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Enabling High Recovery with Flow Reversal and Feed Flushing

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Chino Desalter I

The **Chino Desalter I** is part of the **Chino Desalter Project**, which was established to provide a reliable water supply and manage groundwater quality in the **Chino Basin**, located in Southern California.

CDA CHINO BASIN DESALTER AUTHORITY

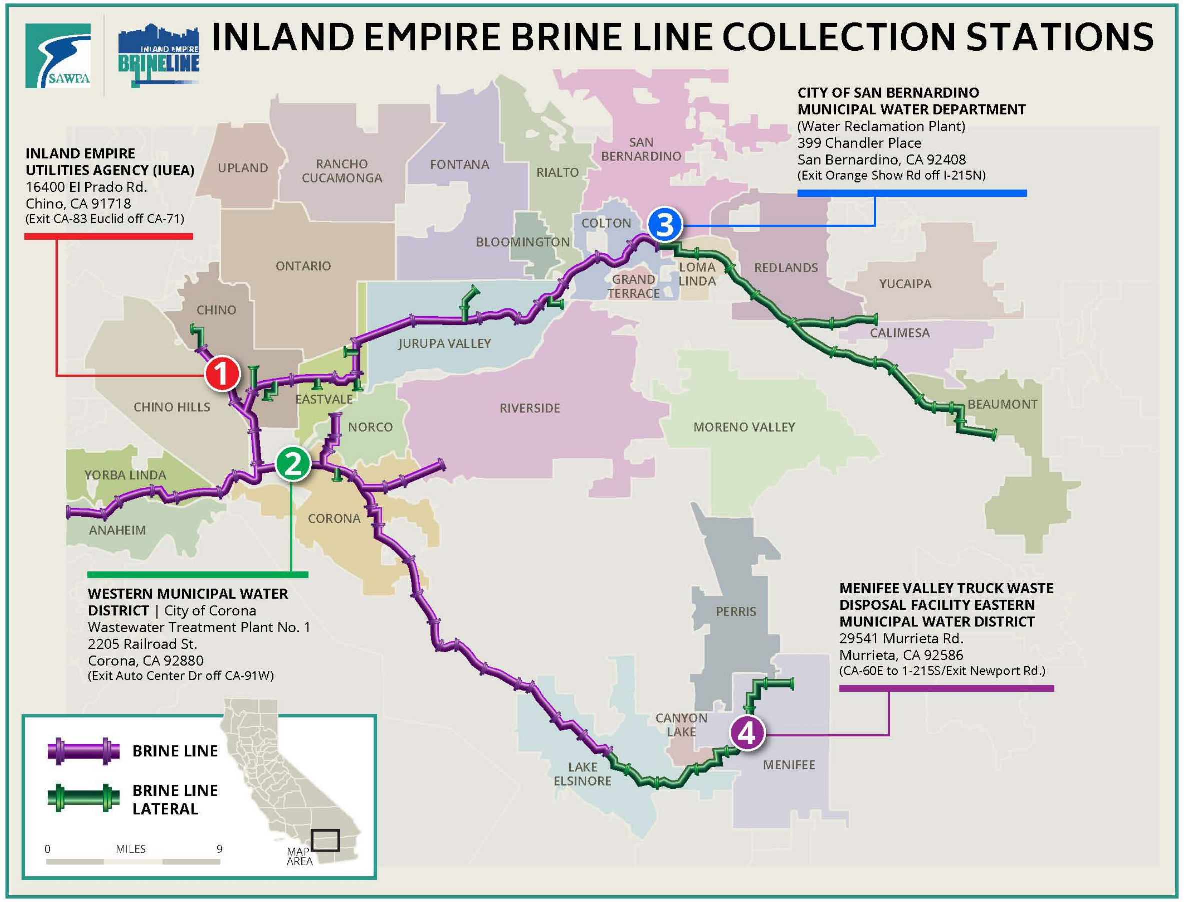
Current Infrastructure

- 14 MGD
- 80% Recovery
- Feed TDS of 950 mg/L

Goals

- Increase recovery from 80% to 90+%
- Minimize Brine Disposal Costs
    - Hard limit on brine disposal
    - Without increased recovery this also limits production
- Estimate retrofit cost and potential savings from adding 3rd RO stage

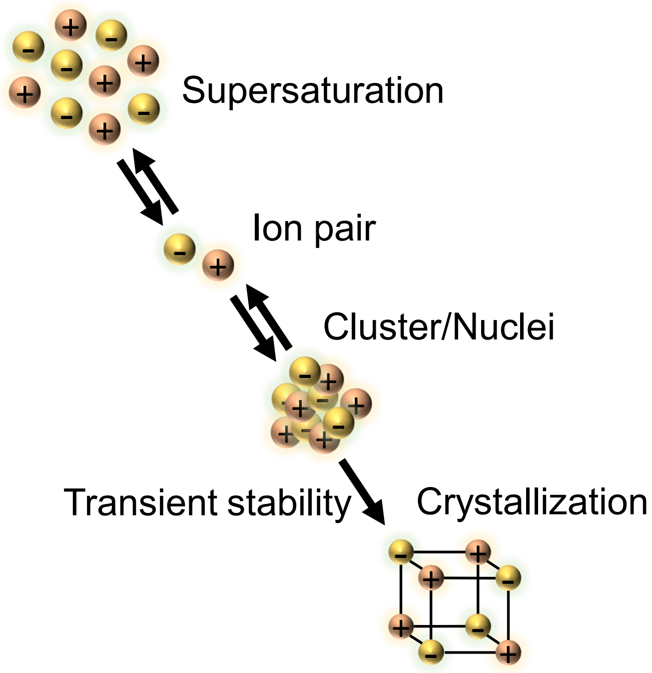
Brine Disposal Costs and the Case For High Recovery

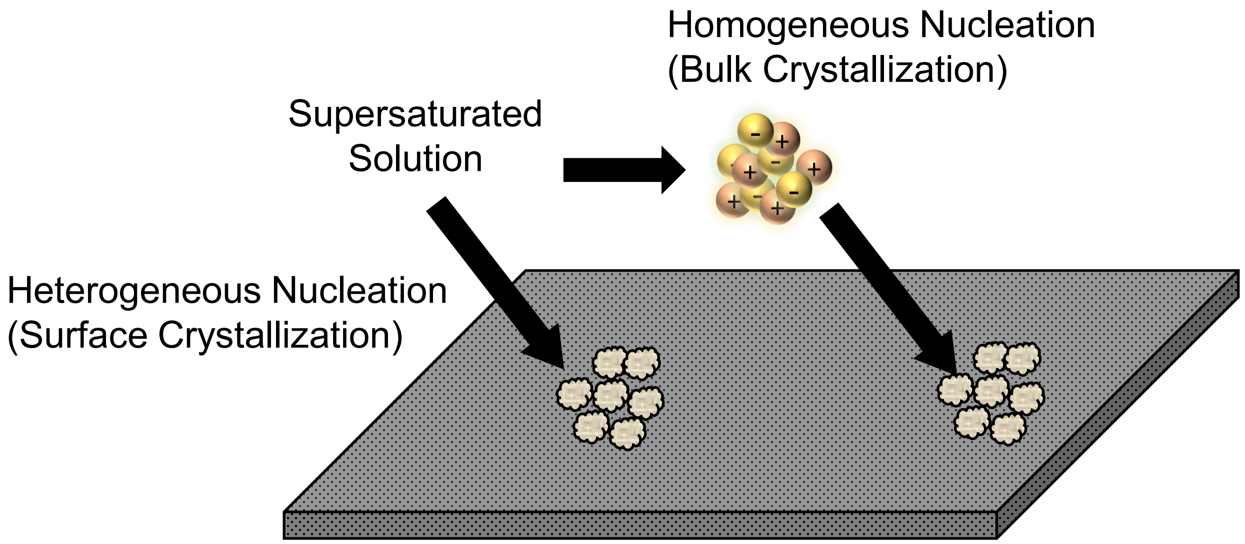


Fiscal Year	Flow (MG)	BOD (1,000 lbs.)	TSS (1,000 lbs.)	Monthly Fixed Pipeline	Monthly Fixed Treatment
2017	$858	$307	$429	$5,639	$11,433
2018	$901	$307	$429	$5,921	$12,007
2019	$946	$307	$429	$6,217	$12,607
2020	$979	$316	$442	$6,398	$12,985
2021 Jan - Jun	$1,018	$329	$460	$6,654	$13,505
2021 Jul - Dec	$979	$316	$442	$6,398	$12,985
2022 Current	$1,018	$329	$460	$6,654	$13,505
2023 proposed	$1,049	$353	$520	$6,654	$13,505
2024 planned	$1,101	$371	$547	$6,654	$13,505
% Change (2017-2024)	28%	21%	28%	18%	18%

[1] "Inland Empire Brine Line - Santa Ana Watershed Project Authority." *SAWPA*, 8 May 2024, sawpa.gov/inland-empire-brine-line/.
[2] Inland Empire Brine Line Rate Resolution 2022-9, Santa Ana Watershed Project Authority, 2022

Scaling is a multi-step and time dependent phenomena





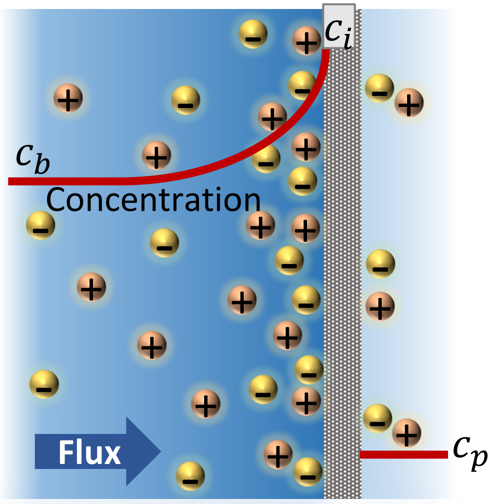
Induction Time: Time between the occurrences of supersaturation to the formation of stable nuclei of the precipitating salt

- Function of saturation index

$$\log t_{ind} = A + \frac{B}{T^3 SI^2}$$

Impact of scaling

- Reduced permeability and membrane life
- Enhanced by concentration polarization



Flow Reversal and Feed Flushing for Scaling Prevention

Flow Reversal: A technique to prevent scale formation by periodically reversing the flow direction in reverse osmosis (RO) systems.

