposite scenario is observed without vibration where new particles are generated faster than particle growth.

A study by Vaneeckhaute et al. in 2012 applied VSEP technology to remove macronutrients from digestate in order to reuse concentrate as inorganic fertilisers with high nutrient availability [68]. Macronutrients such as nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) are required from liquid fractions of digestate and concentration is lowered to a reusable range. Digestate is produced from co-digestion of animal manure, energy maize and food industry residue.

Raw digestate rotated in a drum prior to entering two VSEP units in series. At each stage of treatment, key macronutrients removed are nitrogen and phosphorus. Following VSEP, permeate can be discharged into a lagoon or recycled back into the rotating drum. Concentrate may be offset or recycled back into the process.

The first filtration step removed 93 and 59% of N and P respectively. Concentrates produced could be reused as organic fertilisers due to their high concentration of N and P. Forwarding the concentrate to the second VSEP filtration step, N and P recovery increases to 95 and 69% respectively. Less macronutrients are removed in this stage so concentrate is often recycled. Final permeate had chemical oxygen demand (COD) levels that exceeded the discharge limits due to citric acid treatment. Purification via microbiological nitrification, plant nutrient uptake and dilution were incorporated into the lagoon treatment. Low salt content and total hardness indicate that permeate within the lagoon has potential for re-use in high quality applications. Even though recovery was high across the two stages, VSEP performance is limited by technical and mechanical problems that cause

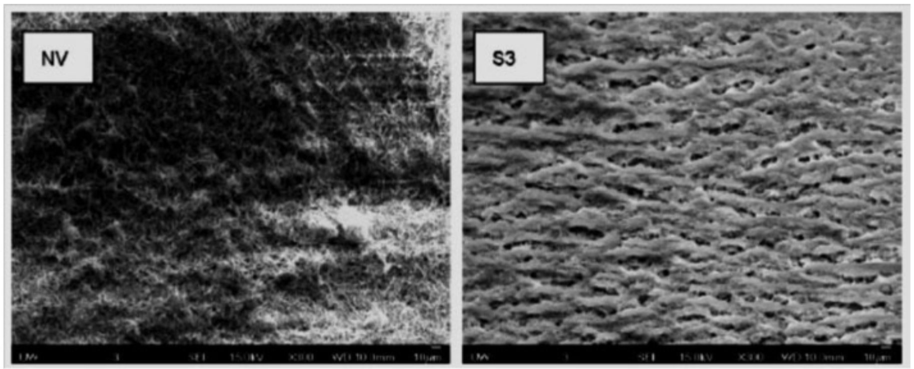

Fig. 10. The SEM images of the layer at membrane surface between non-vibrational (NV) VSEP and vibrational VSEP (S3) Reprinted from Journal of membrane science, 331, W. Shi & M.M. Benjamin, Fouling of RO membranes in a VSEP RO system, pp. 11–20, 2009, with permission from Elsevier [67].

instability and exceeding of statutory levels in the lagoon [68].

Vaneeckhaute et al. noticed optimisation via vibration frequency and amplitude change, filtration time, pH and temperature could improve the reliability of the VSEP process. Earlier studies have indicated that pH and temperature have considerable effects on ammonia–ammonium equilibrium that potentially drives removal efficiency of nitrogen [69].

Another study by Kertesz et al. in 2012 utilised VSEP in order to purify lactose, protein, fat and ionic content from dairy waste streams [70]. Similar to water treatment, membranes dealing with dairy streams are at particularly high risks of inner pore fouling caused by larger particles. Flocculation, chemical cleaning and high shear rotary membranes have all been applied in the past to reduce concentration polarisation and fouling.

Similar to previous studies, membrane vibration was found to increase permeate flux. Generating permeate flux against time curves for different types of membranes in a VSEP system, data were shown to fit with a power law mode given by Eq. (1).

$$J = J_o\, t^{-k} [\mathrm{Lm}^{-3}\mathrm{h}^{-1}] \quad (1)$$

where J = flux ($\mathrm{Lm}^{-2}\mathrm{h}^{-1}$), J_o = initial flux ($\mathrm{Lm}^{-2}\mathrm{h}^{-1}$), t = time (s) and k = fouling constant (–).

This model was utilised to calculate k fouling indices at different vibrations [70]. A lower fouling indices correspond to a reduced decline in initial permeate flux [29]. Lower fouling indices were observed when vibration was applied. It was noted that RO membranes had highest total membrane resistance due to decreasing pore diameter.

