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Enhancing municipal potable reuse recovery with flow-reversal RO: Pilot study, challenges, and retrofit considerations

Han Gu [a,*], Megan H. Plumlee [a], Mingheng Li [b], Auryan Mohseni [c], Ronit Erlitzki [d]

[a] Research and Development Department, Orange County Water District, 18700 Ward Street, Fountain Valley, CA 92708, United States of America
[b] California State Polytechnic University, 3801 W Temple Ave, Pomona, CA 91768, United States of America
[c] Johnson Matthey PLC (previously with Chart Industries), Orchard Road, Royston SG8 5HE, UK
[d] IDE Technologies (previously with Chart Industries), 5050 Avenida Encinas, Carlsbad, CA 92008, United States of America

HIGHLIGHTS

- Achieved 90 % recovery using reverse osmosis with flow reversal in municipal reuse.
- Demonstrated sustainable flux and salt rejection at 90 % recovery over long-term operation.
- Identified fouling issues in concentrate recovery during high-recovery operations.
- Found retrofitting systems with flow reversal to be relatively cost-effective.
- Highlighted the need to optimize reliability and mitigate fouling risks in flow reversal.

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ABSTRACT

An 18-month pilot study evaluated the feasibility of flow reversal reverse osmosis (FR-RO) for municipal wastewater reuse. FR-RO was tested with three feed water sources and in two configurations (primary RO and brine concentrator modes) focusing on recovery, water permeability, fouling rate, salt rejection, and chemical cleaning intervals. Initially, the FR-RO pilot treated microfiltration/ultrafiltration (MF/UF) effluent as a three-stage RO with flow reversal. Optimization trials achieved 90 % instantaneous recovery at 19.7 LMH (11.6 gfd), demonstrating stable water permeability and salt rejection over three months. Next, the pilot treated RO concentrate as a one-stage brine concentrator, reaching ~45 % recovery at 8.5 LMH (5.0 gfd) but experiencing rapid membrane fouling, high chemical usage, and bromination damage to the membrane's active layer. Brine concentrator mode was only viable for two months; long-term operation proved unsuccessful due to poor cleanability. Finally, pilot performance was validated to treat MF/UF effluent again (primary RO mode) after the source water from the full-scale facility began incorporating an additional secondary effluent with greater salinity. Nevertheless, extended operation achieved 90 % recovery and a 3-month runtime between membrane cleanings with acceptable membrane-normalized salt rejection. A site-specific, preliminary cost analysis suggested that a retrofitted FR-RO operating at 90 % recovery would have a combined (capital plus O&M) unit cost of \$0.25/m^3 (\$308 per acre-foot or AF) (considering only the RO portion of the potable reuse treatment train) compared to \$0.21/m^3 (\$259/AF) for a conventional (no flow reversal) RO unit. Overall, the pilot study provided insights into the feasibility and challenges of FR-RO technology for municipal potable reuse, informing potential retrofitting of conventional RO systems.

1. Introduction

Water scarcity and water quality issues are global challenges driven by population growth, agricultural and industrial activities, as well as climate change [1,2]. To meet the rising demand for fresh water, strategies such as stormwater capture, greywater recycling, seawater desalination, and advanced treatment of municipal wastewater are increasingly adopted [3–6]. Innovative water management practices,

* Corresponding author.
E-mail address: hgu@ocwd.com (H. Gu).

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including groundwater aquifer replenishment and potable reuse, help to ensure sustainable water supply and quality [5,7].

Reverse osmosis (RO) is widely used for water reuse, efficiently removing most dissolved substances (mineral salt), macro-molecules, and pathogens. However, conventional RO systems exhibit a limited recovery rate (typically 75–85 % in water reuse applications), primarily constrained by mineral scaling [8,9]. This results in significant concentrated waste, posing challenges for concentrate management [10,11]. Various emerging high-recovery desalination technologies such as closed circuit RO (CCRO) [12–14], membrane distillation [15,16], and forward osmosis-RO (FO-RO) [17–19] have demonstrated potential in enhancing water recovery, and reducing reject (concentrate) discharge. Nonetheless, the performance of these technologies on specific source waters necessitates comprehensive testing and evaluation.

Recent pilot studies at the Orange County Water District (OCWD) Advanced Water Purification Facility (AWPF) have demonstrated the potential of using CCRO and FO-RO to improve recovery rates. The FO-RO pilot, used as a 4th-stage RO to recover more permeate from the AWPF's RO concentrate, achieved a recovery rate of 35 % (FO flux: 5.95 L/m^2/h (LMH) and RO permeate flux: 13.9 LMH) [19], which corresponds to an increase to 89.5 % overall recovery compared to the current 85 % AWPF RO recovery. The CCRO pilot was tested as both a high-recovery primary RO and a 4th-stage RO concentrator, achieving an 91 % overall recovery at a permeate flux of 11.0 LMH [12]. Notably, these higher recovery operations were achieved without the addition of extra antiscalant or other chemicals.

Flow Reversal RO (FR-RO) technology is a promising alternative for improving water recovery. The ROTEC FR-RO system incorporates periodic reversal of the feed flow direction (flow reversal, FR) and stage "block rotation" (BR) to reduce mineral scaling and distribute fouling evenly across the RO system [20,21]. Compared to other high recovery technologies like CCRO or FO-RO, FR-RO offers a distinct advantage—it can be retrofitted into existing RO units/trains through modifications.

FR-RO was successfully validated at demonstration scale by the Singapore Public Utilities Board (PUB) in one of their NEWater Factories between 2017 and 2018. A 10,600 m^3/d (2.8 million gallons per day (mgd)) two-stage RO system treating secondary effluent was retrofitted with a third (dynamic) stage, increasing the recovery rate from 75 % to 90 %. At 90 % recovery, the FR cycle interval was 55 min (personal communication, October 1, 2024). PUB incorporated FR-RO in the systems design for upcoming NEWater Factories in Tuas and Changi [22]. At all PUB NEWater plants, treated municipal wastewater is used for non-potable industrial purposes [23].

For treatment of groundwater for drinking water supply, the City of Santa Monica conducted a pilot study as part of the Arcadia Water Treatment Plant expansion project before proceeding with full-scale retrofitting to FR-RO (37,854 m^3/d [10 mgd], four 9464 m^3/d [2.5 mgd] RO units) completed in late 2023. During the pilot study, the FR-RO system enhanced the overall recovery rate from 85 % to 90 %, effectively removing contaminants. For Santa Monica, higher recovery enhances water supply without increasing groundwater pumping. Full-scale FR performance testing commenced in February 2024 [20].

Based on the above, FR-RO application in municipal wastewater reuse, a highly variable and fouling-prone source, has received limited testing at scale. Hence, the objective of the present study was to evaluate the operational feasibility of FR-RO for a potable reuse application at the OCWD Groundwater Replenishment System (GWRS) AWPF. Specifically, the goals were to:

- Assess the performance of FR-RO as a primary RO (i.e., treating AWPF RO feedwater - MF/UF filtrate).
- Evaluate the feasibility of using FR-RO for direct treatment of RO concentrate produced by the AWPF.
- Perform a preliminary cost estimate for a full-scale RO unit retrofit.

The study was conducted in three phases, each designed to address specific research objectives and operational conditions. Phase 1 optimized recovery rates and cleaning protocols using MF/UF filtrate. Phase 2 tested direct treatment of RO concentrate, while Phase 3 validated the system performance with higher-salinity MF/UF filtrate following the AWPF's final expansion.

This work presents the first pilot evaluation of FR-RO for potable water reuse in the United States, addressing challenges unique to municipal wastewater. Unlike previous implementations for groundwater applications, municipal wastewater presents greater variability in feedwater quality and fouling potential due to its complex contaminant profile. In addition to assessing system performance with two different feed sources and variable salinity, this research identifies key operational challenges, including concentrate overshoot during stage transitions and significant fouling at higher recovery rates. The study also includes a preliminary economic analysis for retrofitting existing systems.

2. Experimental/method section

2.1. Test Site at OCWD Advanced Water Purification Facility (AWPF)

The FR-RO pilot study took place at the OCWD GWRS AWPF in Fountain Valley, California, a globally recognized facility producing up to 492,104 m^3/d (130 mgd) of high-quality recycled water for potable reuse to support water demands of a population of ~2.5 million. The AWPF employs a multi-barrier treatment process, integrating microfiltration (MF) or ultrafiltration (UF) —depending on the membrane type in each specific basin—followed by RO. The RO permeate is further treated by an advanced oxidation process (AOP) utilizing ultraviolet light and hydrogen peroxide (UV-AOP) (Fig. 1).

Throughout the treatment process, chloramine residual is maintained by adding 12.5 % sodium hypochlorite to the MF/UF feedwater, resulting in 3–5 mg/L chloramine in the RO feedwater (ROF). Sulfuric acid (93 %, Univar Solutions, Downers Grove, IL) and antiscalant (AWC A-108, 3.0 mg/L in the ROF stream) are added for pH adjustment and scaling control, maintaining the RO feed water pH at 6.9. After UV-AOP, partial decarbonation and lime addition reduce water corrosiveness. The finished product water is utilized for groundwater recharge and to supply a seawater intrusion barrier. For this study, either RO feed or RO concentrate from the AWPF was utilized as the feedwater for the FR-RO pilot.

The GWRS expansion in January 2023 to its current capacity affected feedwater quality. The AWPF receives a blend of trickling filter (TF) and activated sludge (AS) effluent from Orange County Sanitation District (OC San) Plant 1 (P1) (Fountain Valley, CA) and trickling filter/solids contact (TF/SC) effluent from OC San Plant 2 (Huntington Beach, CA). OC San P2 effluent was not available during Phase 1 but was incorporated to the AWPF feedwater blend during Phase 2 and a majority of Phase 3, at 14–16 % of the feed flow, increasing the total dissolved solids (TDS) by ~40 % and slightly decreasing total organic carbon (TOC) in the MF/UF filtrate (feed water to the pilot).

After completing the plant expansion, OCWD now operates 27 parallel RO units, each producing 18,927 m^3/d (5 mgd) of RO permeate. The RO recovery is currently limited to 85 %, with the RO concentrate (104,560 m^3/d) discharged to the Pacific Ocean via OC San's ocean outfall. A typical clean-in-place (CIP) interval for an AWPF RO unit is 6–12 months.