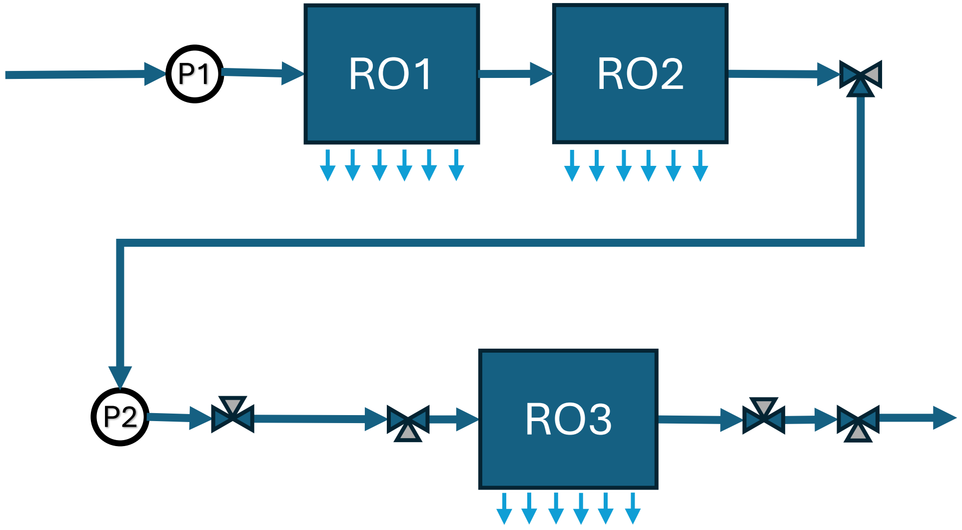
Flushing: Stop permeate production and flush with lower concentration water to rapidly reduce the concentration of the fluid in the system

- Resets the crystallization **induction clock**
- **Mitigates scaling**, potentially eliminating the need for antiscalants.
- **Maintains high system recovery**, even under high supersaturation conditions
- **Continuous Operation**: Unlike traditional cleaning processes, **flow reversal** minimally interrupts RO operations.

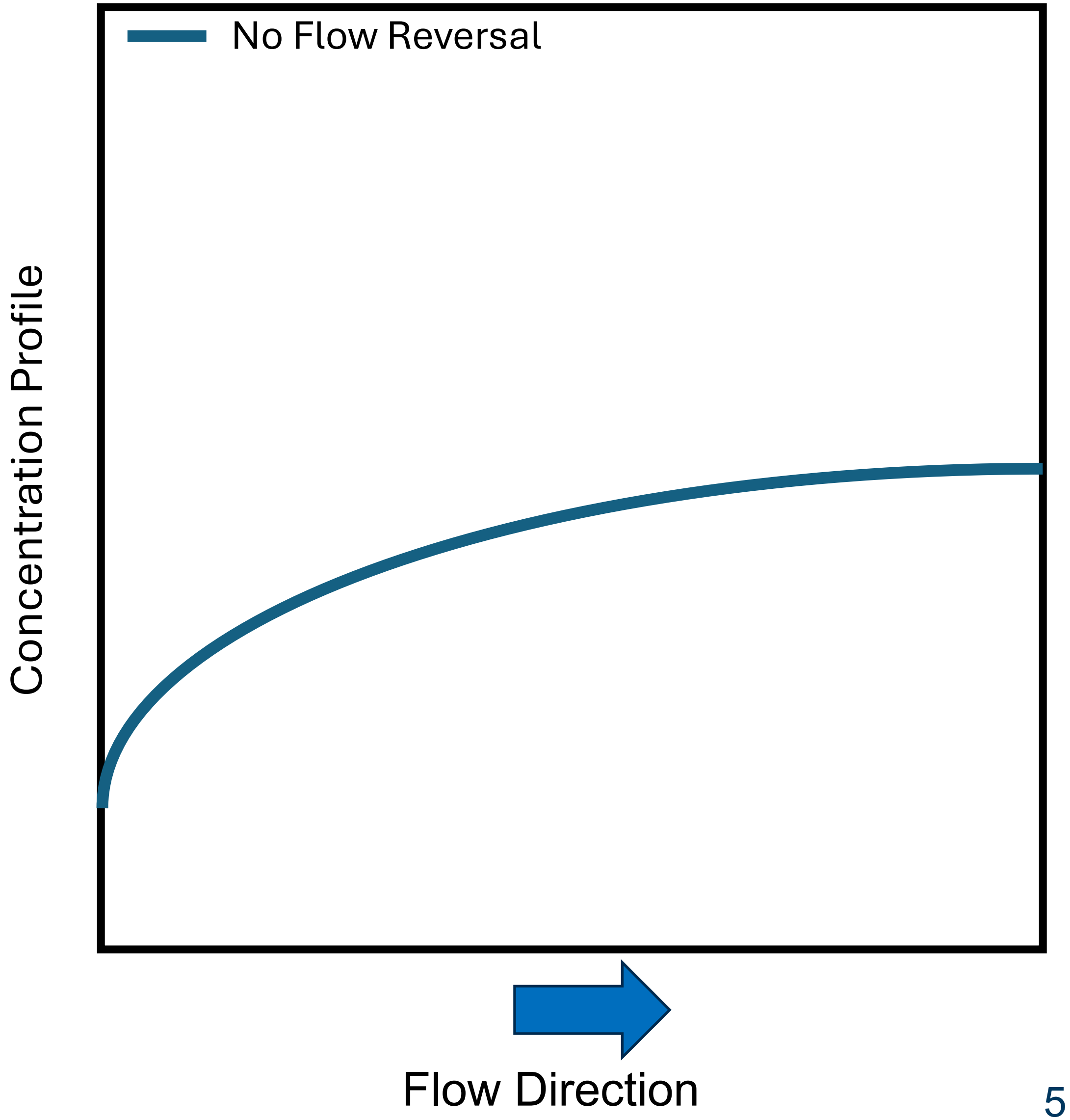
Expected Impact: Significantly enhances system performance, extending membrane life and improving recovery rates in RO desalination processes

Flow Reversal and Feed Flushing for Scale Prevention

A) Normal Operation



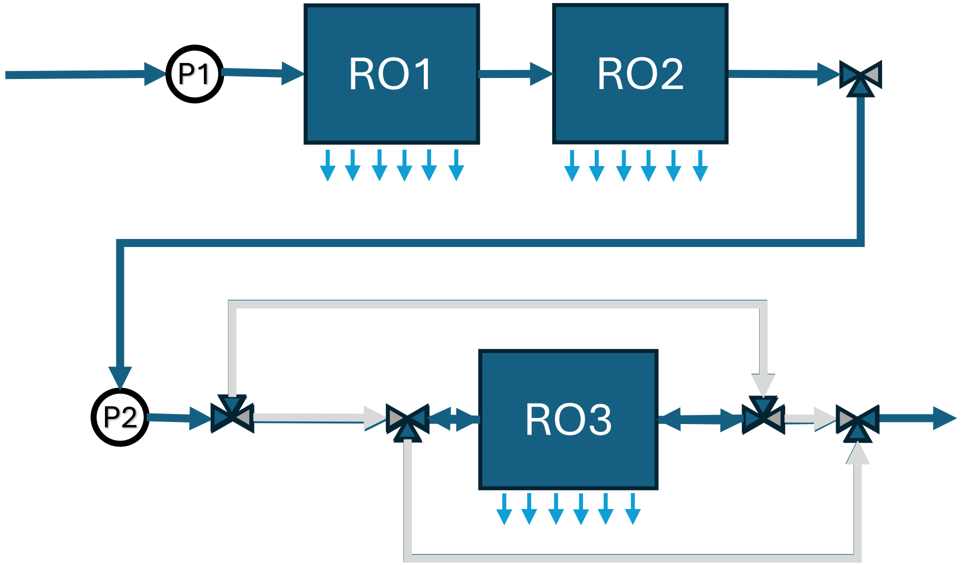
3rd Stage Profile



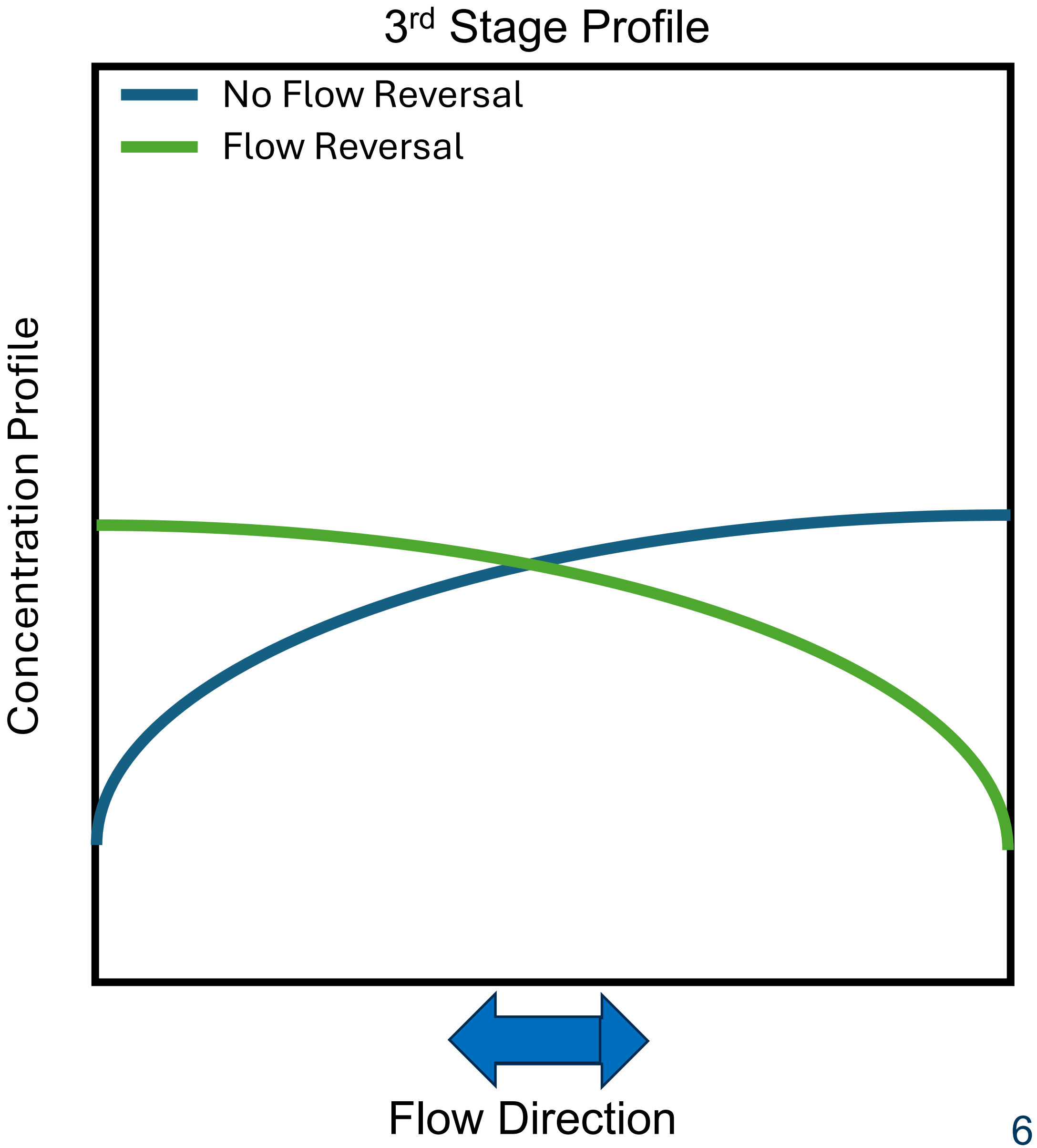
Flow Reversal and Feed Flushing for Scale Prevention

