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The advantages of NF desalination of brackish water for sustainable irrigation: The case of the Arava Valley in Israel

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ABSTRACT

Irrigation with brackish water is a widespread practice in freshwater-poor regions with ample brackish water resources, but it has severe limitations. Desalination is a water saving alternative to brackish water irrigation, but its diffusion as a viable method of water treatment has been limited by high costs and concern about the lack of plant nutrients in desalinated water. In this paper, we discuss the advantages of nanofiltration (NF) membranes for the production of irrigation water based on the simulation of the performance of a solar-assisted pilot plant in the Arava Valley in Israel. It is argued that the proposed system would consume up to 40% less energy than conventional reverse osmosis desalination, reduce by 34% the currently abstracted groundwater volumes, and increase by 18% the total biomass production of the irrigated crops.

Keywords: Brackish water; Irrigation; Nanofiltration; Reverse osmosis; Solar desalination

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1. Agriculture and water scarcity: need for irrigation with desalinated water?

Water scarcity severely affects the agricultural sectors of most countries in the Middle East and North Africa and of many areas around the world. Growing demands for domestic and industrial uses of water exacerbate the competition for the scarce resource and often result in more water being allocated to high-priority sectors at the expense of agriculture [1]. Improving the management of water demand by preventing waste and introducing efficient irrigation techniques is generally a cost-effective and sustainable way to cope with scarcity, but the implementation of such improvements is slow and may not be suitable to the sustainable development of areas suffering from chronic water scarcity. Therefore, water supplies are increasingly being augmented through the exploitation of non-conventional water sources such as water recycling, marginal-quality groundwater aquifers, desalination, and rainwater harvesting.

Irrigation with brackish water from marginal-quality aquifers is largely practiced in Middle Eastern countries and India [1], but the potential of the technique is limited by a variety of drawbacks. First, high salinity levels cause osmotic imbalances and reduce water uptake and transpiration, which results in lower yields than obtainable with freshwater irrigation [2]. Second, the choice of crops is limited by the specific salinity tolerance. Third, even when appropriate irrigation management strategies are implemented, salt accumulates in the root zone unless large volumes of water in excess of plant requirements are used to leach salts, thus limiting the potential for damage to plants and soil structure. Such large water requirements may make irrigation with brackish water highly unsustainable [3].

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Irrigation with desalinated water has the potential to be a more water-efficient and economically viable alternative to brackish water irrigation. Although it accounts for only 3% of the world's total yearly production of desalinated water [4], the agricultural use of desalinated water is a relatively widespread practice in countries such as Spain [4–6], United Arab Emirates [7], and Israel, where the integration in the national water carrier of the large desalination plants located along the Mediterranean coast ensures that large quantities of desalinated water are delivered to farmers [8,9].

The combination of renewable solar energy and desalination for the production of irrigation water is a particularly appealing solution in hot, arid countries. A range of design solutions were investigated in the literature, including solar stills [10], solar greenhouses [11–13], enhanced solar greenhouses [14–19], and hybrid pressure-driven/distillation systems [20]. None of these design solutions, however, achieved commercialization.

Two main issues have prevented desalination from achieving wide application in agriculture. First, irrigation with desalinated water is limited by its high costs relative to other sources of water. The high energy requirements of conventional technologies account for 40–45% of the total costs of desalination [21]. Second, water desalinated with reverse osmosis (RO) and distillation technologies lacks ions such as calcium, magnesium, and sulphate that are essential to plant growth. The absence of such nutrients may adversely affect agricultural productivity and make additional fertilization necessary [9].

In this paper, we argue that for agricultural applications, there are unexplored opportunities for the desalination of brackish water using nanofiltration (NF) membranes. Relative to other desalination technologies, NF membrane based desalination has lower energy requirements and retains the ions essential for plant growth. Desalination by NF membranes may constitute a more water efficient and potentially cost-effective alternative to irrigation with brackish water. The Arava Valley in Israel is presented as a test site, and the design and modelling of a pilot-scale desalination plant featuring both NF membranes and photovoltaic (PV) modules for the integration of renewable solar energy as the power supply is discussed.

