WAIV – Wind Aided Intensified Evaporation for Reduction of Desalination Brine Volume

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Abstract
One of the challenges to inland desalination plants in arid regions is the question of brine disposal. Evaporation ponds proposed for brine disposal present an environmental burden because of the large area required. A process has been developed in cooperation with Lesico Ltd to drastically reduce the land area required for such brine disposal. It is based on vertically mounted and continuously wetted evaporation surfaces with packing densities of 20 m\(^2\)/m\(^2\) footprint and greater. Studies on a pilot unit with 31-43 m\(^2\) evaporation surface showed that evaporation rates (L/D-m\(^2\) evaporating surface) can reach up to 90% of those of open water surfaces with a packing density of 20 m\(^2\)/m\(^2\) footprint. Actual enhancements on the larger scale WAIV unit were 13-fold based on a footprint to footprint comparison between the open pan and the WAIV unit. In addition, materials have been located that do not demonstrate irreversible plugging when used on desalination brines. In small scale studies they were run for several months on desalination brines with efficiencies at least equaling that of open bodies of water.

Keywords: Concentrate disposal, evaporation ponds, brines

Introduction
As desalination is applied in increasingly larger scales and varied locales, the issue of concentrate disposal is becoming an increasing challenge [1-3]. Estimates show that it can be on order of 15% of the costs of desalination in the case of inland locations [4]. This is especially so at many inland installations which are more than 80 km from the seacoast where disposal of concentrate to the sea becomes economically prohibitive. Mickley has surveyed the various methods for dealing with concentrate and these include [3]:

- discharge to surface waters and wastewater treatment plants,
- deep well injection,
- land disposal (spray irrigation),
- evaporation ponds
- mechanical/thermal evaporation (zero discharge).

The first three options depend on the geographical location and the nature of the brine. Sometimes at inland locations, surface waters that would not be significantly polluted by the brine are not available. If they receive concentrate from large scale desalination installations, sewage works will put out treated effluent with a higher salt...
load than may be permitted for downstream use. While deep well injection is used in some regions, such as Florida, the geological conditions are not always appropriate for this solution. Land disposal can lead to salinization of soil from the highly saline concentrate and must usually be diluted with secondary wastewater effluent before application. Mechanical/thermal evaporation is economically prohibitive in many cases.

Evaporation could be used in arid regions where land is available. However, according to a survey by Mickley et al. [2,3], only 6% of the installations in the US use this method of concentrate disposal up to 1993 and only 2% after 1993. This could be because of the large amounts of land required and the fact that not many large desalination installations have been installed at inland locations far from surface waters allowing concentrate discharge. With increasing drought and water shortages in interior locations in the US, Middle East and Asia, this could change. Evaporation ponds are being used in Australia [5] and considered in other agricultural regions where saline ground water and agricultural runoff threaten to cause soil salinization.

The main drawbacks of evaporation ponds are:

- Large land area required and decreasing efficiency with pond area
- Increased hazard of ground and aquifer contamination with increase pond area
- Expense of double lining to prevent the pond leakage and allow proper monitoring

Evaporation rate due to wind, $E$, from a body of water has been correlated to the vapor pressure of the air and of the evaporating water body, and to wind speed $\bar{u}_r$ by [6]:

$$E = N_e \cdot \bar{u}_r \cdot \left( \tilde{e}_w^* - \tilde{e}_a \right)$$

(1)

$E$ and $\bar{u}_r$ are in the same units (e.g. mm/day), and $\tilde{e}_a$ and $\tilde{e}_w^*$ are the vapor pressures of the air and the water at its surface temperature respectively. It has been shown [6] that as pond area increases the efficacy of evaporation drops off significantly as given by the following correlation of the wind coefficient:

$$N_e = 3.367 \cdot 10^{-9} A^{-0.05}$$

(2)

Where $A$ is the area of the evaporating body of water in $m^2$. This correlation was shown to hold for bodies between 4 dunam and 120 km$^2$.

This equation clearly shows that the mass transfer efficiency drops off with the increasing extension of the water body downwind. The efficiency is also lowest at the ground as opposed to higher where the wind has a higher velocity.

