Center of Excellence for Water

WEF Nexus School 2023

Desalination Technologies

Dr. Peter Nasr

Adjunct Faculty

The American University in Cairo

Exchange, Training, and Scholarships Pillar activities are implemented in cooperation with:

Outline

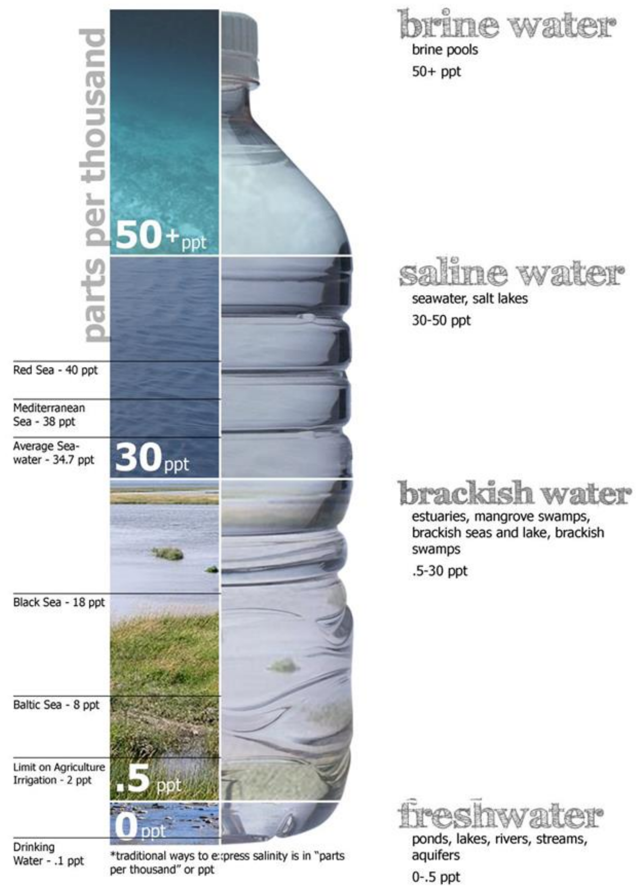
- Desalination
  - What is desalination?
  - Types of desalination technologies
  - Need for desalination
  - Desalination limitations and advantages
- Desalination Technologies
  - Thermal Desalination
  - Membrane Desalination
  - Energy Consumption
- Desalination Challenges
- Reverse Osmosis (RO) and Forward Osmosis (FO)
- Desalination for Irrigation (FDFO)

Classification of Water according to Salinity

Fresh	Brackish	Saline
< 1,500 mg/l	1,500-10,000 mg/l	> 10,000 mg/l

Seawater Composition

- Seawater includes mainly ions of Na, Ca, K, Mg, Ba, SO_4, Cl and CO_3
- All ions in nature can be found in seawater
- The chemical composition of open sea is constant
- However, total dissolved solids changes subject to local conditions



Seawater Composition

Compound	Composition	Mass Percent	ppm
Chloride	Cl^{-}	55.03	19,810.8
Sodium	Na^{+}	30.61	11,019.6
sulfate	$(SO_4)^{--}$	7.68	2,764.8
Magnesium	Mg^{++}	3.69	1,328.4
Calcium	Ca^{++}	1.16	417.6
Potassium	K^{+}	1.16	417.6
Carbonic Acid	$(CO_3)^{--}$	0.41	147.6
Bromine	Br^{-}	0.19	68.4
Boric Acid	$H_3BO_3^{-}$	0.07	25.2
Strontium	Sr^{++}	0.04	14.4
Total		100%	36,000

(Ettouney, 2002)

Why Desalination?

- Desalination can play an important role in increasing the supply of fresh water in both developing and developed nations
- Desalination not only pertains to sea and ocean water but also to brackish water such as agricultural and industrial waters

What is Desalination?

Desalination is defined as the process of removing salt and other dissolved solids from water in order to produce water suitable either for human consumption or agricultural purposes or industrial processes

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Desalination

Multidisciplinary science

- Mechanical Engineering / Thermodynamics
- Chemical Engineering
- Environmental Engineering
- Process Engineering
- Hydraulics / water resources / water treatment
- Material Science (membranes)
- Electronics Engineering (PLCs)
- Energy
- Costing / Life cycle Assessment

Historical Background of Desalination

Back in the first century A.D.,

- Siphons used to pass salt water through wool threads trapping the salt
- Romans filtered seawater through clayey soil
- Greek sailors boiled seawater, collecting the vapor in sponges to quench their thirst

Historical Background of Desalination

- In 1869, the first complete distillation process was built in England to provide fresh water to vessels stopping at the port
- The first land based plant was installed in 1912 in Egypt
- Start of the oil industry increased the production capacity (1929-1937)
- Exponential growth followed (1935 to 1960)
- In 1957, the landmark installation of flash desalination plant in Kuwait

World Desalination Status

18,426	The total number of desalination plants worldwide
86.8 million m^3/day	Capacity of desalination plants
150	The number of countries where desalination is practiced
300 million	The number of people around the world who rely on desalinated water for some or all their daily needs