2. The solar-assisted NF desalination pilot plant in Hatzeva, Israel

2.1. The Arava Valley and the Yair experimental station in Hatzeva

The Arava Valley in Southern Israel contains examples of highly efficient agriculture in a region of extreme water scarcity. The Arava Valley extends for 170 km from the Southern part of the Dead Sea to the Gulf of Aqaba in the Red Sea and is part of the Rift Valley. It is characterized by extremely hot and dry conditions, with an average yearly precipitation of 32 mm and summer temperatures above 40°C. Despite the unfavourable climatic conditions, the Arava Valley is home to the most intensive and profitable agricultural activities in Israel [22]. Mild winter seasons provide a comparative advantage for the seasonal production of high-value export crops such as bio-organic vegetables (e.g., peppers and melons) and flowers. About 60% of Israeli vegetable exports are produced in the Arava. To compensate for the adverse climate, farmers have developed efficient agricultural techniques that make intensive use of greenhouses, cooling systems, and water-efficient irrigation techniques [23].

With the exception of stormwater collected during winter rain events, agricultural activities in the Arava rely exclusively on groundwater extracted from local fossil aquifers. These represent a strategic regional resource that can sustain the current level of exploitation for an extended period [24]. Most local groundwater sources are, however, of poor quality. About 97% of the groundwater is brackish, with a concentration of total dissolved solids (TDS) of more than 1,280 ppm [23]. Irrigation using saline water with an electroconductivity (EC) of 2,200-3,700 μmhos cm^{-1} is common [3]. Water volumes representing two times the potential plant evapo-transpiration rates are commonly used in irrigation [3], and salt leaching with excess irrigation water currently represents the main water requirement for agriculture in the Arava.

Due to the high potential of solar power to improve the cost competitiveness of desalination in the agricultural sector in the Arava Valley [25], a site at the Yair experimental station in the Arava settlement of Hatzeva (30° 46′N, 35° 14′E) was chosen as a case study for the present investigation. The Arava Research and Development (www.arava.co.il) facilities at the Yair experimental station in Hatzeva constitute one of the spearheads of agricultural development in the Arava Valley. The station includes 21 greenhouses where experiments on commercial crop species grown in the Central Arava region are performed. The site enjoys high solar irradiation levels, with average daily global radiation ranges of between about 8,000 Wm^{-2} in June and 3,000 Wm^{-2} in December. A full meteorological station was installed on site for comprehensive meteodata monitoring.

2.2. Influent water characterization

Local wells supply the Hatzeva community with brackish water from the Hatzeva-Idan North aquifer, which is characterized by slightly saline water with an average TDS concentration of 1,178 ppm. Fourteen wells, with a total capacity of 68.7 m^3h^{-1} and from an average depth of 124 m, extract water from the aquifer [24]. The average water quality is considered satisfactory for controlled irrigation [26] and presents a medium sodium alkali hazard (SAR = 16.3) [27].

Well 3A was selected for the present study. Regular water quality monitoring is performed by the national water company Mekorot (www.mekorot.co.il). An extensive water quality analysis on a sample collected during a field trial in July 2008 was performed in the laboratories of Ben-Gurion University of the Negev (Table 1).

The salinity of the groundwater abstracted from well 3A is slightly higher than the average for the Hatzeva-Idan North aquifer. Its turbidity and the concentration of total suspended solids are low. According to the results of the measurements conducted by Mekorot, electroconductivity, chloride concentration, and water turbidity show little seasonal or yearly variation.

Table 1
Water quality at well 3A in Hatzeva as sampled during a field trial (July 22, 2008)

Parameter, unit	Value
Alkalinity as $CaCO_3$, ppm	170
EC, µmhos cm^{-1}	2,420
pH	7.63
TDS, ppm	1,577
TSS, ppm	2
Turbidity, NTU[a]	0.16
B, ppm	0.34
Ba, ppm	0.194
Ca, ppm	150
Cl, ppm	359
CO_3, ppm	n.d.
HCO_3, ppm	208
K, ppm	12.5
Mg, ppm	82.5
Na, ppm	225
NH_4-N, ppm	<0.3
NO_3, ppm	9.6
SO_4, ppm	505
Sr, ppm	5.52
Zn, ppm	0.15

Note: EC = electroconductivity; TDS = total dissolved solids; TSS = total suspended solids; n.d. = not detected; [a] Average of 11 measurements conducted by Mekorot between 2003 and 2008

2.3. Design scheme of the PV-NF pilot desalination plant

The envisaged desalination system is designed for the production of 0.25 m^3h^{-1} of freshwater for the irrigation of 500 m^2 of agricultural plots. PV-powered pressure-driven membrane desalination is among the most mature and reliable technologies available for solar desalination. A relatively large number of small-scale systems have been tested worldwide and the technology is technically mature for commercialization [28]. Fig. 1 illustrates a schematic design of the proposed desalination plant. The project is currently being installed on site.

