

Membrane Desalination of Agricultural Drainage Water: Water Recovery Enhancement and Brine Minimization

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ABSTRACT

The salinity of brackish groundwater in the San Joaquin (SJ) Valley is typically in the range of about 2000-4000 mg/L total dissolved solids (TDS). However, salinity levels as high as 15,000 mg/L have been documented in some areas. In recent years there has been a growing interest in the potential use of membrane desalination technology to reduce the salinity of brackish groundwater in the SJ Valley. Membrane desalination for SJ Valley brackish water would have to be carried out at relatively high water recovery in order to reduce the volume of generated RO concentrate. However, at high water recoveries the concentration of mineral salt ions on the feed-side of the membrane may increase to levels that exceed the solubility limits of sparingly water soluble mineral salts such as calcium sulfate, calcium carbonate and barium sulfate. The ensuing crystallization of these mineral salts, onto on the membrane surface and surface deposition of bulk crystals, results in scale build-up that leads to permeate flux decline, shortening of membrane life, and as a consequence reduction in process efficiency and increased operational cost. Therefore, it is imperative that process strategies are designed so as to enhance product water recovery while reducing the potential for mineral salt scaling. Accordingly, the principal objective of the present study is to evaluate the feasibility of high recovery RO desalting of brackish water.

The present project focuses on evaluating the integration of accelerated mineral salt precipitation (AMSP) for scale mitigation with membrane RO desalting to enable high RO recovery. AMSP treatment would serve to de-supersaturate the RO primary or secondary feed with respect to mineral salt scalants. In the first phase of the project, a systematic theoretical analysis was carried out to evaluate the limits on product water recovery due to mineral salt precipitation. The approach was based on multi-electrolyte thermodynamic solubility calculations to: (a) determine the operational pH range required to mitigate calcite scaling and the achievable level of recovery with feed pH adjustment, and (b) determine the required level of calcium removal by AMSP to enable enhanced water product water recovery. The analysis, based on a typical field water feed composition, revealed that primary RO recovery of up to about 54% is feasible with feed pH adjustment to a level of about 6. Recovery can be increased up to about 80% with the use of antiscalants to suppress gypsum and barite scaling. Recovery in excess of 90% is feasible via secondary RO desalting of the primary RO concentrate, provided that about 92% of the dissolved calcium is removed by AMSP in order to de-supersaturate the RO concentrate with respect to gypsum. Given the high TDS level of the concentrate, the required transmembrane pressure could exceed 500 psi in order to reach a recovery levels in excess of 90%. An alternative process configuration that utilizes nanofiltration in conjunction with primary and/or secondary RO desalting could enable operation at lower pressure. Such an alternative will be considered in the second phase of the study.

Preliminary cost analysis of the integrated Primary RO-AMSP-Secondary RO process was carried out using as a basis an RO plant that desalts a feed of 5×10^6 gal/day (i.e., 5 MGD). The overall desalination cost, at overall recoveries of 80%, 90% and 95%, for permeate quality of 750 mg/L total dissolved solids (TDS) or better, was estimated to be \$0.56/kgal (\$185/acre-ft), \$0.87/kgal (\$284/acre-ft) and \$0.98/kgal (\$319/acre-ft), respectively. If the required capital would be secured by an amortized loan, the desalination cost would increase by ~ 5%.. The above preliminary economic analysis suggest that the cost of high recovery brackish water desalination is reasonable and lower by about a factor of 2-5 relative to the cost of seawater desalination. In the second phase of the study, the process analysis will be refined and alternate process configurations will be considered for additional water source compositions that represent the lower and upper limits of mineral salt scaling potential. IN addition, alternate process configurations will be explored to assess the potential for cost reduction. Experimental evaluation of a water source at the high scaling potential limit will then be carried out to assess the kinetics of AP treatment and verify that scale mitigation is indeed achievable at recovery levels of 95% or potentially higher.

WATER RECOVERY ENHANCEMENT AND BRINE MINIMIZATION (ARIAL 10 – CAPS - BOLD)

OVERVIEW OF APPROACH

San Joaquin Valley brackish water is high in concentrations of divalent cations such as calcium, magnesium, barium as well as carbonate and sulfate anions [1]. Membrane desalination of this water is accompanied by the concentration of the above ions in the retentate stream and near the membrane surface [2]. With increased product water recovery, the concentration of sparingly soluble mineral salts of the above ions (e.g., calcium sulfate, calcium carbonate and barium sulfate) can rise above their saturation level, thereby increasing the potential for mineral salt precipitation and thus membrane scaling [3]. Mineral salt precipitation limits the RO process to operation at water recovery levels at which the concentrations of potential mineral salt scalants will be maintained below saturation. The limit on recovery is specific to the water feed chemistry and thus must be determined for the source water under consideration. One possible approach to high recovery is to de-supersaturate the concentrate from primary RO desalting to its scaling potential, followed by secondary RO desalting to attain product water recovery in excess of 95%. An evaluation of the feasibility of high recovery RO for every possible water source composition in the SJ Valley is outside the scope of the present project. Therefore, the present study focuses on illustrating the feasibility of high RO desalination for typical SJ Valley water source chemistry and for a water source with the highest scaling potential.

