

Hydrodynamic Cavitation as a Physical Pretreatment Strategy for Enhanced Reverse Osmosis Concentrate Recovery and Membrane Fouling Mitigation

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Abstract

Reverse osmosis (RO) membrane desalination is central to global freshwater supply strategies, yet it generates significant concentrate (brine) waste streams that impose severe environmental and economic constraints. Traditional high-recovery operations remain limited by mineral scaling, organic fouling, and concentration polarization, while conventional chemical pretreatments add substantial operating expenditures and ecological footprints. This study evaluates a novel physical pretreatment approach using a single-stage hydrodynamic cavitation (HC) unit integrated into a pilot-scale reverse osmosis system treating post-RO brackish groundwater concentrate in Southern California. Over a multi-week trial featuring both 6–12 hour cyclic operations and extended 24-hour continuous runs, HC pretreatment reduced feed stream electrical conductivity by ~50% (from 5,500–6,500 $\mu\text{S}/\text{cm}$ down to 3,200–3,400 $\mu\text{S}/\text{cm}$). The integrated system achieved consistent permeate recovery exceeding 50% from the concentrate stream without irreversible membrane fouling, and original membrane hydraulic baselines were fully restored following standard flushing protocols. Mechanistic analyses indicate that hydrodynamic cavitation alters inorganic constituent zeta potentials, induces micro/nanobubble-mediated shear effects, and promotes bulk-phase agglomeration to prevent scale adhesion on active polyamide membrane surfaces. Overall, these findings demonstrate that hydrodynamic cavitation offers a scalable, chemical-free pretreatment technology to enhance RO brine recovery, extend membrane operational lifespans, and lower brine management expenses.

Keywords: Hydrodynamic cavitation, Reverse osmosis concentrate, Brine recovery, Membrane scaling, Zeta potential, Fouling mitigation.

1. Introduction

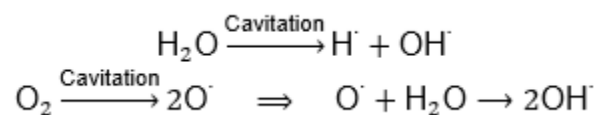
Global freshwater scarcity has accelerated the deployment of membrane-based desalination technologies, with seawater reverse osmosis (SWRO) and brackish water reverse osmosis (BWRO) serving as essential components of municipal and industrial water infrastructure [1, 2]. Modern polyamide thin-film composite (TFC) reverse osmosis membranes operate efficiently; however, overall system performance remains constrained by fluid recovery limits [3]. Standard BWRO facilities typically achieve water recovery rates of 70%–85%, leaving 15%–30% of the influent volume as high-salinity reverse osmosis concentrate. In ocean water desalination, osmotic pressure limits restrict recovery to 40%–50%, generating concentrate volumes equal to or exceeding permeate output [1, 4].

The management of RO concentrate represents a significant technical, financial, and environmental bottleneck [5]. Common disposal pathways—including surface water discharge, deep well injection, evaporation ponds, and thermal Zero Liquid Discharge (ZLD) systems—involve regulatory scrutiny, geographical constraints, high capital expenditures (CAPEX), and substantial operating expenditures (OPEX) [5, 6]. Consequently, secondary recovery of usable permeate from primary RO concentrate has drawn considerable research interest.

The main obstacle to secondary RO concentrate recovery is membrane fouling and inorganic mineral scaling (e.g., calcium carbonate CaCO_3 , calcium sulfate CaSO_4 , and silica SiO_2) [3, 7]. As dissolved ions concentrate beyond their thermodynamic solubility limits in the membrane boundary layer, mineral precipitation occurs directly on the active membrane layer [7, 8]. Standard scaling control methods rely heavily on anti-scalant chemical dosing, acid addition, or interstage lime/pellet softening [4, 9]. However, chemical pretreatments add operational complexity, generate chemical sludge, increase ongoing expenses, and can induce biofouling if anti-scalants act as nutrient sources for microorganisms [3, 10].

