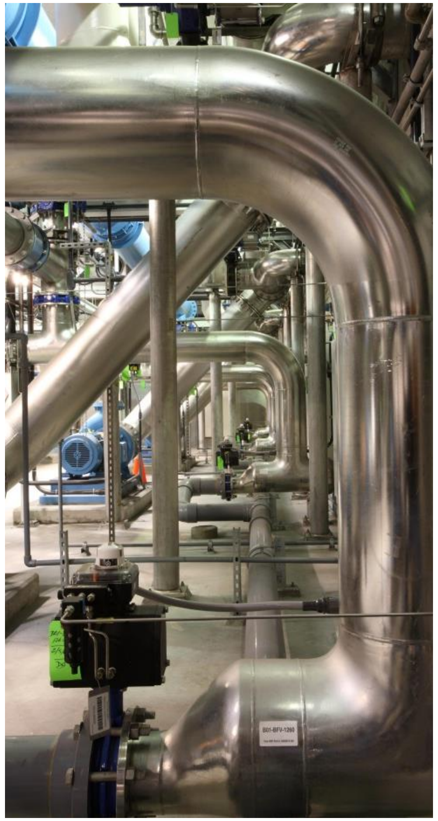
A Low-Energy Wastewater Treatment Process for Producing High Quality Reuse Water

Eric Marchand, University of Nevada, Reno
Andrea Achilli, Humboldt State University
Sage Hiibel, University of Nevada, Reno



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About WateReuse

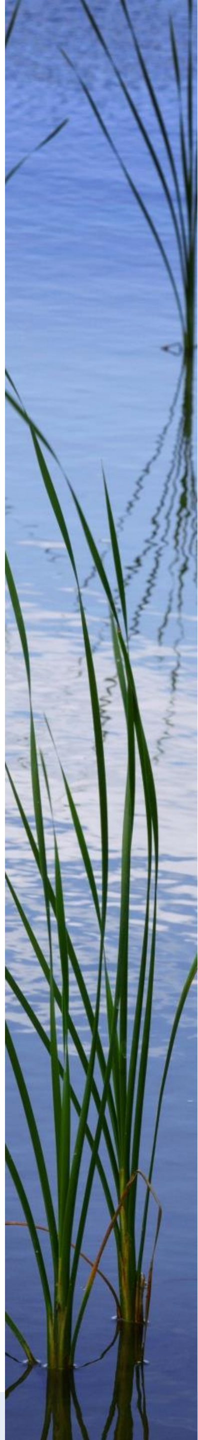
The mission of the WateReuse Research Foundation is to build support for water reuse through research and education.

More information

www.watereuse.org/foundation

Research Reports

www.watereuse.org/foundation/publications



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Logistical Notes

- Today's webcast will be 60 minutes
- A PDF of today's presentation can be downloaded when you complete the survey at the conclusion of this webcast
- There is one Professional Development Hour available
- If you have questions for the presenters, please send a message by typing it into the chat box located on the panel on the left side of your screen
- If you would like to enlarge your view of the slides, please click the Full Screen button in the upper right corner of the window
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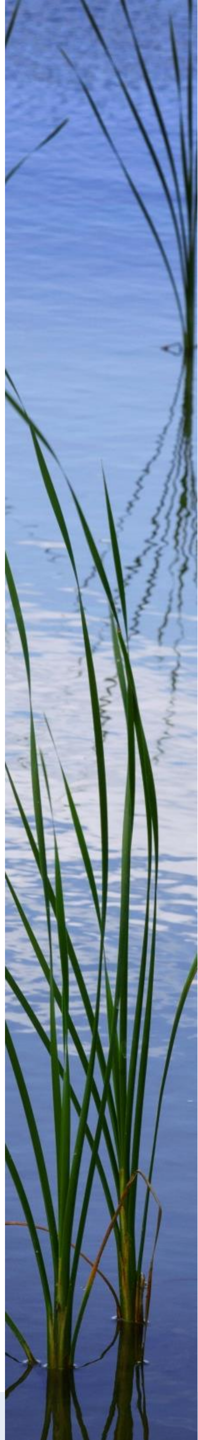
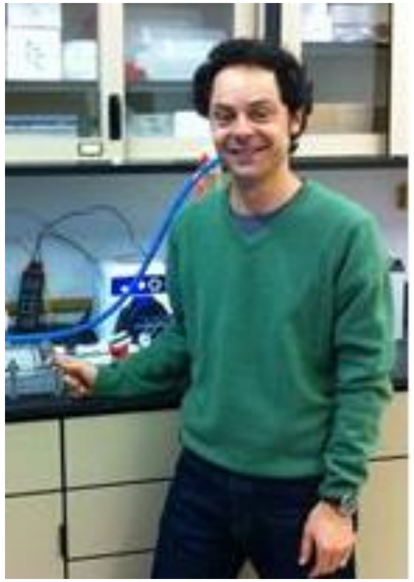


Today's Presenters

Eric Marchand, Ph.D., P.E.
University of Nevada, Reno



Andrea Achilli, Ph.D., P.E.
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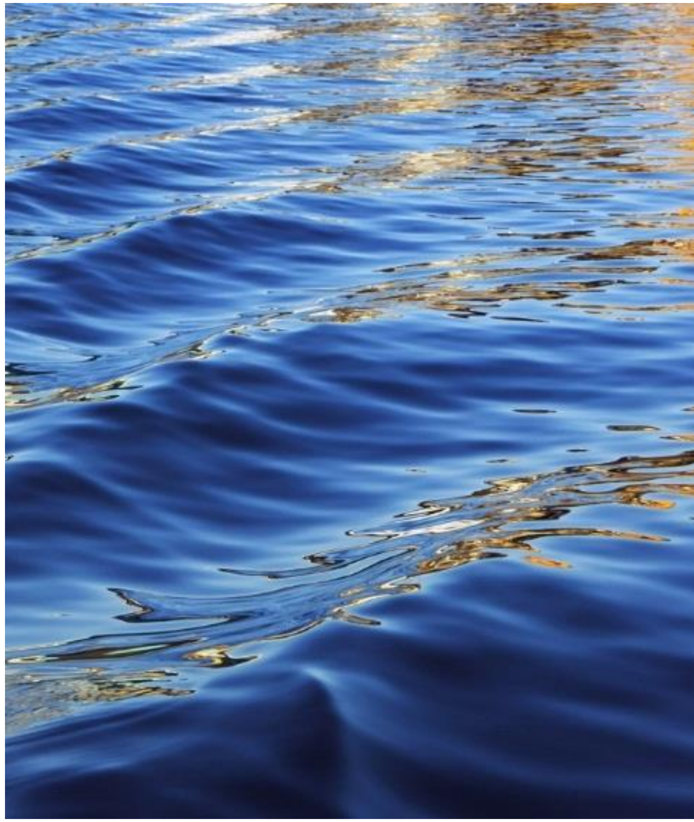
Project Overview

Dr. Eric Marchand



Acknowledgements

- Project Manager – Kristan Cwalina
- Project Advisory Committee
  - Chris Haney, Senior Vice President – Gresham, Smith and Partners
  - Paul Westerhoff, Professor – Arizona State University
  - Charles Bott, Research and Development Manager – Hampton Roads Sanitation District (HRSD)
  - Katherine Dahm, Engineer – Bureau of Reclamation
- Industry Partners
  - Hydration Technology Innovations (HTI)
  - Porifera
  - Washoe County Department of Water Resources
  - Truckee Meadows Water Reclamation Facility (TMWRF)

Presentation Overview

- Project Objectives
- Coupled Forward Osmosis and Membrane Distillation
- Wastewater Concentration by Forward Osmosis
- Anaerobic Membrane Bioreactor Performance
- Discussion and Questions

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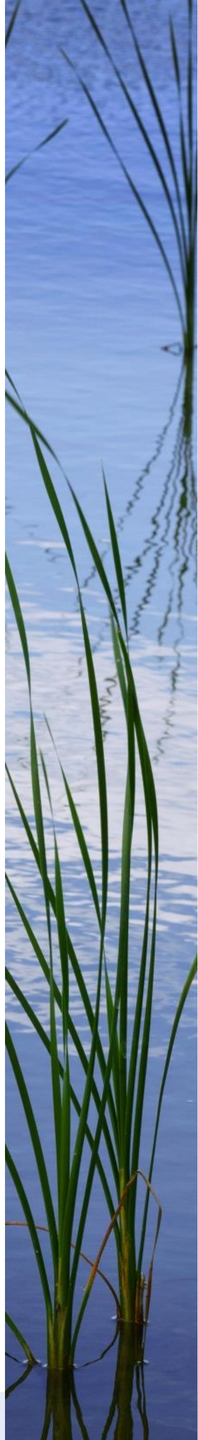
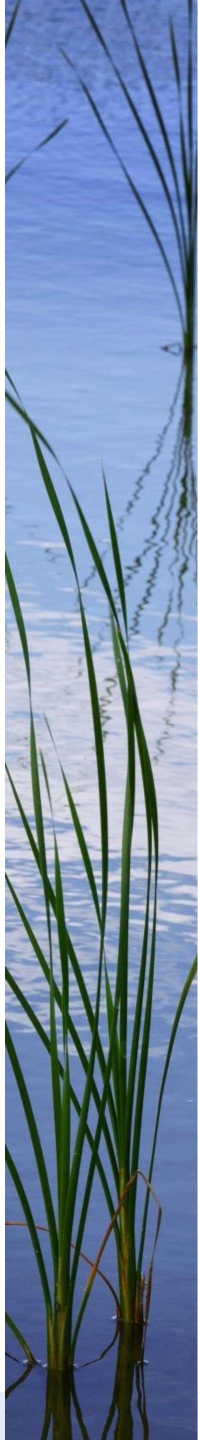


Project Objectives

- Conceptualize a novel treatment scheme to reduce energy associated with domestic wastewater treatment
- Conduct a literature review to establish operating conditions for each unit process
- Develop a process model for the treatment scheme and compare performance to an existing water reclamation facility
- Perform laboratory-scale experiments to optimize operating parameters of individual unit processes



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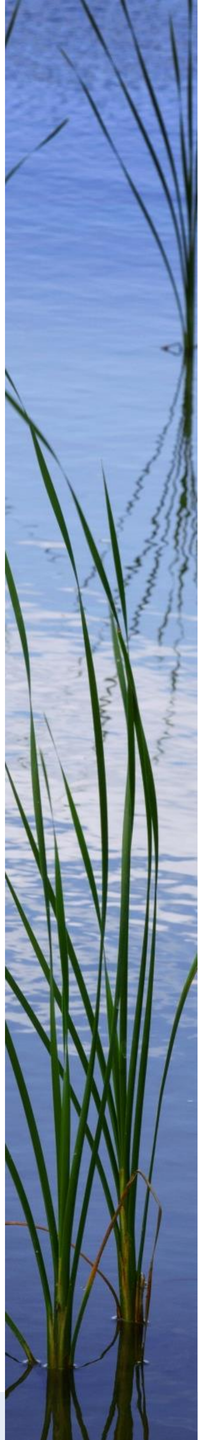
Relevance to WateReuse RFP

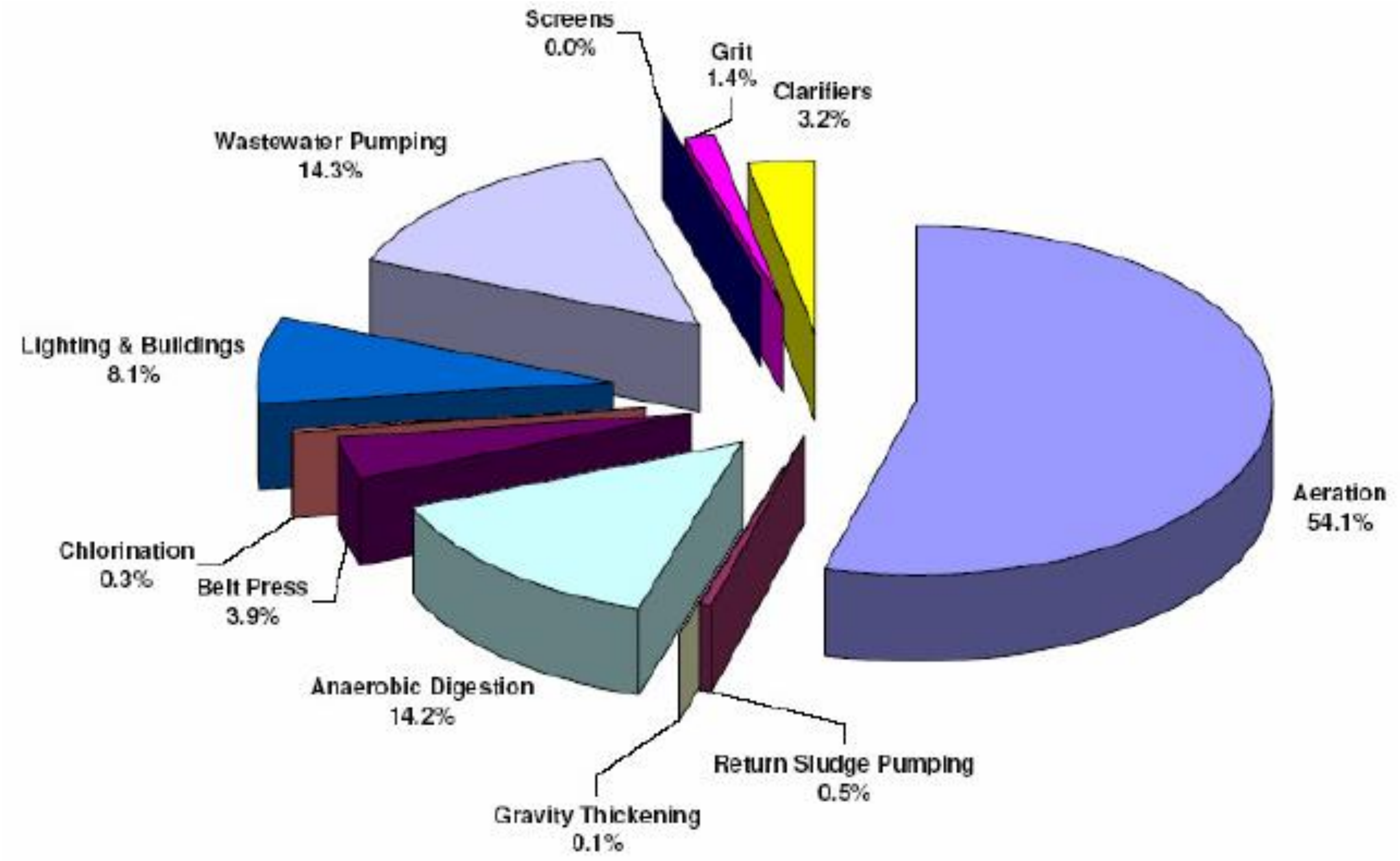
- 10-06: *Challenge Projects on Low Energy Treatment Schemes for Water Reuse*

  The goal of the project is to conceptualize and evaluate alternatives to energy intensive aerated activated sludge systems for providing suitable water for one or more reuse applications, ranging from irrigation to cooling tower water to pretreatment for reverse osmosis or other reuse treatment processes. The project would include two phases, which will be funded separately, a development phase and a testing phase.

- Phase 1 Research – Collect literature data and perform preliminary modeling
- Phase 2 Research – Test system components in lab setting



Energy for Wastewater Treatment



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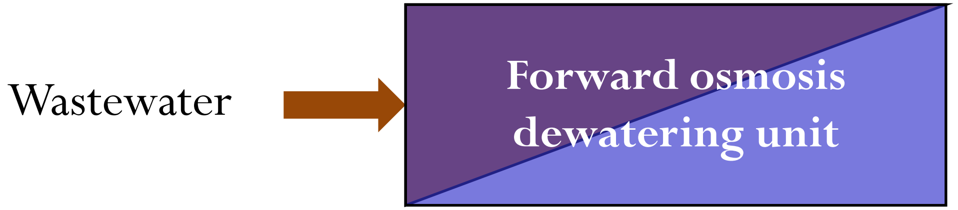
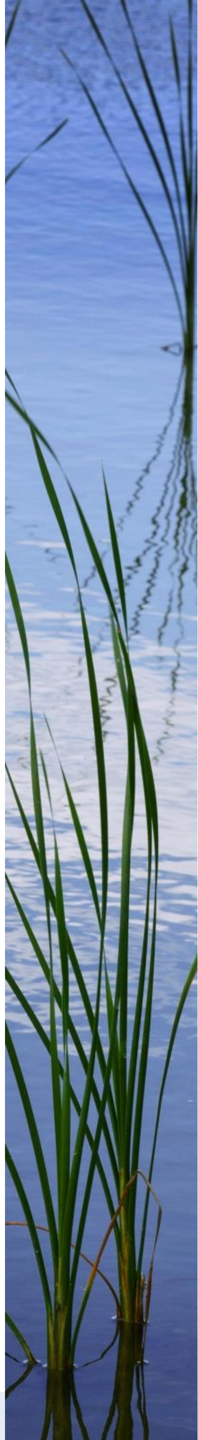
Source: Water Environment Energy Conservation Task Force: Energy Conservation in Wastewater Treatment

Low-Energy System Principles





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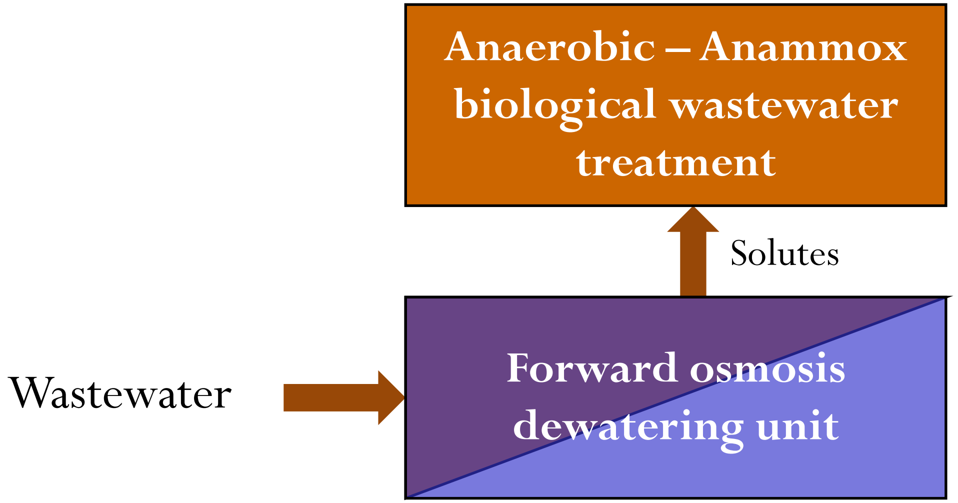

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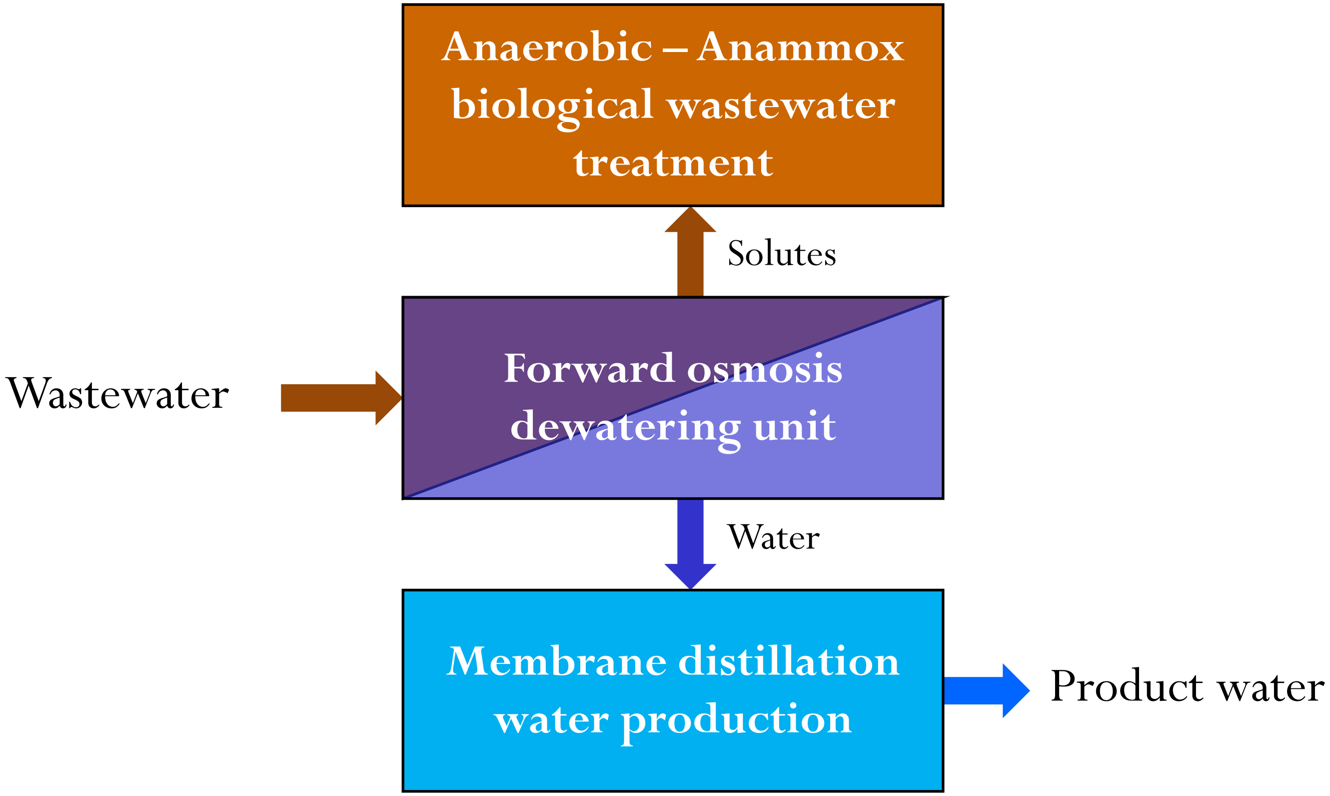