A) Normal Operation

B) Flow Reversal



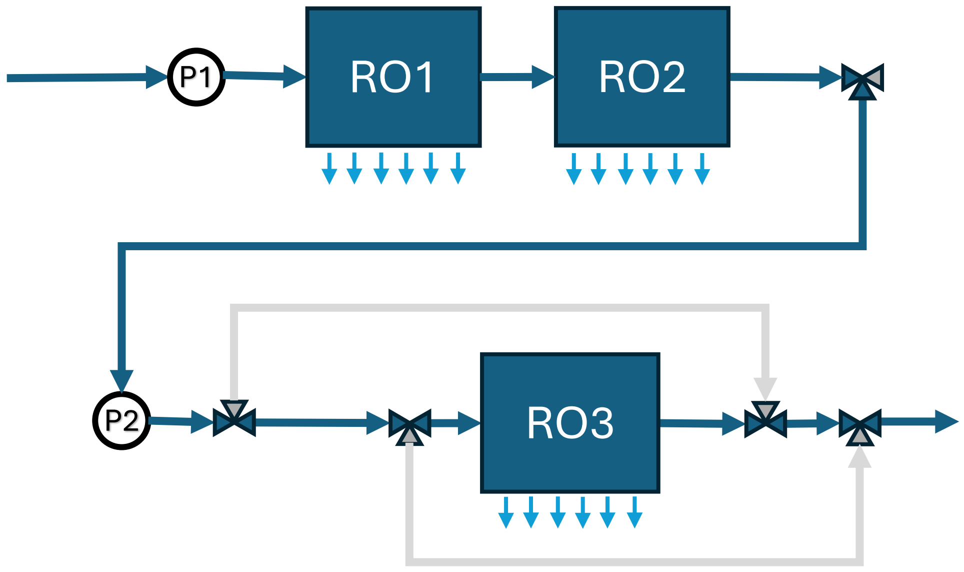
$$Duty\ Cycle = \frac{t_n}{t_n + t_s}$$

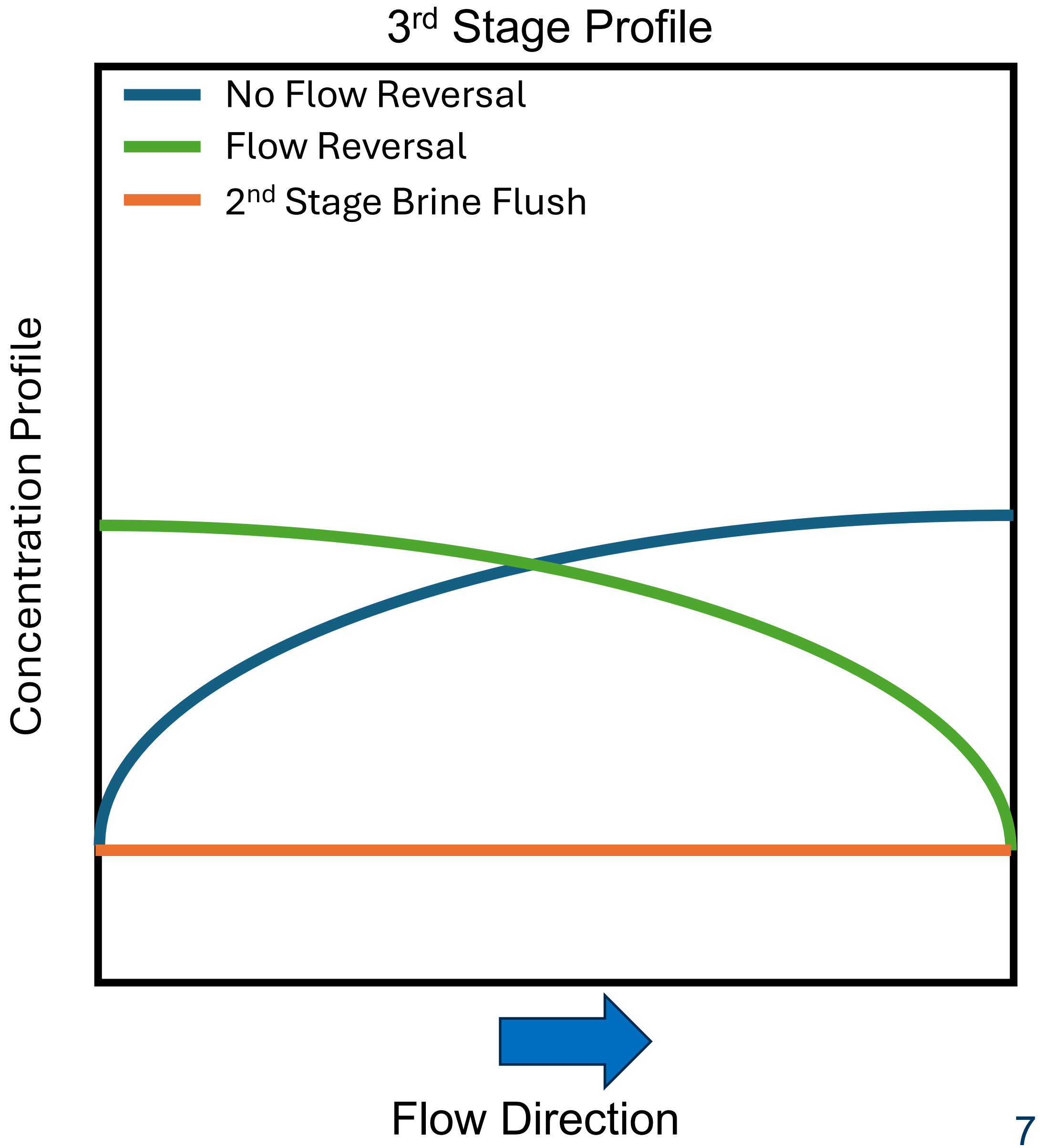


Flow Reversal and Feed Flushing for Scale Prevention

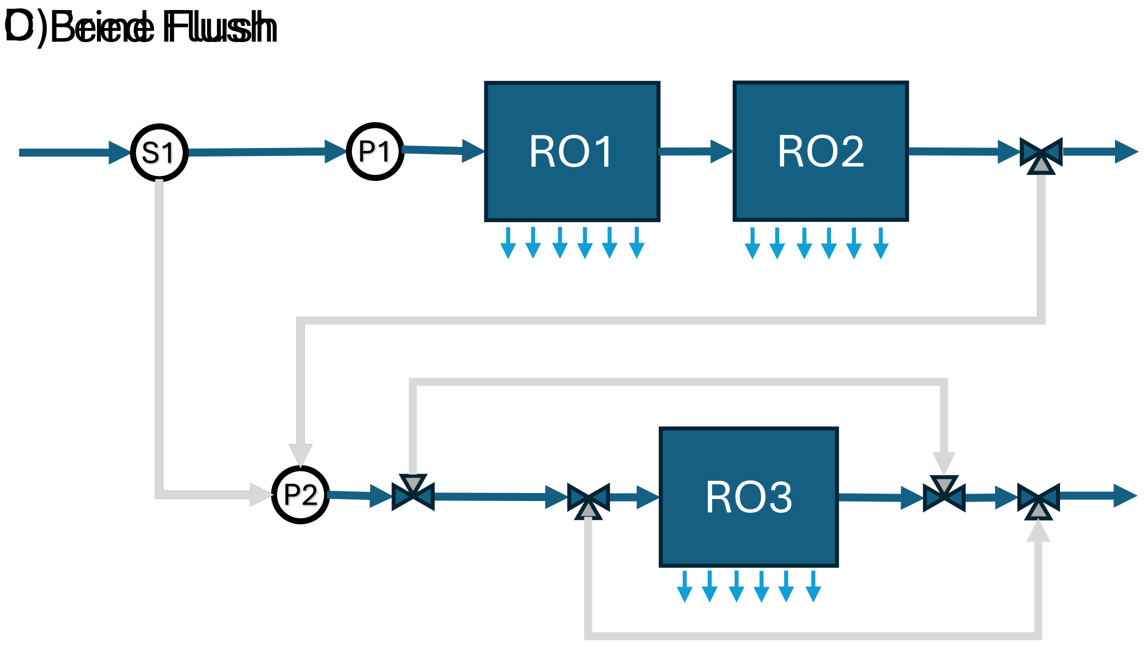
B)Brine Flush

C)Flow Reversal

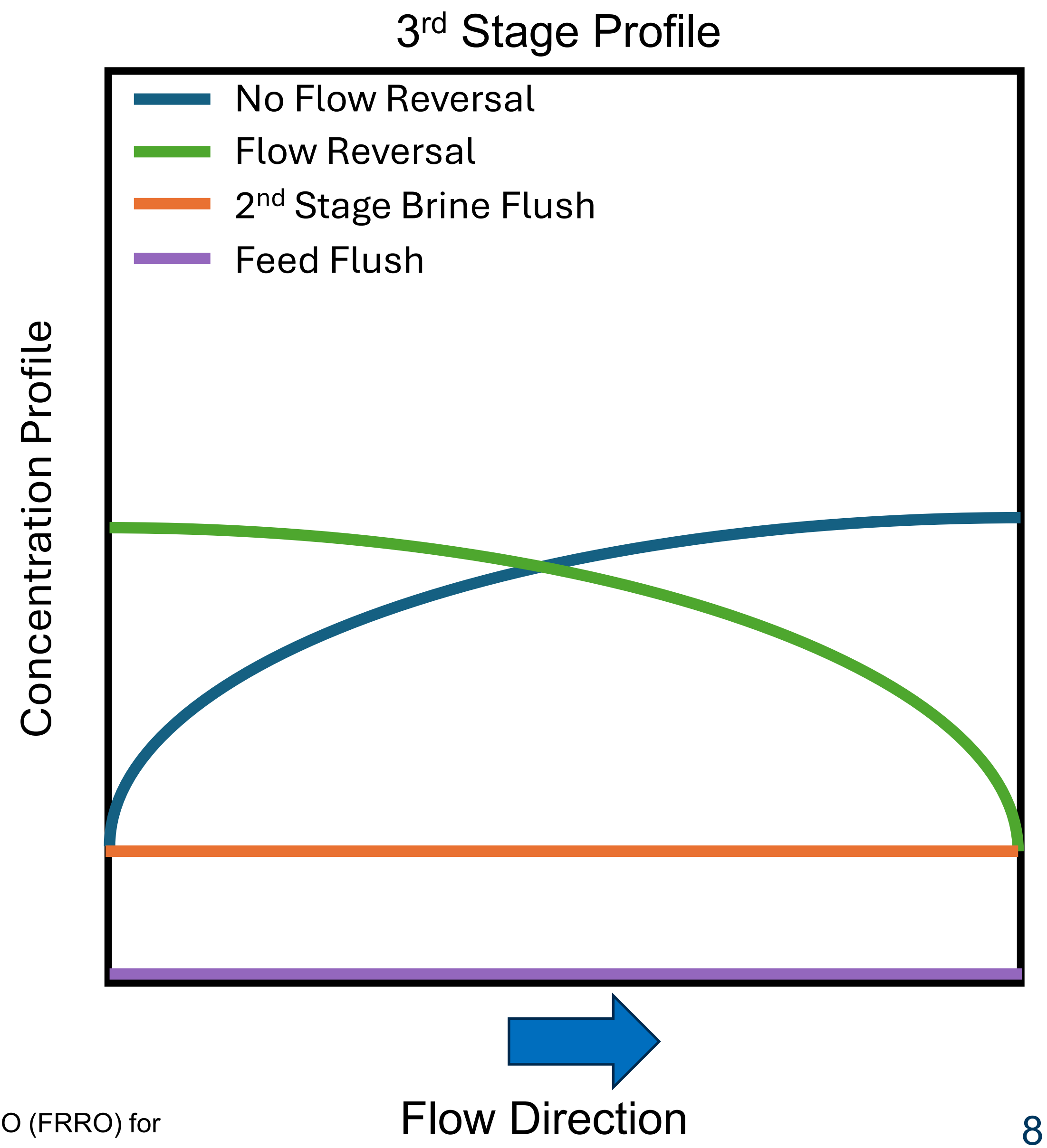




Flow Reversal and Feed Flushing for Scale Prevention



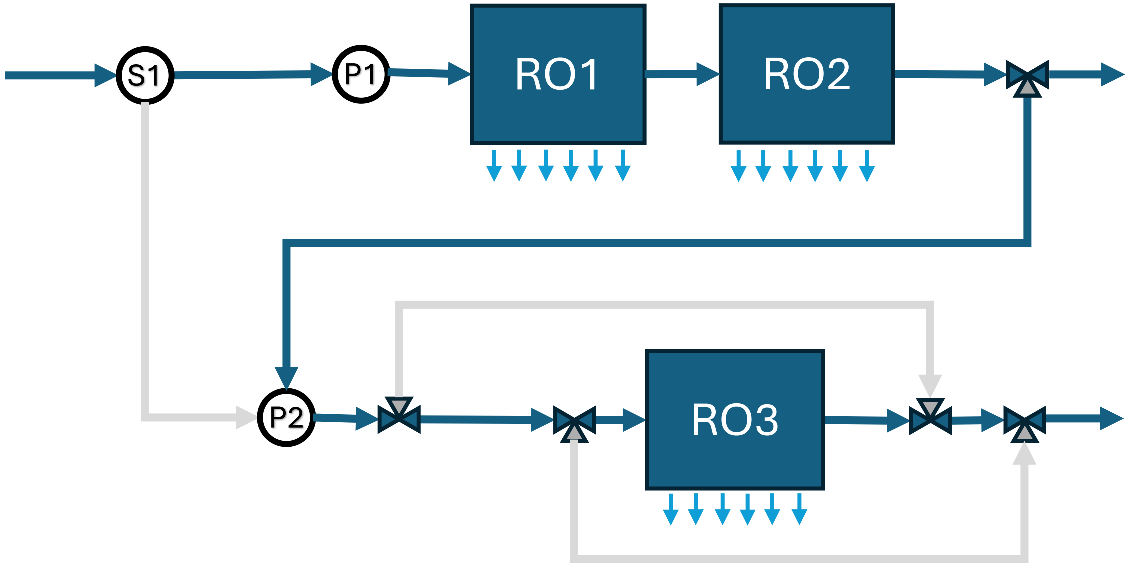
$$Flush\ Volumes = \frac{Q_{flush}t_{flush}}{V_{ch,RO3}}$$

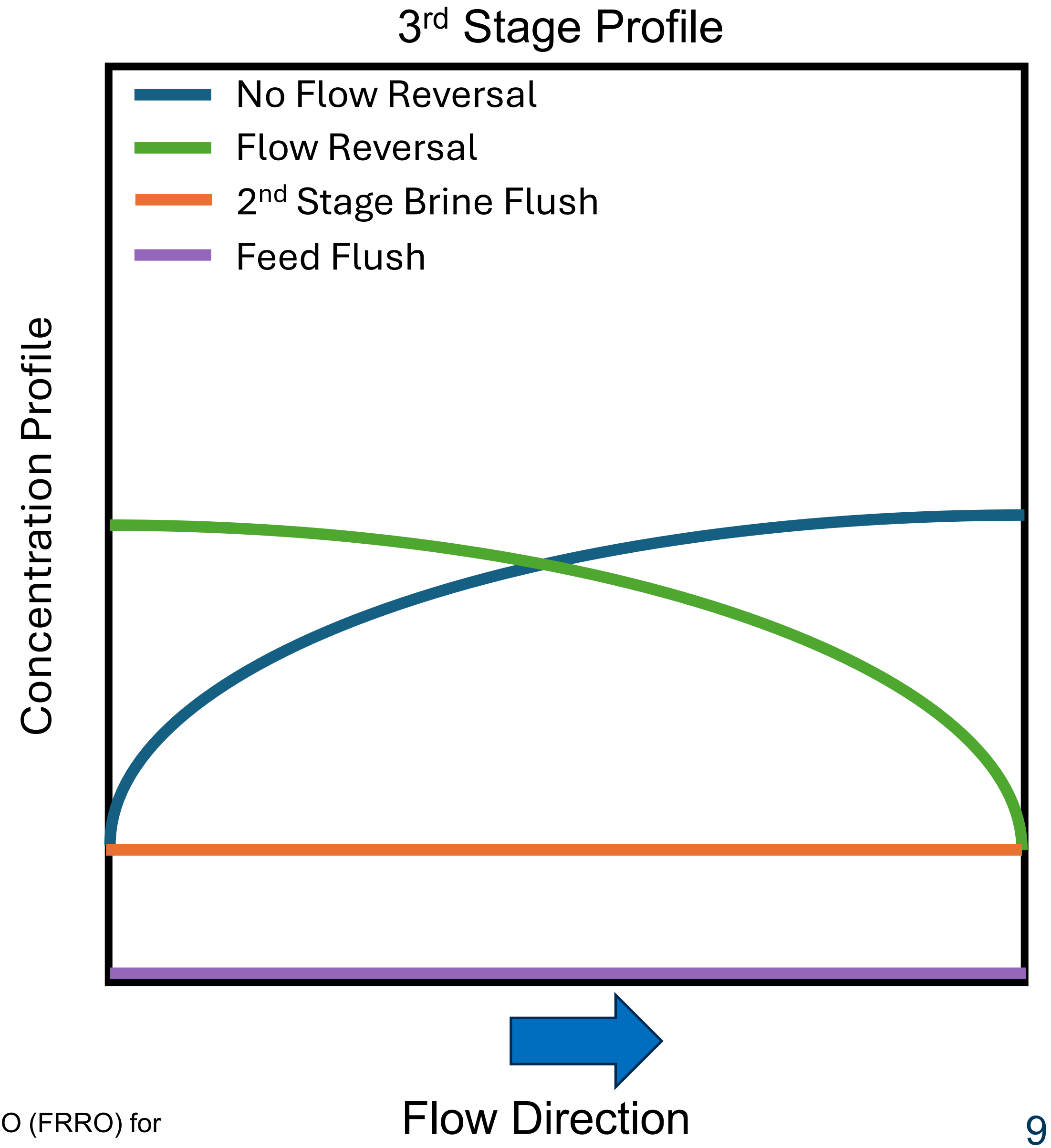


Li, M., Waite, A., & Wang, S. (2024). Piloting experience of ROTEC's flow reversal RO (FRRO) for 90% recovery in brackish water desalination. *Desalination*, *576*, 117348.

Flow Reversal and Feed Flushing for Scale Prevention

