Desalination and Water Treatment
www.deswater.com

13 (2010) 63–73
January

1944-3994/1944-3986
doi: 10.5004/dwt.2010.772

WAIV – Wind aided intensified evaporation for brine volume reduction and generating mineral byproducts

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Received 1 May 2009; accepted 16 June 2009

ABSTRACT

In this study bench pilot WAIV units ($\sim$ 1 m^2 evaporation area loaded on 0.17 m^2 footprint) were operated on two different desalination brines (RO and ED) as well as on a mineral brine concentrate under arid conditions of the Negev Highlands. The evaporation rate with the WAIV unit on these feeds often gave evaporation rates per footprint that were 10-fold or greater than the pan evaporation rate obtained from the local meteorological station at Sde Boker. Desalination brines were concentrated up to 23% TDS when operating on ED concentrate. The evaporation from the WAIV unit demonstrated enrichment in the magnesium ion compared to the calcium and the sodium ion, including over a two-fold enrichment of magnesium relative to calcium as would be expected by the equilibrium solubilities of the different minerals. Despite precipitation of minerals, there is not a large buildup of deposit on the flexible evaporation surface, and this helps establish the feasibility for recovering minerals from the desalination brine by using WAIV unit. For the ED-RO hybrid desalination process which provided one of the feeds to the WAIV unit, WAIV capital costs will only be about 5.5% of the annualized desalination costs (CAPEX and OPEX).

Keywords: Inland desalination; Brine disposal; Concentrate management; Evaporation ponds

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1. Introduction

The demand for freshwater in many regions of the world has outstripped supply. More than 50% of the countries in the world will likely face water stress or water shortage by 2025, and by 2050, as much as 75% of the world's population could face water scarcity [1].

The population growth and the lack of quality resources lead to the need for water utilities to treat impaired water sources and for desalination to generate new water resources. Desalination is growing rapidly, and the efficiency of the technology has significantly improved over the last decade especially in seawater desalination. There are still critical actions that need to be made in order to make this technology more cost effective, especially for inland desalination [2]. One of the main challenges is to find a suitable disposal options for the brines produced in inland desalination plants which is both cost effective and environmentally sustainable.

There are several concentrate disposal methods such as: surface water, sewer system discharge, deep well injection, land application, Zero Liquid Discharge (ZLD), and evaporation ponds. Rarely are more then one or two option available at a given plant site [3]. The most straightforward method for brine disposal is

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Presented at the conference on Desalination for the Environment: Clean Water and Energy, 17–20 May 2009, Baden-Baden, Germany. Organized by the European Desalination Society.

discharge to a surface water body with high salinity such as sea or ocean. If the desalination plants are not near a saline water body, the disposal options are more complicated and estimates show that it can be on order of 15% of the costs of desalination [4]. One of the options for the concentrate disposal inland is discharge in the sewage system. However, this is not often possible because of the large volumes to be discharged and the negative effect of the wastewater treatment plant [5]. Deep well injection is another option for the concentrate disposal, the location of the injection has to be carefully chosen, it require a monitoring wells to ensure that there will be no risk for the groundwater and to the soil around the location of the injection, the injection pipes need to have an additional liner to prevent corrosion.[5,6].

Land application, depending on the availability and the cost of land, size of the concentrate (volume), irrigation need, the tolerance of vegetation to salinity, the ability of the soil to uptake water and the option need to be available year round. Zero Liquid Discharge is a concept that involve using hybrid methods in order to reduce the concentrate volume significantly to get solid byproducts for land-fill disposal and often requiring the application of energy intensive thermal processes. As a result, the capital and operating costs are relatively high.

Evaporation in ponds is the last method considered for disposal. The concentrate is placed in a shallow lined pond which allows the water to evaporate naturally by using the solar energy; after the water evaporates the salt is either left in the pond or removed for disposal. This method often requires large land areas, and can be viable only in arid and semi arid climates with high evaporation rates, and low land value. Expensive liners are required to prevent salt seepage from contaminating the soil and the groundwater.

Mickley's recent report for the U.S. Bureau of Reclamation, indicates that evaporation ponds were used for 6% of the municipal reverse osmosis (RO) plants before 1993, and just 2% since then [3]. The reason for such low use of this method lies in the land area required with attendant liner costs required to cope with the environmental impact to the soil and to the groundwater with potential risk of leakage underneath the pond. As evaporation ponds have almost no economy of scale, these problems expand proportionately as larger plants are designed than in the past. In addition, finding sites for the large ponds required for large plants is quite complicated both for real estate and regulatory reasons.

There is a pressing need for more economic methods of brine volume minimization with less environmental impact. The WAIV (Wind Aided Intensified eVaporaion) is a new proprietary technique [7,8],which entails increasing the evaporative capacity per footprint area by close packing vertically mounted and wetted surfaces and exposing them to the dry winds of the semi-arid regime. This exploits the wind energy to maximize evaporation of the brine using minimal external energy and land area while improving the feasibility of getting minerals byproduct and reusing them.

These surfaces are cooled to near the wet bulb temperature and the temperature gradient between the warmer wind and the cold-water surface drives heat flux to the wetted surface. The vapor pressure gradient drives the evaporation mass transfer from the surface. Comparison of field results to the literature show that the WAIV evaporation behavior qualitatively follows the meteorological evaporation correlations given for ponds. Previous studies on normal desalination brines in a pilot unit with 3l–43 m^2 wetted evaporation surfaces showed that evaporation rates (L/D-m^2) can reach 50–90% relative to open ponds while surface loading reached 15–30 m^2/m^2 per footprint [9].