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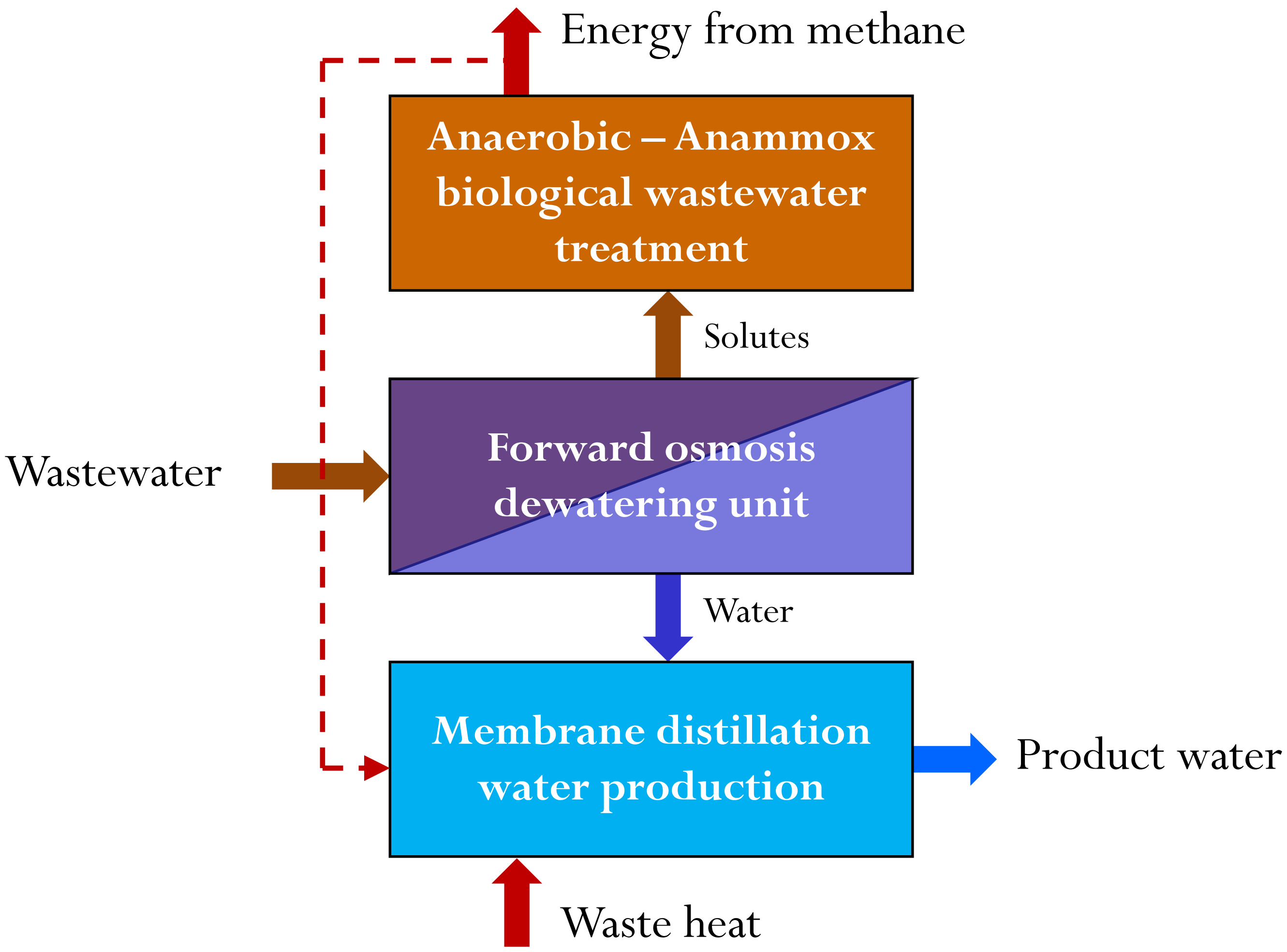

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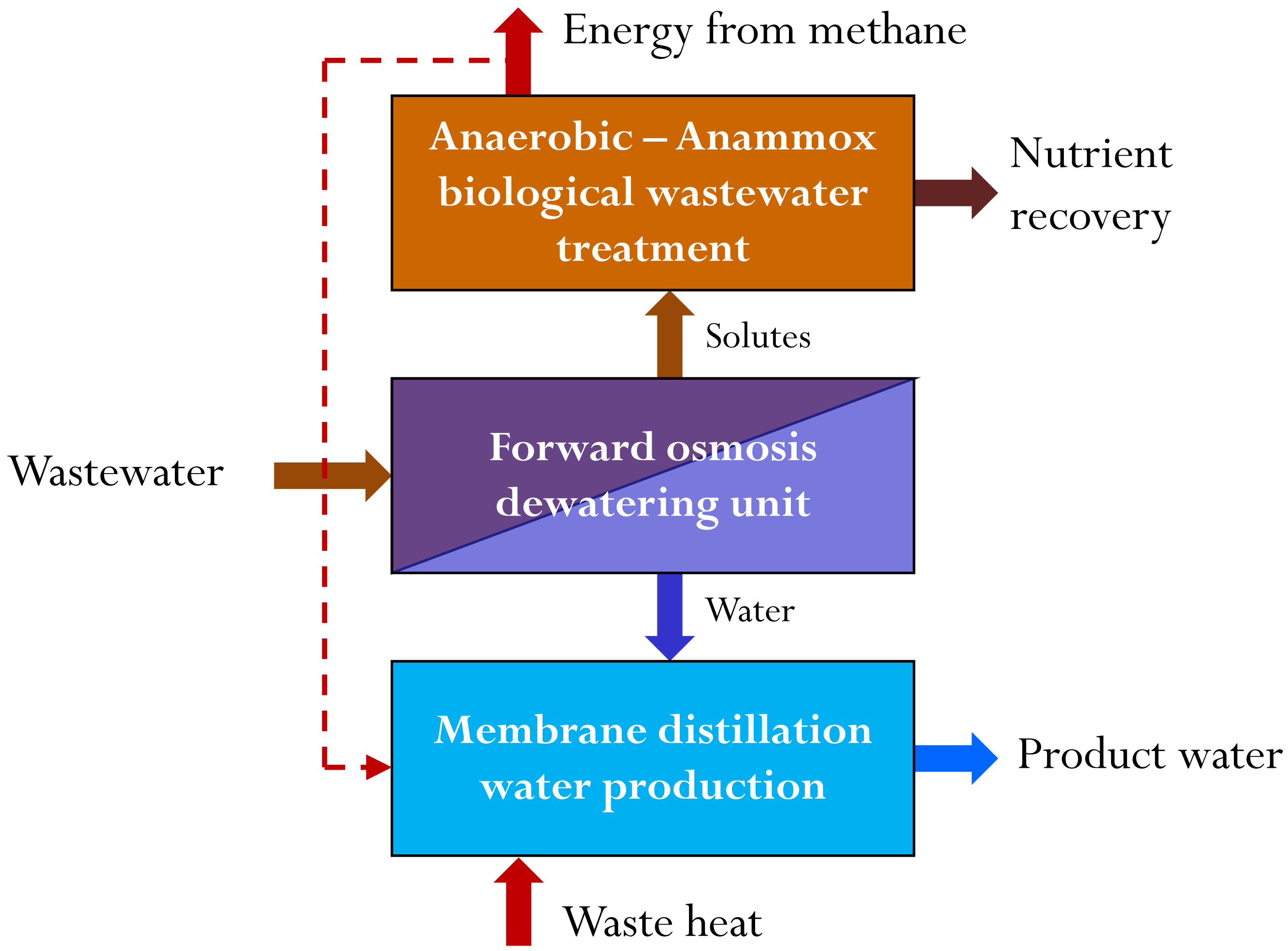

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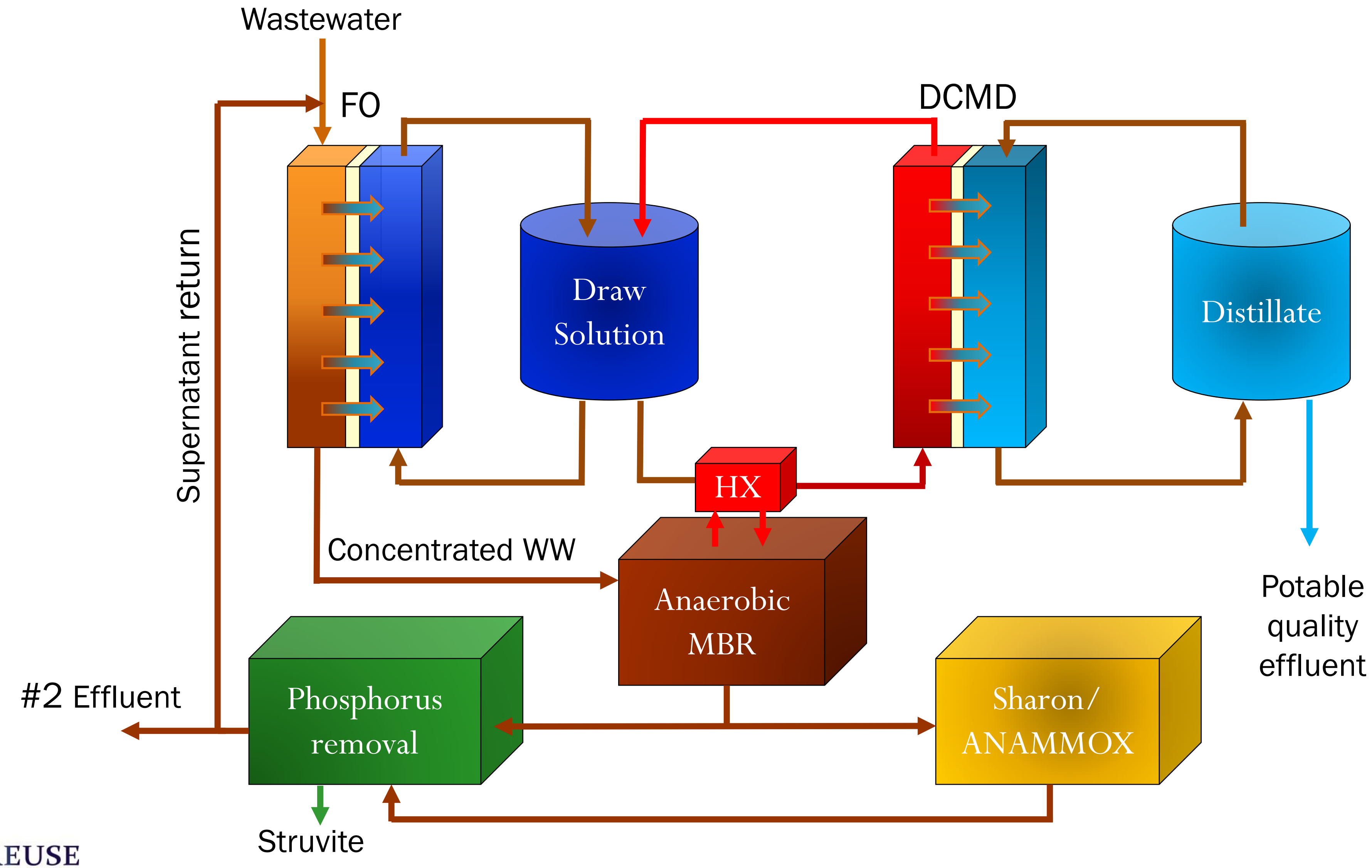
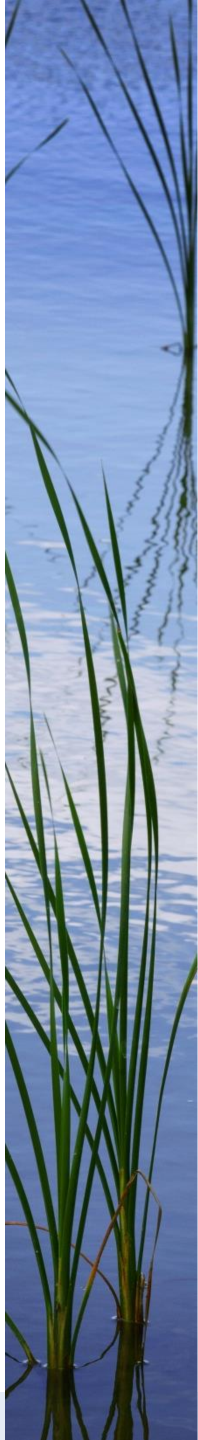
New Conceptual Process Diagram





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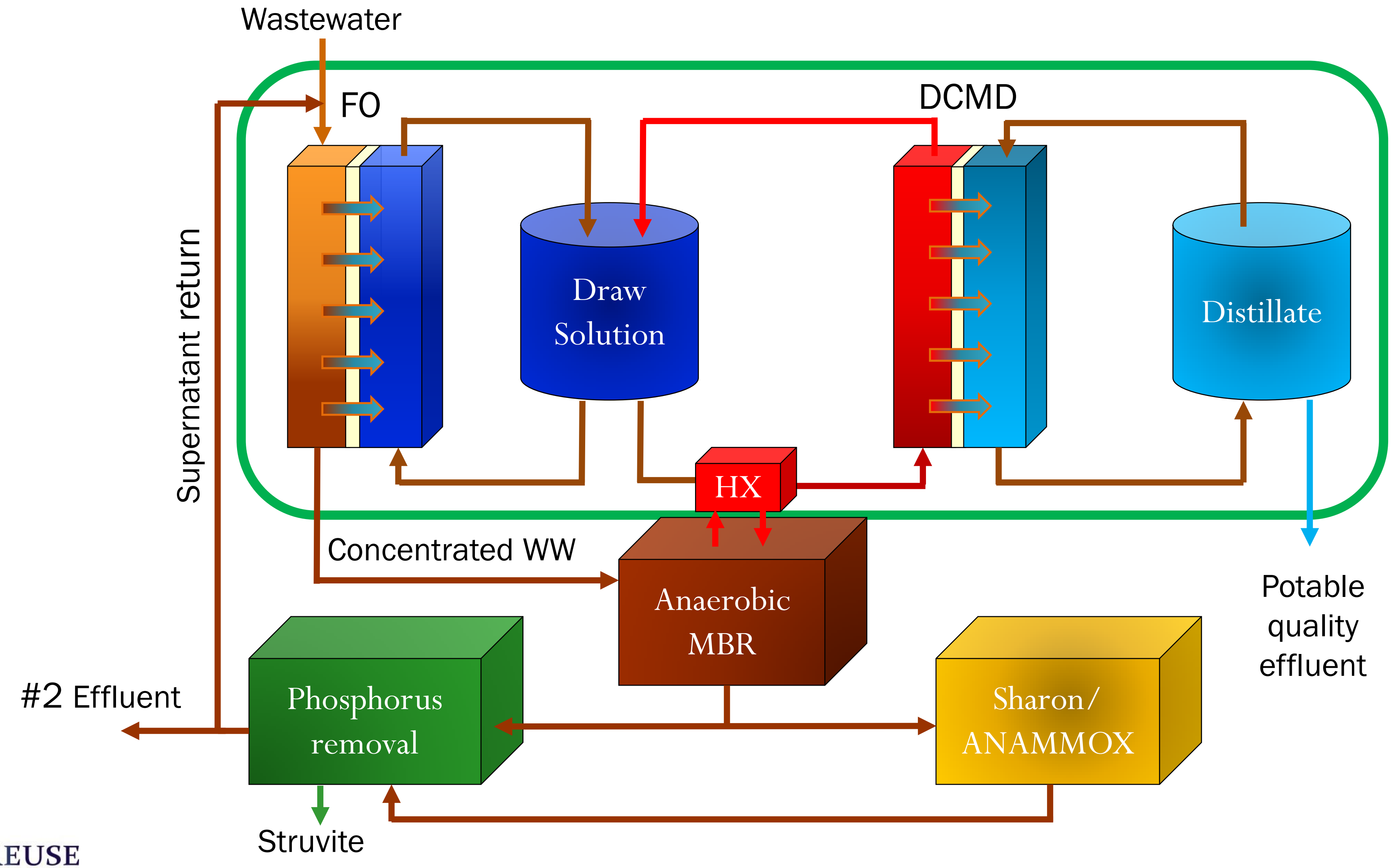

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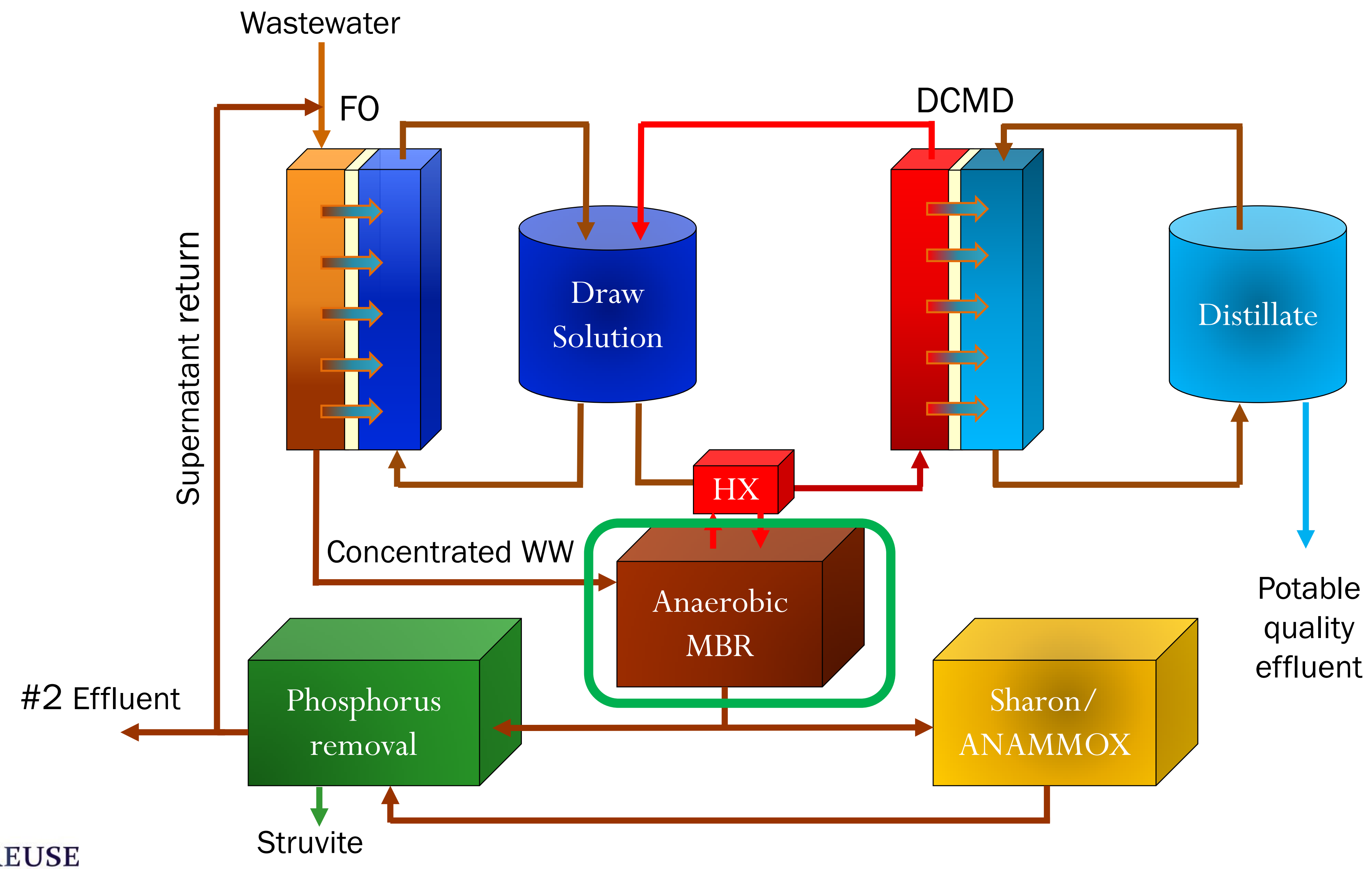

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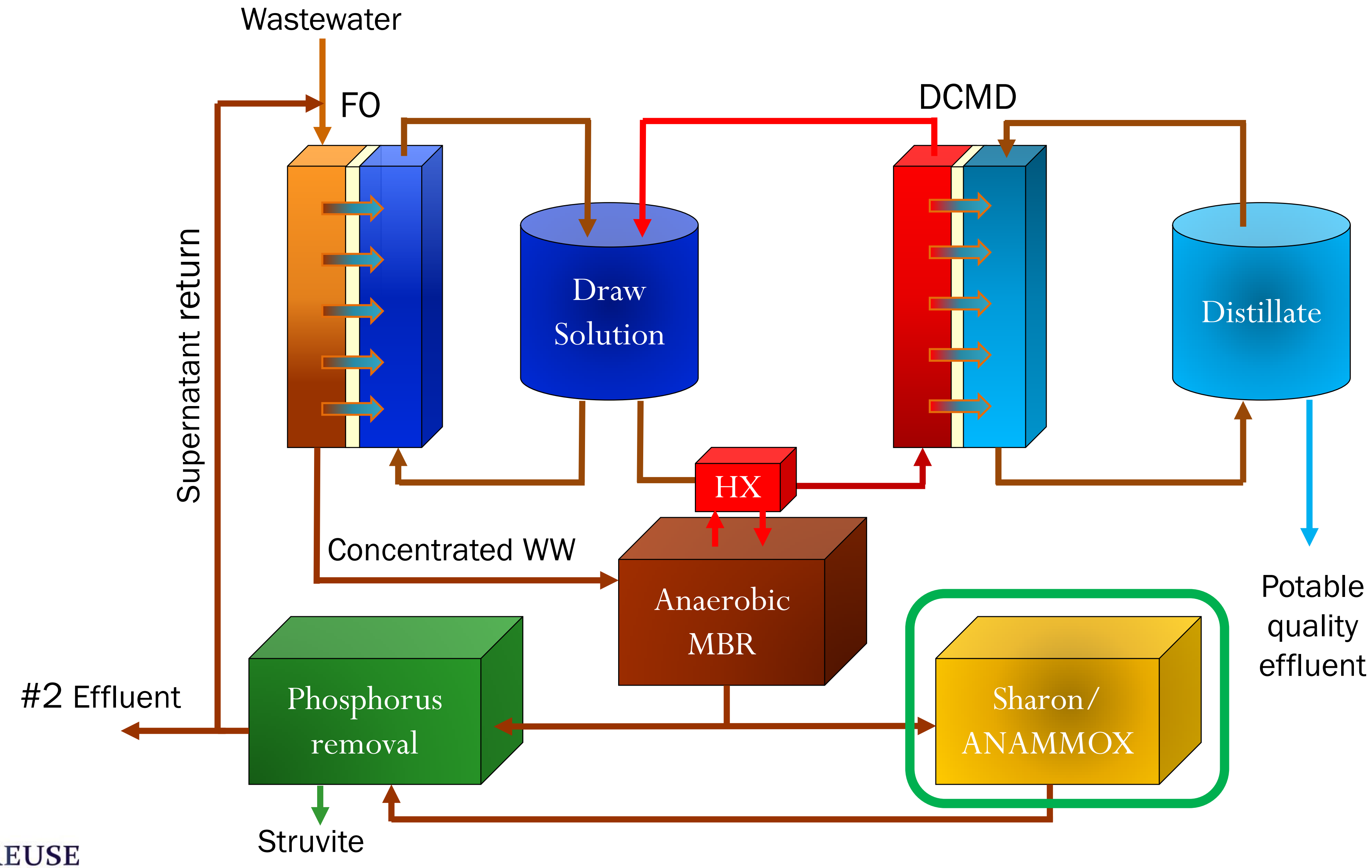

