High-recovery Inland Brine Management for California Water Resilience (Comparative Field Performance of Switchable-solvent Softening and Electro-membrane Concentration Across Five Pilot Demonstrations)

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Abstract:

This study evaluates high-recovery, non-thermal brine management strategies for inland desalination and water reuse applications in California, where water scarcity and regulatory pressures are increasing. The objective was to assess the technical feasibility and cross-site robustness of two alternative treatment pathways: (i) switchable-solvent softening coupled with membrane concentration, and (ii) electrodialysis metathesis (EDM) integrated with osmotically assisted reverse osmosis (OaRO). A mobile pilot system was deployed across five field sites treating diverse feedwaters, including brackish groundwater, reverse osmosis (RO) concentrate, municipal recycled-water brine, winery wastewater, and agricultural greenhouse brine. Site-specific pretreatment and polishing steps were incorporated as required to address variations in chemistry, including silica, organics, and scaling salts. Results show that the EDM–OaRO pathway provided the most consistent and scalable performance, achieving overall water recoveries of 84.2–98.4% across all sites and demonstrating effective control of scaling through ion-selective separation. In contrast, the switchable-solvent pathway successfully removed scale-forming salts in selected cases but exhibited strong dependence on feed chemistry and was constrained by solvent regeneration challenges, particularly flash-chamber performance and residual solvent removal. The findings demonstrate that membrane-based, non-thermal brine management can significantly reduce brine volume while increasing recoverable water, offering a viable pathway toward near-zero liquid discharge (ZLD) for inland applications. Among the evaluated approaches, EDM integrated with OaRO is identified as the most promising near-term solution for deployment across variable water chemistries, while switchable-solvent treatment remains a valuable selective pretreatment technology requiring further optimization.

Keywords: Inland desalination; brine management; SGMA; California agriculture; electrodialysis metathesis; OaRO; switchable solvent; zero liquid discharge; water reuse

1. Introduction

California's water-supply problem is increasingly defined by the intersection of climate stress and groundwater regulation. Groundwater contributes about 41% of statewide supply in average years and up to 60% in dry years, making it the state's principal drought reserve. At the same time, the 2020–2022 period became California's driest three-year period on record, underscoring the growing volatility of the state's hydrology. SGMA, enacted in 2014, requires local agencies in high- and medium-priority basins to form groundwater sustainability agencies, develop groundwater sustainability plans, and avoid undesirable results while bringing over-drafted basins into long-term balance. (California Department of Water Resources, 2026; California State Water Resources Control Board, 2026; Water California)

For California agriculture, the consequences are structural rather than temporary. In the San Joaquin Valley, updated PPIC analysis projects that average annual water supplies for agriculture could decline by about 20% by 2040 under the combined effects of SGMA implementation, climate change, and environmental flow constraints, with nearly 900,000 acres potentially at risk of fallowing in the most constrained scenario (Escriva-Bou et al., 2023). Although local annual impacts may be larger in some basins or drought periods, the best-supported regional benchmark for a submission-ready paper is this 20% valley-scale decline.

Under these conditions, inland brackish desalination and water reuse become increasingly important. Yet inland desalination is often limited less by production of the first increment of permeate than by management of the remaining concentrate. Brine disposal and treatment remain among the principal cost and permitting bottlenecks for inland systems, especially where ocean outfall is unavailable and disposal relies on evaporation ponds, trucking, or deep-well injection (Panagopoulos et al., 2019; Tang et al., 2022). OaRO has emerged as a promising membrane-based route for concentrating high-salinity brines beyond the practical limits of conventional RO, while EDM has gained interest as a selective tool for separating scaling ions and increasing overall hydraulic recovery (Bartholomew et al., 2017; Peters and Hankins, 2019; Oddonetto et al., 2024).

The present work synthesizes five Trevi/GWI field pilots conducted in California to compare two high-recovery, non-thermal brine-management pathways: switchable-solvent softening plus OaRO, and EDM plus OaRO.

