Innovating Water Treatment Technologies in Managing Water-Energy Demand

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THE SINGAPORE POPULATION

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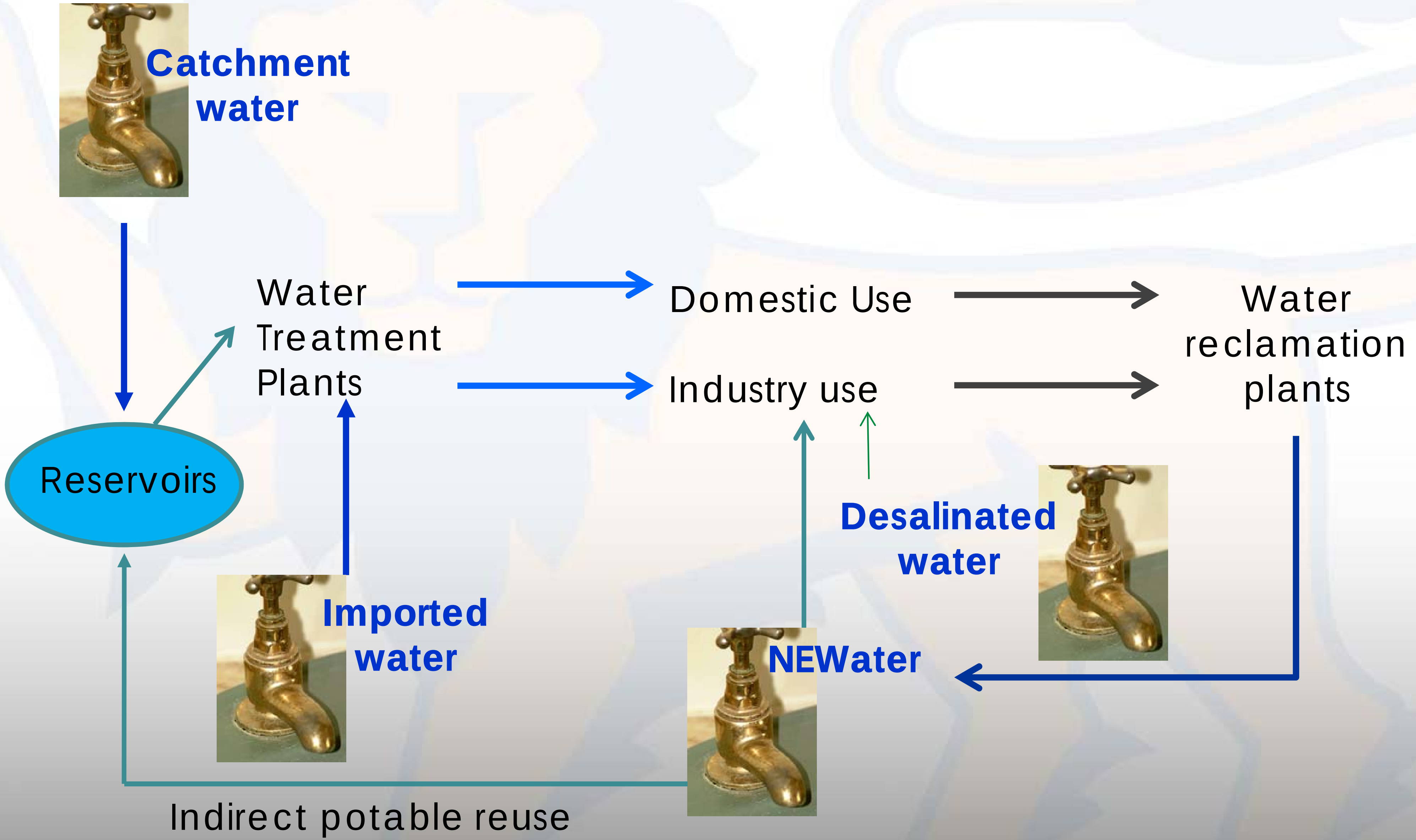
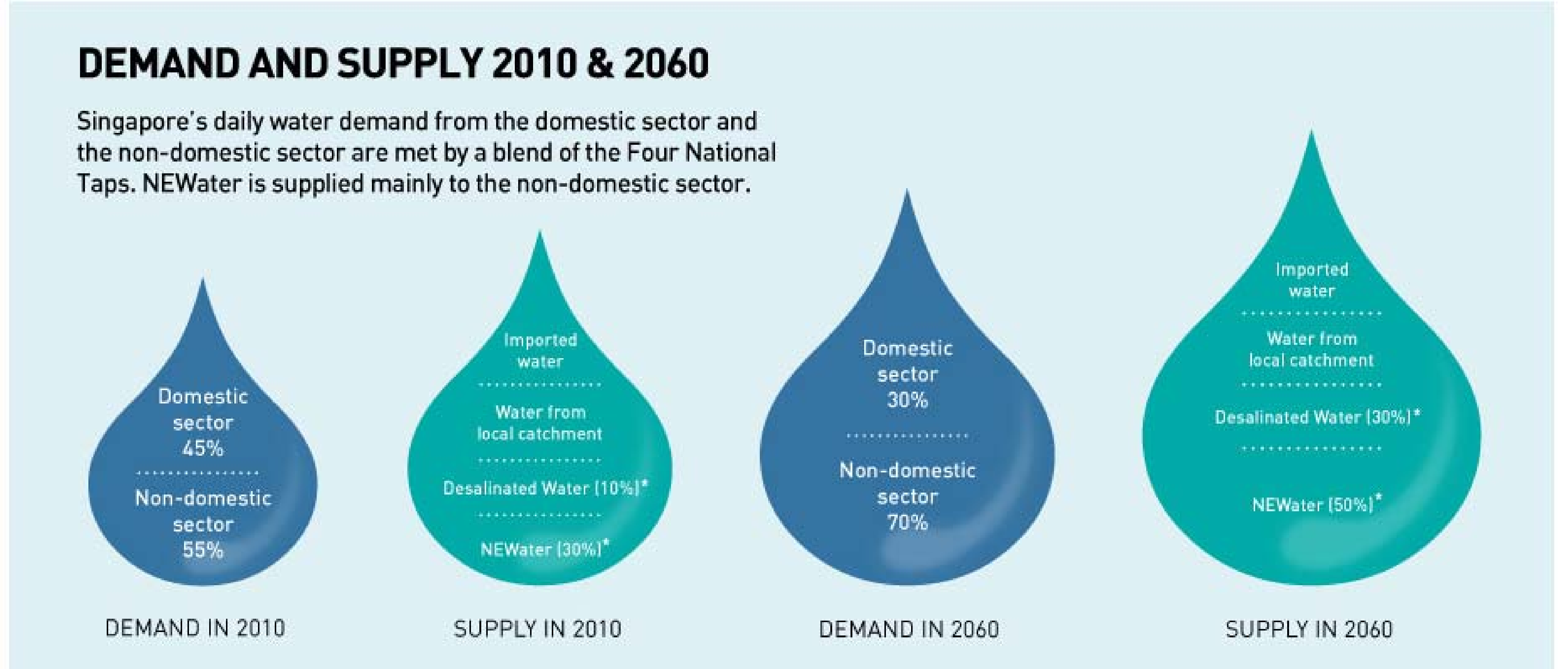
Source: National Population and Talent Division White Paper Graphic: Channel NewsAsia

Singapore's Four National Taps:
Water Demand & Supply Flow



Growing needs of Industrial Water



http://www.pub.gov.sg/LongTermWaterPlans/gwtf.html

NEWater and Industrial Water Supply for **non-domestic use** can free up potable water for consumption

NEWater Process

Domestic wastewater → Wastewater Treatment

Treated effluent → Discharge to Sea

RO Brine

NEWater Factory

NEWater →

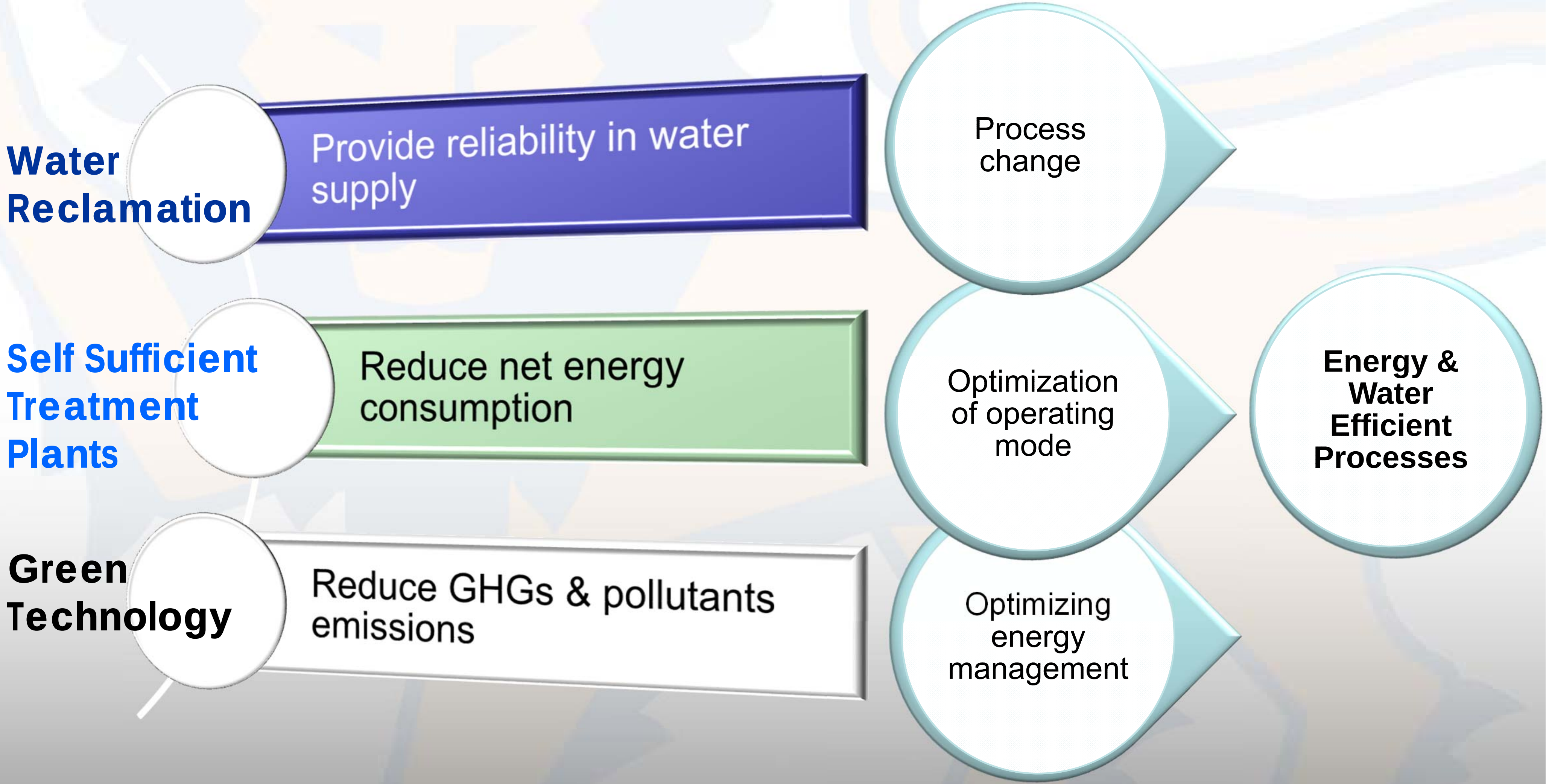
Microfiltration/ Ultrafiltration → Reverse Osmosis → UV Disinfection

Water Quality Comparisons

Water Quality Parameters	Local Reservoir Water	PUB Tap water	NEWater	USEPA / WHO Standards
Turbidity [NTU]	0.5 - 11	< 0.1	< 0.1	5
Total Dissolved Solids [mg/l]	117 - 154	149.5	48.5	500
Lead [mg/l]	< 0.013	0.002	< 0.0005 to 0.002	0.01
Mercury [mg/l]	<0.00003	<0.00003	<0.00003	0.001
Hormones (Synthetic & Natural) [µg/l]	ND	ND	ND	Not Specified
PCBs [µg/l]	ND	ND	ND	0.5
Dioxin [pg/l]	ND	ND	ND	30
Total Organic Carbon [mg/l]	2.6 – 6.2	1.9 – 3.5	<0.1	Not Specified
Total Coliform [cfu/100 ml]	3 - 967	ND	ND	ND
Enterovirus	ND	ND	ND	ND