D)Feed Flush





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WaterTAP Models Can Be Quickly Fit to Experimental Data Using Built-in Tools

Parmest Estimator

- WaterTAP Model
- Experiment List
- Objective Function
- Unknown Parameters
- Experimental Outputs

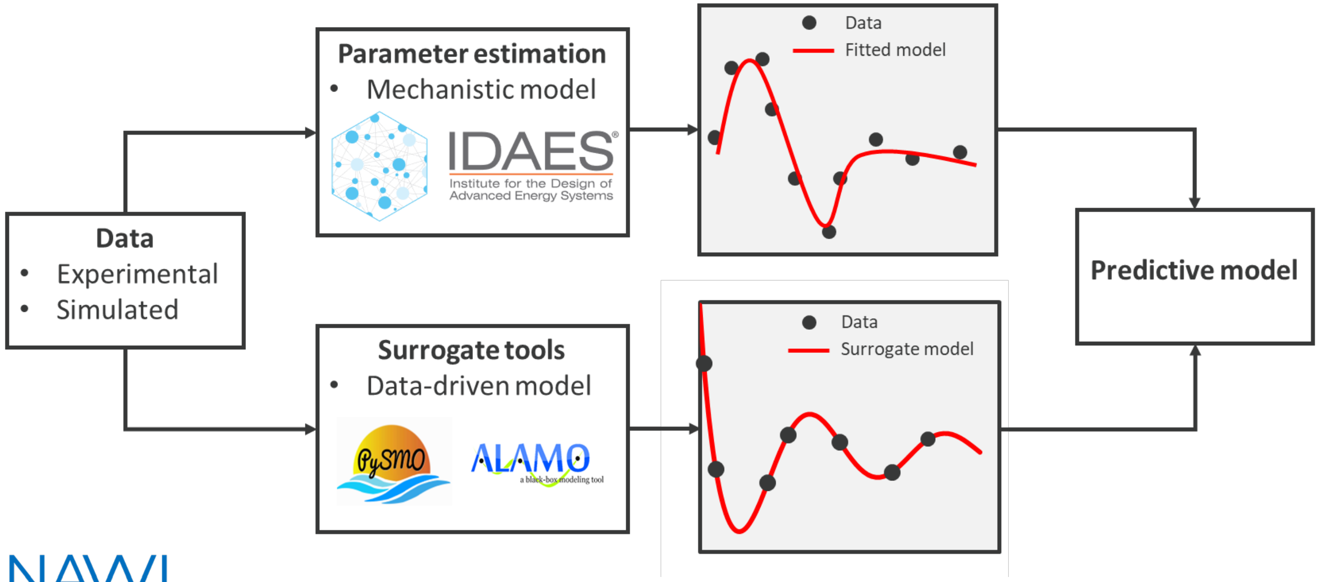
+

Exp. Data

Recovery (%)	ΔP_{RO1} (psi)	ΔP_{RO2} (psi)	Permeate Conc (mg/L)	Pump Work (kW)
81.1	24.6	16.7	28.7	187.4
81.0	25.6	18	28.8	190.8
.	.	.	.	.
90.5	19.4	8.1	33.5	173.6
90.5	19.5	8.2	33.7	174.3
90.4	19.6	8.1	33.8	173.6

Experimental Outputs	Symbol	Units
Feed Flow Rate	Q_f	GPM
Permeate Flow Rate	Q_p	GPM
RO Feed Pressure	P_f	psi
RO1 Pressure Losses	ΔP_{RO1}	psi
RO2 Pressure Losses	ΔP_{RO2}	psi
Permeate Concentration	C_p	mg/L
Pump Work	W_p	kW