2.2. Feedwater quality and characteristics

Table 1 summarizes the average water quality of the feed stream to the RO plant at the OCWD GWRS AWPF. The data includes results from before (2022) and after (2023) the GWRS final expansion, including ROC water quality data in 2023. Key differences include a ~ 38 % increase in TDS (from 991 mg/L to 1364 mg/L) and a rise in electrical conductivity (EC) (from 1688 μS/cm to 2352 μS/cm) attributed to

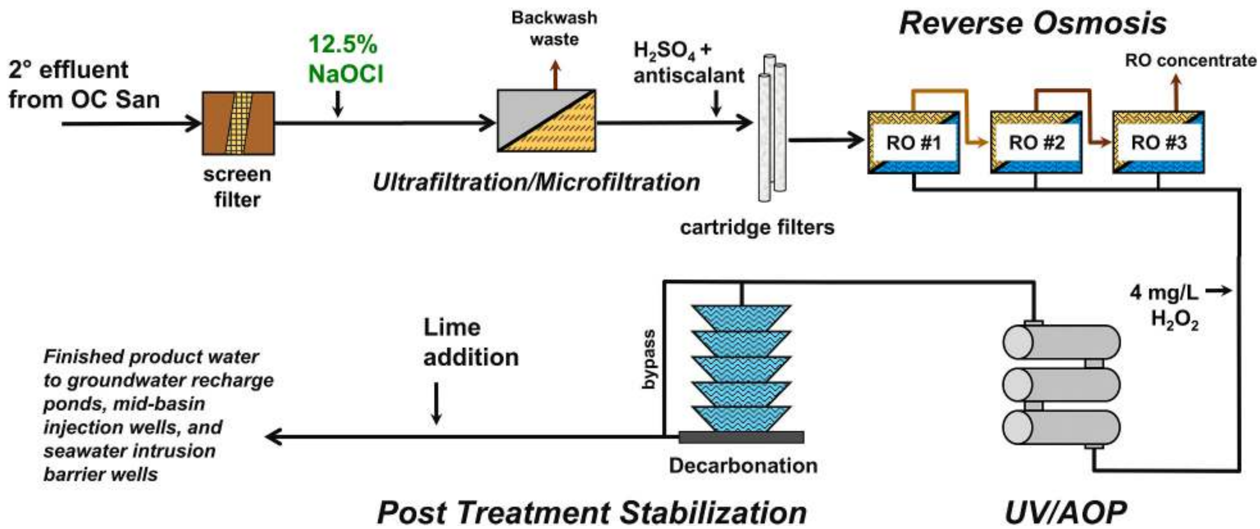

Fig. 1. Simplified schematic of the Orange County Water District (OCWD) Groundwater Replenishment System (GWRS) Advanced Water Purification Facility (AWPF).

Table 1
Average water quality of RO plant feed steam at the OCWD GWRS AWPF (85 % water recovery), comparing results from 2022 (before expansion) and 2023 (after expansion), including 2023 RO concentrate data.

		2022 Average RO Feed Water (Phase 1 Pilot)		2023 Average RO Feed Water (Phase 3 Pilot)		2023 Average RO Concentrate (Phase 2 Pilot)	
Analyte	Unit	Mean	% St. Dev.[a]	Mean	% St. Dev.[a]	Mean	% St. Dev.[a]
Total dissolved solids	mg/L	991	2.93	1364	5.31	8235	16.6
Electrical conductivity	μS/cm	1688	4.43	2352	3.88	14201[b]	12.1[b]
pH	–	6.9	0.03	6.9	0.11	7.7	1.1
Total organic carbon	mg/L	8.7	4.41	7.1	6.17	42.9[b]	19.3[b]
Silica (as SiO_2)	mg/L	18.5	4.45	20.3	5.64	121	11.8
Sodium	mg/L	214	5.91	306.2	6.76	1658	36.2
Calcium	mg/L	75.1	4.21	82.0	2.68	488	30.5
Magnesium	mg/L	27.9	5.23	39.9	7.91	241	18.7
Potassium	mg/L	19.2	4.91	22.3	1.26	139	9.8
Barium	μg/L	37.4	26.9	54.5	7.95	358	32.8
Iron	μg/L	112	13.4	95.2	13.87	637	8.1
Manganese	μg/L	44.0	19.7	57.7	5.28	334	16.0
Zinc	μg/L	21.4	37.2	20.7	25.5	88.9	17.7
Aluminum	μg/L	3.8	35.5	12.2	0.59	4.9	116.5
Sulfate	mg/L	202	4.78	224.3	4.35	1406	10.5
Chloride	mg/L	269	4.03	434.3	21	2622[b]	66[b]
Bicarbonate (as HCO^{3-})	mg/L	239	4.76	263.2	11.0	1589[b]	34.3[b]
Orthophosphate (as $PO_4{}^{3-}$)	mg/L	0.49	27.8	0.3	13.58	3.0	38.2

[a] % St. Dev. = Standard Deviation/Mean × 100 %.
[b] Estimated based on feed concentration and water recovery data.

seawater intrusion to the P2 sewer collection system. Total organic carbon (TOC), decreased by 18 % (from 8.7 mg/L to 7.1 mg/L). Additionally, higher concentrations of silica, sodium, calcium, magnesium, potassium, and other ions in 2023 feedwater reflected the increase in TDS from the new blended source. The 2023 ROC is 6–7 times more concentrated than the RO feed due to concentration effect of the RO process.

2.3. Modeling of scaling risk

The AWC Proton® "Aqueous Membrane Chemistry Calculator" was used to estimate scaling potentials for key compounds at the concentrate exit for recovery rates of 85–92 % (conventional 3-stage RO). Based on the final expansion feed water, the results indicate a high silica scale risk above 89 % recovery and antiscalant precipitation risk above 90 %. Without antiscalant, $CaCO_3$ nucleation may occur. Proton® recommends a maximum recovery of 88.8 %, noting higher Fe^{3+} and Al^{3+} levels could necessitate higher antiscalant dosage. It should be noted that the calculator assumes a standard 3-stage RO and thus may not fully represent the actual scaling risk in FR-RO. Detailed results are provided in Supplemental Information Text S1.

2.4. Flow-reversal RO pilot system

The FR-RO pilot system (ROTEC-Water, Caesarea, Israel), described by Li et al. [20], utilizes pressure vessels (PVs) that hold 101.6 mm outer diameter × 1016 mm spiral-wound RO elements (Hydranautics ESPA2-LD 4040, Oceanside, CA). The system is divided into six blocks (A to F), each with two PVs. Each PV holds three or four RO elements connected in series, forming a seven-element long PV. A 5 μm cartridge filter (US Filter, Indianapolis, IN) on the feed line removes suspended solids and debris. The pilot includes a low-pressure feed pump (Movitec VSF006, KSB, Germany), a high-pressure pump (Movitec LHS6–16, KSB), and two inter-stage booster pumps (Movitec VSF004 and VSF002, KSB), all controlled by variable-frequency drives (VFDs) (Altivar 212, Schneider, France). The pilot features a 1324 L feed tank, a 1136 L flush tank, and analyzers for online monitoring (details in Supplemental information Fig. S1 and Table S1). The flush tank stores RO permeate water for system flushing after system shutdown. The flush tank is also used during chemical cleanings (CIPs).

The high-recovery FR-RO technology developed by ROTEC operates based on the concept of FR and BR. In conventional RO, the feed water enters continuously from one end of the RO pressure vessel, while the concentrated water exits from the tail element. This flow direction is fixed, causing concentration polarization (CP) that leads to greater mineral salt accumulation at the membrane surface, particularly in the concentrate exit region where scaling is likely to occur first. In a RO system with FR, the feed flow periodically switches direction to enter from the opposite end, reversing the axial CP profile and the solution saturation profile in the RO feed channel. This process reduces mineral scaling by resetting the crystallization induction clock, enabling higher recovery rates without the need for additional antiscalant [21,24,25]. Further, BR alternates the assignment of PV blocks between the first and third stages, distributing the salt and foulant load more evenly [20,21]. FR and BR are managed by actuated valves and a proprietary triggering system based on crystallization induction time. The PV configurations and block rotation directions for the pilot are shown in Fig. 2.

In 3-stage FR mode with a 3:2:1 array, at any given time, one block from the lower A-D blocks operates as the third stage, while the other three blocks function as the first stage. The third stage feed flow direction is always opposite to the first stage. The second stage, comprising of blocks E and F, only reverse the feed flow internally and does not participate in block rotation. There are a total of eight configurations or "stage states" the FR-RO pilot can be in, plus a transitional state (Fig. S2). During transitions between configurations, recovery rates dropped to 40–55 %, resulting in an estimated overall recovery loss of about 1 % at 90 % instantaneous recovery and one-hour cycle time.

In brine concentrator (BC) mode, the pilot operates as a one-stage RO system in a 3:3 configuration. The six PV blocks are divided into two groups: Block I (A, C, E) and Block II (B, D, F). At any given time, one group is in filtration mode, while the other is flushed with permeate water from the permeate side or in standby.

The cleaning process in BC mode begins with a "mini flush" (~68 L/min) in the reverse feed flow direction using RO permeate from the flush tank for 90 s, pumped by the third-stage booster pump. After the mini flush, each PV undergoes a permeate flush dosed with sulfuric acid (~pH 2) for approximately 75 s (reduced to 67 s after January 16, 2023) using a digital metering pump (Grundfos DDA 7.5–16). After the flush, Block I entered standby mode, while Block II remained in filtration. The pH was ~2 during the flush. This alternating process repeats throughout the run. Due to block switching, the actual membrane run time in concentrator mode is 50 % of the total operational time.

2.5. Experimental plan

To systematically evaluate FR-RO performance, the study was divided into three phases, each with distinct feedwater types and objectives. Table 2 provides an overview of the configurations and goals for each phase to clarify their differences and relationships.