In the first phase of the study, analysis of the recovery limits was carried out based on the water source composition given in Table 1. This water composition is typical of SJ Valley brackish water. The first step in analyzing RO feasibility involved thermodynamic solubility calculations for the major scalants (gypsum, calcite and barite) using the OLI software [4] for multi-ion systems subsequent to reconciliation of the data to ensure appropriate charge balance. The limit on recovery was calculated by evaluating the expected saturation levels, expressed in terms of the mineral salts saturation indices, at various recovery levels. The theoretical product water recovery limit was specified when the mineral salt saturation index reached unity. Based on the above analyses, the required feed pH adjustment and degree of calcium removal were determined so as to reach reasonably high recovery limits (above 90%). Subsequently, a series of process simulations were carried out along with costing analysis to estimate the cost of water desalination. The above analysis was carried out for a typical water source composition from the San Joaquin Valley (Table 1). Analysis for the highest scaling potential SJ Valley water source will be carried out in the second phase of the study. Initial experiments of accelerated mineral salt precipitation were also carried out with a water source of the highest scaling potential in the SJ Valley (determined based on analysis of DWR groundwater water quality data [1]) to provide preliminary assessment of the feasibility of AMSP and the expected precipitation kinetics. The assessment of RO recovery limits and economic feasibility will be refined in the second phase of the project using selected field samples for which experimental AMSP and RO desalting data will be obtained.

PH DEPENDENCE OF MINERAL SALT SOLUBILITY

The limit imposed by mineral salt scaling on product water recovery was first determined, by calculating the saturation indices, for the mineral salts of concern as a function of pH. This analysis provided information on the feasibility of feed pH adjustment to reduce scaling potential with respect to calcium carbonate scaling since its solubility is pH sensitive. The saturation indices for calcite, gypsum and barite are defined as follows:

$$SI_{\text{calcite}} = \frac{(Ca^{2+})(CO_3^{2-})}{K_{sp\text{calcite}}}, \quad SI_{\text{gypsum}} = \frac{(Ca^{2+})(SO_4^{2-})}{K_{sp\text{barite}}}, \quad SI_{\text{barite}} = \frac{(Ba^{2+})(SO_4^{2-})}{K_{sp\text{barite}}} \quad (1)$$

Where (Ca^{2+}) , (Ba^{2+}) , (SO_4^{2-}) and (CO_3^{2-}) are the activities of the calcium, barium, sulfate and carbonate ions, respectively, and $K_{sp\text{calcite}}$, $K_{sp\text{gypsum}}$ and $K_{sp\text{barite}}$ are the solubility constants (products) for calcite, gypsum and barite, respectively. Variation of the above saturation indices with pH is depicted in Fig. 1 for source water OAS-2548 (Table 1). It is clear that calcite is most sensitive to pH while the saturation indices of calcium sulfate and barium sulfate are pH insensitive. Barite has the highest saturation index; however, barite is a metastable mineral salt (up to $SI_{\text{barite}} \sim 60$) present at very low concentrations (≤ 0.5 mg/L) with slow nucleation kinetics [5]. Given the above, it is likely that the amount of barite scale (per unit surface area), if it could form, would be lower by about two orders of magnitude relative to gypsum. Therefore, given its low concentration and slow precipitation kinetics, barite is not expected to precipitate over the course of typical residence times in commercial RO modules.

RECOVERY LIMITATIONS DUE TO SCALING and RECOVERY ENHANCEMENT via FEED pH ADJUSTMENT and ANTISCALANT DOSING

The saturation index for gypsum, for the typical feed water composition given in Table 1, is below unity over the pH range of practical interest (Fig. 1), while $SI_{\text{calcite}}=0.88$ at the native pH (~ 7.1) of this water source. The saturation index for calcite reaches unity at pH ~ 7.15 and therefore this mineral salt is the primary limiting scalant for RO desalting of the above water source. As water recovery increases, the concentrations of the various ions increase, leading to an increase in of the saturation indices of the various mineral salts. In order to ensure that, for a given product water recovery operation, that calcite concentration does not exceed saturation, it is necessary to reduce the feed pH. A series of calculations was carried out to determine the pH level required to keep the saturation index of calcite at unity for different levels of desired product water recoveries (Fig. 2). Clearly, RO desalting at the feed's native pH (~ 7.1) would not be feasible due to calcite scaling. With increased recovery the feed would have to be adjusted to increasingly lower pH (Fig. 2). For example, adjustment of the feed to pH ~ 6 would mitigate calcite scaling and enable RO recovery of up to $\sim 92\%$ (Fig. 2 and Table 2). However, as demonstrated in the analysis of Fig.3, gypsum saturation is reached at recovery of about 53%. At this recovery the saturation index of barite is above the recommended level for RO desalting [6]. The above analysis is conservative since feed antiscalants dosing can provide some degree of scale suppression and thereby attain a higher recovery relative to the above thermodynamic-based estimate (i.e., 53%). Effective antiscalants are available for suppression of gypsum precipitation and such antiscalants are also known to also assist in mitigating barium sulfate scaling. Effective use of antiscalants for gypsum scale control is generally recommended for RO desalting in which the saturation index of gypsum does not exceed about 2.3 [6]. Accordingly, antiscalants treatment would enable RO desalting up to recovery of about 81% (Fig. 3). It must be recognized that strategic pH adjustment and antiscalant use must be determined based on process optimization with respect to the target recovery, permeate quality and overall water production cost.

