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Authors

Wright, William F

Longley, Karl E

Mizuno, Walter K

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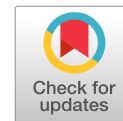
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Production of Agricultural Water and Nutrients from Brackish Water Sources

William F. Wright, Ph.D., P.E.¹; Karl E. Longley, Sc.D., P.E., M.ASCE²;
Walter K. Mizuno³; Sankha Banerjee, Ph.D.⁴; Mike Waite⁵;
William Stringfellow, Ph.D.⁶; and Pei Xu, Ph.D.⁷

Abstract: Arid agricultural regions worldwide face critical challenges of water scarcity and soil salinization, significantly reducing crop production. This study investigates a circular economy and systems approach to desalination with nutrient recovery (DNR), economically producing irrigation-quality water while recovering valuable nutrients from brackish waters. A preliminary design tool for sizing the calcium (Ca) and magnesium (Mg) hardness ion removal component was developed through laboratory testing of the cation exchange (CIX) process. Key findings include (1) KCl and NaCl salts effectively regenerated the CIX resin, reducing and facilitating recovery of scale-causing Ca and Mg ions by greater than 99.5% to approximately 1 mg/L as CaCO₃. KCl benefits agriculture and the environment relative to traditional NaCl regenerant as K can be recovered, along with the Ca and Mg, and used locally as plant nutrients, reducing fertilizer production/importation and waste generation. (2) The amount of regenerant used correlated with reductions in product water hardness (leakage) and increases in hardness-removal capacity (HRC), with HRC approaching 82 g-CaCO₃/L-resin per process cycle for KCl; (3) regenerant solution salt concentration had minimal impact on leakage and HRC, and high concentrations are advantageous, reducing brine byproduct volume and resin regeneration time; and (4) the feedwater salinity impact on HRC was small for up to 6 g/L dissolved solids, indicating that CIX is a viable option for softening moderately brackish waters. The DNR process will efficiently separate nutrients from phytotoxic NaCl, producing nutrients and water for irrigation, reducing water and fertilizer importation, brine waste, energy use and associated GHG emissions, resulting in more sustainable and reliable water and nutrient supplies. **DOI: 10.1061/JIDEH.IRENG-10528.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <https://creativecommons.org/licenses/by/4.0/>.*

Practical Applications: The achievement of sustainable agriculture in arid and semiarid agricultural regions worldwide requires advancements in water resources and salinity management strategies because these regions are increasingly experiencing water scarcity and higher source salinity, limiting agricultural production opportunities. Increased utilization of impaired water sources, such as brackish groundwater, agricultural drainage water, oil and gas produced water, and effluent from wastewater treatment processes is required to address the water shortage issue. This study investigates a circular economy and systems approach to desalination with nutrient recovery (DNR) that aims to economically separate plant nutrients in the source water from phytotoxic NaCl, producing nutrients and water suitable for irrigation. This approach reduces water and fertilizer importation and brine waste, thereby reducing energy use and associated greenhouse gas emissions and resulting in more sustainable and reliable water and nutrient supplies. Through laboratory testing of the hardness-removal cation exchange (CIX) process, a preliminary design tool for sizing the CIX component has been developed. Results from ongoing studies of other DNR system components will be reported in the future. The efficient use and reuse of local water and nutrient resources is necessary to achieve sustainable water and nutrient management in drought-challenged regions of the world.

Author keywords: Agriculture; Aridification; Circular economy; Desalination; Ion exchange; Irrigation; Nutrient recovery; Salinity; Water scarcity; Water softening.

¹Professor, Dept. of Civil and Geomatics Engineering, Lyles College of Engineering, California State Univ., Fresno, 2320 East San Ramon, MS EE94, Fresno, CA 93740 (corresponding author). ORCID: <https://orcid.org/0009-0001-9044-5294>. Email: wfwright@csufresno.edu

²Research Engineer, Center for Irrigation Technology, California State Univ., Fresno, 5370 N. Chestnut Ave., Fresno, CA 93740. Email: karll@mail.fresnostate.edu

³Director of the Center for Engineering Innovation and Design, Lyles College of Engineering, 2320 East San Ramon, MS EE94, Fresno, CA 93740. ORCID: <https://orcid.org/0009-0008-4827-5923>. Email: walterm@mail.fresnostate.edu

⁴Professor, Dept. of Mechanical Engineering, Lyles College of Engineering, 2320 East San Ramon, MS EE94, Fresno, CA 93740. Email: sankhab@csufresno.edu

⁵Chief Executive Officer, Agua DB Ltd., Cirencester GL6 7AD, UK. Email: mike.waite@aguadb.com

⁶Senior Scientist, Stringfellow and Associates, 525 South Eliseo Dr., Greenbrae, CA 94904. Email: williamstringfellowassociates@gmail.com

⁷Professor, Dept. of Civil Engineering, New Mexico State Univ., Las Cruces, NM 88003; Research Director of New Mexico Produced Water Research Consortium, Las Cruces, NM 88003-0001. ORCID: <https://orcid.org/0000-0002-4053-9495>. Email: pxu@nmsu.edu

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Introduction

Achieving sustainable agriculture in California's Central Valley (Central Valley) and arid and semiarid regions globally requires advancements in salinity management strategy, salt extraction technology, and sustainable supplies of fresh water and crop nutrients. These regions are increasingly experiencing water scarcity and higher source salinity due to climate change and population growth, limiting agricultural production opportunities (Nicolas et al. 2023; Roy et al. 2012; Stanton et al. 2017). Water scarcity and soil salinization diminish agricultural yields and profitability in arid regions. The Central Valley, renowned as one of the world's most productive agricultural regions, has an estimated 6.5 million residents. The ongoing population growth intensifies the competition for water resources. Existing groundwater supplies are diminishing in quantity and quality, and surface water is highly allocated. Unfortunately, the prevalence of elevated concentrations of salts and toxic substances renders numerous groundwater sources unsuitable for irrigating crops and unpalatable for consumption by humans, livestock, and wildlife. The saline water not only compromises soil quality, making it unsuitable for cultivating most commercial crops, but also, in some instances, necessitates the removal of land from beneficial use. The economic loss of excessive salinity in many of the Central Valley's water supplies was described by Howitt and coworkers as possibly exceeding \$1.5 billion per year by the year 2030 unless effective salinity management measures are implemented (Howitt et al. 2009). The cost of soil salinization statewide in California was estimated to be between \$1.7 and \$7 billion dollars in 2014 (Welle and Mauter 2017). Public and private stakeholders are developing plans to mitigate increasing salinity and nitrate levels as part of a long-term management strategy (CV-SALTS 2016; Kuriger et al. 2017). This challenging scenario is not unique to California, as similar salinity conditions are encountered in other regions of the Southwestern United States (US) and elsewhere throughout the world (Suvendran et al. 2024).

Optimizing local water and nutrient resource utilization through innovative treatment technologies is essential for addressing water scarcity and salinity management challenges. While impaired water sources such as brackish groundwater, agricultural drainage water, oil and gas produced water, and effluent from wastewater treatment processes could help meet demand, their high salt content limits their use in agriculture. Recent technological advancements enable the treatment of nontraditional water sources to irrigation standards at a cost that can be sustainable where fresh water is scarce (Edirisooriya et al. 2024; Thu et al. 2023). Implementation of distributed water desalination systems to mitigate the effects of drought, soil salinization, and negative ecological impacts of agricultural drainage in the Central Valley has been proposed by Welle et al. (2017). However, the authors estimated that desalination treatment is likely to be profitable in only 4% of the locations during periods of severe drought. Salt removal processes are expensive,

and the problem is compounded by the Central Valley having limited salt disposal options. Welle and coworkers estimated that that treatment costs would need to be reduced by 70%–90% for desalination to be adopted “on the median acre” (Welle et al. 2017).

Conventional approaches to desalination treatment use membrane or thermal processes with upstream pretreatment, as shown in Fig. 1. Reverse osmosis (RO), a pressure-driven membrane-based process, is the most common desalination technology for low-to-moderately saline waters, and thermal processes are used for highly saline waters (Buvaneshwari et al. 2020; Dong et al. 2018; Longley et al. 2020; Thu et al. 2023; Xu et al. 2022). Power consumption by the RO unit and disposal of the waste brine byproducts are responsible for most of the costs of desalination in inland locations (Lugo et al. 2023; Tong et al. 2025; Thu et al. 2023; Xu et al. 2022). Operation, maintenance, and consumables represent most of the remaining costs. Extensive research of technologies and approaches that can reduce the cost of treating inland brackish waters is needed for widespread utilization of impaired water sources.