2.5.1. Phase 1: FR-RO treating MF/UF filtrate

The objective of Phase 1 was to determine the maximum sustainable recovery of the FR-RO pilot treating AWPF MF/UF filtrate (i.e., RO feed water). Initially, a control experiment was conducted with the pilot functioning as a conventional 3-stage RO at 85 % recovery, the same as the AWPF RO, without utilizing FR and BR. Subsequently, the pilot

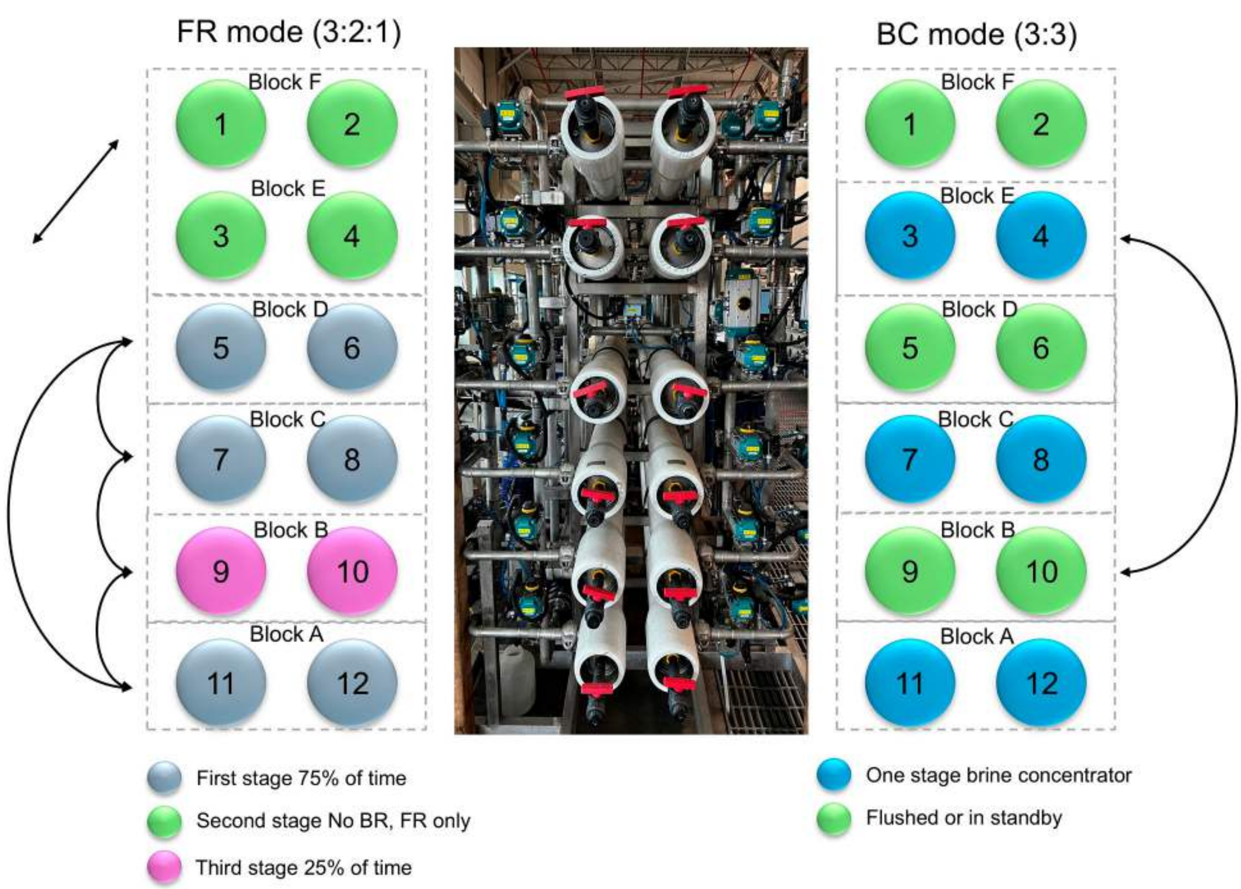

Fig. 2. FR-RO pilot pressure vessel (PV) block configurations and block rotation (BR) direction. The flow reversal (FR) mode is a 3-stage FR-RO in 3:2:1 configuration, the brine concentrator (BC) mode is one stage alternating between Block I (A,C, E) and II (B, D, F).

Table 2
Summary of study phases, feedwater types, and objectives.

Phase	Feedwater Type	Configuration	Objectives
1	Microfiltration/ ultrafiltration (MF/ UF) filtrate	Control phase (primary RO mode without FR and BR), primary RO mode with FR and BR	Optimize recovery, flow reversal frequency, and CIP effectiveness
2	AWPF RO concentrate	Concentrator mode with block switching	Evaluate the feasibility of directly treating RO concentrate to recover water
3	MF/UF filtrate (higher salinity)	Primary RO mode with FR and BR	Validate performance with higher salinity feedwater

operated as a 3-stage RO with FR and BR, simulating a retrofit option for the AWPF RO process to enhance recovery and generate additional permeate. Recovery rates were increased incrementally from 85 % to determine the maximum sustainable recovery without rapid fouling. Permeate flux per stage and the frequency of FR and BR was also optimized.

The pilot performance was assessed based on: (a) sustainable recovery rate, (b) membrane water permeability (or specific flux), (c) clean-in-place (CIP) frequency, and (d) permeate water quality. Key performance indicators included the water permeability, L_p (normalized to 25 °C, described in [20]), normalized salt passage, and normalized differential pressure. The goal for the extended testing was to demonstrate that the FR-RO system could maintain operation for at least three months between CIP events while meeting the following targets: (1) a relative decline in L_p of <30 % from initial value, (2) a normalized salt rejection increase of <15 %, and (3) a normalized differential pressure increase of <30 %.

2.5.2. Phase 2: FR-RO treating AWPF RO concentrate

In Phase 2, the FR-RO pilot treated RO concentrate (ROC) directly from an AWPF RO unit to determine the maximum sustainable recovery as a single-stage brine concentrator. The same approach of step changes in recovery was used as in Phase 1. If implemented at full-scale, this configuration could serve as a standalone FR-RO system (instead of a retrofit) for AWPF ROC (brine), with its permeate blended with the main RO system's permeate to boost overall recovery. Block switching with RO permeate flush was employed (discussed in Section 2.2).

2.5.3. Phase 3: FR-RO treating AWPF RO feedwater with higher TDS

In Phase 3, the FR-RO pilot again treated the AWPF MF/UF filtrate as described in Phase 1, but following the full-scale plant final expansion, which introduced a higher-salinity treated wastewater source to the feedwater blend. The maximum sustainable recovery that was determined in Phase 1 was repeated in long-term operation in Phase 3 to confirm operability.

3. Results and discussion

3.1. Phase 1: FR-RO treating AWPF MF/UF filtrate (RO Feedwater)

3.1.1. Control phase

The pilot study began with a ~ 35 day break-in period as a control phase, during which the pilot operated as a conventional 3-stage RO system at 85 % recovery, with a permeate flux of 19.8 LMH. This control phase demonstrated stable water permeability (L_p) and salt rejection (Figs. S4 and S5 in Supplemental Information). Table 3 shows the relative decline in L_p over the control phase (including projected L_p decline over a 3-month period) and the overall fouling rates. Stage-specific fouling rate and relative decline data are shown in Table S2. A 24-h composite water sample was collected between October 11 and 12, 2021, to assess water quality. The results confirmed the pilot's stable and consistent analyte removal, comparable to that of the full-scale RO unit (see Supplemental Information Fig. S17).

Table 3
Average fouling rate and relative decline in L_p during the FR-RO pilot study Phase 1 and 3.

	Overall recovery (actual)	Run time	Fouling rate	Relative decline in L_p	Relative decline in L_p over 90 days (projected)
	%	days	LMH/ bar/day	%	%
Conventional RO (Control)	85	35	0.00280	3.8 %	9.8 %
FR-RO (Phase 1a)	85	29	0.00434	5.0 %	16 %
FR-RO (Phase 1a)	87	28	0.00552	6.3 %	21 %
FR-RO (Phase 1a)	90	37	0.00269	4.5 %	11 %
FR-RO (Phase 1a)	91	49	0.00764	16 %	29 %
FR-RO (Phase 1a)	92	53	0.01265	32 %	55 %
FR-RO (Phase 1b)	89	72	0.00745	23 %	29 %
FR-RO (Phase 3) After Final Expansion	89	113	0.00343	15.5 %	13 %

3.1.2. FR-RO recovery rate optimization (phase 1a)

Fig. 3 shows the step change in pilot recovery during Phase 1a, initiated on 11/1/2021 at 85 % overall recovery with FR and BR. The BR frequency was set at 1 h for the first and third stages and 10 h for the second stage, with a pilot feed flow rate of ~114 L/min and a total permeate flux of 19.8 LMH. The relative % L_P decline and fouling rate with active FR and BR over 29 days were slightly higher than in conventional (control) RO mode.

On 12/10/2021, the overall recovery was increased to 88 % (or ~ 87 % actual recovery accounting for the transitional periods). The pilot operated at this setpoint for about 27 days, maintaining stable stage-specific water permeability. On 1/14/2022, the recovery was raised to 90 % and the pilot operated for 37 days with minimal fouling (Fig. 4). The overall relative L_p decline was only 4.5 %, corresponding in an overall fouling rate of ~0.00269 LMH/bar/day, and a projected 3 months L_p decline of 11 % (Table 3).

Following a complete cleaning-in-place (CIP #1, Text S3 and Table S4), the recovery was raised to 91 % on 2/24/2022. Over 49 days, the overall L_p decline reached 16 %, with stage-specific declines of 25 % (Stage 1), 11 % (Stage 2), and 3.2 % (Stage 3). The fouling rate increased to ~0.00764 LMH/bar/day, with a projected 3-month L_p decline of 29 % (Fig. 4, Table 3, Table S2). Unexpectedly, the permeability in the first stage decreased at a much faster rate (about four times faster) than during the 90 % recovery period (0.016 LMH/bar/day vs. 0.040 LMH/bar/day), noted in Table S2. This increased fouling rate on the first stage necessitated decreasing the BR interval for Stages 1 and 3 from 1 h to 40 min on 3/3/2022 while keeping the second stage FR at 10 h.