RECOVERY LIMIT IMPOSED BY OSMOTIC PRESSURE

Commercial vessels for nanofiltration (NF) and ultra-low pressure RO membranes are typically rated for ~350 psi maximum pressure limit. Low pressure RO and extra high rejection modules are generally rated for a 600 psi pressure limit, while seawater desalination RO module are usually made to withstand pressure of up to about 1200 psi. In order to determine the pressure limit imposed by the feed, the osmotic pressure of the retentate stream for the OAS-2548 source water was determined for different levels of water recovery. Accordingly, the osmotic pressure as a function of product water recovery is shown in Fig. 4. Also, recoveries that correspond to osmotic pressure over the range of 200 psi to 600 psi are listed in Table 2. Clearly, if ultra-low pressure RO is the process of choice, then water recovery would be limited to less than about 75% in order to ensure that the maximum operating transmembrane pressure of 350 psi is not surpassed (Fig. 4). Higher recoveries would necessitate membranes and modules that can withstand higher pressures. For example, at 600 psi transmembrane pressure, the osmotic limit on achievable recovery would be about 93%. The above analysis suggests that high recovery membrane desalination could be achieved using a combination of low-pressure high rejection membranes for the primary RO and extra high rejection RO membranes (rated up to 600 psi) for the secondary RO desalting stage.

CALCIUM REMOVAL REQUIREMENTS FOR SCALE SUPPRESSION and ENHANCED PRODUCT WATER RECOVERY

Accelerated mineral salt precipitation (AMSP) under alkaline conditions is a potential approach to reducing the scaling potential of the primary RO concentrate. This can be achieved by a combination of sodium hydroxide and/or sodium bicarbonate (Na_2CO_3) to increase the pH [5] and increase the carbonate ion concentration, respectively, along with calcium carbonate seeding to accelerate the crystallization kinetics. The purpose of AMSP is to reduce the supersaturation level of mineral salts scalants in the primary RO feed or the primary RO concentrate as a pre-treatment prior to a secondary RO desalting stage. The AMSP treated stream is then filtered and further desalted in a secondary RO stage with the feed pH adjusted to acidic condition. Antiscalant makeup can also be added to reduce the potential for calcite scaling. The required percent of calcium removal by AMSP to achieve specified overall water recovery via the addition of a secondary RO desalting, is shown in Fig. 5. The analysis was carried out by requiring calcium removal such that the gypsum saturation index would be unity at the desired level of secondary RO recovery. The secondary RO recovery was set at the level needed to attain the desired overall recovery above the 54% recovery limit (due to gypsum scaling) attained in the primary RO desalting step. For example, to reach an overall recovery of 95% would require 90% calcium removal from the primary RO concentrate and secondary RO desalting at 75% recovery. It is noted that, the above analysis of the thermodynamic recovery limit is conservative since primary RO desalting can be carried out up to a product water recovery of about 80% via antiscalants dosing of the RO feed.

A preliminary evaluation of calcium removal by AMSP was carried out for model water solutions based on the composition of a high TDS water source from location OAS-2548 which was monitored on 3/22/2004 [1]. This particular source water was determined to have the highest saturation index with respect to gypsum (~0.99) when compared to other monitored groundwater locations in the SJ Valley [1]. A theoretical analysis of the percent of calcium removal from the above model solution via precipitation induced by NaOH and Na_2CO_3 was carried with the results depicted in Fig. 6. The source water listed in Table 3 is limited in terms of its carbonate concentration. Therefore, if one would only add NaOH to this RO feed, this will result in calcium carbonate precipitation up to the point where the carbonate ion has been exhausted.

Therefore, the addition of NaOH alone is insufficient and Na₂CO₃ addition is needed to increase the carbonate concentration. It is feasible to remove calcium as precipitate by a combination of NaOH and Na₂CO₃ dosing as shown in Fig. 6.

An initial experimental verification of the above analysis was carried out via batch equilibrium tests. Five AMSP runs were conducted for each AMSP condition in 50-mL capped vials immersed in a temperature-controlled water bath (20°C). Precipitation was induced with 1.4 g/L calcite seed loading and varying amounts of sodium carbonate. The precipitation reaction was allowed to proceed for a period of ~30 hours (to ensure that equilibrium was reached). At the termination of the AMPS treatment the solution was filtered through a 0.1-micron filter and the pH and calcium ion potential were measured with a calcium specific electrode (Orion 97-20 BN, Orion, Beverly, MA). The experimental precipitation results (expressed as calcium potential depletion) followed the theoretical calculations (Fig. 6), thus suggesting that the process is indeed feasible. The use of NaOH was previously demonstrated [5] for a water source of a similar TDS but lower saturation indices with respect to calcite and gypsum. Clearly, the combined use of NaOH and Na₂CO₃ would have to be optimized based on cost and this would be assessed in the second phase of the study. Although the above precipitation experiments were carried out over a 30 hr period, steady-state was reached over a much shorter period as verified based on a simple kinetic precipitation test. The precipitation test was carried out using 500-mL of the model solution in a 600 mL a magnetically-stirred beaker. Precipitation was induced by dispersing a charge of calcite seeds, followed by the addition of a predetermined amount of 1-M sodium carbonate stock solution. Precipitation kinetics was followed by continuous monitoring of both pH and calcium ion potential until steady was reached. The results (Fig. 7) illustrate that the removal of calcium (in the form of precipitate of calcium carbonate and calcium sulfate) in this open system was accompanied by a decrease in pH (also due to absorption of atmospheric carbon dioxide). It is noted that the steady-state removal, which was approached within a reasonable period of ~ 15 minutes, was closely predicted by the equilibrium prediction.