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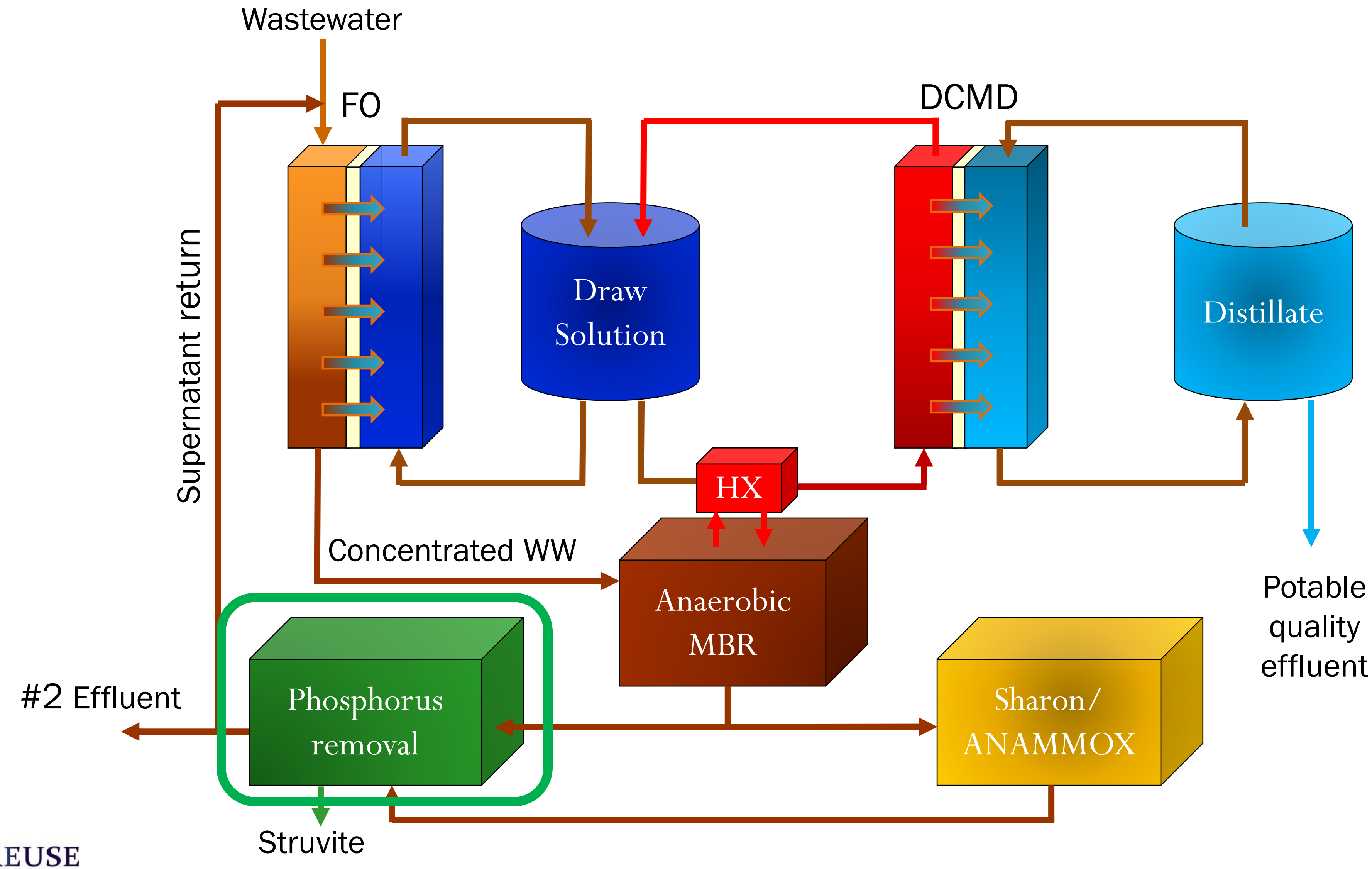
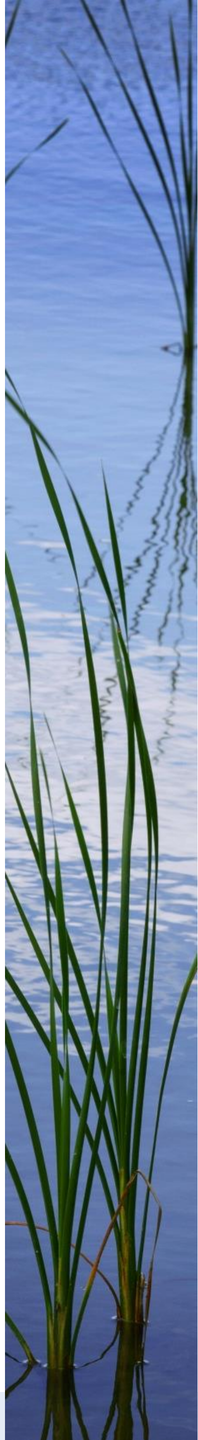


Phase 1: Proof of Concept Testing

- Perform literature review for system components
  - Forward Osmosis
  - Membrane Distillation
  - Anaerobic MBR
  - Sharon – Anammox
  - Struvite Precipitation
- Identify typical operating conditions for each process
- Develop BioWin Model
- Perform simulation at two FO recoveries (50% and 70%)
- Compare performance to water reuse facility



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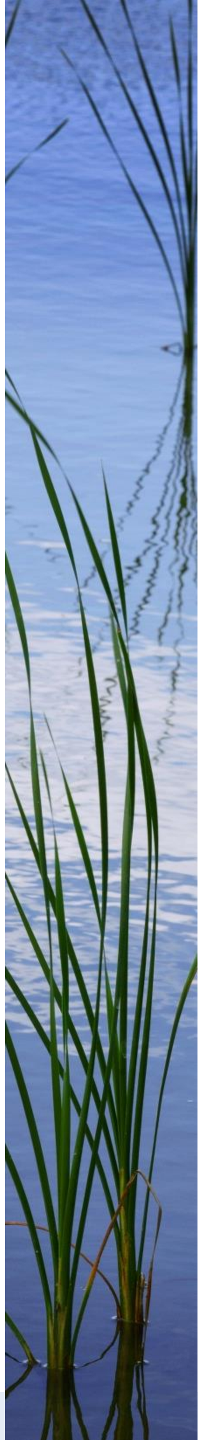
Forward Osmosis (FO)

FO serves as a pre-concentration step: clean water in the influent wastewater diffuses across the forward osmosis membrane into the draw solution.

www.htiwater.com

Parameter	Typical Values
Flux (L/m^2*hr, LMH)	2.7 - 12.9
Draw Solution	NaCl or $MgCl_2$
Solute Ionic Strength (M)	2.0 – 5.0
Water Recovery (%)	50 - 70
Reverse Salt Flux	Variable, ~0.15*Flux



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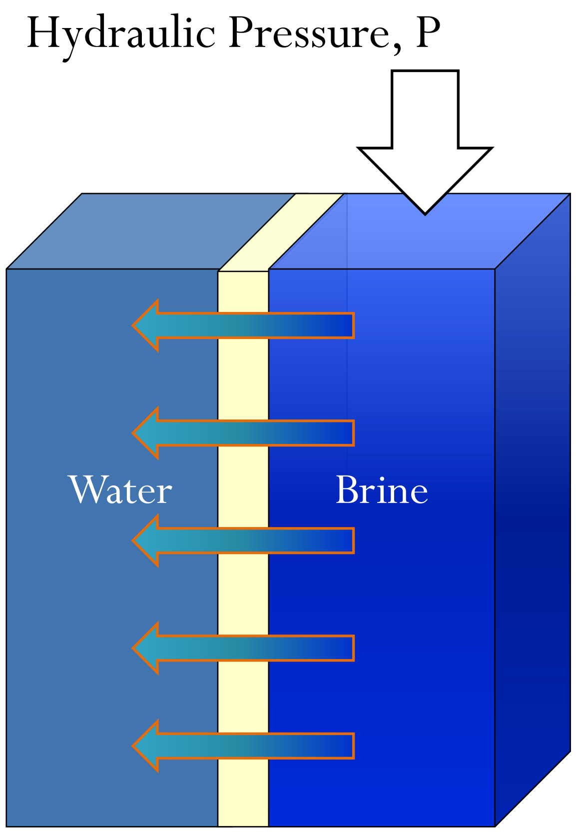
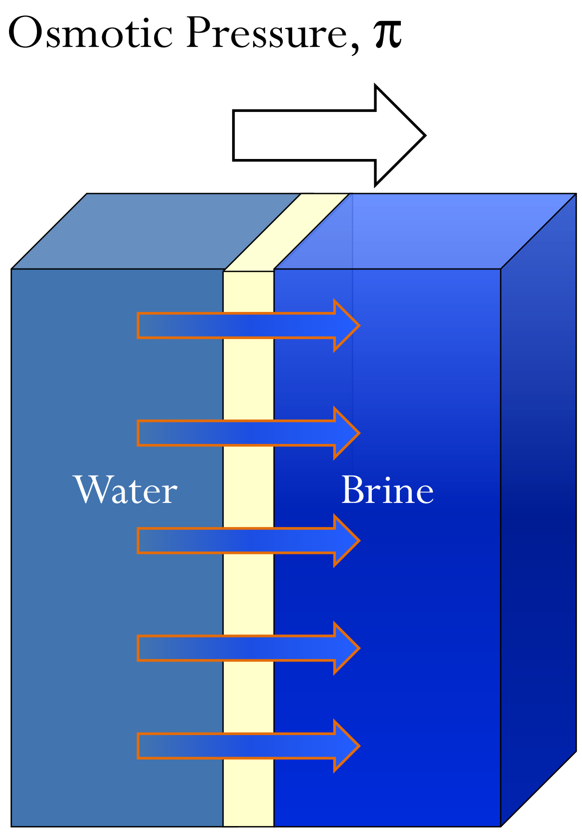
Reverse Osmosis *vs.* Forward Osmosis



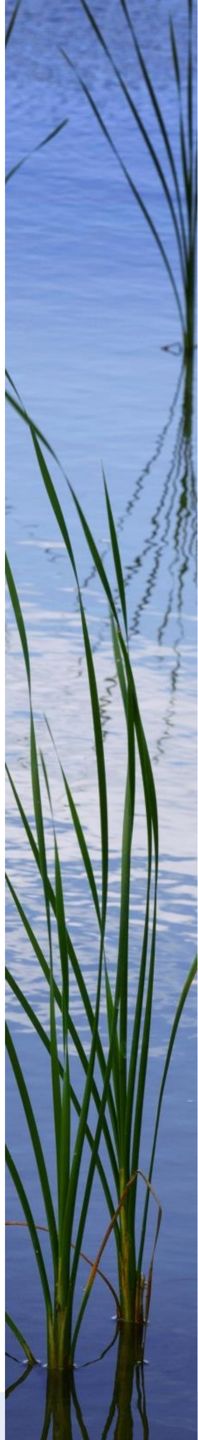
Reverse Osmosis

$\Delta\pi < \Delta P$



Forward Osmosis

$\Delta\pi$



Membrane Distillation (MD)

MD uses a porous hydrophobic membrane to facilitate the transfer of clean water from a heated feed solution to a cold distillate stream.

www.advantage-environment.com

Parameter	Typical Values
Feed Temp (°C)	40.0 – 80.0
Permeate Temp (°C)	17.5 – 23.0
Flux (L/m^2*hr, LMH)	10 – 80
Water Recovery (%)	80 – 95
Salt Rejection (%)	> 95

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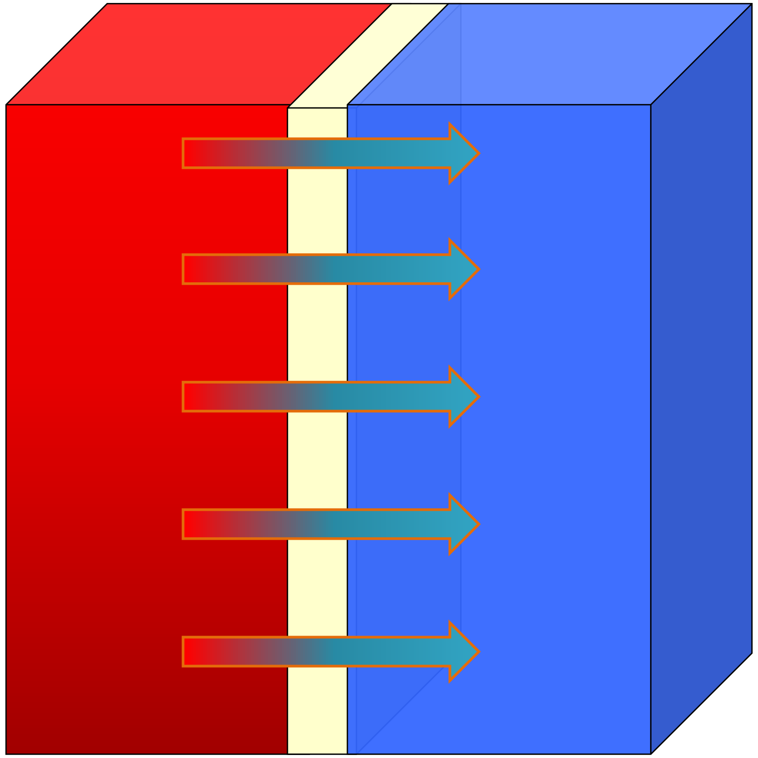
Membrane Distillation (MD)



40°C → 20°C
ΔT = 20°C

- Hydrophobic membrane
- Thermally driven process
- Low energy input

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Anaerobic Membrane Bioreactor (AnMBR)

An AnMBR serves two main purposes: removal of chemical oxygen demand (COD) and production of methane biogas.

www.gewater.com

Parameter	Typical Values
Methane (L/g COD)	0.2 – 0.35
MLSS (g/L)	5 – 30
Flux (L/m^2*hr, LMH)	5 – 8
COD Removal (%)	>80
SRT (days)	> 60

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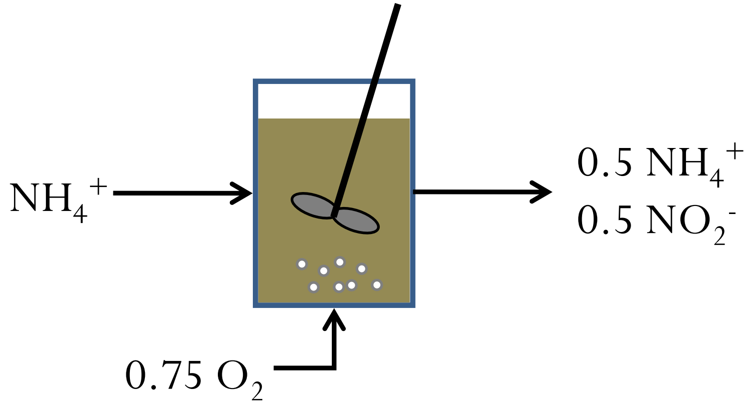
Sharon Process

The SHARON (single-reactor high-yield ammonium removal over nitrite) process is known as partial nitrification.

The target result of SHARON is an even molar ratio of ammonium to nitrite.

Incomplete nitrogen oxidation reduces the oxygen required.

Parameter	Typical Values
Temp (°C)	19 – 35
Nitrogen Load (kg/m^3*d)	0.1 – 3.3
$NO_2^-:NH_4^+$	1:1
HRT & SRT (hr)	4.8 – 36



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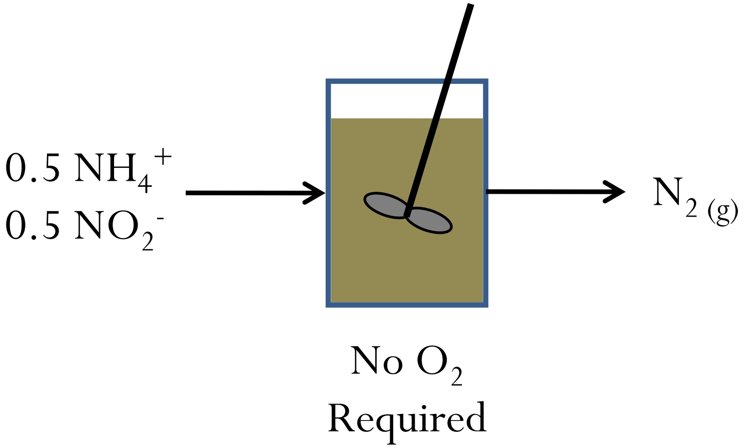
Anammox Process

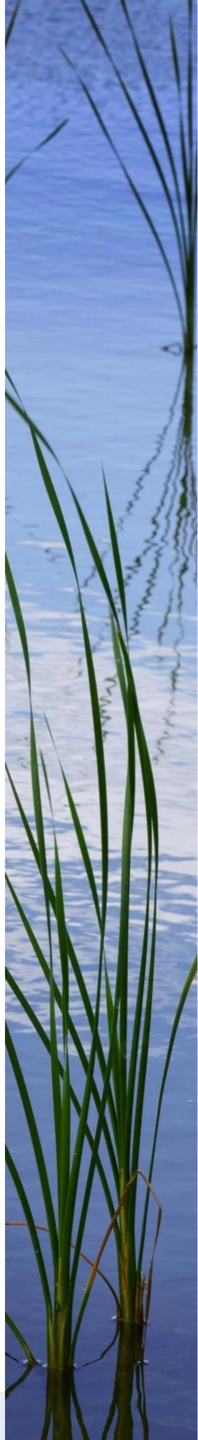
In the ANAMMOX process (ANaerobic AMMonium OXidation), ammonium is used as an electron donor while nitrite is used as an electron acceptor.

Nitrogen is released from the ANAMMOX process as nitrogen gas.

$NH_4^+ + NO_2^- \rightarrow N_2 + 2\ H_2O$

Parameter	Typical Values
Temp (°C)	22 – 35
SNR (g N/g VSS*d)	0.15 – 1.15
$NO_2^-:NH_4^+:NO_3^-$	1 : 1.2 : 0.2



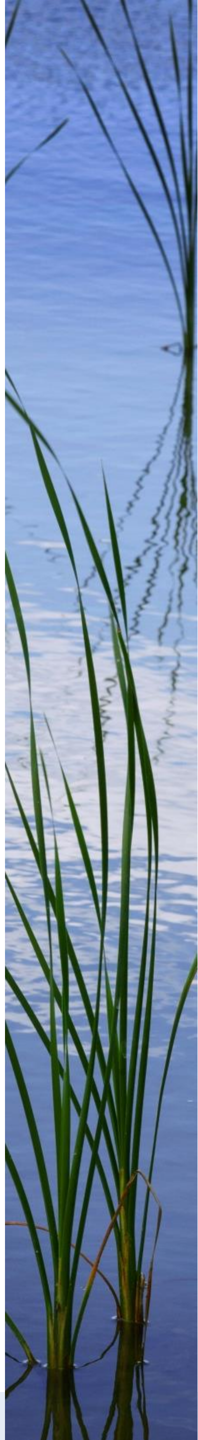


Struvite Precipitation

Struvite ($MgNH_4PO_4*6\ H_2O$) naturally precipitates from wastewater through the addition of magnesium and by increasing pH.

www.ostara.com

Parameter	Typical Values
pH	8 – 9
Temp (°C)	14.5 – 25
Mg:P Molar Ratio	1:1
HRT (hr)	< 4



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Comparison with Water Reuse Facility in Reno

- Selected 100% water reuse facility for comparison (South Truckee Meadows Water Reclamation Facility, STMWRF)
- Developed BioWin model for conceptual facility
- Evaluated BioWin model with STMWRF inputs
  - Varied FO recovery (50% and 70%)
  - Evaluated model for extreme operating ranges
- Compared costs between facilities

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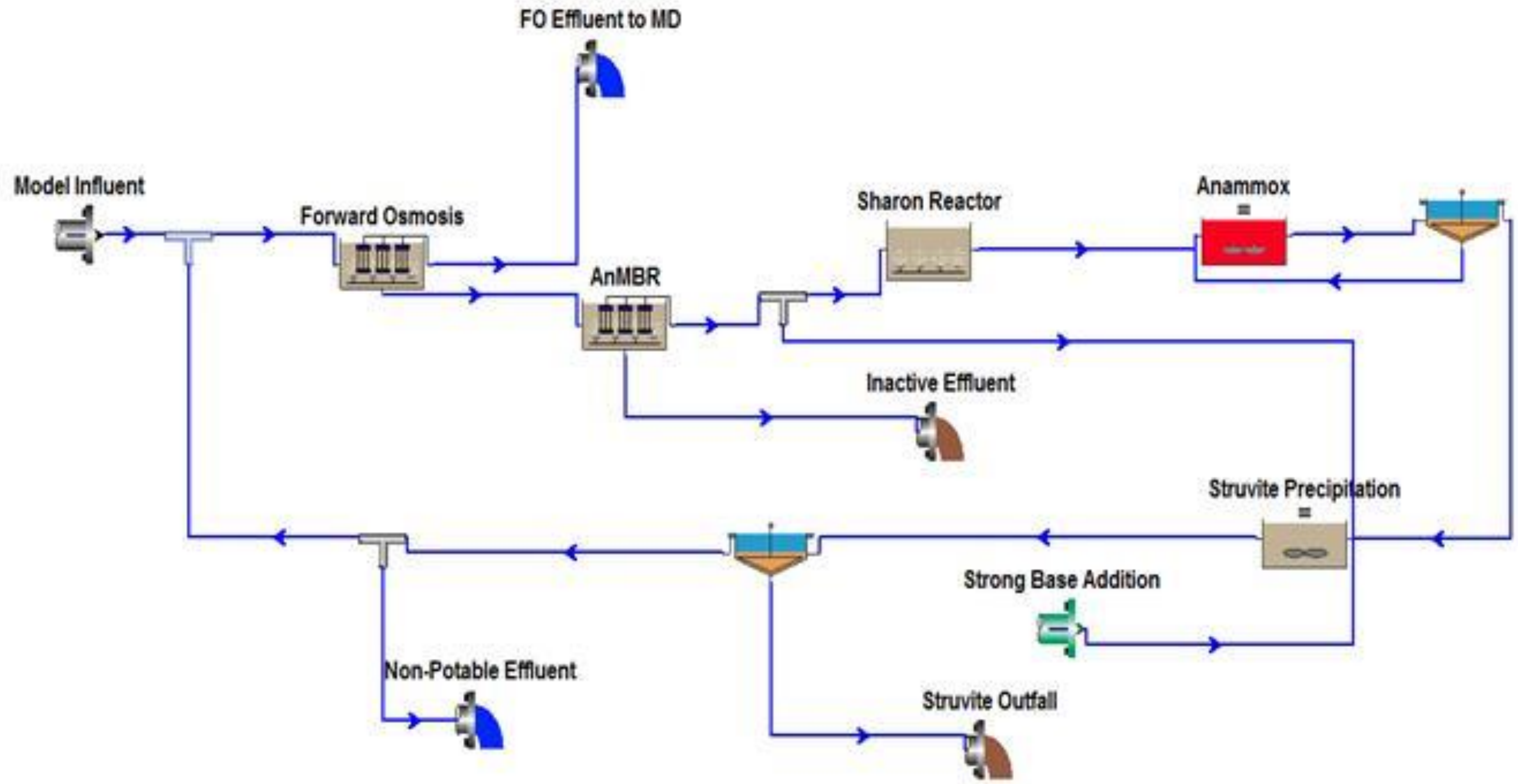
BioWin Model Development