To illustrate the conceptual basis of the two treatment approaches evaluated in this study, schematic representations are provided below. These figures highlight the fundamental differences between precipitation-driven softening and electro-membrane-based ion separation for enabling high-recovery brine concentration.

Figure 1. presents the switchable-solvent-based treatment pathway, in which sparingly soluble salts are removed through selective precipitation prior to downstream concentration.

Figure 2. presents the EDM-based pathway, where ion-selective transport is used to generate a lower-salinity diluate stream and chemically conditioned concentrate streams suitable for further membrane concentration.

Fig 1. Switchable Solvent driven brine concentration (courtesy INL).

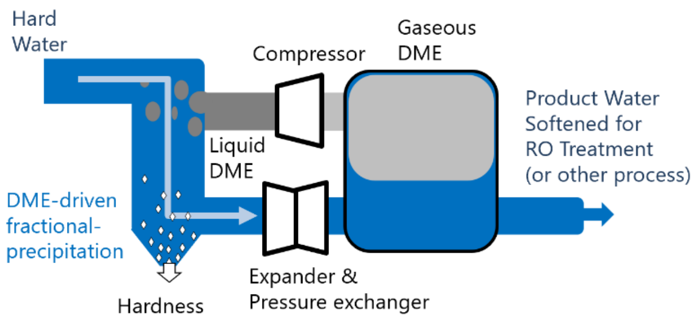
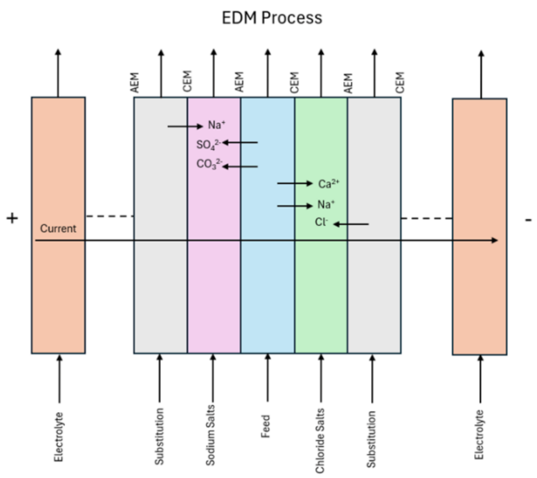


Fig 2. EDM driven brine concentration.



The objective was not merely to demonstrate technical feasibility at a single water chemistry, but to evaluate cross-site robustness under realistic agricultural, municipal, and industrial conditions. The pilots therefore provide a field basis for assessing which process route is better suited for near-term deployment in SGMA-constrained California settings.

2. Materials and methods

2.1. Pilot program overview

A mobile Trevi/GWI pilot platform was deployed at five California sites: Pleasant Valley (Coalinga brackish groundwater), San Luis Obispo (evaporation BWRO pond brine), Trinchero Winery (MBR brine from winery wastewater), Cambria (municipal recycled-water BWRO brine), and Windset Farms (greenhouse BWRO brine). The report's stated program objective was to test whether high-recovery, non-thermal process trains could achieve 95%+ water recovery across brines spanning approximately 8,000 to 30,000 ppm with varying chemistries and scaling tendencies. The broader commercialization target was to reduce the cost of inland near-ZLD brine treatment well below conventional thermal ZLD price points.

2.2. Process configurations

Two alternative treatment trains were evaluated. In the first, RO brine or feed brine was contacted with a switchable solvent to precipitate sparingly soluble salts, primarily $CaSO_4$ and $CaCO_3$, followed by solvent regeneration and, where feasible, OaRO concentration. In the second, EDM was used to produce a lower-salinity diluate stream and one or two concentrate streams suitable for downstream OaRO concentration. Site-specific pretreatment included ultrafiltration, degasification, silica-removal media, and final RO polishing. At Cambria, a monovalent selective electrodialysis (MSED) sub-trial was also performed.