INCREASING PRODUCT WATER RECOVERY via ACCELERATED MINERAL SALT PRECIPITATION TREATMENT OF RO FEED

Two-Step Membrane Desalting with an Interstage Accelerated Mineral Salt Precipitation

High product water recovery is feasible via a two-step membrane desalting process. The conceptual system configuration is shown in Fig. 8. The feed is pre-treated by microfiltration and the pH is adjusted to suppress calcite scaling. A primary RO desalting step is then applied (with about 3 ppm antiscalants feed dosage) to achieve a recovery level of about 80%. Subsequently, calcium removal is achieved by accelerated mineral salt precipitation in a crystallizer reactor. After a subsequent filtration step to remove the mineral salt precipitate, the treated primary RO concentrate is desalted in a second RO step (with feed pH adjustment and antiscalant addition) to achieve the desired overall recovery with permeate quality of 750 mg/L total dissolved solids (TDS) or better.

Economic evaluation of water desalting was carried out for the two-step process (Fig. 4) considering overall recovery levels ranging from 80% to 95%. The analysis was carried out for the water source composition of Table 1 which is typical of the composition of SJ Valley brackish groundwater. The cost analysis was based on a desalination plant that would process 5x10⁶ gallons/day feed water (5 MGD). Process simulations and costing analysis were carried out using the two interfaced membrane process simulators RO-PRO and Cost-PRO [7] with the membranes TF C-UPL, TFC-HR and TFC-XR considered in various stages of the primary and secondary RO desalting process. Equipment costs for membrane modules, pumps, piping, filters, crystallizer and control equipment were assessed based on information provided from various equipment manufacturers. Operational cost included membrane replacement based on a four year cycle, membrane cleaning, chemical additives, energy and maintenance. Energy

cost was determined based on pumping costs and bulk rate cost of chemical additives (e.g., NaOH, Na₂CO₃, HCl, H₂SO₄, and antiscalants) was obtained from their respective manufacturers.

For all cases considered the primary RO recovery was set at 80% (Tables 4-7). The capital cost was dominated by the primary RO step since it involved processing of 80% of the feed (Tables 4). The capital cost for the accelerated mineral salt precipitation step was about 30% of the total operating cost. The secondary RO step, which increased with overall product water recovery, was about 14%-23% of the total operating cost (Table 5). The capital cost associated with the AMSP was independent of the overall recovery since the volume of treated primary RO concentrate was identical for all three process configurations. The contribution of capital cost to the overall water production cost was 9%-11% (Tables 4 and 5). In the absence of interest charges the overall water production cost ranged from \$185/acre-ft to \$319/acre-ft with increased product water recovery from 80% to 95%, respectively (Table 5). The operating cost for AMSP increased by 12% as the overall recovery was increased from 90% to 95%, owing to the increase in chemical cost needed for greater removal of calcium from the primary RO concentrate (Table 6). The primary RO step represented the dominant cost of about 56%-60% of the total operating cost. Finance charges were estimated based on a 15 year amortization of the capital cost of the plant at an annual interest rate of 5.75 % (Table 7). The overall product water cost increased by about 6% when interest charges were included resulting in an overall water production cost of \$0.59-\$1.04 per kgal (equivalent to \$195-\$340 per acre-ft). It is interesting to note that the cost seawater (~\$2-\$3) is about a factor of 2-5 higher than the estimated cost of desalination of SJ Valley brackish water.

The present analysis suggests that the integration of membrane RO desalination and accelerated mineral salt precipitation for high recovery desalting is technically and economically feasible. The integrated desalination process consists of a primary RO step, followed by accelerated mineral salt precipitation treatment of the primary RO concentrate and subsequently a secondary RO desalting step. The second phase of the project will extend the present analysis by considering a range of SJ Valley brackish groundwater with the highest scaling potential. Alternate process configurations will be considered to explore means of lowering the overall water desalination cost. In conjunction with the above analysis, diagnostic membrane RO scaling tests and AMSP tests will be conducted to verify the conclusions reached based on the present theoretical analysis of recovery limits.

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Table 1. Composition of Agricultural Drainage Water from Monitoring Station OAS-2548 in the San Joaquin Valley.

Concentration (mg/L)	
Na ⁺	1,080
SO ₄ ²⁻	2,340
TDS	3,828
Cl ⁻	468
Total Alkalinity	239
HCO ₃ ⁻	290
EC	5,610
Hardness	988
Ca ²⁺	224
Mg ²⁺	104
K ⁺	2.7
B	9.3
Ba ²⁺	0.25
Se	0.061
pH	7.1
Temp, °C	21
Gypsum SI	0.41
Calcite SI	6.3
Barite SI	41

^(a) DWR San Joaquin Valley Drainage Monitoring Program Database [1]. Sample Location: OAS-2548, Sampling Date: 9/9/2003. SI – saturation index, TDS – total dissolved solids (mg/L).

Table 2. Summary of RO Product Water Recovery Limits for Primary RO Desalting of San Joaquin Valley Source Water from Location OAS-2548.

Percent Recovery Limit ^(a) due to Scaling		
Mineral Salt Scalant		
pH	Gypsum	Calcite
7.1	54%	~ 0%
6	53%	90%
Limiting Recovery Due to Osmotic Pressure (pH=6)		
Osmotic Pressure (psi)	Limiting Recovery Due to Osmotic Pressure (pH=6)	
200	84.6%	
250	87.9%	
300	90%	
600	95.1%	

(a) The limiting recoveries are set at SI = 1. All calculations were performed at 20 °C and 200 psia. (b) The limiting recoveries for osmotic pressure were calculated at pH=6 as adjusted with the addition of HCl.