Unknown Parameters	Symbol	Units
Water permeability coefficient	A	$m^1\ s^{-1}\ Pa^1$
Salt permeability coefficient	B	$m^1\ s^{-1}$
Darcy's friction factor coefficient	C_1	
Darcy's friction factor exponent	n	
Sherwood coefficient	C_2	
Pump Efficiency	ξ	%



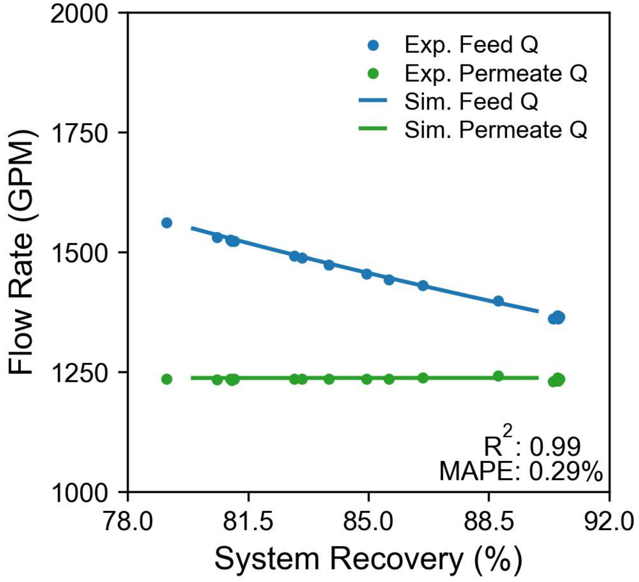
Data
- Experimental
- Simulated

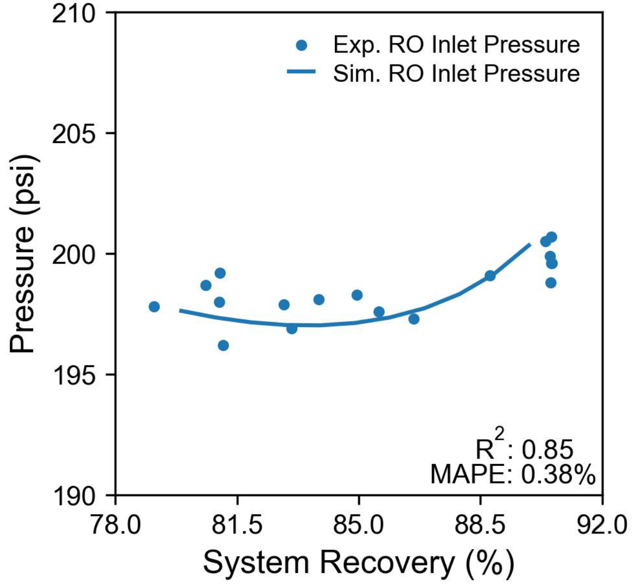
Parameter estimation
- Mechanistic model

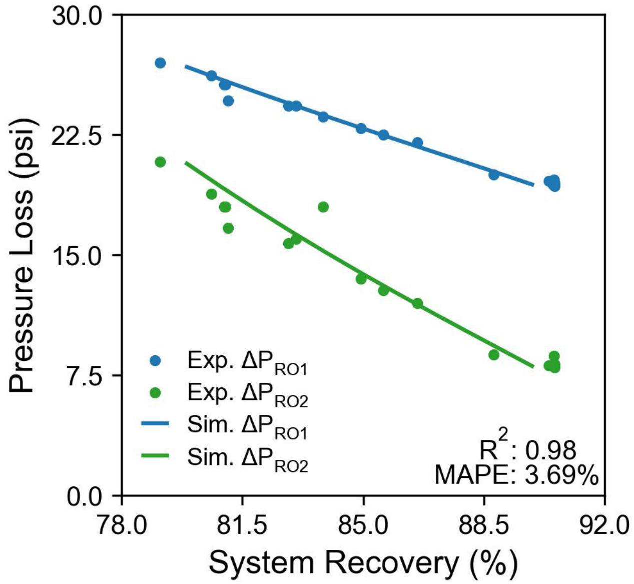
Surrogate tools
- Data-driven model

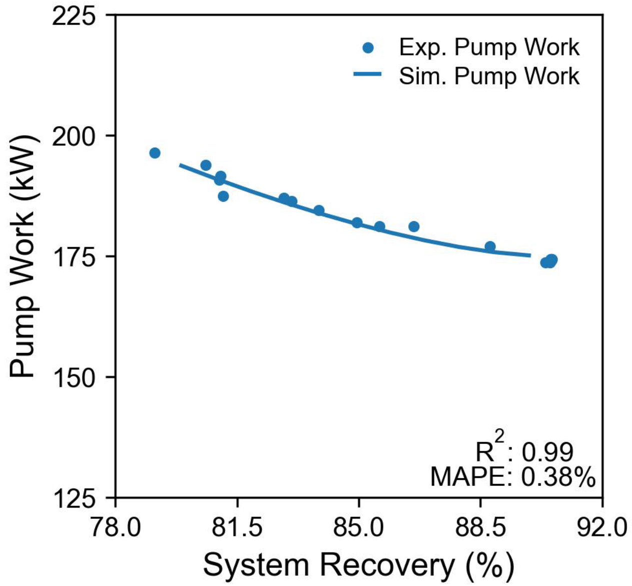
Predictive model

Experimental Data and Parameter Estimation Results





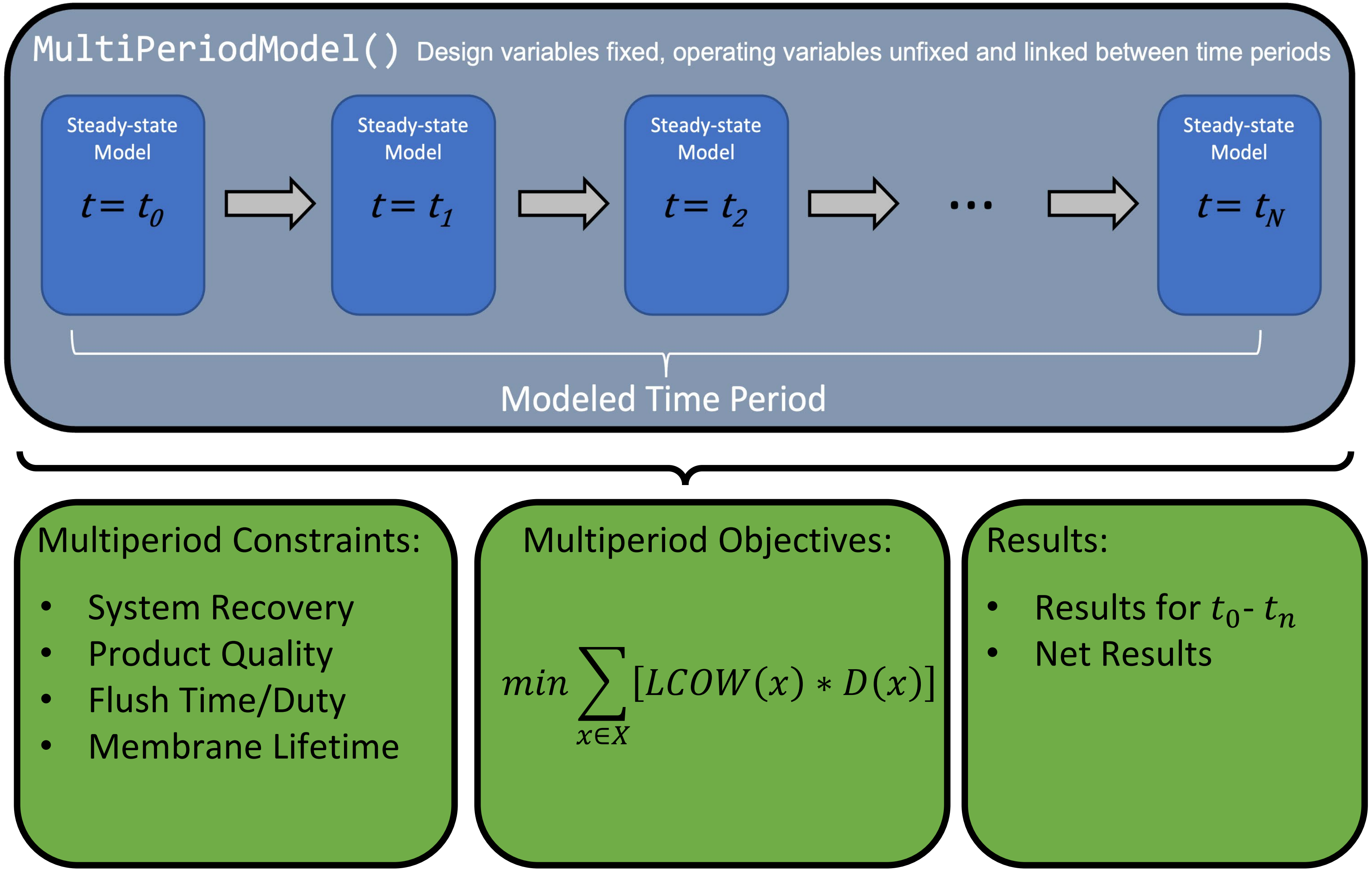




Parameter	Symbol	Value	Units
Water permeability coefficient	A	8.80e-12	$m^{1}\ s^{-1}\ Pa^{1}$
Salt permeability coefficient	B	8.00e-08	$m^{1}\ s^{-1}$
Darcy's friction factor coefficient	C_1	7.82	dimensionless
Darcy's friction factor exponent	n	0.354	dimensionless
Sherwood coefficient	C_2	4.73	dimensionless
Pump Efficiency	ξ	65.1	%

Metric	R^2	MAPE (%)
Flow Rates ($Q_f + Q_p$)	0.99	0.29
Pump Pressure (P_f)	0.85	0.38
Pressure Losses (ΔP_{RO1} + ΔP_{RO2})	0.98	3.89
Permeate Concentration (C_p)	0.91	8.11
Pump Work (W_p)	0.99	0.38

Multiperiod Model Unlocks Optimization Across Operating Modes



`MultiPeriodModel()` Design variables fixed, operating variables unfixed and linked between time periods

Steady-state Model $t = t_0$

Steady-state Model $t = t_1$

Steady-state Model $t = t_2$

…

Steady-state Model $t = t_N$

Modeled Time Period

Multiperiod Constraints:

- System Recovery
- Product Quality
- Flush Time/Duty
- Membrane Lifetime

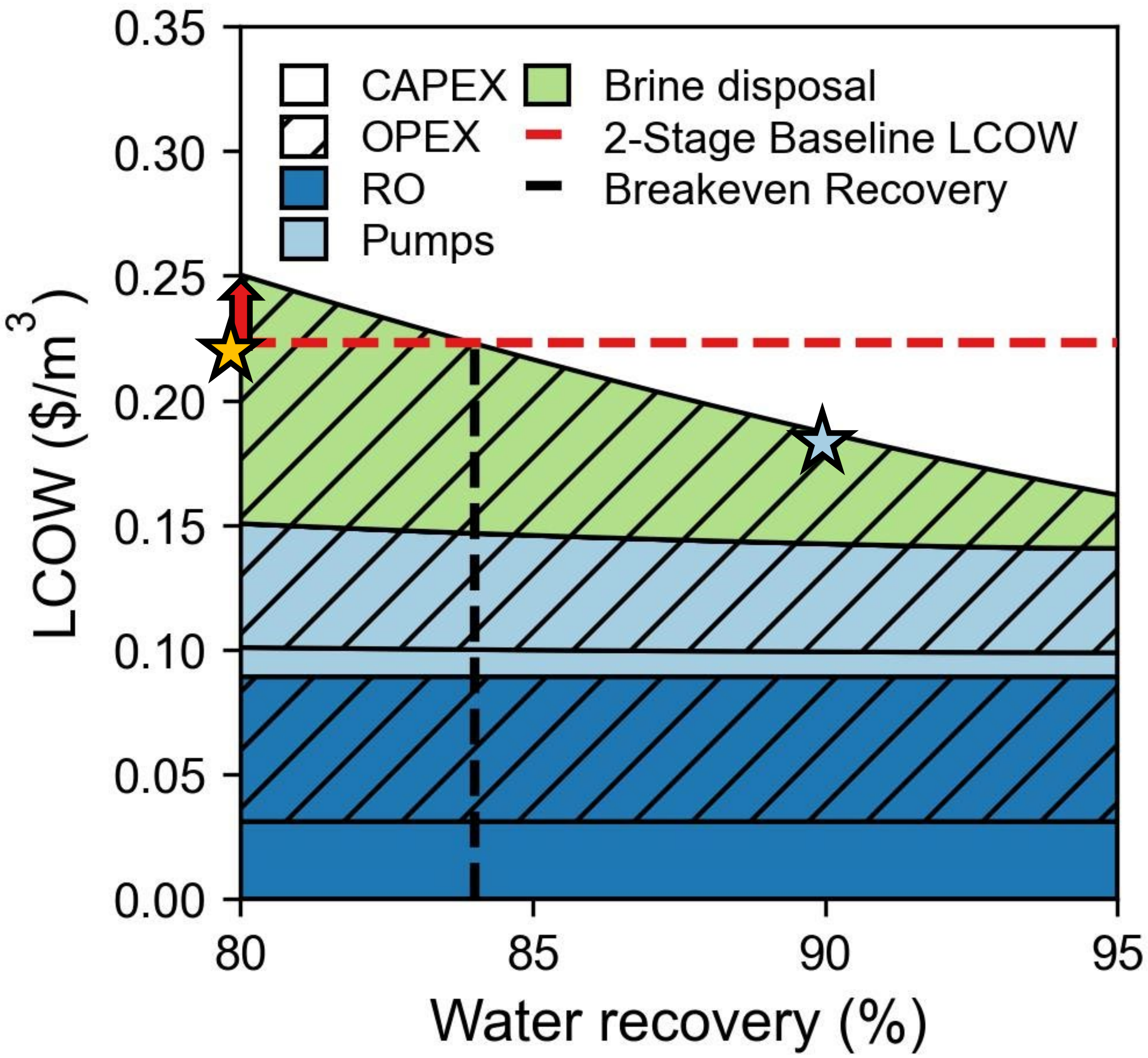
Multiperiod Objectives:

$$min \sum_{x \in X} [LCOW(x) * D(x)]$$

Results:

- Results for t_0- t_n
- Net Results

Retrofit Increases Capital Cost But Unlocks Higher Recovery

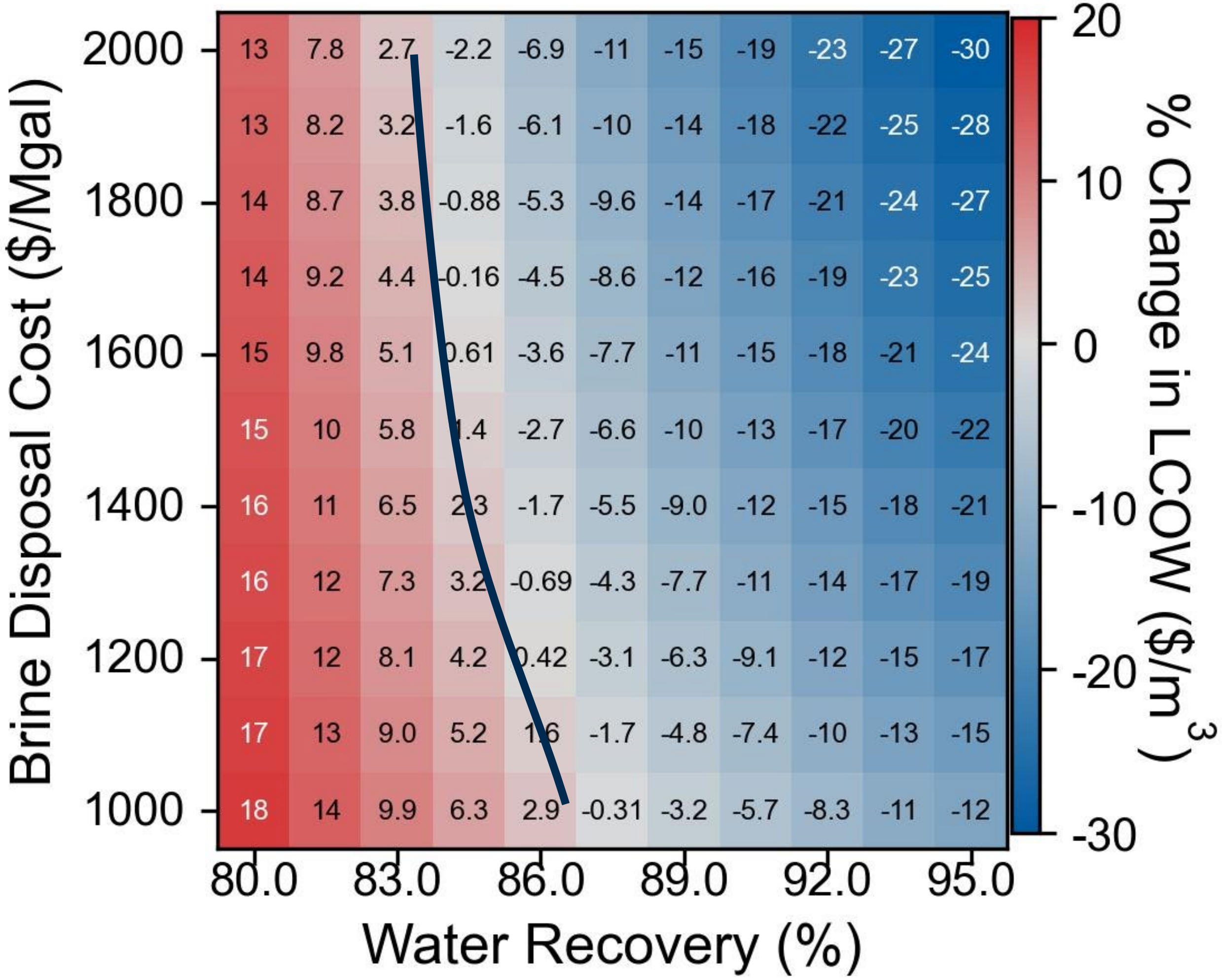


	2-Stage Baseline (80%)	3-Stage FFRRO (**90%**)
Total Capital Cost	$909,604	$1,061,951
Total Operating Cost	$457,492	$359,695
- Brine Disposal Cost	$245,787	$109,876
Total Annualized Cost	$548,452	$460,874
LCOW	$0. 223	$0.187

Assumptions:

Flow Reversal Duty Cycle	95%
3rd Stage Membrane Life	1 Yr.
Brine Disposal Cost	$1500/MGallon

Disposal Costs Are A Primary Driver for Operation



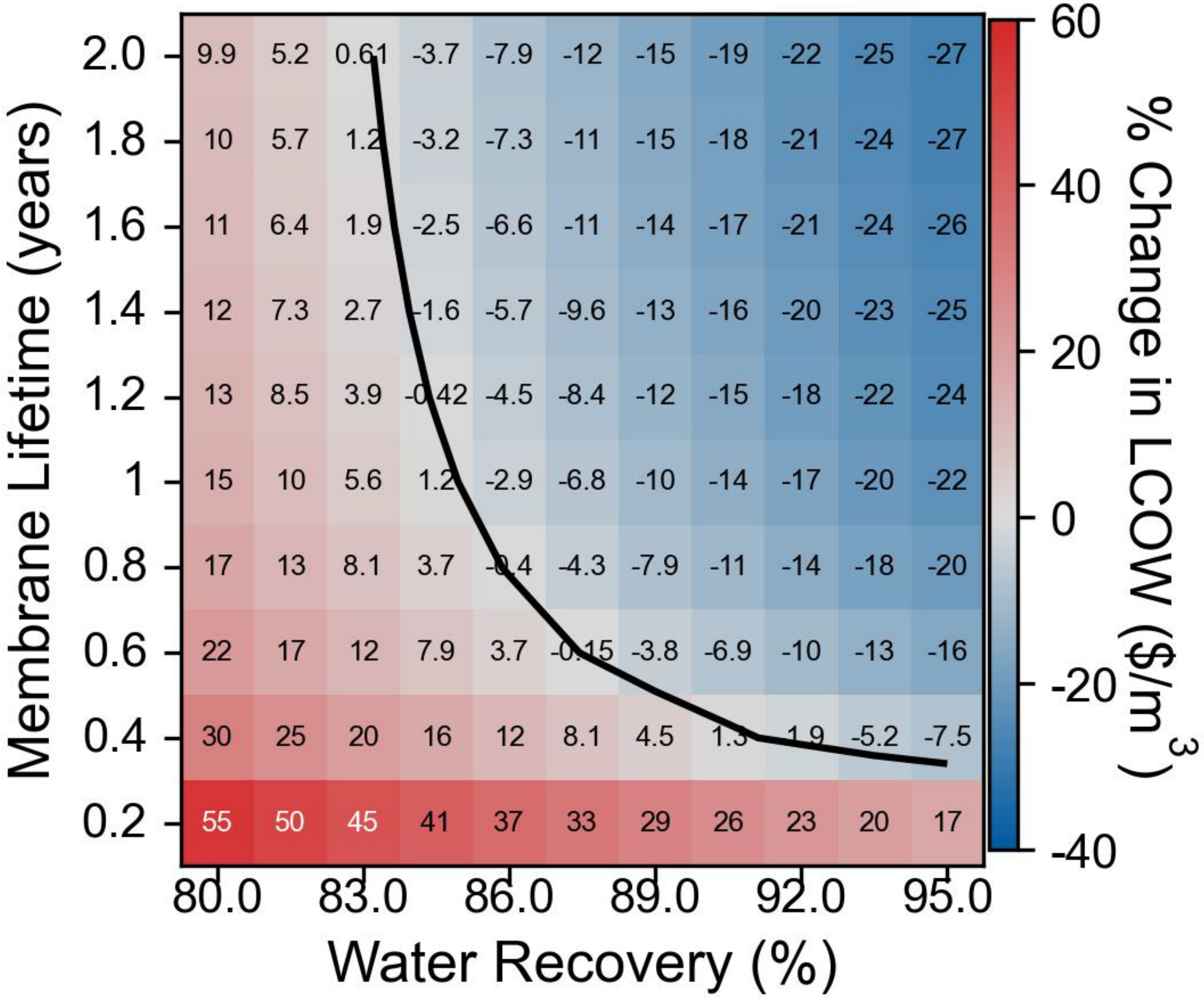
Brine Disposal Cost ($/Mgal)	80.0		83.0		86.0		89.0		92.0		95.0
2000	13	7.8	2.7	-2.2	-6.9	-11	-15	-19	-23	-27	-30
	13	8.2	3.2	-1.6	-6.1	-10	-14	-18	-22	-25	-28
1800	14	8.7	3.8	-0.88	-5.3	-9.6	-14	-17	-21	-24	-27
	14	9.2	4.4	-0.16	-4.5	-8.6	-12	-16	-19	-23	-25
1600	15	9.8	5.1	0.61	-3.6	-7.7	-11	-15	-18	-21	-24
	15	10	5.8	1.4	-2.7	-6.6	-10	-13	-17	-20	-22
1400	16	11	6.5	2.3	-1.7	-5.5	-9.0	-12	-15	-18	-21
	16	12	7.3	3.2	-0.69	-4.3	-7.7	-11	-14	-17	-19
1200	17	12	8.1	4.2	0.42	-3.1	-6.3	-9.1	-12	-15	-17
	17	13	9.0	5.2	1.6	-1.7	-4.8	-7.4	-10	-13	-15
1000	18	14	9.9	6.3	2.9	-0.31	-3.2	-5.7	-8.3	-11	-12