The WAIV can also give a good solution for volume minimization of other streams such as cooling tower blowdown, mine drainage, and agricultural drainage water. Another application of interest is in the production of minerals from waste brines, wherein evaporation ponds are commonly used today. The most common example is the use of evaporation ponds for production of table salt, which has been extensively used for thousands of years. Currently, the Sabha seawater RO plant located near the Red Sea port of Eilat sends its reject brine to salt production evaporation ponds. A pond area of 700,000 m^2 is needed in order to handle about 5000 m^3 perday of concentrate. A WAIV plant could reduce the land area required by an order of magnitude.

In our current research we built a bench-pilot WAIV plant (1 m^2 evaporative area per test position on 0.17 m^2 footprint) to screen the ability of the WAIV to evaporate concentrated brine (TDS$\geq$ 10%) from brakish water revers osmosis (BWRO) and Electrodialysis (ED). Our purpose in doing so was to show that it is practical to use the WAIV unit to concentrate highly concentrated brines even when their vapor pressure begins to decline with their increased salt content. A secondary purpose of these experiments was to explore to what extent highly soluble magnesium salts could be enriched relative to less soluble salts of other cations as we concentrated the brines. Such magnesium salts may be potentially useful as raw materials to industry (automotive, aerospace etc.) and thus could provide another way to defray the relatively high costs of brine disposal in inland desalination.

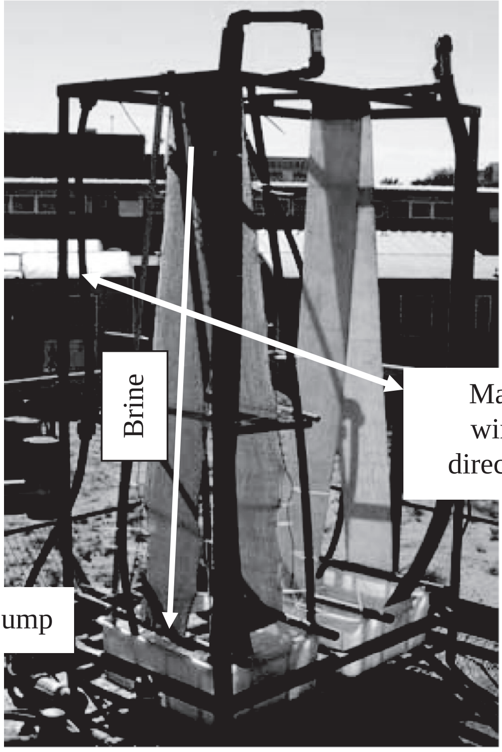

Fig. 1. Lab scale WAIV unit.

2. Methodology

2.1 WAIV experimental setup

WAIV runs were carried out on two lab-scale units constructed with a polycarbonate feed basin (32 L), recycle pump and distribution pipe for two 1.5 m lengths of wettable plastic surface (see Fig. 1). The footprint was 0.171 m^2 and the wetted WAIV area was 1 m^2 per test position. The two units were mounted on the second floor of an outdoor test stand. The plane of the wetted surfaces was oriented parallel to the dominant wind direction (NNW). The distance between the edge of the wetted surface to the edge of the feed basin was about 5 cm. This led to a measurable loss of drops that fell off the net at distances up to 0.5 cm when winds were high. Mass balance procedures were instituted (see below) to account for this fluid loss. A larger retaining basin has now been placed under the WAIV unit to prevent this problem in the future.

The height of solution was measured each day and if it dropped to near the bottom of the basin, the basin was topped up with fresh brine.

The volumetric WAIV concentration factor (VCF) of the RO and the ED brines was determined by measuring the water height in the WAIV feed tank to get the initial volume (V_0) and then each day height of the water in the tank was measured (Vt) before adding make up water of volume $\triangle Vi$. The nominal cumulative VCF was then evaluated as follows:

$$\mathrm{VCF} = \frac{V_o + \sum_i \Delta V_i}{V_t} \tag{1}$$

In addition to the nominal VCF the real VCF was measured based on the Mg^{2+} concentration which is a conservative ion that had does not precipitate during the time of the experiment even at very high concentration. The mass balance on this ion gives the following relation between the real VCF and the measured quantities:

$$\begin{aligned} &\frac{C_t}{C_i} = \frac{V_o + \sum_i \Delta V_i}{V_t} + \frac{V_o}{V_t}\left[\frac{C_o}{C_i} - 1\right] \\ &if \\ &C_o = C_i \rightarrow \\ &\frac{C_t}{C_i} = VCF \end{aligned} \tag{2}$$

The difference between the two VCF values can be explained due to the escape of water drops from the perimeter of the feed basin, since the WAIV fabric is very close to the basin border (Fig. 1).

The extent of nominal daily evaporation was obtained by measuring the change in the water height in the basin times the footprint of the basin of water and divided by the time of between measurements:

$$Q_{nom}(L/d) = \frac{\Delta h(\mathrm{mm}) \times 0.171\mathrm{m}^2}{\Delta t(\mathrm{days})} \tag{3}$$

The evaporation rate normalized to the footprint is given by:

$$E_{nom}(\mathrm{mm/d}) = \frac{\Delta h(\mathrm{mm})}{\Delta t(\mathrm{days})} \tag{4}$$

This value of the evaporation rate was compared to pan evaporation from the nearest meteorological station (Sde Boker Meteorological Station-SBMS) to determine the enhancement effect over a standard pan evaporation. Such a comparison is a conservative evaluation of the enhancement that evaporation with WAIV provides. This is so since standard pan evaporation uses tapwater and the WAIV uses brines which when they concentrate above 10% TDS begin to show significant drops in their vapor pressure relative to pure water (See Fig. 3).