The total resistance across the membrane was also measured for each of the type of membranes. Contributors to resistance include fouling, membrane and osmotic pressure difference generated by differences in salt content between the bulk fluid and permeate. UF membranes having the largest pore diameters release molecules more readily during vibration. So, fouling resistance is decreased in UF to a larger extent [70].

Vibration was also shown to increase COD rejection significantly in UF. Rejection was less significant in NF and RO as values were already high prior to without vibration. Specific energy demand per volume permeate was measured comparing non-vibrating and vibrating systems at different pressures. At lower pressures, energy consumption in vibratory systems is higher than non-vibration; however at higher TMP, vibrational shear becomes more economical. No critical pressure was observed [70].

The role of VSEP has not been limited to conventional volume-reduction-based technologies. In 2005, Low et al. applied different mechanical motions on a membrane bioreactor (MBR) system [71]. MBR systems often operate on mixed liquor suspended solids that suspend and clog the membrane, thereby reducing its flux. The study tested cross-oscillation, lengthwise oscillation and VSEP to clean the membrane surface and enable high permeate flux via higher TMP. The experiment determined that VSEP under extremely high TMP conditions stabilised flux up to 70% of its initial value after 5 h and had 6.8 times greater flux than the submerged cross-oscillation measurements.

4. Performance and cost of volume-reduction & ZLD Technologies

The following section explores multiple case studies where volume-reduction technologies have been considered for industrial applications. In each case study, different effluents have been applied through one or multiple units of technology discussed in Section 3. Although annual volumetric treatment capacity and overall percentage recovery differ between cases, the overall operating and maintenance costs per unit volume were determinable and comparable.

4.1. Case 1

A case study explored in the Big Bear Valley (BBV) area east of Los Angeles focused on augmenting existing potable water for use during periods of drought or high water demand [38]. The paper explored seven alternative methods to dispose of concentrate from a proposed recycled water facility processing 605,666 litres per day to make estimates on operation and maintenance for life-cycle cost calculation.

The estimation of costs was limited by the amount of information available from technology vendors and the estimating system in place. Conceptual design was based around a 20-year life cycle. The present worth in life-cycle costs taking into account 5.375% discount rate, 3% inflation rate and capital cost estimates is given by Eq. (2).

$$P = A\left\{\left(\frac{1+E}{1-E}\right) \times \left[1 - \left[\frac{1+E}{1-E}\right]^N\right]\right\} + \text{capital cost} \quad (2)$$

The location was selected due to minimal public perception issues, climate suitable for reduced wetland size, low altitude and the potential for wastewater treatment plant expansion. However, disposal of concentrates is limited. Discharge to surface water is not feasible due to the lack of perennial stream flow. Deep-well injection is not allowable due to the underlying bedrock in the region. Land irrigation is heavily restricted by discharge limitations. Concentrate management schemes were categorised into three groups; effluent mixing, volume-reduction processes and zero liquid discharge technology.

High concentrations of chloride and TDS in the effluent stream limited RO reject for mixing to only 121,133 litres per day, well below the RO concentrate generated. No new equipment and pipelines are required to implement effluent mixing leading to a low capital cost as well as O&M costs.

Volume-reduction processes including EDR, VSEP and EMS were also explored. Using proprietary performance software WATSYS, an EDR system was designed. A maximum recovery of 79% was obtained reducing the 605,666 lpd of concentrate to 128,704. Selective ion exchange and RO are suggested prior to secondary treatment as EDR product is high in chloride concentration. Capital cost accounted for pumps, panels, disposable filters, control valves and a decarbonator as well as installation.

Unlike other methods considered, a VSEP pilot unit was installed to operate over a 4-week period to evaluate concentrate management from an RO unit. Onsite testing utilised two RO membranes, a LFC1 (low fouling composite) for RO and a NE90 (from CSM) for NF. In both cases, both RO and NF membranes reduce concentrate volume by up to 85%. Although higher percentages could be obtained, reduced flux and higher feed pressure requirements prevented optimal operation from occurring.

Two approaches were identified to improve volume reduction based on this recovery. Approach 1 focused on discharging the remaining 128,704 lpd of VSEP concentrate to EP. Approach 2 focused on bypassing 20% of the initial RO concentrate around the VSEP and blending it together with VSEP permeate and secondary treated wastewater effluent. Ideally, this would reduce the size of the unit and lower treatment costs.

When considering capital and O&M costs for VSEP, New Logic Research Incorporation provided information on equipment and installation. Other factors contributing to the costs include the SCADA control system, hoist crane for maintenance, acid for feed conditioning, membrane replacement and labour.