ND – Not Detected

Emphasis on *Energy & Water Efficient Technologies*



PROCESS CHANGE & NEW TECHNOLOGIES
in Wastewater Treatment & Water Reclamation

Wastewater Treatment

Anaerobic process → *Lower energy consumption, biogas production, reduced GHGs emission*

Membrane Bioreactor (MBR) → *High treated effluent quality free from suspended solids*

Water Reclamation

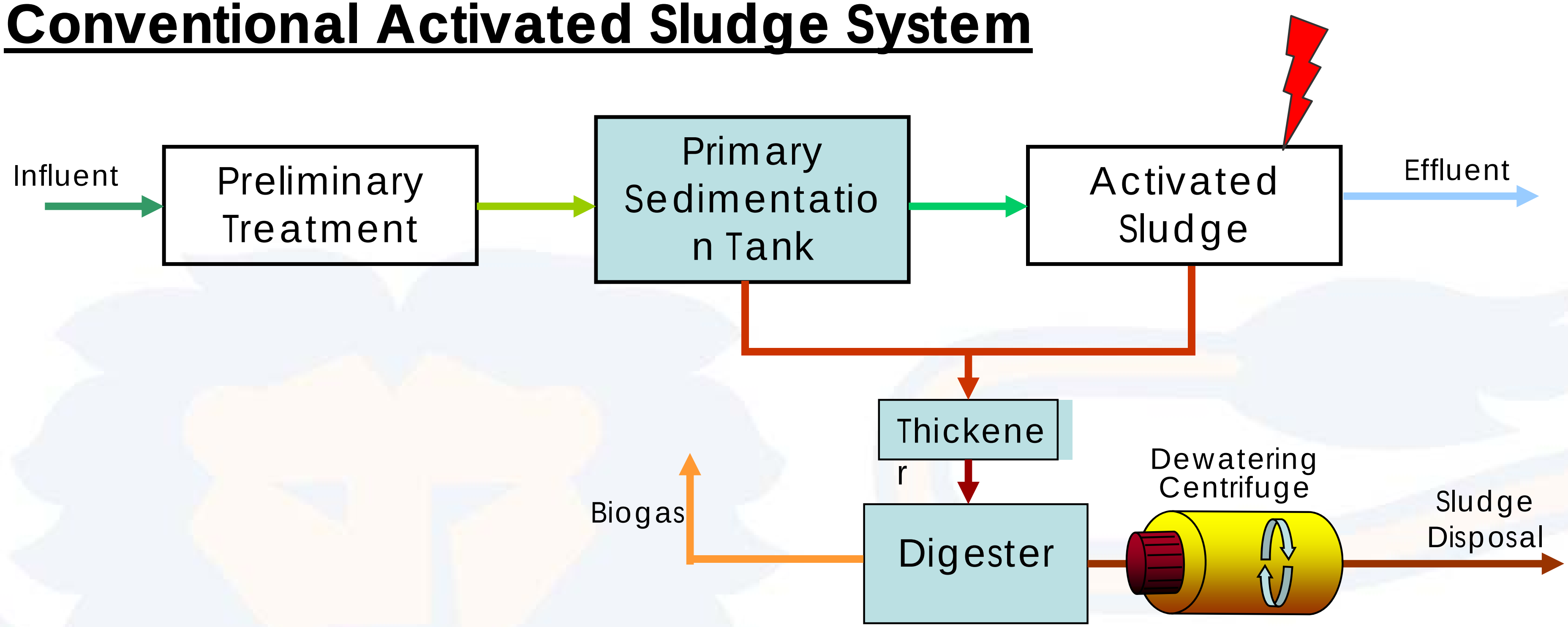
Reverse Osmosis (RO) Process
Forward Osmosis (FO) Process → *Lower energy for water reclamation*

Capacitive Deionization (CDI) Process → *Lower energy & increased water recovery*

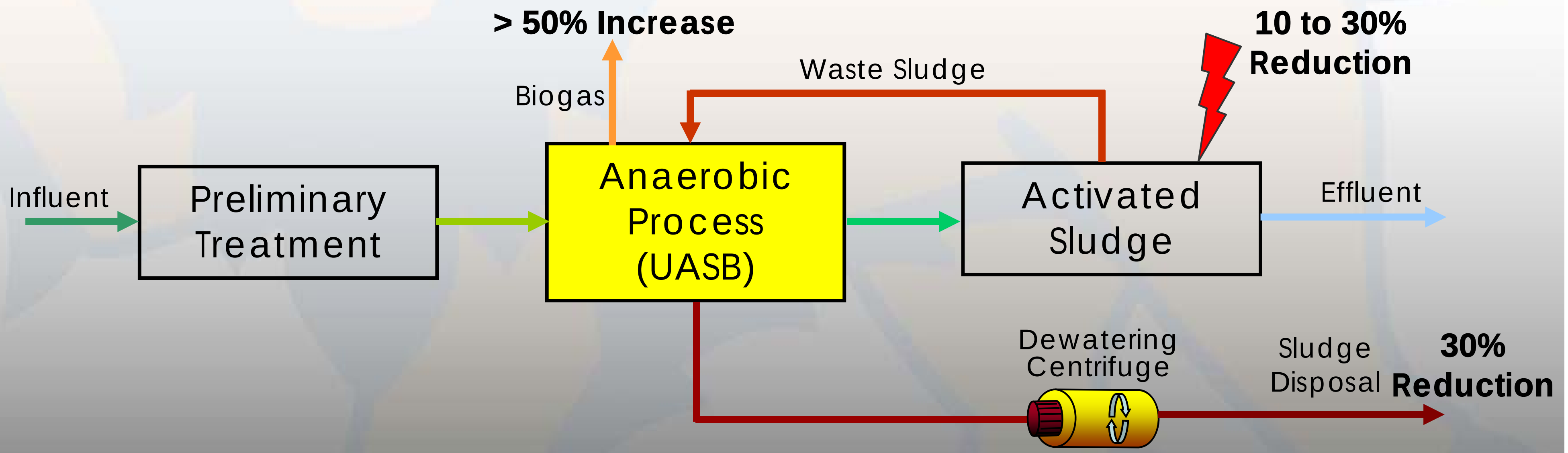
Wastewater Treatment

Anaerobic Processes

Conventional Activated Sludge System



Integrated Anaerobic and Aerobic System



High Rate Anaerobic Treatment Designs

Anaerobic filters

Upflow Anaerobic Sludge Blanket (UASB)

Sequencing Batch Anerobic Reactor (AnSBR)

Anaerobic Membrane Bioreactor (AnMBR)

Advantages:

- Compact – small footprint
- Low energy requirement
- Ability to withstand shock loading and treats from toxicants
- Bioenergy production

Aerobic post-treatment system performance at HRT 4 h treating anaerobic effluents (HRT = 6 h)

	Influent WW	UASB Effluent	CAS Effluent	MBR Effluent
SS (mg/l)	248 – 850 (440)	200 – 425 (322)	4 – 41 (18)	N.D.
VSS (mg/l)	196 – 425 (350)	64 – 196 (134)	3 – 28 (12)	N.D.
tCOD (mg/l)	318 – 766 (562)	101 – 329 (227)	19.6 – 68.2 (42.7)	6.8 – 37.5 (23.2)
sCOD (mg/l)	36 – 157 (93)	34 – 84 (57)	10.5 – 34.3 (21.2)	
$tBOD_5$ (mg/l)	122 – 330 (230)	41 – 151 (79)	1.7 – 13.9 (6.3)	0.1 – 1.5 (0.8)
$sBOD_5$ (mg/l)	17 – 75 (35)	11 – 34 (19)	0.7 – 2,3 (1.3)	
NH_4^+-N (mg/l)	31 – 83 (43)	25 – 61 (41)	N.D.	N.D.
NO_3^- -N (mg/l)	N.D.	N.D.	25.6 – 58.0 (41.3)	23.3 – 47.1 (33.9)

Estimation and Comparison of IAATP and AS

- **Average Influent Flow = 325,000 m^3/d; Average Influent total Chemical Oxygen Demand = 590 mg/L**
- **Discharge: BOD5 = 10 mg/L; SS = 20 mg/L**

Parameter	IAATP	AS
Overall Plant Energy Consumption (kWh per 1000 m^3 of wastewater treated)	61	195
Aeration Energy Consumption (kWh per 1000 m^3 of wastewater treated)	57 (without nitrogen oxygen demand)	181 (without nitrogen oxygen demand)
Sludge Production (kg per 1000 m^3 of wastewater treated)	116	280
Total Reactor Footprint (m^2)	44,442	56,300

Wastewater Treatment

Membrane Bioreactors

MBR Demonstration Plant at Ulu Pandan WRP

- Capacity: 23,000 m^3/d
- Feed: Primary settled domestic sewage effluent
- Energy requirement: designed less than 0.7 kWh/m^3

→ system optimization enabled the plant to be operated at 0.4 kWh/m^3

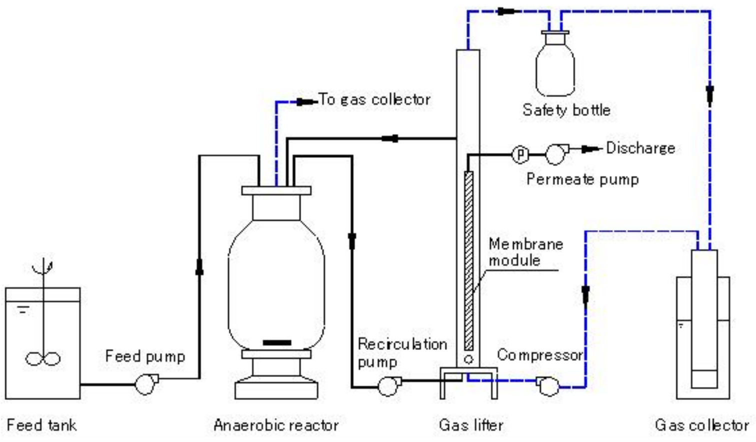
Reference: G. Tao: Large Scale Membrane Bioreactor Plant Design (Retrofit) and Optimisation, Conference Proceedings IWA MTC 2009.

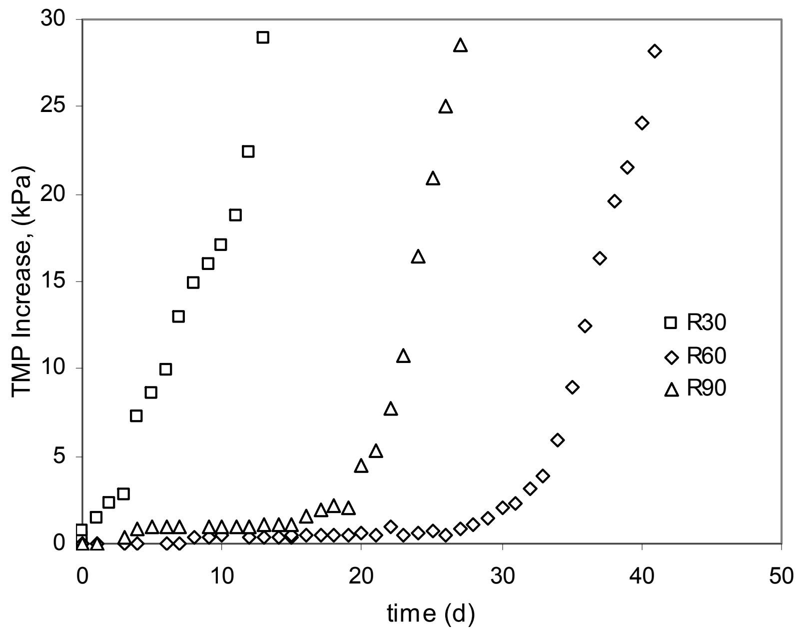
Pictures from: http://www.siww.com.sg/tour-4

Anaerobic MBR for Domestic Wastewater Treatment

- **Effect of SRT (30, 60 and 90 d)**

Parameter	Feed (Concentration/Value)
COD, mg/l	426.77± 59.41
TOC, mg/l	56.99± 10.17
Ammonium, mg/l	57.43± 5.54
TN, mg/l	50.3± 9.20
pH	～ 7.0
Temperature, °C	25 ～ 30