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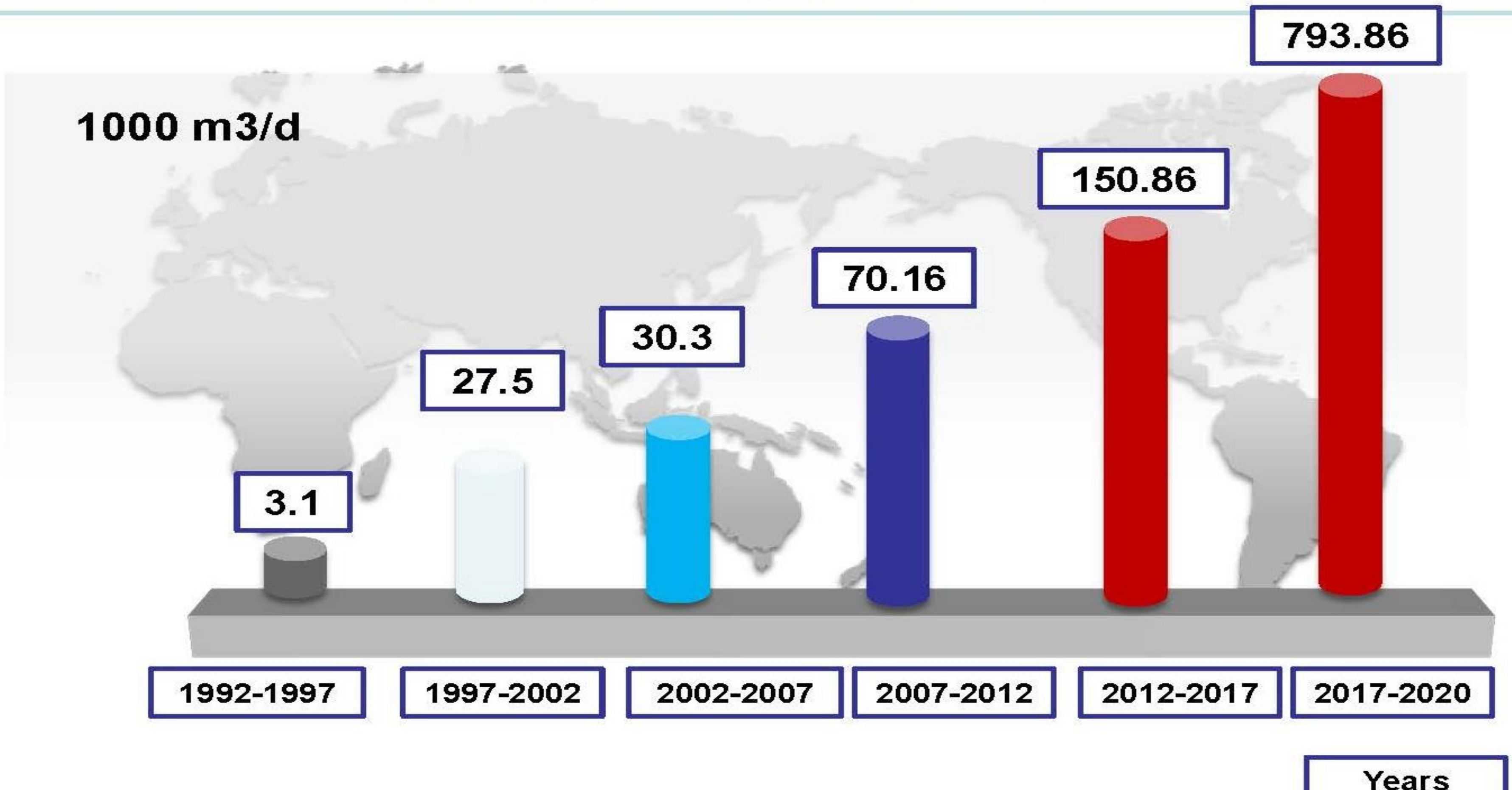
Desalination in Egypt

Governorate	Location	Owner	2018 Capacity (m^3/day)
North Sinai	Al Arish	Government	13,960
	Al Arish	Private	2800
	Al Hasana	Private	300
	Nakhel	Private	200
	El Kuntilla	Private	150
	Abu Aweigila	Private	100
South Sinai	Taba	Government	600
	Taba	Government	2000
	Nuweibh	Government	300
	Dahab	Government	500
	Sharm El Shaihk	Government	500
	Sharm El shaiekh	Government	4,000
	Nuweibh	Government	2,000
	Taba	Private	4,750
	Nuweibh	Private	540
	Sharm El shaiekh	Private	20,000
	Dahab	Private	4,800
Red Sea	Hurghada	Government	40,000
	Safaja	Government	6,000
Matruh	Alamine	Government	150,000
	El Galala Mountain	Government	150,000