Raising the recovery to 92 % resulted in even more rapid fouling. Over about 53 days, the overall L_p decline was 32 %, corresponding to fouling rate of ~0.0127 LMH/bar/day and a projected 3 months L_p decline of 54.5 % (Table 3). It was later realized that between 4/23/2022 to 5/18/2022, the total permeate flux was set too high at 22 LMH while operating at 92 % recovery. This over-fluxing led to an imbalance in stage flux and rapid fouling in all three stages (Fig. 4). To mitigate this, the permeate flux was lowered to 19.8 LMH on 5/18/2022, aligning with the previously mentioned optimal flux. The L_p for the third stage

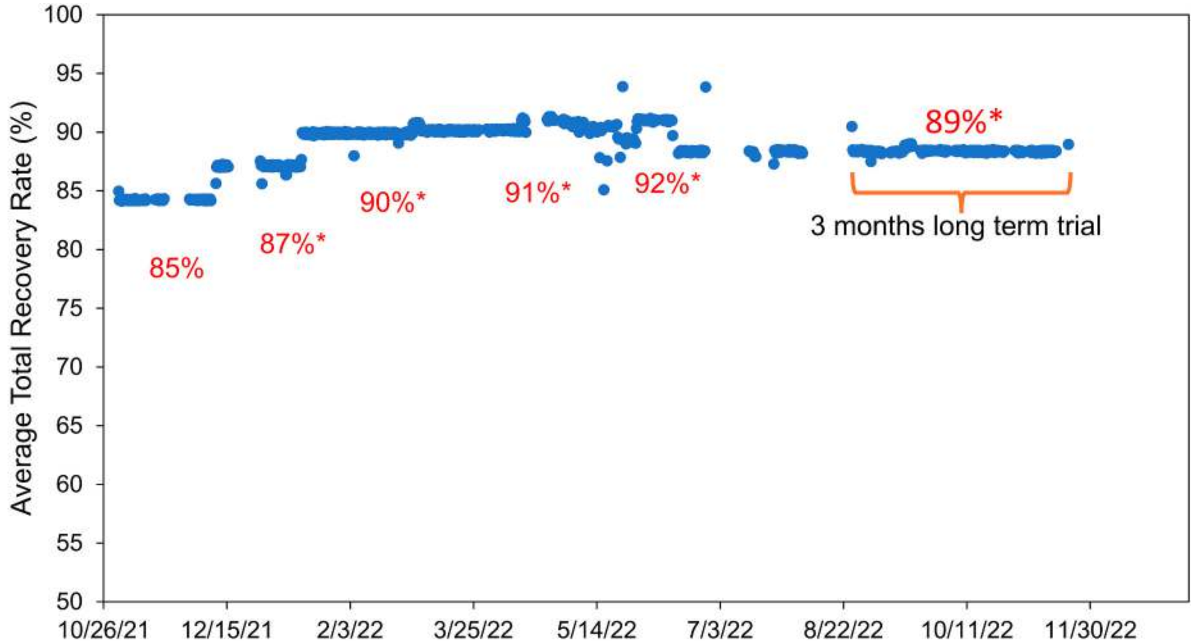

Fig. 3. Step changes in pilot overall recovery during Phase 1a (recovery optimization) and Phase 1b (steady state operation). The * symbol indicates the estimated actual recovery rate, accounting for transition period between block rotation and flow reversal, whereas the instantaneous recovery is about 1 % higher. RO feed conditions: pH 6.9, TDS ~1000 mg/L, and antiscalant AWC A-108 at 3.0 mg/L.

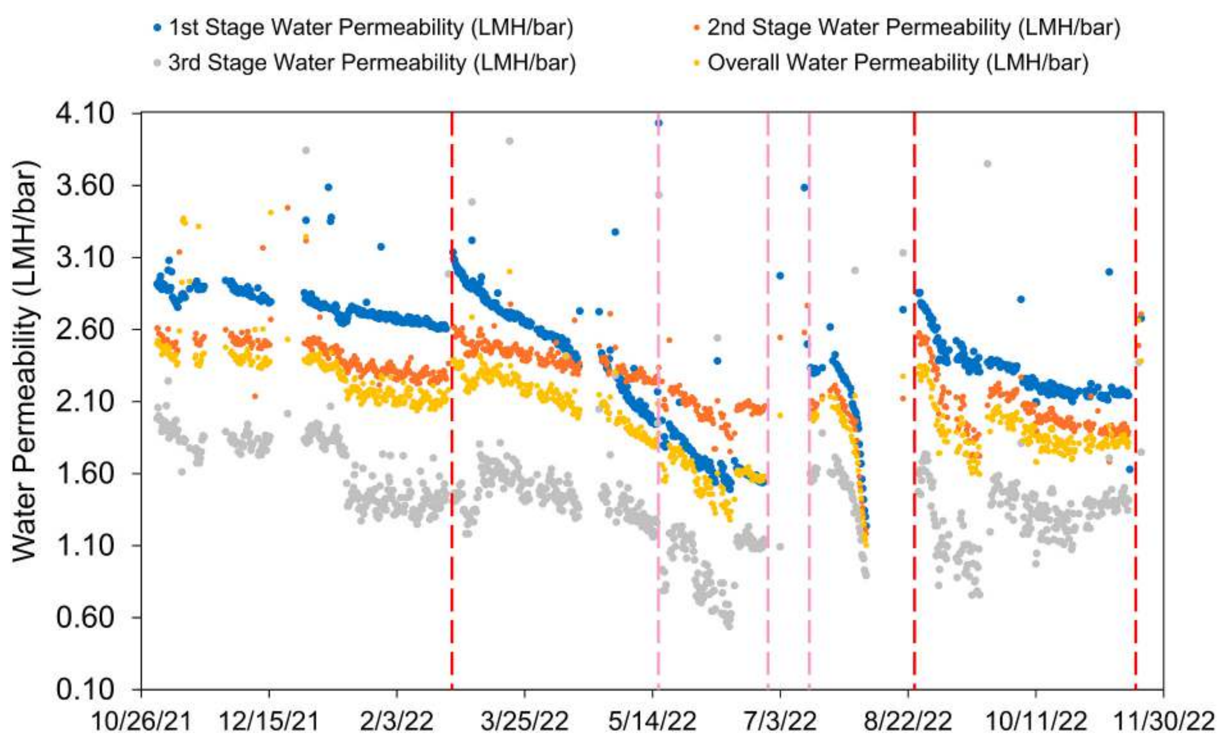

Fig. 4. Phase 1 FR-RO pilot stage-specific water permeability (normalized to 25 °C). RO feed conditions: pH 6.9, TDS ~1000 mg/L, and antiscalant AWC A-108 at 3.0 mg/L. Each data point represents an 8-h average. Red and pink dashed lines indicate successful and unsuccessful clean-in-place (CIP) events, respectively (details in Table S4 in SI). The next figure provides a detailed view of the final CIP interval (August to November 2022).

decreased below 0.98 LMH/bar (due to fouling), likely causing membrane damage (Fig. 4).

Several mechanical and fouling issues arose during Phase 1a. Details, including solutions and impacts, are provided in the Supplemental Information Text S2. Notably, in July 2022, the use of citric acid for pH control led to rapid fouling and severe biological fouling, but switching to sulfuric acid (93 wt%) as is utilized for RO at full-scale effectively mitigated these issues. Based on Phase 1a results, 90 % recovery provided a reasonable balance between fouling rate and run time. The normalized electrical conductivity (EC) rejection remained stable from Oct 2021 to March 2022 but started to decrease in April 2022 and reached its lowest point (~94 %) in mid-August 2022 (Fig. 5).

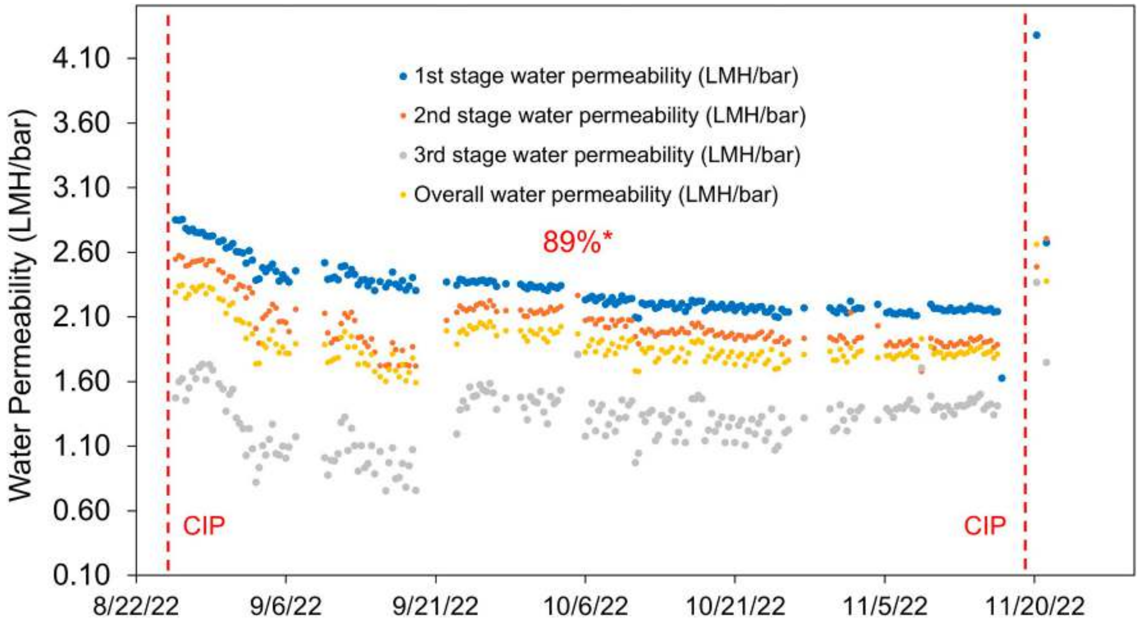

Fig. 5. Stage-specific water permeability (normalized to 25 °C) during long term trial Phase 1b. RO feed conditions: pH = 6.9, TDS = ~1000 mg/L, and antiscalant = AWC A-108 at 3.0 mg/L. Red dashed line indicates successful clean-in-place (CIP) event (Table S4 in SI).

3.1.3. Steady state operation (phase 1b)

Following a high pH CIP (CIP #6, Table S4), a steady-state trial for nearly three months was carried out from August 25 to November 16, 2022 to confirm whether stable performance could be maintained at the maximum recovery identified in Phase 1a. The trial achieved ~89 % overall recovery (90 % instantaneous recovery) with a total permeate flux of 19.7 LMH. Fig. 5 shows the normalized L_p across the three stages; no rapid declines were observed. The gradual L_p decline was faster than the previous 90 % recovery trial (perhaps due to the multiple prior membrane CIPs, Table S4) and similar to the previous 91 % recovery run. As shown in Table 2, the relative L_p declines over 72 days were 23 %, corresponding to an overall fouling rate of 0.00745 LMH/bar/day and a projected three months L_p decline of 29 %. Compared with a full-scale AWPF RO unit (85 % recovery) during a similar period, the FR-RO pilot exhibited more uniform fouling rates across all stages, whereas the full-scale system showed higher fouling rates in the second and third stages, with the third stage fouling the fastest (0.00852 LMH/bar/day). The overall fouling rate for the conventional RO unit was lower (0.00502 LMH/bar/day), as anticipated based on its lower recovery (Supplemental Information Fig. S6; Table S3).