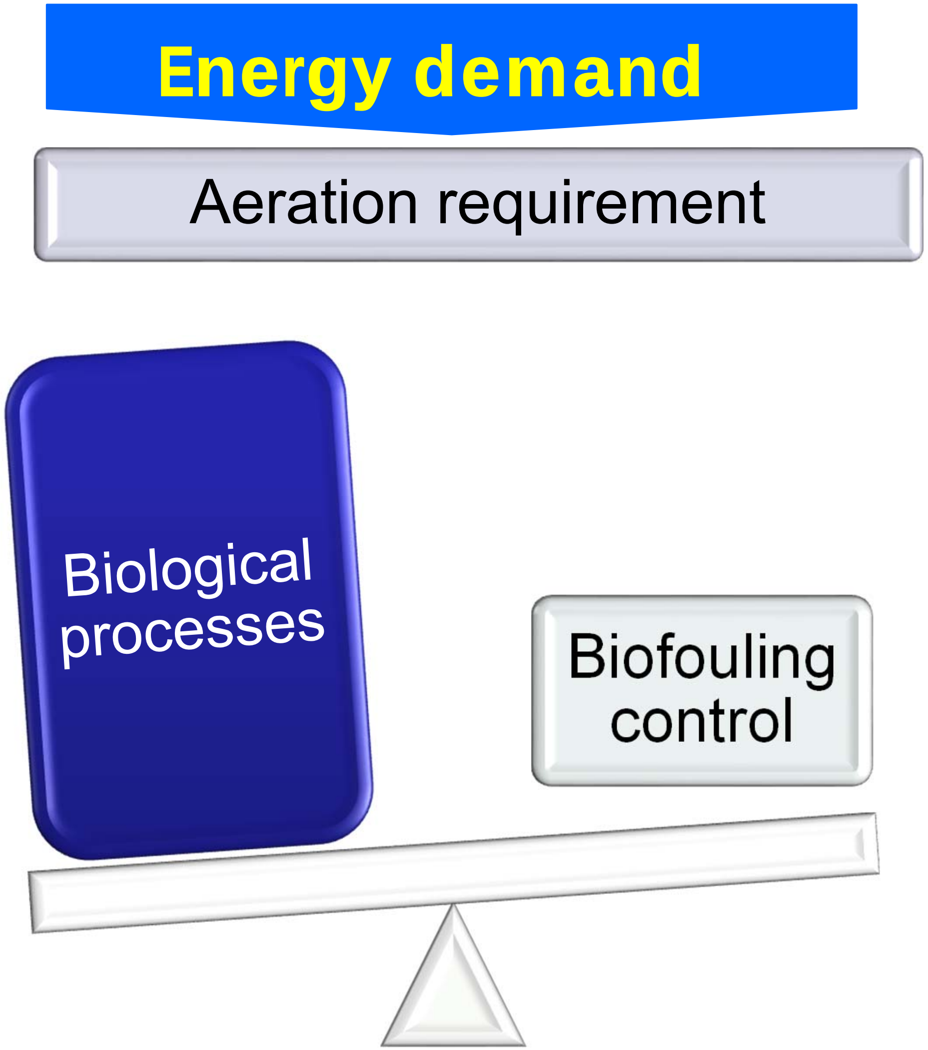




- **COD Removal Efficiency of ~85%**
- **Effluent COD: 62 to 69 mg/L**

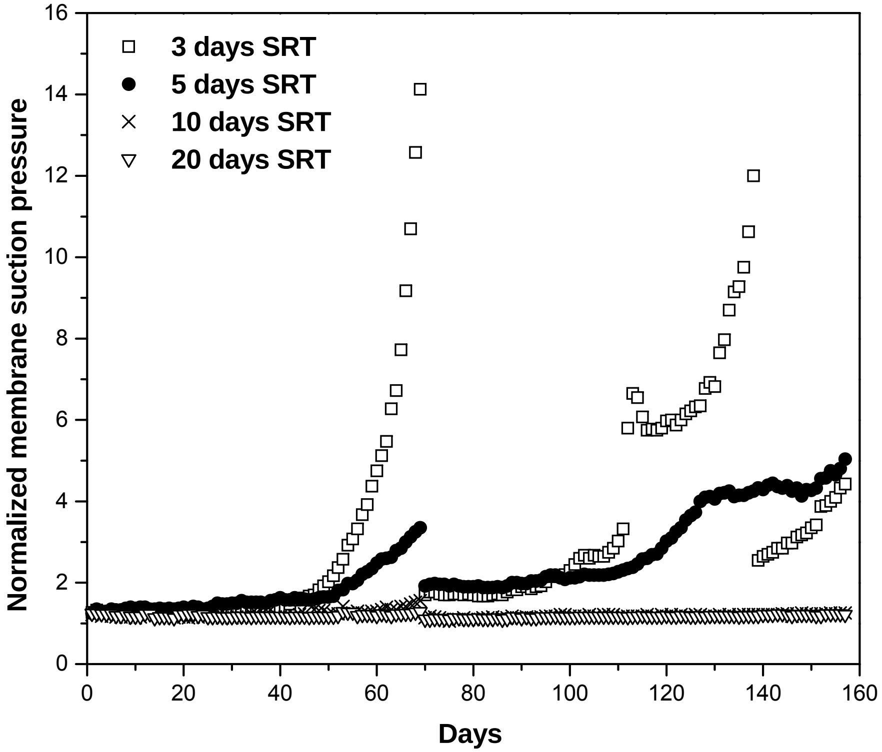
Huang et al. (2013) J. of Biotechnology; Huang et al. (2011) Water Research

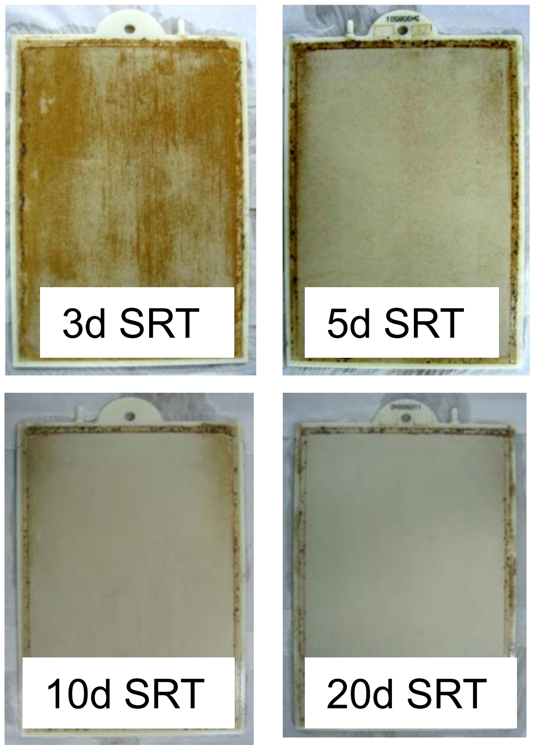
Main Challenge in MBR Process Optimization



SRT Impact on MBR Fouling

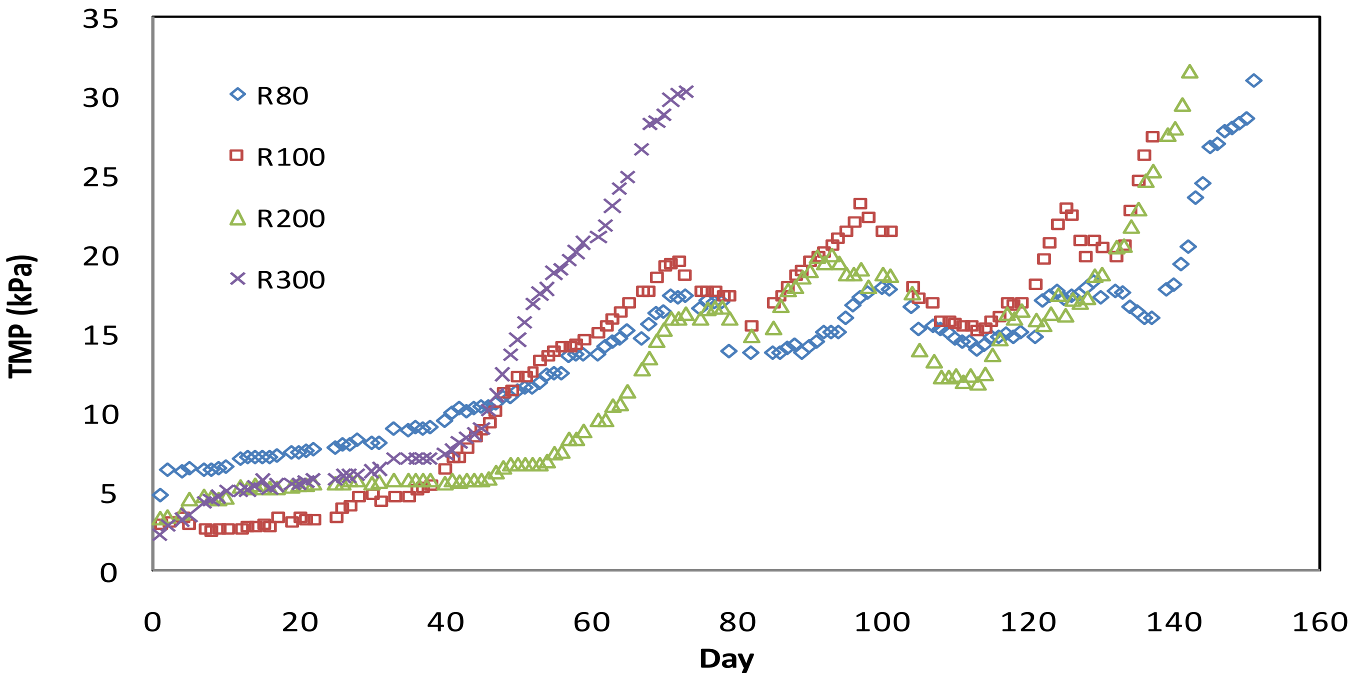
- **Submerged MBR operated at less than 5 days experienced rapid fouling.**
- **Fouling rate dependent on the amount of SMP (particularly the carbohydrates) and NOT the concentration of MLSS.**

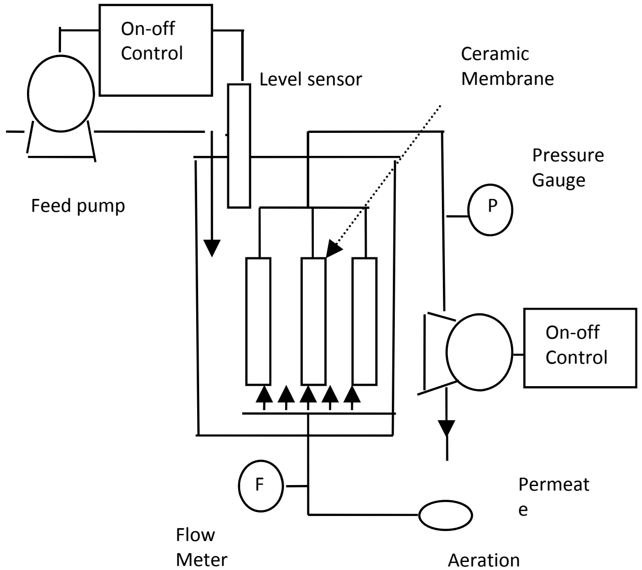




Reference: Ng et al. (2006) Environ Sci. & Tech., 40 (8), 2706-2713.