Desalination in Egypt

Accumulative Design Capacity For Desalination Plants

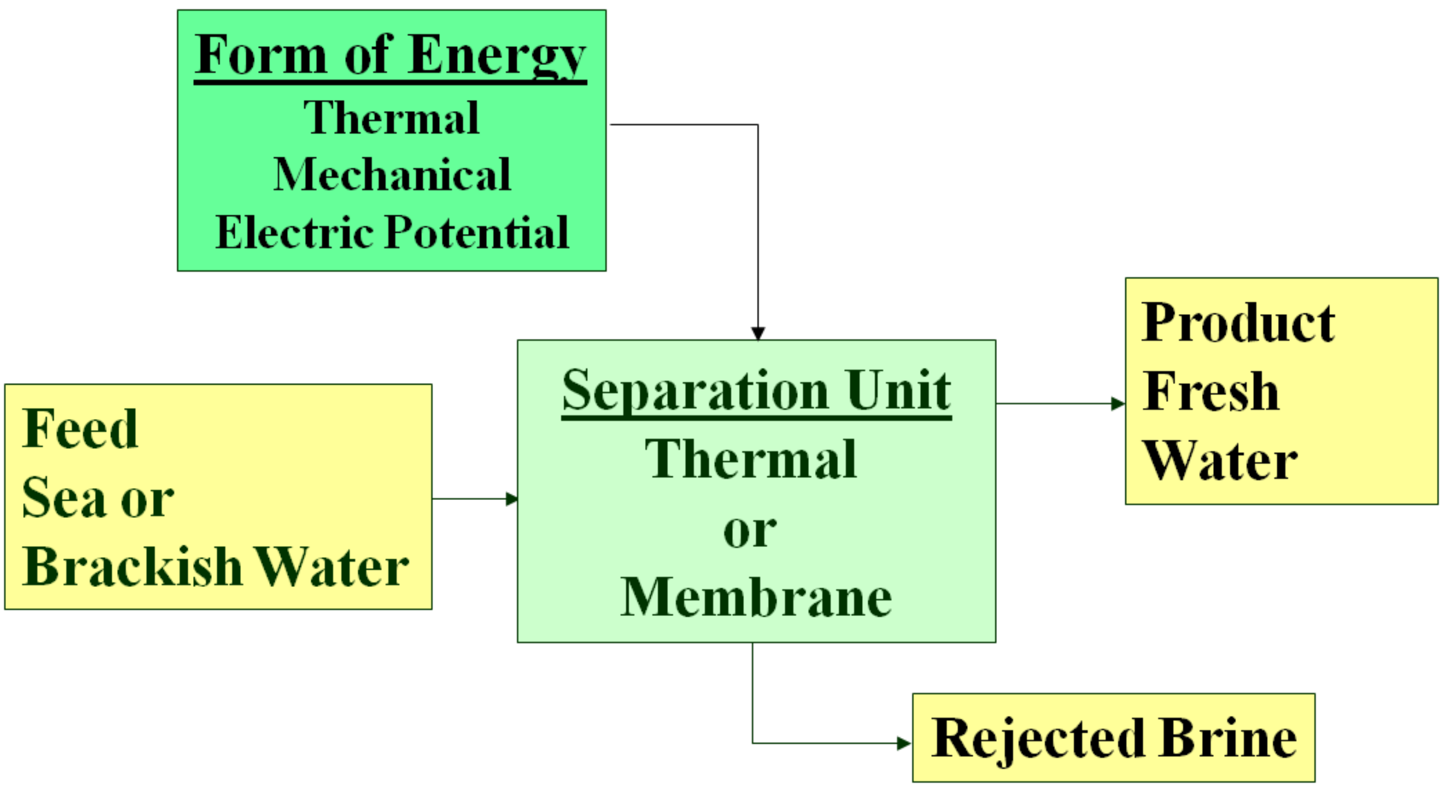


Current Status of Desalination in Egypt

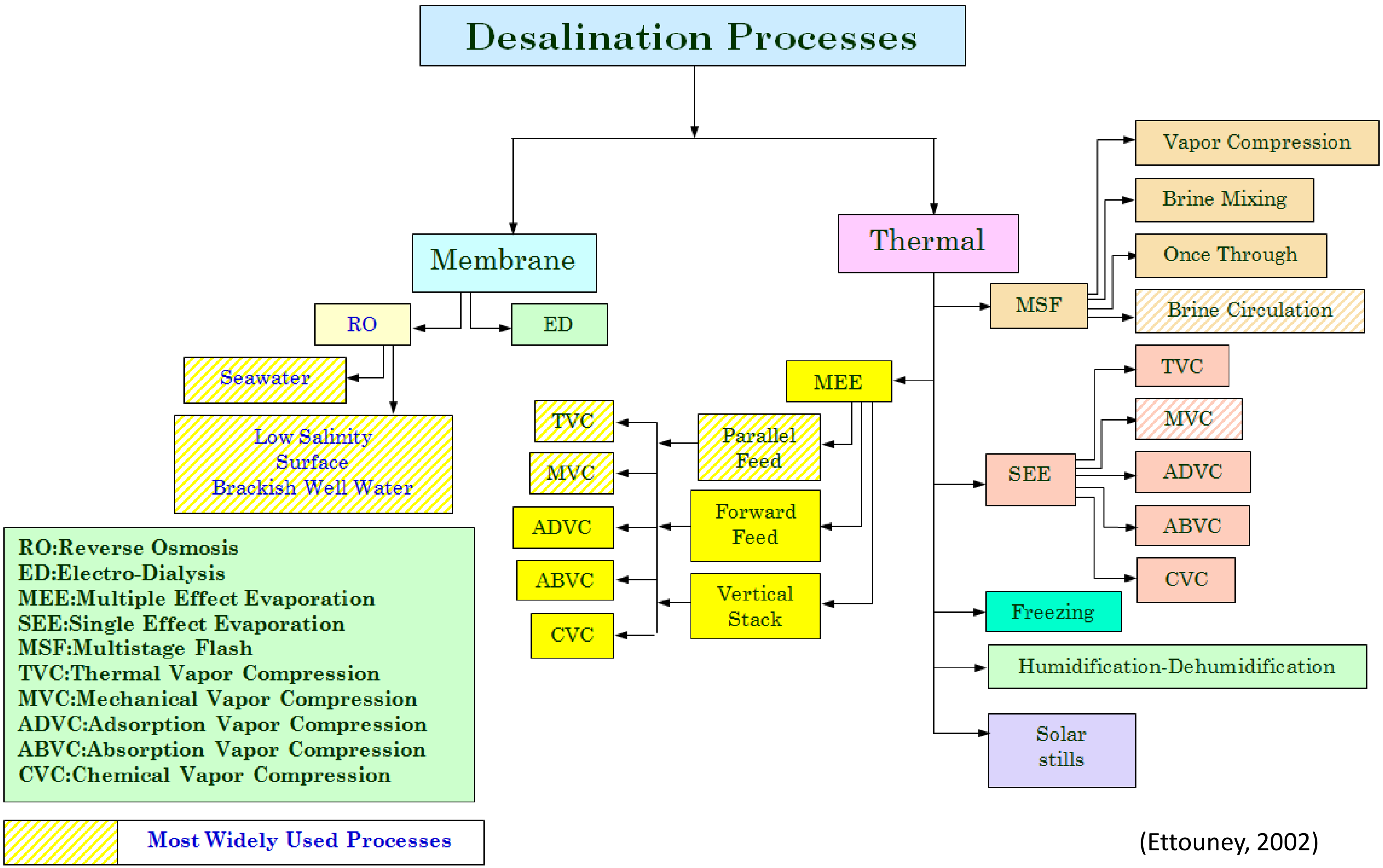
Plant site	Current (m^3/day)	By 2037 (m^3/day)
North Sinai	13,960	138,960
South Sinai	45,000	247,000
Red Sea	20,600	490,870
Matruh	64,500	232,500
El Galala mountain	--	150,000
Alamine	--	150,000
Total (m^3/day)	**144,060**	**1,559,330**

Fundamentals of Desalination Process

Fundamental Desalination Process



Desalination Technologies



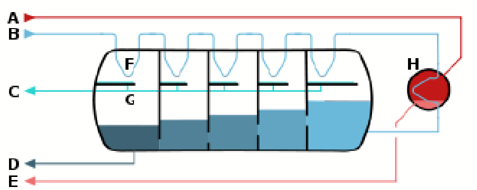
(Ettouney, 2002)

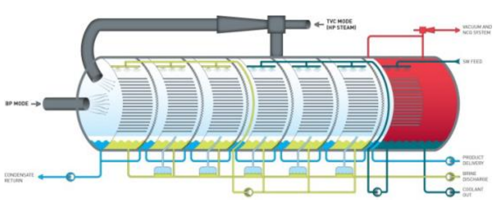
Desalination Technologies

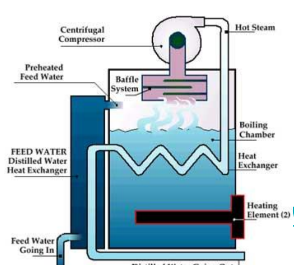
Desalination

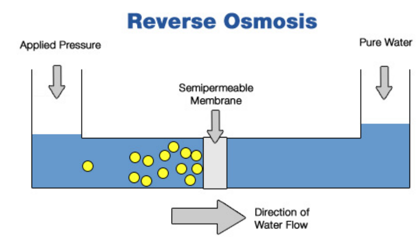
Thermal Evaporation
- Multistage flash (MSF)
- Multi-effect distillation (MED)
- Vapor compression distillation (VCD)