Pretreatment is required before membrane and thermal desalination processes (Fig. 1) to protect these processes from fouling, scaling, and plugging. Common pretreatments before desalination processes include sediment removal by filtration, trace organic compound removal by activated carbon adsorption, and scale formation potential reduction by pH reduction, antiscaling chemical addition, or cation exchange (CIX). The CIX process is typically used to remove calcium (Ca^{2+}) and magnesium (Mg^{2+}) hardness ions that form mineral deposits (scaling) on membrane and heat exchanger surfaces if not removed upstream of those processes (Flodman and Dvorak 2012; Mejía-Saucedo et al. 2025; Thu et al. 2023). The accumulation of Ca and Mg minerals on RO membranes results in a corresponding loss in process efficiency and an increase in operation costs (Logsdon et al. 1990; Lugo et al. 2025; Smith and Sengupta 2015; Thu et al. 2023). The collection and concentration of Ca and Mg by CIX as a pretreatment before RO presents an opportunity to recover these elements for beneficial use. The efficient recovery of these constituents for local use in fertigation makes sense from the perspectives of water and nutrient management and long-term sustainability of agricultural operations.

To address many of these needs, an innovative circular economy and systems approach to desalination with nutrient recovery (DNR) is being developed to expand the range of water sources that can be utilized and to reduce water and fertilizer importation and brine waste. Energy use and associated greenhouse gas (GHG) emissions will also be reduced, resulting in more sustainable and reliable water and nutrient supplies. The efficient use and reuse of local water and nutrient resources results in a circular economy that is necessary to achieve sustainable water and nutrient management in drought-challenged regions of the U.S. and globally.

The objective of the broader, long-term project is to demonstrate that water suitable for irrigation and other beneficial uses

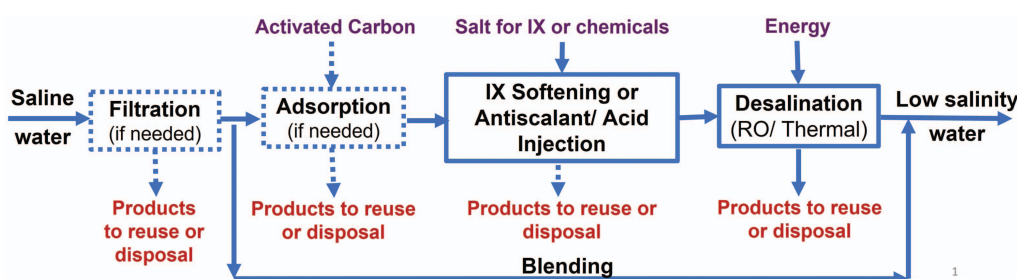


Fig. 1. (Color) Conventional desalination process flow diagram. IX = ion exchange; and RO = reverse osmosis.

and valuable salts, including crop nutrients, can be efficiently produced from brackish water with net costs being lower than those of conventional desalination approaches that do not recover valuable constituents to offset operation and byproduct disposal costs. Initial research efforts have focused on establishing baseline performance characteristics of the CIX component of the DNR system and optimization of the process for nutrient recovery. Lab-scale columns were used to treat water that had the same dominant ion concentrations as agricultural drainage water sampled on the west side of the Central Valley in 2016. CIX is a proven technology for removing Ca and Mg hardness ions (Logsdon et al. 1990; Thu et al. 2023; USEPA 2024). Thu et al. (2023) provide a good review of research conducted on CIX treatment of brackish waters; however, the available literature is limited, particularly for agricultural drainage water. CIX test results are presented here along with a design tool for estimating process parameter values for full-scale brackish water softening units. Additional results from the CIX optimization study and results from ongoing studies of other DNR system components will be reported in the future.

Materials and Methods

Economical Desalination with Nutrient Recovery Concept Development

Literature on commercially available water treatment technology and methodology was reviewed to establish the universe of proven water treatment options that could be used to develop a DNR conceptual model that maximized benefits (i.e., valuable products) and minimized overall costs.

The proposed multistage DNR process is presented in Fig. 2. Particulate matter filtration and granular activated carbon adsorption components remove sediment and dissolved organic matter; an electrodialysis reversal component removes sodium (Na) and chloride (Cl) ions; a CIX component removes Ca and Mg hardness ions; an anion exchange (AIX) component removes nitrate (NO_3), sulfate (SO_4), and bicarbonate (HCO_3) ions; and a RO component separates the remaining constituents from the water. Investigation of a process for separating Na from K in the final step is ongoing.

The separated K ions with Cl ions are recovered and used to partially regenerate the CIX resin, thereby shifting the conventional approach toward a more sustainable process by reducing the need for imported salt and reducing the amount of salt waste generated.

Nitrate in the water source is *harvested* as a usable fertilizer using the DNR process. This transforms the *nitrate time bomb* into a sustainable nitrate source thereby reducing or eliminating the need to import nitrate produced by the Haber Bosch process. Consequently, the associated energy and GHG emissions from manufacture and transport to the farm are reduced. In addition, the DNR approach innovatively uses nonconventional salts to regenerate the ion exchange resin that have beneficial uses rather than the conventional phytotoxic NaCl. Either potassium chloride (KCl) or potassium nitrate (KNO_3) is used to regenerate the CIX resin, and KCl is used to regenerate the AIX resin, producing nutrient-rich byproducts that include potassium nitrate (KNO_3) and potassium sulfate (K_2SO_4) that can be applied through drip irrigation as part of a fertigation program without additional processing. This reduces the amount of waste generated, the dependence on imported fertilizer, and the carbon footprint of the process. There is further potential when the CIX stage is regenerated with KNO_3 to recover Ca and Mg as nitrate salts to admix with the products from the AIX stage, managing the nutrient balance of the products.

Cation Exchange Component Testing

Bench-scale studies of the CIX water hardness-removal component of the DNR model were conducted. Two CIX test units were constructed and operated in parallel, receiving the same feedwater. One CIX test unit was regenerated with NaCl and the other with KCl brine solution. The test system piping and instrumentation diagram is shown in Fig. 3, and a photographic image of the upper part of one of the two test units is shown in Fig. 4. Design and operational parameter target values are provided in Table 1, and the feedwater chemical characteristic target values are summarized in Table 2.

A strong acid cation polystyrenic gel ion exchange resin from Purolite® (Shallow Shell™ SSTC60) was used in sodium (Na) and potassium (K) forms. The shallow shell resin was selected for its proven ion exchange performance (Thu et al. 2023) that exhibits fast exchange kinetics (Purolite 2018). The test column

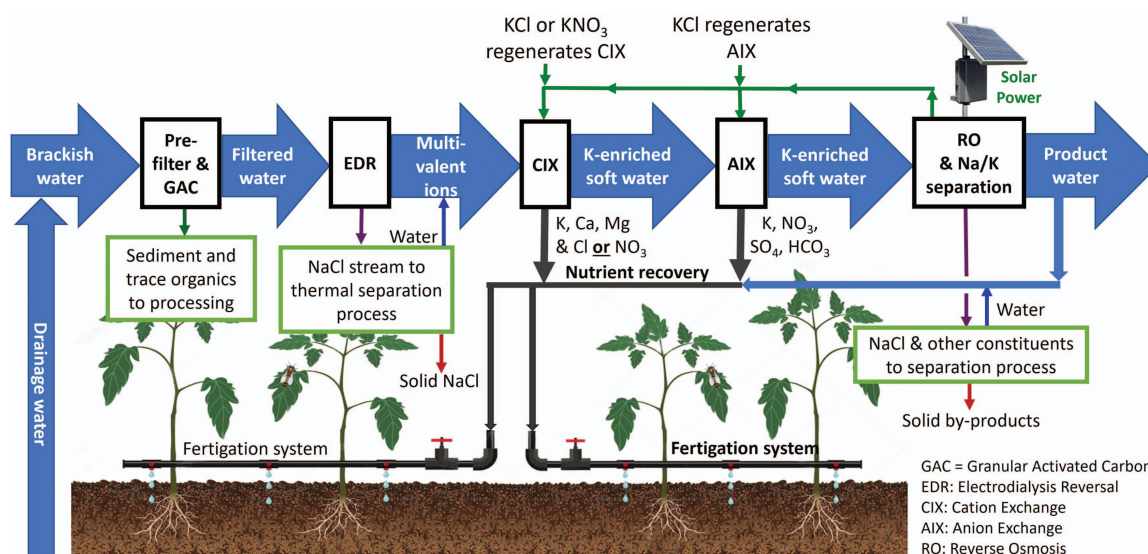


Fig. 2. (Color) Process flow diagram of the proposed innovative multistage desalination with nutrient recovery (DNR) process featuring the recovery of nutrients for fertigation in addition to the traditional water recovery capability. The CIX component is the focus of this study. Future studies will involve testing other treatment components and the integrated treatment train.