2.3. Performance metrics

The principal response variables were overall water recovery, product-water salinity, switchable-solvent residual concentration, switchable-solvent regeneration energy, EDM $CaSO_4$ removal, EDM energy use, and OaRO energy use. Where late-stage OaRO was not physically run for a given switchable-solvent stream, the report explicitly identified modeled rather than directly demonstrated outcomes; those distinctions are preserved in the discussion below.

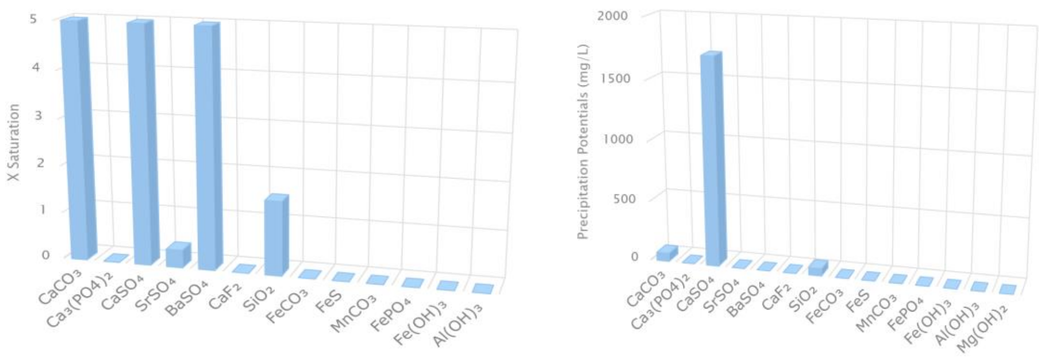
3. Results and discussion

3.1. Pleasant Valley: both trains were viable, but EDM/OaRO was more operationally robust

Pleasant Valley groundwater had relatively modest TDS of 1777mg/L and significant calcium carbonate, as well as calcium and barium sulfate scaling with the scaling indices at 5X saturation as shown in Fig 3 below. Scaling compounds are identified by first running standard scaling analysis software against a hypothetical recovery rate of 80%, then the actual RO was then operated close to the modeled 80% limit. At 77% recovery, the RO permeate measured 10 mg /L TDS.

The switchable-solvent pathway removed 60% of CaSO4 from the RO brine and achieved 98.3% overall recovery, but residual solvent remained high after the flash step and required repeated membrane-contactor DME strip passes, with projection to 5.4 mg/L only after 11 passes.

Fig 3. Pleasant Valley water @80% recovery – scaling compounds of concern.

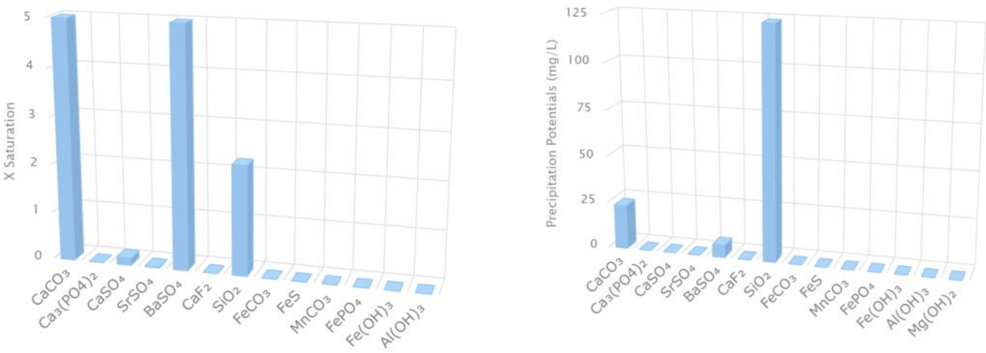


Regeneration energy was 9.0 kWh/m3. By contrast, the EDM/OaRO pathway removed 86.5% of CaSO4, used 0.91 kWh/m3 for EDM and 1.45 kWh/m3 for OaRO, and achieved 98.4% overall recovery with blended permeate of 216 mg/L. The site therefore showed that both pathways were technically feasible, but EDM/OaRO was simpler and less regeneration-limited.