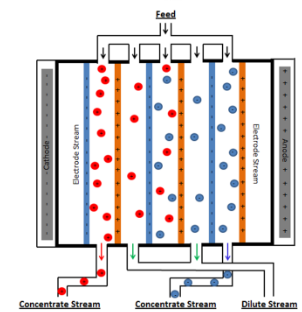
Membrane Separation
- Pressure Driven
- Electric Field Driven
- Concentration Gradient Driven





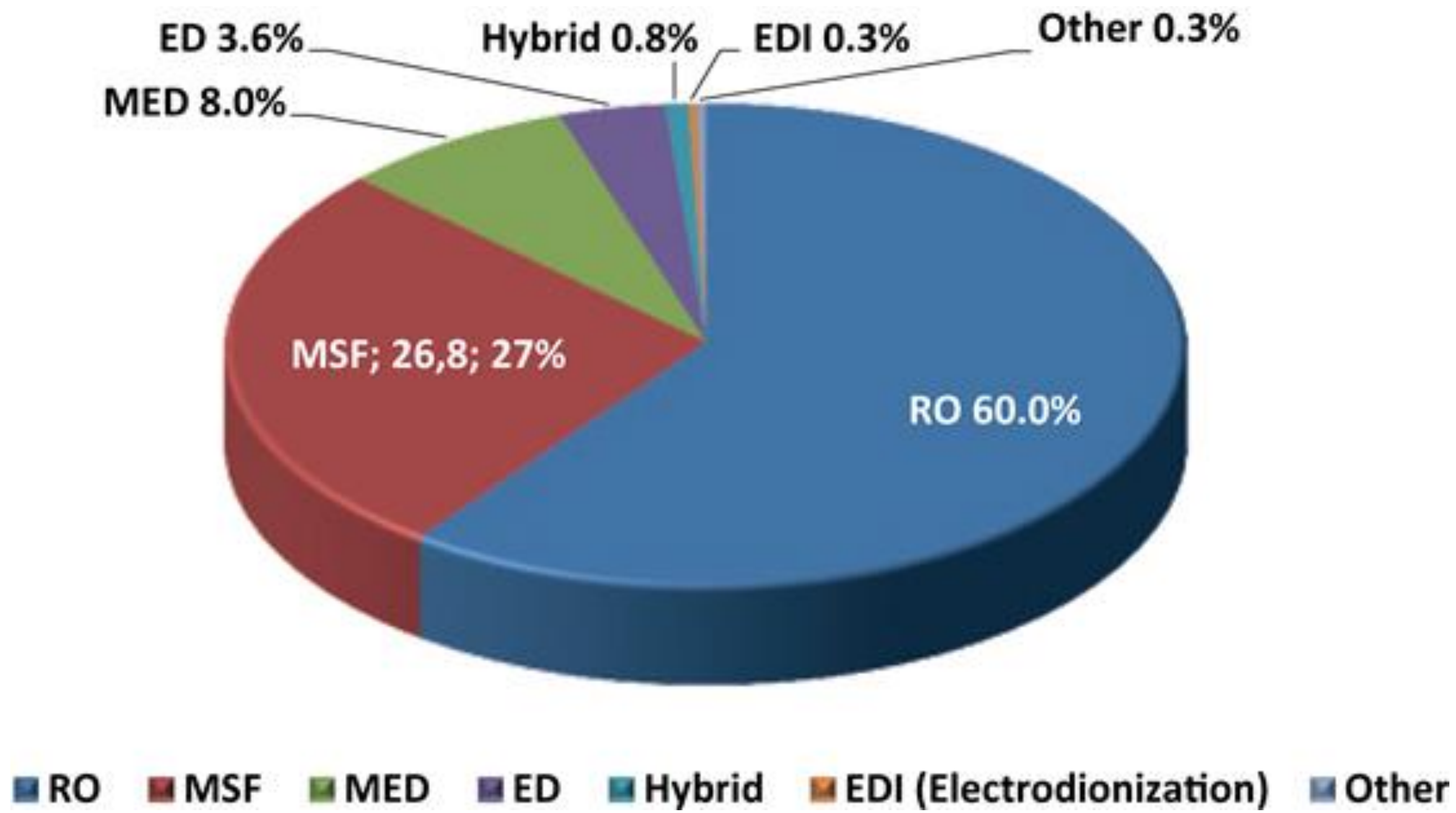






(Wetterau, 2011)

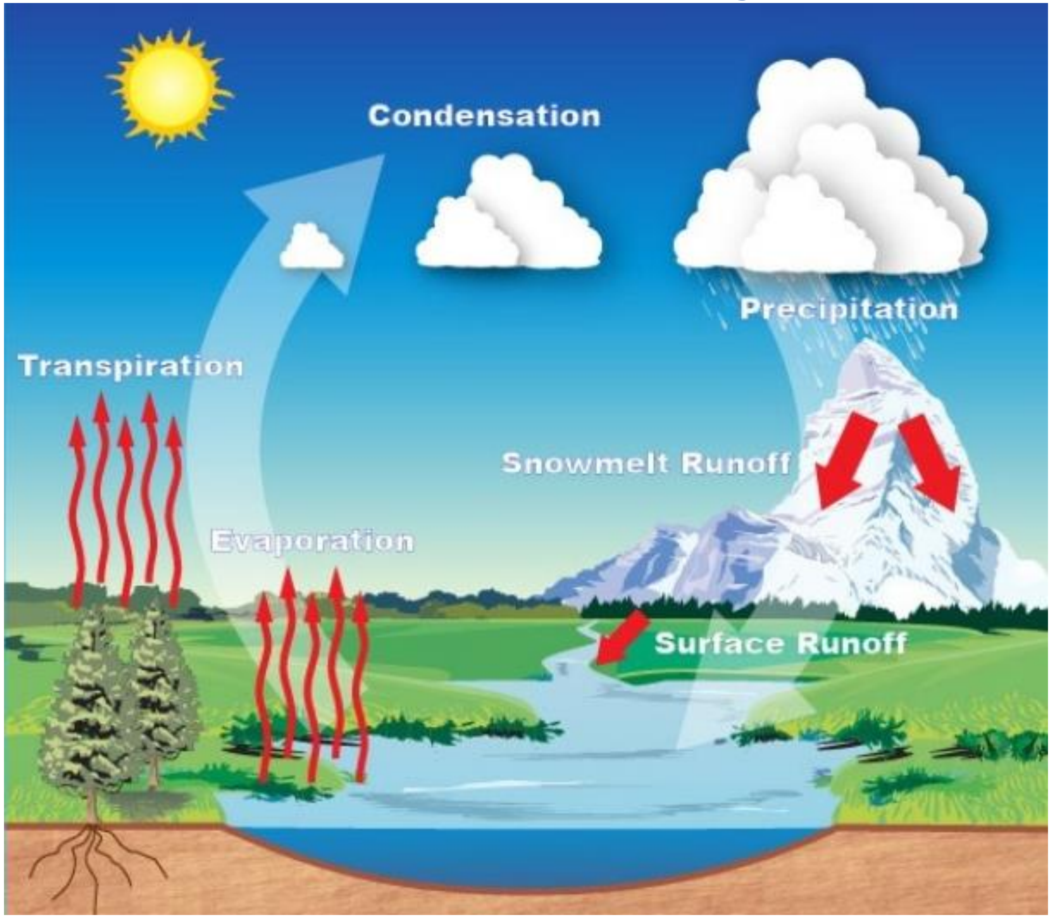
World Desalination Technology Capacity Distribution