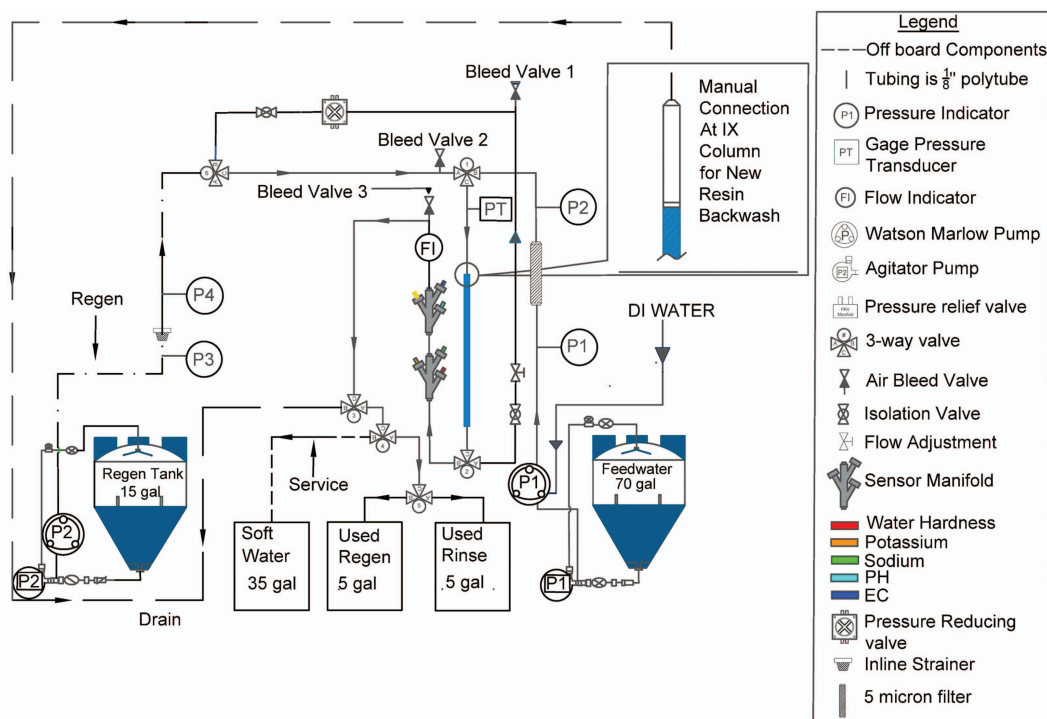


Fig. 3. (Color) CIX test system piping and instrumentation diagram.

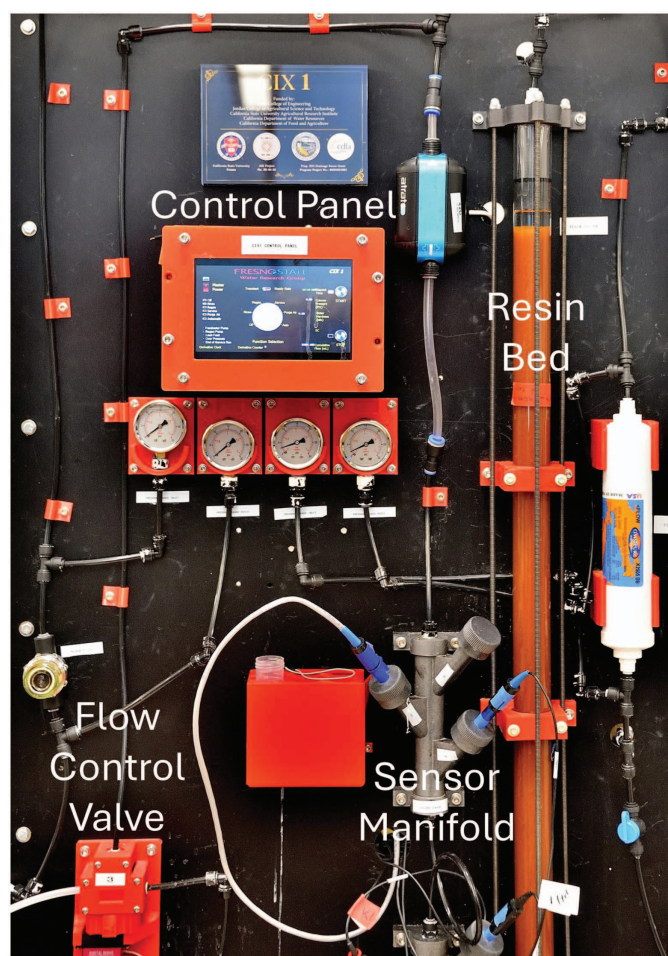


Fig. 4. (Color) Photographic image of the upper part of one of the two CIX test systems.

was made of borosilicate glass, and the resin bed dimensions (30 mm diameter $\times$ 80 cm depth) met the minimum requirements for obtaining meaningful test data that scale directly to full-scale design where mass transfer and operating exchange characteristics are similar and error due to channeling of the water down the walls of the column is minimized (Crittenden et al. 2012). The design and operation parameter target values used (Table 1) are within the recommended ranges published by Purolite (2018), except the slow and fast rinse steps were combined into one step and the rinse operation was terminated when electrical conductivity (EC) in the effluent dropped to 2.00 mS/cm rather than reaching a target volume or set time interval.

Feedwater and resin regeneration solutions were made in separate tanks using education grade or reagent grade salts (Thermo Fisher Scientific) and deionized water (Evoqua PURELAB Ultra Genetic). The solutions were delivered to the CIX columns using variable speed peristaltic pumps (Watson Marlow 323Du Drive with 314D Pumphead and Watson Marlow 120U/DV, respectively). The CIX test columns and solution supply tanks were housed in a temperature-controlled environment. The influent flow was measured by a calibrated ultrasonic flowmeter (Atrato 710-E-0-1-SA). Water quality was measured using sensors and grab samples as indicated in Table 3. Water hardness was measured four times per minute with a double-junction ion-selective probe (Cole-Parmer EX27077-18) connected to a Jenway 3510 signal processor (Cole-Parmer EW-35459-03), and sensor data were collected by a DATAQ Instruments DI-710 data acquisition system. Data from the DATAQ DI-710 were transmitted to a computer over an Ethernet connection and recorded using the WinDaq software. Grab sample water hardness concentration was measured using Hach Method 8030 (<4 mg CaCO_3/L) and Method 8226 (>4 mg CaCO_3/L) and also calculated based on Ca and Mg concentrations measured using microwave plasma emission spectroscopy (Agilent Model 4100) or gallery discrete analyzer (Thermo Fisher Scientific Gallery Plus 2). Only hardness values are reported in this paper.

Table 1. CIX test design and operation parameter target values

Parameter	Units	Value
Contactor dimensions:		
Height	cm	150
Inner diameter	cm	3.0
Area, cross section	cm ²	7.1
Resin bed dimensions:		
Depth after stratification ^a	cm	80
Volume	cm ³	570
Feed:		
Bed loading rate	BV/h ^b	10
	gpm/ft ³	1.3
Volumetric rate	L/h	5.7
Velocity (superficial)	m/h	8.0
Empty bed contact time	min	6.0
Backwash ^a :		
Water source	—	Deionized
Bed expansion	%	100
Duration—ramp-up	min	5
Duration—sustain	min	10
Duration—turn-down	min	5
Regeneration (coflow):		
Salt	—	NaCl or KCl
Water source	—	Deionized
Bed loading rate	BV/h	2.0
	gpm/ft ³	0.25
Volumetric rate	L/h	1.2
Velocity (superficial)	m/h	1.7
Duration ^c	min	Varied
Volume of regenerant ^c	L	Varied
Rinse:		
Water source	—	Deionized
Bed loading rate	BV/h	4.0
	gpm/ft ³	0.50
Volumetric rate	L/h	2.3
Velocity (superficial)	m/h	3.2
Duration ^d	min	Varied
Volume of rinse water ^d	L	Varied
Termination elec. cond.	mS/cm	2.0
Water temperature:	°C	20

^aBackwash was performed one time after new resin was loaded into the test column. During backwash, the resin bed was expanded 100% for 10 min, and then the flow was gradually reduced to zero over a 5-min period to stratify the bed.

^bBV = bed volume of water. 1 BV (bed volume) of water is equivalent to the volume of the resin bed. Water volume is expressed in (normalized to) BV units to facilitate comparison of results with other studies that use a different volume of resin.

^cDuration and volume of regenerant solution varied with the regenerant salt loading rate and concentration used in the test.

^dDuration and volume of rinse water was dependent on attainment of target EC value in the CIX unit effluent stream.