3.2. San Luis Obispo: high silica and low hardness favored EDM over switchable-solvent treatment

The San Luis Obispo brine pond was dominated by magnesium chloride as the major constituent with relatively little precipitable hardness (calcium carbonate) and substantial silica with a TDS of 11,277mg/L as shown in the scaling analysis, at 50% recovery in Fig 4 below (limited by silica scaling). Actual RO recovery was capped near 50% because of the silica scaling risk. As anticipated, switchable-solvent treatment removed minimal scaling salts, left 4,481 mg/L solvent after a single contactor stage, and could not proceed to OaRO because the resulting stream remained silica-limited; reported regeneration energy rose to 34.3 kWh/m3. The EDM/OaRO route performed substantially better: EDM reduced the diluate from 11,277 to 1,910 mg/L, OaRO concentrated the brine to 85,170 mg/L, and overall recovery reached 84.2%. OaRO recovery to 140,000mg/L was subsequently achieved in laboratory testing, allowing recoveries to 91%.

Fig 4. San Luis Obispo water @50% recovery – scaling compounds of concern.

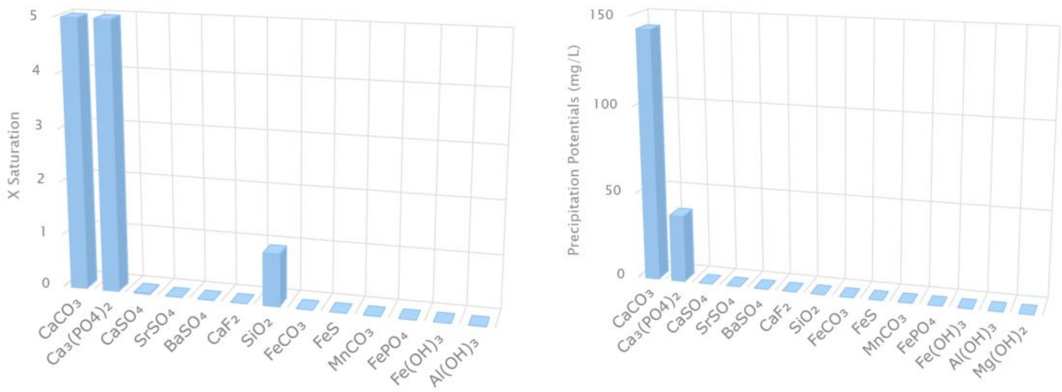


The mechanistic advantage here was that silica remained with the diluate rather than entering the PFO concentrate stages, thereby enabling higher downstream membrane concentration. Final overall recovery was limited by the high starting salinity of the feed and single stage PFO limitation of 140,000mg/L.

3.3. Trinchero Winery: pretreatment and fouling control were decisive

Trinchero MBR waste with a starting TDS of 2103mg/L required degasification and ultrafiltration before meaningful downstream concentration as shown in Fig 5 below where calcium carbonate and calcium phosphate dominates the scaling risk. Degassing reduced carbonate from 843 to 181.5 ppm as CaCO3, allowing RO to run at 80% recovery with permeate in the 20–40 mg/L range. Switchable-solvent treatment was of limited value because divalent scale formers were already low and silica remained high: CaSO4 fell only from 190.7 to 150.8 mg/L, while silica fell by only about 10%, preventing subsequent OaRO operation on that branch. Still, solvent regeneration improved materially relative to the first two pilots, reaching 746 mg/L after one contactor stage and <10 mg/L after six contactor passes, with regeneration energy of 4.59 kWh/m3 following improvements in heat recovery in the flash recovery step.

Fig 5. Trinchero water @50% recovery – scaling compounds of concern.