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BioWin Modeling Conditions

- Input water quality parameters were based on STMWRF influent

Parameter	Value	Parameter	Value
Flow	3 MGD	**COD**	300 mg COD/L
TKN	20 mg N/L	**Total Phosphorus**	5 mg P/L
Nitrate	0.3 mg N/L	**pH**	7.3
Alkalinity	5.5 mmol/L	**Calcium**	45 mg/L
Magnesium	15 mg/L	**Dissolved Oxygen**	0 mg/L

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Model Results – Cost Breakdown

- Projected cost varied between $86.3K – $199.4K per MGD per year

Process	50% Recovery (Minimum / Maximum)		70% Recovery (Minimum / Maximum)	
$/MGD treated / year	$107.4K	$199.4K	$86.3K	$188.8K

- Comparison facility cost: $96.3K per MGD per year

- Important distinction: Product water from membrane distillation is high quality reuse water

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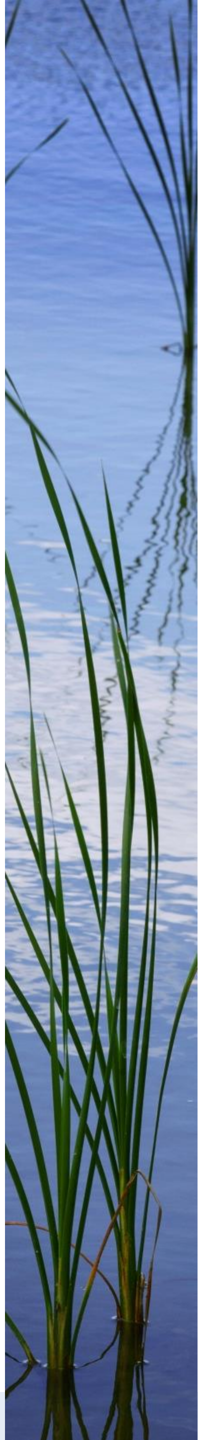
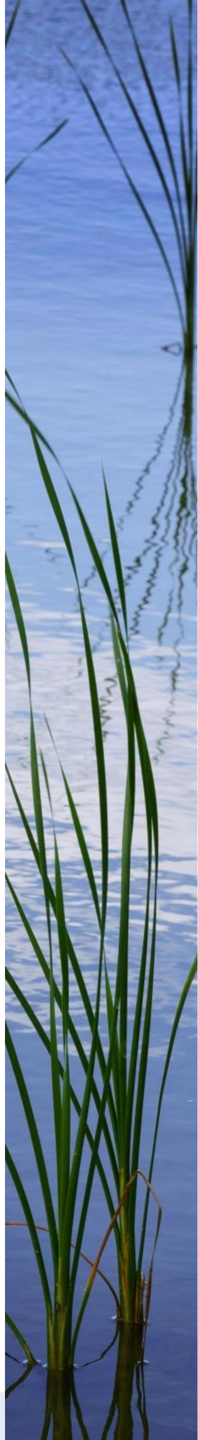


Transition to Phase 2 Research

- Overall feasibility of conceptual model facility was validated
- Cost estimates are reasonable when compared with traditional reuse facility
- Research needed to answer the following questions:

1. How does the coupled FO-DCMD system respond to transient operating conditions?
2. What are the limitations of concentrating domestic wastewater with a FO module?
3. Is AnMBR performance affected by FO pre-concentration?



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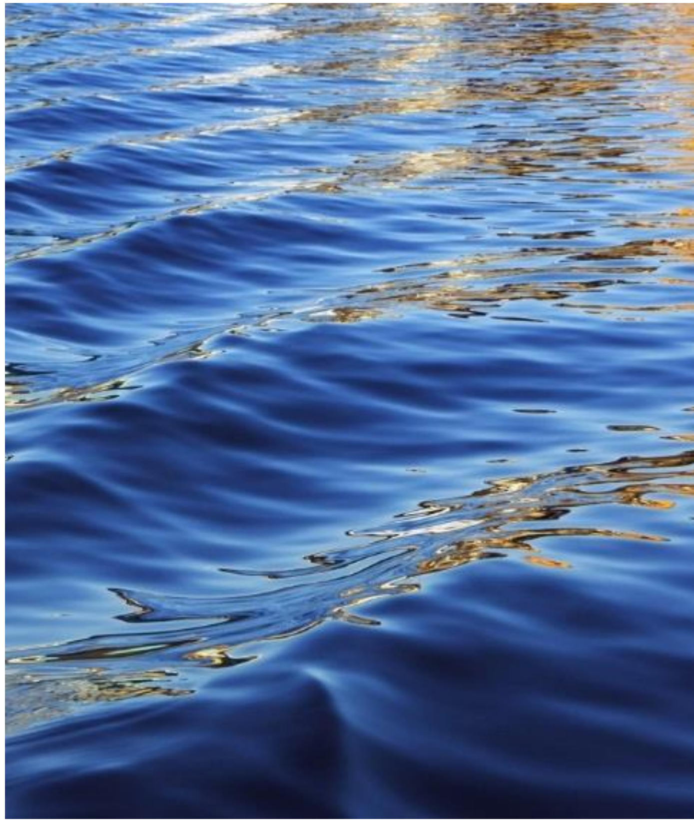
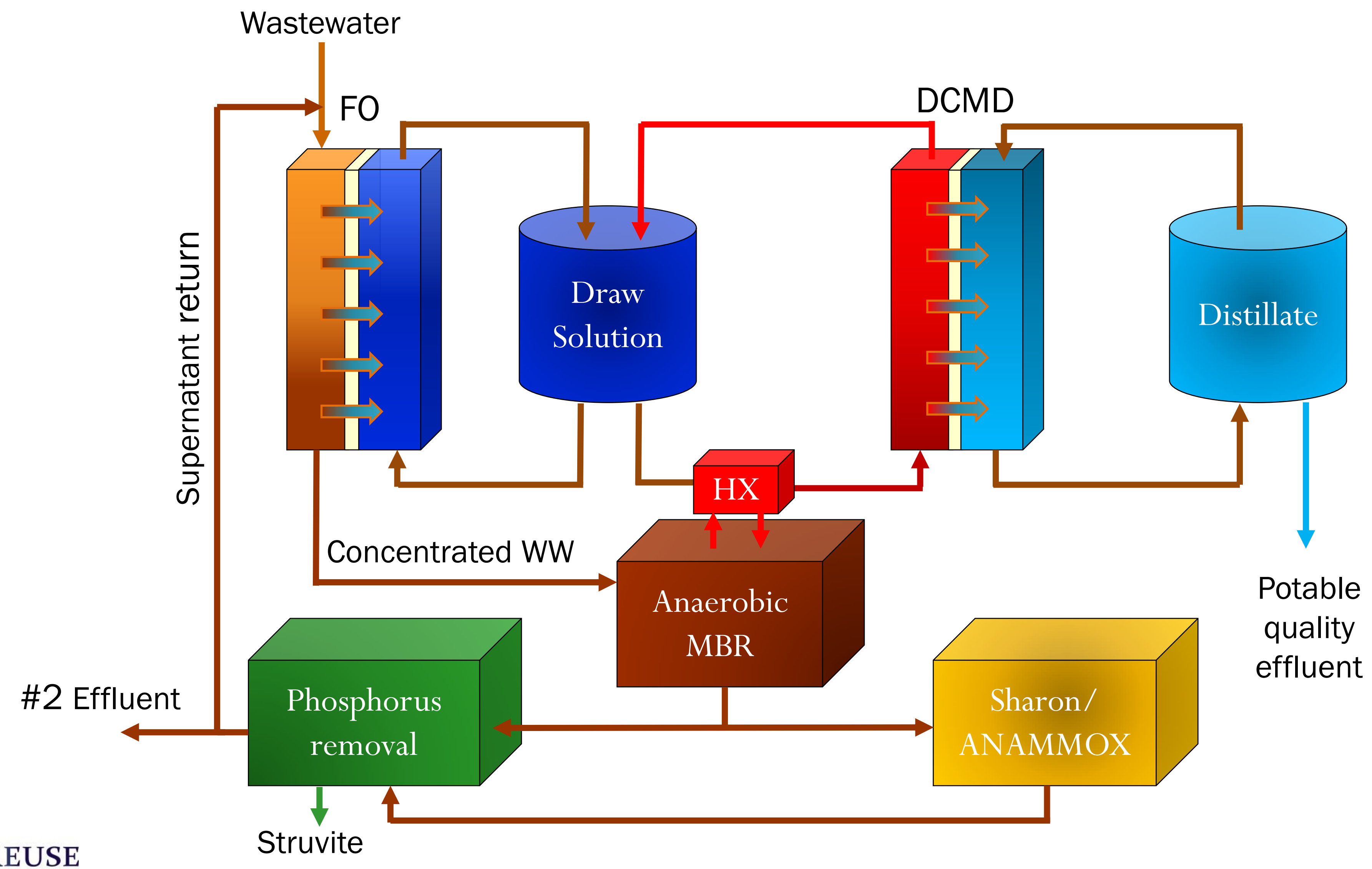
Coupled Forward Osmosis and Membrane Distillation

Dr. Andrea Achilli



Forward Osmosis and Membrane Distillation



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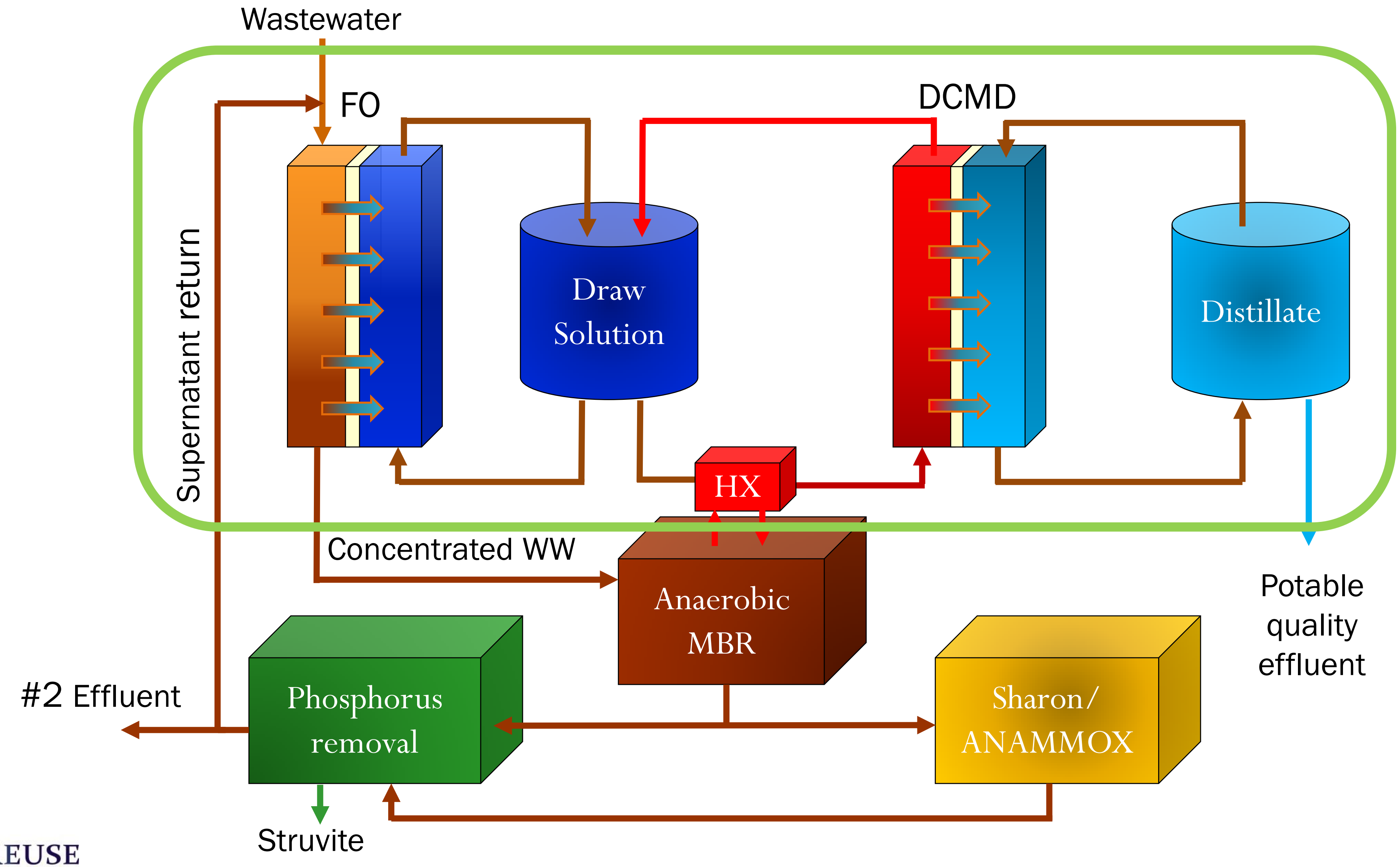
Forward Osmosis and Membrane Distillation



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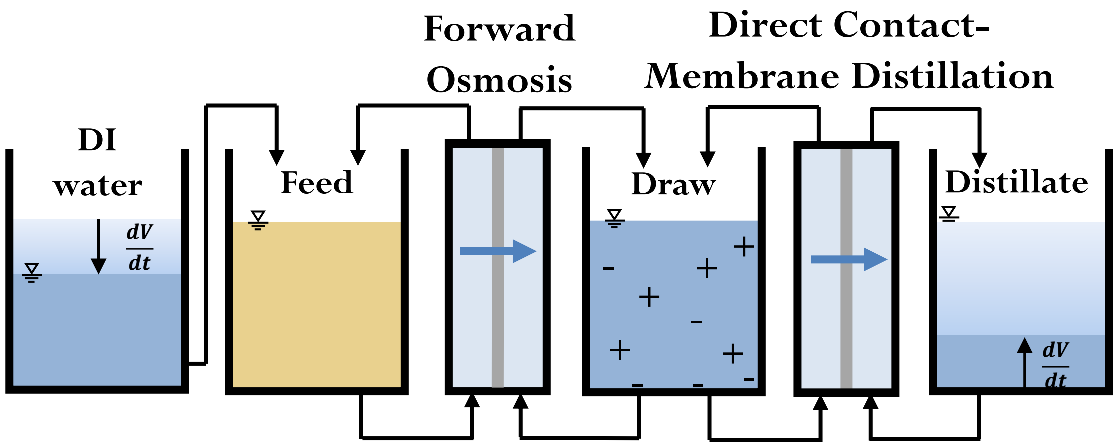
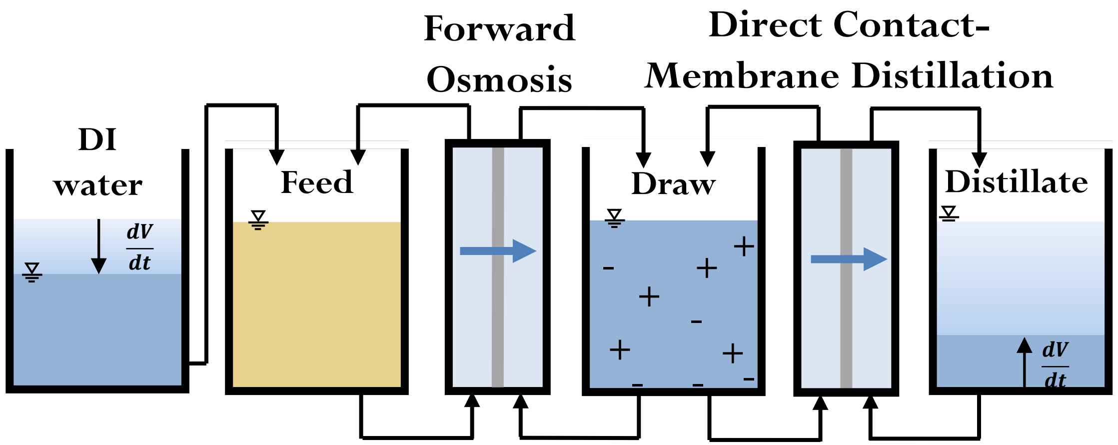
Physical System



Physical System



Experimental Conditions		
Draw Solution	=	35-40 g/L NaCl
Pump Flow Rates	=	1 L/min
Forward Osmosis Membrane Area	=	170 cm^2
Membrane Distillation Membrane Area	=	140 cm^2
Heated Stream Temperature	=	35-50 ^oC
Distillate Stream Temperature	=	20-22 ^oC

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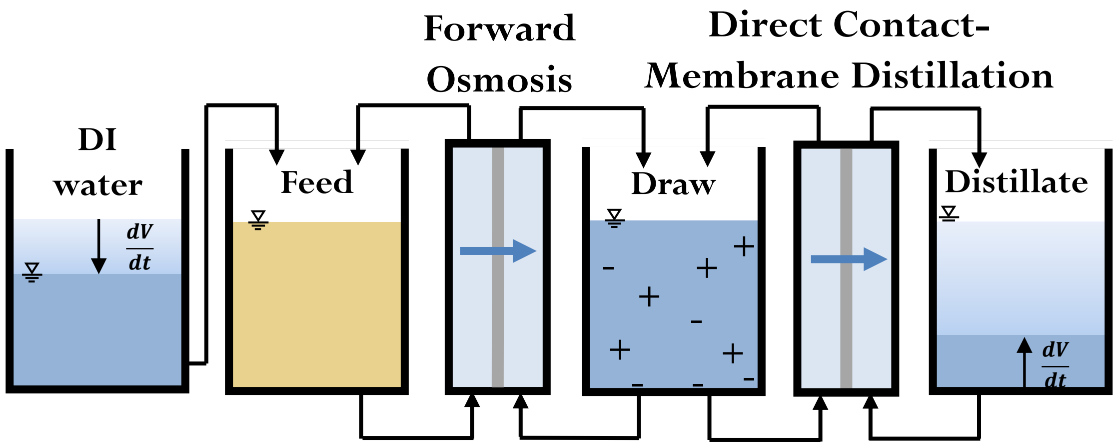
Physical System



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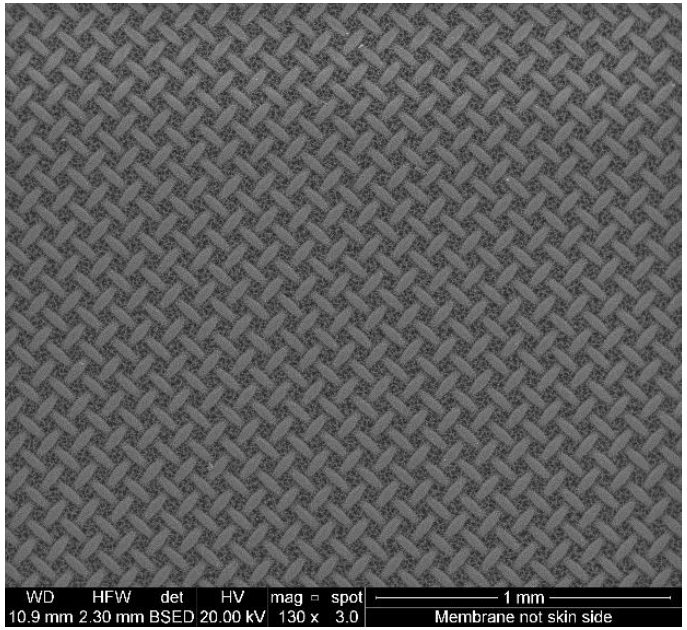
Membranes and Spacers

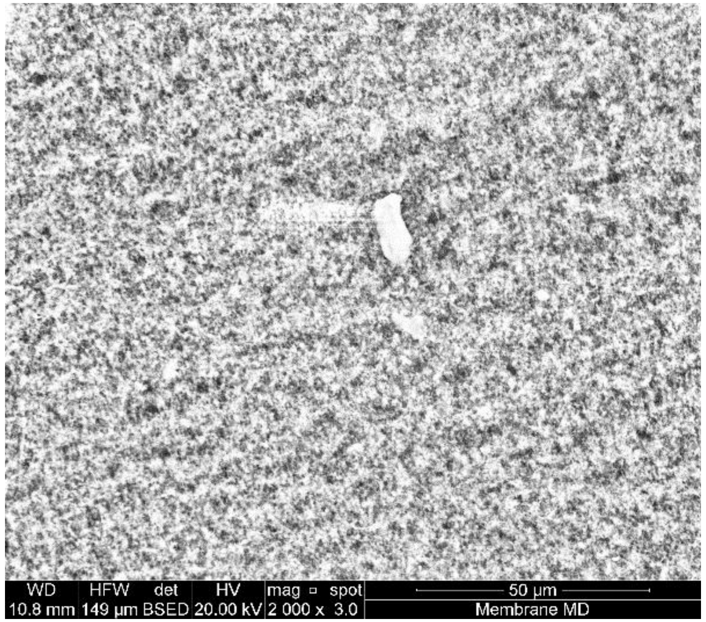
Forward Osmosis Membrane



1 mm

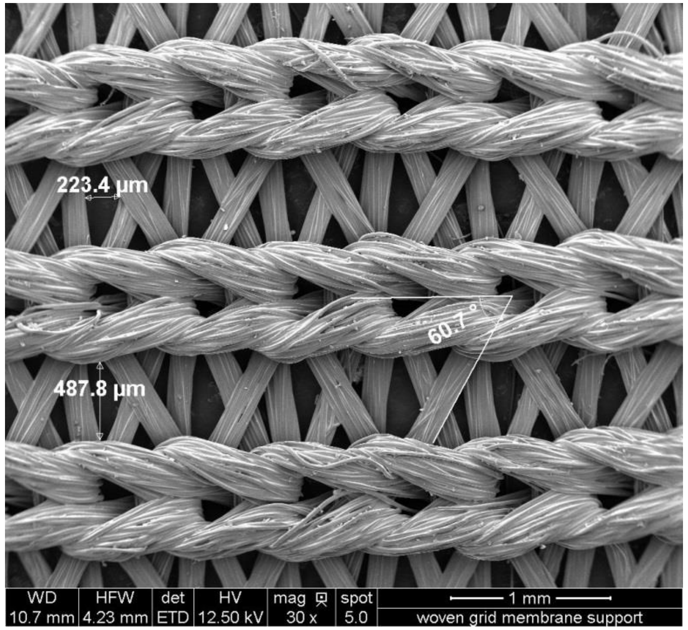
Porifera

Membrane Distillation Membrane



50 µm

Woven Grid Membrane Support



1 mm

HornwoodINC

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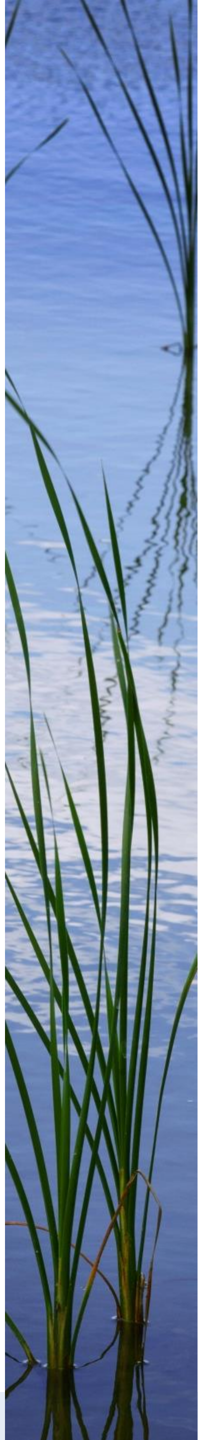
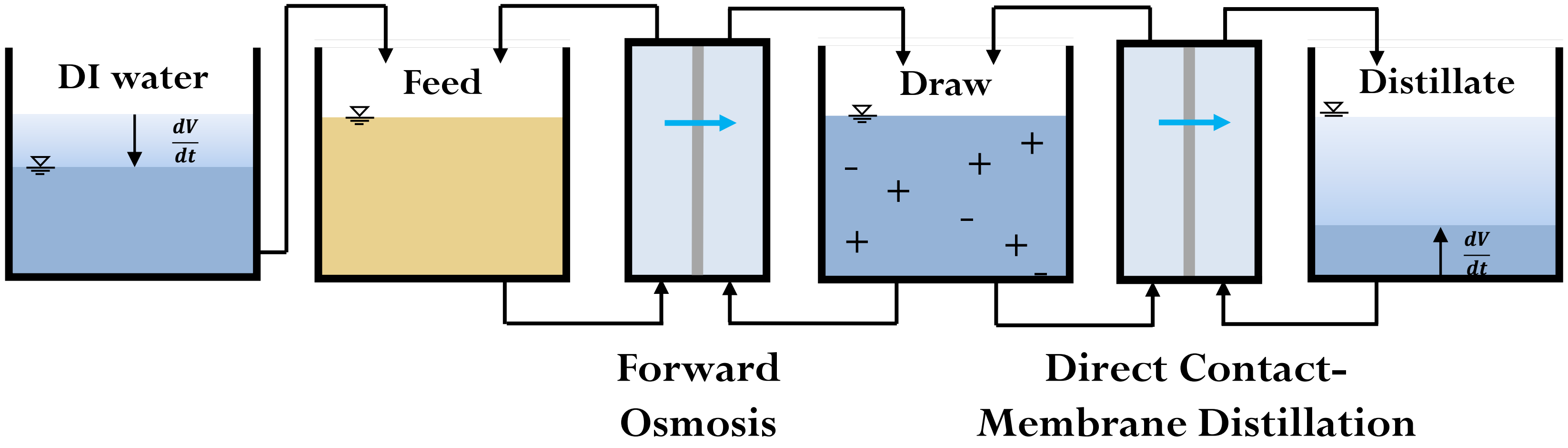