Hydrodynamic cavitation (HC) offers a chemical-free physical alternative for fluid conditioning and scale suppression [11, 12]. HC occurs when a liquid passes through a geometrical constriction (such as an orifice plate, Venturi tube, or rotational assembly), inducing a localized drop in static pressure below the vapor pressure of the liquid (P_v) [11, 13]. This rapid pressure differential generates millions of microscopic vapor cavities. As these cavities transition into regions of higher static pressure downstream, they implode violently within nanoseconds [12, 14].

The localized collapse of cavitation bubbles produces micro-scale extreme conditions: localized hot-spot temperatures exceeding 4,000 K, local transient pressures greater than 100 MPa, intense shear forces, acoustic microstreaming, and reactive hydroxyl radical ($\text{OH}^\cdot$) generation via thermal dissociation of water molecules [11, 13, 15]:



While HC is established in organic contaminant degradation and water softening [12, 14], its direct application as a physical feed conditioner for secondary RO concentrate recovery remains less explored.

This paper presents pilot-scale experimental results evaluating a patented, single-stage hydrodynamic cavitation unit integrated upstream of a secondary RO system treating brackish groundwater RO concentrate at a groundwater desalter facility in Southern California. We evaluate process stability, electrical conductivity reduction, volumetric recovery kinetics, and membrane fouling resistance under cyclic and continuous operating conditions.

2. Materials and Methods

2.1 Feedwater and Concentrate Characteristics

Pilot testing was conducted using post-RO concentrate sourced from a primary groundwater desalting plant in Southern California. The primary plant processes approximately 7.0 MGD (26,500 m³/day) of brackish groundwater at an 75% primary recovery rate, yielding 1.8 MGD (6,800 m³/day) of concentrate currently directed to a regional brine line.

A summary of typical feed water and concentrate operational profiles across brackish and seawater desalination platforms is presented in **Table 1**.

Table 1: Baseline operational characteristics of primary desalination streams.

Water Source	Permeate Recovery (%)	Concentrate Output (%)	Primary Limit to Higher Recovery
Groundwater (Brackish)	70% - 85% (Typical: ~75%)	15% - 30% (Typical: ~25%)	Mineral scaling risk (CaCO ₃ , CaSO ₄ , SiO ₂)
Ocean Water (Seawater)	40% - 50%	50% - 60%	Extreme osmotic pressure & biofouling

During the preliminary pilot testing period, the feed concentrate electrical conductivity (EC) ranged from 5,500 to 6,500 μ S/cm, corresponding to an estimated Total Dissolved Solids (TDS) content of approximately 3,500--4,200 mg/L.

2.2 Pilot Test Skid and Experimental Setup

The pilot system was configured by tapping into the main facility's RO concentrate header. The stream passed sequentially through:

1. A high-pressure feed pump.
2. A patented single-stage hydrodynamic cavitation device engineered from erosion-resistant alloy.
3. A secondary pilot RO membrane separation unit.

Main Plant RO Concentrate —> High-Pressure Pump —> Hydrodynamic Cavitation Unit —> Secondary Pilot RO Unit —> Permeate (Recovered Water)
 └─> Final Brine Stream

The pilot RO skid was equipped with six pressure vessels arranged in a 2-pass array (configured 4:2), with each vessel housing three Toray Model TM710D commercial spiral-wound polyamide composite membrane elements. The pilot system operated without a variable frequency drive (VFD); flow velocity and inlet pressures were governed directly by fixed-speed hydraulic pump dynamics, forcing the system to run at nominal full capacity across all test runs.

2.3 Experimental Protocols and Testing Phases

Testing was performed over a six-week period to evaluate process repeatability, conductivity suppression, volumetric permeate recovery, and membrane cleaning recovery. The testing was structured into three operational phases:

- **Phase 1 (Short-Term Cyclic Runs, 6–8 Hours):** Daily operational cycles of 6 to 8 hours designed to assess immediate recovery kinetics, pressure development, and short-term fouling propensity.
- **Phase 2 (Extended Cyclic Runs, 12 Hours):** Operational duration extended to 12 hours per cycle to evaluate intermediate membrane cake layer compaction and scale deposition dynamics.
- **Phase 3 (Continuous 24/7 Long-Term Testing):** Continuous multi-day operation without intermediate shutdowns to evaluate steady-state hydraulic behavior and long-term scaling resistance.