Natural Desalination (Water Cycle)

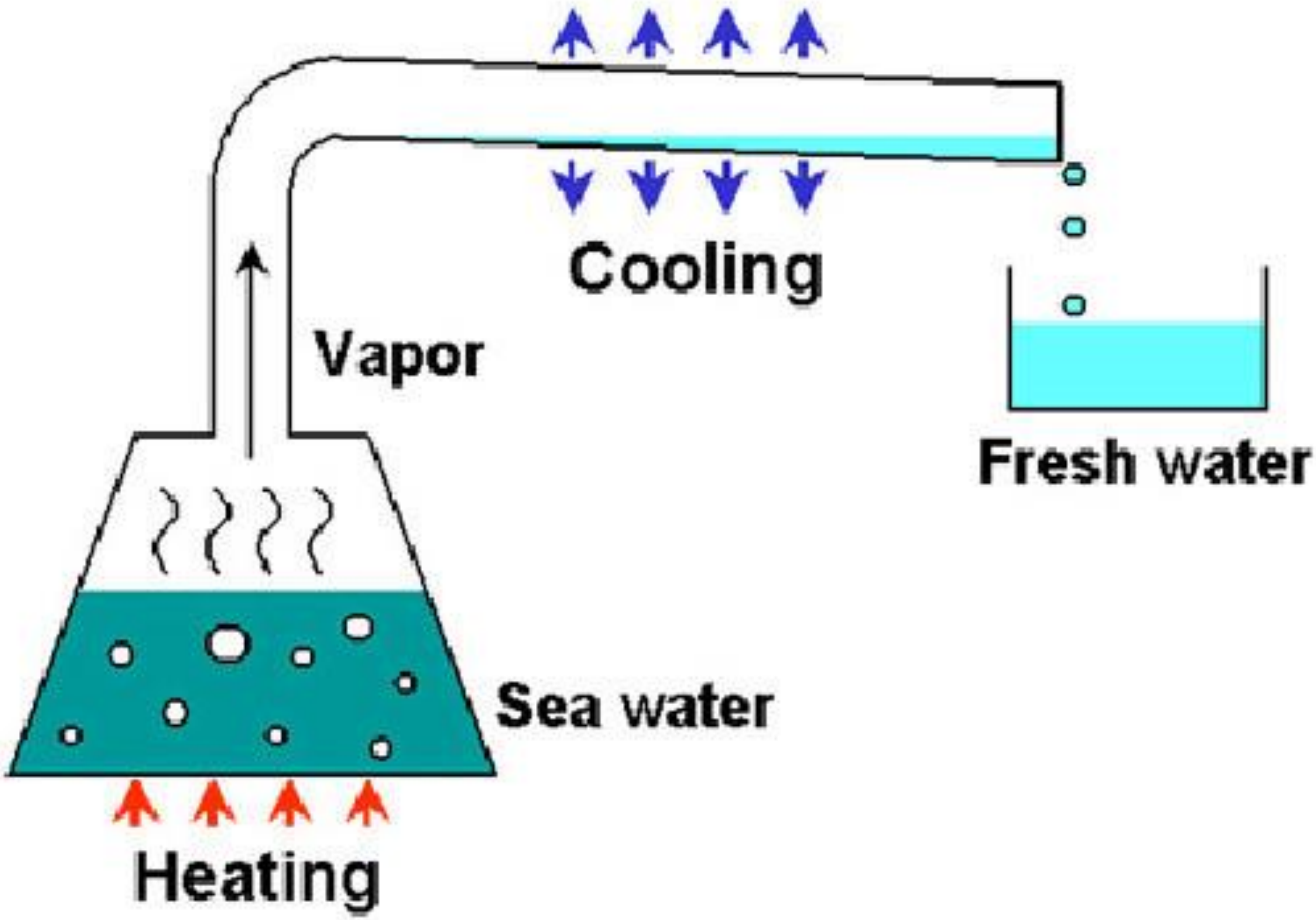
Major Stages:

- Evaporation
- Condensation
- Precipitation
- Collection

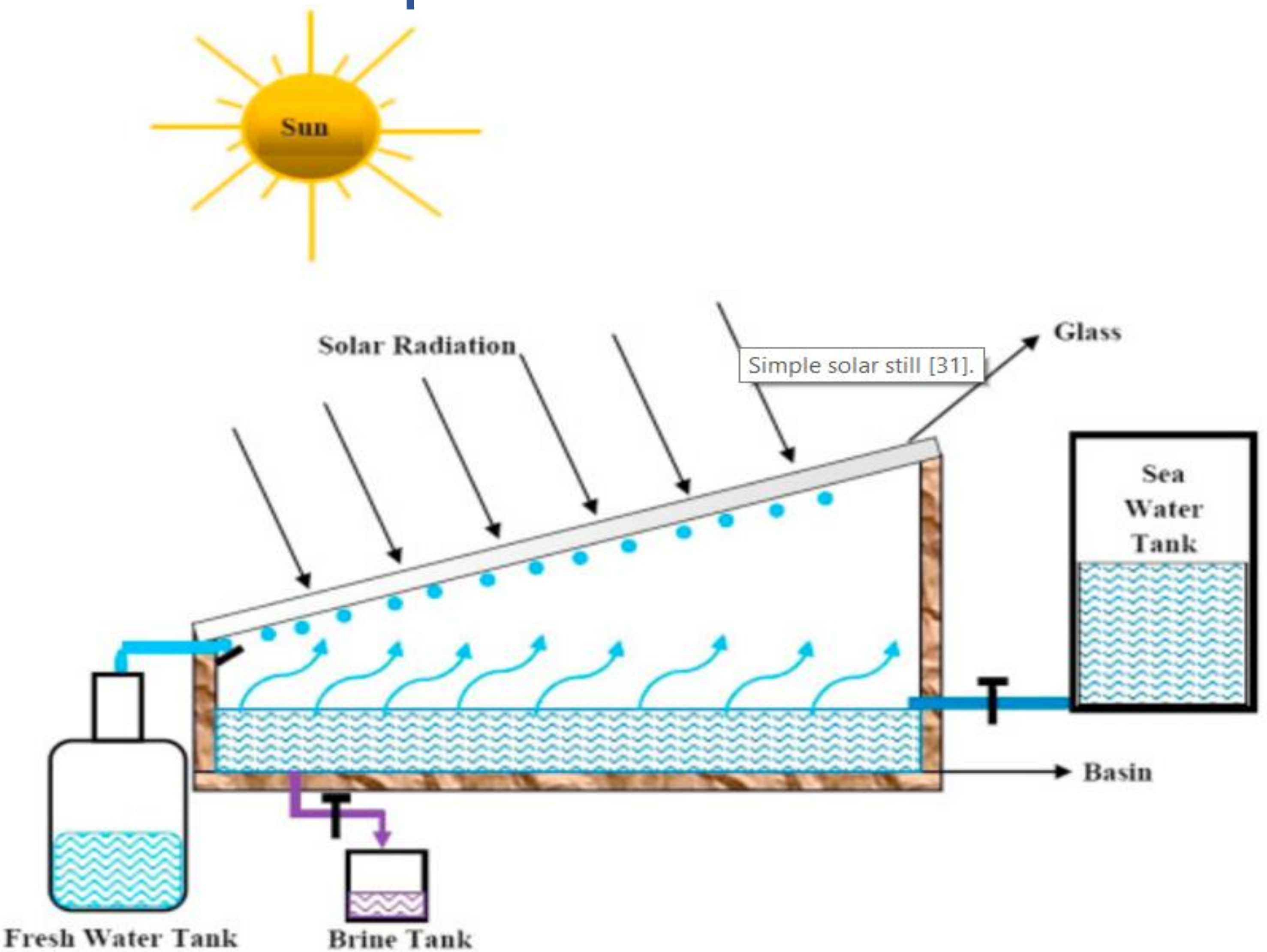


http://water.usgs.gov/edu/watercycle.html

Thermal Desalination Principle

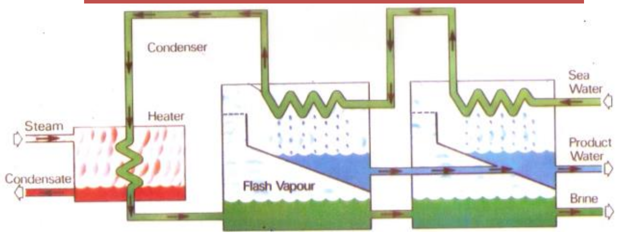


Simple Solar Still



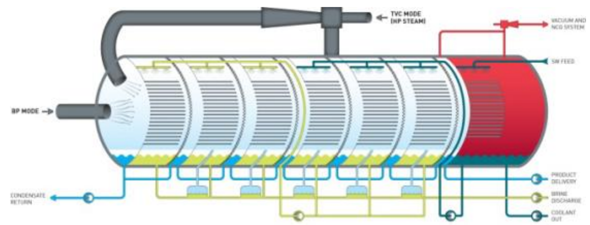
Thermal Evaporation

Multistage flash (MSF)



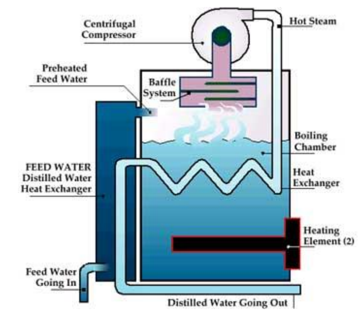
https://youtu.be/cdf-fKOMGR8

Multi-effect distillation (MED)



https://youtu.be/5nDcxhkq8Js

Vapor compression distillation (VCD)



https://youtu.be/GVDKimUkHj4

Energy consumption of different desalination technologies

Desalination Method	Total equivalent electrical energy (kWh/m^3)
Multi-stage Flash MSF	13.5–25.5
Multi-Effect Distillation MED	6.5–11
Mechanical Vapor Compression MVC	7–12
Reverse Osmosis RO	3–5.5

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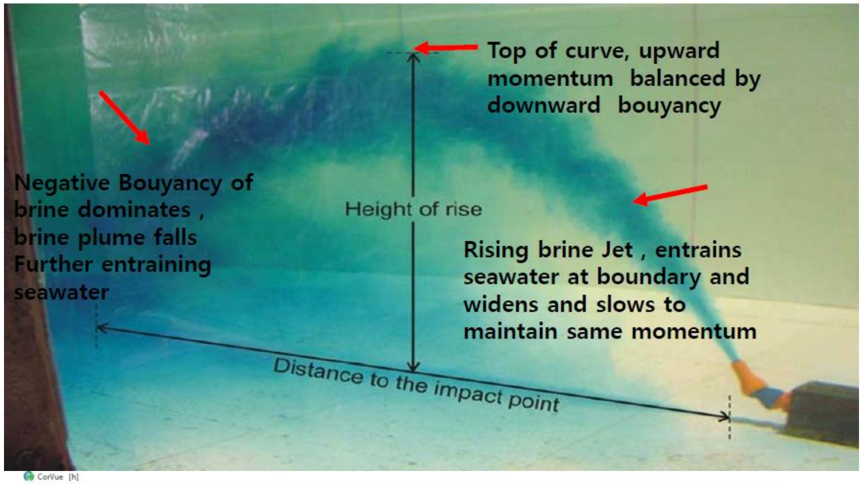
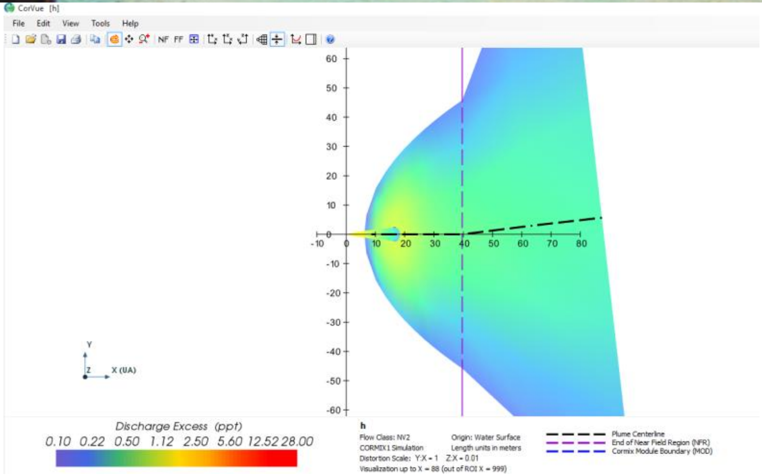
Brine Disposal