The following brine solutions were used as feed for the WAIV units:

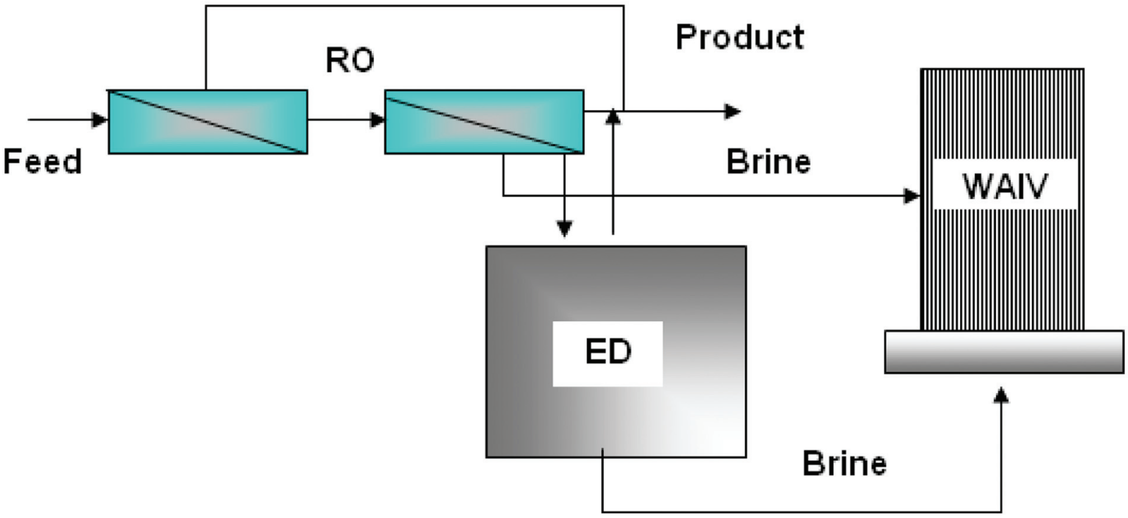

Fig. 2. General layout of RO-ED-WAIV process.

2.1.1. RO concentrate

As part of a larger project of the European Union (MEDINA), there is an effort to explore methods of recovering minerals from desalination brines. The final crystallization of these brines is being carried out by membrane distillation. The WAIV unit generated super-concentrates (10–15% TDS) from RO concentrates (75% recovery) as feed to the membrane distillation unit. The samples generated were as follows:

- RO concentrate without antiscalant
- RO concentrate with antiscalant (sodium hexametaphosphate)

The well water of the Mashabe Sadeh aquifer was first treated by passing it over a column containing weak anion exchange resin to adsorb potential organic contaminants, before pumping it into the RO membrane plant. TOC measurements showed that the organic level was somewhat reduced by this treatment. The feedwater was then treated in modified batch mode with four 4-inch BWRO elements (ESPA-2) at a flux of about 20 L/m^2 h to generate a concentrate of 4 fold concentration (75% recovery).

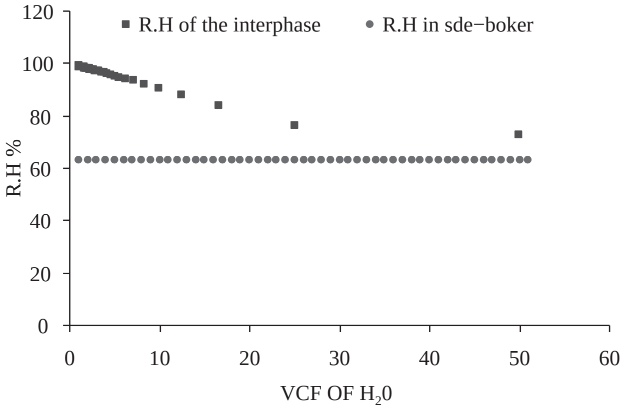

Fig. 3. Projected relative humidity (RH) of RO brine (88% recovery) as it is concentrated by evaporation. Average relative humidity of Sde Boker is shown for comparison.

A total volume of 1600 L of well-water were treated producing 1200 L of permeate and 400 L of concentrate. Compositions of RO feed (Mashabe Sadeh well water) and concentrate are provided in Table 1. It can be seen that the weak anion exchange resin treatment caused the pH to drop precipitously. This is probably due to inadequate washing of the column to remove the regenerant solution.

In a second run the feed was fed directly to the RO process run at 75% recovery and the pH was set low enough by addition of sulfuric acid to ensure no calcium carbonate precipitation (the only significantly precipitating salt at this recovery) and sodium hexametaphosphate was added to prevent gypsum precipitation. The acidic concentrate was neutralized with caustic soda to pH 8.2 before running the WAIV.

Both of these feeds to the WAIV unit were run until a nominal 20-fold volumetric concentration factor (VCF) was achieved.

2.1.2. BWRO-ED concentrate

Our group is running a process in which brackish water RO concentrate is fed to electrodialysis [10,12]. This allows recoveries to reach 97–98%. The RO concentrate (75% recovery) was fed into the ED 1000 (PC-Cell, Germany) system, with 50 cell pairs, 5 m^2

Table 1
Mashabe Sadeh well water and RO and ED concentrates used for WAIV concentration runs

Sample	Unit	Well water (RO feed)	RO conc.	ED Feed	ED Brine
pH		8.22	7.13	7.30	1.96
EC	dS m^{-1}	3.90	13.50	13.20	50.85
HCO_3	mmolc	4.58	5.10	5.07	0.00
Cl	mmolc	33.0	191.0	189.6	1371.0
Ca	mmolc	9.44	52.00	51.24	91.57
Mg	mmolc	7.91	42.00	39.66	230.34
SO_4	mmolc	9.63	54.00	53.96	121.99
F	mg L^{-1}	1.21	5.40	5.83	20.98
Sr	mg L^{-1}	6.07		28.84	150.23
Fe	mg L^{-1}	0.00		0.01	0.51
Mn	mg L^{-1}	0.00		0.00	0.02
Ba	mg L^{-1}	0.06		0.29	0.17
K	mmolc	0.66		2.22	14.13
Na	mmolc	28.6		129.8	1183.0
SiO_2	mg L^{-1}	18.96		98.69	105.10
P	mg L^{-1}	0.02		1.24	3.96
Al	mg L^{-1}	0.09		0.25	1.01
Cu	mg L^{-1}	0.03		0.15	7.20
TOC	mg L^{-1}	10.0		1.00	5.00

active membrane area, operated in EDR mode. (see Fig. 2). By operating the ED with extremely high concentrations in the brine stream, lower power is required for the ED step.