Table 3. Composition of OAS-2548 source water based on 3/22/04 monitoring [1] and corresponding model solutions (a)

3/22/04 OAS-2548 Water Source		Model Solution ^(b)	
Ions	Concentration (mg/L)		Concentration (mM)
Sodium	2,379	Na ₂ SO ₄	49.28
Barium	0.5	MgSO ₄ ·7H ₂ O	9.15
Calcium	454	CaCl ₂ ·2H ₂ O	11.29
Potassium	10	NaNO ₃	0.73
Magnesium	223	NaHCO ₃	2.91
Sulfate	5,630	pH	7.8
Chloride	847	SI _{Gypsum}	0.99
Nitrate	45	SI _{Calcite}	3.98
Bicarbonate	178		
TDS	9,703		

(a) Reconciled at 20°C (b) pH adjusted with HCl

Table 4. Capital Cost for Brackish Water Desalination^(a)

Percent Product Water Recovery		Capital Cost (\$)			
Secondary RO	Percent Overall Recovery	Primary RO	AMSP	Secondary RO	Total Capital Cost
0%	80%	\$1,390,000	\$0	\$0	\$1,390,000
50%	90%	\$1,390,000	\$170,000	\$165,000	\$1,725,000
75%	95%	\$1,390,000	\$170,000	\$685,000	\$2,245,000

^(a) Based on 5 MGD water feed. Primary RO is carried out at 80% recovery.

Figure 5. Estimated Cost of Brackish Water Desalination by integrated RO and accelerated mineral salt precipitation at various levels of overall product water recovery^(a)

Water Recovery			Total Capital Cost (\$)	Cost of Water Production (\$/kgal)			\$/ Acre-ft
Primary RO	Secondary RO	Overall Recovery		Capital Cost	Operating Cost	Total Cost	
0.8	0	80	\$1,390,000	\$0.063	\$0.50	\$0.56	\$185
0.8	0.5	90	\$1,725,000	\$0.070	\$0.80	\$0.87	\$284
0.8	0.75	95	\$2,245,000	\$0.086	\$0.89	\$0.98	\$319

(a) Based on 5 MGD feed. Cost per 100 gallons or acre-ft s on the basis of total permeate produced. Note: Cost values expressed per kgal were rounded to two significant digits.

Table 6. Operating Cost for RO Desalting

Percent Product Water Recovery		Operating Cost (\$/kgal)			
Secondary RO	Overall	Primary RO ^(a)	AMSP ^(b)	Secondary RO ^(c)	Total ^(d)
0%	80%	\$0.50	\$0	\$0	\$0.50
50%	90%	\$0.50 (\$0.45)	\$1.09 (\$0.24)	\$1.01 (\$0.11)	\$0.80
75%	95%	\$0.50 (\$0.42)	\$1.22 (\$0.26)	\$1.33 (\$0.21)	\$0.89

(b) Cost per water permeate produced in the primary RO step. ^(b) Cost per kgal of primary RO concentrate treated. The cost in parenthesis is per kgal of total product water produced. ^(c) Cost per kgal of secondary permeate water product. ^(d) Cost per total kgal of product water permeate produced. Note: Cost values expressed per kgal were rounded to two significant digits.

Figure 7. Cost of water desalination including financial charges^(a)

Water Recovery			Total Capital Cost (\$)	Cost of Water Production (\$/kgal)			\$/ Acre-ft
Primary RO	Secondary RO	Overall Recovery		Capital Cost	Operating Cost	Total Cost	
0.8	0	80	\$2,073,427	\$0.09	\$0.50	\$0.59	\$195
0.8	0.5	90	\$2,588,054	\$0.12	\$0.80	\$0.92	\$300
0.8	0.75	95	\$3,348,807	\$0.15	\$0.89	\$1.04	\$340

(c) Based on 5 MGD feed. Cost per 100 gallons or acre-ft s on the basis of total permeate produced. Operating cost is as given in Table 4. Capital cost is amortized over 15 years at 5.75% interest rate. Note: Cost values expressed per kgal were rounded to two significant digits.

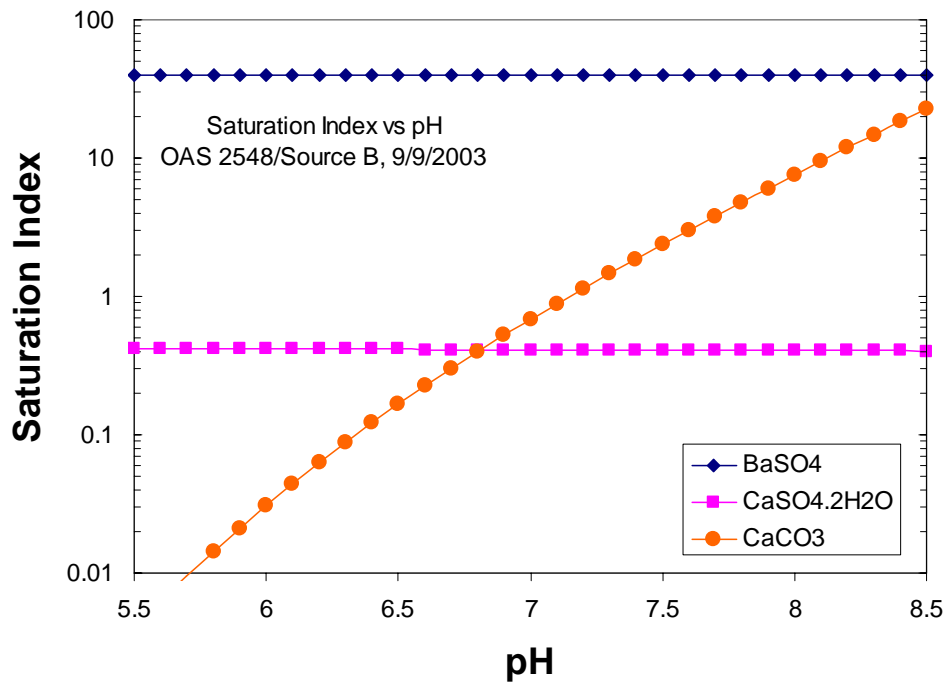


Figure 0. Saturation indices for calcite, gypsum and barite for the OAS-2548 source water (Table 1).

