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Brackish water desalination in the Algerian Sahara—Plant design considerations for optimal resource exploitation

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ABSTRACT

A huge geothermal aquifer is located in the northern Algerian Sahara, with brackish water free from toxic inorganic compounds and organic matter. Therefore, this water is appropriate for good quality potable water production after partial desalination. This paper deals with the basic desalination plant design considerations in the context of overall optimal aquifer exploitation. The main types of criteria for such optimization are economic and environmental. Implementing the concept of "blending" reservoir water (at appropriate proportion) with desalinated water, allows cost-effective and environmentally attractive resource exploitation; the latter would be achieved by reinjecting the retentate (after desalination) free from any chemicals that may degrade the reservoir water quality by accumulation over the years. Results are summarized of a typical case study based on low pressure reverse osmosis (RO) membrane desalination. Key RO membrane performance data from a pilot unit are employed in support of this study. The results highlight the main features and the constraints in plant design and desalinated water recovery; constraints are mainly imposed by the need to avoid membrane scaling with no use of undesirable synthetic anti-scalants. The proposed cost-effective plant configuration and operating mode are in accord with the overall optimum resource exploitation. A cost analysis is also performed for a typical potable water production plant. Finally, possibilities are outlined of integrated exploitation of this geothermal reservoir, whereby energy is extracted in addition to potable water production.

Keywords: Brackish water membrane desalination; Albian geothermal aquifer; Optimization of reservoir exploitation; Retentate reinjection; Membrane scaling restrictions

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1. Introduction—Scope

The Sahara desert, covering the greatest part (~80%) of Algeria's vast territory, is an arid region in the south characterized by lack of potable water. Consequently, more than 80% of the population live in the northern part, which covers only approx. 20% of the land [1]. Moreover, this imbalance is aggravated by migration from the southern remote regions due to shortages of fresh water and energy [2]. To remedy this situation, the Algerian government has launched an ambitious program for the transfer and demineralization of brackish water to the south, by taking advantage of the Continental Intercalaire (C.I.) aquifer, discovered in 1954 in northern Sahara, also commonly referred to as *Albian aquifer* [3,4]. This is a huge geothermal reservoir (of water temperatures ranging from 35 to 70˚C), that covers approximately 1 million km^2, with its largest part (~700.000 km^2) within Algerian territory. Aside from its modest salinity, the reservoir water is of fairly good quality [4]. Therefore, production of good quality potable water with appropriate treatment of reservoir water, by means of modern membrane desalination technology, is an attractive prospect. The Algerian government program involves extraction of reservoir water from the area of *In Salah* in the north and transfer by a 736 km long pipeline to the city of *Tamanrasset* in the south [4–6].

In view of the vast capacity of the Albian aquifer, its exploitation is foreseen to substantially increase in forthcoming years, considering also water scarcity problems that are expected to become more severe due to climate change [7]. Therefore, appropriate reservoir management policies should be established to ensure the optimum reservoir exploitation. In this respect, for developing a comprehensive exploitation plan, and in particular for designing membrane desalination facilities, one should consider the significant issues impacting on economics and the environment. The biggest environmental issues at present (related to desalination plants) are (a) the management and/or disposal of the retentate/brine after potable water production [8–10] and (b) the minimization of energy consumption, or elimination (if possible) using renewable energies [11–13]. In view of these concerns, conserving as much as possible the Albian aquifer resource and protecting its good quality status are obviously of paramount importance, in addition to minimizing energy consumption and cost for desalination.

This study aims to contribute towards meeting the above goals, by dealing with the main factors involved in designing membrane plants for treating the brackish water from the Albian reservoir. Therefore, the scope of the paper is to identify the range of appropriate design and operating parameter values of a membrane desalination plant in the context of optimal aquifer exploitation. The basic desalination plant design considerations are discussed first and their impact on designing a plant for potable water production are elaborated next. Implementation of these criteria is demonstrated by summarizing the results of a typical case study, involving the design of a potable water production plant based on partial desalination of, and blending with, aquifer water. Experiments in support of this study are summarized. Finally, a cost analysis of a typical plant is also provided and possibilities for integrated exploitation of heat and water are outlined.

2. Albian aquifer water characteristics and potable water standards

The (C.I.) aquifer is an extensive horizontal sandstone reservoir and ranks as one of the largest groundwater systems in the world, commonly known as *Albian aquifer*. It is composed of Upper Carboniferous to Lower Cretaceous rocks, covering an area of about 1 million km^2, which is shared between Algeria, Tunisia and Libya, as indicated in Fig. 1. The basin contains approximately 60 trillion m^3 of brackish groundwater. The depth of the reservoir varies between 400 m in the west to more than 1,800 m in the east [14]. Deeper wells can provide water at 100–400 L/s flow rate and average total dissolved solids (TDS) less than 2 g/L. The highest discharge temperature can reach 73˚C [14]. In a recent study by Guendouz and Michelot [15], it was concluded that the major ion concentrations and the conductivity of the Albian aquifer water tend to increase along the main flow direction west to east (i.e. from the Atlas mountains in Algeria to Gabes Gulf in Tunisia). This suggests that water mineralization in the reservoir is enhanced by dissolution, apparently due to significant water-rock reactions.