Test Unit Operation

The CIX process performance was quantified over feedwater salinity levels ranging from 1 to 6 g/L total dissolved solids (TDS) and resin regeneration salt loading rates ranging from 60 to 240 g NaCl or KCl salt per liter of resin per process cycle (nominal values). Regeneration solution salt concentrations ranged from 8% to 14% (w/w, nominal). Feedwater and regeneration flow directions were downwards (i.e., coflow regeneration). Regeneration solution salt concentration was varied while holding the regeneration salt loading rate constant and, in separate testing, the regeneration salt loading rate was varied while holding the regeneration solution salt concentration constant. Performance characteristics of the CIX resin were reported in terms of the operating hardness-removal capacity (HRC) and concentration of hardness in the product water (leakage). For each test condition, water production, resin regeneration, and rinse operation cycles were performed under nearly identical conditions and repeated until hardness leakage profiles stabilized, indicating attainment of a steady-state, long-term performance response.

Tool for Preliminary Design of Full-Scale Water Softening Units

An electronic spreadsheet program was developed that generates preliminary design data for sizing full-scale CIX treatment units. The program uses algorithms derived from CIX test results, if-and-then statements, and cell references. Additional details are provided in the Results and Discussion section of this paper.

Results and Discussion

Cation Exchange Performance Characterization

Results of the initial phase of CIX testing are presented below. The two CIX test units, one regenerated with NaCl and the other with KCl and operated in parallel, were subjected to 16 different operation conditions as described below. A minimum of four tests were conducted per operation condition to achieve a steady-state (repeatable) response from the CIX resin bed. The resin bed depth was 80 ± 0.5 cm (target 80 cm) immediately after new resin was added to the column and backwashed for the test data used in Figs. 7–12 and in the CIX design tool. The resin bed depth was 78.2 cm for a preliminary test that yielded the data presented in Figs. 5 and 6. Values for other key parameters are summarized in Table 4. In Table 4, global mean values for feedwater and regeneration solution flowrates and regeneration solution salt concentration were within 5% of the target values shown in Table 1 [10 and 2 bed volumes (BVs) per hour and 11%, respectively; see Table 1, footnote (b) for the definition of BV]. The rinse water flowrate was 13% below the target value of 4 BVs/h due to fluctuations in deionized water supply pressure. Feed, regeneration, and rinse water temperatures for the NaCl-regenerated test unit are summarized in Table 4.

Table 2. Feedwater chemical characteristic target values

TDS ^a	EC ^b	Ca ²⁺	Mg ²⁺	Total hardness	Na ⁺	SO ₄ ²⁻	Cl ⁻	HCO ₃ ⁻	NO ₃ ⁻	pH
(g/L)	(mS/cm)	(g/L)	(g/L)	(g/L CaCO ₃)	(meq/L)	(g/L)	(g/L)	(g/L)	(g/L)	
1.0	1.5	0.07	0.03	0.30	5.97	0.20	0.40	0.08	0.20	7.90
2.0	2.7	0.15	0.06	0.62	12.4	0.40	0.80	0.30	0.20	7.90
4.0	5.1	0.34	0.12	1.34	26.9	0.80	1.60	0.80	0.20	7.90
6.0	7.1	0.51	0.18	2.00	40.3	1.20	2.40	1.25	0.20	7.90

^aTDS = total dissolved solids concentration.

^bEC = electrical conductivity.

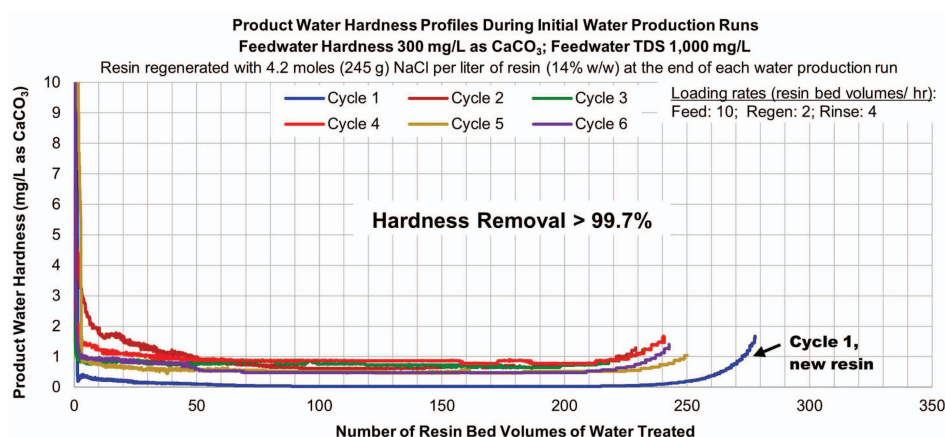
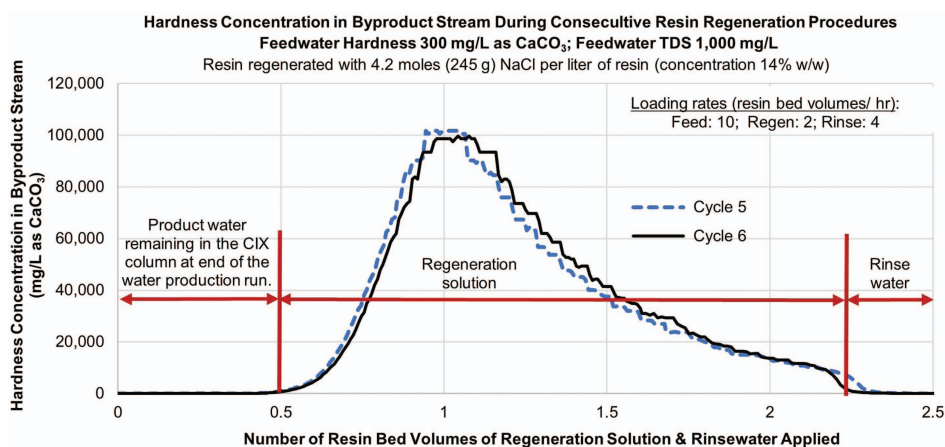
Table 3. Water quality parameters measured

Parameter	Sampling method ^a	Analytical method	Standard solution
Calcium	Grab	Colorimetric (Hach, GDA), MPAES	Thermo Scientific, 1 mg/mL Ca #195885000
Magnesium	Grab	Colorimetric (Hach, GDA), MPAES	Ricca, 1 mg/mL Mg, #AMG1KN100
Hardness	Sensor and grab	Colorimetric (Hach), ISE ^{a,b}	Ricca, 1 mg/mL CaCO ₃ , #178032
Sodium	Sensor and grab	ISE ^{a,b} , MPAES	Hach, 0.020 N Na ₂ CO ₃ , #18149
Potassium	Sensor and grab	Colorimetric (Hach, GDA), ISE ^{a,b} , MPAES	LabChem, 1 mg/mL K, #LC201001
Alkalinity	Grab	Colorimetric (GDA)	Hach, 0.020 N Na ₂ CO ₃ , #18149
Sulfate	Grab	Colorimetric (GDA)	Thermo Scientific, 1 mg/mL SO ₄ , #984727
Nitrate	Sensor and grab	Colorimetric (GDA), ISE ^{a,b}	Thermo Scientific, 1 mg/mL NO ₃ , #984724
Chloride	Sensor and grab	Colorimetric (GDA), ISE ^{a,b}	Thermo Scientific, 1 mg/mL Cl, #984721
Specific conduct	Sensor	Electrical conductivity probe ^c	Oakton, 1413 μ S, #EW-00653-18
Temperature	Sensor	Electrical conductivity probe	
pH	Sensor and grab	ISE ^{a,c}	Thermo Scientific, 4.0, 7.0, & 10.0, #910110

^aISE = ion selective electrode; MPAES = microwave plasma emission spectroscopy; and GDA = gallery discrete analyzer.

^bProbe voltage was recorded and subsequently converted to parameter units based on effluent grab sample water quality data and probe voltage recorded at the time the grab samples were taken.

^cProbe was calibrated on the bench with standard reference solutions.

**Fig. 5.** (Color) Product water hardness concentration (leakage) during the first six soft water production runs.**Fig. 6.** (Color) Water hardness concentration in the CIX process byproduct stream during consecutive resin regeneration procedures when at steady state.

Temperature data for five operating conditions of the KCl-regenerated test unit were collected and the values were similar to that of the NaCl-regenerated test unit (data not shown). Water temperatures were controlled between 19.4°C and 23.7°C for the first 13 test operating conditions and then began fluctuating outside of this range for the last three test operating conditions

(see Table 4) due to a failure of the building temperature-control system.