The ED concentrate was fed to one of the WAIV test units while the other basin was filled with tapwater as a control. The place of the WAIV unit in the overall flow scheme is provided in Fig. 2. The composition of the ED concentrate fed to the WAIV unit is found in Table 1.

2.1.3. *Concentrated mineral brine, TDS = 25–28%*

The efficiency of the WAIV unit was also tested with very concentrated brines with a TDS of 25–28%. Four main minerals were traced during the time of the experiment in order to check the feasibility to achieve selective precipitation.

2.2. *Analyses and saturation calculations*

Most cations were determined by inductively coupled plasma spectrometry (ICP). Mg and Ca were determined by colorimetric titration, standard methods 2340-c. Chloride was determined by argentometric, standard methods 4500-a titration and sulfate was determined by turbidimetry, standard methods426-e. TDS was measured by standard methods2540-c.

2.3. *Calculation of evaporative driving force*

Many correlations have been developed for the rate of evaporation from bodies of quiescent water.

The total evaporation rate can be correlated with the actual driving force of a wet surface according to the following equation

$$E = f_e(\overline{u}_r)(\overline{e}_w^* - \overline{e}_a) \tag{5}$$

where $\overline{e}_w^*$ and $\overline{e}_a$ refer to the vapor pressure of the water at its surface temperature and the actual vapor pressure of the air, respectively. The bar over each symbol indicates that it is a time-averaged value. The mass transfer function f_e is a function of the average wind speed in height r [11].

Saturation vapour pressures of air and water were calculated from the measured air and water temperatures on the WAIV rooftop unit using the modified Clausius-Clapeyron equation where temperatures are expressed in degree Kelvin:

$$\ln e^* = 53.67957 - \frac{6743.769}{T} - 4.8451 \ln(T) \tag{6}$$

The relative humidity (RH) of the interface of the solution was calculated to get equilibrium vapor pressure of the solution, $e_s{}^*$ in place of the pure water vapor pressure, $\mathrm{e_w}{}^*$ used in Eq. (5). This was used to calculate the vapor pressure difference Δe for according to the following equations:

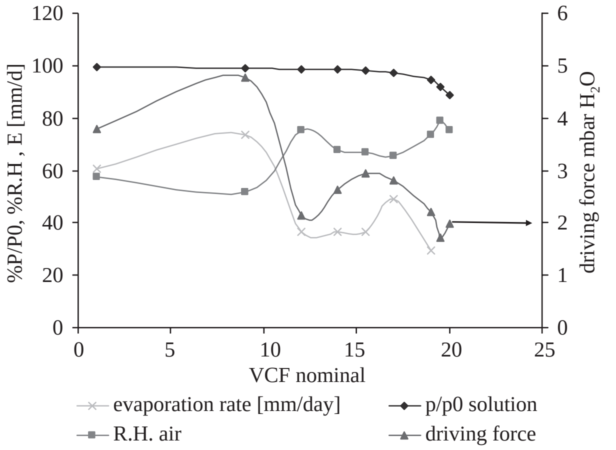

Fig. 4. $VCF_{nominal}$ vs. R.H, driving force and evaporation rate (mm/d based on WAIV footprint).

$$\frac{P}{P^0} = \exp(-\frac{V_W\Pi}{RT}) \tag{7}$$

$$\Delta e \equiv e_s^* - e_a = [P^0_{W.B}\left(\frac{P}{P^0}\right)_{T_{W.B}} - (P^0)_{air}(RH)_{air}] \tag{8}$$

Π is the osmotic pressure estimated from the brine composition by using strong elecrolyte thermodynamic equilibrium software (OLI systems Inc.), P and P^0 are the equilibrium vapor pressures of the solution and that of pure water respectively, with T in degree Kelvin.

In order to evaluate the concentration factor that is attainable by evaporation from the RO solution, simulations were carried out with the thermodynamic software for concentrated electrolytes (OLI systems Inc.). A starting composition of an RO concentrate (recovery of 88% from water with composition of the Mashabe Sadeh well field) was taken as the original feed to the WAIV unit. The software was run for successively smaller quantities of water up to an effective VCF of 50 to get the osmotic pressure for every stage, and to calculate the equilibrium vapor pressure as in Eq. (8).

3. Results and discussion

Based on Table 1, the concentration ratio of most major ions and components was concentrated between 3 to 4 fold in the RO step and 6 fold concentration in the ED step.

3.1 RO concentrate-WAIV

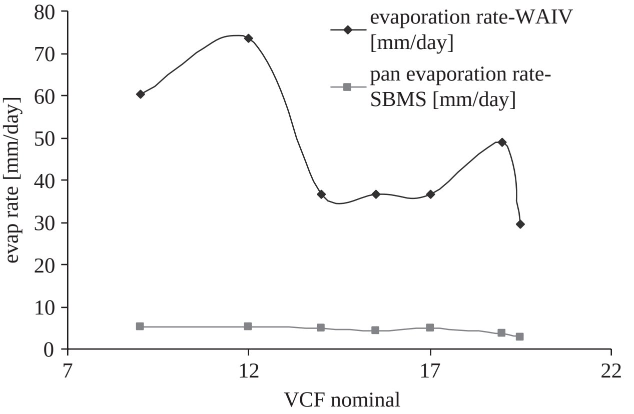

Fig. 5. WAIV evaporation of RO concentrate. Starting concentration of ∼ 1.2% TDS.