The raw water considered in this study is pumped from 48 wells (within an area of ~4 ha) at Oued Rjem which is located 70 km from *In Salah* (Fig. 1). The water is collected in a large reservoir of 50.000 m^3 capacity before transferring to *Tamanrasset* which is 736 km away in the south of the Sahara desert. Typical physico-chemical data for this water source are included in Table 1 and will be subsequently employed for the purposes of this work. By comparison with the acceptability criteria defined by the Algerian potable water standards (listed in Table 1), it appears that the Albian aquifer water conductivity is near the maximum allowable value,

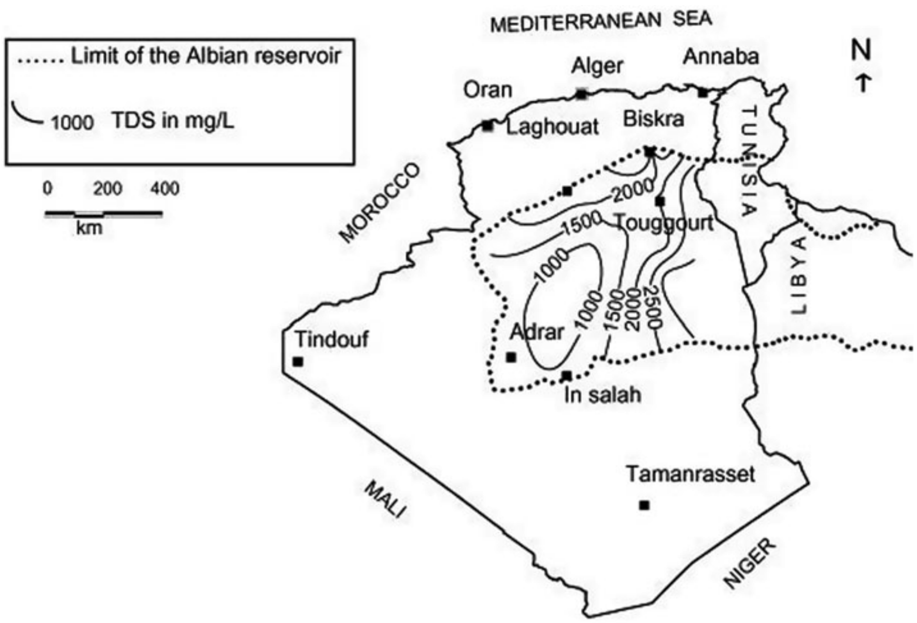

Fig. 1. A simplified map of Albian reservoir indicating equal concentration contours [16].

which is 2.8 mS/cm. The calcium, chloride, and magnesium concentrations are below the limits of Algerian standards, unlike sodium and sulfate ions which exceed those limits [4]. These parameters are not considered to cause a public health problem, but give an unpleasant taste to the well water. Furthermore, the long-term exploitation of the Albian aquifer can lead to an increase of raw water salinity, possibly up to a maximum value of 3.2 g/L [4]. Therefore, desalination seems to be an unavoidable solution to improve potable water quality and to face groundwater salinity increase. Regarding brine reinjection to the aquifer, to be discussed in the following, no significant impact is expected even if its concentration is double that of well water (currently below 2 g/L), provided that no other chemicals are contained therein.

Table 1
Albian aquifer water chemical analysis (*In Salah* site) [4] and potable water standards in Algeria [17]

Parameters	Unit	Value	Algerian standards
Temperature	℃	34.3	25
pH	–	6.91	≥6.5 and ≤9
Turbidity	NTU	0.15	5
Alkalinity $CaCO_3$	mg/L	–	500
Conductivity	mS/cm at 20℃	2.94/3.14	2.8
Cl	mg/L	495.00	500
Na	mg/L	298.50	200
K	mg/L	22	12
Ca	mg/L	172.33	200
SO_4	mg/L	567.33	400
NH_4	mg/L	0.06	0.5
Ba	mg/L	–	0.7
B	mg/L	–	1
Fe	mg/L	0.044	0.3
F	mg/L	0.56–0.63	1.5
Mn	μg/L	0.014	50
NO_3	mg/L	27.73	50
P	mg/L	25.97	5
As	μg/L	0.0009	10
Mg	mg/L	63/88	150

3. Basic desalination plant-design criteria

In formulating desalination plant-design criteria for cases such as the present one (i.e. exploitation of groundwater reservoirs), the overarching considerations are related to the need for *optimal reservoir management*; specifically:

- to prolong as much as possible the aquifer exploitation under conditions which would preserve the good quality of reservoir water, and
- to develop economically optimum aquifer exploitation plans.

In view of these general considerations, basic targets for designing plants producing potable water should include:

(i) *Minimization of retentate* (from reservoir water desalination), as for large capacity land-locked plants its re-injection in the reservoir appears to be the only solution.
(ii) *No use of water treatment chemicals*, which would end-up in the reinjected retentate and possibly degrade reservoir water quality in the long run.
(iii) *Exploitation of treated reservoir water enthalpy* to improve overall economics.

To achieve these targets, considering also the generally good quality of the Albian aquifer water, it is proposed *to blend reservoir water with desalinated water*, at an appropriate proportion which would satisfy potable water quality standards, perhaps more stringent than those accepted in Algeria (Table 1). Moreover, the desalination plant should be designed so that the concentrate is of good quality (i.e. free of chemicals) for reinjection; in this manner, there would be no environmental impact from the desalination plant operation. To optimize economics of this scheme, one should pursue maximization of desalinated water recovery in the membrane plant as well as utilization of the treated reservoir water enthalpy.