At the completion of each daily cycle during Phases 1 and 2, the system underwent a standard 30-minute low-pH chemical flush utilizing clean permeate water and Diamite LpH® membrane cleaner to remove acid-soluble mineral deposits.

2.4 Analytical Methods and Performance Metrics

System performance was monitored in real time via digital instrumentation and benchtop validation:

- **Volumetric Recovery (R):** Defined as the ratio of permeate volumetric flow rate (Q_p) to feed volumetric flow rate (Q_f):

$$R = \left(\frac{Q_p}{Q_f} \right) \times 100\%$$

- **Operating Transmembrane Pressure (P_{op}):** Monitored across feed, interstage, and concentrate channels as an indicator of foulant deposition and cake layer hydraulic resistance.
- **Electrical Conductivity (EC):** Measured using calibrated temperature-compensated conductivity meters ($\mu\text{S}/\text{cm}$) on feed, post-HC, permeate, and concentrate streams to assess apparent ion activity and total dissolved solids variations.

3. Results and Discussion

3.1 Electrical Conductivity and Apparent TDS Reduction

A primary observation during the pilot trials was the change in electrical conductivity of the concentrate stream following passage through the hydrodynamic cavitation orifice. Feed concentrate entering the HC unit demonstrated baseline EC values between 5,500 and 6,500 $\mu\text{S}/\text{cm}$. Immediately downstream of the single-stage HC device, EC measurements consistently dropped to 3,200–3,400 $\mu\text{S}/\text{cm}$ across all trial runs—a reduction of approximately 42%–50%.

This drop in measured electrical conductivity without bulk mass removal suggests physical modification of the ionic constituents. The localized pressure drops and high micro-shear forces in the cavitation zone promote homogeneous bulk-phase micro-crystallization (bulk precipitation) of bulk hardness ions (Ca^{2+} , Mg^{2+} , HCO_3^-) into suspended sub-micron crystallites [12, 14]. Concurrently, the collapse of cavitation microbubbles alters the double-layer electrokinetics and zeta potential (ζ) of suspended colloids and mineral nuclei [16, 17].

By shifting the zeta potential to a more negative charge regime, mutual electrostatic repulsion between suspended particulates and the negatively charged polyamide active layer is enhanced [16, 18]. Additionally, ions sequestered into suspended particulate aggregates no longer contribute to free ionic mobility in solution, resulting in reduced bulk fluid electrical conductivity [12, 17].

3.2 Short-Term and Extended Cyclic Permeate Recovery

The primary operational target was to achieve and maintain at least 50% recovery of permeate water from the primary RO concentrate stream. **Figure 1** shows transient recovery profiles across multiple daily test runs during Phase 1 and Phase 2.

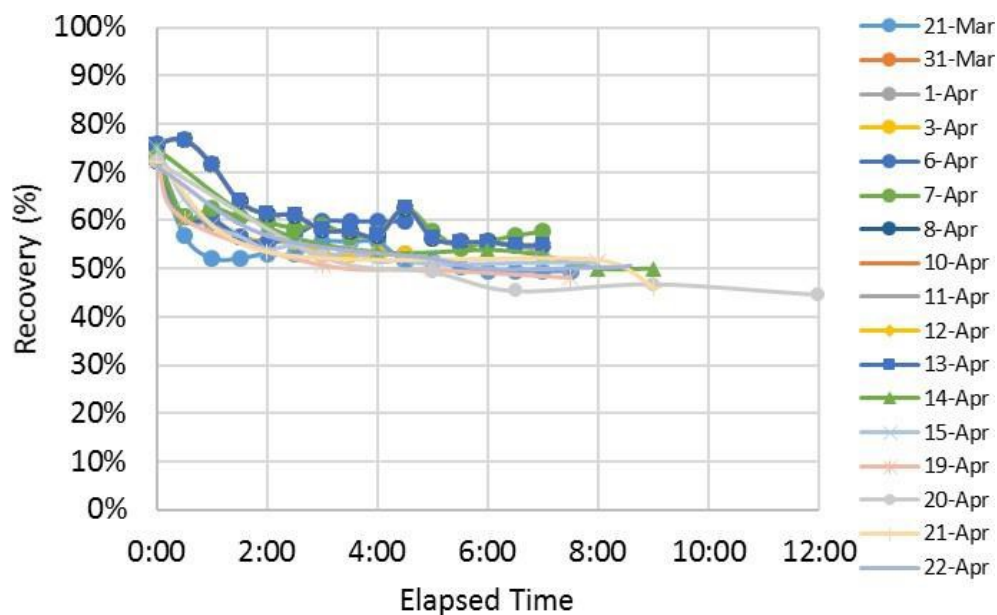


Figure 1: Representative transient permeate recovery profiles as a function of elapsed operational time across multiple test days.