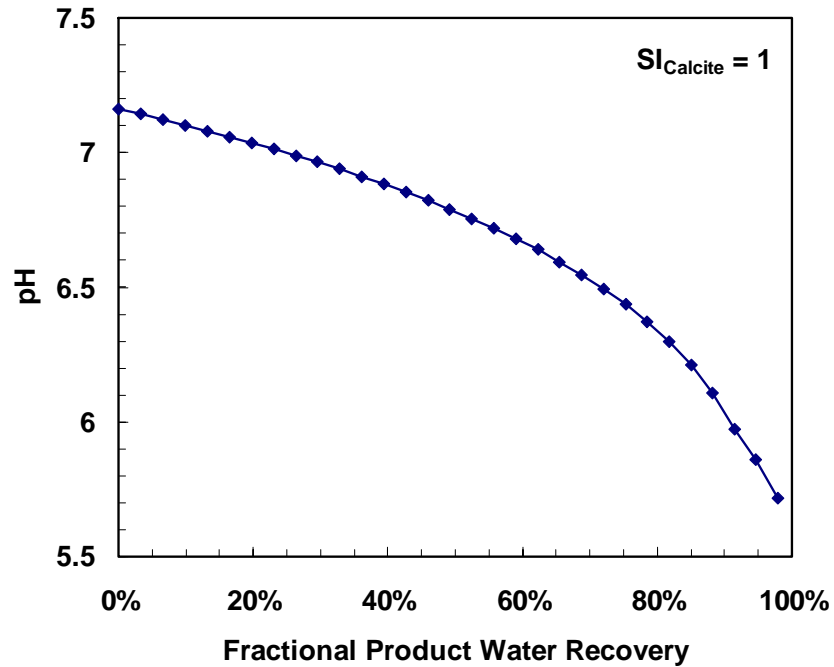


Figure 2. Feed pH adjustment at various product water recovery levels needed to keep the saturation index of calcite at unity for source water OAS-2548 (Table 1).

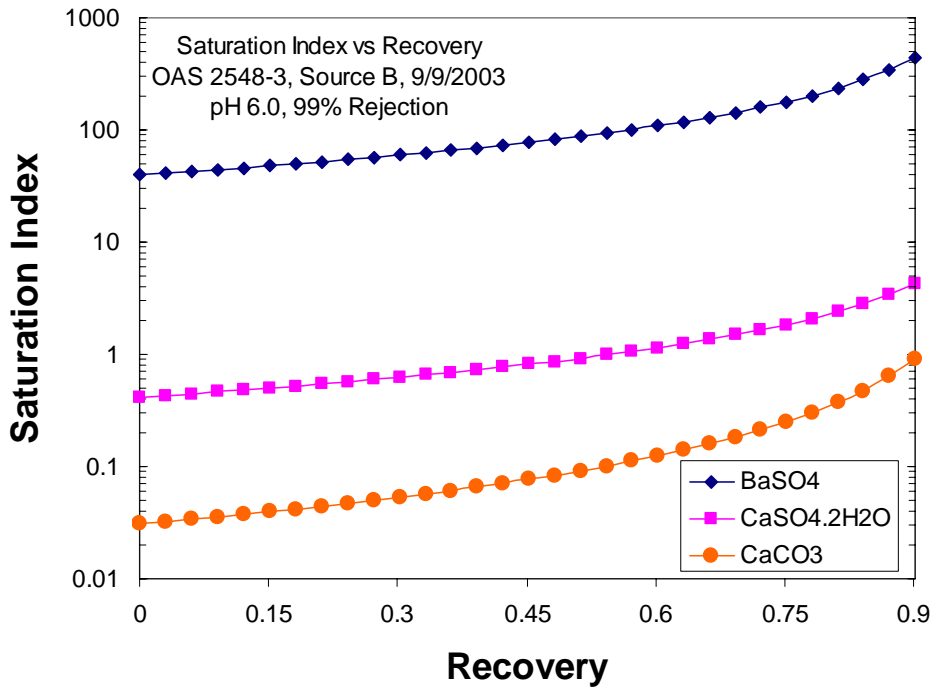


Figure 3. Dependence of mineral salt saturation indices on the level of product water recovery for membrane desalting (at 99% salt rejection and feed pH=6) of brackish groundwater from location OAS 25485 (Table 1).