Water and Solute Fluxes



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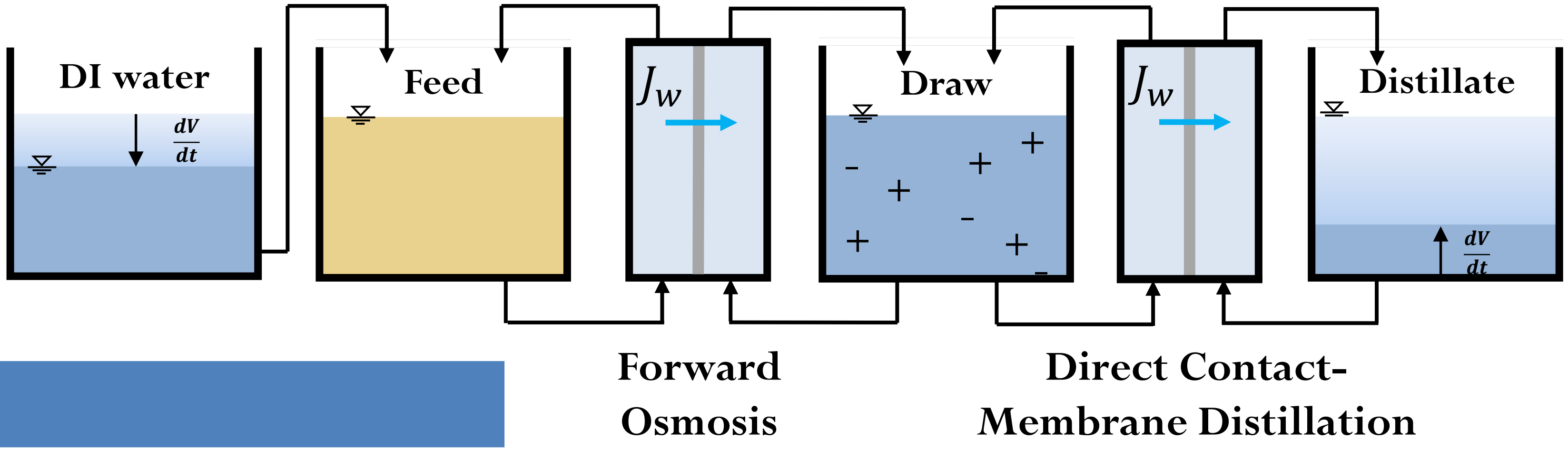

Where:		
V	=	Volume [L]
t	=	Time [hr]
A_m	=	Effective Membrane Area [m^2]
A_{FO}	=	FO Membrane Area [m^2]
C_p, C_f	=	Concentration of Permeate, Feed [mg/L]

$$J_w = Water\ Flux = \frac{dV}{dt} \cdot A_m^{-1} \quad [\mathrm{L \cdot m^{-2} \cdot h^{-1}}]$$

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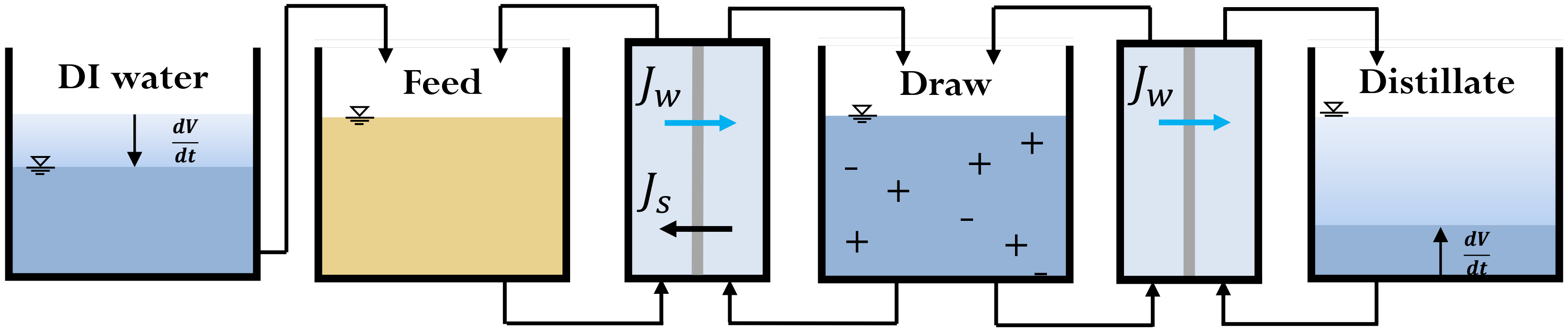
Water and Solute Fluxes



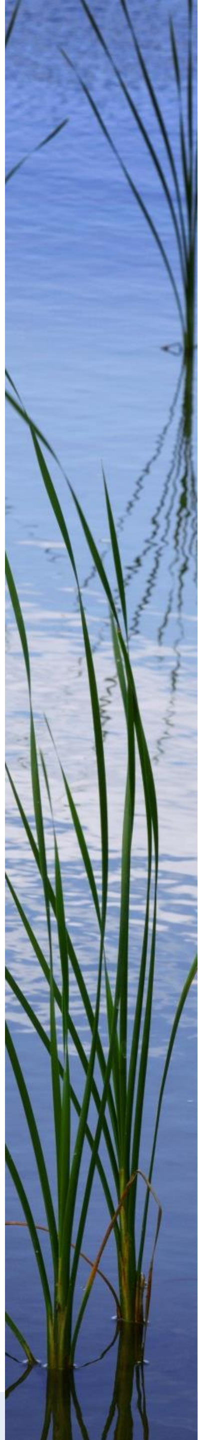
Forward Osmosis

Direct Contact-Membrane Distillation

Where:		
V	=	Volume [L]
t	=	Time [hr]
A_m	=	Effective Membrane Area [m^2]
A_{FO}	=	FO Membrane Area [m^2]
C_p, C_f	=	Concentration of Permeate, Feed [mg/L]

$$J_w = Water\ Flux = \frac{dV}{dt} \cdot A_m^{-1} \quad [\mathrm{L \cdot m^{-2} \cdot h^{-1}}]$$

$$J_s = Reverse\ Salt\ Flux = \frac{dc_f}{dt} \cdot V_f \cdot A_{FO}^{-1} \quad [\mathrm{g \cdot m^{-2} \cdot h^{-1}}]$$



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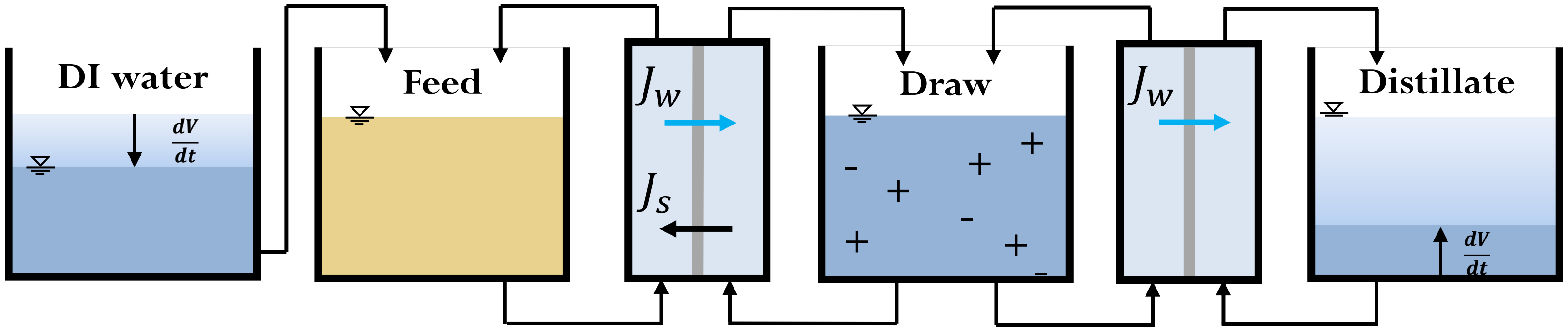
Water and Solute Fluxes



Where:		
V	=	Volume [L]
t	=	Time [hr]
A_m	=	Effective Membrane Area [m^2]
A_{FO}	=	FO Membrane Area [m^2]
C_p, C_f	=	Concentration of Permeate, Feed [mg/L]

$$J_w = Water\ Flux = \frac{dV}{dt} \cdot A_m^{-1} \quad [\mathrm{L \cdot m^{-2} \cdot h^{-1}}]$$

$$J_s = Reverse\ Salt\ Flux = \frac{dc_f}{dt} \cdot V_f \cdot A_{FO}^{-1} \quad [\mathrm{g \cdot m^{-2} \cdot h^{-1}}]$$

$$Rejection = \left(1 - \frac{C_p}{C_f}\right) \cdot 100\ \%$$

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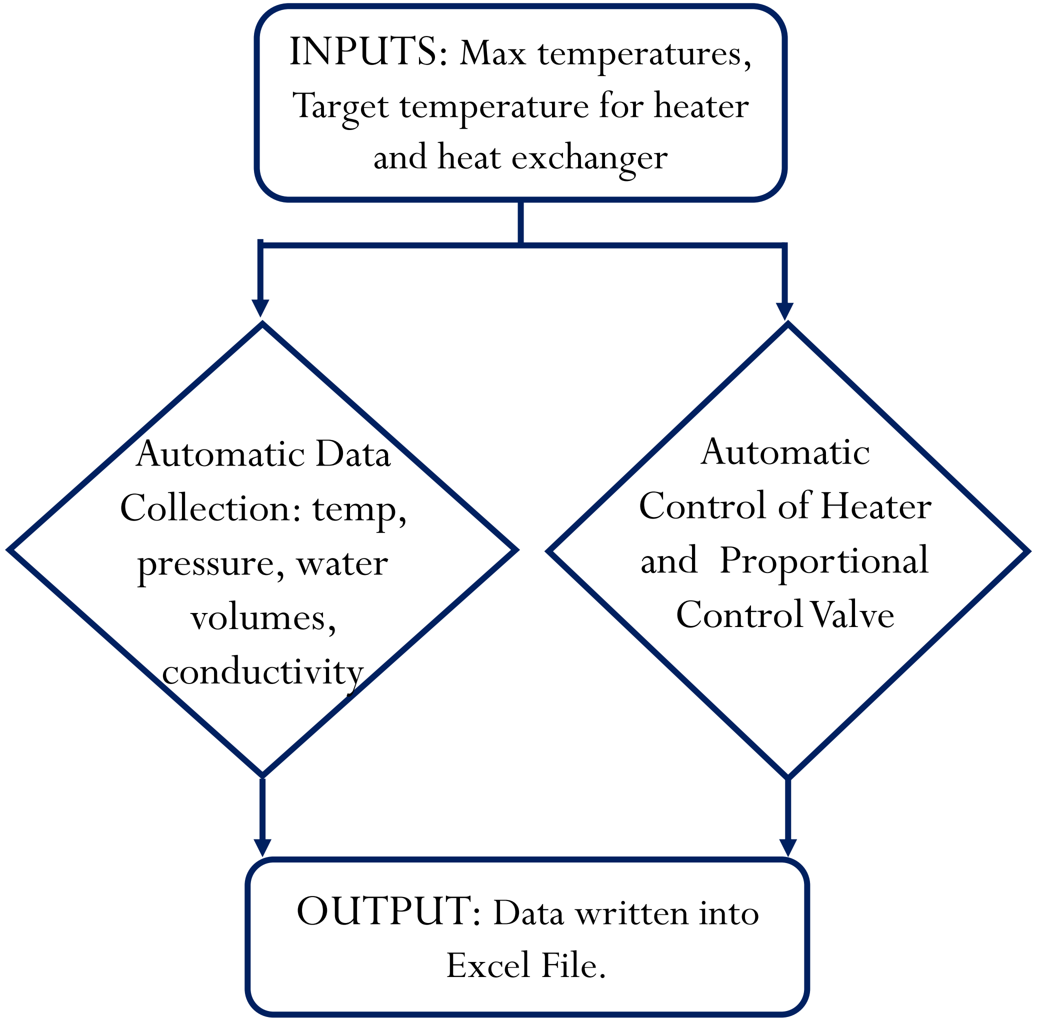
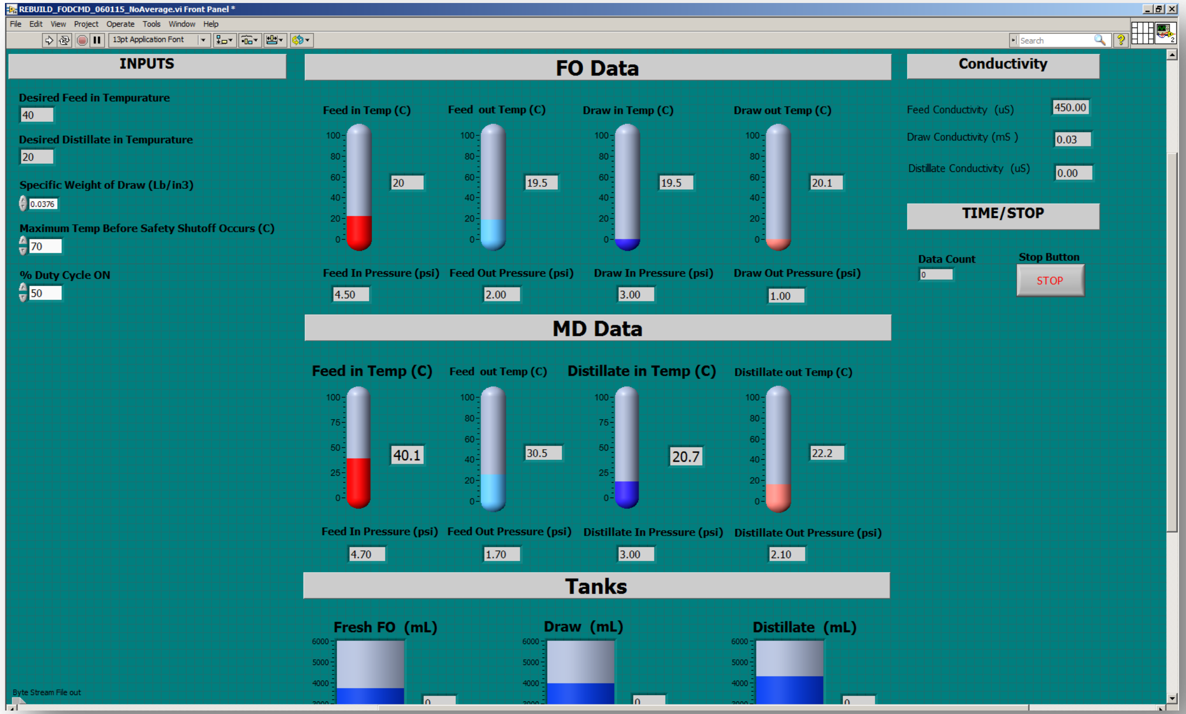
Monitor and Control System



LabVIEW Monitoring and Control

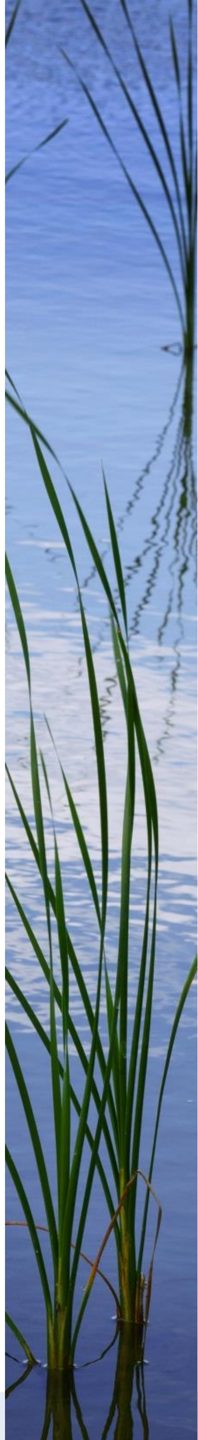


Feed and Draw Solutions

Surrogate Wastewater Feed Solution

Constituent	C (mg/L)
Nutrient Broth (Peptone:Beef Extract Ratio 5:3)	180
Humic Acid, Crystalline Powder	100
Urea	70
Ammonium Chloride	70
Monopotassium Phosphate	50
Sodium Alginate	30
Sodium Bicarbonate	50
Calcium Chloride	30
Ferrous Sulfate	30
Arizona Test Dust (Grade: A2 Fine)	420
Dodecylbenzone Sulfonic Acid (Sodium Salt)	220

WATEREUSE



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Draw Solutions

- Sodium Chloride ($NaCl$)
- Magnesium Chloride ($MgCl_2$)
- Sodium Propionate ($NaC_3H_5O_2$)