3.1. Desalination plant design considerations

For the intended treatment of low salinity feedwater, *Low Pressure Reverse Osmosis (LPRO)* membranes are appropriate leading to a minimal energy-related cost. Regarding maximization of desalinated water recovery, there are limitations imposed by the membrane scaling propensity of retentate (at high recoveries) due to sparingly soluble calcium salts (mainly $CaCO_3$ and calcium phosphate) exceeding saturation limits. Taking into account the relatively low pH (6.9) of Albian aquifer water, the best approach to increase recovery appears to be the *acidification of feedwater,* thus avoiding the use of undesirable synthetic anti-scalants. To optimize the design of a desalination plant, it is evident that one should strive to achieve minimization of production cost (through minimization of specific energy cost and of fixed expenses as well as maximization of recovery) with a minimum of acid use that would allow smooth plant operation and acceptable retentate reinjection conditions.

4. Laboratory pilot experiments

A series of laboratory tests, with water salinity similar to that of Albian reservoir water, was carried out in a fully instrumented pilot unit at CERTH, employing a typical low pressure RO spiral-wound membrane (SWM) element (Dow, Filmtec XLE). The scope of these test was to examine the membrane performance (i.e. recovery as a function of feed pressure, permeate water quality, SWM pressure drop) under various operating pressures and feed flow rates. These data are useful for guiding the selection of a narrow range of values of desalination design and operating parameters.

4.1. Pilot plant experimental setup

RO desalination experiments were conducted in a laboratory-pilot unit presented in Fig. 2. A low pressure RO SWM element (Filmtec XLE 2540) with membrane area 2.6 m^2 was employed since it exhibits (according to manufacturers) rather high ion rejection and good permeability, i.e. low pressure requirements. The feed solution was pumped to the single SWM element RO pressure vessel from a 40 L feed tank using a high pressure pump. Pressure sensors (PI-1, PI-2) located at the inlet and outlet of the pressure vessel were used for continuous recording of feed and concentrate pressure. Permeate and concentrate flows were monitored through digital flow-meters (FI-1 and FI-2). Permeate stream quality was characterized in terms of conductivity by an online electronic conductivity meter (CI). Temperature was maintained constant at 25 ± 0.1 °C through a plate heat exchanger (PHE) connected to a water cooler, through a flow control valve (CV-4).

An automation software (GeniDAG 4.25) was employed to control the pilot system operation. Thus, the controlled variables were the concentrate flow rate, adjusted through a flow control valve (CV-2), and the applied pressure at the inlet of membrane element, whereas the measured parameter values were the permeate flow-rate and pressure at concentrate exit (PI-2). Controlling the applied pressure was achieved by adjusting the pump speed through an inverter. In this manner, it was possible to determine the most important SWM element performance characteristics, such as membrane element pressure drop, rejection and permeate recovery. As subsequently discussed, these data were compared with predictions obtained from an appropriate commercial software (ROSA software, Dow) [18], in order to assess the performance of the particular SWM element type in a range of conditions appropriate for Albian aquifer brackish water desalination.

During the desalination tests, both permeate and concentrate flows were recycled back to the feed tank, while samples of permeate flow were regularly taken

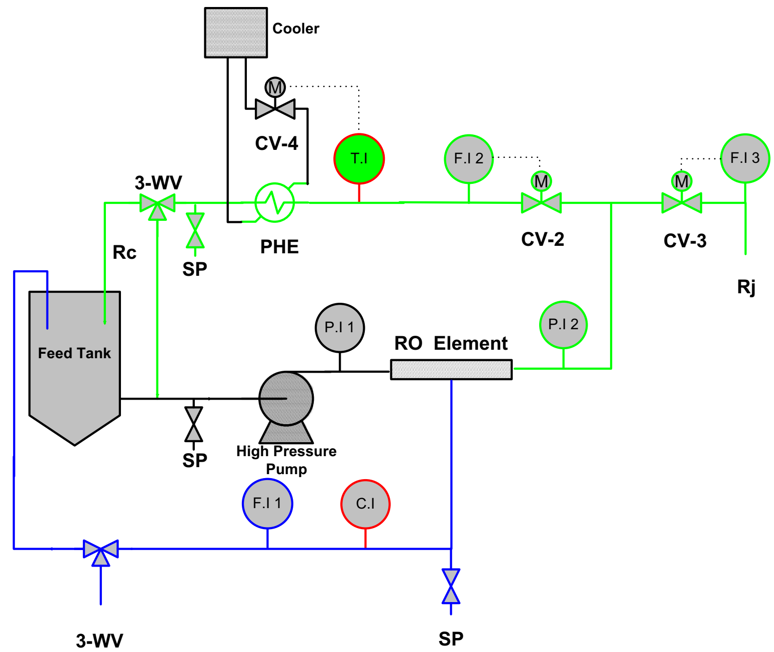

Fig. 2. Schematic diagram of the pilot unit for testing SWM desalination performance.

to determine permeate characteristics. Prior to each filtration test, membrane conditioning was done with distilled water under the desired applied pressure and cross-flow rate for an adequate time period to attain SWM performance stability. Subsequently, a concentrated sodium chloride stock solution was diluted in the feed tank with tap water to achieve feedwater conductivity close to that of Albian water. Tap water quality characteristics have been presented in a previous publication [19]; then, the system was run by imposing pairs of values of applied pressure and cross-flow velocity. Experimental conditions and related data, included in Table 2, are from a series of tests with feedwater salinity similar to that of Albian reservoir water.