The NaCl-regenerated CIX unit's transient and steady-state responses to feedwater with a hardness concentration near 0.30 g CaCO₃/L and TDS concentration near 1 g/L are shown in Fig. 5. Average hardness leakage during the first water production run

Table 4. Key operating parameter values (see also data in the narrative and figures)

Parameter	Stream	Test condition	Units	Average value per steady-state run			
				Range	Global mean ^a	Max COV ^b	Count
Flowrate	Feed	All	BVs/h	9.4–10.4	9.8	10.0%	32
	Regen.	All	BVs/h	1.6–2.3	2.1	27.6%	32
	Rinse	All	BVs/h	2.3–5.1	3.5	68.3%	32
Temperature	Feed	All NaCl-regeneration tests except the specific tests shown below	°C	19.4–23.5	21.7	5.6%	13
	Regen.	All NaCl-regeneration tests except the specific tests shown below	°C	19.6–23.6	21.5	2.1%	13
	Rinse	All NaCl-regeneration tests except the specific tests shown below	°C	20.0–23.7	21.6	1.4%	13
		Specific NaCl-regeneration tests—temperature not controlled			Mean	COV	
	Feed	4 g TDS/L feed; 60 g salt/L resin regen	°C	16.2–18.5	17.8	2.8%	>820
		6 g TDS/L feed; 60 g salt/L resin regen	°C	23.9–28.5	26.4	4.9%	>600
		6 g TDS/L feed; 120 g salt/L resin regen	°C	23.6–25.7	25.2	1.9%	>730
	Regen.	4 g TDS/L feed; 60 g salt/L resin regen	°C	15.6–15.8	15.7	0.3%	>54
		6 g TDS/L feed; 60 g salt/L resin regen	°C	24.0–24.2	24.1	0.4%	>55
		6 g TDS/L feed; 120 g salt/L resin regen	°C	23.4–23.5	23.5	0.2%	>110
	Rinse	4 g TDS/L feed; 60 g salt/L resin regen	°C	15.8–16.6	16.1	2.0%	>52
		6 g TDS/L feed; 60 g salt/L resin regen	°C	24.0–24.6	24.4	0.7%	>47
		6 g TDS/L feed; 120 g salt/L resin regen	°C	23.5–24.2	23.8	1.2%	>50
Hardness	Feed	1,000 mg/L nominal feed TDS	mg/L CaCO ₃	288–301	296	1.7%	5
Conc.		2,000 mg/L nominal feed TDS	mg/L CaCO ₄	596–634	621	2.4%	5
		4,000 mg/L nominal feed TDS	mg/L CaCO ₅	1,350–1,375	1,365	1.0%	3
		6,000 mg/L nominal feed TDS	mg/L CaCO ₆	1,985–2,010	2,000	0.7%	3
Salt conc.	Regen.	All tests that used 11% concentration	% by weight	10.6–12.1	11.2	4.2%	24

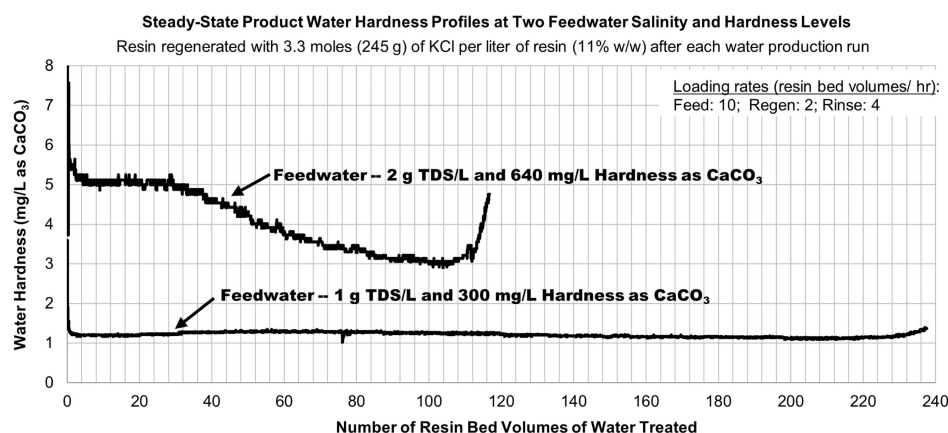
^aMean of the set of test average values.^bCoefficient of variation (COV) = standard deviation divided by the mean.

with new resin was less than 0.2 mg/L as CaCO₃ (Fig. 5, Cycle 1). Hardness in the product water increased during the next run, approaching a steady-state value of approximately 0.8 mg/L as CaCO₃. Greater than 99.7% of feedwater hardness was removed. This test was repeated with a different batch of resin, and the average leakage value for that test was approximately 1.2 mg/L as CaCO₃ (99.6% removal). During each water production run, hardness leakage eventually began to increase, signaling the end of the run and the need to restore the resin's HRC with a regeneration procedure. This occurred after approximately 240 BVs of water were treated in the initial test (Fig. 5). Steady-state leakage values of the initial and repeated test were similar to the value predicted by a model that Flodman and Dvorak published in 2012 for CIX treatment of water containing Na, Ca, Mg, and Cl ions at a strength of 0.092 g/L TDS and hardness level of 0.198 g/L as CaCO₃ (3.96 meq/L). In that study, approximately 0.4% of the feedwater

hardness (0.85 mg/L as CaCO₃ or 0.017 meq/L) leaked through the unit after steady-state conditions were achieved. The resin was regenerated with 4.21 moles (246 g) of NaCl per liter of resin at 10% w/w concentration (Flodman and Dvorak 2012).

Effluent hardness concentration profiles during the last two resin regeneration and rinse procedures of the initial test are shown in Fig. 6. Approximately 4.2 moles (245 g) of NaCl per liter of resin at 14% concentration (w/w) was used to remove accumulated Ca and Mg ions from the resin. Leading edges of the hardness profiles can be seen after approximately 0.50 BV of soft water remaining from the water production run was displaced by the regeneration solution. Rinse water, which displaced the regeneration solution, reached the sensors at approximately 2.25 BVs into the regeneration-rinse procedure.

Steady-state hardness leakage profiles are shown in Fig. 7 for feedwaters with two levels of salinity and hardness. The resin

**Fig. 7.** Product water hardness concentration at two levels of feedwater salinity and hardness when at steady state.

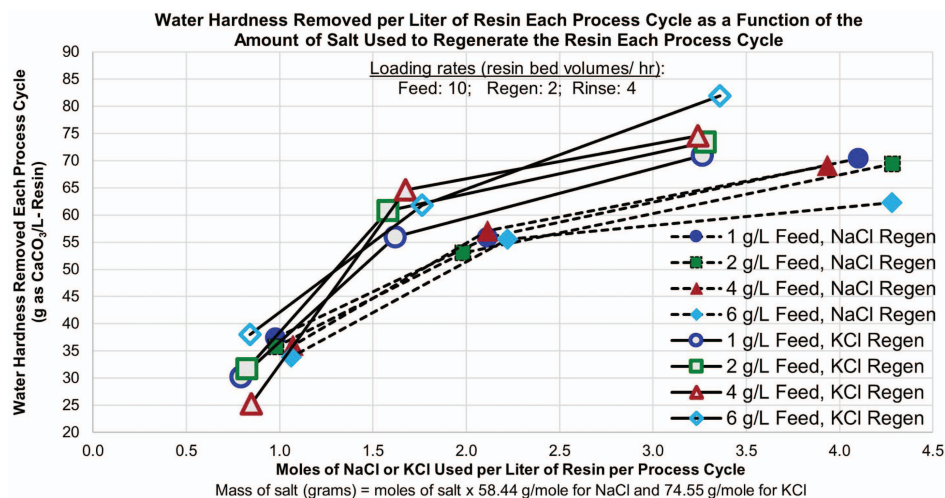


Fig. 8. (Color) Steady-state HRC as a function of the amount of salt used to regenerate the resin each operational cycle.

was regenerated with 3.3 moles (245 g) of KCl at 11% w/w concentration. Hardness leakage for the 2 g TDS/L feedwater was greater than for the 1 g TDS/L feedwater, and this is attributed to the larger ionic strength of the 2 g TDS/L feedwater that reduces resin selectivity (bonding preference) for hardness ions. The smaller volume of water produced from the 2 g TDS/L feedwater is mostly attributed to the larger hardness content of that feedwater (0.64 g CaCO_3/L) relative to the 1 g TDS/L feedwater (0.30 g CaCO_3/L), which consumed the resin's ion exchange capacity at a faster rate. The larger ionic strength of the 2 g TDS/L feedwater may also have reduced the run length relative to that of the 1 g/L feedwater. A recent study by Mejía-Saucedo et al. (2025) reported the same trend that higher TDS and hardness concentrations lead to faster resin saturation for CIX.