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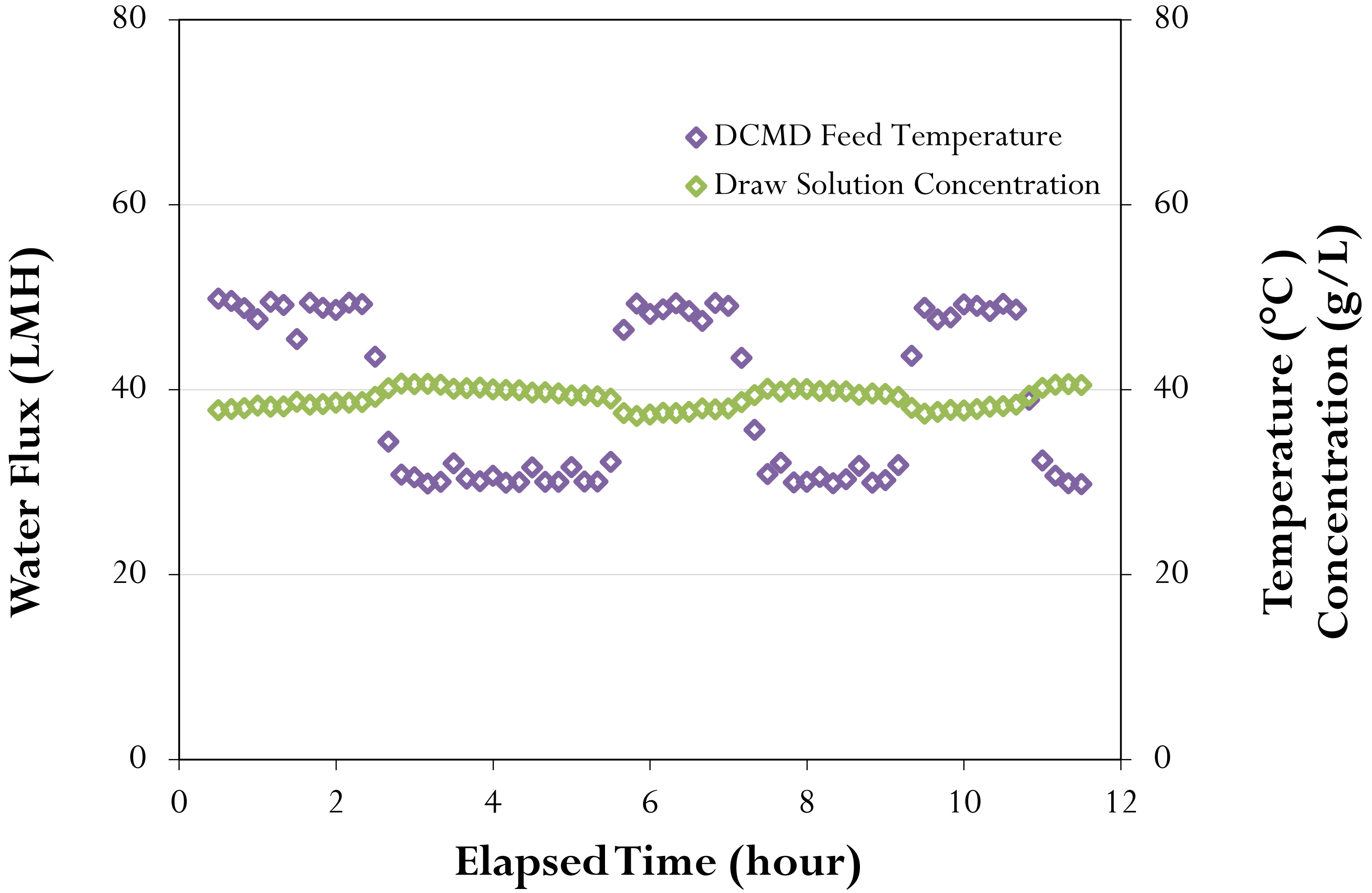
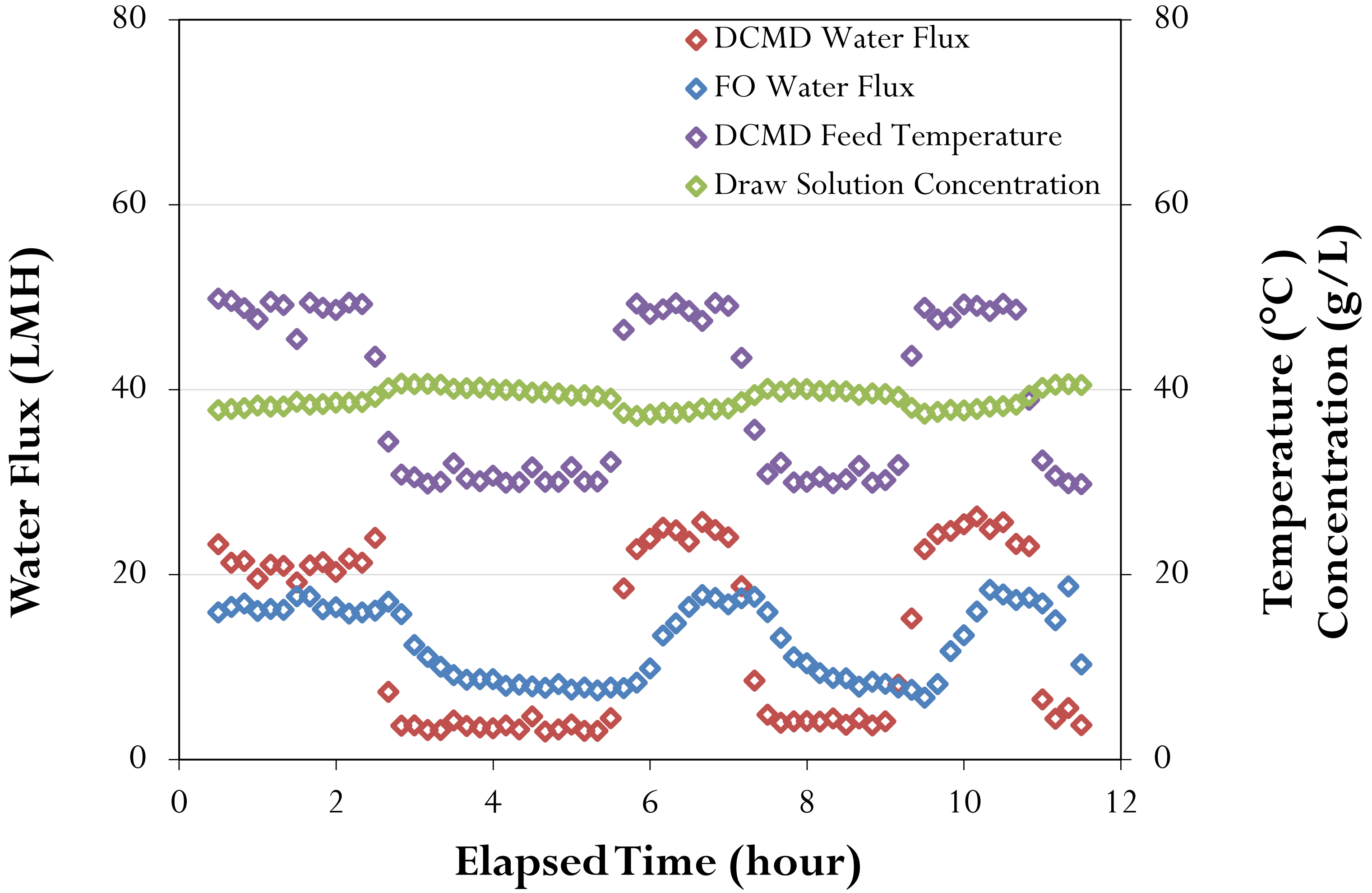
Water Fluxes and System Stability



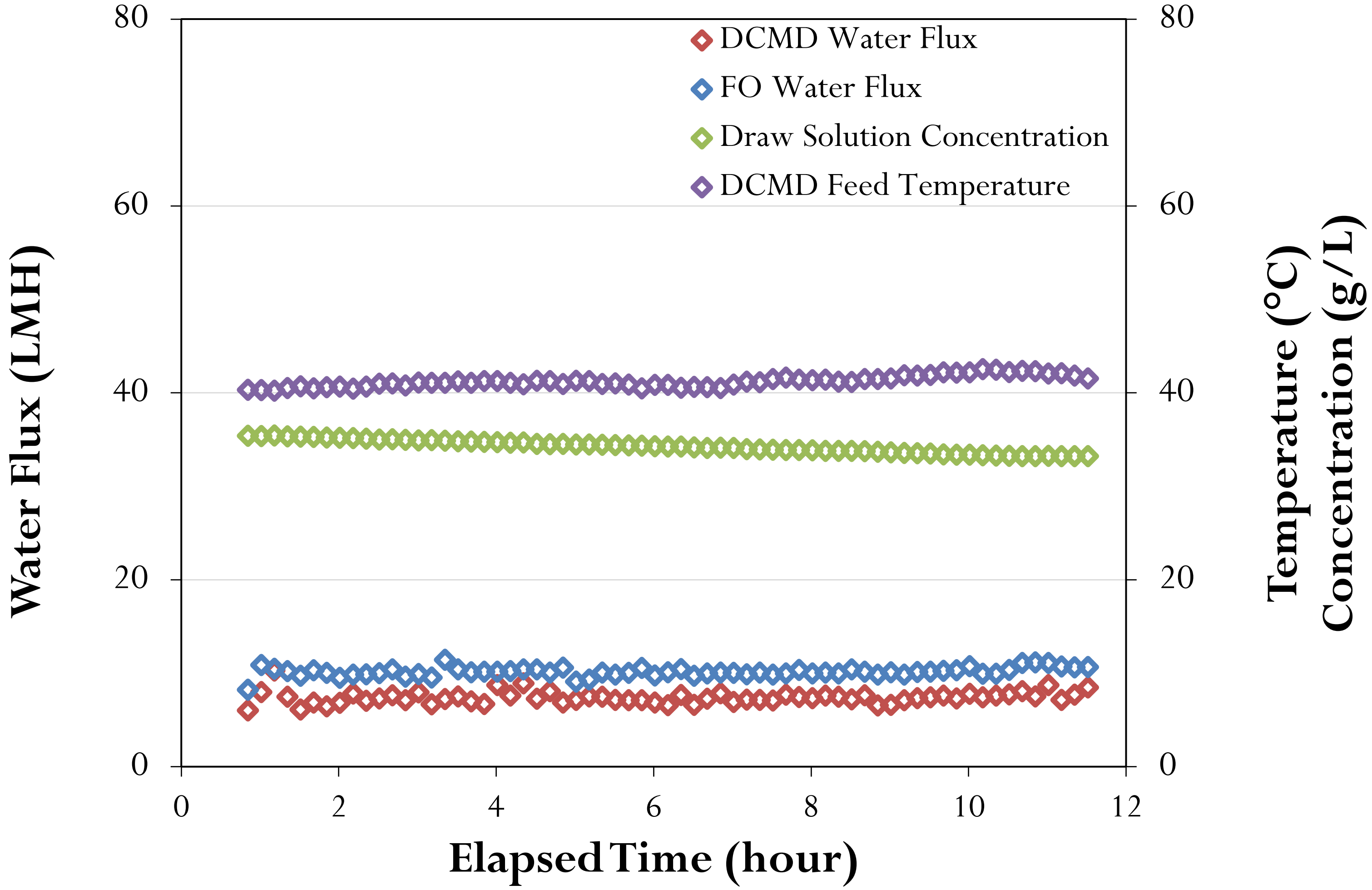
WATEREUSE

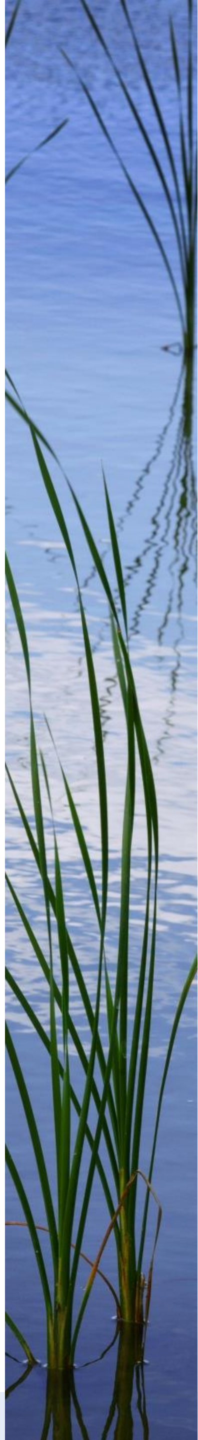
Water Fluxes and System Stability



WATEREUSE

Water Fluxes and System Stability





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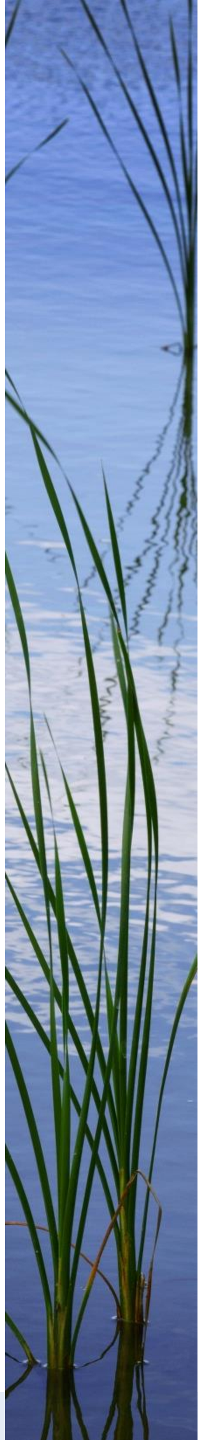
Water Quality

Rejection Results of Total Nitrogen (TN) and Total Organic Carbon (TOC)

Forward Osmosis (FO) Rejection		Membrane Distillation (MD) Rejection		System Rejection	
TOC	TN	TOC	TN	TOC	TN
97%	68%	68%	97%	98%	98%



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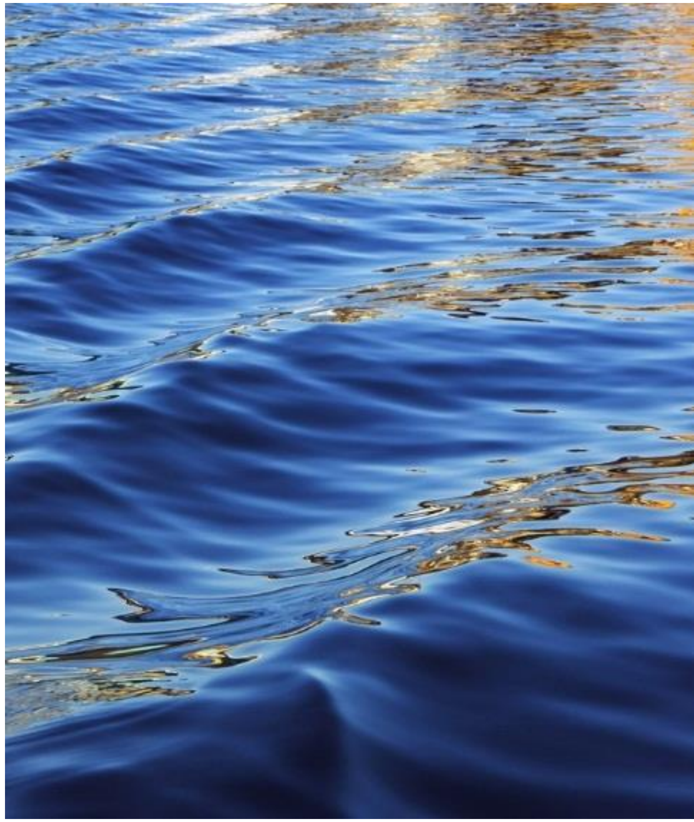
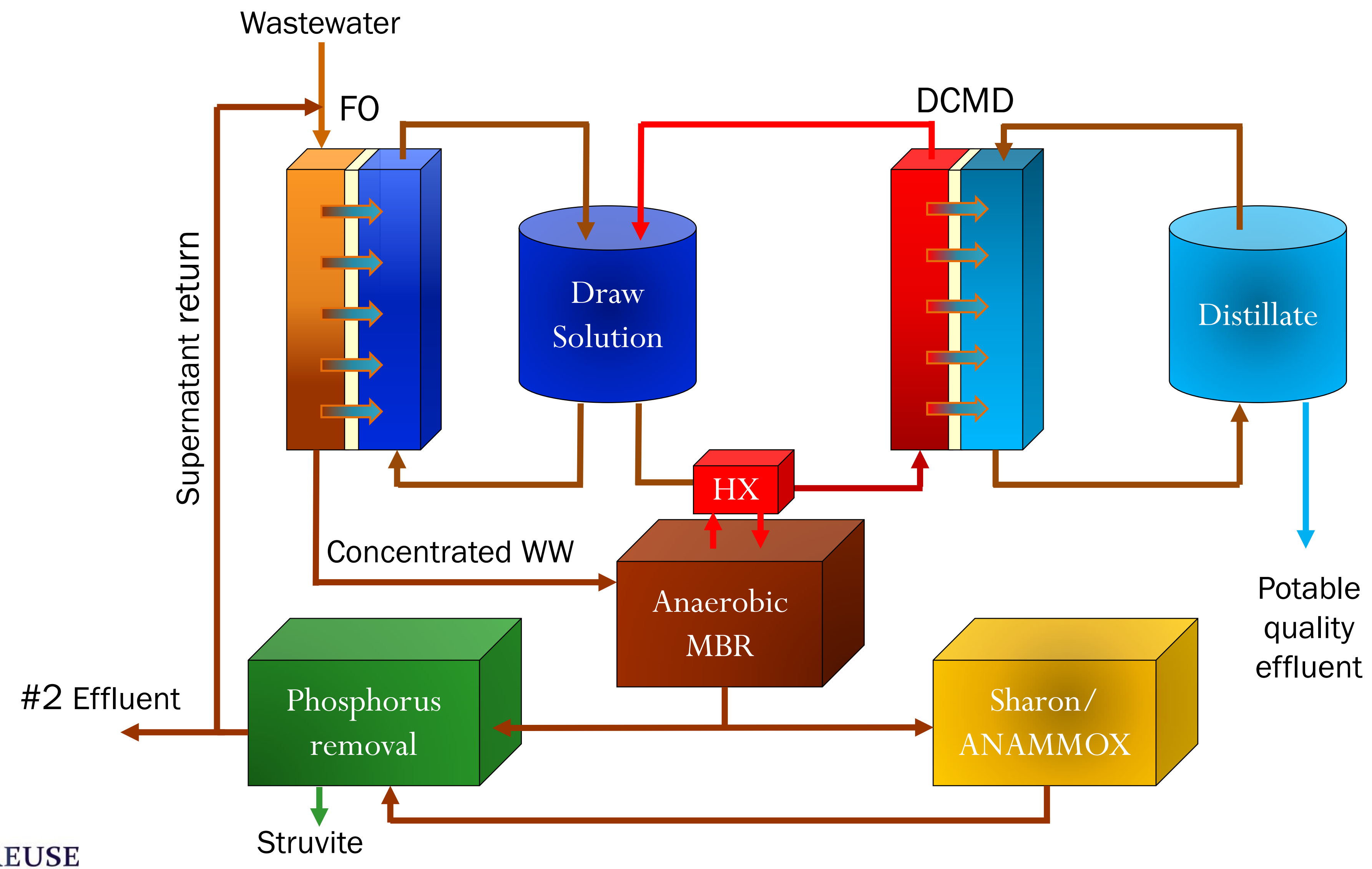
Wastewater Concentration by Forward Osmosis