4.2. ULPRO membrane performance; effect of cross-flow velocity

Particular attention was paid in these tests to the effect of cross-flow velocity on membrane permeate rate, recovery, and SWM pressure drop; this effect was very significant at the low operating pressure level of the brackish water membrane as it affected

Table 2
Experimental data of brackish water desalination with a single SWM element in a pilot unit; water salinity ~1827 mg/L TDS (equ. NaCl)

N°	Feed flow (m^3/day)	Inlet pressure (psi)	Permeate flow rate(m^3/day)	Permeate flux ($Lm^{-2}h^{-1}$)	Recovery (%)	Concentrate flow (m^3/day)	Crossflow velocity *(cm/s)	Pressure drop (psi)	Rejection (%)
1	14.63	90.9	1.96	31.4	13.4	12.67	17.5 (20.2)	4.0	96.6
2	14.55	78.5	1.70	27.2	11.7	12.85	17.7 (20.0)	3.8	96.2
3	14.99	74.5	1.57	25.0	10.8	12.92	17.8 (20.7)	4.0	96.0
4	13.96	91.5	2.01	32.4	4.4	11.95	16.5 (19.2)	3.0	96.6
5	13.66	81.5	1.75	28.1	12.8	11.91	16.4 (18.8)	3.0	96.3
6	13.60	74.5	1.59	25.5	11.7	12.01	16.6 (18.7)	3.0	96.0
7	17.65	79.5	1.66	26.65	9.42	15.98	22.02 (24.3)	7.0	96.3
8	16.25	79.5	1.71	27.35	10.50	14.54	20.04 (22.4)	5.5	96.3
9	12.55	79.5	1.75	28.04	13.94	10.80	14.88 (17.3)	2.1	96.3

*Cross-flow velocity at SWM element exit; values in the brackets correspond to the inlet of SWM element.

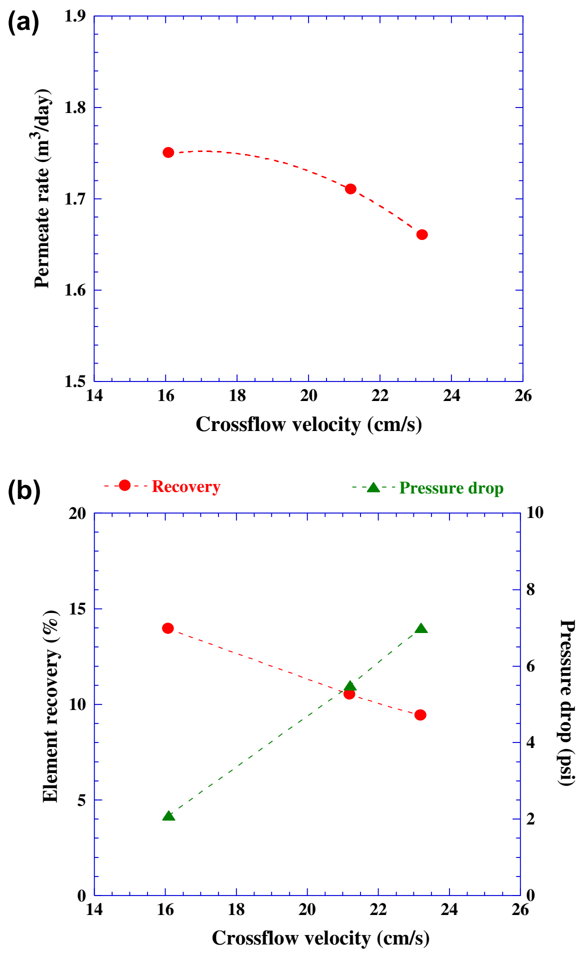

Fig. 3. Experimental data on the effect of cross-flow velocity on membrane performance. Effect on a) SWM element permeate rate and b) SWM element recovery and pressure drop. The plotted cross-flow velocity is an average value of the respective SWM inlet and outlet cross-flow velocities.

directly the SWM pressure drop. To facilitate data comparison, the applied pressure in these tests was kept constant at ~80 psi by adjusting the high pressure pump operation. Fig. 3 (a,b) presents permeate rate, SWM element recovery, and pressure drop with respect to cross-flow velocity. It is observed that an increased cross-flow velocity results in significant reduction of both permeate rate and percent recovery. This behavior is attributed to the relatively significant increase of pressure drop in the SWM element with increasing cross-flow velocity (Fig. 3(b)), which reduces the effective trans-membrane pressure along the element; the sensitivity of low-pressure membrane desalination performance to SWM pressure drop variation is documented in a recent study [20]. In the data of Fig. 3(b), it is observed that a modest increase of the mean cross-flow velocity (average value of velocities at the inlet and exit of the SWM element) from 16 to 24 cm/s leads to more than threefold pressure drop increase (i.e. from 2 to 7 ψ). This is not unexpected, as the pressure drop in the SWM elements is strongly dependant on superficial cross-flow velocity [21,22]. It is also interesting that the membrane salt rejection appears to be essentially unaffected by such a cross-flow velocity change, remaining constant at ~96.3%, which suggests that (in the range of conditions tested) the expected reduction of concentration polarization due to cross-flow velocity increase [22] does not lead to significant improvement of average salt rejection of the particular SWM element.

4.3. Comparison of experimental data with predictions

Predictions of desalination performance, regarding the *leading* SWM element in a usual multi-element pressure vessel, have been performed using the ROSA design software [18]. For comparison with the pilot tests, input data for the element Filmtec XLE 2540 as well as the typical Albian aquifer water composition (listed in Table 1) were used in the computations. The results of ROSA projections for two membrane vessel recoveries (namely 60% and 65%, with *single pass*) are summarized in Table 3. For each recovery value, three different scenarios regarding the number of membrane elements per pressure vessel were examined; thus, RO membrane performance parameters were determined for the cases of 5, 6, and 7 SWM elements per vessel. It should be noted that, in running the ROSA computations, a kind of "optimization" procedure was followed whereby the minimum number of pressure vessels was selected, for a fixed recovery per vessel, without violating the design criteria or other restrictions imposed by the software [18].