The normalized salt rejection of the RO membrane gradually increased during the trial, though it remained relatively low (Fig. 6). The water permeability and salt rejection results indicate that the FR-RO pilot can maintain stable performance over an extended period before requiring a CIP. At the end of Phase 1, a high pH CIP (CIP #7, Table S4) was completed in order to transition to the next phase. The CIP restored permeability (Fig. 5) and maintained good salt rejection (Fig. 6).

An autopsy of the tail element from PV block D —operating 25 % of the time as a third-stage element and 75 % as a first-stage element—revealed that reduced water permeability was caused by organic deposition and silica precipitation at feed spacer contact points. Abrasion at these points likely contributed to decreased salt rejection. Dye testing detected membrane damage at locations with heavier granular deposits.

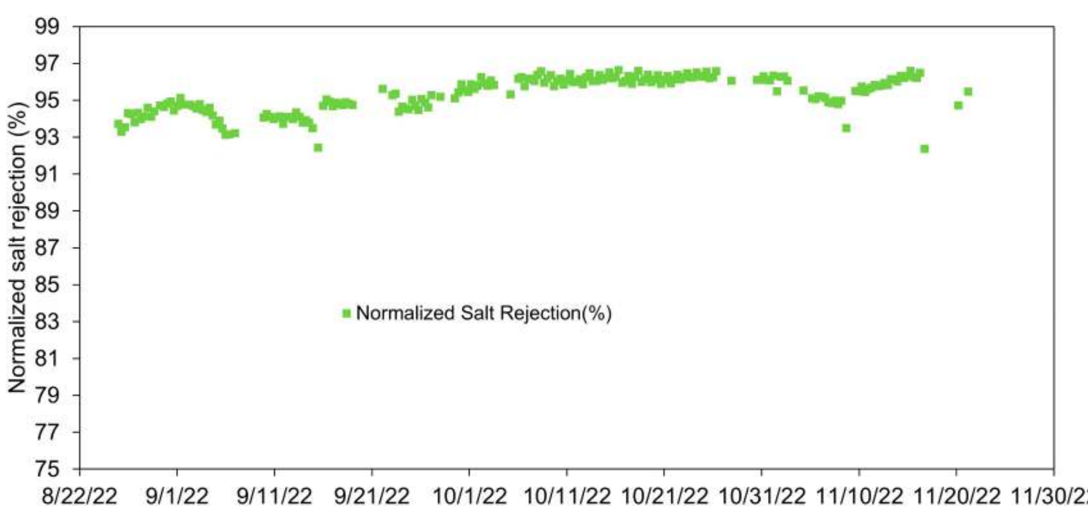

Fig. 6. Normalized salt rejection of the FR-RO pilot (8-h average) during 3-month operating period at 89–90 % recovery rate (Phase 1b). RO feed condition: pH adjusted to 6.9. TDS: ~1000 mg/L.

3.1.4. Concentrate overshoot issue and observations

In FR-RO systems, "concentrate overshoot" is observed during state transitions, particularly during feed flow reversal in the second stage [20]. This phenomenon occurs due to a temporary disruption in the concentration profiles along the membrane modules, leading to a significant increase in solute concentration in the brine. This overshoot can potentially cause scaling and fouling issues, adversely affecting the performance and longevity of the membranes.

Fig. 7 shows the concentrate overshoot observed during the FR-RO pilot trials in Phase 1a at 90 % recovery. During each transition period, ROC EC increased by 6–15 %, with more pronounced concentrate overshoot (15–17 %) during second stage FR (highlighted by the red circled areas in Fig. 7). These concentrate overshoots create local concentration hotspots within the membrane elements, which are suspected to accelerate scaling. Similar overshoot issues were reported in the City of Santa Monica FR-RO pilot study, which recorded overshoots of up to 20 % at 90 % recovery [20]. Less frequent second stage FR could help mitigate this issue.

3.2. Phase 2: FR-RO treating AWPF RO concentrate (brine concentrator mode)

3.2.1. Recovery rate optimization

The brine concentrator (BC) mode test began on January 10, 2023 (Fig. 8), with a block switching time of 1 h and a 75-s acidic RO permeate flush from the permeate side. To ensure the effectiveness of the antiscalant, 4 mg/L of AWC A-108 was added to the ROC (pilot feed). Proton® modeling indicated that a conventional one-stage RO concentrator could operate at 40 % recovery with this antiscalant dosage (see Supplemental Information Text S1).

The recovery setpoints were gradually increased from 28 % to 45 %, corresponding to a permeate flux of 6.63–8.84 LMH (Fig. 8). At the initial low recovery of 28 %, the normalized L_P showed a sharp decline, with an initial water permeability at 2.50 LMH/bar (Fig. 9). The fouling rate in the first 15 days (0.066 LMH/bar/day) was about 10 times greater than in primary RO mode, indicating rapid fouling or scaling. Between February 4–19, a caustic permeate flush was performed every 12 h from the feed side, in addition to the more frequent acidic permeate flush, to evaluate performance improvement. Despite increasing the recovery to about 45 %, the rate of L_P decline did not worsen, with feed pressure remaining at 15.9–17.2 bar. By the end of the trial, the normalized L_P declined to 0.96 LMH/bar (55 % of the initial value), while the feed pressure increased to 16.6 bar.

The highest recovery achieved during this phase of testing (BC mode) translated to an overall recovery of 91.8 % (i.e., assuming permeate from FR-RO given 45 % recovery is added to primary facility RO permeate in theoretical full-scale system). However, accounting for permeate loss due to flushing (~358 L every 1.5 h), the actual overall recovery of the FR-RO pilot would be ~90.7 %.

Fig. 10 shows the normalized salt rejection (based on EC) over the course of the trial. As membrane fouling progressed, the normalized permeate conductivity decreased and stabilized. This may be due to the gradual recovery of the polyamide RO membrane pores from a swollen state to a normal state over time, leading to decreased pore size and increased rejection [26].

3.2.2. Performance issues in brine concentrator (BC) mode

In BC mode, the pilot aimed to recover water from challenging feed water: ROC from the AWPF RO system. Feedwater quality variability during 2023 (Table 1) significantly impacted pilot performance. The AWPF ROC showed substantial EC variations due to changes in the proportion of OC San Plant 2 TF/SC effluent within the secondary wastewater stream feeding the AWPF. For example, in late February 2023, the RO feed EC dropped from 2500 μS/cm to ~1800 μS/cm, causing the AWPF ROC EC to fall below 9000 μS/cm on several days (Supplemental Information Fig. S3). These fluctuations posed operational challenges, affecting recovery rates and system stability.

Based on the BC mode results, the operation was deemed unsustainable due to rapid fouling, high chemical usage, and ineffective CIP cleaning. The initial drastic L_P decline suggests rapid fouling or scaling, or potentially membrane damage, as indicated by autopsy X-ray photoelectron spectroscopy (XPS) results. The chemical usage during this phase was high, from sulfuric acid use for acidic permeate flush, and particularly the consumption of 4 mg/L of antiscalant (in addition to the 3 mg/L antiscalant already added to the primary RO system feed in the full-scale facility). For example, approximately 488 L of 93 % sulfuric

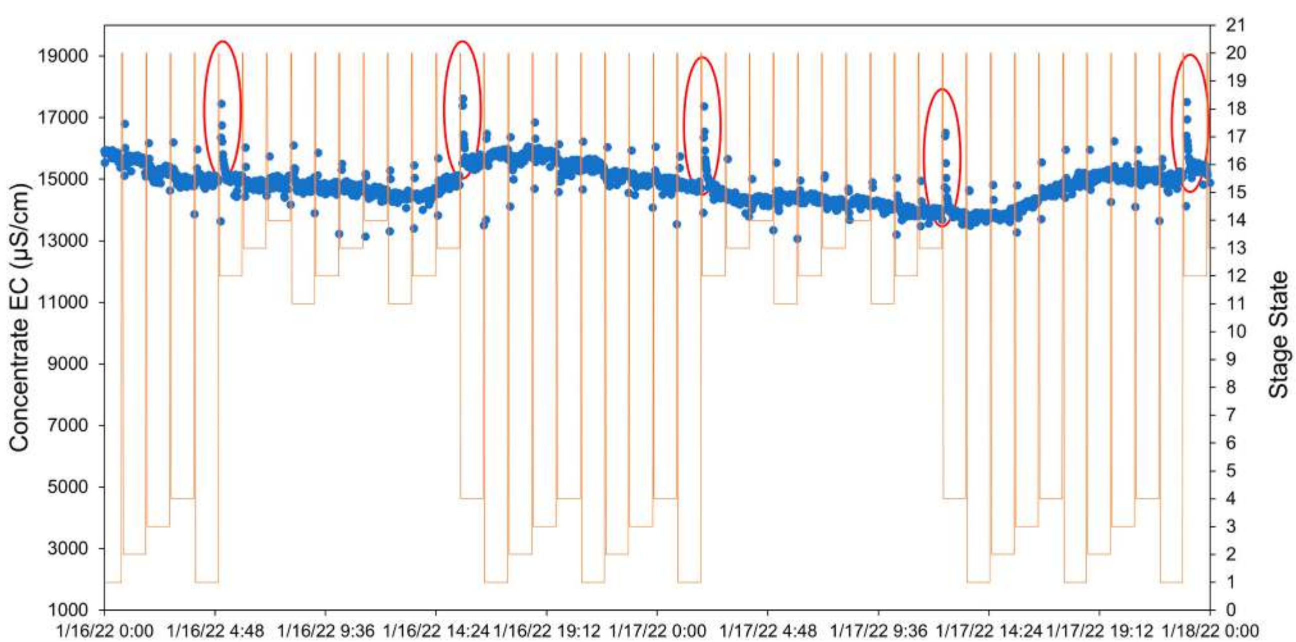

Fig. 7. Illustration of concentrate overshoot in FR-RO pilot during operation at 90 % recovery, showing RO concentrate electrical conductivity (EC) (primary y-axis) and stage state (secondary y-axis) from Phase 1a. Each system configuration has a designated state number (see Fig. S2 for details). States 11–14 mirror States 1–4 but with reversed feed flow in the second stage. In State 20, blocks are temporarily isolated, reducing system capacity.