Plots of steady-state HRC as a function of moles of salt used to regenerate the resin each process cycle are shown in Fig. 8 for all four feedwater TDS concentrations (1, 2, 4, and 6 g/L) and both types of regenerant salt (NaCl and KCl). The HRC values generally increased with the amount of regenerant salt used, approaching limiting maximum values. When salt loading rates were above 1.1 moles salt/L of resin, HRC was larger in the unit that was regenerated with the nonconventional KCl salt than the unit that was regenerated with the traditional phytotoxic NaCl salt.

The impact of feedwater salinity on HRC appears to be relatively small for the range of TDS levels tested (Fig. 8), indicating that CIX can be a viable option for softening moderately brackish groundwater up to at least 6 g/L TDS. In Fig. 8, HRC appeared to generally decrease as feedwater TDS increased in the NaCl-regenerated unit, and the opposite appears to be true for the KCl-regenerated unit, which may be attributable to variability in testing conditions. HRC values ranged from 34 to 70 g CaCO_3/L resin per process cycle for regeneration salt loading rates of 1.0 to 4.3 moles of NaCl/L resin per process cycle, respectively, and 25 to 82 g CaCO_3/L resin per process cycle for regeneration salt loading rates of 0.8 to 3.4 moles of KCl/L resin per process cycle, respectively. For comparison, HRC in the Flodman and Dvorak's model described above was approximately 80 g as CaCO_3 (1.6 eq)/L resin per process cycle for a regeneration salt loading rate of approximately 4.2 moles of NaCl/L resin per process cycle on feedwater with a relatively low TDS concentration, as noted above.

Fig. 9 shows plots of HRC as a function of regeneration solution salt concentration for feedwater TDS concentrations of 1 and 2 g/L when regenerated with approximately 240 g of salt (NaCl and KCl) per liter of resin per process cycle at concentrations that ranged from approximately 8 to 14% w/w. Operating HRC values ranged

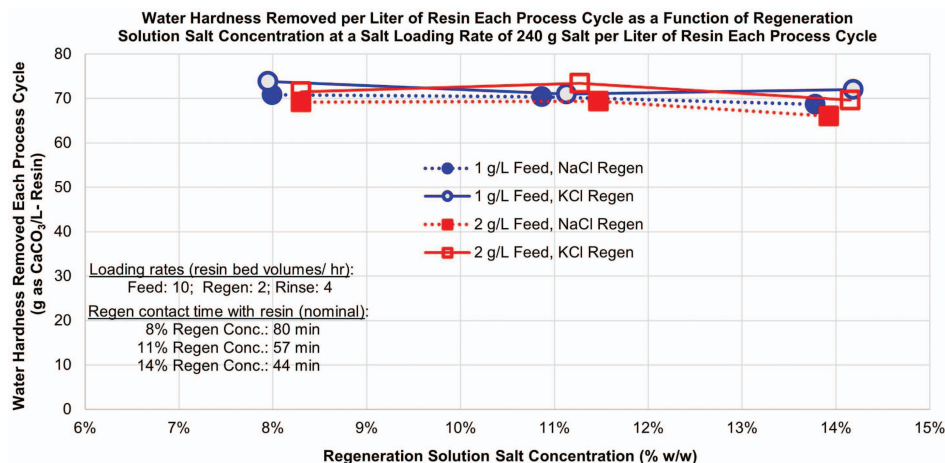


Fig. 9. (Color) Steady-state HRC as a function of the regeneration solution salt concentration.

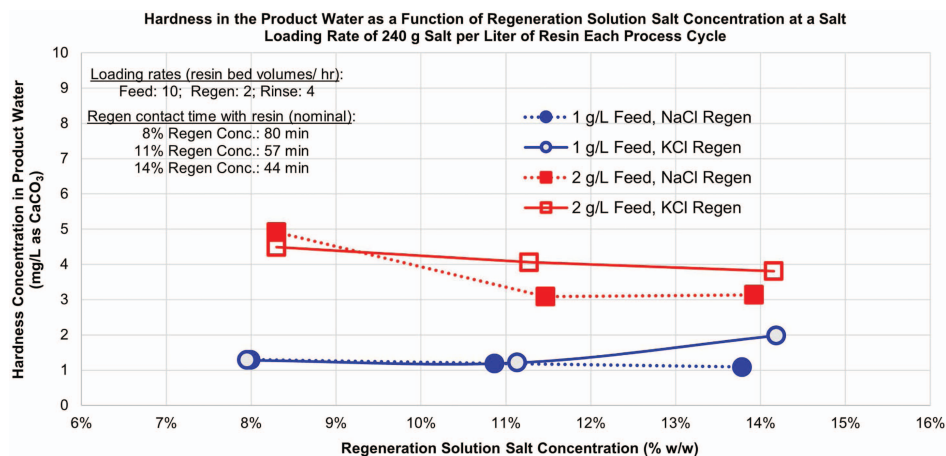


Fig. 10. (Color) Product water hardness concentration as a function of regeneration solution salt concentration at steady state.

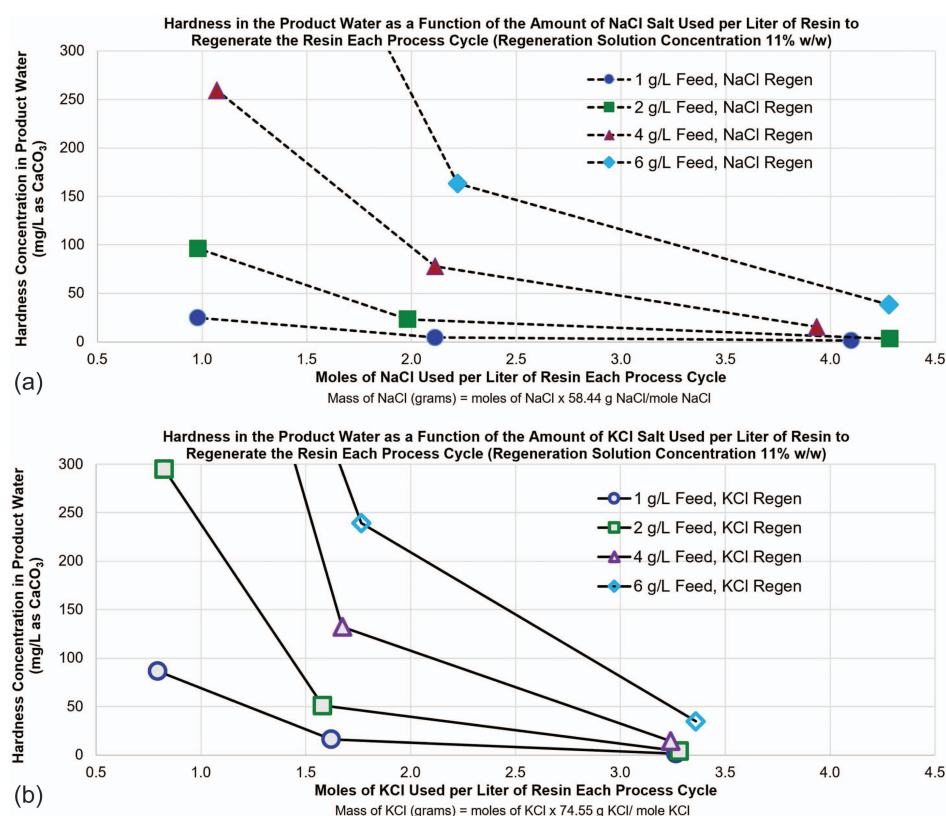


Fig. 11. (Color) Product water hardness concentration as a function of the amount of salt used to regenerate the resin each process cycle when using: (a) NaCl; and (b) KCl salts for regeneration (steady-state conditions).

from approximately 66 to 71 g CaCO_3/L resin per process cycle for NaCl and 70 to 74 g CaCO_3/L resin per process cycle for KCl. The nearly flat and overlaying profiles clearly indicate that the regeneration solution salt concentration had little impact on HRC for the range of salt concentration tested. This result leads to the conclusion that a high concentration of regeneration solution should be used because it reduces the volume of salt byproduct generated and reduces the time required to regenerate the resin. Hardness leakage is shown in Fig. 10 for the same loading conditions. The impact of feedwater salinity on hardness leakage is clearly seen, with leakage greater for the feedwater with the larger TDS content, as was also seen in Fig. 7.