The results of the simulation of evaporation of the RO brine up to VCF of 50 are displayed in Fig. 3. The equilibrium vapor pressure (expressed as relative humidity – R.H.) is compared to the average relative humidity of the Sde Boker Meteorological Station (SBMS). It can be seen from Fig. 3 that for VCF greater than 20 the relative humidity difference is significantly decreasing and with it the driving force for brine evaporation.

Fig. 4 illustrates results from an actual WAIV concentration run on RO concentrate (75% recovery) from the fall season of 2008. Air R.H. values were taken from the SBMS, and the vapor pressure of the concentrated brine was calculated according to Eqs. (6) and (7).

There is a clear correlation between the relative humidity difference ($p/p° - R.H_{air}$) to the evaporation rate and the driving force. It can be seen from the graph that as the driving force decreases, evaporation rate decreases as well, As the concentration of the brine increases the driving force and evaporation rate drop off significantly.

This Figure also illustrates the limit of geographical applicability of WAIV for reducing end-brine volumes. Even at driving forces as low as 2 mbar and differences of relative humidity (brine solution – air) as low as 10%, the WAIV unit could evaporate 20 L m^{-2} footprint (five fold typical pan evaporation rates). This means that for relatively dilute brines (1–2%), significant evaporation could be achieved with a WAIV unit even where average relative humidities are in the range of 85–90%.

Fig. 5 shows the nominal evaporation rates normalized to the WAIV footprint for the same run as in Fig. 4 and compares it to the pan evaporation rates taken from the SBMS at the same time at the WAIV run. The points on the pan evaporation rate curve are the daily values measured for the date on which the WAIV unit reached the nominal VCF listed on the x-axis. Overall, even at the highest brine VCF values with the lowest

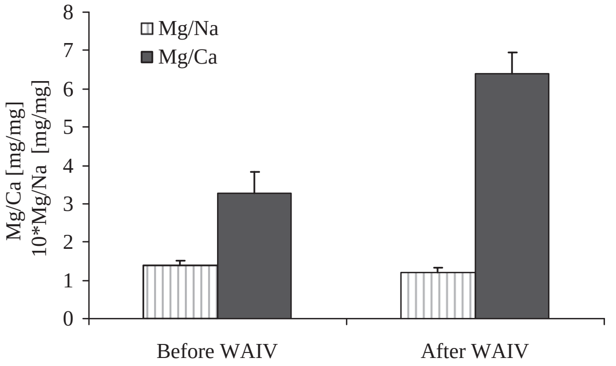

Fig. 6. Enrichment of magnesium relative to other major cations as a result of WAIV evaporation.

driving force, the evaporation rate from the WAIV is higher than the pan evaporation rate by a factor of 7.

The enrichment of magnesium relative to sodium and calcium ions as the brine is concentrated is shown in Fig. 6. This ratio was evaluated in order to see if calcium salts precipitate first as would be expected by the solution equilibria. The concentration ratio of magnesium to calcium ions more than doubled during the WAIV run while the ratio of magnesium to sodium remained almost unchanged. This enrichment can be explained from the precipitation of the gypsum on the evaporation surfaces and in the feed basin. It should be noted that only a very thin layer of gypsum (1–2 mm maximum thickness) was found on the evaporation surfaces, so the rest of the deposit was in the feed boxes below. The increase in the concentration ratio Mg^{2+}/Na^{+} is marginal due to the fact that by the end of this experiment the TDS of the solution had only reached about 10% and was still far from halite saturation. Any extent of increase in the ratio, can be attributed to halite precipitation on the wetted surfaces where local conditions of supersaturation are possible.

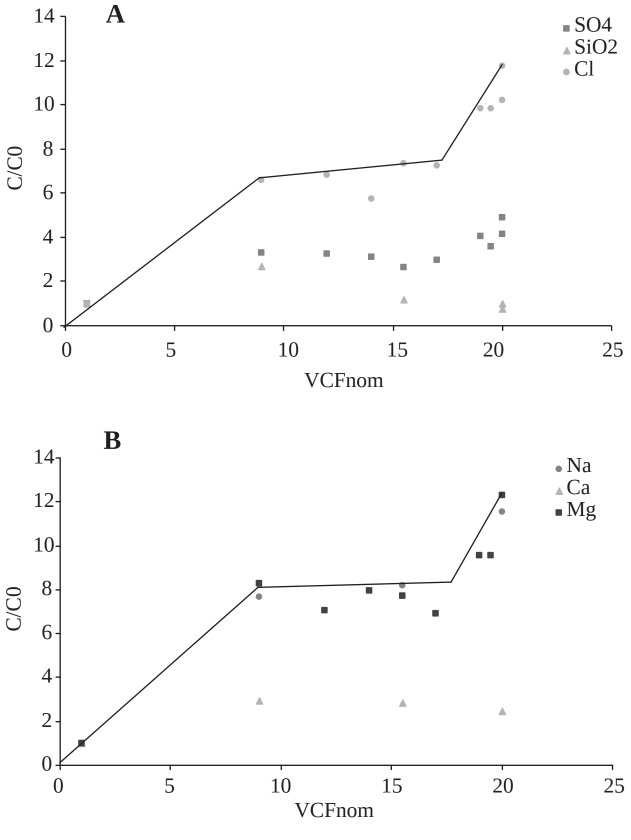

Fig. 7. Concentration factor of the major ions as a function of nominal volumetric concentration factor in WAIV. a) anions b) cations.

Fig. 7 a and b show the concentration factor for anions and cations respectively as a function of the nominal volume concentration factor. As can be seen, major anions chloride, sodium and magnesium – which do not precipitate – follow the VCF almost linearly only between VCF 1-9 and VCF 17–21. The intervening VCF shows that there was some apparent malfunctioning of the unit – perhaps an undetected leak from the piping.