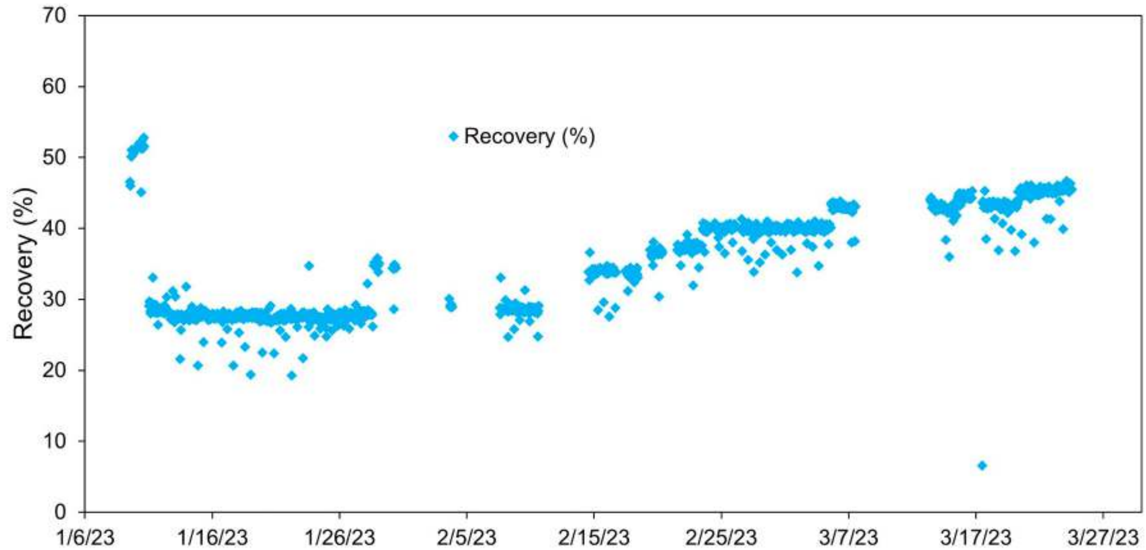

Fig. 8. FR-RO pilot recovery during brine concentrator (BC) mode test (Phase 2). RO feed condition: pH = 7.5, EC: ~8000–14,000 μS/cm. Antiscalant: AWC A-108 addition of 4.0 mg/L in the feed (AWPF RO concentrate).

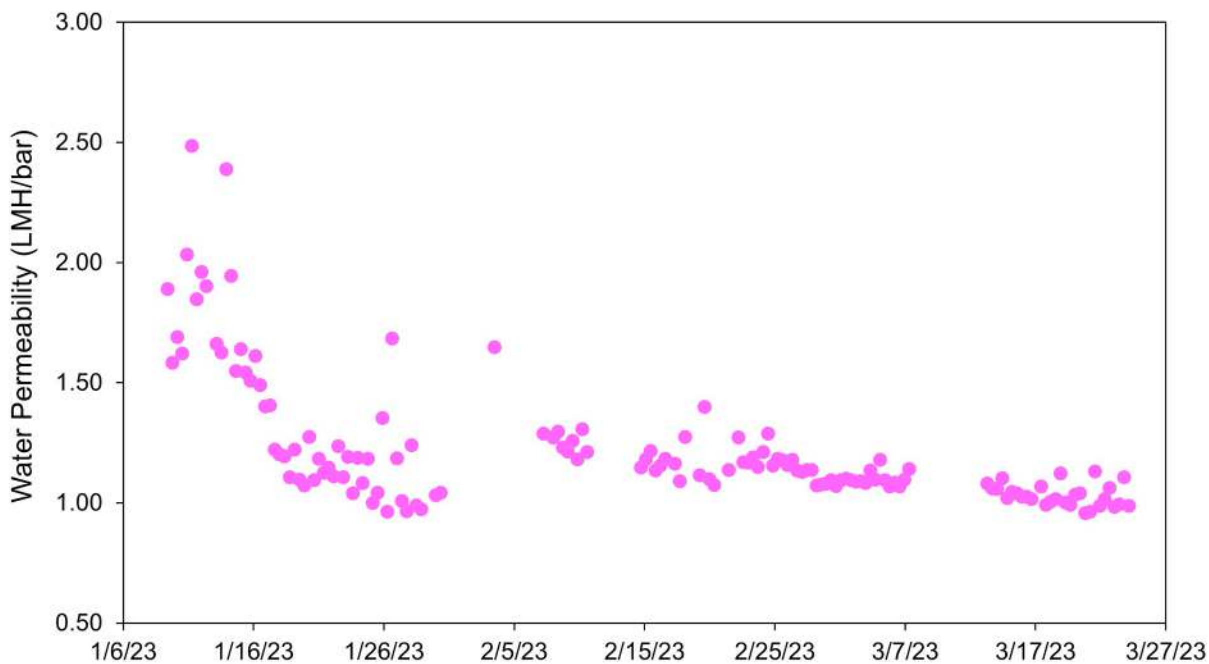

Fig. 9. FR-RO pilot water permeability (normalized to 25 °C) during brine concentrator (BC) mode test (Phase 2). RO feed condition: pH = 7.5. EC: ~8000–14,000 μS/cm. Antiscalant: AWC A-108 addition of 4.0 mg/L in the feed (AWPF RO concentrate).

acid was required over two months. Safety concerns were raised due to the large volumes of concentrated sulfuric acid.

Despite performing high and low pH CIPs (CIP no. 8, Table S4), the pilot's post-CIP feed pressure remained elevated at 14.5 bar when treating RO feedwater in primary RO mode. Troubleshooting ruled out mechanical issues, as stage differential pressure appeared normal, and membrane visual inspection showed no signs of physical damage or fouling. Post-CIP unrecoverable membrane fouling is often due to irreversible compaction, which can occur at pressures as low as 7–14 bar [27].

A membrane autopsy on a tail element from PV block C revealed no serious scaling or fouling, pointing to potential change in membrane properties as the cause of the L_p decline. XPS scans showed Br and Cl peaks, suggesting bromination damage to the membrane's active layer, likely due to bromide reacting with chloramines present in the RO permeate used for flushing. Bromine, being bulkier than chlorine, creates a steric hindrance effect that decreases pore space, reducing permeability [28]. The total RO permeate flush time was about 24 h for BC mode, with the membrane's actual run time being 50 % of the total operating time, indicating rapid membrane degradation. Additional tests, including single-element flow tests and CIP studies (data not shown), confirmed low L_p and rejection across all PVs and membrane positions.

3.3. *Phase 3: FR-RO treating AWPF RO Feedwater with higher TDS*

3.3.1. *Pilot performance in phase 3*

The Phase 3 study aimed to confirm the operability of the FR-RO

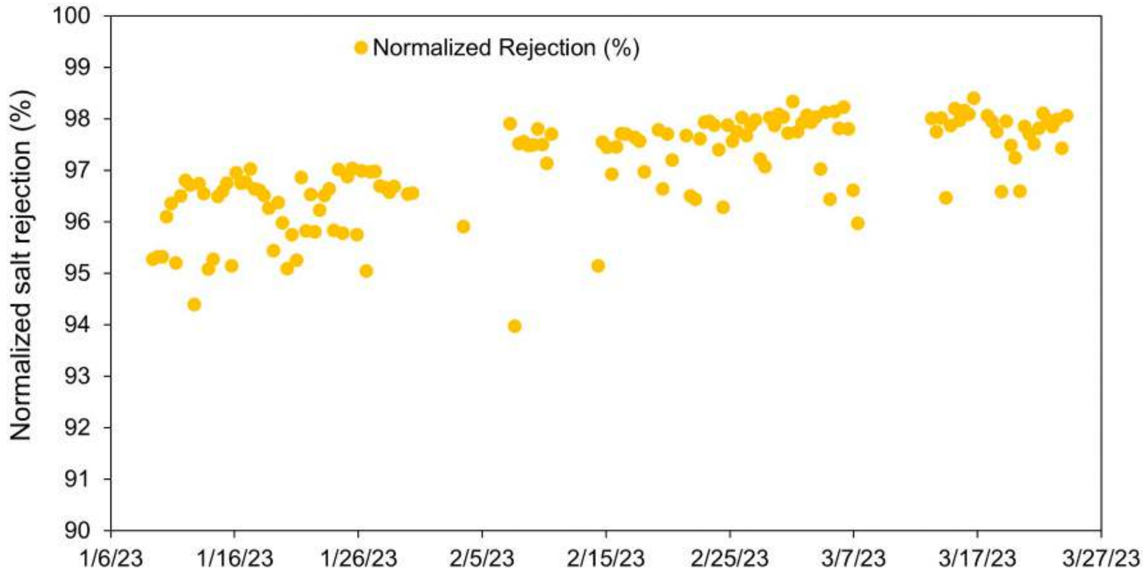

Fig. 10. FR-RO pilot normalized salt rejection during brine concentrator (BC) mode test (Phase 2). RO feed condition: pH = 7.5. EC: ~8000–14,000 μS/cm. Antiscalant: AWC A-108 addition of 4.0 mg/L in the feed (AWPF RO concentrate).

pilot at the maximum sustainable recovery rate determined in Phase 1, using AWPF RO feed water with higher TDS following the GWRS Final Expansion. The same approach was used as in Phase 1, with the objective of evaluating whether FR-RO could achieve higher recovery without the addition of further antiscalant or pH adjustment (beyond the existing dosages of antiscalant and acid in the primary facility ROF). A new set of membrane elements was installed to the pilot prior to starting. There were no changes in the operational parameters, such as BR every hour in the first and third stages and FR every 10 h in the second stage.

Fig. 11 shows the normalized L_P during Phase 3. Initially, the pilot operated at an 85 % recovery rate for a 6-day break-in period. The recovery was then increased to 87 % (i.e., 88 % instantaneous per Fig. 11) for 9 days. An extended run was conducted at 89 % recovery (i.e., 90 % instantaneous), with a total permeate flux of 20 LMH, from June 22 to October 21, 2023. During this period, the OC San P2 feed was offline for two months (August 7 to October 4, 2023), resulting in higher quality feed water with a TDS range between 952 and 1050 mg/L.

The relative L_P decline over the 114-day period (64 days with P1 + P2 blend feed and 50 days with P1 feed alone) was 14.6 %, 7.1 %, 13.4 %, and 15.5 % for the first, second, and third stages, and overall, respectively, as shown in Table 3 and Table S2. This corresponds to an overall L_P decline rate of 0.00343 LMH/bar/day. During the 50 days of running with P1 water alone, almost no change in L_P was observed. For the blended (higher TDS) feedwater (P1 + P2 blend), the expected estimated CIP interval would be approximately 6 months.