A variant to traditional RO systems was considered. EMSs such as the HERO system apply multiple stages of treatment such as chemical softening, ion exchange and pH precipitation. Projected water quality was expected to be similar to permeate from a VSEP unit as both of the technologies use RO membranes. In order to simplify cost estimates, the product from the EMS system was assumed to be blended with wastewater effluents in the same way as VSEP treatment. As no testing was performed to characterise permeate of the HERO process, the design flow capacity was assumed to be 605,666 lpd.

ME such as multi-stage systems of a vertical tube falling film concentrator followed by a brine crystalliser was considered as an alternative. In the conceptual design on the system, a recovery of 95% was assumed across the concentrator. Initially, the RO reject is concentrated into slurry and then undergoes crystallisation via flash evaporation of water, allowing a salt cake to form on the belt filter.

For the concentrator to process 605,666 lpd of concentrate, the sizing of the equipment would be 22.86 m in height. Furthermore, the crystalliser is highly energy-intensive and relies heavily on mechanical compression making it less reliable than other

ZLD methods. Due to the high operating cost, the best option proposed for ME usage is to first treat the concentrate with volume-reduction technology such as VSEP. Power calculation was based around the cost of \$0.13/KWh.

An evaporation pond was selected as a viable alternative due to the proximity of the BBV facility with a nearby Lucerne Valley (LV) site. LV was selected due to its low altitude promoting high evaporation rates, potential for expansion and distance from the public. The significant hurdle of conveying RO concentrate from BBV to LV requires construction of a new pipeline spanning 20 km through a national forest.

The average annual evaporation rate recorded in LV is 1183.64 mm per year which would correspond to an area of 566,560.4 m^2 required for EP. An area like this is highly infeasible and the volume would have to be significantly reduced prior to commencement. Implementing a hybrid system of VSEP followed by EP could be a potential solution.

Similar to the case of EP, constructed wetlands are better suited for LV due to higher evapotranspiration rates and higher air temperatures.

Table 1 summarises the capital cost and annual O&M costs in each of the alternative technologies evaluated. Notably, effluent mixing is the cheapest alternative but is highly limited by discharge limits. Both VSEP and EDR are similar in terms of costs and have low costs in comparison to other processes such as EMS, ME & the Crystalliser (CRYS). EP and Wetlands have significant capital costs due to the area required. Reducing the capacity of the wetlands will reduce the area needed and also the capital costs (Fig. 11).

The study explored the need to combine EP and wetlands with volume-reduction and ZLD systems. Implementation of volume-reduction technology such as EDR and VSEP will reduce the overall volume of concentrate being discharged into EP and hence lower areas required and associated costs. Volume can further be reduced by effluent mixing. In the study, the cheapest possible alternative was to incorporate VSEP and wetlands in series whilst bypassing 128,704 lpd of RO reject to mix with VSEP permeate. Calculations for life-cycle costs can be seen in the Table 1.

4.2. Case 2

In 1998, a wastewater system incorporating VSEP was installed at a hospital laundry facility in Seattle [72]. The laundry which mainly focuses on cleaning linen, bed sheets and towels operates 14 h per day and 364 days per year. Prior to VSEP implementation, the laundry used up to 378.54 Litres of freshwater per minute. Wastewater from the process is collected into a pit prior to being discharged in the sewer.

A VSEP unit with a UF membrane module was installed to treat laundry wastewater and recycled up to 70–80% of the water used. Suspended solids, oils and grease were primarily removed from the wastewater. Each of the contaminants was removed to trace levels. Fig. 12 shows the block flow diagram of the basic process and demonstrates potential to recycle laundry permeate and save on freshwater feed.

Operating costs were determined for certain recycle water to freshwater flow ratios. Total costs incorporated power costs of the unit, pumps, filter cleaning and replacement and any water heating involved. Without the VSEP unit, the total annual operating cost was \$218,000. With increasing recycle percentage, the total amount of freshwater required was significantly reduced and led to substantial annual savings. At 70% recycle flow, the net water and sewer charge was \$29,000. Higher recycle rates would result in a shorter payback period. The payback period at 70% recycle flow was 12 months compared to 17 months at 50% recycle flow.