Dr. Sage Hiibel

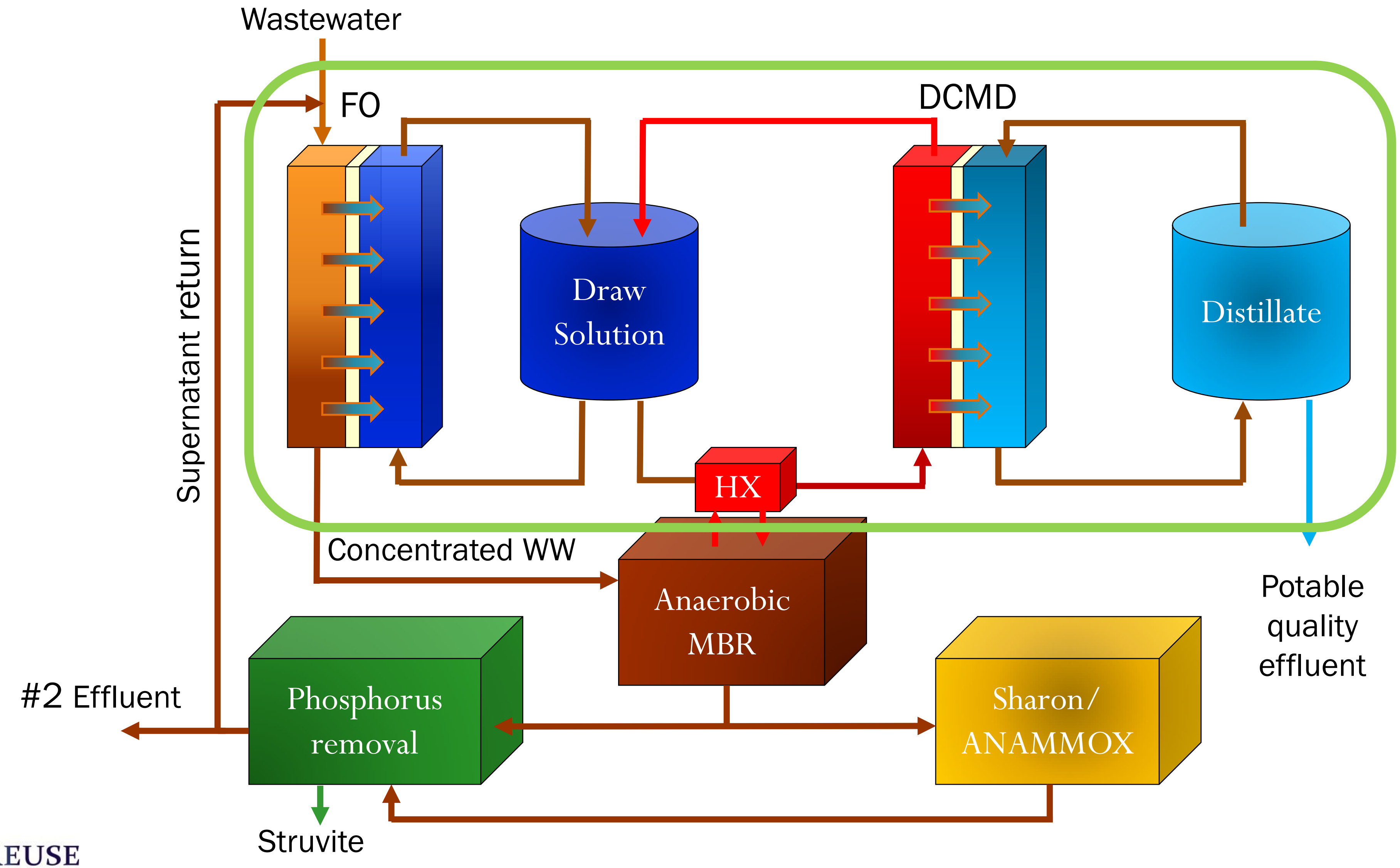


Wastewater Concentration by FO

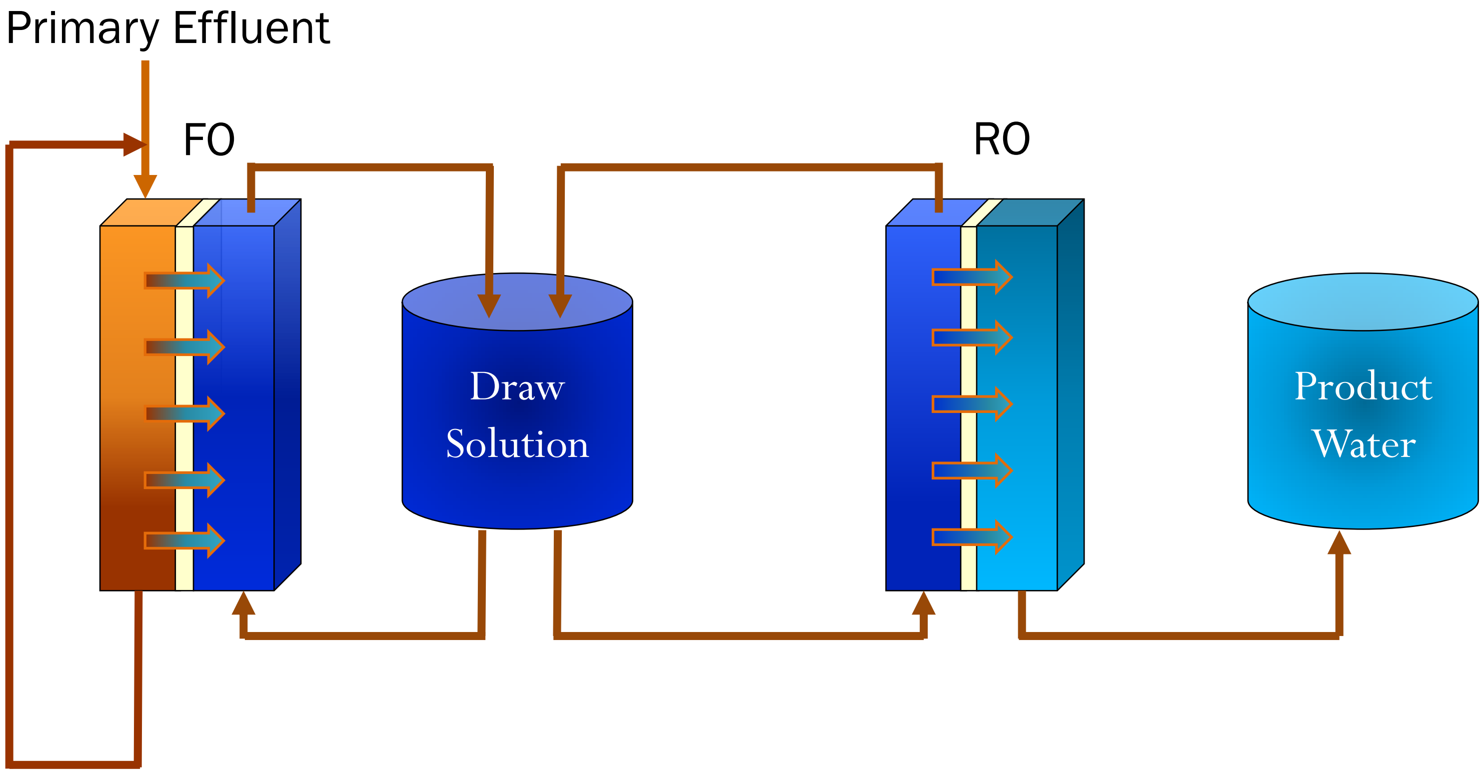


WATEREUSE

Wastewater Concentration by FO

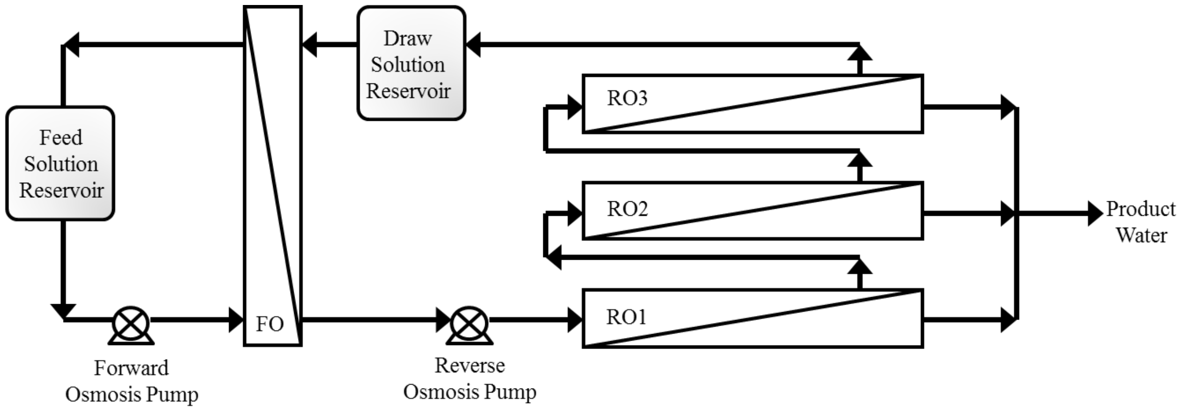


RO for Draw Solution Reconcentration



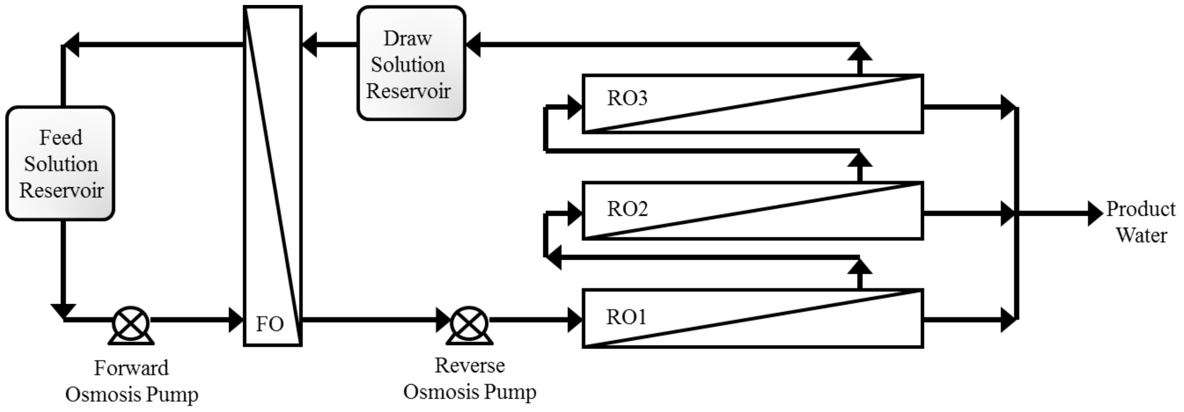
WATEREUSE

Physical System



WATEREUSE

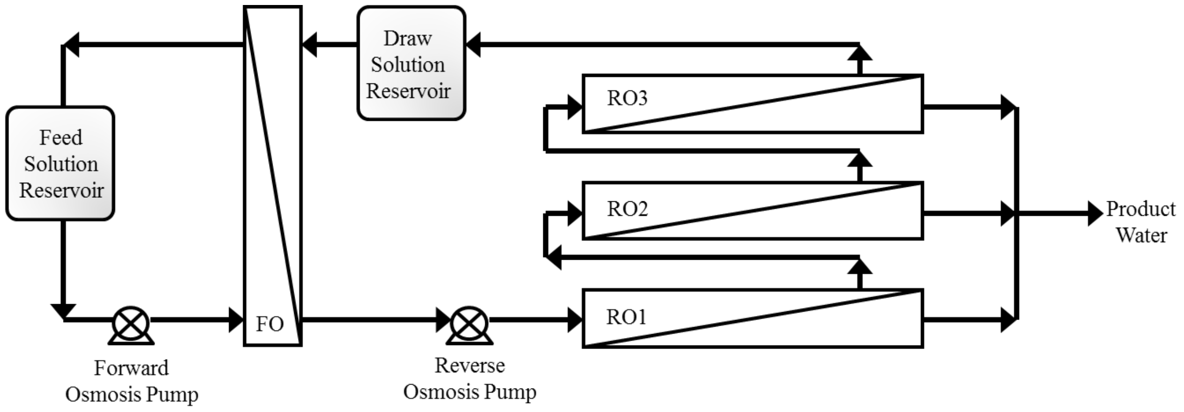
Physical System



Experimental Conditions		
Draw Solution	=	40-45 g/L NaCl
Pump Flow Rates	=	16.5 L/min
FO Membrane Area	=	1.5 m^2
RO Membrane Area (3 in series)	=	1.5 m^2 total
RO Operating Pressure	=	400 psi
Operating Temperature	=	20-22 °C

WateReuse

Physical System



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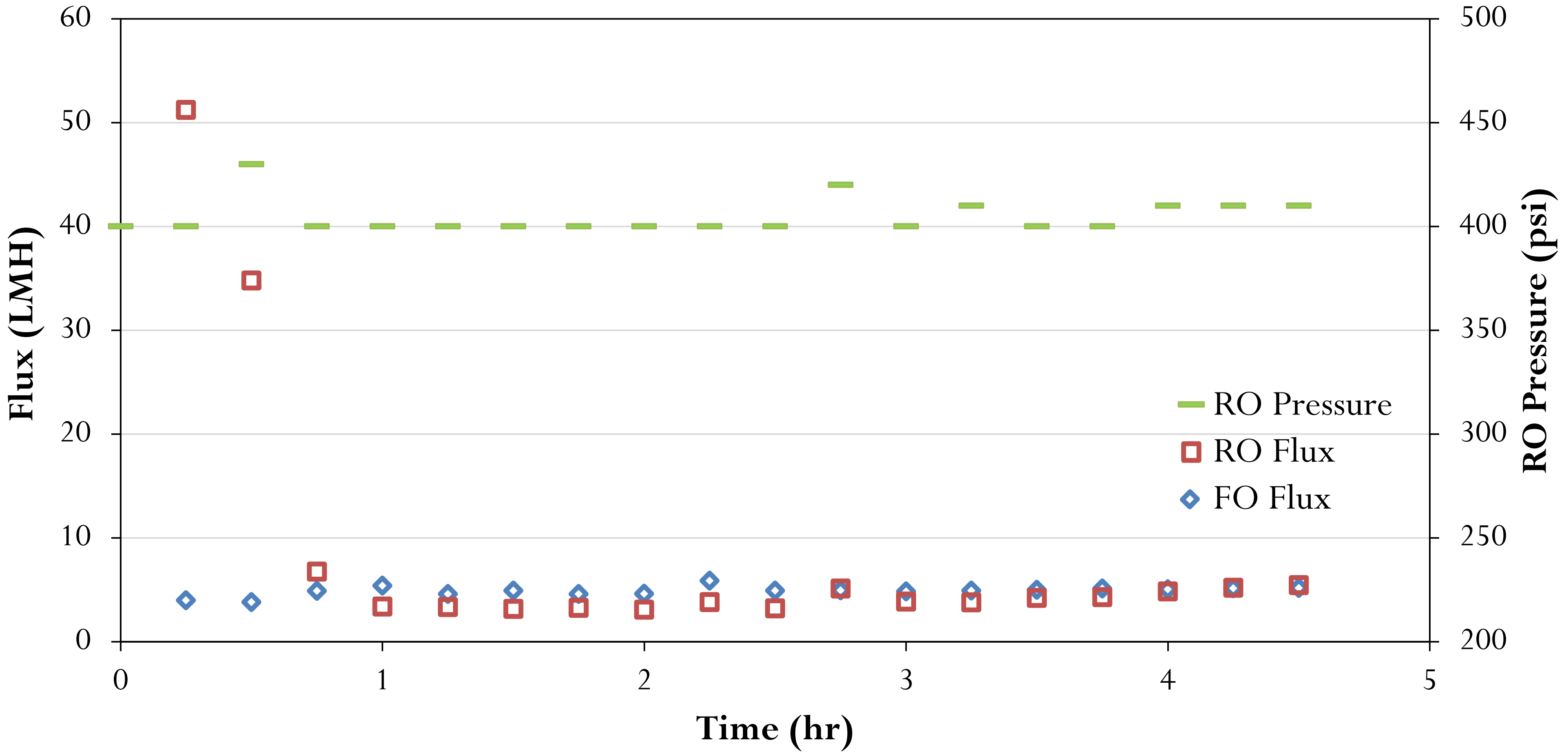
Membrane Flux



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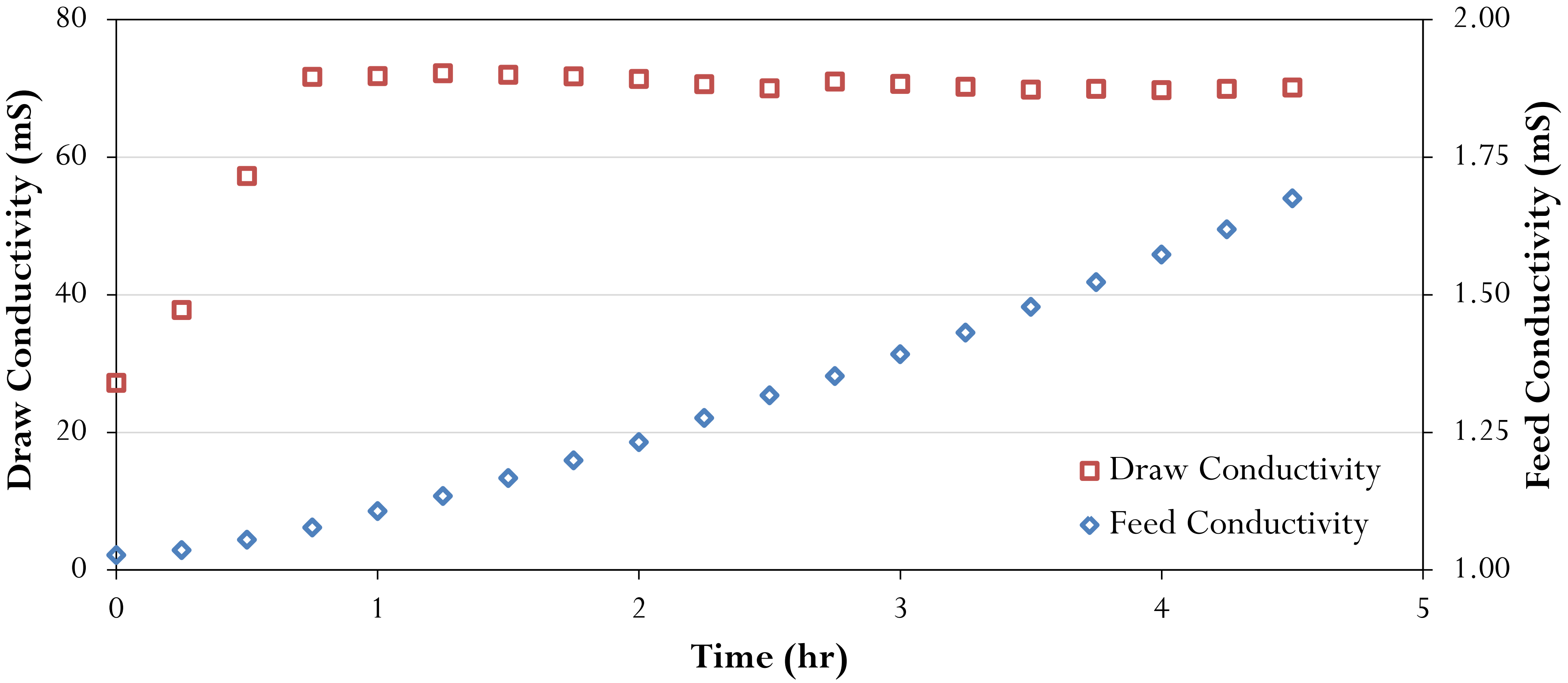
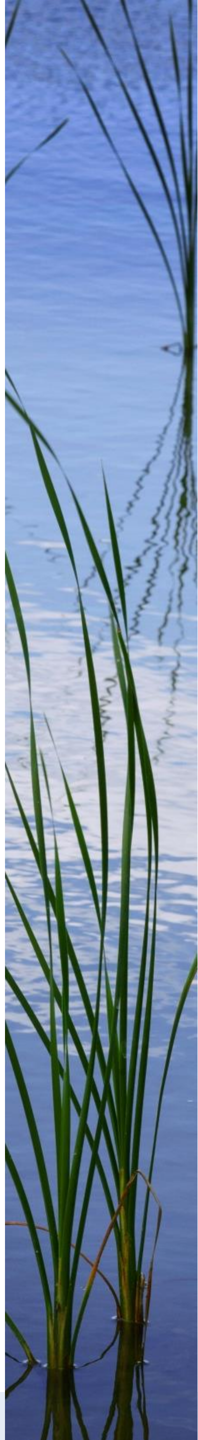
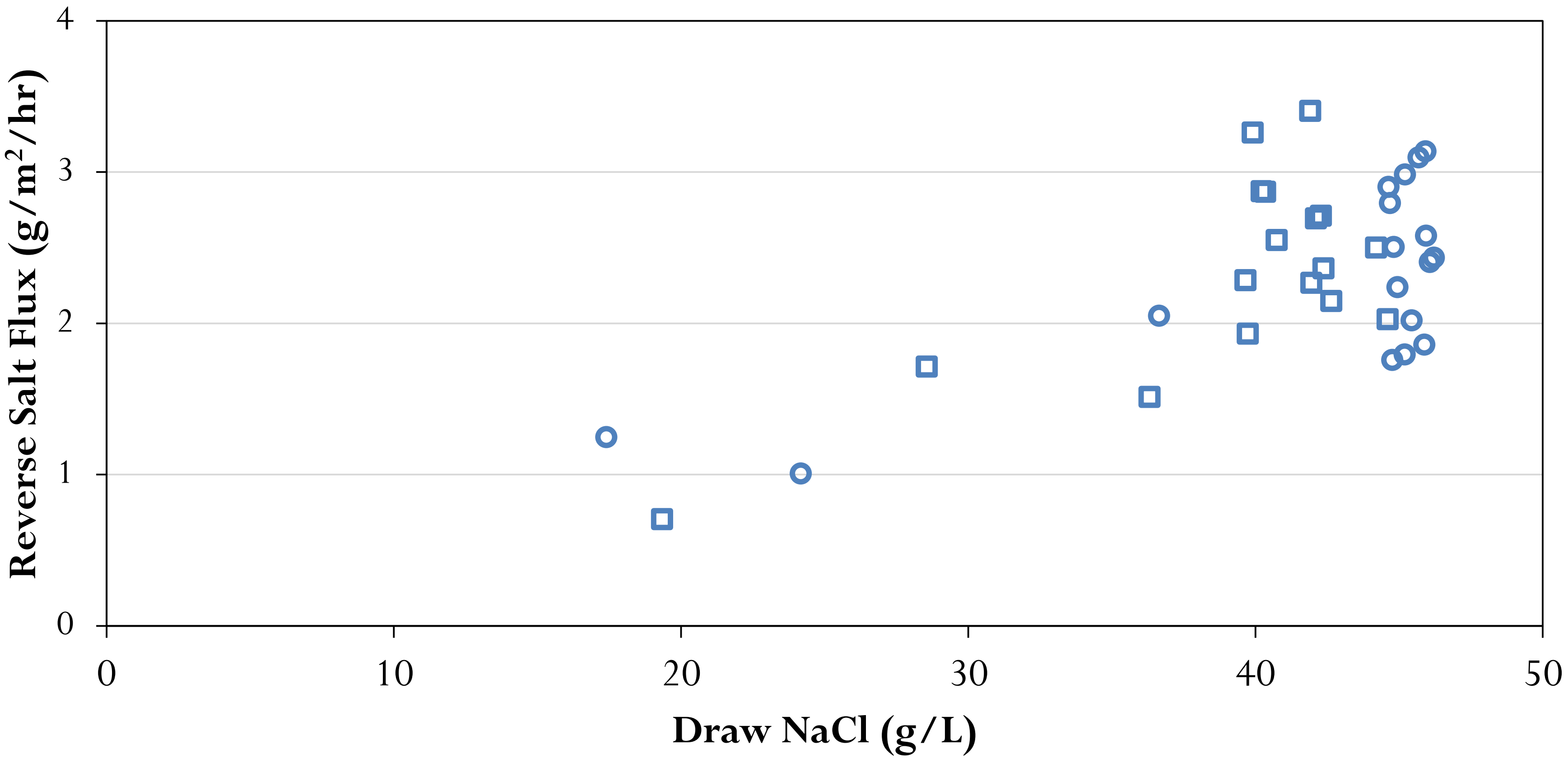
Conductivity



WATEREUSE



Reverse Salt Flux

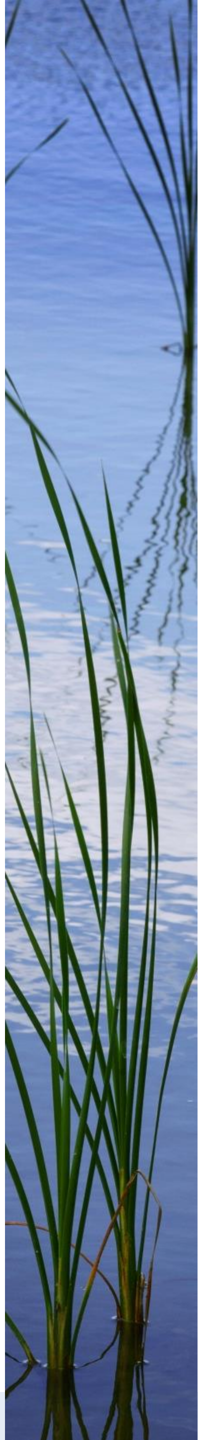


Water Quality

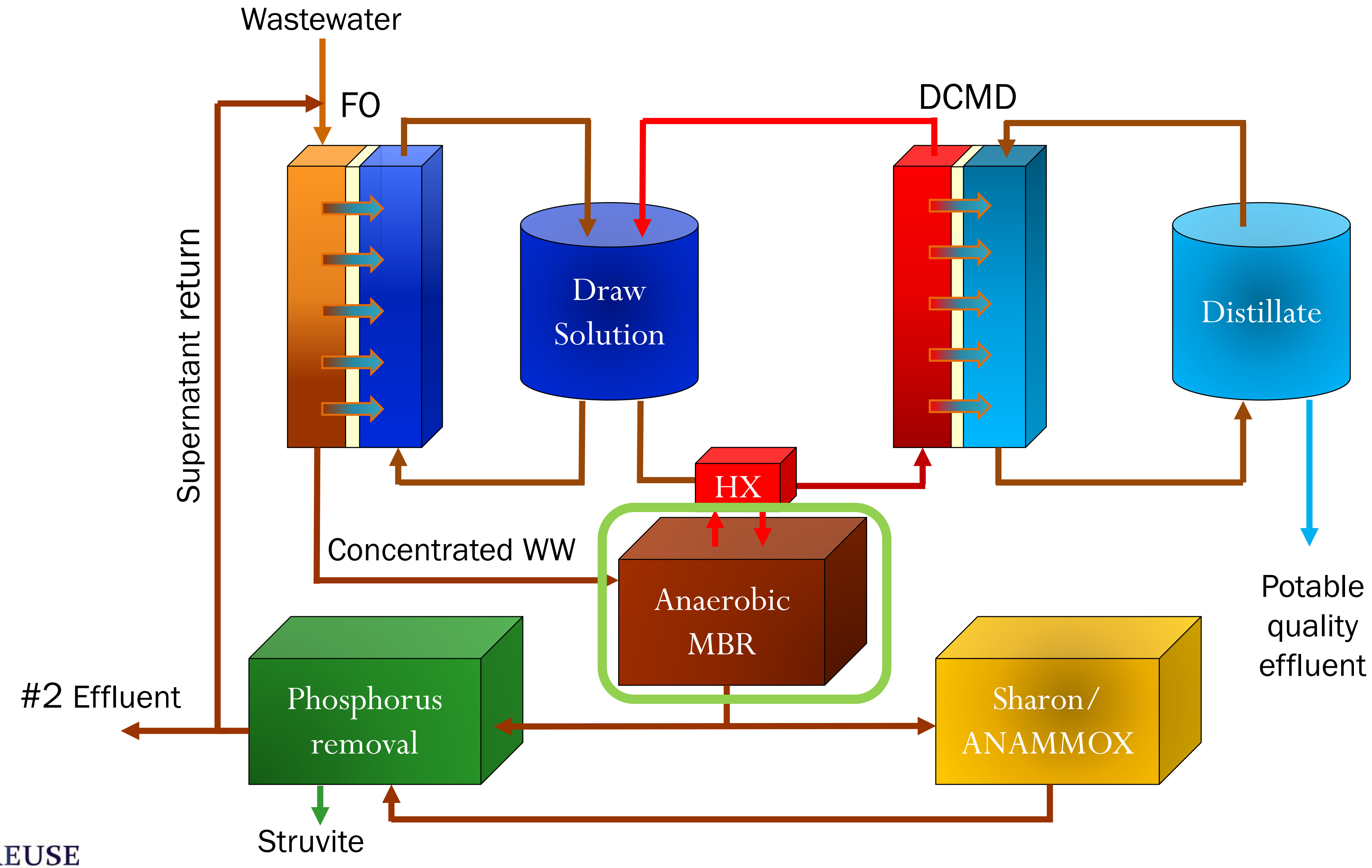
Total Organic Carbon and Total Nitrogen Rejection