Compared to a full-scale AWPF RO unit operating at 85 % recovery during a similar period (2023), the FR-RO pilot demonstrated more evenly distributed fouling across all stages. In contrast, the full-scale AWPF RO unit had fouling rates of 0.00375, 0.00401 and 0.00897 LMH/bar/day, in the first, second, and third stages, respectively, with

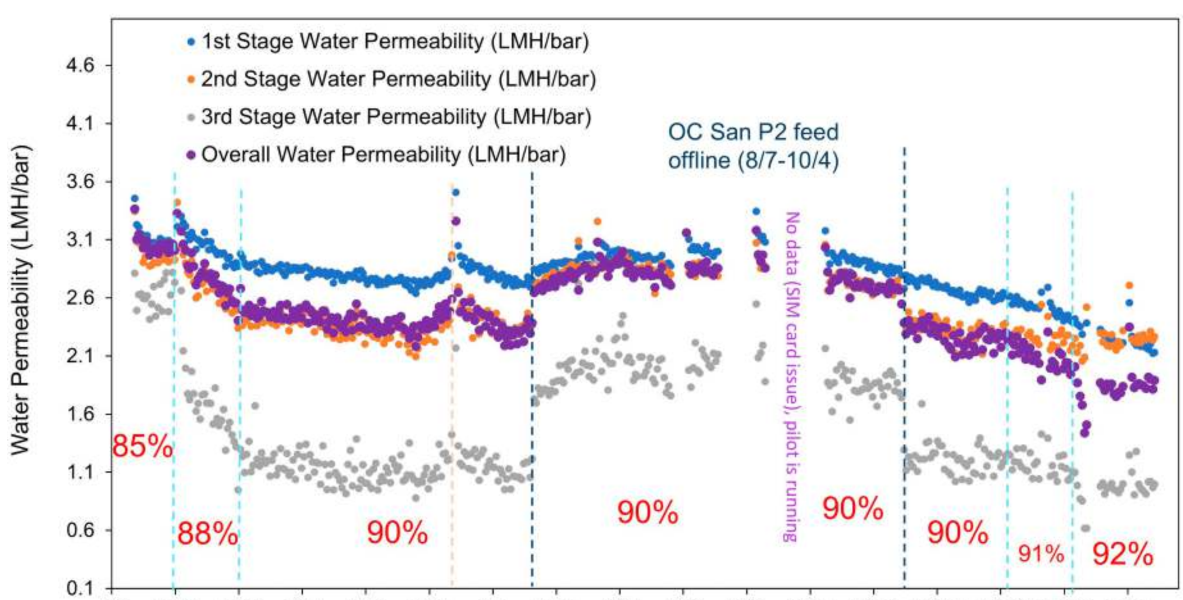

Fig. 11. Phase 3 FR-RO pilot stage-specific water permeability (normalized to 25 °C) (trial completed in 2023). RO feed conditions: pH 6.9, TDS ~900–1500 mg/L, and antiscalant AWC A-108 at 3.0 mg/L. Instantaneous pilot recovery is indicated in red below the curves.

the third stage fouling the fastest. The overall fouling rate for the conventional RO unit (0.00426 LMH/bar/day) was comparable to that of the FR-RO pilot during this phase (Supplemental Information Fig. S7; Table S3). These results confirmed the pilot's acceptable performance with current (post-Final Expansion) AWPF RO feed water, validating its suitability for potential full-scale implementation.

After the 90 % run, the pilot was stress tested at 91 % and 92 % instantaneous recovery. Shortly after increasing the recovery from 91 % to 92 %, a rapid decline in Stage 3 water permeability occurred, likely due to silica scaling, as described in the next section. Overall, the results suggest that 92 % recovery is not sustainable but that 91 % (90 % actual) may be feasible. Despite the rapid decline in L_p at greater recovery, the normalized salt rejection remained within an acceptable range (Fig. 12), affirming the system's ability to consistently produce high-quality permeate with rejection values predominantly above 98 %. On July 11–12, 2023, 24-h composite samples were collected; the results confirmed the pilot's stable and consistent constituent removal capability, which was comparable to the full-scale RO unit (see Supplemental Information Fig. S19).

3.3.2. System operation during a fouling event

During a fouling event at 92 % recovery in Phase 3, Stage 3 of the FR-RO pilot system experienced a rapid decline in L_P, likely due to silica scaling triggered by the recovery increase from 91 % to 92 % (Fig. 13). The event was marked by elevated feed pressures, reduced permeate production, and slower L_P stabilization across stages, with Stage 3 showing the most severe effects.

Further analysis suggested that the Stage 2 flow reversal during BR contributed to the rapid scaling, disrupting the concentration profiles and potentially causing concentrate overshoot. During these transitions, Stage 1 also exhibited delayed stabilization of L_p, suggesting that fouling may have migrated from Stage 3. Despite Stage 2 maintaining relatively stable specific flux, the frequent BR cycles led to pressure spikes in Stage 3, reaching over 25 bar, indicating rapid fouling of relatively clean blocks as they rotated into the final stage. Additional discussions including timing details and figures are provided in the Supplemental Information Text S4.

Insufficient brine flow, below the recommended 15.1 L/min for 10 cm diameter RO elements, likely further accelerated fouling. RO permeate flushing after the event partially reversed the scaling, restored the L_p for all stages to their pre-scaling levels (as shown in Fig. 11, 92 % recovery region). These findings underscore the challenges of maintaining high recovery rates and emphasize the need for refined BR and FR protocols, as well as optimized brine flow.

An experimental approach involving temporarily lowering recovery in the first two stages during block rotation could potentially restore system functionality. In full-scale operations, a "relaxation" step—-where pump speeds decrease and the third stage booster shuts off—may contribute to fouling mitigation. It is hypothesized that the reduced recovery could promote scale dissolution in the first stage, while negative permeate osmotic pressure in the third stage could trigger a mild flushing effect via forward osmosis. Implementing such adjustments alongside increased crossflow velocity in the third stage may help reduce scaling risks and improve system stability during high-recovery operations.

3.4. Preliminary cost estimate for purification facility FR-RO retrofit

FR-RO technology offers the potential to increase the recovery rate of existing RO units or trains by implementing flow reversal (FR) and block rotation (BR) through modifications. ROTEC provided a preliminary retrofit design proposal to improve recovery from the current 85 % to 90 % (actual recovery of 89.5 % accounting for lower recovery during the transition period) for the GWRS AWPF RO facility, which has 27 RO units. The estimated capital cost for retrofitting a single 18,927 m^3/d RO unit to include FR and BR capabilities is approximately $1,790,000 (2023 dollars), or $1,863,390 after adjusting for inflation to 2024.The key assumptions and methods used in the cost estimate are detailed in Supplemental Information Text S5. The retrofit design includes additional PVs at stages 1 and 3 (total of 9 additional PVs), an additional booster pump between stages 2 and 3, and 34 actuated valves for FR operation (Fig. 14).

In terms of unit cost (i.e., dollars per volume of water produced), since an FR-RO retrofit of one RO unit would produce an additional 387,107 m^3/y or 1061 m^3/d, the unit cost is estimated to be $0.64/$m^3$ for capital costs (retrofit) only and assuming amortization over a 30-year loan period (Fig. 15). Note that if no loan is assumed, the cost is $0.27/$m^3$ over a 30-year assumed equipment life. For comparison, constructing a GWRS AWPF RO unit with a capacity of 18,927 m^3/d and an annual production of 6.9 million m^3 was estimated to cost $4,608,631 (in 2020

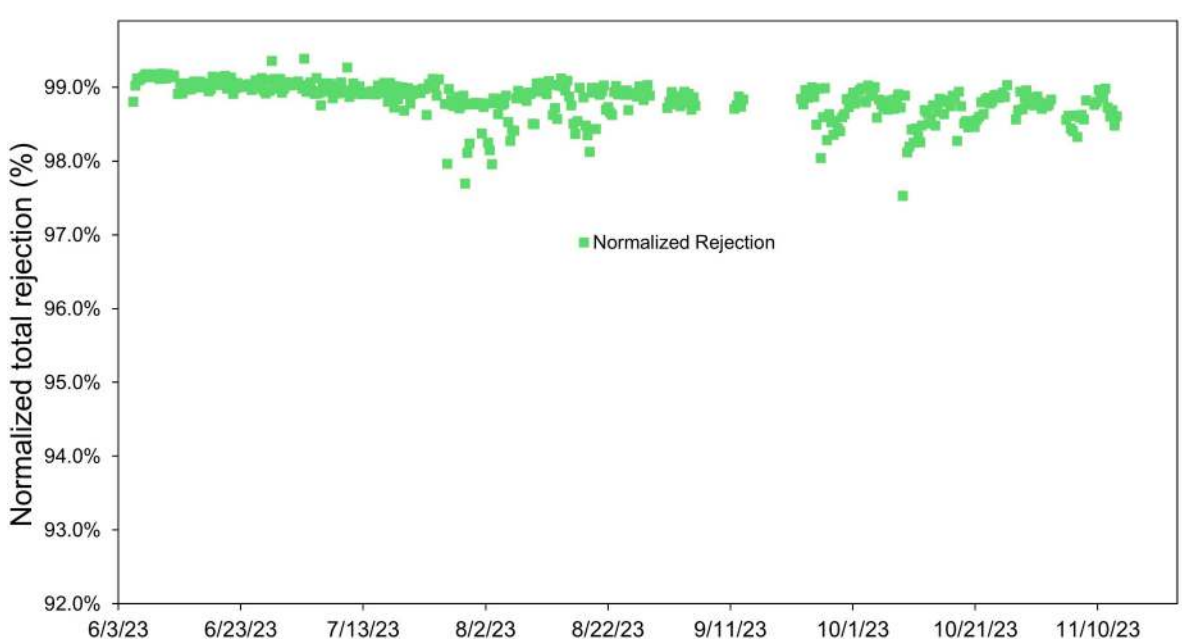

Fig. 12. Normalized total salt rejection (%) based on electrical conductivity over time during Phase 3 of the FR-RO pilot study from June 3 to November 10, 2023.