The authors have developed a method [7-8] exploiting wind energy to evaporate wetted surfaces that are packed in high density per footprint. It has been termed Wind-Aided Intensification of eVaporation (WAIV). By deploying such surfaces in arrays with large lateral dimensions, significant height and with minimal depths (e.g.
3-4 m) the wind can be exploited while it is still less than saturated with vapor and the driving force is maintained as shown in equation 1. In devising such a unit, an optimum must be found in the hydrophilic nature of the surface, that it should be hydrophilic enough to allow spreading but not so hydrophilic as to reduce the effective vapor pressure. Packing should be optimized so that it is high enough to get a good enhancement of evaporation capacity per footprint without unnecessary blocking of the wind.

This article describes the results to date in development of the WAIV process and its performance on tapwater and desalination brines.

2. Experimental

2.1. Screening of evaporative materials

Three different evaporation surfaces were tested on the rooftop WAIV screening installation at the Blaustein Institute for Desert Research in Sde Boker:

- Tuff (volcanic rock) arranged in trays
- Nonwoven geotextiles
- Woven netting

The fabrics were mounted as shown in figure 1, with a head tank or feed pipe providing a constant supply of water running down the fabric at a rate of 1-2 L/hour per 5 cm wide strips. The fabrics had an exposed length of ~1.75 meter per length of fabric running from head tank to collection tank. The details of the different wetting methods and setups are illustrated in figure 2. The methods only differ in the way they get the water out of the head-tank or pipe and onto the strip. The first method (A-B) makes use of capillary rise, the second (C-D) makes use of gravity. Figure E shows the wetting setup for volcanic rock in which the water flows in a shallow trough so that the volcanic rock is partially submerged in the water. Water travels by capillary rise in the pore system of the rock to the rock surfaces exposed to the wind.

Nominal evaporation rates were calculated on the following basis:

\[ NER = \frac{\Delta V}{A \Delta t} \]

where \( \Delta V \) is volume change (L) in unit, \( \Delta t \) is the time (Hr) over which volume changed and \( A \) is the nominal evaporation area of the wetted surface.

The area \( A \) used is the area of the tray for tuff and for the fabrics, both sides of the fabrics were counted in calculating the evaporation rate. For a control, we used an open tank of water with identical construction, and area as the collection tank of test units. The free area of the water was used as the area for calculating evaporation rates. Water was recycled between the control tank and its own head tank, just as in the case of the test units, but without part of the water going to evaporate fabric surfaces. This was done so temperatures would be the same as a result of the same pump energy going into each position. Test areas were of the order of 0.2 – 0.6 m² depending on the wetted material tested and the test unit used.
To allow for possible water loss due to leaks or wind carried drops, a salt balance was conducted. Assuming all salt is lost due to leakage and not to deposits on the wetted surface, and that such leaks are constant during an evaporation experiment, it can be shown that the following holds for the calculated (corrected) evaporation rate (CER):

$$CER = NER \frac{\ln(K / K_0)}{\ln(V_o / V)}$$  

(3)

Where Vo and Ko are the initial volumes and conductivities (measured in 50 fold dilution to bring conductivity in range where linear in salt concentration) respectively. It can be seen that the true evaporation rate will lie between the NER (maximum possible) and the CER (minimum possible).

The testing done on the roof which is still ongoing, was on brine from Mekorot’s Sabha B desalination installation in Eilat. This has a TDS of around 16,000-18,000 ppm and is supersaturated with respect to sparingly soluble calcium salts. Because of the precipitation potential, it was considered the severest test of the different materials and wetting methods. The test was carried out by charging each evaporation station with an initial volume of the brine, and makeup was then added from a combination of brine and tapwater to maintain the concentration at its initial concentration.

2.2. Unit for long-term testing

A unit was prepared for long-term testing of evaporation with a larger set of evaporation surfaces (10-40 m²). This unit was supplied with piping, pumps and a feed tank to allow the wetting of the surfaces. The picture of the unit is shown in figure 3.

Arrangements were made for two different types of hydrophilized evaporation surfaces: Nonwoven geotextile strips and woven netting. The nonwoven geotextile materials initially chosen for the long term tests later turned out not to be the optimal one. In the end this confirmed the problem with nonwoven geotextile materials. The netting was then installed and is presently being studied in tests that are still ongoing.