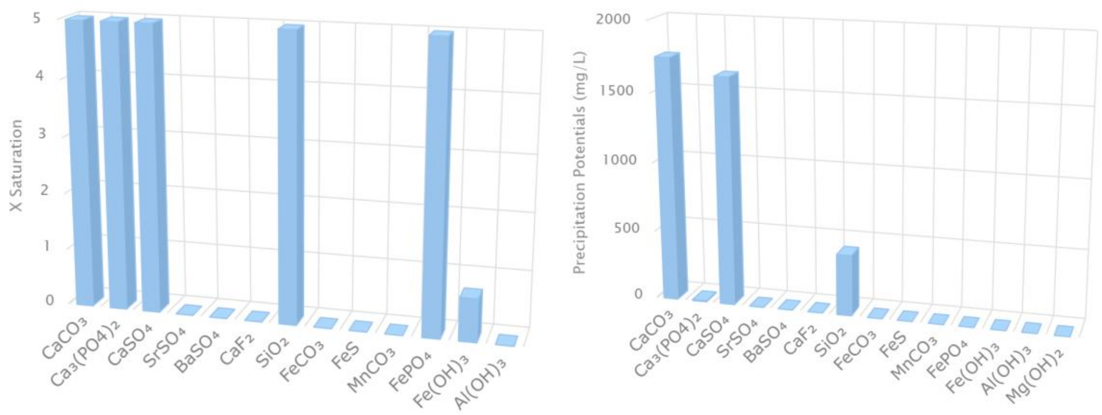


The EDM branch initially fouled because of residual polarized organics concentrated in the RO brine, but after an additional UF step the diluate fell to 220 ppm, blended product water reached 87 ppm, CaSO4 removal was 82.0–83.3%, and OaRO concentrated the EDM concentrate streams to a combined 120,127 mg/L at 98.3% overall recovery.

3.4. Cambria: site-specific pretreatment enabled the highest-quality municipal reuse outcome

Cambria provided the strongest overall demonstration of a high-recovery municipal reuse train. Because calcium carbonate, sulfate and phosphate, as well as silica and iron phosphate were near scaling levels as shown in Fig 6 below, scaling concerns required a silica-removal media in order to attempt RO recovery. Subsequently, softening was incorporated as pre-treatment to allow RO recovery of 50%. In Method 1, a silica removal resin reduced SiO2 from 260 to 26 ppm, while EDM reduced feed salinity from 5,933ppm to 42 ppm, and polishing RO was successfully operated at 99% recovery in order to meet title 22 drinking water standards for the municipality. In Method 2, which better represented typical feed conditions, silica resin removal again reduced SiO2 to ~25 ppm, and upstream RO ran at 81.7% recovery with 20.2 ppm permeate, EDM produced a 237 ppm diluate with 98.8% CaSO4 removal at 1.31 kWh/m3, and OaRO concentrated the two brine streams to 150,942 and 174,368 mg/L, respectively.

Fig 6. Cambria water @50% recovery – scaling compounds of concern.