Pilot-Scale FO		Pilot-Scale FO-RO System	
TOC	TN	TOC	TN
90%	84%	94%	85%

WATEREUSE



Anaerobic Membrane Bioreactor



WATEREUSE

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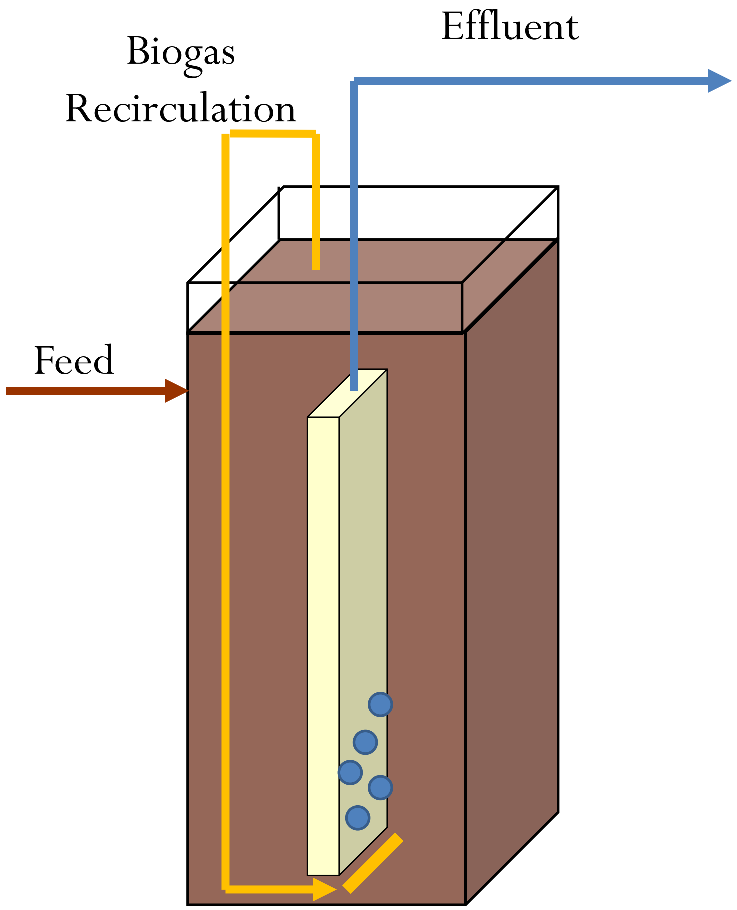

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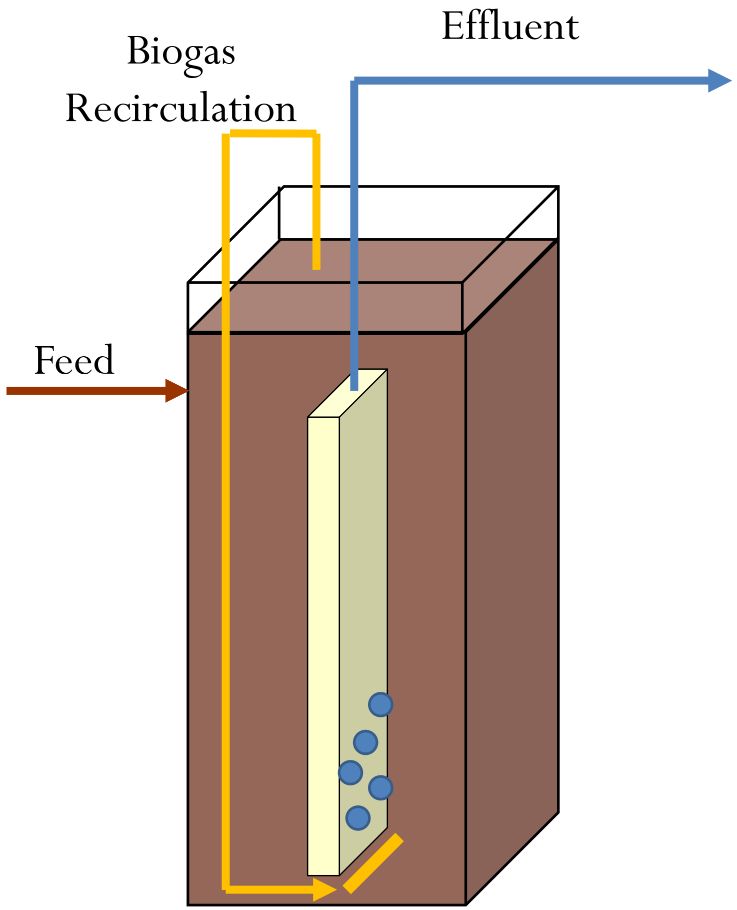

- Biogas recirculation
  - Control membrane fouling
- Four experimental conditions
  - Temperature
  - Wastewater strength

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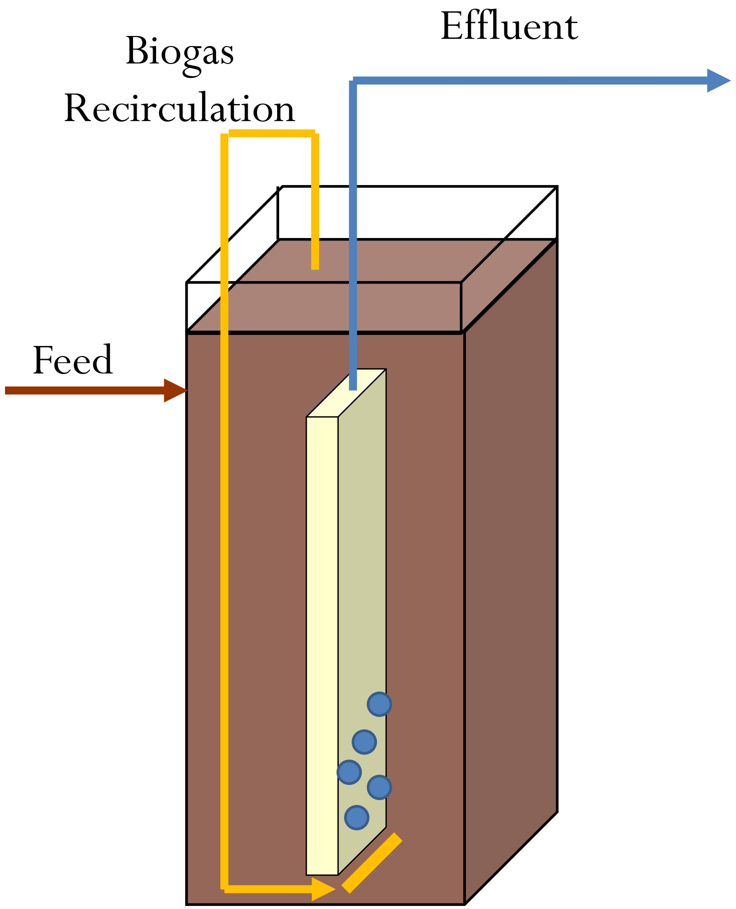

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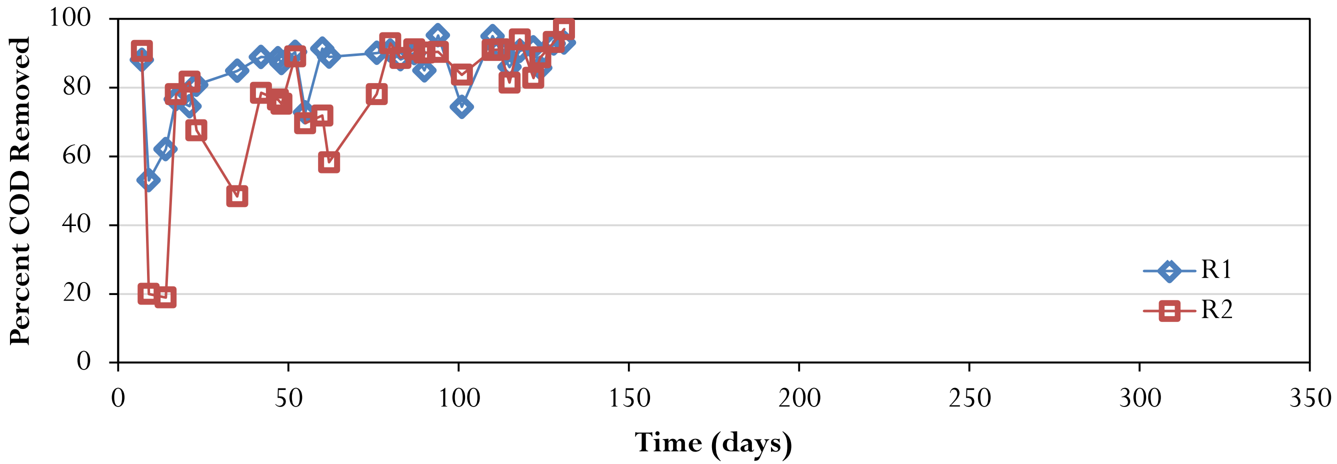
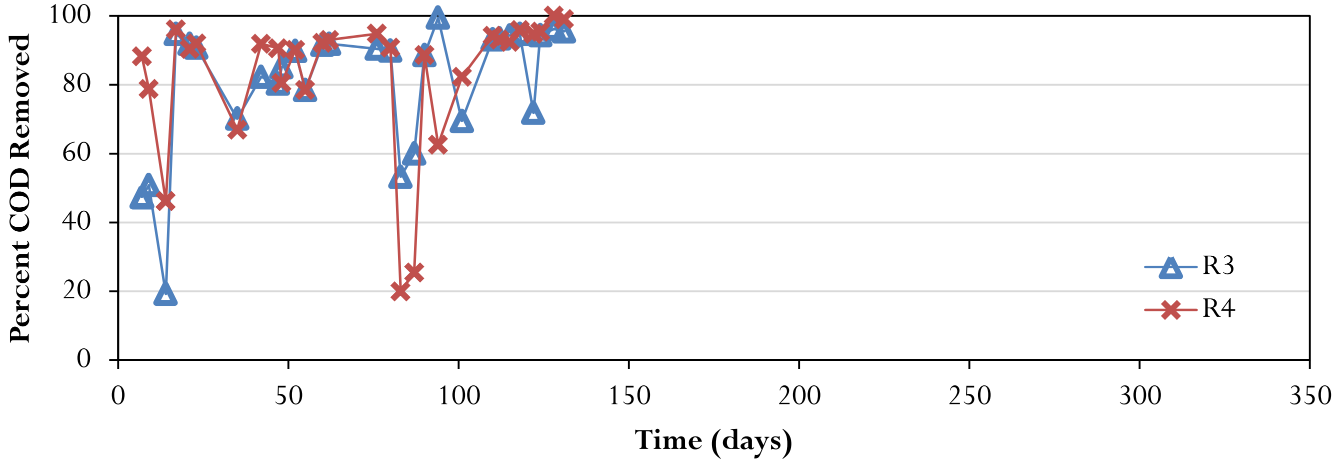
Reactor Performance





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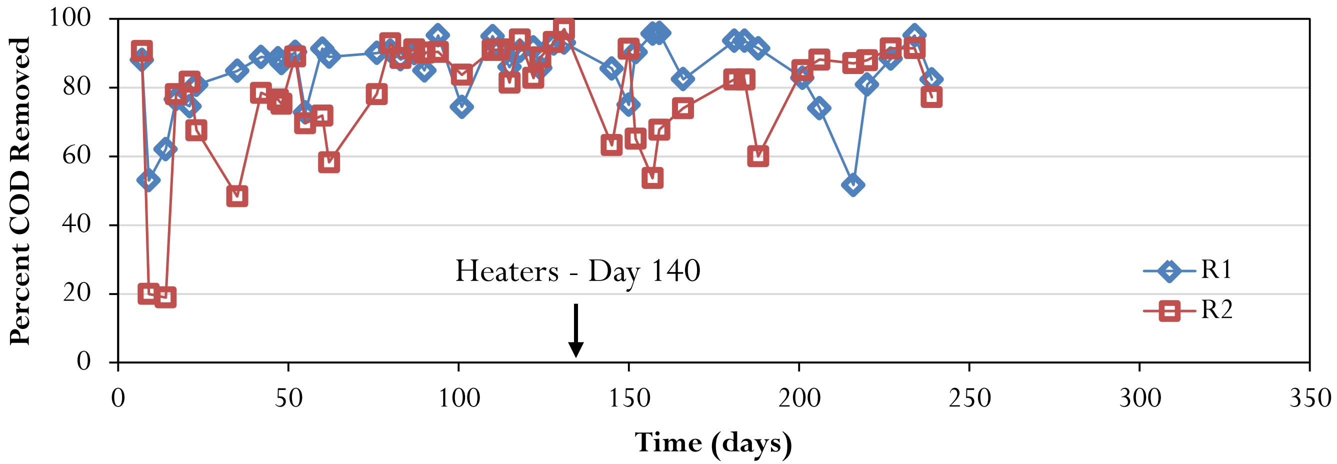
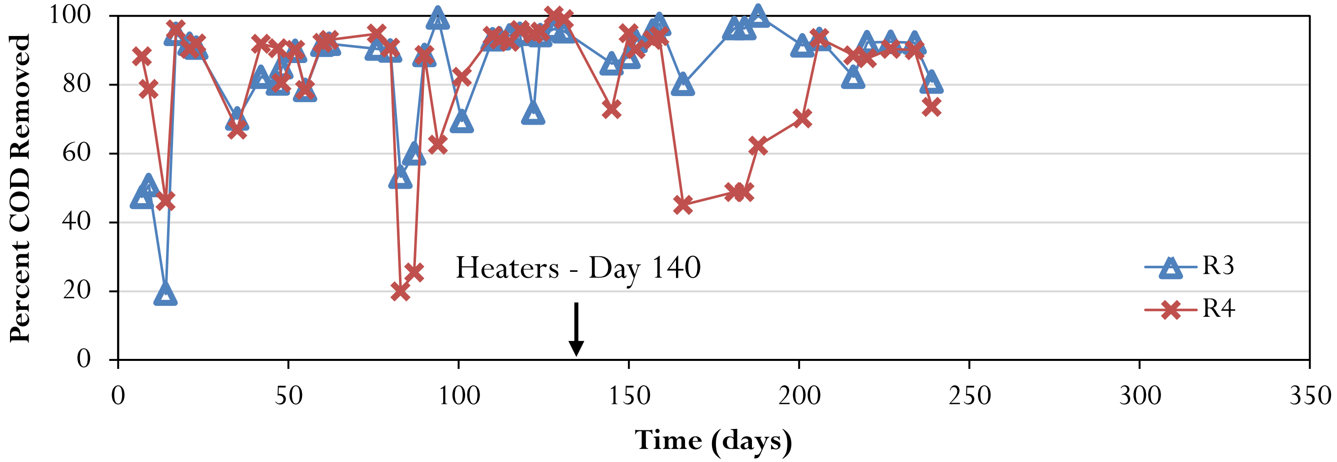


22-24 °C
37 °C



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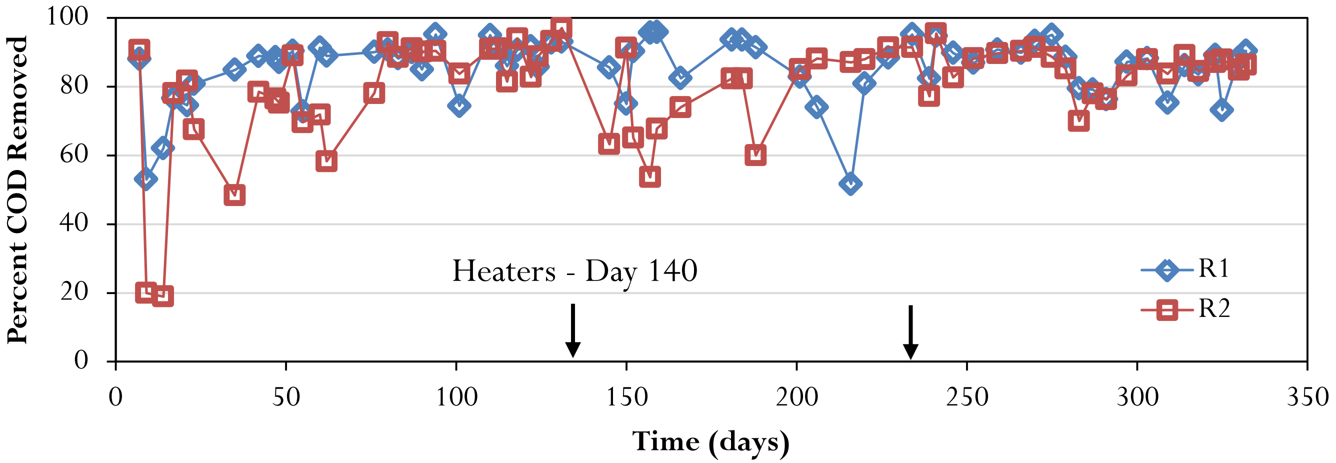
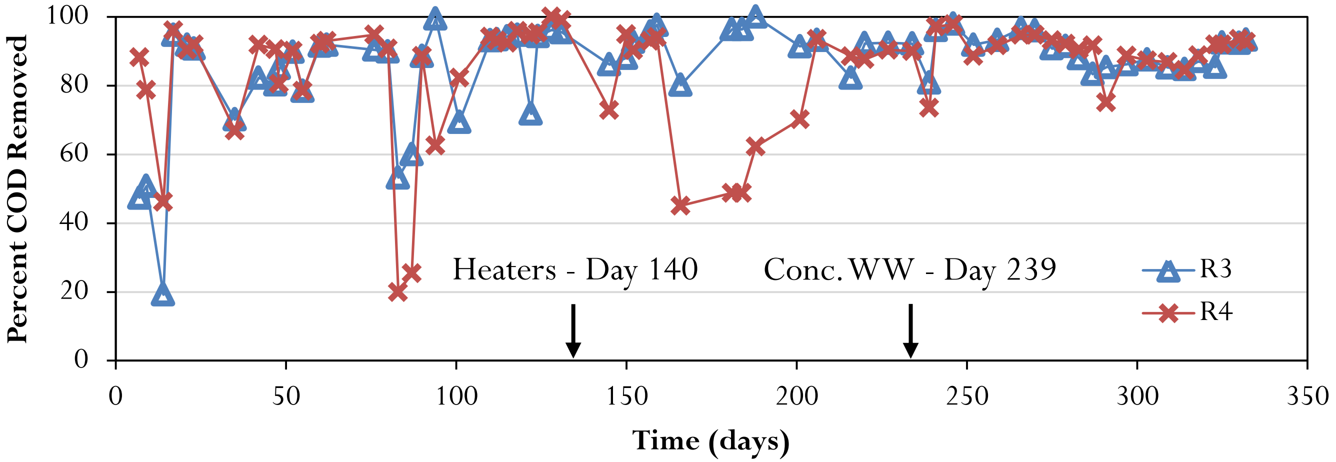


Primary Effluent

22-24 °C
37 °C



Concentrated Wastewater

WATEREUSE

90 Day Average COD Removal

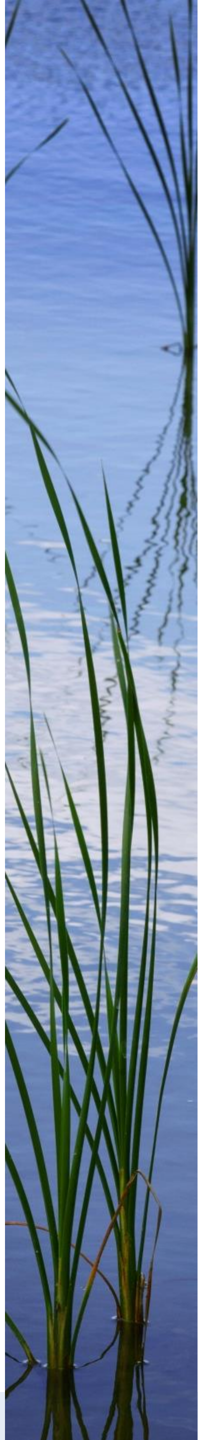
	Primary Effluent		Concentrated Wastewater	
Influent COD	248 mg/L		357 mg/L	
Condition	Ambient	37°C	Ambient	37°C
Effluent COD	36 mg/L	37 mg/L	35 mg/L	34 mg/L
Percent Removal	86%	86%	90%	91%

Specific Energy Comparisons

	Forward Osmosis		Direct Contact Membrane Distillation		Anaerobic Membrane Bioreactor	
	kWh/m^3	Primary Energy Use	kWh/m^3	Primary Energy Use	kWh/m^3	Primary Energy Use
Bench	3.36	Pumping	1,664	Thermal and Pumping	111.4	Pumping and Biogas Recirculation
Pilot	0.23	Pumping	2,000	Thermal[+]	1-5	Recirculation[*]

WATEREUSE

[+] Predicted value – Gustafson et al. (2014) NAMS 2014
[*] Drews et al. (2010) JMS 363



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Expected offset from pilot-scale AnMBR biogas production = 0.65-1.14 kWh/m^3

WATEREUSE

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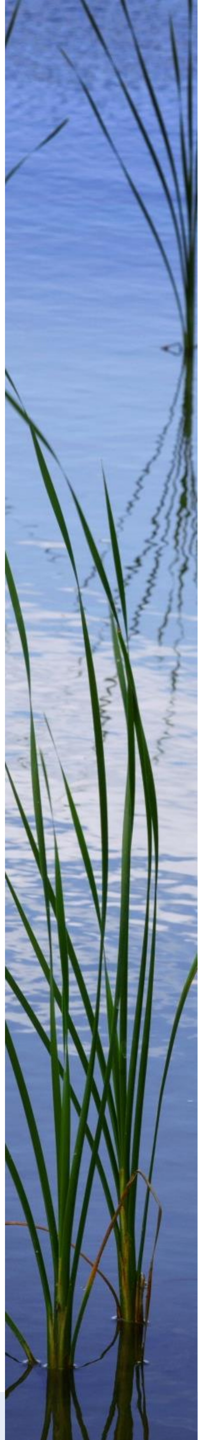
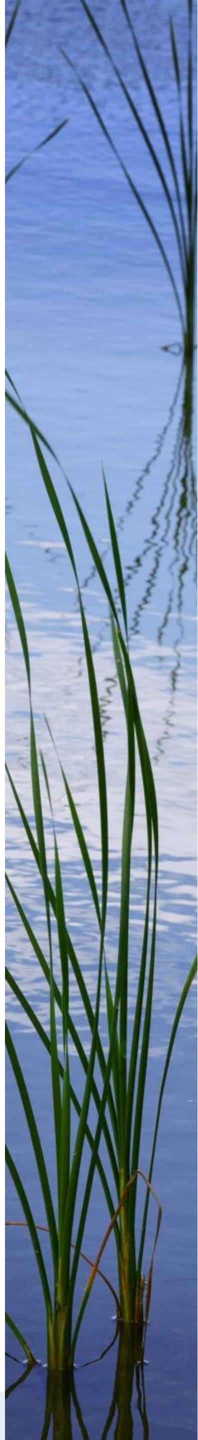


Conclusions

- FO/DCMD System
  - High nutrient and organic carbon rejection
  - Temperature has strongest influence over flux
  - Reverse salt flux
- AnMBR
  - High COD removal
  - No detrimental temperature effects observed
- Energy Considerations
  - Biogas production can offset electrical requirements
  - On-site waste heat for DCMD thermal energy requirements



Q & A Period

Submit questions via the chat box

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