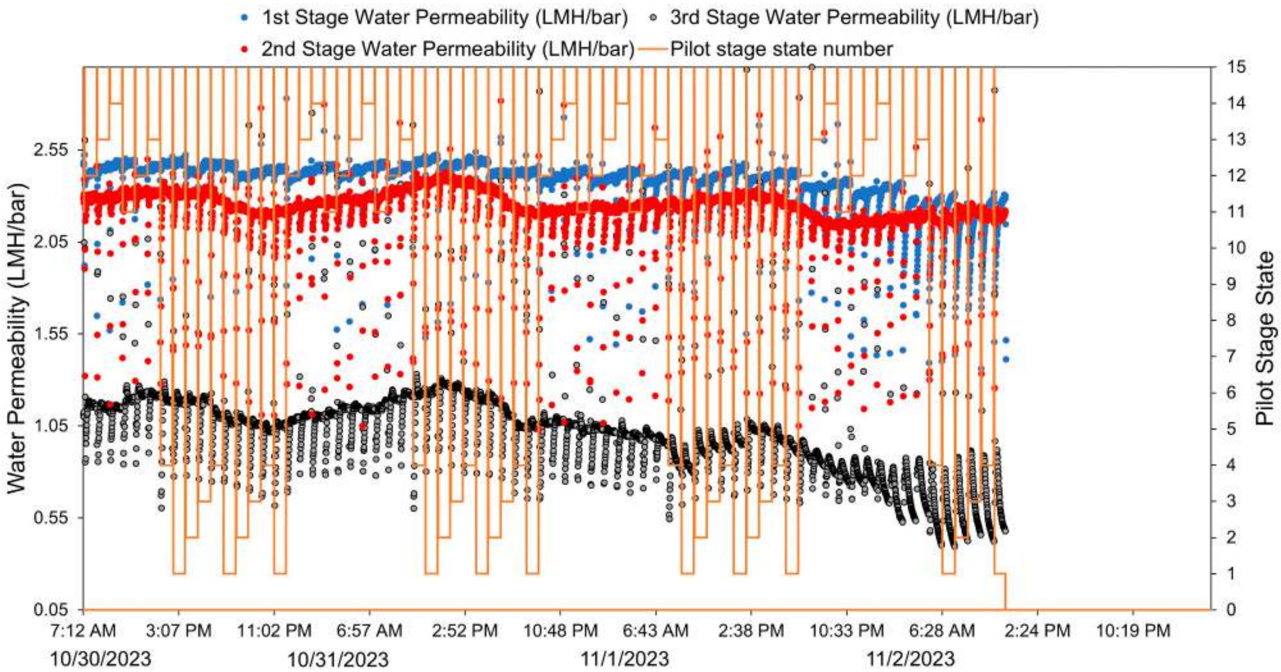

Fig. 13. Normalized membrane water permeability (LMH/bar) for the three stages of the FR-RO pilot in Phase 3 treating primary RO feed water. The recovery was increased from 91 % to 92 % shortly after 12 am on November 1, 2023. A rapid decline in Stage 3 specific flux occurred two hours after increasing recovery from 91 % to 92 %.

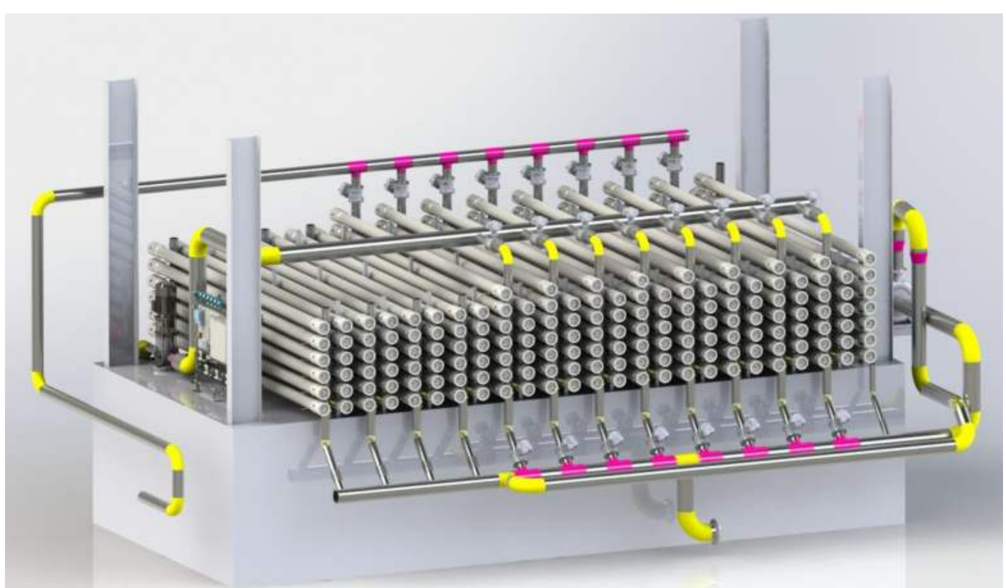

Fig. 14. Illustration of the retrofit design for a 3-stage GWRS AWPF RO unit to enhance the system's recovery rate from 85 % to 90 %. The retrofit would include additional pressure vessels, booster pump and actuated valves for flow reversal and block rotation.

dollars), or $6,768,927 after adjusting for inflation to 2024. Amortized over 30 years, this equates to about $0.13/m^3 of permeate water produced (Fig. S22). The capital unit cost of the retrofit is higher because the capital investment produces a relatively lower amount of *additional* (new) water, i.e. only about 1060 m^3/d for an almost $2 M investment compared to 18,927 m^3/d from the original $7 M investment. However, when the unit cost considers the total production (i.e., 18,927 m^3/d plus 1060 m^3/d retrofit), the combined unit cost (capital only) for a 19,987 m^3/d FR-RO (90 % recovery) system is approximately $0.16/m^3. Incorporating O&M costs based on the current 18,927 m^3/d RO unit and accounting for additional CIPs required due to increased recovery observed in the pilot study, the total life-cycle unit cost for the 19,987 m^3/d FR-RO system rises to $0.25/m^3 (including capital and O&M), compared to $0.21/m^3 for the original 18,927 m^3/d RO unit (Fig. S22). Note that these costs only reflect the RO portion of the MF/UF-RO-AOP treatment train at AWPF; for comparison, the overall AWPF water cost is approximately $0.71/m^3 and the cost of treated imported water in southern California (the study site) is $1.02/m^3 for 2024 and $1.13/m^3 for 2025.

The preliminary cost estimate indicates that while the FR-RO retrofit enables a higher recovery rate to produce more water, it requires a significant investment. Not surprisingly, including the base production

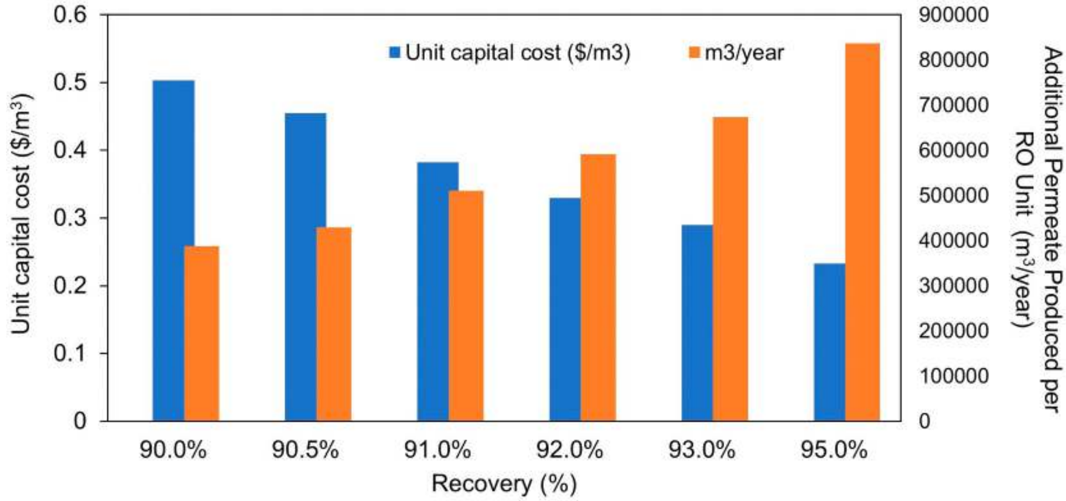

Fig. 15. Estimated unit Capital Cost ($/m^3) for FR-RO retrofit and additional permeate produced per RO Unit (m^3/year) vs. FR-RO system permeate recovery.

(in this case, 18,927 m^3/d) of the RO system *significantly* reduces this apparent unit cost. In any case, future advancements in FR technology, antiscalant, or membrane performance could significantly reduce the unit capital cost, as illustrated in Fig. 15 where just a 1 % increase in recovery from 90 % to 91 % is estimated to increase the additional permeate produced by the RO unit by 123,104 m^3/y and therefore lower the unit capital cost by $0.153/m^3. A professional cost estimate is necessary in future project stages to confirm the findings from this preliminary analysis.

4. Conclusions

This study demonstrated the potential for employing flow-reversal RO (FR-RO) technology to enhance recovery of municipal potable reuse. Through an 18-month pilot study conducted over three phases, the research evaluated the performance of FR-RO across different feed water sources and configurations. Treatment of RO concentrate to recover more water by FR-RO was not successful, exhibiting rapid membrane fouling and high CIP chemical usage. When FR-RO was implemented to treat MF/UF filtrate (representing RO retrofit), a 5 % improvement in recovery rate was achieved, reaching 90 % recovery. Water permeability and salt rejection performance remained sustainable at ~90 % recovery over long-term operation, with potential for ~91 % with additional refinements. Preliminary cost estimates suggest that retrofitting existing systems with FR-RO is economically viable, although further advancements may reduce costs and improve efficiency. Research is needed to address challenges such as concentrate overshoot that was observed during flow reversals, as well as to optimize system reliability and mitigate fouling and scaling risks during high recovery.

CRediT authorship contribution statement

Han Gu: Conceptualization, Visualization, Investigation, Funding acquisition, Writing – original draft. **Megan H. Plumlee:** Conceptualization, Resources, Supervision, Funding acquisition, Writing – review & editing, Project administration. **Mingheng Li:** Formal analysis, Visualization, Investigation, Writing – review & editing. **Auryan Mohseni:** Investigation, Resources. **Ronit Erlitzki:** Conceptualization, Resources, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Auryan Mohseni and Ronit Erlitzki reports financial support was provided by U.S. Department of the Interior, Bureau of Reclamation. Han Gu and Megan H. Plumlee reports financial support was provided by Southern California Salinity Coalition. Mingheng Li reports financial support was provided by the National Science Foundation. Auryan Mohseni, Ronit Erlitzki reports a relationship with Chart Industries that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.desal.2025.118594.

Data availability

Data will be made available on request.

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