Plots of hardness leakage through the CIX resin bed as a function of the moles of salt used to regenerate the resin each process cycle are shown in Fig. 11 for NaCl regeneration [Fig. 11(a)] and KCl regeneration [Fig. 11(b)] at approximately 11% w/w solution salt concentration. Leakage of hardness through the resin bed was large when the amount of salt used to regenerate the resin was small, and leakage decreased as the amount of salt used increased. Hardness leakage ranged from approximately 650 to 1.2 mg/L as CaCO_3 for regeneration salt loading rates of 1.0 to 4.3 moles of NaCl/L resin per cycle, respectively, and 780 to 1.2 mg/L as CaCO_3 for regeneration salt loading rates of 0.8 to 3.4 moles of KCl/L resin per cycle, respectively.

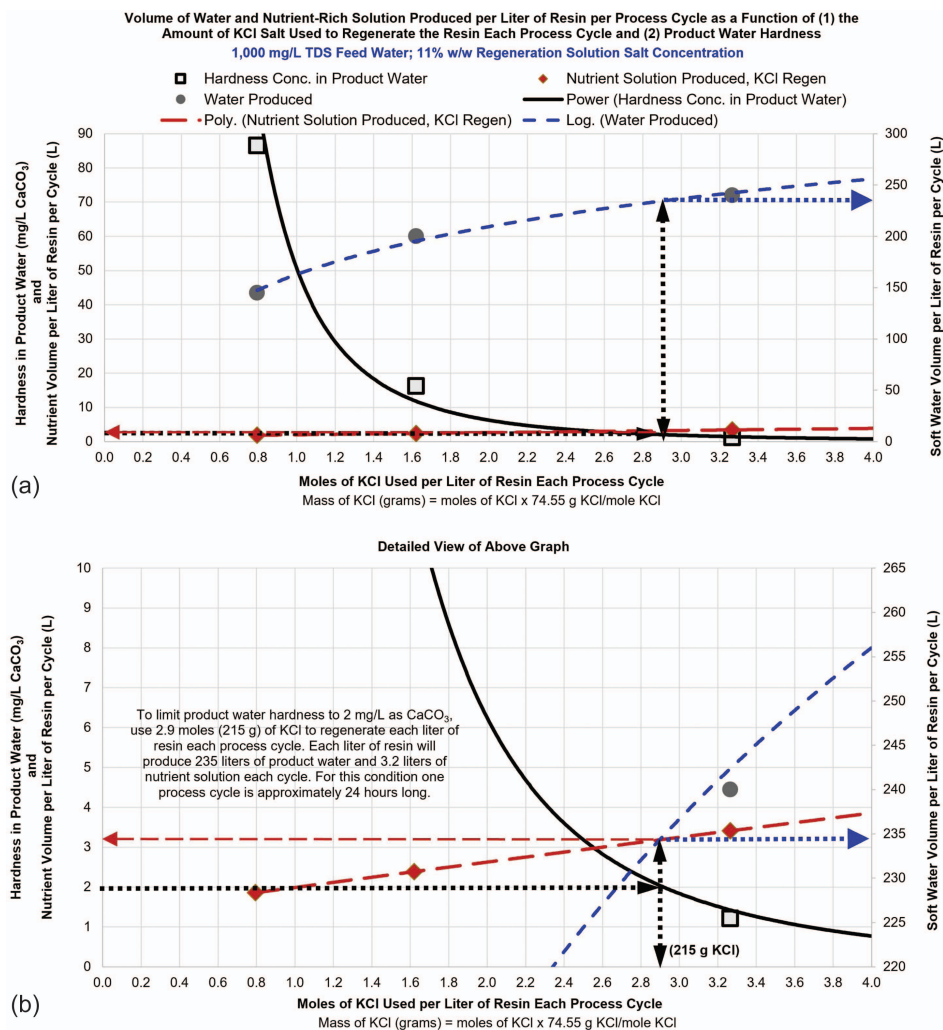


Fig. 12. (Color) Volume of softened water and nutrient-rich byproduct produced per liter of resin each process cycle as a function of the amount of KCl salt used to regenerate the resin at a concentration of 11% w/w for a feedwater salinity level of 1 g TDS/L (steady-state conditions): (a) full range of data; and (b) detailed view in the range of interest.

The level of hardness in the product water is a major consideration in desalination applications where it has a significant negative impact on desalination system operation, maintenance, and costs due to scale formation (Thu et al. 2023). Optimization of the desalination system requires finding the balance between the amount of salt used in regeneration to lower leakage and the cost of importing the salt and its disposal after use. Hardness leakage in the CIX unit that was regenerated with NaCl [Fig. 11(a)] cannot be directly compared to that of the unit that was regenerated with KCl [Fig. 11(b)] due to the limited number of data points, the moles of NaCl and KCl not being the same in the test, and the rapid change in leakage at the lower regeneration salt loading values. Additional tests using the same number of moles of NaCl and KCl are needed to obtain better resolution of the leakage and make a direct comparison.

Plots of volume of softened water and nutrient-rich byproduct produced per liter of resin each process cycle are shown in Fig. 12 as a function of the amount of KCl salt used to regenerate the resin at a concentration of 11% w/w for a feedwater salinity level of 1 g TDS/L. Plots like this can be used to estimate design parameter values for full-scale water production units. First, the level of hardness leakage is selected, and then the amount of salt required per liter of resin per process cycle can be determined by placing a vertical line where the hardness leakage best-fit curve intersects the

selected hardness level. The volumes of product water and nutrient byproduct produced are obtained by drawing horizontal lines where their respective best-fit curves intersect the vertical line. In this example, 2 mg/L of hardness in the product water was selected. The corresponding amount of KCl required each process cycle is 2.9 moles (215 g) per liter of resin. Each liter of resin will produce 235 L of product water and 3.2 L of nutrient solution each process cycle. The process cycle time can be calculated based on flow volumes and flowrates and the result used to calculate daily water production rate per liter of resin. The daily water production rate per liter of resin can then be used to calculate the minimum volume of resin required to meet the water demand for a given application, the daily amounts of feedwater and salt needed, and the amount of nutrient solution byproduct generated. This approach was used to construct a spreadsheet tool that can be used in the preliminary design of large-scale treatment units.

Spreadsheet Tool for Preliminary Design of Full-Scale Water Softening Units

An electronic spreadsheet program was developed using data from the CIX tests to aid in the preliminary sizing of large-scale commercial water softening units. Details of the spreadsheet are shown

Table 5. Brackish water softening design tool

Parameter	No.	Value	Units	Comment
Installation input				
Soft water volume needed per day	(1)	229,785	L/day	
Product water avg. hardness conc.	(2)	2.00	mg/L as CaCO ₃	Choose between 1 and 20
Feedwater salinity 1, 2, 4, or 6 g/L	(3)	1.00	g/L	Choose 1, 2, 4, or 6 g/L
Feedwater avg. hardness conc.	(4)	300	mg/L as CaCO ₃	
Type of salt used to regenerate resin	(5)	KCl		Choose NaCl, KCl, or KNO ₃
Installation output				
Resin volume required	(23)	1,007	L	= (1)/(18)
Salt required per day	(24)	219	kg/day	= (8)*(23)
<i>Volume per day:</i>				
Regeneration solution required	(25)	1,745	L/day	= (19)*(23)
Rinse water required	(26)	1,271	L/day	= (20)*(23)
Byproduct produced	(27)	3,017	L/day	= (21)*(23)
Feedwater required	(28)	232,802	L/day	= (22)*(23)
Design tool internal calculations				
Output per liter of resin per cycle				
Total hardness removed	(6)	71.8	g CaCO ₃ /L-resin/cycle	= BFF-THR ^a based on (3), (5), and (7)
Salt required	(7)	2.92	moles/L-resin/cycle	= BFF-n ^b based on (2), (3), and (5)
	(8)	0.217	kg/L-resin/cycle	= (7)*(34, 35, or 36) based on (5)
<i>Volume:</i>				
Soft water produced	(9)	241	L/L-resin/cycle	= (6)*1,000/[(4)-(2)]
Regeneration solution required	(10)	1.83	L/L-resin/cycle	= (8)*100/[(29)*(30)]
Rinse water required	(11)	1.33	L/L-resin/cycle	= (32)*(16)
Byproduct produced	(12)	3.16	L/L-resin/cycle	= (10) + (11)
Feedwater required	(13)	244	L/L-resin/cycle	= (9) + (12)
<i>Time:</i>				
Water production	(14)	1,446	min	= (9)/(33)
Regeneration	(15)	54.9	min	= (8)*100/[(29)*(30)*(31)]
Rinse	(16)	20.0	min	Observed value ± 5 min
Total cycle time	(17)	25.3	h	= Sum [(14),(15),(16)]/60
Output per liter of resin per day				
<i>Volume:</i>				
Soft water produced	(18)	228	L/L-resin/day	= (9)*24/(17)
Regeneration solution required	(19)	1.73	L/L-resin/day	= (10)*24/(17)
Rinse water required	(20)	1.26	L/L-resin/day	= (11)*24/(17)
Byproduct produced	(21)	3.00	L/L-resin/day	= (12)*24/(17)
Feedwater required	(22)	231	L/L-resin/day	= (13)*24/(17)
Reference data (fixed)				
Regeneration salt concentration	(29)	11.0	percent	
Regeneration solution density	(30)	1.08	kg/L	
Regeneration flowrate (1 liter resin)	(31)	0.033	L/min	= 2.0 BVs/h
Rinse flowrate (1 liter resin)	(32)	0.067	L/min	= 4.0 BVs/h
Water production flowrate (1 liter resin)	(33)	0.167	L/min	= 10 BVs/h
Atomic mass NaCl:	(34)	58.44	g/mole	
Atomic mass KCl:	(35)	74.55	g/mole	
Atomic mass KNO ₃ :	(36)	101.10	g/mole	

^aBFF-THR = Best fit function for HRC/L resin per cycle as a function of the type of regenerant salt selected and amount of salt required.