Upon initiation of each daily run, initial permeate recovery started high, in the 70%–75% range. Over the first 3 to 4 hours of operation, recovery gradually declined and stabilized in the 50%–60% range, where it remained steady for the remainder of the 8-hour and 12-hour operational cycles.

Figure 2 summarizes the time-averaged permeate recovery achieved on individual consecutive testing days.

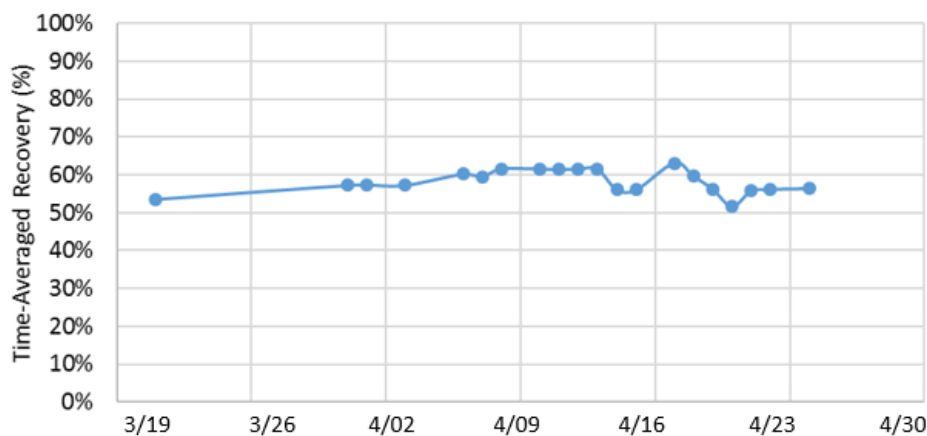


Figure 2: Time-averaged volumetric permeate recovery achieved per testing day over a 7-day representative period.

Throughout the cyclic evaluation, time-averaged recovery remained above 50% for every trial day. Despite minor daily fluctuations caused by raw groundwater quality variations, no progressive downward trend in recovery was observed over the multi-week trial.

3.3 Operating Pressure Dynamics and Cleanability

In high-recovery RO operations, mineral scaling typically causes rapid, irreversible increases in feed-to-concentrate differential pressure and operating pressure (P_{op}), alongside irreversible permeate flux decline [3, 8]. **Figure 3** illustrates operating pressure performance as a function of runtime for multiple cyclic test runs.

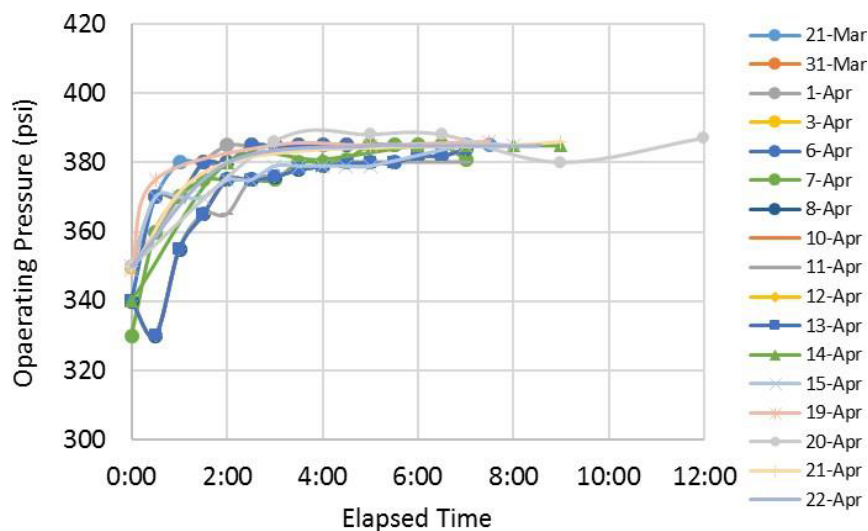


Figure 3: System operating pressure as a function of test duration for multiple cyclic runs.