In each case the surfaces were stretched over a vertical surface ~1.5 m in height and arranged in a rectangular array. The water was pumped from a 1 m³ feed tank to the array. The method of wetting of the nonwoven geotextile strips was by capillary rise as shown in figure 2a. The nonwoven geotextile strips were wetted by flowing water from the entrance of the trough to the exit and maintaining a level somewhat below the level of the strips, using the bend in the outlet tube to control the level. The water level was kept ~2 cm below the fold of the strips going over the bay in the trough side to prevent water running down the trough side and dripping.

The method of wetting Netting was by pressure through holes in the distribution pipe as shown in figure 2d. The netting was looped around distribution pipes of only 27
mm as opposed to 50 mm in the rooftop installation. As a result the inner surfaces of the loop were closer to each other. After 2 days the loops were arranged in a zig zag pattern (see figure 4) to allow more exposure of the inner surfaces to the wind.

Extra volumes of water from the pump were returned by the distribution system to the feed tank. The total volume evaporated (L) was normalized relative to the following areas (m²):

- Total area of wetted evaporation surface (both sides of strips), mm or L/m².
- Footprint of WAIV unit underneath the vertical strips, mm or L/m².

Evaporation rates were obtained by dividing the normalized evaporated volumes by the days over which the measurement had been made.

To allow for the changes in weather, the evaporation rate of the WAIV unit was compared to evaporation rates from a standard pan evaporation installation at the Sde Boker Meteorological Station (SBMS). An evaporation efficiency was calculated by dividing the WAIV evaporation rate (per unit evap surface) by the pan evaporation rate.

3. Results

3.1 Rooftop tests on desalination brine

The results of this testing to date are in figures 5-6. In figure 5 one sees that the control trough on the roof has a lower corrected evaporation rate than the pan evaporation at the meteorological station (SBMS). This is to be expected since the control trough contains brine and the average wind speed on the roof is less than half that at the SBMS. As shown in figure 5, the netting does significantly better than tuff, nonwoven geotextile strips and the control trough. As seen in figures 5 and 6 this trend holds whether the comparison is based on nominal rates or rates corrected for salt balance. Similarly it can be seen from both figures that with a potentially precipitating feed, gravity feed is better than feed by capillary rise with the same wetting material (nonwoven geotextile).

Deposits were collected from the strips for analysis. XRD analysis showed that white deposits found on the edges of the strips were gypsum. The significant difference between the netting and the nonwoven geotextile can be attributed to the absence of internal surfaces in the netting. No fluid pathways can be blocked as in the nonwoven geotextile and all flow is delivered on the netting on outside surfaces. This is further demonstrated by a comparison of the deposit remaining in the evaporation materials after nearly two months continuous running including several weeks run on desalination brines. As shown in table 1, the Netting has much less salt and also much less calcium salt deposits compared to nonwoven geotextile strips. In addition, 2/3 of the deposit could be rinsed from the netting by water and practically all the remainder by citric acid. However, 25 - 33% of the deposit remained in the nonwoven geotextile strips even after citric acid rinse. In any
event the amount of salt deposit is small compared to the estimated weight of water attached to one strip during operation: ~250 g/strip.

Table 1: Results of deposit analysis on evaporation surfaces after about two months operation

<table>
<thead>
<tr>
<th>Strip sample</th>
<th>Weight of strip, g</th>
<th>Deposit (g/strip)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clean</td>
<td>After run</td>
<td>After water rinse</td>
<td>After citric acid rinse</td>
<td>Total</td>
<td>Ca salt</td>
</tr>
<tr>
<td>net 1</td>
<td>37.3</td>
<td>85.5</td>
<td>55.3</td>
<td>37.8</td>
<td>48.2</td>
<td>18</td>
</tr>
<tr>
<td>net 2</td>
<td>31.3</td>
<td>68.6</td>
<td>47.9</td>
<td>31.7</td>
<td>37.3</td>
<td>16.6</td>
</tr>
<tr>
<td>Nonwoven geotextile 1</td>
<td>55.0</td>
<td>169</td>
<td>128.2</td>
<td>91.1</td>
<td>114</td>
<td>73.2</td>
</tr>
<tr>
<td>Nonwoven geotextile 2</td>
<td>55.4</td>
<td>148</td>
<td>107.4</td>
<td>78.1</td>
<td>92.6</td>
<td>52</td>
</tr>
</tbody>
</table>

3.2 Long-term testing on larger-scale unit

3.2.1 Nonwoven geotextile

It should be noted that even before wetting was stabilized when there was extensive dripping from troughs in the interior of the array, almost no drops were felt or seen outside the perimeter of the array. The outermost fabric strips served as drop scavengers for the droplets within. This bodes well for the practicality of larger arrays with respect to preventing drop propagation outside the WAIV unit.