From examination of Fig. 7 we can also identify the following trends as well:

- SiO_2 – In the beginning of the concentration run there is an enrichment in the silica until it reaches saturation and starts to precipitate. Over-all the end concentration reaches a level similar to that of the beginning. This could reflect the decreased solubility of silica at high ionic strength solutions.
- SO_4^{2-} – The volume concentration ratio in the sulfates is clearly lower than that for magnesium, which can be attributed to precipitation of the gypsum during the concentration of brine by evaporation
- Ca^{2+} – The phenomenon here clearly mirrors that of sulfate.
- Mg^{2+},Na^{2+},Cl^{-} – For all these components the concentration factor increases linearly with the nominal volume concentration factor over the course of the experiment. This is consistent with the fact that no minerals containing these ions have reached their saturation limit as a result of the evaporative concentration in the WAIV unit.

3.2 BWRO-ED concentrate – WAIV

WAIV provides a tremendous enhancement of the evaporation rate from the BWRO-ED concentrate compared to the pan evaporation. Based on the relative slopes of cumulative volume evaporated versus time, this represents an enhancement factor of 10 (see Fig. 8).

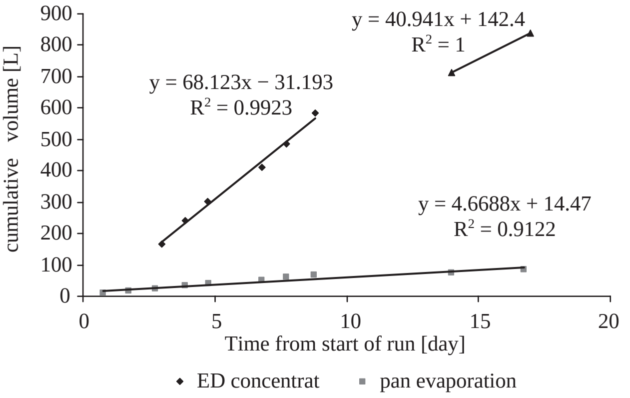

Fig. 8. Cumulative volumes evaporated per unit footprint by WAIV unit operating on ED concentrate as compared to pan evaporation of tapwater.

In addition it is clear from Fig. 8 that there are two trend lines for the cumulative volume that evaporated from the WAIV unit, during the time of the experiment. The drop in the slope of the second trend line reflects the decreasing evaporation rate as a result of the decreased vapor pressure of the concentrated brine.

In the end of the run, deposit samples were taken from the evaporation surface for XRD (Fig. 9) and SEM (Fig. 10 a and b) analysis, to check what kind of minerals precipitated during the run. Both of the analyses indicate that the salts that precipitate are halite (NaCl) and gypsum ($CaSO_4$*$2H_2O$). This is in contrast to the run on RO concentrate in which only gypsum precipitated.

The difference in the minerals that precipitate during the ED run to the one that precipitates during the RO was the precipitation of the halite. The ED run start with TDS of 10% and the RO start with TDS of 1%. In the evaporating ED concentrate, the saturation index of the halite which will occur at TDS of 26%, which is obtained on the evaporating surfaces of the WAIV unit. On the other hand, the precipitation of the halite during the RO run will take a much higher VCF, and as can be seen from Fig. 3, after VCF of 20 it becomes less efficient.

From Fig. 11 one can also see the enrichment in the magnesium ion relative to calcium ion. The reason for the small enrichment in the Mg/Na ratio is due to the fact that the run was stopped shortly after the brine reached the saturation index of halite. As a result, only a small amount of halite had precipitated by the end of the experiment.

Table 2 summarizes the TDS content of the brines in the WAIV evaporation experiments with RO and BWRO-ED concentrates. It can be seen that in terms of TDS, the concentration factor was almost 10-fold for the RO brine and only about 2.5 fold for the ED brine. Since similar volumes were evaporated in each case, it is necessary to explain why the TDS ratio (end:beginning) is higher for evaporating RO concentrate than it is for evaporating ED concentrate. The ED brine starts out at a much higher concentration so that during the course of the evaporation of this brine, the saturation limit for sodium chloride is reached and it begins to precipitate (see Fig. 10 for corroboration). This is not the case for the RO brine, since even at the end (95 g/L TDS), the solution is significantly undersaturated with respect to sodium chloride.

3.3 Concentrated mineral brine TDS = 25–28%

From Fig. 12 the effect of selective precipitation during WAIV operation became very clear as the

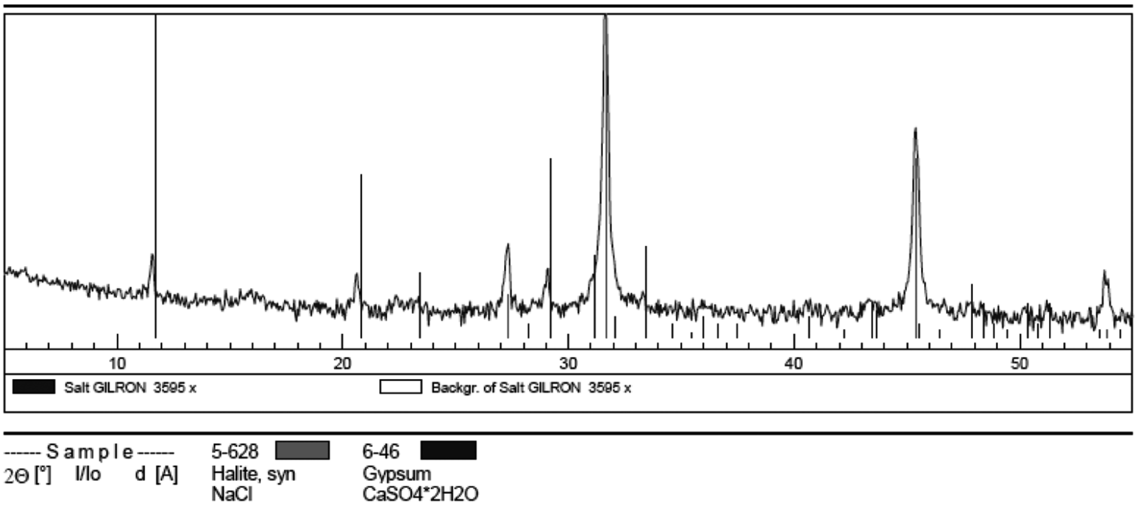

Fig. 9. XRD analysis for a salt sample in the end of the ED run.