4.3. Case 3

In 2007, Lahnid et al. undertook an economic analysis on a ED unit at an industry-sized plant supplying drinking water to an estimated population of 50,000 situated in Benguerir, Morocco [73]. The plant had a capacity of 2,200 m^3/day water consumption and the primary role of ED is to remove fluoride from the water. Other methods of de-fluoridation have low selectivity, high initial costs and low capacity [74]. NF and ED have been selected as the best membrane-based processes ideal for this scenario. A total of 10 years was allocated to membrane life and the ED is capable of 94% recovery rate. Raw water is pumped to pre-treatment sand filters and a sequestering agent is injected to control precipitation. Pre-treated water is pumped under low pressure to the ED stack before being stored in a product tank.

Capital costs of the unit covered pre-treatment and treatment equipment, building construction costs, auxiliary equipment and non-depreciable items. Operating costs considered consumables such as anti-scalant, energy usage, membrane and electrode replacement. The total capital cost determined was €833,207. The calculated operating cost was €0.154/m^3 of water produced. Technical and economic data were based from real data collected from the plant. Values obtained

Table 1
The calculated life-cycle costs for multiple system design scenarios in BBV (adapted from Lozier) [38]

Design scenarios	Capital cost ($USD)	Annual O&M cost ($USD)	Life-cycle costs ($USD)
Evaporation Pond Only + Flow Conveyance + Evaporation Pond	$13,106,000	$342,000	$18,613,000
VSEP + Flow Conveyance + Evaporation Pond	$6,169,000	$491,000	$14,075,000
Effluent Mixing + VSEP + Flow Conveyance + Evaporation Pond	$6,199,000	$450,000	$13,444,000
EMS + Flow Conveyance + Evaporation Ponds	$9,206,000	$514,000	$17,482,000
EDR + Flow Conveyance + Wetlands	$6,896,000	$514,000	$15,172,000
VSEP + Flow Conveyance + Wetlands	$6,067,000	$483,000	$13,844,000
Effluent Mixing + VSEP + Flow Conveyance + Wetlands	$5,820,000	$433,000	$12,792,000

from the study were significantly higher than those calculated from a previous work which used an adopted model to determine costs [75].

4.4. Case 4

A study in Negev Highlands, Israel, a bench pilot WAIV unit with a $1m^2$ evaporation area, was operated using two different desalination brines from a RO system with 75% recovery [56]. Following RO, concentrate is fed to EDR which allows recovery to reach 98%. Operation of the EDR occurred under high concentrations of brine to reduce the power requirements. Concentrates of up to 15% TDS content were achieved by the WAIV unit.

A notable observation was evaporation rates in the WAIV dropped off as brine concentrate reached 15% and greater. This was due to the lower vapour pressure gradient experienced. At up to 85% humidity, a correlation demonstrated that as vapour pressure driving force decreased, evaporation rates would also decrease.

The entire RO-ED-UF-WAIV process was evaluated economically. Costs were analysed annually. Though the process was near ZLD, the brine removal step i.e. WAIV contributed roughly 5.5% of the total annual costs for water recoveries of 75, 83 and 88% (See Table 2). In this set-up, WAIV costs were observed to be 16,556 €/yr for a brackish feed flow of $100\,m^3/h$. A key economic assumption was that 1.05 € is required to remove $1\,m^3$ of brine via the WAIV unit [56].

4.5. Case 5

A study by Macedonio et al. studied the processing of RO concentrate via WAIV and membrane crystallisation units [53]. The WAIV units were cre-

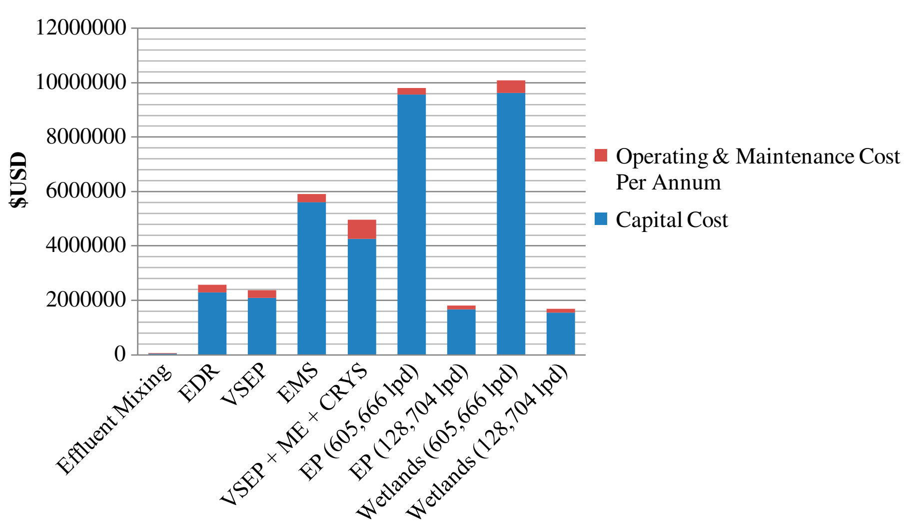

Fig. 11. Costs of technology alternatives in Big Bear Valley (adapted from Lozier) [38].