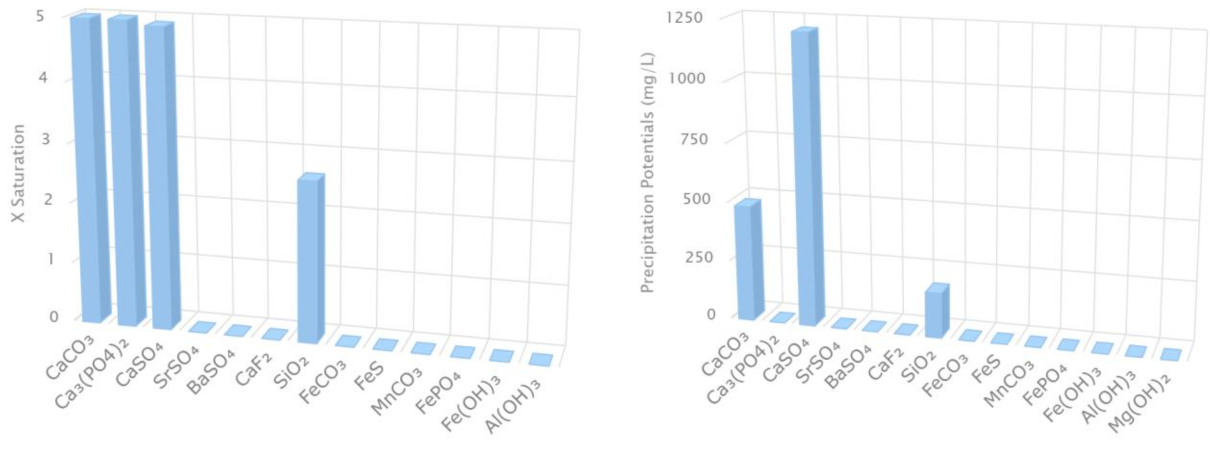


The reported overall recovery for the EDM-based route was 98.1%, with a blended product around 63 ppm after polishing. Switchable-solvent softening was effective for $CaSO_4$ removal, but again required multiple projected contactor stages and relied on modeled, rather than directly run data for OaRO performance in Method 2. Silica remained a concern for the OaRO membranes as it was not reduced in the switchable solvent stage, so that concentration stage was omitted.

3.5. Windset Farms: EDM/OaRO achieved high recovery, but nitrate remained the limiting constituent

Windset greenhouse RO brine at 2651mg/L represented an agricultural case with elevated carbonate, phosphate, sulfate, silica, and nitrate contamination as shown in Fig 7 below (nitrates don't scale but are of concern in greenhouses). Switchable-solvent treatment removed 73.5% of CaSO4 and reduced silica to 48.4 mg/L, which made OaRO theoretically feasible; however, because the full feed rather than an RO concentrate fraction was processed through the solvent system, regeneration energy rose to 29.61 kWh/m3. EDM performed well on salinity and scaling control, reducing diluate TDS to 106 ppm and removing 96.2% of CaSO4, but nitrate in the diluate remained at 3.8 mg/L, above the <1 mg/L target for reuse as RO-permeate-quality water.

Fig 7. Windset Farms water @50% recovery – scaling compounds of concern.



OaRO successfully concentrated the two brine streams to 145,645 and 138,453 mg/L, and final RO polishing yielded 17.0 ppm TDS water. Overall recovery was 97.4%, but the product remained more suitable for well-water blending than for the more stringent nitrate target.

3.6. Cross-site comparison

Across the five pilots, the EDM-OaRO route was the more consistently industrially transferable platform. It remained effective across low- to moderate-salinity groundwater, silica-limited brines, municipal recycled-water concentrate, and agricultural RO brines. Even when energy use rose above target at San Luis Obispo and Windset, the pathway still maintained the central advantages of selective ion transfer, strong control of $CaSO_4$ scaling, and compatibility with downstream OaRO concentration. Switchable-solvent treatment, in contrast, was highly dependent on whether the dominant barrier to recovery was precipitable hardness rather than silica or organics. Most importantly, the limiting problem in the solvent route was not precipitation itself but solvent regeneration, especially flash-chamber performance and the number of membrane-contactor passes needed to reach the residual-solvent target. The solvent route appears more applicable to recovery of high value materials such as rare-earth elements than as a low-cost agricultural softening technology.

From a broader desalination perspective, the observed field behavior is consistent with the literature. OaRO is increasingly recognized as a membrane-compatible method for concentrating brines beyond conventional RO limits at lower energy intensity than purely thermal concentration, while EDM is attractive where ion selectivity can convert a scaling-limited brine into a more manageable concentrate stream (Bartholomew et al., 2017; Peters and Hankins, 2019; Oddonetto et al., 2024). The Trevi pilots extend that literature by showing cross-chemistry field performance rather than only lab-scale or single-site behavior.