While the nonwoven geotextile fabric collected dust, and external strips became quite brown and caked with dust, they did not lose their mechanical strength or wetting properties. The results of using the wetted nonwoven geotextile fabric in the initial two months of the long-term test are given in table 2. The chloride mass balance shows that practically the entire volume change can be attributed to evaporation. These results also show that each m2 of fabric was evaporating water at a rate comparable to and even greater than that of open pan evaporation over the same time period. If one counts both sides of the fabric, then its overall efficiency is still higher than 50% of the open pan evaporation rate targeted as the minimum operational goal.

It should however be noted that the evaporation rate of the array is significantly less than the same fabric on the roof, where maximum estimated evaporation rates were 60-100% higher for tapwater during the same period (5.6 L/D-m2 fabric, 2.8 L/D-m2 evaporative area). This can probably be explained by the fact that in the center of the array the local humidity is higher and the local wind inside the array is lower than for isolated strips on the roof.

The raw data for the overall period of 85 days is shown in figure 7 which plots the cumulative volume evaporated as a function of time. It can be seen that the WAIV unit evaporates tapwater at a rate that is more than 10 times the daily rate for a control evaporation pond with the same area (2.48 m2) as the footprint of the WAIV array. While this demonstrates that the WAIV can increase the capacity of each footprint, this factor is less than the ratio of WAIV evaporation area to control pond evaporation
area (43 : 2.5). If the daily rate data is normalized to evaporation surface (L/m²-d = mm/d), one can calculate the efficiency of WAIV evaporation surface relative to the control pond surface. One can then plot the efficiency of the WAIV evaporation surfaces as a function of the cumulative volume evaporated per m² of WAIV evaporation surface. This is done in figure 8. As can be seen, between 60 and 120 L/m² evaporated there is a steady drop in efficiency from 100% to 60% before the efficiency steadies and then it begins to show additional signs of dropping off again.

The drop in evaporation efficiency corresponded to observations that some of the strips began to dry out after two months of testing. This was especially notable after one weekend two months into the long term testing. During that weekend because of the hot and dry weather conditions, the evaporation rate was so great that most of the entire contents of the 1m³ feed tank was evaporated and the pump ceased to deliver liquid to the troughs. The fabric as a result dried out. Re-wetting the fabric was found to be difficult. Only after rinsing the fabric by raising the water level over that of the bays in the troughs was the fabric wetting again substantial. Even so, the evaporation rate of the fabric was not as good as before it had completely dried out. It was speculated that salts had deposited in the fabric and impeded the flow of water down the fabric. An analysis of salts found in one of the fabric loops after it had dried out, bore out this conclusion. It was found to contain 6.5 g of NaCl (130 g/m² of fabric) and 1 g of calcium salt as calcium carbonate (~ 6 g/m² of fabric). While this is much less than the actual weight of 360 g/m² of fabric, it could be enough to interfere with the flow of water down the strip so that water evaporated faster than it could be re-supplied.

The conclusion is that nonwoven geotextile is an impractical surface and that woven netting should be preferred for further work.

<table>
<thead>
<tr>
<th>Table 2: Long-term operation on nonwoven geotextile fabric</th>
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<tbody>
<tr>
<td>Days elapsed</td>
</tr>
<tr>
<td>Makeup water added, L</td>
</tr>
<tr>
<td>Volume in tank, L</td>
</tr>
<tr>
<td>Chloride conc., mg/L</td>
</tr>
<tr>
<td>Evaporation rate</td>
</tr>
<tr>
<td>L/d-m² fabric</td>
</tr>
<tr>
<td>L/d-m² evap surface</td>
</tr>
<tr>
<td>Average open pan evap rate, L/m²-day</td>
</tr>
</tbody>
</table>

1) Based on initial tapwater chloride concentration of 220 mg/L, this projects to: Mg/L of concentrate = (6100 + 1000) L * 220 mg/L ÷ 800 L = 1950 mg/L

3.2.2 Netting

Figures 9 and 10 give results for the first 3 weeks of operating 15.6 m² of netting on the larger scale unit with evaporation surface of 31.2 m². Figure 9 shows that with
the packing density achieved on the WAIV with the netting, the evaporation rate per footprint is about 12-13 times that of an open pan evaporation.