Key Takeaway: As disposal costs increase it is critical to increase recovery.

- As disposal costs increase, the capital cost investment becomes less of a burden.

Assumptions: Flow Reversal	
Flow Reversal Duty Cycle	95%
3rd Stage Membrane Life	1 Yr.

Increasing Recovery Offsets Retrofit Cost If Membrane Lifetime Improves



Key Takeaway: Flow reversal or feed flushing can see positive returns if they can increase membrane lifetime at higher recoveries.

Assumptions: Flow Reversal	
Flow Reversal Duty Cycle	95%
Brine Disposal Cost	$1500/MGallon

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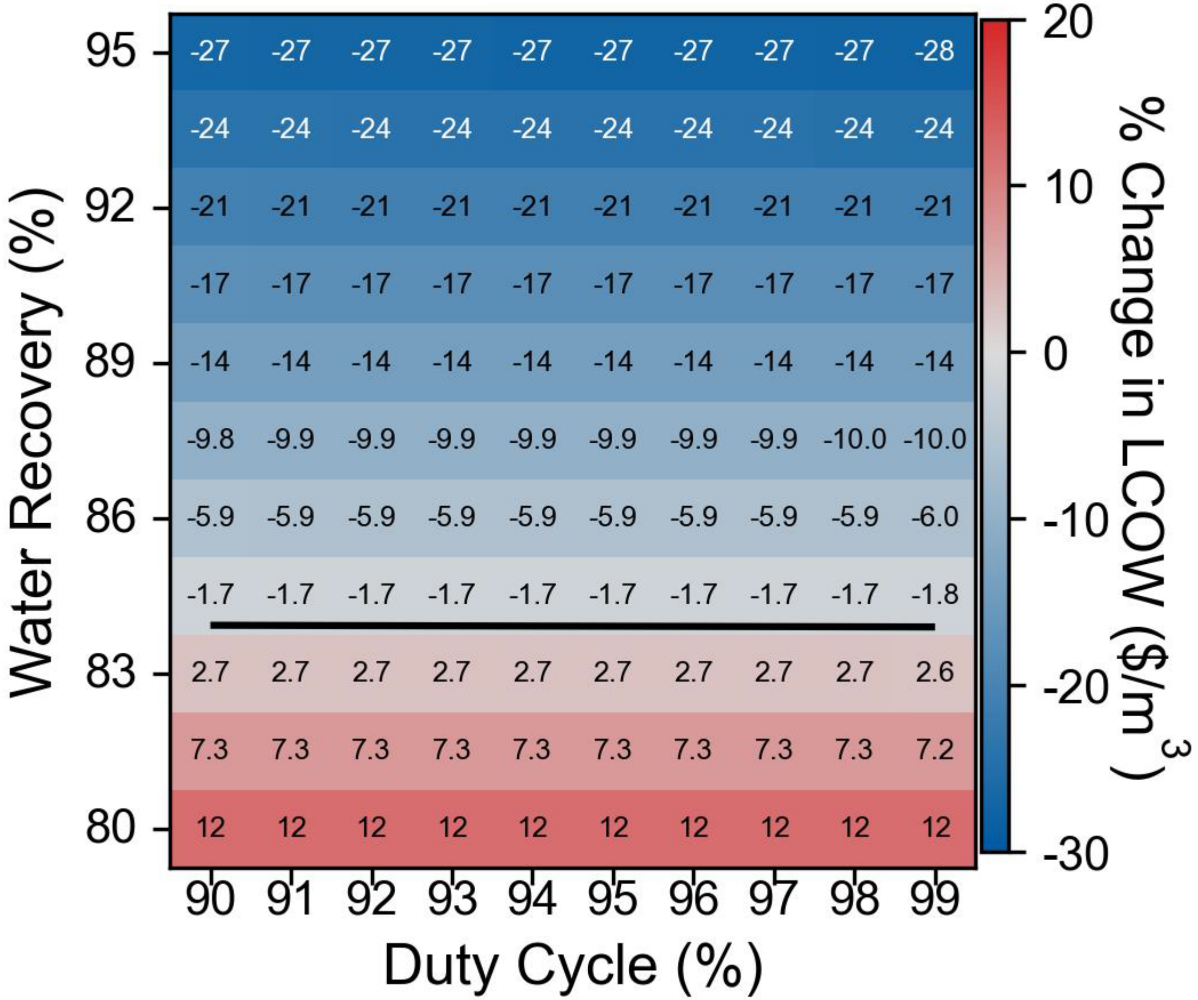
Duty Cycle Has Minimal Impact on LCOW



Water Recovery (%)	90	91	92	93	94	95	96	97	98	99
95	-27	-27	-27	-27	-27	-27	-27	-27	-27	-28
	-24	-24	-24	-24	-24	-24	-24	-24	-24	-24
92	-21	-21	-21	-21	-21	-21	-21	-21	-21	-21
	-17	-17	-17	-17	-17	-17	-17	-17	-17	-17
89	-14	-14	-14	-14	-14	-14	-14	-14	-14	-14
	-9.8	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-10.0	-10.0
86	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9	-5.9	-6.0
	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.7	-1.8
83	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.6
	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.2
80	12	12	12	12	12	12	12	12	12	12

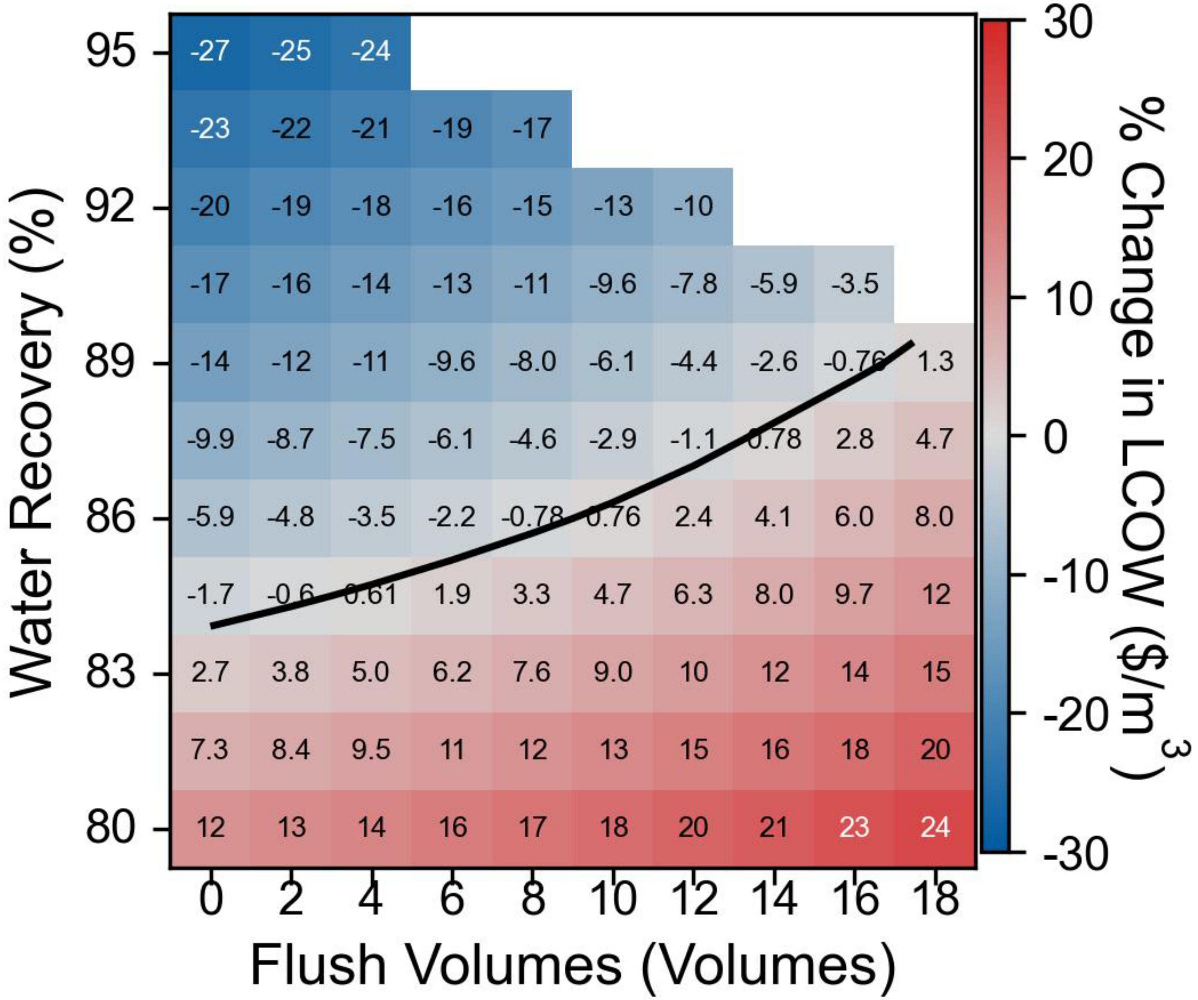
Key Takeaway: The duty cycle for flow reversal doesn’t impact system costs very much.