Initial baseline operating pressures were observed in the range of 330 to 350 psi. Over the first 4 hours of operation, hydraulic resistance increased moderately, with system operating pressure rising to 380–390 psi, coinciding with the stabilization of recovery at 50%–60%. Pressure then stabilized for the remaining operational duration.

Following each operational cycle, a 30-minute permeate and low-pH clean (Diamite LpH®) was performed. Following this cleaning step, system operating pressure returned to the baseline level (330–350 psi) at the start of the next cycle. This full baseline restoration indicates that the foulant layer deposited during HC-pretreated operation formed a loose, highly permeable cake structure rather than an adherent scale layer, preventing irreversible surface scaling [10, 18].

3.4 Continuous 24/7 Long-Term Performance

To confirm that periodic shutdowns and flushes were not masking gradual membrane scaling, Phase 3 evaluated continuous 24/7 operation. **Figure 4** presents concentrate recovery performance during continuous multi-day testing.

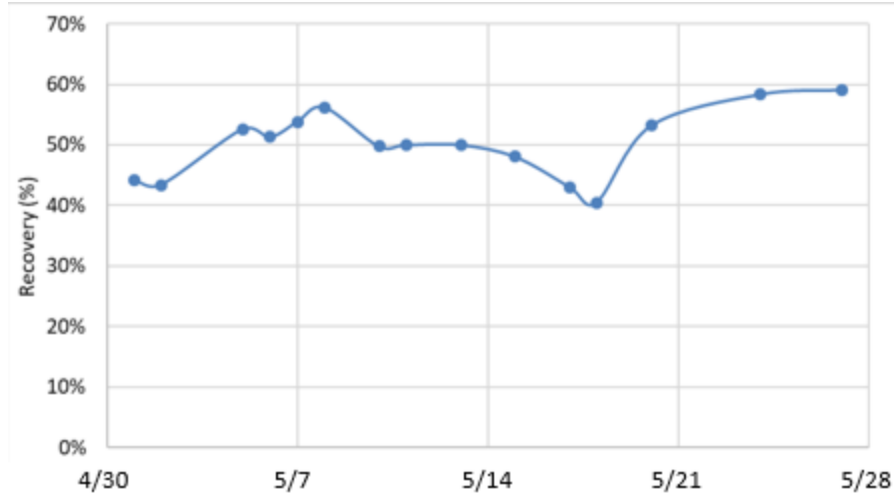


Figure 4: Permeate recovery efficiency during continuous 24/7 long-term testing.

Under unconditioned control conditions (without HC pretreatment), feeding primary RO concentrate directly into a secondary RO stage under these high-saturation conditions would typically cause heavy membrane scaling within 24 to 48 hours [3, 7]. However, with continuous hydrodynamic cavitation pretreatment, the system maintained volumetric recovery above 50% throughout the continuous multi-day testing period, with a slight upward trend toward the end of the trial.

4. Mechanisms of Action & Techno-Economic Implications

4.1 Physical and Electrokinetic Mechanisms

The pilot observations can be explained by three synergistic mechanisms induced by hydrodynamic cavitation:

1. **Zeta Potential Modification & Electrostatic Repulsion:** Hydrodynamic cavitation alters the electrokinetic potential (zeta potential, ζ) of inorganic scale precursors and colloids [16, 17]. Moving ζ toward a higher net negative potential increases electrostatic repulsion relative to the negatively charged polyamide membrane surface, preventing mineral adhesion [16, 18].
2. **Bulk Phase Homogeneous Precipitation:** Localized thermal and pressure spikes within collapsing cavitation microbubbles exceed the activation energy required for homogeneous mineral nucleation in the bulk liquid phase [11, 14]. Calcium carbonate and sulphate ions precipitate as loose bulk micro-crystallites before reaching the membrane surface, converting dissolved scaling ions into particulate foulants that remain in the bulk crossflow stream [12, 17].
3. **Micro-Shear and Scouring via Micro/Nanobubbles:** The implosion of microbubbles near boundary layers generates micro-jets (> 100 m/s) and intense micro-shear stress along the membrane channel [13, 19]. This shear stress disrupts the stagnant concentration

polarization boundary layer, enhancing mass transfer and preventing particulate cake compaction [18, 19].