Effect of Membrane Pore Size on MBR Fouling





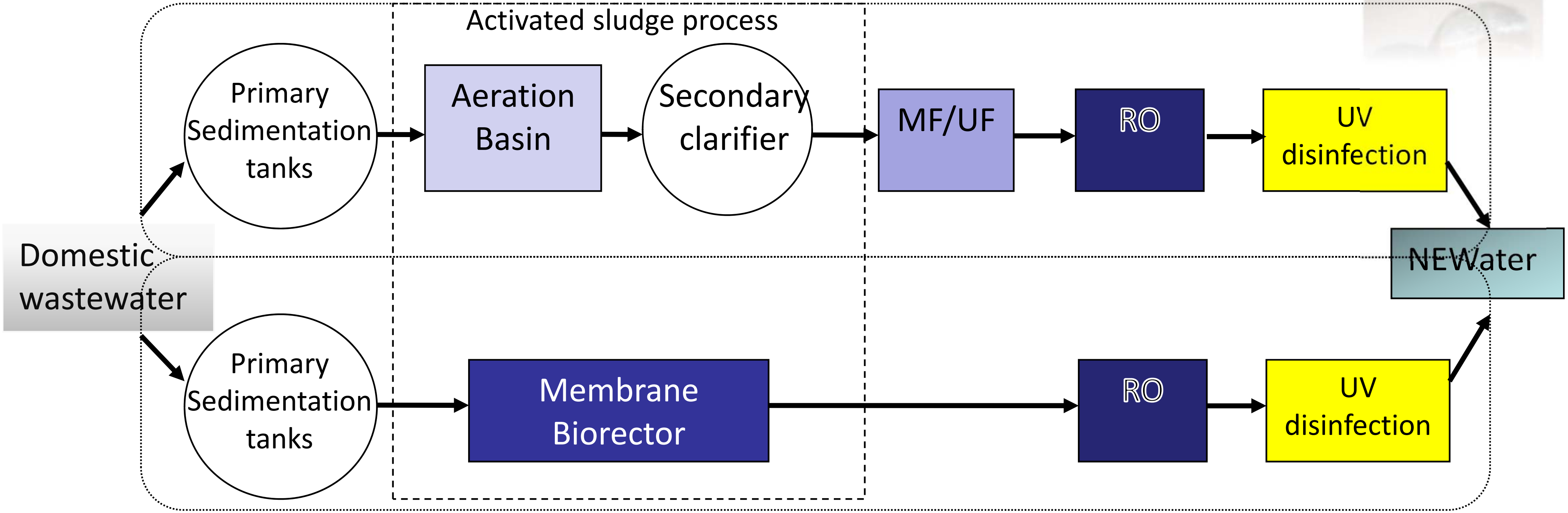
- The biggest pore-sized ceramic membrane had the highest fouling potential, while the ceramic membrane with the smallest pore size encountered least fouling.
- Rougher membrane fouled faster.

Parameters	
Material	α-Al_2O_3 /TiO_2/ZrO_2
Support layer	α-Al_2O_3
Permeability	3300/1450/1450/260 L/m2*h*bar
Pore size	300/200/100/80nm

Jin et al. (2013) J. of Membrane Sci.; Jin et al. (2010) Water Research

Enhancing Water Reclamation Process: Integrating MBR-RO for NEWater Production

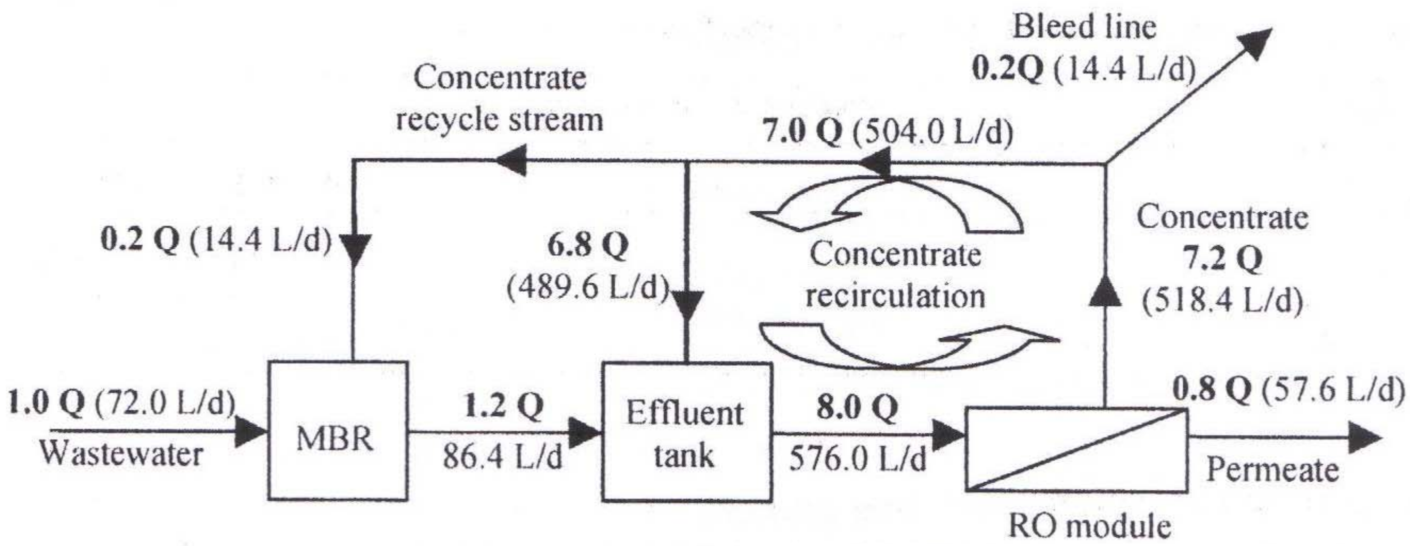
- **Integrating Membrane Bioreactor with Reverse Osmosis (MBR-RO) provides a new option for NEWater production**



Qin et al. (2006). "New option of MBR-RO process for production of NEWater from domestic sewage". *Journal of Membrane Science*, 272, 70-77.

Integrating MBR-RO for NEWater Production

- MBR operated at a
  - **SRT : 20 days and HRT : 5.5 h**
- Overall recovery efficiency : 80%.



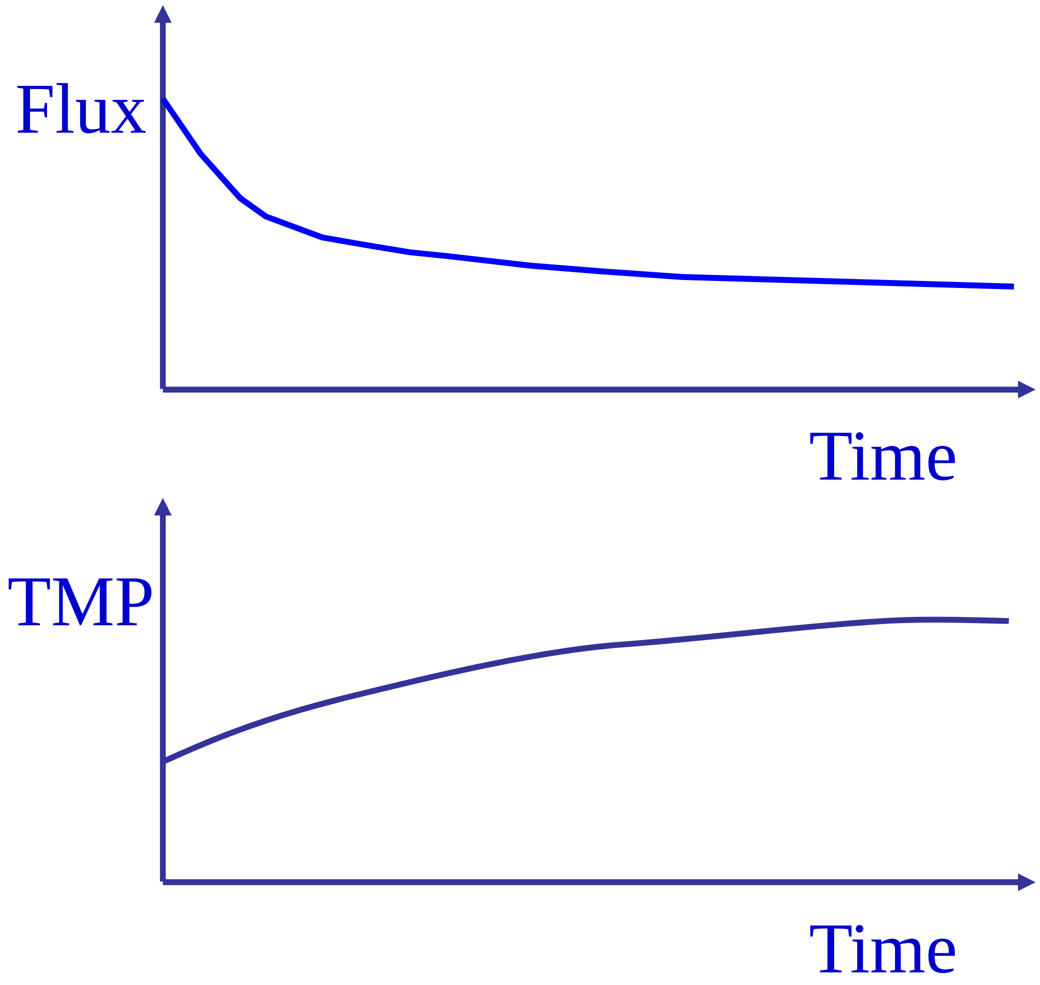
Water Reclamation

Membrane Processes

Fouling Management

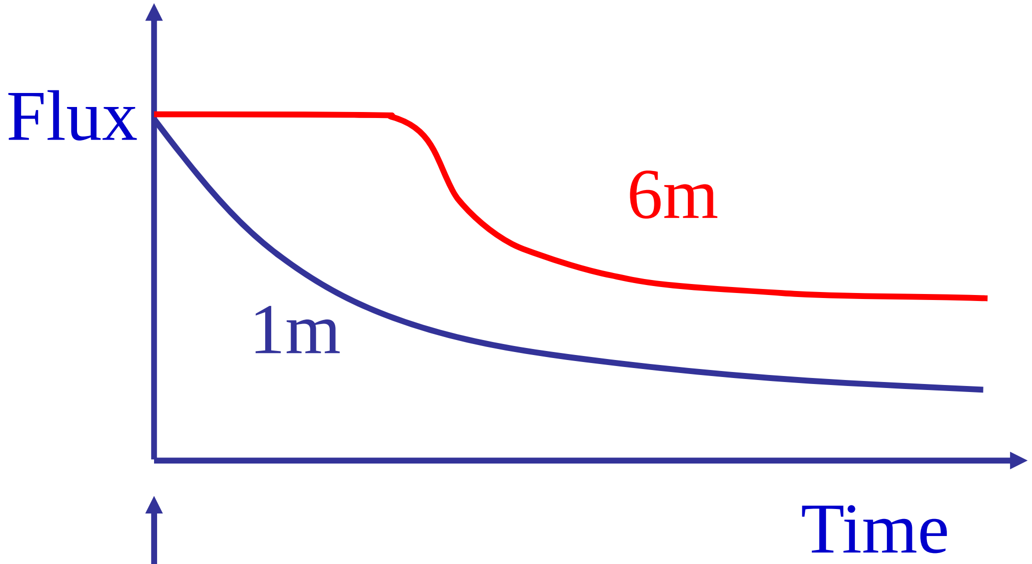
Fouling Measurement

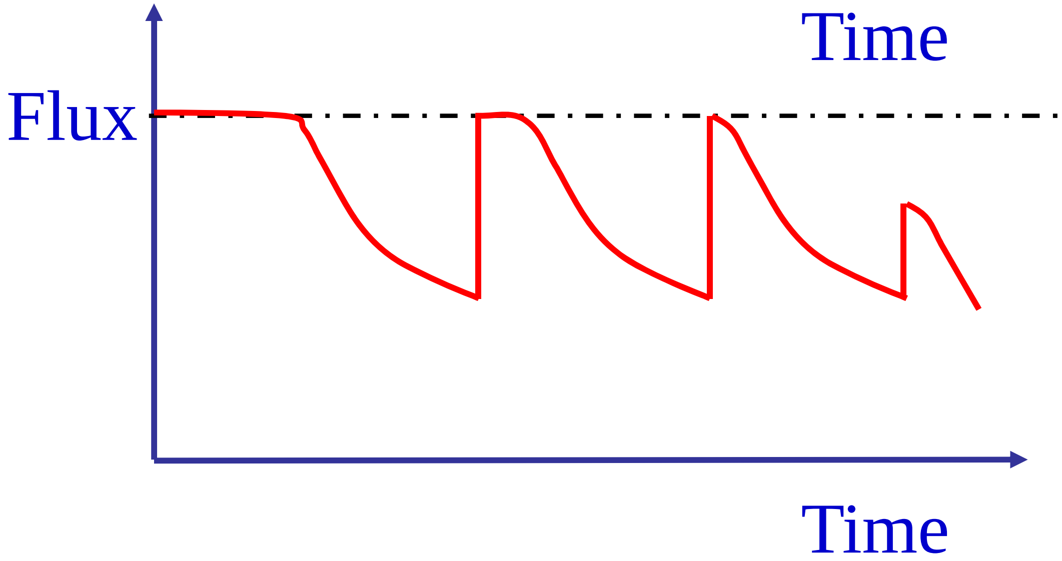
- **Traditionally membrane fouling can be indicated by:**
  - ➢Flux decline under constant pressure, or
  - ➢Pressure increase for constant permeate flux
- **Are these suitable for full-scale RO?**