To facilitate comparison, the pilot experiments and the simulations using the commercial software were performed with the same applied pressure at the inlet of membrane element, P_{in}, and with the same cross-flow velocity. Furthermore, it should be noted that performance characteristics presented in Table 3 correspond to the first element of each pressure vessel of the desalination unit, which should be comparable to the single SWM element of the laboratory pilot. In Fig. 4, permeate flow values are presented with respect to applied pressure P_{in} for two cross-flow velocities from both ROSA projections and experiments. It is evident that, regarding permeate productivity, agreement between experimental data and predictions is satisfactory; however, the performance of the tested membrane appears to be somewhat inferior (by approx. 7%) compared to ROSA

Table 3
Predicted desalination performance data of SWM elements (Dow XLE) in 5- to 7-element pressure vessels. Estimates obtained by commercial design software ROSA [18]

			1st element								
N°	Plant recovery %	Elements per vessel	Concentrate flow rate, m^3/d	Feed flow rate, m^3/d	Permeate flow rate, m^3/d	Inlet Pressure, psi	Mean Flux, $L/m^2 h$	Cross flow velocity, cm/s	Pressure drop,psi	Rejection %	Recovery %
1	60	5	12.72	14.89	2.17	91.3	34.8	17.6	3.3	98.3	15.0
2		6	12.98	14.89	1.91	80.4	30.6	17.9	3.3	98.1	13.0
3		7	13.16	14.89	1.73	74.9	27.7	18.2	3.5	98.0	12.0
4	65	5	11.54	13.74	2.20	92.6	35.24	15.9	2.9	98.3	16.0
5		6	11.81	13.74	1.93	82.4	30.92	16.3	3.0	98.1	14.0
6		7	11.99	13.74	1.75	75.6	28.04	16.6	3.0	98.0	13.0

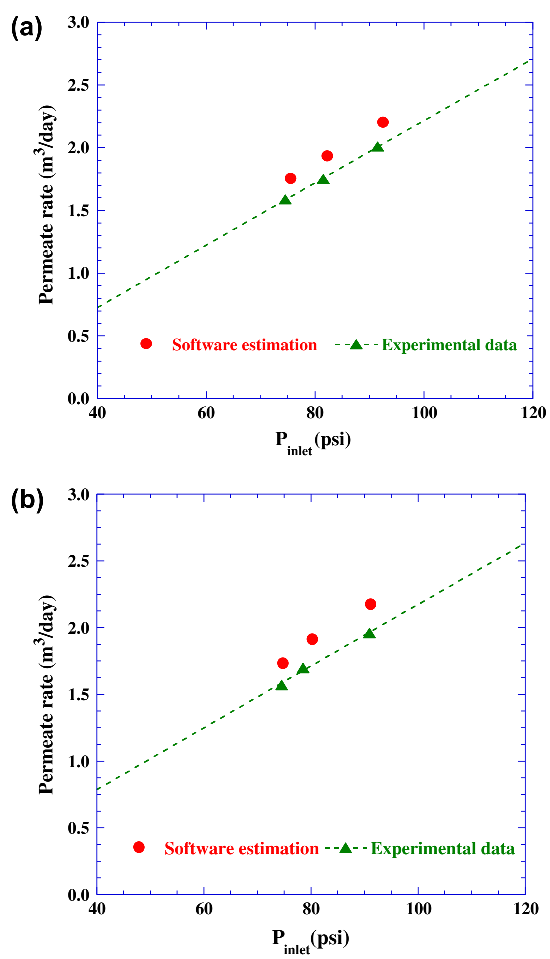

Fig. 4. Comparison of experimental data on performance characteristics with theoretical estimates (obtained with the commercial design software ROSA) for the low-pressure membrane (Filmtec XLE). Average cross-flow velocity: a) 17.5 cm/s and b) 19 cm/s.

projections. The same trend is also observed for the related permeate recovery. This rather small discrepancy between measurements and predictions may be attributed to experimental errors as well as to the use of input parameter values for the computations which differ from those of the pilot experimental system. Comparing other membrane performance data (listed in Table 2) with the corresponding simulation results (Table 3) it is concluded that computed and experimental values of pressure drop are quite close, whereas membrane salt rejection theoretical estimates are somewhat greater than those measured in the present tests. In general, it is concluded that the ROSA program predictions in regard to both permeate water quality and quantity are in fair agreement with the experimental results under the same conditions; therefore, this software can be used (for the same type of RO SWM element) for the following desalination-plant design calculations.

5. A case study

In this case study, the aforementioned general criteria were taken into account in order to obtain a near-optimum design of a potable water production plant of capacity 10.000 m^3/day. The results from this study can be easily adapted and extrapolated to larger plant capacities, which is possible due to the modular type of membrane units that facilitate plant scale-up. On the basis of the Albian water characteristics (Table 1), which indicate no membrane fouling propensity and only potential for scaling beyond a certain level of permeate recovery, this study was performed in two sequential steps as follows.