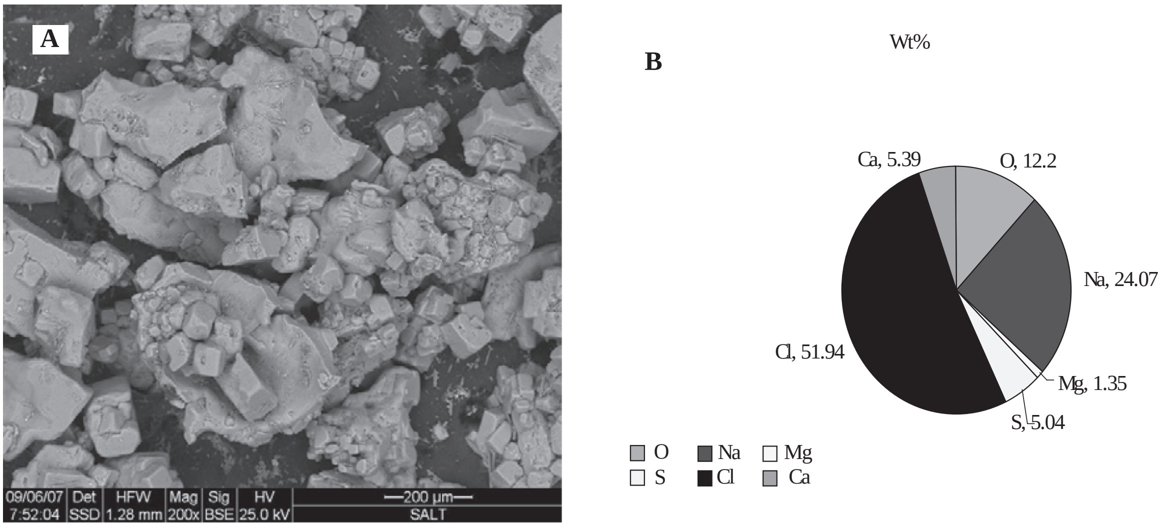

Fig. 10. a) SEM micrograph of the precipitated solids in the WAIV unit b) SEM EDAX element distribution analysis of a precipitate sample taken at the end of the WAIV run on ED concentrate.

concentration of three out of four mineral increases during the time of the run, and only the concentration of the halite decrease. The decrease can be explained by the precipitation of the halite. This usually will precipitate at TDS of about $\sim$ 25%.

4. Economic analysis [10]

The economic analysis was based on an RO-ED-crystallizer-UF-WAIV process [10] and was carried out on the basis of a comparison of relative energy and capital costs based on costs in Israel. Energy, capital charge and brine removal costs are provided in Table 3.

To simplify matters, only power and capital costs were used for the RO section since these are the same costs included in the ED section. Chemical costs for acid in the ED section were also included based on 105 €/m^3 of sulfuric acid. The overall costs for the desalination and brine recovery can be divided into three cost centers:

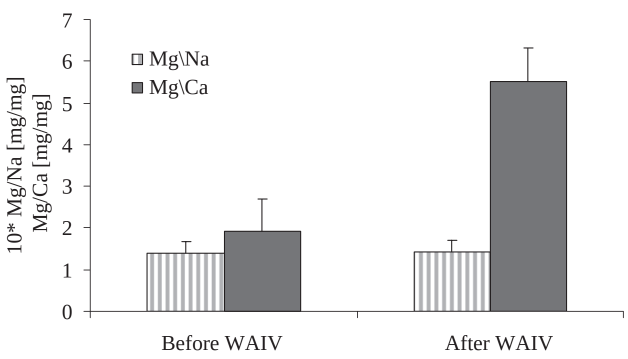

Fig. 11. Enrichment of magnesium relative to other major cations as a result of WAIV evaporation.

(1) RO
(2) ED-UF-settler
(3) Brine disposal

The overall cost/m^3 of product water is given by the following equations:

$$WC_{TOT} = UC_{RO} \cdot V_{RO} + UC_{ED} \cdot V_{ED} + UC_{Brine} \cdot V_{Brine} \tag{9}$$

where V is the volume (m^3) concerned, WC_{TOT} are total water costs (€), UC are unit water costs (€/m^3) and subscripts refer to the process step. The overall unit cost for product water is therefore given by:

$$UC_{TOT} = \frac{WC_{TOT}}{V_{RO} + V_{ED}} = UC_{RO} \cdot \frac{Y_{RO}}{Y_{TOT}} + UC_{ED} \cdot \frac{Y_{ED}}{Y_{TOT}} + UC_{Brine} \cdot \frac{1 - Y_{TOT}}{Y_{TOT}} \tag{10}$$

Table 2
Comparison of the TDS before and after concentrating RO and BWRO-ED concentrates with the WAIV unit

BWRO-ED	RO	Parameters
94	10	TDS [gr/L] start
230	95	TDS [gr/L] end
400	400	Initial volume evaporated [L]

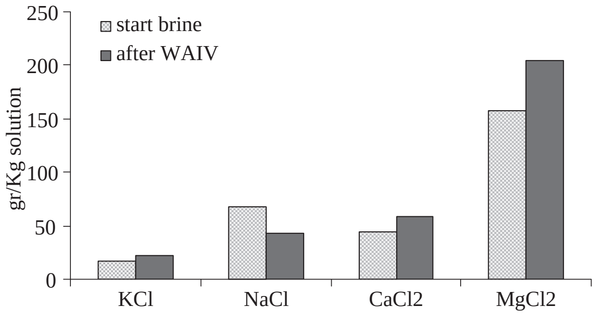

Fig. 12. Selective precipitation during WAIV concentration of a mineral brine.