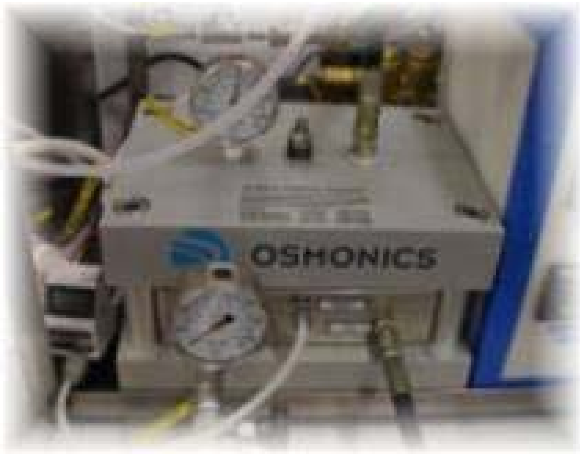
Observations from Full-Scale RO System

- Cannot detect initial fouling
- Cannot explain cleaning efficiency





Laboratory and Full-Scale System



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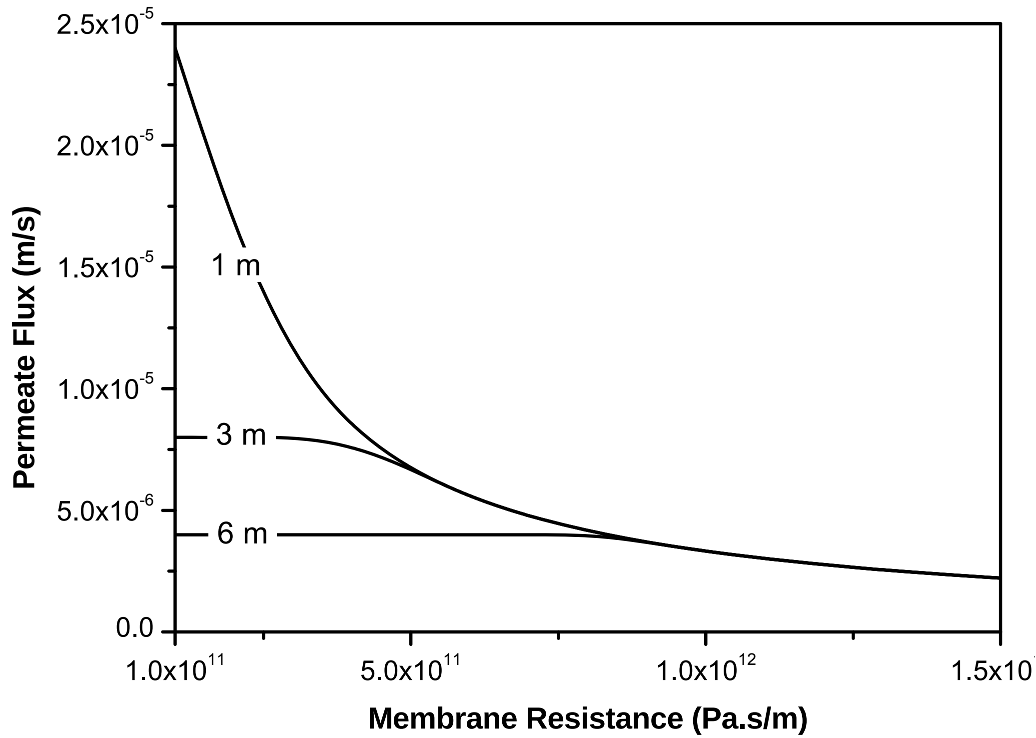
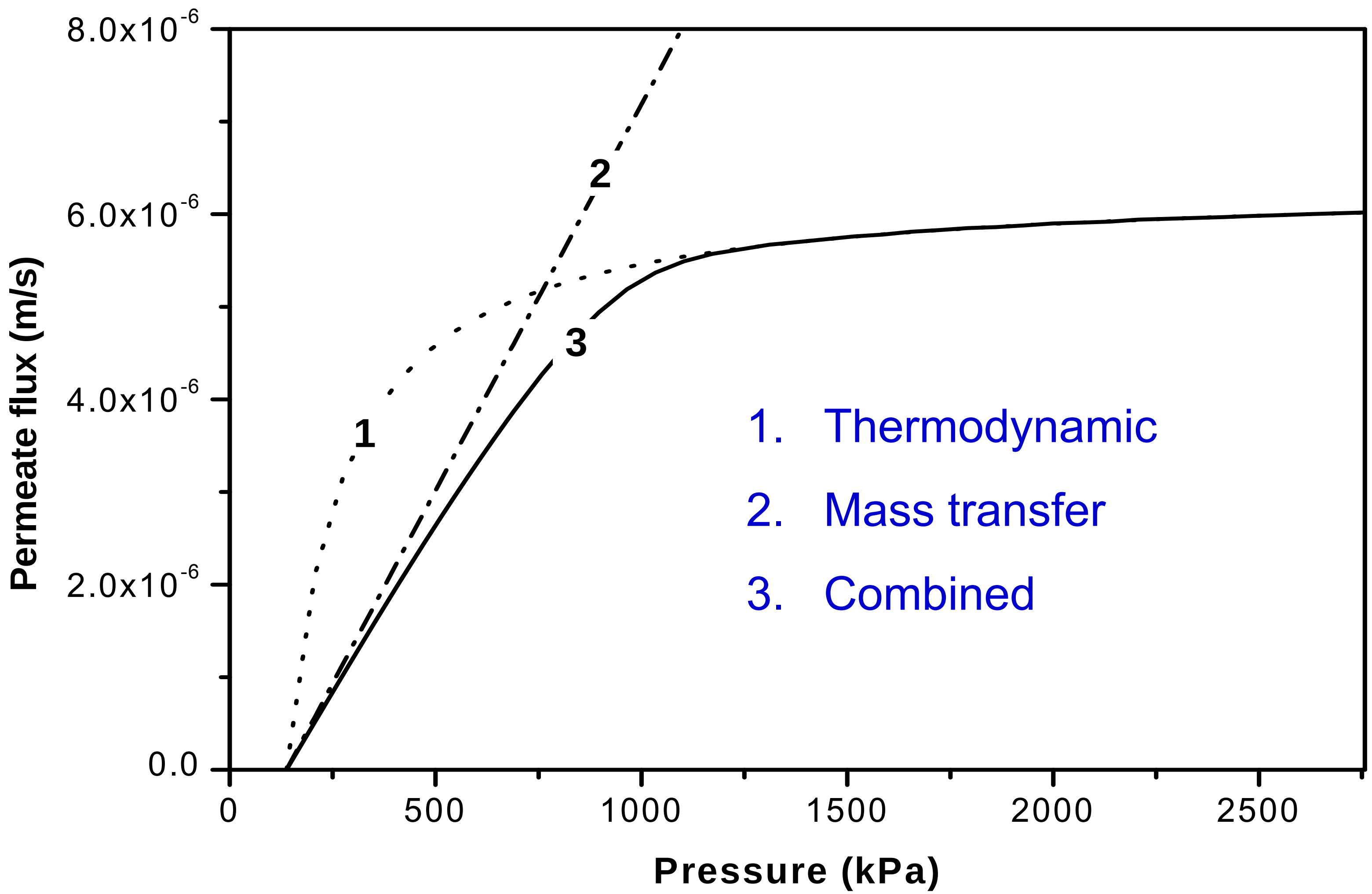
- Fouling behavior can be very different between lab and full-scale RO processes
  - Full-scale RO is less sensitive to initial fouling

Effect of Channel Length

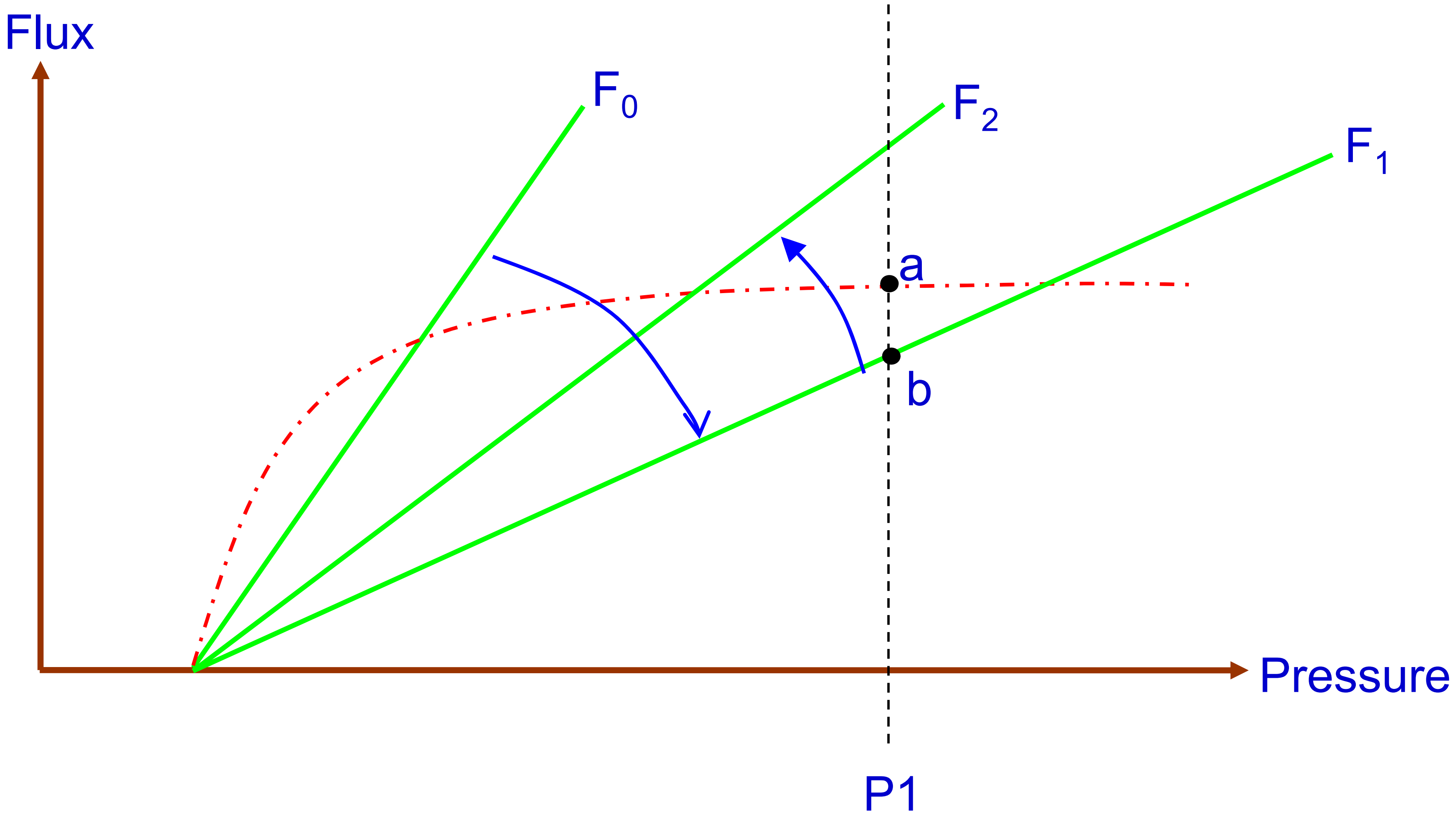
- ❖ Short channel has high average flux
- ❖ Constant average flux does not appear for 1 m
- ❖ The period of constant flux increases with channel length
- ❖ Fouling cannot be "seen" in the initial stage
  - ➢ Flux decline is not a good indicator for fouling