5.1. Determination of the scaling propensity of retentate

The retentate scaling potential was determined as a function of key operating parameters, including permeate recovery, feedwater, pH, and temperature. For the required accurate equilibria calculations of the retentate stream, a thermodynamic ion-association model (PHREEQC computer program, version 2.15.07) was used, implementing the extension of the Debye-Hückel theory [23], because commercial software of membrane manufacturers (e.g. ROSA) is considered inadequate. For these calculations, the most complete literature database (*minteq.v4.dat)* available at present was employed [24]. For permeate recovery in the range 50–65%, the pH of retentate stream was estimated (through ROSA projections) to be approx. 7.1–7.2 with no acid addition in the feedwater stream. For pH~7.1 (i.e. for 50% permeate recovery) and for the relatively high temperature of feedwater stream (34.3°C), it was estimated through the PHREEQC code that there is scaling potential for the following phases: aragonite, calcite, chalcedony, dolomite, hydroxylapatite, and quartz. This is evident from the positive saturation indices calculated for these solid phases which are depicted in Fig. 5; hydroxylapatite appears to have the greatest scaling potential. Fig. 5 also includes the saturation indices of the above solid phases estimated for retentate stream pH 6.1; this is the maximum tolerable pH value of the retentate stream in order to avoid the precipitation of sparingly soluble salts (i.e. associated with negative saturation indices), apart from two phases of SiO_2 (chalcedony and quartz) which are insensitive to pH changes. Finally, it should be pointed out that in order to achieve a retentate stream with pH = 6.1 (to prevent scaling of RO membranes), the feedwater stream should be acidified to a pH value ≤ 5.9. Estimates of required acid dosages are also calculated, using the ROSA software, and are employed in the following section which deals with the design and a brief techno-economic assessment of the desalination plant.

5.2. Design of desalination plant (base case)

A desalination plant (base case) was designed within the aforementioned range of permissible pH and permeate recovery. *Blending* is implemented, based on maximization of the "aquifer-" over "desalinated-water" ratio, to satisfy improved potable water standards. For a base-case design, after trials, a blending ratio 65/35 (aquifer/desalinated water) is selected which ensures potable water with composition summarized in Table 4. It should be noted that the blended water quality (Table 4) is satisfactory with the exception of the pH value which is low. As is common in desalination plants for potable water production, the pH can be increased by adding lime before storage and distribution. Based on the above considerations, three different projections were made, with the ROSA software, in order to evaluate three design alternatives of the desalination plant. These alternatives involve a

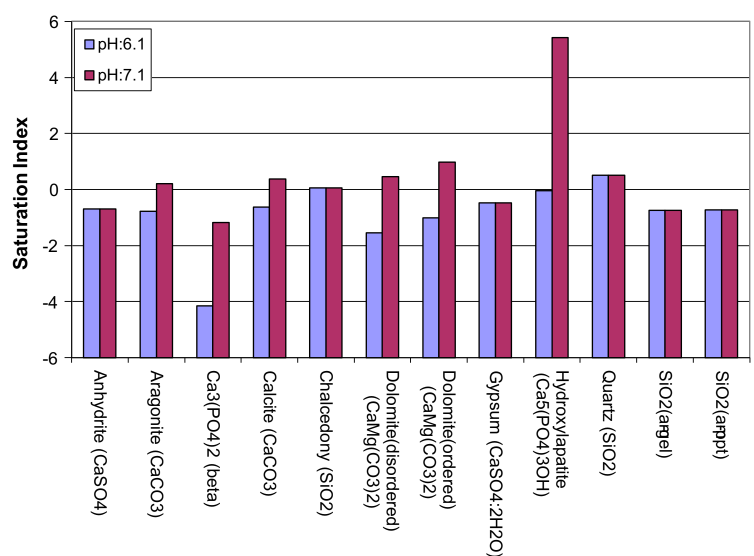

Fig. 5. Saturation indices of solid phases in the retentate stream for untreated and treated (acidified) feedwater; pH values in exiting retentate stream, 7.1 and 6.1 for untreated and treated feed, respectively.

Table 4
Chemical composition of permeate and final "blended" potable water

Parameter	Permeate from RO plant	"Blended" potable water
NH_4^+ (mg/L)	0.02	0.05
Na^+ (mg/L)	18.45	200.49
Mg^{2+} (mg/L)	2.05	59.30
Ca^{2+} (mg/L)	3.83	113.35
HCO_3^- (mg/L)	3.56	60.97
NO_3^- (mg/L)	13.31	22.68
Cl^- (mg/L)	24.67	359.39
SO_4^{2-} (mg/L)	10.03	372.26
SiO_2 (mg/L)	0.45	8.02
CO_2 (mg/L)	70.89	71.48
TDS (mg/L)	76.38	1196.52
pH	4.83	5.75

single-pass RO membrane train using *5, 6, or 7 SWM elements per pressure vessel*, *50% recovery, and blending ratio 65/35*. For these design calculations, 8-inch XLE-440 Filmtec membrane elements were selected. The performance characteristics of this membrane type were evaluated (with satisfactory results) in the laboratory tests using a similar (but of smaller diameter) XLE-2540 membrane element; therefore, one can scale-up the desalination system to plant size with increased confidence. The main results of the design calculations are summarized in Table 5, including

Table 5
Summary results of design calculations for single-pass brackish water desalination using trains of 5, 6, or 7 SWM element pressure vessels (PV). Eight-inch XLE-440 SWM elements. Plant capacity: 10.000 m^3/day potable water