^bBFF-n = Best fit function for moles of salt required/L resin per cycle as a function of the hardness leakage concentration and type of regenerant salt selected.

Table 6. Brackish water softening design tool best-fit function coefficients. Negative values are shown in parentheses

Regen salt	Feed TDS	A	B	C	D	E
NaCl	1 g/L	23.02	(2.124)	(2.885)	25.239	15.426
	2 g/L	99.12	(2.337)	(3.076)	26.374	12.863
	4 g/L	327.86	(2.163)	(4.759)	35.371	3.581
	6 g/L	759.23	(2.026)	(4.796)	34.451	2.697
KCl	1 g/L	50.56	(3.017)	(8.898)	52.612	(5.942)
	2 g/L	177.56	(3.111)	(12.695)	69.126	(16.732)
	4 g/L	507.90	(3.051)	(17.282)	91.323	(39.814)
	6 g/L	616.68	(2.234)	(5.213)	39.314	8.676

in Table 5. A best-fit function of the data shown in Fig. 11 [Eq. (1) with coefficient values A and B from Table 6] was used in the design tool to calculate the number of moles of salt required (MSR) per liter of resin each process cycle based on user inputs for product water hardness concentration [Coefficient L in Eq. (1)], feedwater salinity (TDS) concentration, and regenerant salt type. The resulting MSR value is used to estimate total HRC per liter of resin each process cycle using a best-fit function of the data shown in Fig. 8 [Eq. (2) with coefficient values C, D, and E from Table 6]. The HRC is then used to calculate the minimum volume of resin required at scale based on the volume of product water desired per day (a user input) and assumed values for other process parameters specified in the “Design Tool Internal Calculations” section of Table 5

$$\text{MSR} = 10^{\frac{\log\left(\frac{L}{A}\right)}{B}} \quad (1)$$

$$\text{HRC} = C(\text{MSR})^2 + D(\text{MSR}) + E \quad (2)$$

where MSR = best-fit function for calculating moles of salt required per liter of resin per cycle; HRC = best-fit function for calculating total hardness removed per liter of resin per cycle; L = hardness leakage concentration (user input); and A, B, C, D, and E = best-fit function coefficients.

Program inputs for a hypothetical installation requiring 1.0 m³ of resin are shown in Table 5. The spreadsheet tool estimates that the treatment unit would produce 230 m³ of soft water (60,000 US gallons) per day and consume about 220 kg of KCl per day. Comparison of “Output per liter of resin per cycle” values in Table 5 with values obtained in Fig. 12 shows close agreement.

The results obtained when scaling up to commercial CIX units should be similar to those obtained in this study when (1) the same CIX resin is used; (2) the source water to be treated has a similar chemistry and range of temperatures; (3) the treatment system is operated with similar salt and hydraulic loading rates; (4) the resin bed dimensions meet the guidelines specified in Crittenden et al. (2012); and (5) appropriate pretreatment is provided to remove constituents that would negatively impact CIX performance, including, but not limited to, sediment, organic matter including microorganisms, heavy metals, silica, and iron. Deviations from any of these may lead to different results. The design tool needs validation with additional data obtained during field trials.

Conclusions

Achievement of sustainable agriculture in arid and semiarid agricultural regions worldwide will require advancements in salinity management strategy, salt extraction technology, and sustainable supplies of fresh water and crop nutrients. These regions are increasingly experiencing water scarcity and higher source salinity due to climate change and population growth, limiting agricultural production opportunities. Increased utilization of impaired water sources, such as brackish groundwater, agricultural drainage water, oil and gas produced water, and effluent from wastewater treatment processes is required to address these water shortage and impairment issues. The efficient use and reuse of local water and nutrient resources is necessary to achieve sustainable water and nutrient management in drought-challenged regions of the world.

Advancements in treatment technology have made it possible to treat nontraditional water sources to irrigation standards at a cost that can be sustainable where fresh water is scarce. Extensive research of technologies and approaches that can reduce the cost of treating inland brackish waters is needed for widespread utilization of impaired water sources. To address this need, an innovative ion separation and recovery process is being developed that economically separates nutrients from phytotoxic NaCl and produces nutrients and water suitable for irrigation, reducing water and fertilizer importation and brine waste, thereby reducing energy use and associated GHG emissions, and resulting in more sustainable and reliable water and nutrient supplies. Therefore, using the DNR process a circular economy and systems approach is achieved that expands the range of water sources that can be beneficially utilized. Initial research efforts are focused on establishing baseline performance characteristics of the CIX component of the DNR system and optimizing the processes for nutrient removal. Additional results from the CIX optimization study and results from ongoing studies of other DNR system components will be reported in the future.

Results of the CIX Component Study

1. NaCl and KCl salts effectively regenerated the CIX resin, reducing scale-causing hardness ions to 1.2 mg/L as CaCO₃. The use of KCl as a resin regenerant has important benefits to agriculture and the environment relative to the traditional NaCl regenerant as K can be recovered, along with the calcium and magnesium ions, and used locally as plant nutrients, reducing fertilizer production/importation and waste generation.
2. The amount of regenerant salt used correlated with reductions in product water hardness (leakage) and resin HRC, with HRC approaching values of approximately 70 and 82 g-CaCO₃/L resin per process cycle for NaCl and KCl regeneration, respectively.
3. Regenerant solution salt concentration had minimal impact on leakage and HRC for salt concentrations ranging from 8% to 14% w/w, and high concentrations are advantageous, reducing salt byproduct volume and resin regeneration time.
4. The impact of feedwater salinity on HRC is small for up to 6 g/L dissolved solids, indicating that CIX is a viable option for softening moderately brackish waters.
5. The resin bed dimensions used in the study met the minimum requirements to scale test results up to full-scale design. As such, data generated from this study can be used in the preliminary design of commercial-scale water and nutrient production facilities, and a spreadsheet-based design tool was developed for that purpose. However, data from pilot-scale studies are needed to confirm the bench-scale results for final process design of the treatment system.

The DNR process will efficiently separate nutrients from phytotoxic NaCl and produce nutrients and water suitable for irrigation, reducing water and fertilizer importation, brine waste, energy use, and associated GHG emissions, resulting in more sustainable and reliable water and nutrient supplies.

Ongoing and Future Work

Ongoing and future work includes investigating the merits of the following:

1. Using KNO₃ to regenerate the CIX unit, allowing for recovery of both K and NO₃ ions for beneficial use as plant nutrients.
2. Recovering KNO₃, K₂SO₄, and other nutrients using K-based AIX regeneration.
3. Using the desalination process concentrate as a regenerant for the CIX and AIX resins (cyclic regeneration), thereby reducing the amount of imported salt required.
4. Using electrodialysis reversal to remove NaCl upstream of the CIX, AIX, and desalination processes to improve their performance and to permit harvesting of waters with greater levels of salinity.
5. Investigating possible processes to separate Na from K to recover K for use in regenerating the CIX and AIX units and subsequently as a plant nutrient.
6. Using CIX to evaluate chromatographic behavior of Na, K, Ca, and Mg on CIX resin enabling partial separation and recovery of NaCl.
7. Determining the economic benefits of recovering water, nutrients, and other byproducts using the DNR process during the prototype stage of technology development.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

William F. Wright: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review and editing. Karl E. Longley: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Validation; Visualization; Writing – original draft; Writing – review and editing. Walter K. Mizuno: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review and editing. Sankha Banerjee: Funding acquisition; Writing – review and editing. Mike Waite: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Validation; Writing – original draft; Writing – review and editing. William Stringfellow: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Writing – original draft; Writing – review and editing. Pei Xu: Conceptualization; Writing – original draft; Writing – review and editing.

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