Flux Controlling Mechanisms

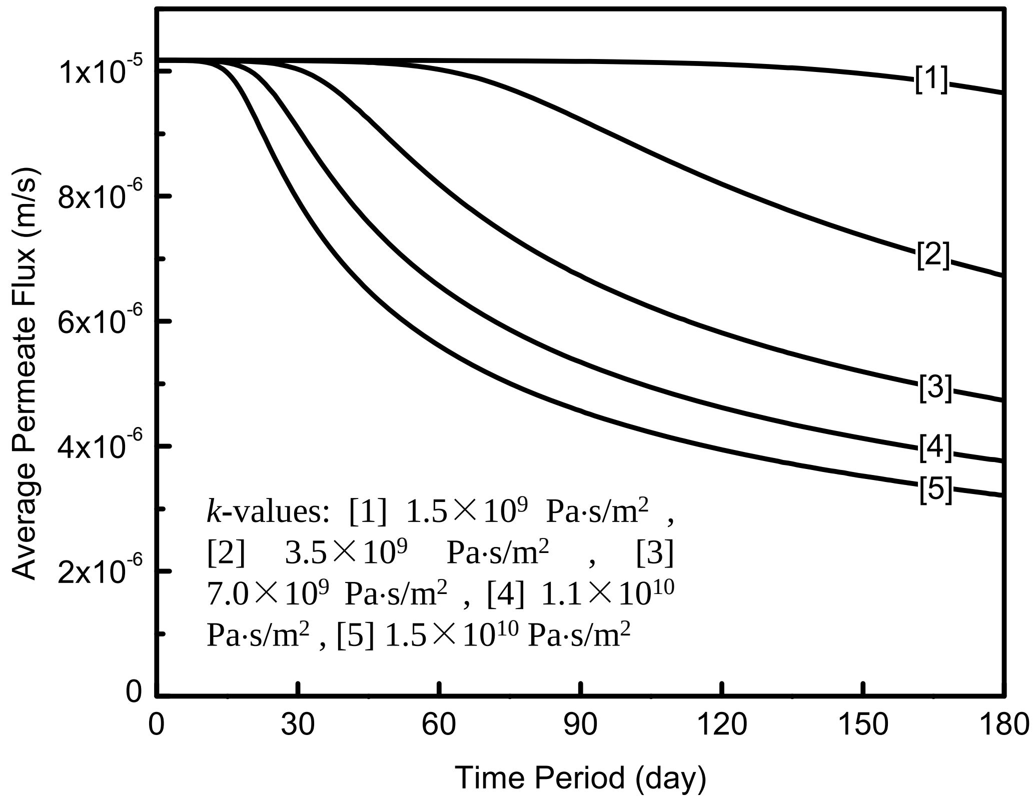


Fouling Development



Effect of Water Fouling Potential

- **Average permeate flux is strongly affected by feed water quality**
- **The figure shows:**
  - **Effectiveness of pretreatment can be assessed by fouling potential**
  - **Water quality is linked to performance of full-scale RO**



Fouling Characterization Index

A effective fouling characterization index can be defined by the following equation:

$$I_f = \frac{F_0 - F_t}{F_0}$$

where $$F = \int_0^L \frac{1}{R_m(x)} dx$$

F_0 : **Initial filtration coefficient**

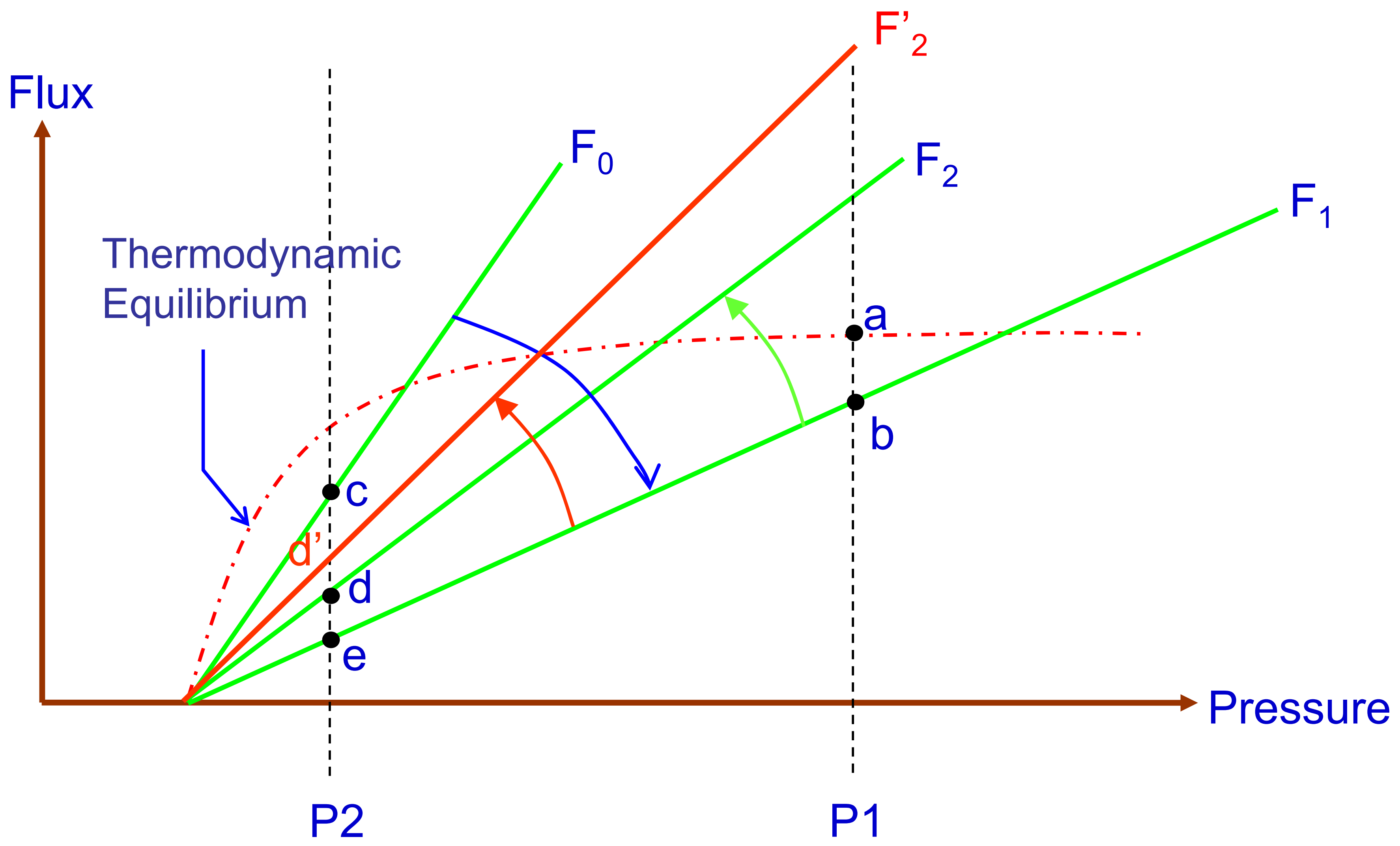
F_t : **Measured filtration coefficient at time t**

EXAMPLES

Case 1: No fouling, $F_t = F_0$, so that $I_f = 0$

Case 2: Most serious fouling, $F_t = 0$, so that $I_f = 1$

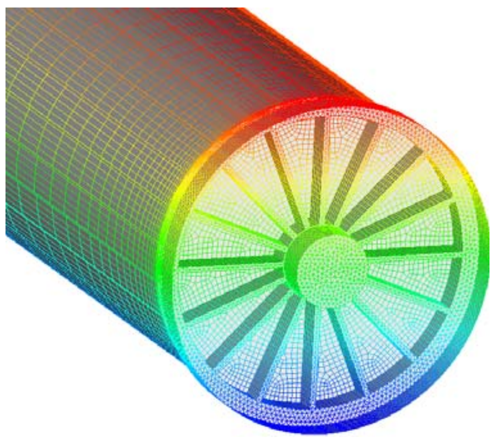
Effectiveness of Cleaning Protocols

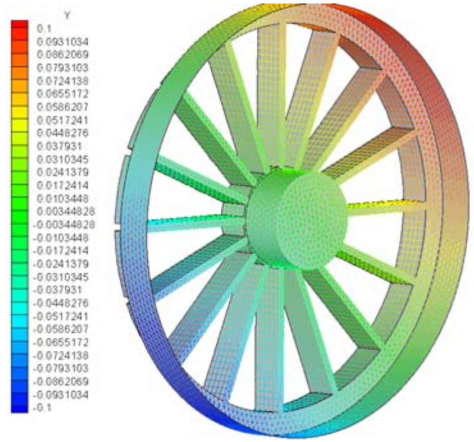


Configuration Management

Performance Enhancement

- Demo-scale study (16-inch RO system)
- Modeling of flow distributor using CFD and reverse osmosis process
- Membrane fouling study