Parameters	5-element PV	6-element PV	7-element PV
Number of pressure vessels (PV)	24	21	20
Number of SWM elements	120	126	140
Feed pressure, bar	5.82	5.99	5.93
Desalinated water recovery, %	50	50	50
Overall aquifer water utilization, %	74.08	74.08	74.11
PV pressure drop, kPa	117	168	206
Average PV flux, $L/m^2 h$	29.73	28.32	25.52
Pumping power, kW	58.98	60.69	60.06
Specific energy, kWh/m^3	0.14	0.15	0.14
Acid dose (100% HCl), mg/L	55.92	55.92	55.92

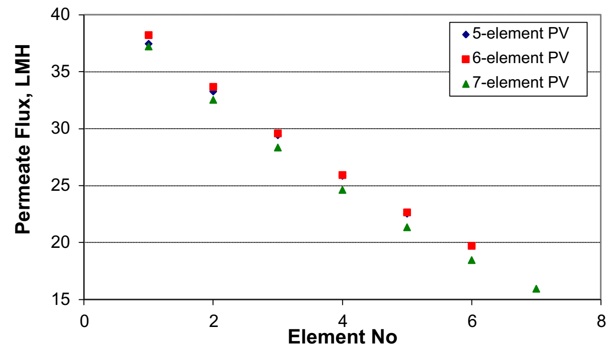

Fig. 6. Profile of mean permeate flux of each SWM element in a pressure vessel, for three cases; i.e. plants with 5-, 6- or 7-element pressure vessels.

partial aquifer water desalination and subsequent blending. The desalination unit has a feedwater treatment capacity of 7.000 m^3/day, operating at 50% permeate recovery. 10.000 m^3/day potable water is produced by blending 3.500 m^3/day desalinated water with 6.500 m^3/day aquifer water. Retentate water to be reinjected or further utilized is ~3.500 m^3/day.

The profile of mean permeate flux for each individual membrane element along a pressure vessel is depicted in Fig. 6 for different design alternatives. Differences in SWM element flux are relatively small, yet systematic with expected trends [20]; i.e. the design case involving the largest number of elements per vessel (7 elements) is associated with the smallest fluxes (for a fixed recovery), as one would expect. The fluxes in the leading three SWM elements are somewhat high (i.e.~38 to ~24 $L/m^2 h$) as is the case with permeable membranes treating brackish water [20,25]; however, no operating problems are expected since the Albian feedwater is free of organic matter, with no apparent fouling potential [19].

Upon inspection of the results in Table 5, it will be noted that the 5-element-per vessel case requires the smallest number of SWM elements, exhibits the smallest pressure drop per pressure vessel; thus, requiring the smallest pumping power (although the effect is small). Moreover, a large number of small-size pressure vessels is required in the 5-element case.

5.3. Cost analysis for selection of optimum number of SWM elements per vessel

In Table 6, results of a preliminary economic analysis are summarized regarding the cost of a brackish water desalination plant. In addition to other benefits, this analysis permits selection of the optimum number of elements per pressure vessel, among the three

Table 6
Potable water plant cost analysis for 5, 6, or 7 elements per pressure vessel. Potable water plant capacity 10.000 m^3/day; blending 65% reservoir with 35% desalinated water

Project scenarios	5 elements	6 elements	7 elements
System water production (m^3/h)	416.69	416.70	416.86
System recovery (%)	74.08	74.08	74.11
Project economic variables			
Project life (years)	10	10	10
Interest rate (%)	8	8	8
Power cost ($kWh)	0.028	0.028	0.028
Projection results			
Pass 1 permeate production (m^3/h)	145.85	145.87	146.03
Pass 1 feed pressure (bar)	5.82	5.99	5.93
Pass 1 concentrate pressure (bar)	4.31	3.97	3.52
Pass 1 recovery (%)	50.00	50.00	50.00
Capital expenses			
Pass 1 pressure vessels	24	21	20
Pressure vessel cost ($/vessel)	1,259	1,329	1,419
Pass 1 capital for pressure vessels	$30216.00	$27909.00	$28380.00
Pass 1 total elements	120	126	140
Element cost ($/element)	$700.00	$700.00	$700.00
Pass 1 capital for elements ($)	84,000	88,200	98,000
Pass 1 capital ($)	114,216	116,109	126,380
Pass 1 capital ($/$m^3$)	0.0089	0.0091	0.0099
Operating expenses			
Energy cost			
Pass 1 pumping power (kW)	58.97	60.68	60.06
Pass 1 pump specific energy (kWh/m^3)	0.142	0.146	0.144
Pass 1 net energy consumption (KWh/m^3)	0.142	0.146	0.144
Pass 1 net energy cost ($/year)	$5062.85	$5210.13	$5160.32
Energy expense NPV ($)	33972.11	34960.42	34626.18
Pass 1 energy expense ($/$m^3$)	0.0040	0.0041	0.0040
Membrane replacement cost			
Pass 1 replacement rate (%/year)	10	10	10
Replacement price ($/element)	$700.00	$700.00	$700.00
Pass 1 replacement cost for elements ($/year)	$8400.00	$8820.00	$9800.00
Pass 1 replacement membrane NPV ($)	$56364.68	$59182.92	$65758.80
Pass 1 membrane replacement expense ($/$m^3$)	0.0066	0.0069	0.0077
Operating expense subtotal			
Pass 1 operating expense NPV ($)	$90336.80	$94143.34	$100384.97
Pass 1 operating expense per m ($/$m^3$)	0.0105	0.0110	0.0117
Pass 1 total			
Pass 1 cost NPV ($)	$204552.80	$210252.34	$226764.97
Life cycle cost ($/$m^3$)	0.0056	0.0058	0.0062

design alternatives examined; i.e. 5, 6, and 7 elements per vessel. It should be noted that this comparison includes only the cost of pumping, of membrane pressure vessels and of membrane elements, considering that all the other cost parameters (for operating, materials, and capital expenses) will remain the same for all three examined scenarios. This is the reason for the low values of both capital and operating costs listed in