While still too early for certain conclusions, it appears from figure 10 that the evaporation efficiency is improved by switching to a zig-zag arrangement of the strips. However, overall the netting does not do quite as well as the open pan evaporation. This is in contrast to the results with individual netting loops on the rooftop where the evaporation rate per unit area was often higher than with the control or pan evaporation. This can be explained by a lower driving force due to higher average humidities in the air surrounding the array.
To date there is no problem with drying out of the netting as with the nonwoven geotextile.

3. Conclusions
A WAIV unit was constructed with hydrophilic materials and wetting methods that allowed increasing the evaporative capacity per area footprint by a factor of 10 or more.
Materials with no internal surfaces (netting) are less susceptible to plugging than those with internal surfaces (nonwoven geotextiles).
A certain drop-off in efficiency relative to open pan evaporation should be expected as one goes from isolated vertical evaporation surfaces to those in a close packed array of surfaces.

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References
Figure 1: Evaporation surface test unit at Sde Boker with 4 of 8 test units shown in operation. Control trough is shown at left.

Figure 2: Wetting methods for evaporation surfaces in WAIV test units. A and B are based on capillary rise, C on gravity, D on pressure and E on capillary rise within porous structure of volcanic rock.
Figure 3: Larger scale WAIV unit with nonwoven geotextile strips mounted.

Figure 4: Arrangements of Netting on larger-scale WAIV unit.  a) netting in individual loops.  b) netting in continuous zig-zag.
**Figure 5:** Performance of different wetted evaporation surfaces on BW RO brine. Cor means evaporation rate corrected for leaks or droplet dispersion.

**Figure 6:** Cumulative results of 18 day run in summer 2002 on rooftop evaporation test unit at Sde Boker. All positions contain desalination brine except the evaporation pan at the meteorological station which contains tapwater.
Figure 7: Raw data of long term test on tapwater with 21.5 m² nonwoven geotextile strips installed on WAIV unit. Cumulative volume evaporated by control pond is based on pan evaporation data using the same area as the net footprint of the WAIV unit.

Figure 8: Results of long term testing with nonwoven geotextile strips on tapwater that was continuously concentrated.
Figure 9: Performance of larger scale WAIV unit equipped with 15.6 m$^2$ of netting. Cumulative volume evaporated is normalized to area of footprint of WAIV or evaporation pan area (SBMS).

Figure 10: Evaporation efficiency of netting on large-scale WAIV unit. Efficiency expressed as evaporation rate per wetted area of WAIV surfaces (mm/day) divided by evaporation rate of SBMS evaporation pan (mm/day).
Appendix: Effect of leak or droplet loss on nominal rate of evaporation

In this analysis, the rate of leakage (Q) and evaporation (E) is assumed to be constant over time. Applying differential volume and mass balances on the evaporation units one obtains:

System Volume Balance:
\[ dV = (E + Q)dt \]
where E and Q will be < 0 for evaporation and leakage out of the system and > 0 for condensation and leakage into the system respectively.

System Salt Balance assuming salt leaves system by leakage only:
\[ dM_s = QCdt = d(CV) = CdV + VdC \]
Dividing the salt balance by C*V and substituting for dt in terms of dV from the volume balance and rearranging gives:
\[
\frac{-E}{E + Q} \frac{dV}{V} = \frac{dC}{C}
\]
And integrating from start of evaporation run to the end gives:
\[
\frac{E}{E + Q} = \frac{\ln(C/C_o)}{\ln(V_o/V)} = \frac{\ln(K/K_o)}{\ln(V_o/V)}
\]
where the expression in terms of conductivities, K, is used on the assumption that conductivity is linear in concentration in range of evaporation test. Since the nominal evaporation rate (NER) is given by E+Q and the corrected evaporation rate (CER) assuming all salt is lost from leaks is given by E, we have:
\[
(CER) = (NER) \frac{\ln(K/K_o)}{\ln(V_o/V)}
\]