- Stage 3 recovers the last ~10% and is down ≤10% of the time. These losses can easy be made-up during the rest of the duty cycle.

Assumptions: Flow Reversal

Brine Disposal Cost	$1500/MGallon
3rd Stage Membrane Life	1 Yr.

The Impact of Flow Reversal and Flushing is Minimal Compared to Recovery

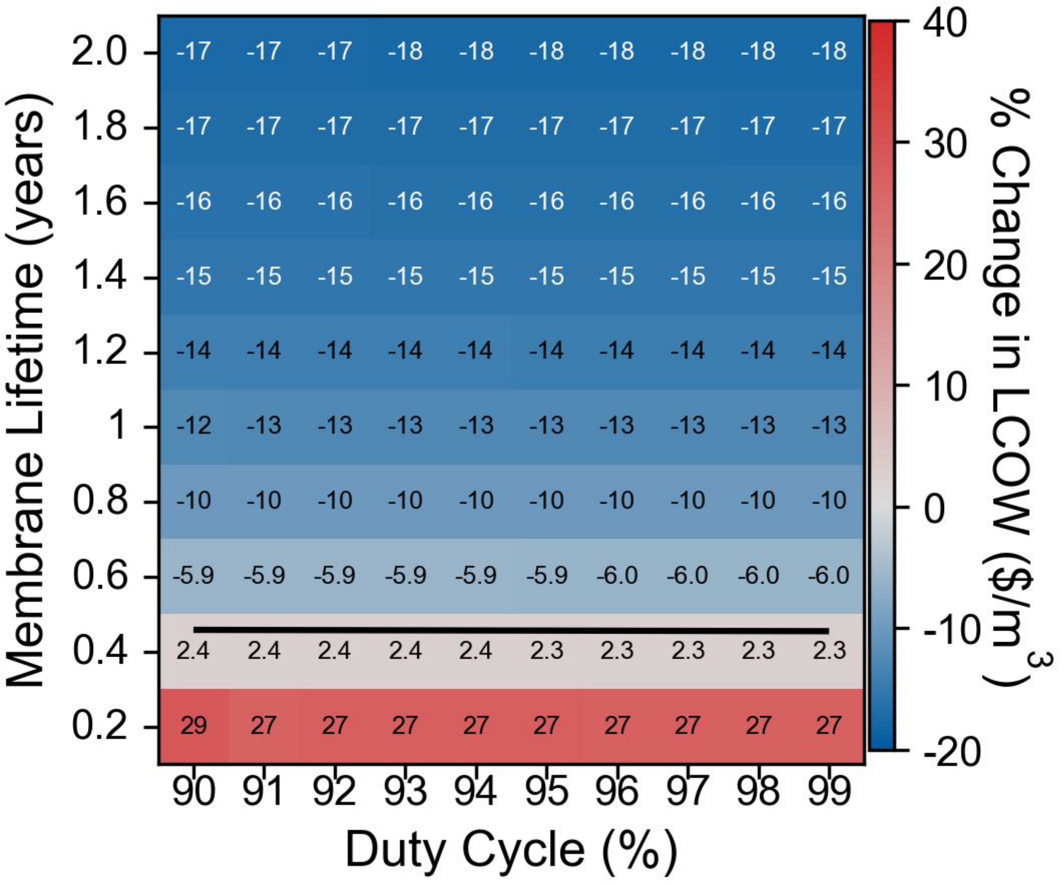


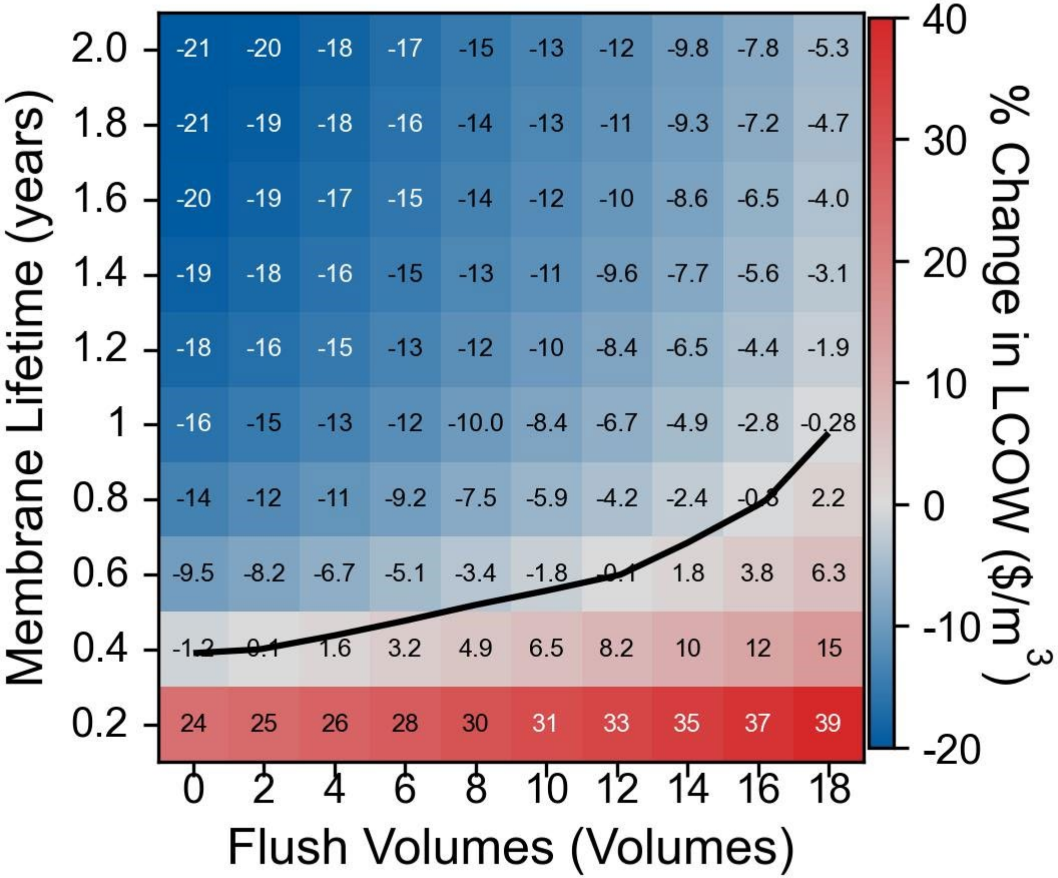
	0	2	4	6	8	10	12	14	16	18
95	-27	-25	-24							
	-23	-22	-21	-19	-17					
92	-20	-19	-18	-16	-15	-13	-10			
	-17	-16	-14	-13	-11	-9.6	-7.8	-5.9	-3.5	
89	-14	-12	-11	-9.6	-8.0	-6.1	-4.4	-2.6	-0.76	1.3
	-9.9	-8.7	-7.5	-6.1	-4.6	-2.9	-1.1	0.78	2.8	4.7
86	-5.9	-4.8	-3.5	-2.2	-0.78	0.76	2.4	4.1	6.0	8.0
	-1.7	-0.6	0.61	1.9	3.3	4.7	6.3	8.0	9.7	12
83	2.7	3.8	5.0	6.2	7.6	9.0	10	12	14	15
	7.3	8.4	9.5	11	12	13	15	16	18	20
80	12	13	14	16	17	18	20	21	23	24

Key Takeaway: The wasted flush volumes are expensive compared to flow reversal, but can be offset by increased recovery and may be more effective in resetting induction time.

Assumptions: Feed Flushing	
Brine Disposal Cost	$1500/MGallon
3rd Stage Membrane Life	1 Yr.

The Relationship Between Flow Reversal, Flushing, and Membrane Life Is Critical





Assumptions:	
Water Recovery	90%
Brine Disposal Cost	$1500/MGallon

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Conclusions

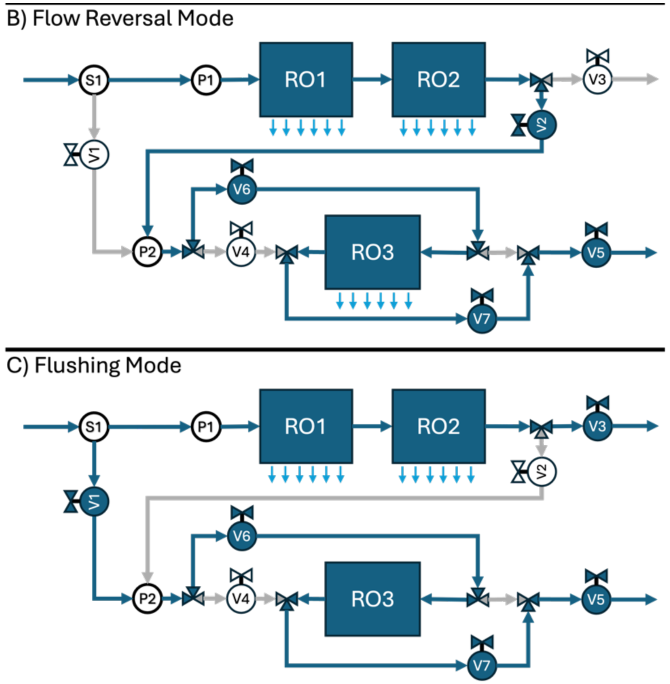
High Recovery: Implementing a 3rd RO stage process can increase recovery rates at Chino I beyond 90%, significantly reducing brine disposal costs.

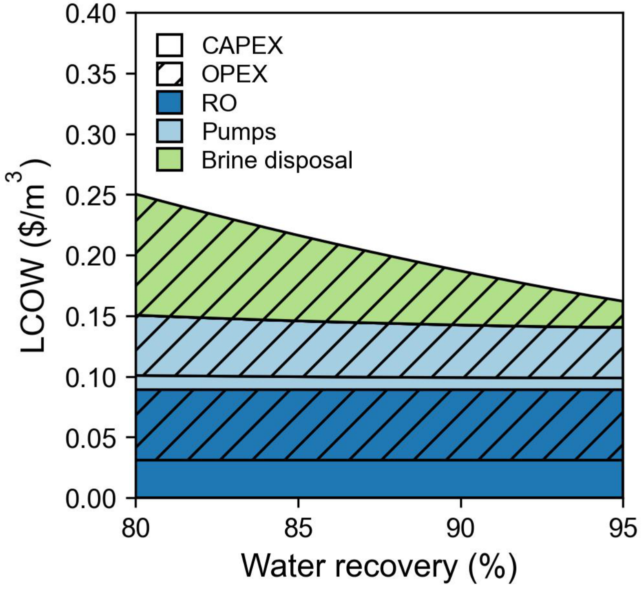
Economic Viability: Retrofit costs are offset by reduced brine disposal costs.

Key Factor: **The impact of flow reversal and flushing frequency on membrane life is critical** in ensuring long-term process sustainability and estimating system performance.

Future Work: Reaktoro will be integrated to model the impact of flow reversal and feed flushing on membrane lifetime.

- Move beyond sensitivity analysis and perform system optimization





Thank You

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