Table 6. The unit cost for feedwater acidification, to prevent precipitation of sparingly soluble salts, was estimated to be 0.0212 $/m^3. The acid dose is calculated through ROSA software (data in Table 5), assuming HCl (33% wt.) cost ~200 $/tn. The cost analysis results summarized in Table 6 suggest that the *5-element per vessel option* is preferable because it is associated with the smallest capital and operating expenses. It should be noted that the "percentage system recovery" (~74.1%), included in Table 6, corresponds the overall system potable water recovery, obtained with the blending proportion "65% reservoir water" and "35% desalinated water", and 50% recovery of desalinated water in a desalination facility treating 7.000 m^3/day; therefore, 3.500 m^3/day retentate is left for reinjection and/or further utilization.

6. Integrated exploitation of Albian reservoir water resources

For large scale exploitation of the Albian reservoir geothermal water, considering its significant enthalpic content, the combination of potable water production with other uses would offer substantial economic and environmental benefits. A relevant issue is whether energy exploitation of the Albian water should be placed before or after the desalination process. To address this issue, it should be recalled that for the desalination process the significant water enthalpy (or its relatively high temperature) has a negative effect, as it aggravates the scaling problem by shifting the Ca salt equilibria towards smaller ionic species concentrations; i.e. for feedwaters of a certain composition, the supersaturation of the inverse solubility salts is greater at higher temperatures. This trend necessitates either reduced recovery or an increased dosage of acid (or anti-scalants) to maintain a certain level of permeate recovery. Therefore, in principle, energy extraction from these geothermal waters should precede their desalination, provided that no feedwater degradation would take place in such an initial exploitation step.

Potentially attractive, large-scale geothermal energy exploitation options include building-space climatization (of residential compounds, public buildings, and industrial facilities), preferably in regions neighboring the potable water production plant. Other *indirect heat transfer* applications may be possible in various industrial and agricultural products processing fields. In all these applications, it is envisioned that the extracted reservoir water would be processed to such an extent and in such a manner that the remaining part (retentate) would be of a quality allowing its reinjection in the reservoir. However, there are other possible options, which are already implemented [26] or considered for application in Algeria [27] and in neighboring countries. Related activities and plans include fish farms [26] for which the Albian water seems to be ideal as well as facilities for cultivating spirulina; the latter is a product of high nutritional value and much in demand in recent years. The prospects for other geothermal applications are significant; for instance, Mahmoudi et al. [27] recently proposed the use of geothermal water from the Albian reservoir to power a brackish water greenhouse desalination system (SWGH) to facilitate development of arid regions of Algerian desert. Geothermal resources can be used both to heat the greenhouses and to provide fresh water needed for irrigation of crops cultivated in the greenhouses. Such units can be powered by solar or wind energy [1]; moreover, it should be considered whether geothermal resources needed for the greenhouse desalination unit could be substituted by the RO desalination brine. Similarly, it should be studied whether the discharge brine can be used for fish ponds. Therefore, integrated utilization of Albian resources for potable water production, SWGH systems, and other applications (e.g. fish pond or spirulina cultivation) can help the establishment of human habitats in these arid areas.

7. Concluding remarks

The geothermal water from the Albian aquifer is characterized by modest salinity, which at present is at the borderline between hard potable water (of unpleasant taste) and brackish water in need of demineralization. To improve its quality for human consumption and to cope with an expected reservoir salinity increase (mainly due to increased exploitation), membrane desalination is an attractive option. A study of this option was performed, within the context of overall optimization of reservoir exploitation. The latter entails maximization of extracted reservoir water use, and reinjection of the unused part (retentate) in a good condition, thus avoiding reservoir degradation and ensuring its preservation.

To systematically study a potable water production facility, experimental data obtained from a laboratory-pilot unit have assisted in the selection of the plant near-optimum design and operating conditions, which are summarized as follows:

- For a typical Albian water composition, near optimum potable water production conditions include blending extracted aquifer water with desalinated water, at a proportion 65% with 35%, respectively.
- The desalinated water can be produced in a cost-

effective manner, in a low pressure desalination facility at 50% recovery; a limitation in increasing recovery is due to the membrane scaling propensity of retentate.

- Acid addition is preferred to combat membrane scaling (mainly due to calcium phosphate), over organic anti-scalants that might harm the reservoir in the long run as they would be mixed in the reinjected retentate.
- A single pass RO membrane facility, involving pressure vessels with five (5) SWM elements, appears to be the best desalination plant configuration for this task, ensuring minimum product unit cost as well as small specific energy consumption.
- These results, based on a realistic case study for feedwater treatment capacity 7.000 m^3/day and total potable water production 10.000 m^3/day, can be readily adapted to larger plants in an almost linear scale-up due to the modular form of the desalination units.

The economics of integrated reservoir water exploitation would be much improved if additional applications involving Albian water (e.g. geothermal energy content exploitation, and retentate further utilization) were made before or after the water demineralization process. In any case, potable water production with partial desalination appears to be the backbone of Albian water alternative exploitation schemes in the near future. Therefore, the results of this study, regarding the methodology employed, the plant configuration suggested and the quantitative estimates obtained, are expected to be quite useful in such endeavors.

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