2.3.1. Pretreatment unit

The proposed design includes a pretreatment step comprising micro-filtration (pore size 5 µm) and active carbon cartridge filtration. The active carbon filtration step is included as a safety measure to protect the membrane from possible damage by free chlorine. No disinfection of the feed water is performed upstream of the desalination plant. Other pretreatment solutions were considered, including ultrafiltration, which provides a high level of protection from membrane biofouling in the presence of high bacteria counts. The high quality of the feed water in Hatzeva, however, does not warrant the higher investment costs required for ultrafiltration membrane pretreatment.

2.3.2. Power supply and high pressure pump

The power supply of the pilot plant is designed according to a hybrid configuration that allows for the high pressure pump and the other auxiliary systems to be powered with energy either from the PV modules or from

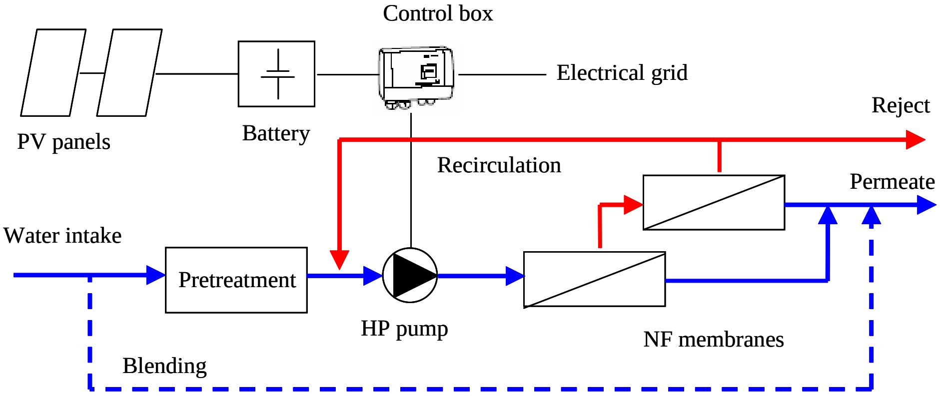

Fig. 1. Schematic design of the solar-assisted desalination plant in Hatzeva.

the electric grid. Accordingly, the purpose of the battery is to facilitate smooth daytime operation rather than to store energy for nighttime operation, and as such, its size is held to a minimum. The Grundfos SQFlex 1.2–2 positive displacement pump with a helical rotor was selected due to its highly flexible operation, i.e., at variable speed directly from the PV modules, with a constant DC power supply from the battery, or on the AC power supply from the grid thanks to a built-in inverter. Such flexibility of operation will allow testing for different operation strategies once the system is operational. A control box for switching between battery and grid power is included.

2.3.3. Water recirculation

The importance of high water efficiency for a system operating in the water scarce conditions of Hatzeva demanded that the system be designed to achieve a high overall water recovery rate of 80%. Nearly 90% of the concentrate from the NF membranes, i.e., 0.5 m^3h^{-1}, is recycled back through the membranes.

2.3.4. Membrane selection

Two Dow Filmtec NF90-4040 membranes in one pressure vessel were selected for their good performance and relatively high salt retention in brackish water desalination measured in previous studies [29–31]. The membranes are designed to operate at a pressure of 5.0 bar and a permeate flux of 16.3 lmh. The design recovery rates for each membrane are 17% and 16%, respectively.

3. Advantages of NF desalination over RO desalination and brackish water irrigation

NF membranes are characterized by lower salt retention than RO membranes, but they operate at lower pressures and correspondingly lower energy requirements. Table 2 compares the differences in operating pressure, power consumption, and effluent quality that can be obtained with the selected NF membranes and with the low pressure RO Dow Filmtec BW30-4040 membranes. The two scenarios have identical assumptions concerning the number of membranes (two membranes per pressure vessel), overall water recovery rate (80%), feed flow and quality (0.31 m^3h^{-1}), and recycle flow (0.50 m^3h^{-1}). Power consumption and specific energy costs at the different operating pressures were calculated based on the performance curves of the SQFlex pump model 1.2–2 reported in the Grundfos product guide.