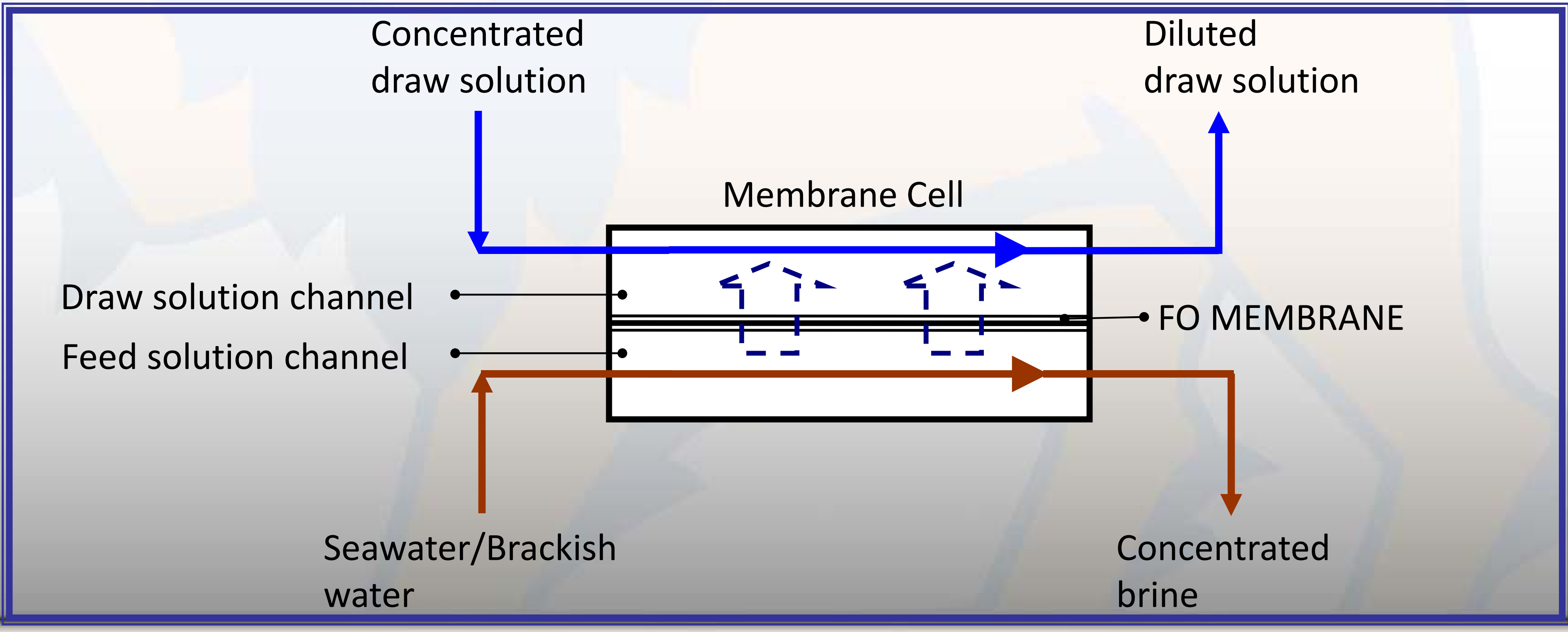




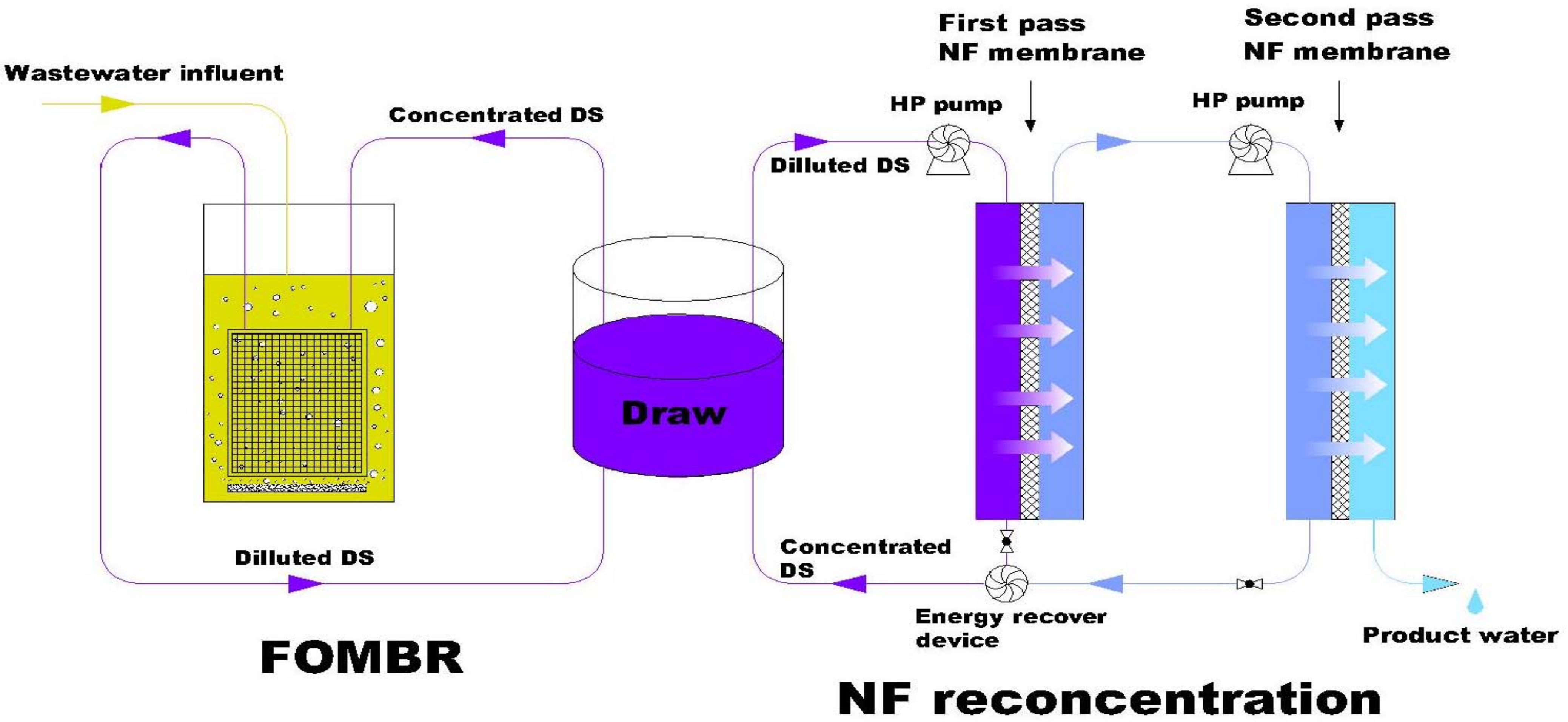
Forward Osmosis (FO)

FORWARD OSMOSIS (FO) PROCESS

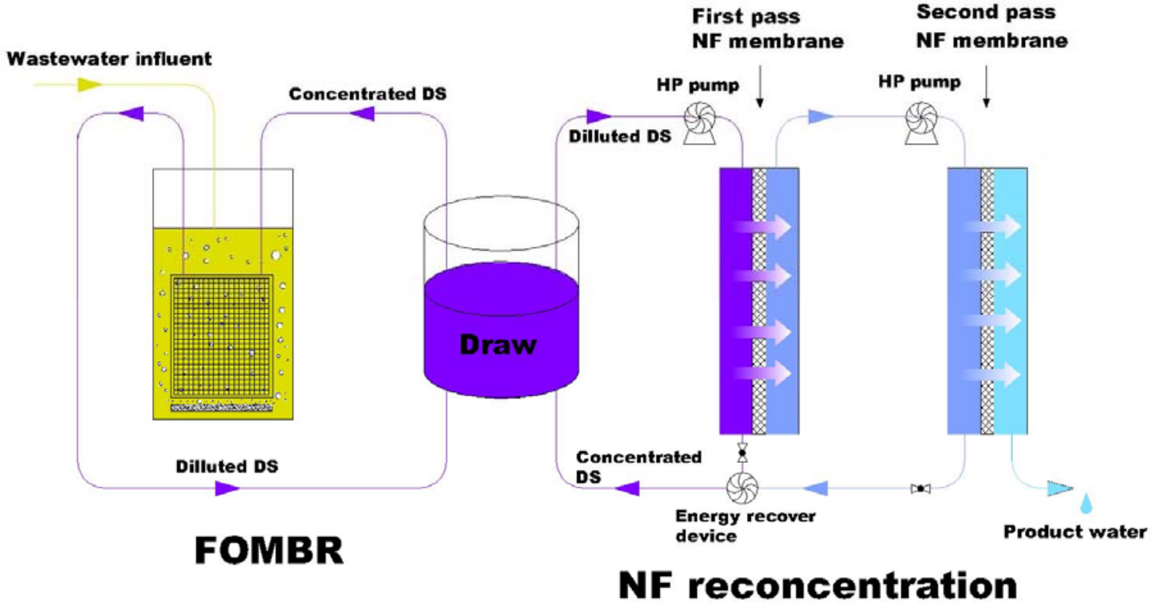
- Natural phenomenon using osmotic driving force
  - 1.5M (117,000 ppm) Na_2SO_4 solution → 74 bar OP
- Main advantage: Low pumping energy requirement
- Estimated energy requirement is ~ 15 – 28% of the current desalination technologies



FO-MBR CONCEPT



FO-MBR : LAB-SCALE SYSTEM



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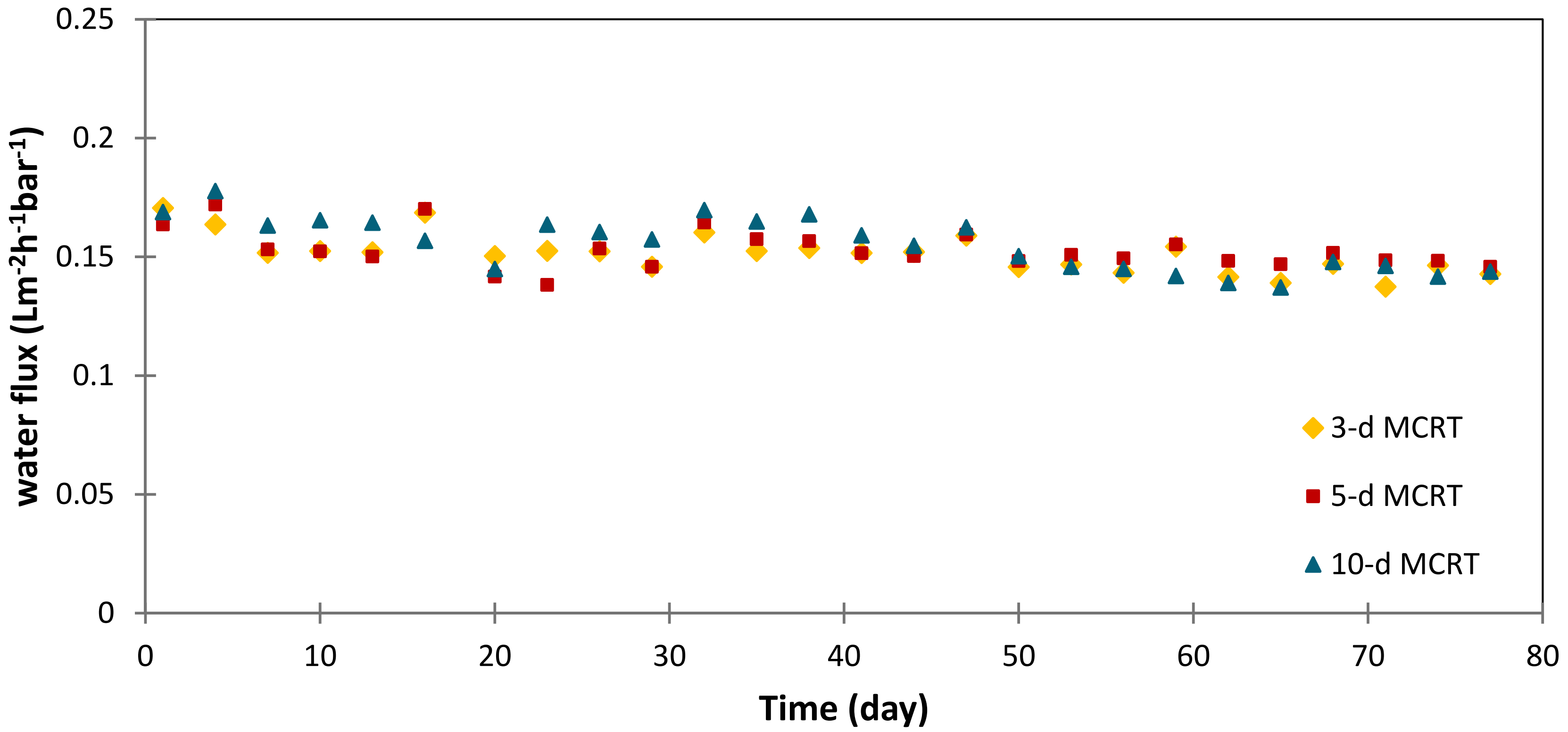
NORMALIZED FLUX – A FOULING INDICATOR



- **Normalized water flux indicated insignificant flux decline, flux decline by fouling was minimal.**
- **3 MCRTs normalized water flux were similar →fouling similar**

NF PERMEATE QUALITY

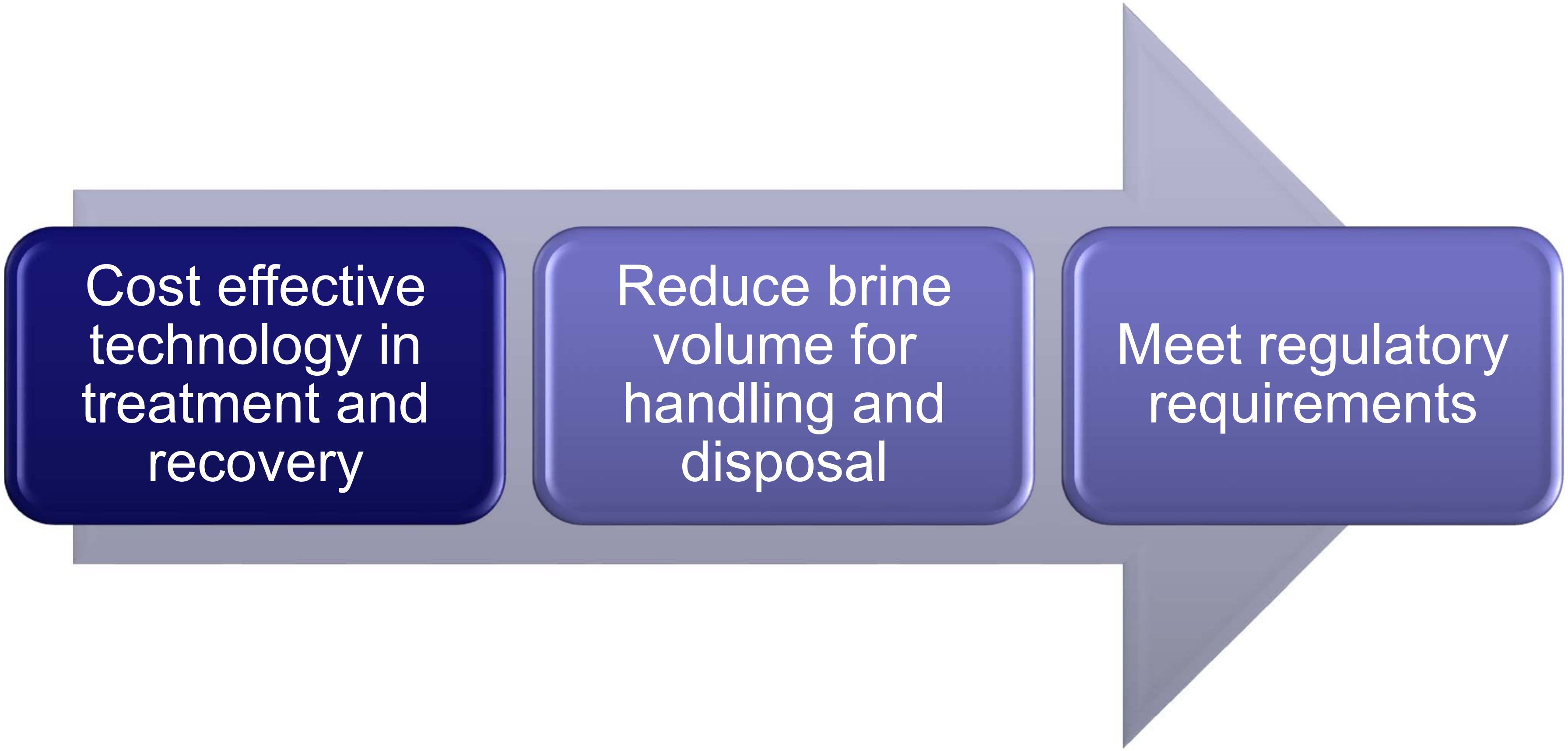
MCRT	TOC	COD	TDS	TN	NO_3^--N
(day)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
3	< 1	7.5 ± 8.1	356.0 ± 64.6	26.3 ± 4.4	28.4 ± 7.5
5	< 1	5.9 ± 6.5	336.8 ± 93.3	28.5 ± 5.8	32.0 ± 9.1
10	< 1	6.5 ± 6.5	389.2 ± 82.1	31.6 ± 7.4	34.0 ± 10.5