4. Implications for California water management:

The significance of these results is sharpened by California's policy context. SGMA compels long-term reductions in unsustainable pumping, especially in the San Joaquin Valley, while drought volatility increases the value of every increment of recoverable nontraditional water. High-recovery inland desalination and reuse will only scale if brine volume can be reduced without reverting to the cost and energy burdens of conventional thermal ZLD. That is precisely the gap these pilots address. (Escriva-Bou et al., 2023; Panagopoulos et al., 2019).

For near-term commercialization, the evidence from these five pilots points to EDM integrated with OaRO, supported by targeted pretreatment, as the most bankable route. Switchable-solvent treatment remains promising, especially for sulfate- and carbonate-rich waters, but it appears better positioned as a selective front-end softening tool than as the dominant cross-site platform until solvent-regeneration hardware is further optimized. Given the solvents Class 1 Div 1 handling requirement, skilled operators impose an additional restriction on its widespread use in the field.

5. Conclusions

The five California field pilots demonstrated that non-thermal, high-recovery brine management can materially improve inland water recovery for agricultural, industrial, and municipal reuse applications. The EDM-OaRO pathway was the most robust and consistently high-performing route, delivering overall recoveries from 84.2% to 98.4% in the first two pilots and from 97.4% to 98.3% in the latter three pilots, while maintaining strong control of $CaSO_4$ scaling and producing highly concentrated final brines.

Switchable-solvent softening achieved meaningful scale-former removal in selected waters and showed improved regeneration performance over the course of the pilot campaign, but it remained more sensitive to feed chemistry and more constrained by regeneration-system limitations than by precipitation chemistry itself. The principal engineering priority for that pathway is therefore improved flash and polishing performance rather than proof of selective precipitation.

In California's SGMA era, technologies that reduce inland brine-management cost and increase recoverable water can help preserve agricultural productivity, sustain municipal reuse, and improve drought resilience. The present field data indicate that electro-membrane concentration integrated with OaRO is the nearer-term pathway to that outcome (California Department of Water Resources, n.d).

Based on the findings from the five pilot demonstrations, the following recommendations are proposed:

- Prioritize EDM–OaRO process trains for near-term deployment, as they demonstrated the most consistent performance across diverse water chemistries and achieved high overall recoveries with manageable energy consumption.
- Further optimize switchable-solvent regeneration systems, particularly flash-chamber design and membrane-contactor integration, to reduce residual solvent levels and improve operational efficiency.
- Implement robust, chemistry-specific pretreatment strategies, including silica removal, organics control, and carbonate management, as these were critical determinants of downstream process feasibility and performance.
- Develop site-screening criteria based on key parameters such as silica concentration, hardness, organics content, and end-use water quality requirements to guide process selection and system design.
- Advance integration with polishing and targeted contaminant removal steps, particularly for applications requiring stringent nitrate, boron, or regulatory compliance thresholds.
- Evaluate modular and decentralized system configurations to enable scalable deployment of high-recovery brine management in inland and industrial settings.
- Conduct full techno-economic and lifecycle analyses at commercial scale, including capital costs, operational expenditures, and waste handling, to validate the projected cost advantages over thermal ZLD systems.
- Explore hybrid process configurations, including integration with emerging membrane technologies, to further improve efficiency and expand applicability to higher-salinity or more complex feedwaters.

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CRediT authorship contribution statement

Clark Easter: Conceptualization, Methodology, Investigation, Writing – original draft. Michael Greene: Methodology, Formal analysis, Validation, Writing – review and editing. John Webley: Resources, Project administration, Writing – review and editing. Clark Easter: Supervision, Funding acquisition, Writing – review and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The pilot data that support the findings of this study are available from the corresponding author on reasonable request, subject to any applicable commercial and partner confidentiality restrictions. The comparative field results summarized here were derived from the five-site Trevi/GWI NAWI pilot report.

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The California policy and drought statements in this manuscript were grounded in DWR, State Water Board, and PPIC sources, and the OaRO/EDM literature framing was grounded in peer-reviewed sources cited above. (Water California)

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