4.2 Techno-Economic Comparison

Conventional RO concentrate management methods—such as pellet softening, solids contact clarifiers, or electrodialysis reversal (EDR)—require significant chemical dosing, continuous sludge handling, large physical footprints, and substantial auxiliary energy inputs [4, 9].

A preliminary comparative analysis of secondary recovery technologies is summarized in **Table 2**.

Technology	Chemical Footprint	Sludge Generation	Equipment Complexity	Relative OPEX	Relative Footprint
Pellet Softening / Clarification	High (NaOH, Lime)	High (Lime/Calcium Sludge)	High (Moving parts, clarifiers)	High	Large
Electrodialysis Reversal (EDR)	Moderate (Acid/Antiscalant)	None	High (Stack Maintenance)	Moderate - High	Moderate
Thermal Evaporation / ZLD	High (pH adjustment)	High (Dry Salt Cakes)	Extremely High (Evaporators)	Very High	Large

Table 2: Comparative overview of secondary RO concentrate treatment technologies.

The hydrodynamic cavitation system operates without moving parts inside the cavitation reactor, using only the booster pump's electrical power to generate the differential pressure across the orifice [11, 14]. For a typical 7 MGD groundwater desalter yielding 1.8 MGD of concentrate, implementing an HC-assisted secondary recovery stage achieving 50% recovery yields an additional 0.9 MGD (3,400 m³/day) of high-quality permeate. This increases overall plant water recovery from 75% to 87.5% while reducing brine discharge volumes by 50%.

4.3 Proposed Operational Strategy

The pilot data support a cyclic operational strategy for full-scale facilities. An operational schedule consisting of two 10-hour processing cycles per day—each followed by a 2-hour low-pH flushing cycle—can maintain continuous long-term production while preventing mineral scale consolidation. Future system optimization using advanced multi-stage or rotational hydrodynamic cavitation reactors [11, 14] is expected to improve single-pass conductivity reduction and extend operational cycle durations.

5. Conclusion

Pilot testing of a patented, single-stage hydrodynamic cavitation system treating post-RO brackish groundwater concentrate demonstrated the following outcomes:

- **Sustained Concentrate Recovery:** The HC-RO integrated system consistently recovered over 50% of RO concentrate as usable permeate water, raising total plant recovery from ~75% to >87.5%.
- **Conductivity Suppression:** Pass-through of concentrate through the cavitation orifice reduced measured electrical conductivity by approximately 50% (from 5,500–6,500 $\mu\text{S}/\text{cm}$ down to 3,200–3,400 $\mu\text{S}/\text{cm}$).
- **Fouling Mitigation & Membrane Restorability:** Operation under high saturation conditions produced no irreversible membrane scaling. Standard low-pH flushing completely restored membrane operating pressures to baseline levels (330–350 psi) after each run.
- **Scalable Chemical-Free Operation:** Hydrodynamic cavitation offers a compact, low-OPEX alternative to chemical lime/pellet softening for RO brine management and zero liquid discharge (ZLD) schemes.

Abbreviations

BWRO	=	Brackish Water Reverse Osmosis
CAPEX	=	Capital Expenditures
EC	=	Electrical Conductivity
EDR	=	Electrodialysis Reversal
GPD	=	Gallon Per Day
GPM	=	Gallons Per Minute
HC	=	Hydrodynamic Cavitation
OPEX	=	Operating Expenditures
RO	=	Reverse Osmosis
SWRO	=	Seawater Reverse Osmosis
TDS	=	Total Dissolved Solids
TFC	=	Thin-Film Composite
TMP	=	Transmembrane Pressure
VFD	=	Variable Frequency Drive
ZLD	=	Zero Liquid Discharge

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Conflicts of Interest

There are no conflicts of interest.

Author Contributions

R. Hill: Conceptualization, Data curation, Writing – original manuscript, Writing - editing

M. Malmquist: Resources, Visualization, Data Analysis, Writing - editing

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