- **TOC and COD removal above 97.6% for all MCRTs studied.**
- **High TN (NO_3^--N) in permeates suggests requirement to include anoxic mode in FO-MBR operation.**

Water Reclamation

Capacitive Deionization (CDI) Process

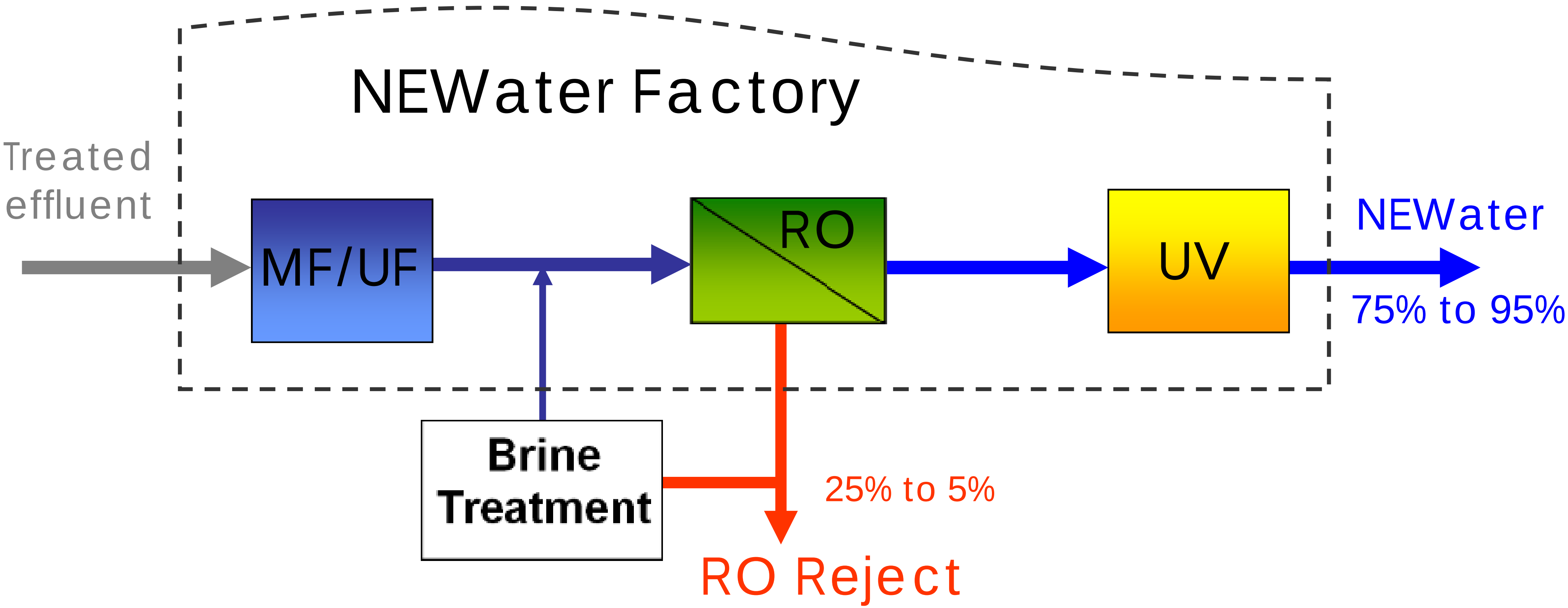
RO Reject Treatment & Recovery



Technology for RO reject treatment & recovery needs to address two major pollutants in RO reject:

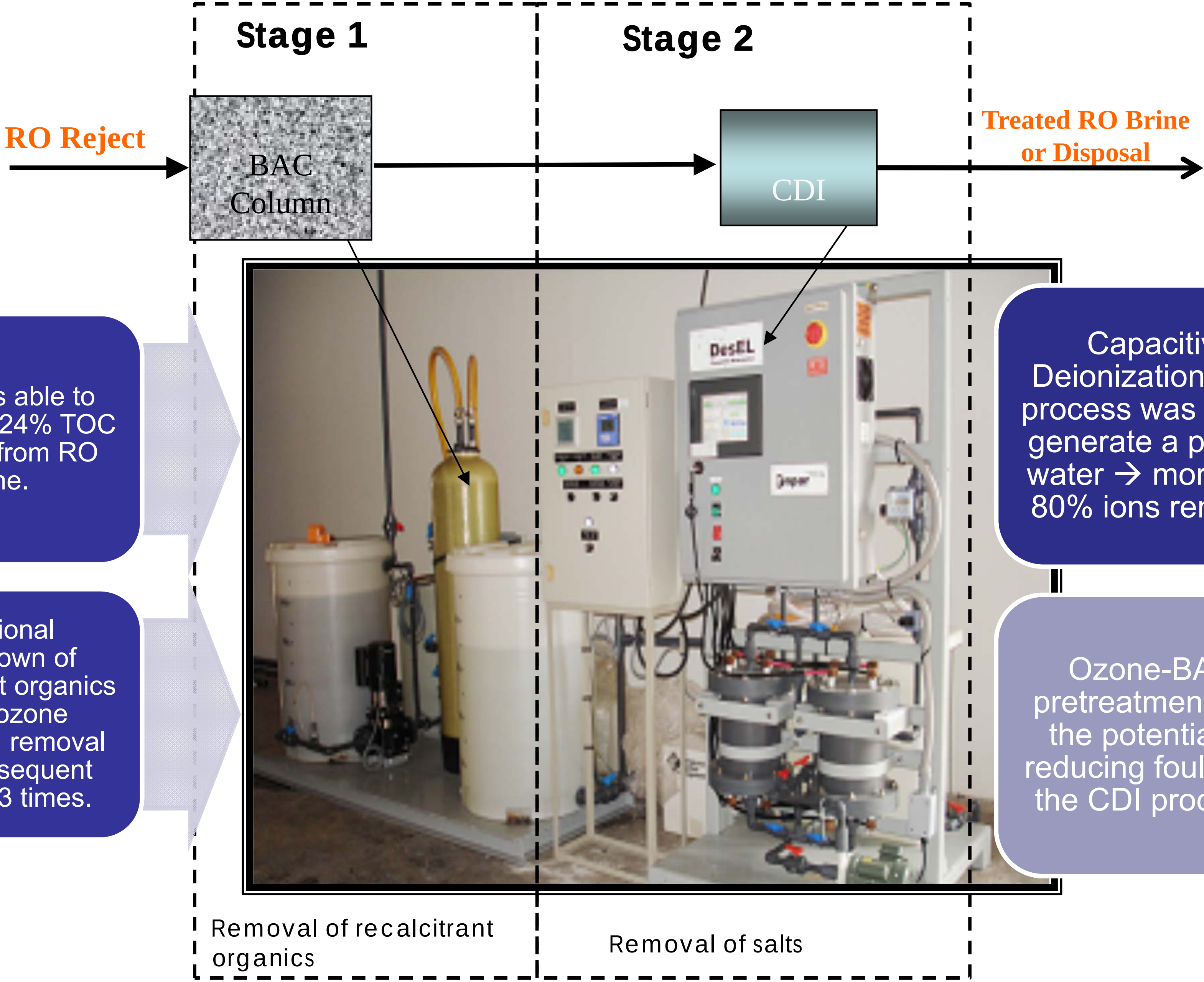
1. **Recalcitrant organics**
2. **Salts retained by RO membrane**

RO Reject Treatment & Recovery



Harnessing more water with RO reject treatment

Pilot Scale RO reject treatment & recovery system



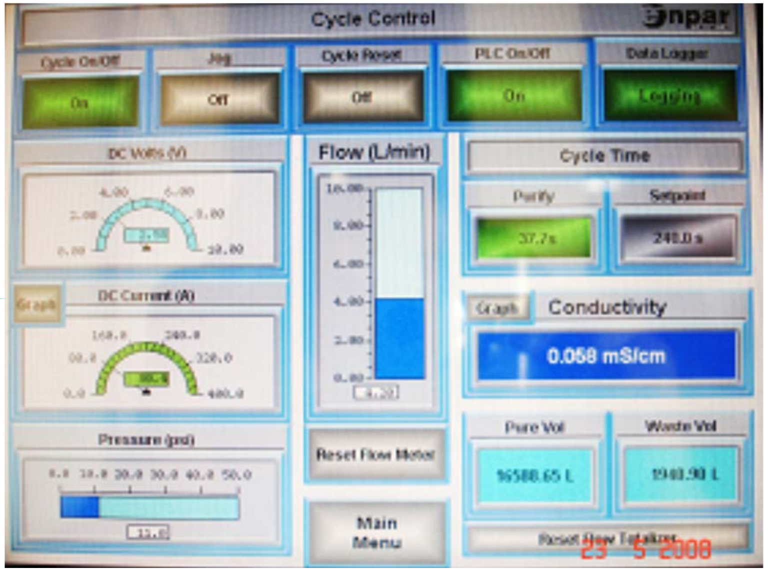
BAC was able to achieve ~ 24% TOC removal from RO brine.

Additional breakdown of recalcitrant organics using ozone increased removal with subsequent BAC by 3 times.

Capacitive Deionization (CDI) process was able to generate a product water → more than 80% ions removal.

Ozone-BAC pretreatment has the potential of reducing fouling in the CDI process.

Pilot CDI Unit



Description	
Power source	230 V AC, 50Hz,9 Amps
Flow rate	Up to 4,800 L/d
CDI cell	
Electrode surface area	20 m^2 (2 cells, each 10 m^2)
Power supply	2.58 VDC

- **Power consumption is estimated at 0.85 kWh/m^3**
- **Lower than the target of 1 kWh/m^3 computed based on a pressure-driven membrane process**

Water Quality (BAC Pretreatment)

Parameter	Water quality			
	RO brine	BAC effluent	CDI effluent	CDI permeate
Conductivity (mS/cm)	1490	1500	314	9.97
TDS (mg/L)	974	906	173	6.15
TOC (mg/L)	19.6	2.53	0.96	<0.1
COD (mg/L)	68.4	2.5	<2	-
SiO_2(m/L)	36.4	34.9	34.7	0.25
Anions (mg/L				
Cl^-	176	198	46.4	1.47
NO_3^-	122	148	29.2	0.9
PO_4^{2-}	43	39.8	15.2	<0.08
SO_4^{2-}	198	207	10.2	0.14
Cations (mg/L)				
Na^+	189	179	51.7	1.23
K^+	53.2	53.6	12.2	0.112
Mg^{2+}	6.97	6.97	0.786	<0.027
Ca^{2+}	63.2	57.8	5.66	0.037

A Search for Energy Efficient Technologies

Singapore's National Research Foundation - Environment and Water Industry (NRF-EWI) Roadmap includes:

Water Reclamation Systems

Energy Self-sufficiency in Wastewater Treatment

- To reduce the energy consumption in municipal wastewater treatment by 80% or less than 0.1 kWh/m^3

Seawater Desalination

To achieve energy efficient desalination system

< 0.75 kWh/m^3

https://rita.nrf.gov.sg/ewi/default.aspx

Thank you

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