Table 3
Economic assumptions assumed in calculating the cost of treating water

Economic assumptions [13]		
Electricity costs	0.072	(Euro/kWh)
Annual capital charge rate (%)	8.00%	
RO feed pumping and pretreat	0.14	€/m^3 feed
RO production costs (power and capital)	0.131	€/m^3 product
Brine removal costs (by evap ponds)	1.40	€/m^3 brine
Brine removal costs (by WAIV)	1.05	€/m^3 brine

Y refers to the product water volume relative to the feed volume.

Using the above method for calculating product water costs and setting conditions to produce blended product water with 200 mg/L of chloride, projected costs are provided in Table 4.

In comparing the costs of different unit operations in this near-ZLD process, one can see that brine removal costs are only about 5.5% of the total processing costs. This arises from the very high recovery afforded by the near-ZLD process. If mineral recovery is eventually achieved, this could reduce these costs even further or even turn it into a revenue source.

Recently a larger scale WAIV unit is being operated on RO concentrate at the plant site of a major manufacturer in North America located in a semiarid zone. This unit is evaporating $\sim$ 730 m^3/day per hectare of WAIV unit footprint. This compares to $\sim$ 35 m^3/day per hectare for an evaporation pond (operating at 70% of pan evaporation rates typical of pond efficiencies).

5. Conclusion

- The solutions for the brine disposal in semi arid and arid region are usually evaporation ponds, the WAIV unit can provide an excellent alternative for the brine disposal, Evaporation enhancements of greater than ten-fold have been found with a variety of different brine concentrates as feed to the WAIV unit.
- Evaporation rates do tend to drop off after brine concentrations of 15% or more are reached as a result of lowered vapor pressure gradient.
- There is a clear correlation between vapor pressure driving force and evaporation rates in runs of WAIV concentration of RO brines. This correlation shows that significant evaporation can be achieved with WAIV on initial RO brines (1–2%) even where average humidity reaches up to 85%.
- It is feasible to get an enrichment of the magnesium salts ($MgCl_2$) from BWRO and BWRO-ED brine for potential recovery by prior precipitation of the less soluble gypsum
- It was feasible to get enrichment of magnesium relative to sodium ion for a mineral concentrate brine with initial TDS = 25%.
- This process is more economical than conventional RO (88%) and brine disposal by 20,000–40,000 €/y for a plant producing 2400 m^3/day.

Future work will focus on the evaporation of RO-ED concentrates (initial TDS of 10%) with high enough VCF factors to precipitate out most of the sodium

Table 4
Annual water production costs (capital, power and chemicals) for 98% overall water recovery for brackish water feed of 100 m^3/h ($\sim$ 3000 mg/L similar to Mashabe Sadeh)

Recovery in RO step	75%	83%	88%	
Annual ED costs	107,281	89,318	78,031	€/y
RO Production costs	187,466	195,666	200,790	€/y
TOTAL Annual process costs	294747	284983	278821	€/y
Brine removal costs	16556	16556	16556	€/y
Total annual costs	311303	301540	295377	€/y
Annual production	772632	772632	772632	m^3/y
Specific costs for total water	0.403	0.390	0.382	€/m^3

chloride and get a brine highly enriched in magnesium salts for potential mineral recovery. In addition runs of WAIV on RO concentrate will use brine from 88% recovery with an antiscalant (PC191) to determine effect on WAIV operation and subsequent downstream processing to extract minerals from the WAIV super-concentrate from these RO brines.

Acknowledgements

Dr. Rosa Fainshtain and Dr. Ludmila Katz- for analytical support, ZIWR technical staff – Mr. Isaac Lutvak, and Michael Waisman for support on WAIV unit.

Mr. Yuval Shani and Dr. Naftali Lazarovitch-meteorological and data equipment. Financial support was provided by BMBF-MOS project grant WT 0504, ''Near-ZLD Strategy for Optimal Management of Inland Brackish Water Desalination'', MEDINA (MEmbrane Desalination – an INtegrated Approach) project (EU FP6 grant #_036997) and to Bauer and Rosoff Prize for Excellence in Research.

List of symbols

V	Volume (L)
C	Concentration (mg/L)
h	Height of the water in the feed basin (mm)
t	Time from the beginning of experiment (day)
E	Evaporation rate normalized to footprint area (mm/day)
Q	Evaporation rate (m^3/day)
f_e	Mass transfer coefficient (mm*day^{-1} mbar)
$\bar{e}_w^*$–	Equilibrium vapor pressure of the water at the water temperature (mbar)
$\bar{e}_a^*$–	Vapor pressure of the air (mbar)
p	Vapor pressure of the solution (mbar)
P^0	Vapor pressure of pure solvent (mbar)
T	Temperature (K)
Ur	Wind speed at height r (m/sec)
Π	Osmotic pressure (atm)
WCtotl	Total water cost (€)
UC	Unit water cost (€/m^3)
T_{wb}	Wet bulb temperature of the brine, (in °K)
Y	Product water recovery

Subscripts

i	Makeup water–initial water, RO brine
t	When the sample collected
0	Initial value of certain WAIV run

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