Table 2 shows that given identical feed water and plant design characteristics, NF membranes operate at a 45% lower pressure than reverse osmosis membranes (5.00 bar vs. 9.04 bar). The difference in operating pressure translates into significantly lower specific energy costs for the NF membranes relative to the RO membranes (0.89 kWh m^{-3} vs. 1.49 kWh m^{-3}, i.e., 40% lower power consumption). Assuming continuous operation with grid electricity and an average electricity price from the grid equal to \$0.115 kWh^{-1}, such low specific energy consumption would result in a savings of \$0.41 d^{-1} for the solar panels. For continuous operation powered by the PV panels, savings would be even higher. Taking into account the retail price for PV modules, which in the US and European markets currently stand at \$4.83 and €4.70, respectively, for watt peak produced [32], the higher energy efficiency leads to an estimated savings of \$3,700 and €3,630, respectively, in the investment costs for the pilot plant. The optimal percentage of total desalination plant energy input that will be supplied from the solar panels to the pilot plant will be determined based on the analysis of different operation strategies once the system is installed. It is worth noting that for a fixed permeate salinity, the model predicts lower energy consumption for NF desalination relative to RO desalination combined with feed blending.

But what is the effect on crop yields of the lower salt retention of NF membranes as compared to RO membranes? And how does irrigation with NF permeate compare to that with water from brackish water desalination in terms of crop yields and water requirements? The response of crops irrigated with brackish water, NF permeate, or RO permeate in terms of total biomass production was simulated based on a model developed by Shani et al. [33] and applied to bell peppers grown on sandy loam soil in the Arava Valley by Ben-Gal et al. [3]. The salinity levels reported in Table 1 and Table 2, respectively, for brackish and desalinated water are assumed. The results of the analysis are graphically illustrated in Fig. 2 for two scenarios with different irrigation rates.

Table 2
Design operating pressures, power consumption, and permeate quality with NF90-4040 and BW30-4040 membranes

	Dow Filmtec BW30-4040	Dow Filmtec NF90-4040
Membrane type	RO	NF
Total active area, m^2	14.49	15.24
Operating pressure, bar	9.04	5.00
Power consumption, kW	0.37	0.22
Specific energy costs, kWh m^{-3}	1.49	0.89
Permeate TDS, ppm	65	318
Permeate Ca^{2+}, ppm	3.5	14.1
Permeate Mg^{2+}, ppm	2.0	7.9
Permeate SO_4^{2-}, ppm	10.2	33.5

Notes: Results obtained with the Reverse Osmosis System Analysis (ROSA) design tool by The Dow Chemical Company, © 2007 (www.dow.com/liquidseps/design/rosa.htm)

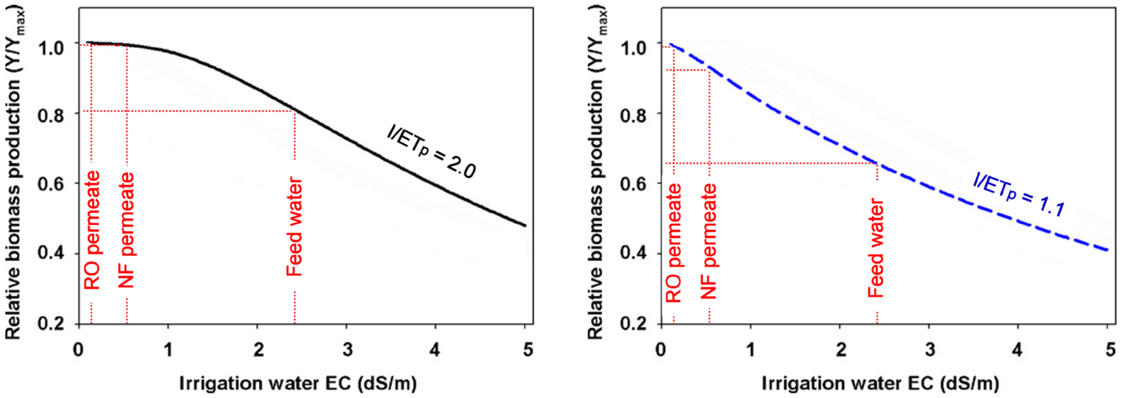

Fig. 2. Simulated yield response at different irrigation salinities and for two different irrigation rates (modified from [3]).