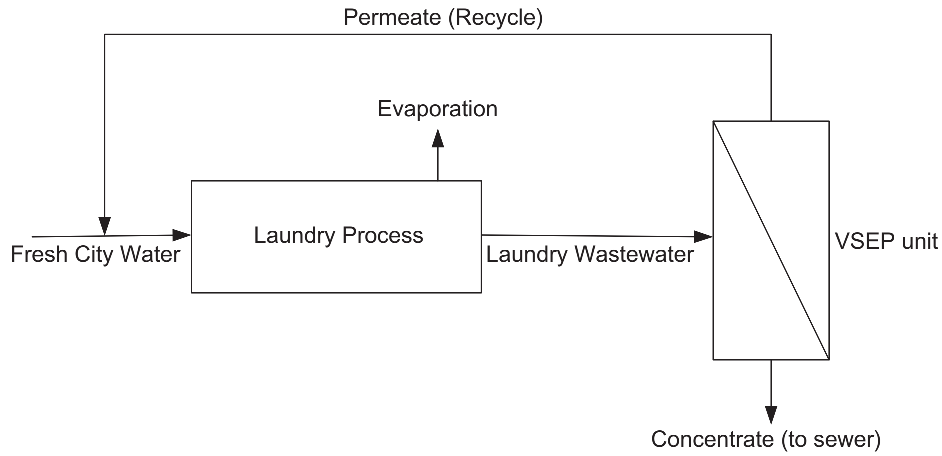

Fig. 12. The basic set-up of VSEP in laundry water wastewater treatment (image adapted from New Logic Inc. case study) [72].

Table 2
Total costs of ZLD system at different percentage recovery (adapted from Katzir) [56]

Recovery in RO step	75%	83%	88%
RO production costs (€/y)	187,466	195,666	200,790
Annual ED costs (€/y)	107,281	89,318	78,031
Brine removal costs (€/y)	16,556	16,556	16,556
Total annual costs (€/y)	311,303	301,540	295,377
Annual production (m^3/y)	772,632	772,632	772,632

ated to be lab-scale having 1 m^2 of wetted area and a footprint of 0.17 m^2. WAIV units were operated until total dissolved content of 10% was achieved. Within the study, the presence of an anti-scalant on the crystallisation process caused a reduction of 17.5% in the amount of Ca^{2+} ions within the WAIV super concen-

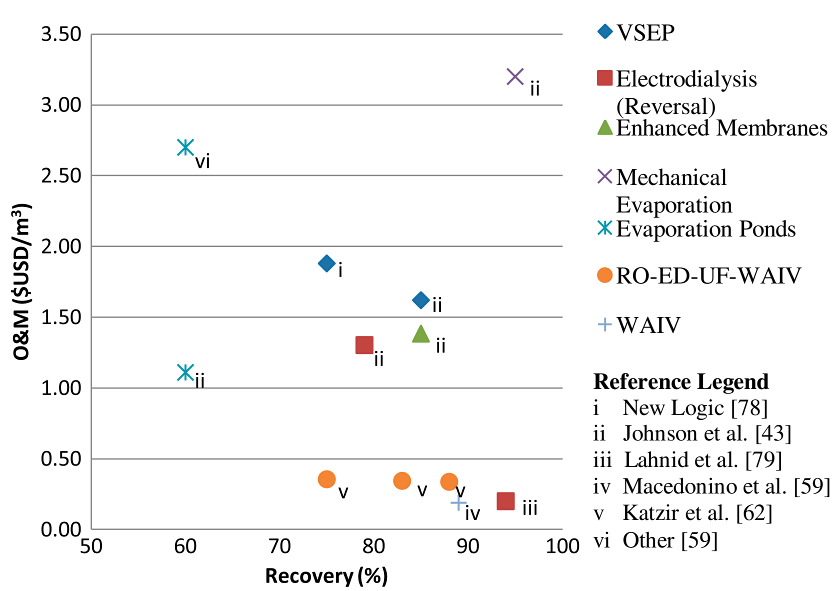

Fig. 13. The O&M costs in $USD per m^3 determined for different technologies in the cases summarised.