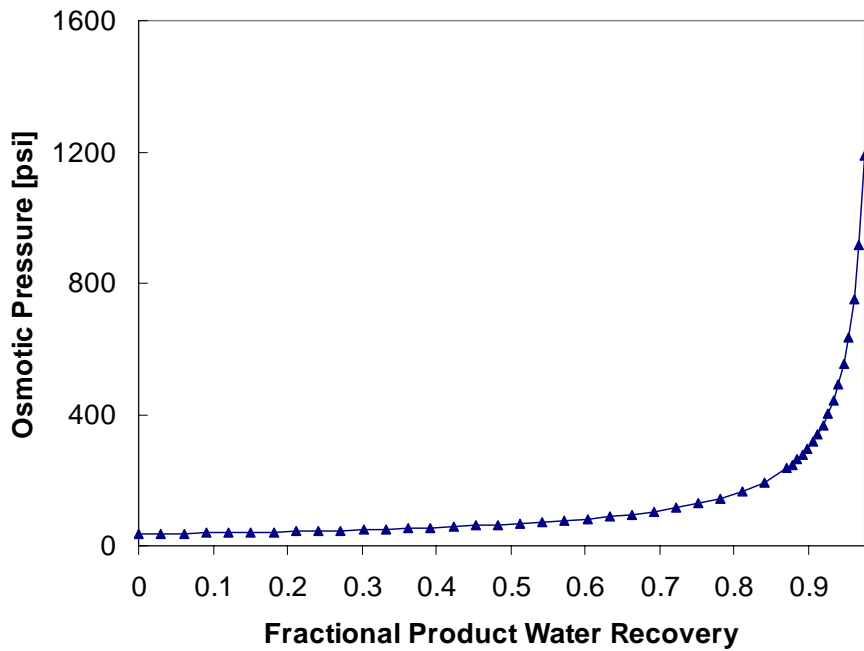


Figure 4. Variation of osmotic pressure of the RO retentate for Water source B (Table 1) produced from desalting at 99% rejection.

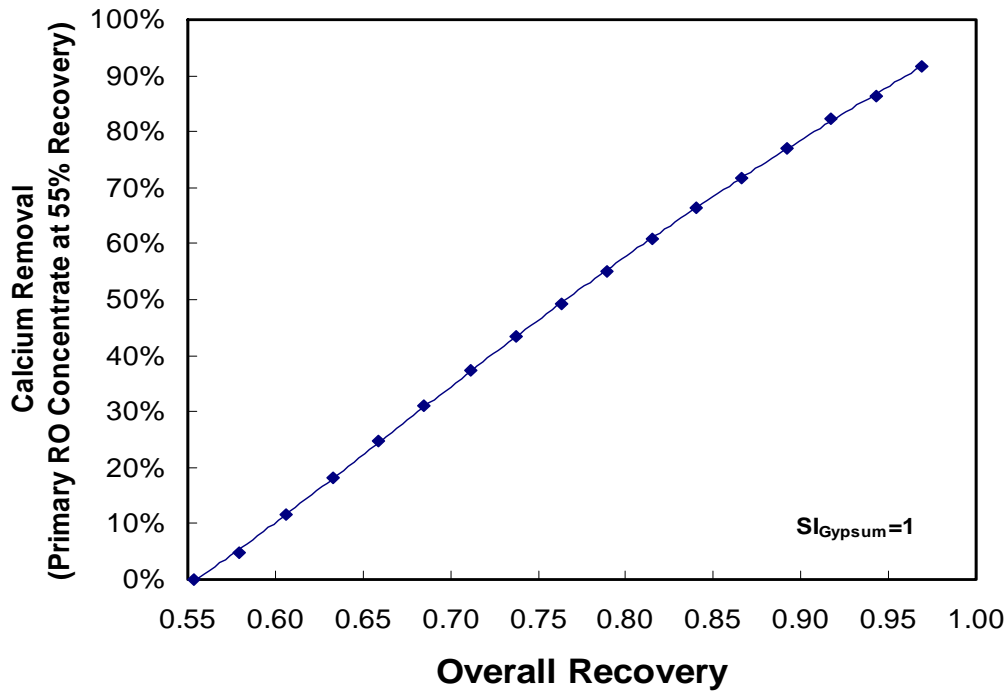


Figure 5. Required percent of calcium removal from primary RO concentrate of source water OAS-2548 (produced from desalting at 99% salt rejection and 51% recovery) required to keep the saturation index of gypsum at saturation (i.e., saturation index of unity).