The first (Fig. 2, left) assumes that a volume of irrigation water (I) twice in excess of the potential plant evapo-transpiration (ET_p) rate is applied. This scenario reflects the current agricultural practice in the Arava Valley. The second assumes a volume of irrigation water just above the potential plant evapo-transpiration rate.

In the first scenario, a volume of irrigation water twice in excess of potential evapo-transpiration is used. Brackish water irrigation produces a yield equal to 80% of the theoretical maximum. As expected, irrigation with desalinated water leads to increases in total biomass production. The difference in salinities between water desalinated with NF and RO membranes, however, does not result in a substantial difference in yields. In both cases the yield will be higher than 99% of the theoretical maximum, i.e., irrigation with NF and RO permeate are both expected to increase the current yields by about 24%. In the second scenario (Fig. 2, right), a volume of irrigation water 10% higher than the potential evapo-transpiration rate is used. Irrigation with RO permeate results in a slightly higher yield than with NF permeate (99% and 94% of the maximum yield respectively).

These results have significant implications for irrigation management. According to the analysis, irrigation with desalinated water would facilitate a 45% reduction in the current water irrigation volume while simultaneously resulting in an increase in crop yields with respect to the current management practices (24% increase with RO permeate, 18% increase with NF permeate). Taking into account the water recovery rate of the desalination plant and assuming that the brine cannot be used for any further irrigation use, such a reduction in irrigation volume corresponds to a savings in the quantity of abstracted groundwater of 34%.

Furthermore, the increase in biomass yield that can be obtained by irrigating with desalinated water is a function of the initial brackish water salinity. For instance, for a brackish water salinity equal to 5 μmhos cm^{-1} — a value that is frequently exceeded by groundwater wells in the Arava Valley [24] — and assuming an irrigation volume twice in excess of the potential evapo-transpiration, the model illustrated in Fig. 2 predicts that irrigation with NF permeate would roughly double the crop yield, which would increase from 48% to 96% of the theoretical maximum yield.

NF desalination has a further advantage with respect to RO desalination in the higher permeate concentration of ions that are essential to plant growth such as calcium, magnesium, and sulphate (see Table 2). Blending the NF permeate in Table 2 with 0.04 m^3h^{-1} of feed water would allow for compliance with the water quality standards recommended by Yermiyahu et al. [9] for calcium (32–48 ppm), magnesium (12–18 ppm), and sulphate (> 30 ppm) without a substantial reduction in crop yield. Blending with feed water would reduce the design specific energy costs of the NF desalination pilot plant to 0.76 kWh m^{-3}.

4. Conclusions

In areas that suffer from freshwater scarcity but that are rich in brackish water resources, irrigation with desalinated water may provide a water-saving and more sustainable solution with respect to the widespread practice of brackish water irrigation. In this paper, we explore the opportunities for the implementation of NF membranes in desalination plants for the production of irrigation water as compared to brackish water irrigation and RO desalination. The design of a hybrid solar-powered NF desalination plant is proposed for the production of irrigation water in the Arava Research and Development facilities at Hatzeva, Israel. Based on the results of the simulation of desalination plant operation and the modelled response of crops to irrigation with desalinated water, the study prompted the following conclusions:

- The design specific energy costs of desalination with NF membranes are lower than with RO membranes (40% reduction using NF90-4040 membranes compared to BW30-4040 membranes). This results in a significant savings in the operation costs during when the plant is functioning under grid electricity and in the investment costs for the solar sub-unit.
- For the brackish groundwater in Hatzeva (TDS = 1,577 ppm) and assuming that irrigation practices will remain unchanged, irrigation with NF permeate would increase the current biomass production by 24%. Irrigation with RO permeate would not substantially increase yields. Even higher increases in crop yield could be achieved by desalinating brackish water with higher salinity.
- Irrigation with RO or NF permeate would enable a 45% reduction in the water volume used while simultaneously facilitating a 24% or 18% increase, respectively, in crop yields over the yields obtained with the current management practices.
- NF membrane permeate contains higher concentrations of essential micronutrients such as calcium, magnesium, and sulphate. Blending with feed water would enable compliance with recommended standards for irrigation water and reduce specific energy costs to 0.76 kWh m^{-3}. Product yield would be reduced negligibly.

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