Table 3
Summaries the advantages and disadvantages of alternatives explored

Alternative technology	Advantages	Disadvantages
	Excellent at monovalent ion removal	Less effective with divalent ions & non-charged contaminants
	Reversal can assist in fouling control	Lower recovery in comparison to other methods
Electrodialysis	Reduced footprint	
Enhanced membranes	Recovery of greater than 95%	High capital and operating costs
		Energy intensive
Mechanical evaporation	Recovery of greater than 95%	High capital and operating costs
	Recover brine in forms of crystals	Energy intensive
	Low operating costs & energy requirements	Low productivity
WAIV	Low footprint	Not feasible in areas where strong wind is absent
	Low operating costs	Large footprint
Wetlands	Reduced discharge costs	
VSEP	Low footprint	Reduced capability when used as isolated alternative
	High recoveries (Above 80%)	Not economical when dealing with small volumes
	Capable of being implemented into any existing system	

trate being fed to the crystalliser. This reduced Ca^{2+} was recoverable as $CaCO_3$ precipitate in the pre-treatment step before crystallisation. The integrated system was able to reach as high as 88.9% recovery and discharge less than 0.27% of the raw water fed to the system.

Based on evaporation rates of 3 mm per day, economic evaluation on the WAIV unit was calculated. Capital cost of the WAIV system was 0.707 €/m^3 and the total operating cost was 0.189 €/m^3. Comparative to conventional EP (\$2.76–\$3.06/m^3), WAIV provides a 64% reduction in capital costs. Although not as economically feasible as VSEP, EDR also shows promise in terms of minimising concentrate volume.

4.6. Summary of case studies

Fig. 13 summarises all the operating and maintenance costs determined in each study based in $USD per m^3 of concentrate treated. No general trends were observed; however, significant differences in pricing observed are likely due to the capacity of the unit. The scatter plot shows that ME whilst producing high recoveries is highly expensive to operate. On the lower scale, EPs have low recoveries with varying O&M costs. Notably, some O&M costs less than $1USD/m^3 were observed; however, this was for multi-stage systems. Calculation conversions were based on conversion rates on day of writing (€1 = $1.29USD on 5 April 2013).

Table 3 shows some of the key benefits and shortcomings of each technology. Each of these must be considered when deciding upon a technology for a given application.

5. Conclusions

This review has explored the current state of desalination and concentrate management around the world. With membrane-based processes becoming more and more prevalent, the need for alternative concentrate disposal methods has become serious. Current disposal methods such as surface water discharge, EP and deep-well injection are only sustainable for a short period of time and are limited by size constraints, geographic location and high capital costs.

To minimise the amount of concentrate produced, volume-reduction technologies as well as ZLD systems have been proposed. In these cases, the combination of several volume-reduction methods can help achieve extremely high recovery percentages. Some technologies explored in the review were ED, enhanced membranes, ME equipment, wind-aided intensification process and VSEP. All methods explored have varying degrees of benefits and liabilities.

VSEP, a shear-based membrane process, has shown high percentage of recovery of up to 98% in case studies dealing with effluents ranging from brackish water to laundry water to dairy concentrate. VSEP was shown to be particularly advantageous as a secondary treatment process. Studies have often applied VSEP after treatment via ion exchange, ED or spiral RO. The technology consists of a small footprint and reduced energy requirements when compared to other alternatives such as enhanced membranes and mechanical evaporation. Selected as a potential alternative to EP, WAIV uses natural evaporation via wind to precipitate salt onto high density sheets. Comparatively with EP, WAIV can reduce the area required for deal with the same capacity by 10-fold. Consequently, the capital cost for when using WAIV is significantly lower. Many WAIV units have been piloted as final treatment stages in potential ZLD systems. There remains a possibility that WAIV can be implemented with a VSEP system given the right conditions.

Case studies exploring the economics of concentrate disposal methods have indicated that VSEP has a lower life-cycle cost than other technologies discussed. However, to improve the overall process efficiency, VSEP should be coupled with other disposal methods such as EP or WAIV.

Further studies on processes such VSEP and EDR via up-scaling from pilot to industrial scale may reap benefits and explore territory not covered in this review. However, volume-reduction and ZLD technologies provide a solution to the problem that is concentrate disposal.

Nomenclature

lpm	—	litres per minute
lpd	—	litres per day
MLD	—	million litres per day

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