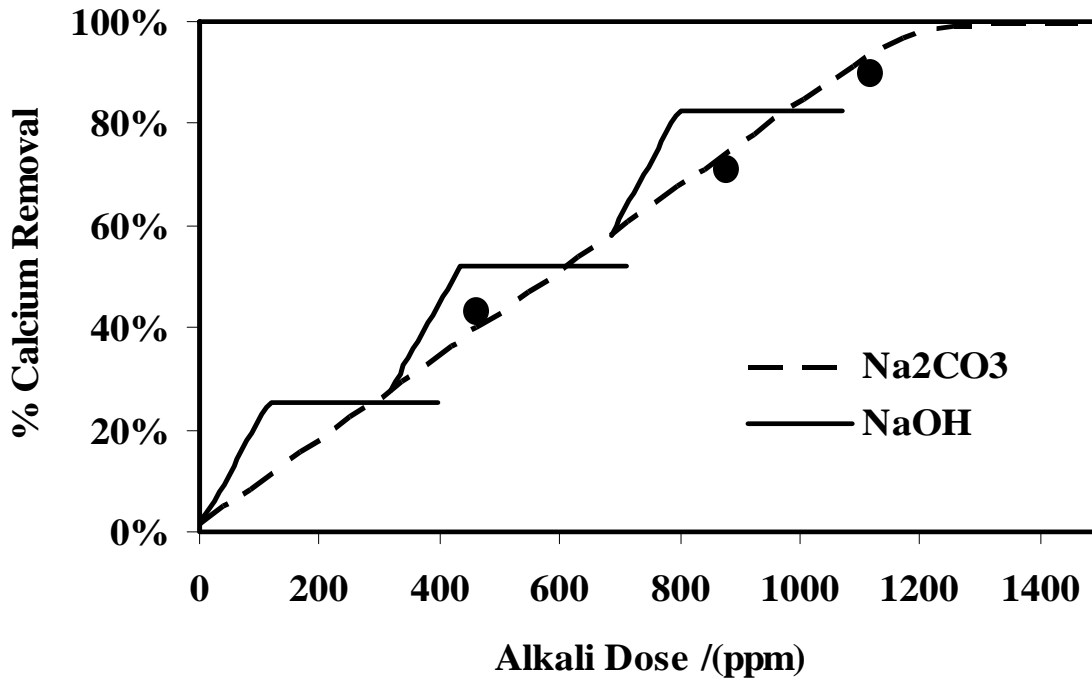


Figure 6. Theoretical equilibrium analysis of calcium removal by accelerated mineral salt precipitation for a model solution (Table 3) with a high scaling potential.

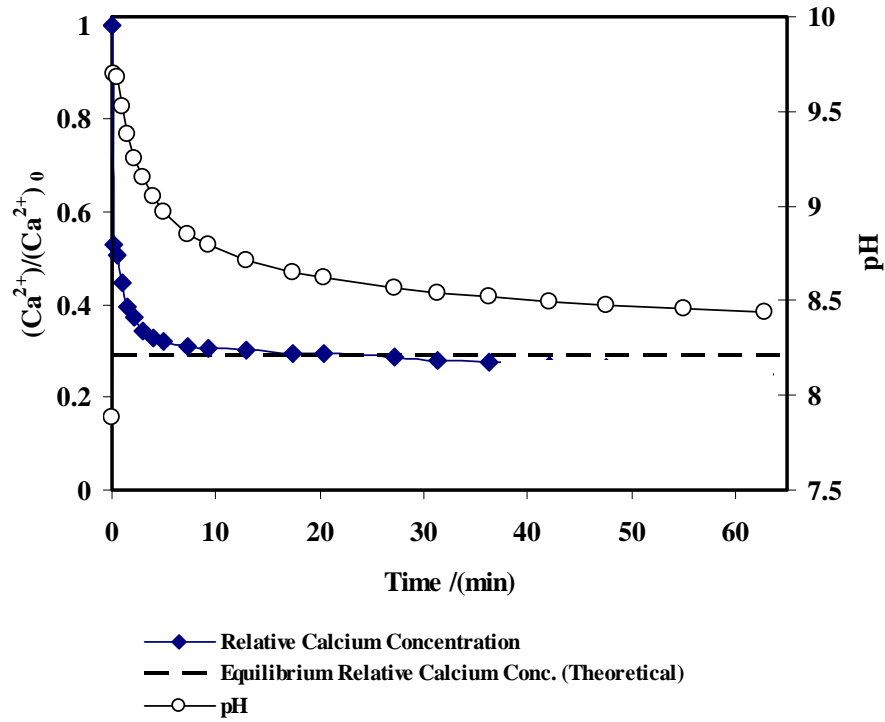


Figure 7. Kinetics of accelerated precipitation of a high scaling potential model solution (Table 3). Precipitation was initiated with 841 mg/L Na₂CO₃ and 1.4 g/L calcite seed load.

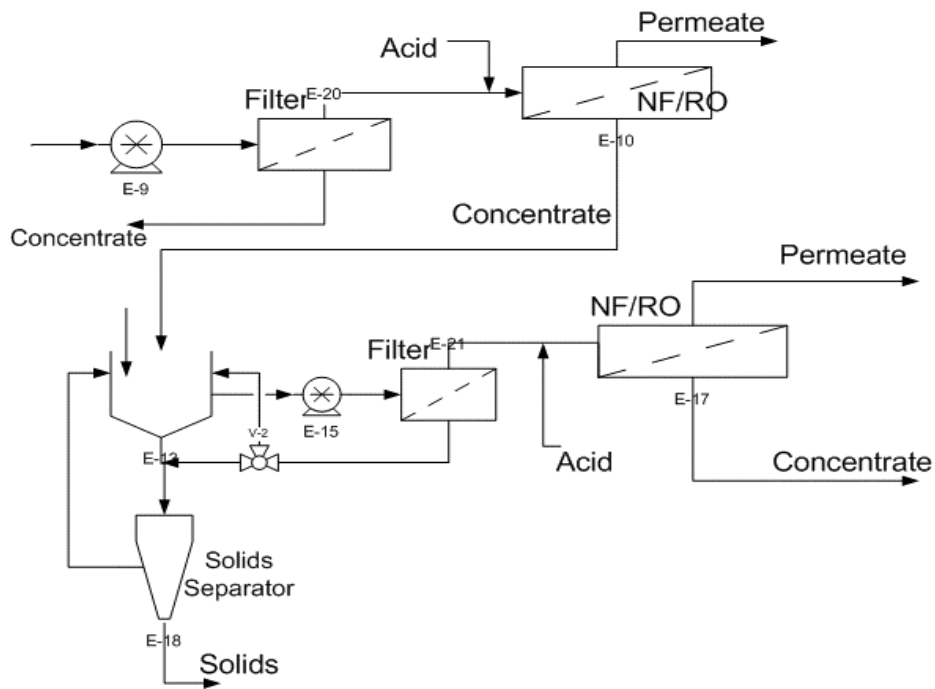


Figure 8. Two-step high recovery RO desalination – Integration of accelerated mineral salt precipitation.