Old Brine Outfalls

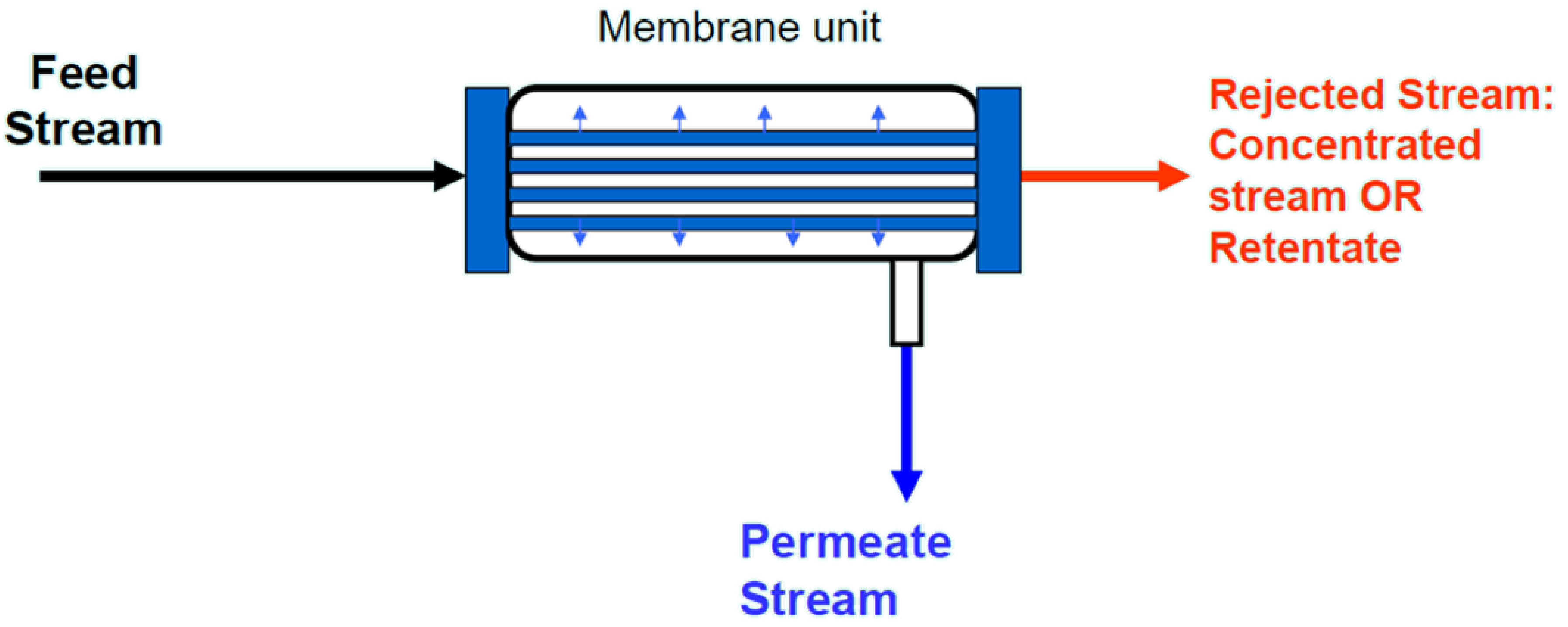
Brine Disposal



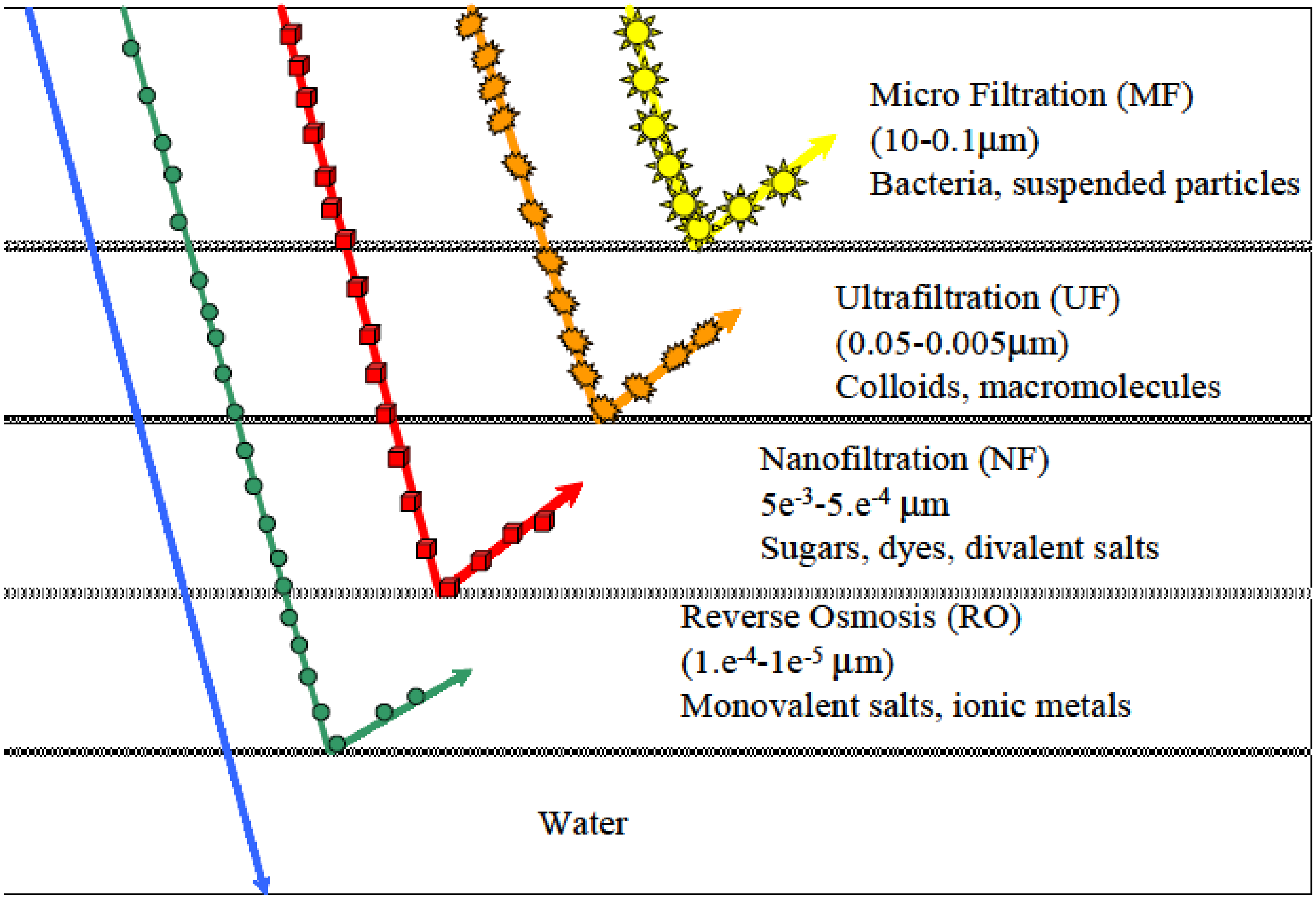


New technology of Brine Outfalls ensuring rapid brine dilution

Principle of Membrane Process



Membrane Process as a Function of Particle Size



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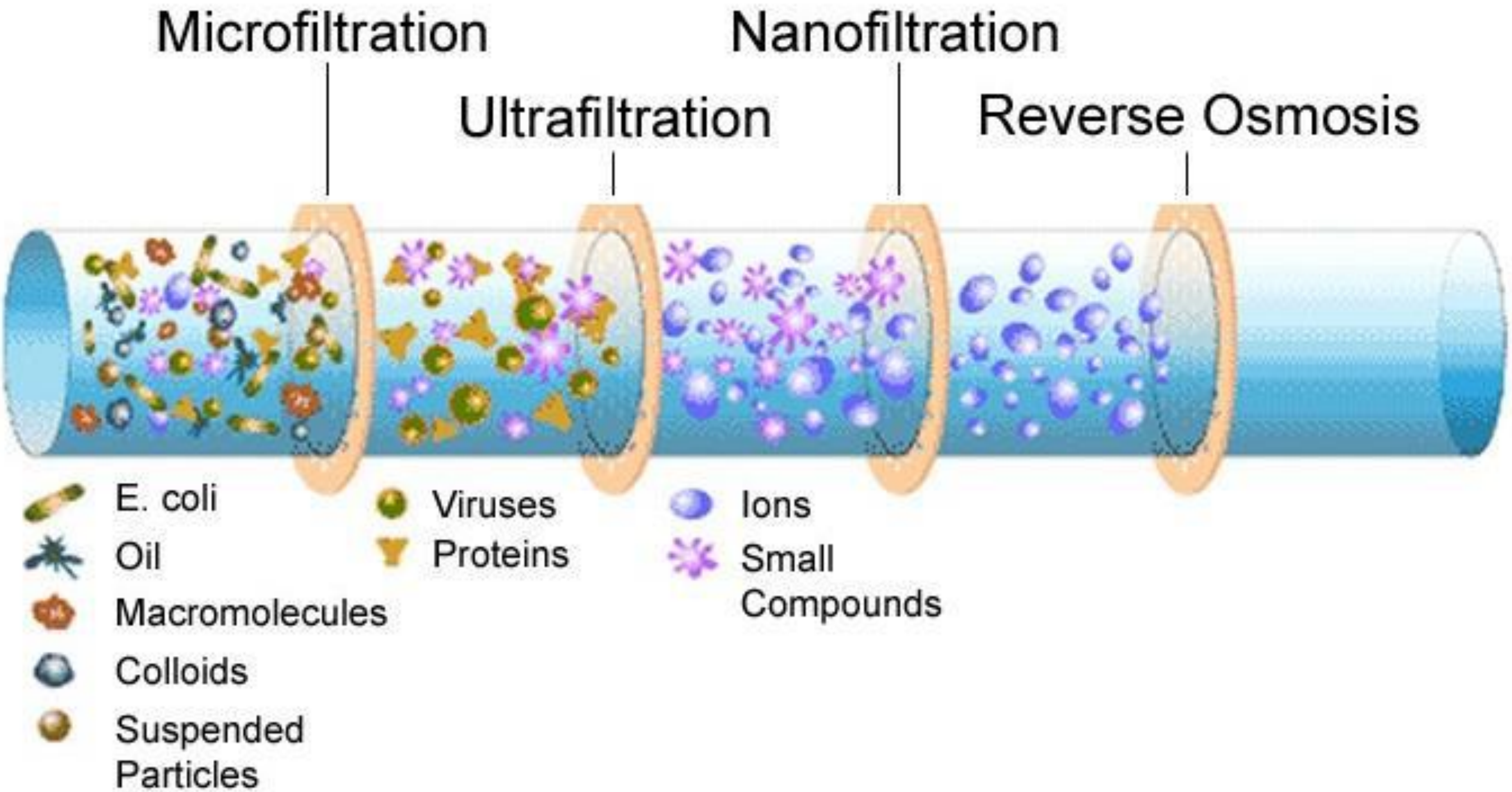

General Info about RO

- Developed in the 1950's
- Very popular and used nowadays
- Pore size < 1 nm
- Driving force: pressure difference
- Operating pressure between 10-25 bar (brackish) and 40-80 bar (seawater)

  (1 Bar = 0.98 atm = 100 kPa = 100 kN/m^2 = 14.5 psi = 750 Torr)
- Water molecules freely pass (0.2 nm)
- Average flux: 5-40 L /m^2/h.

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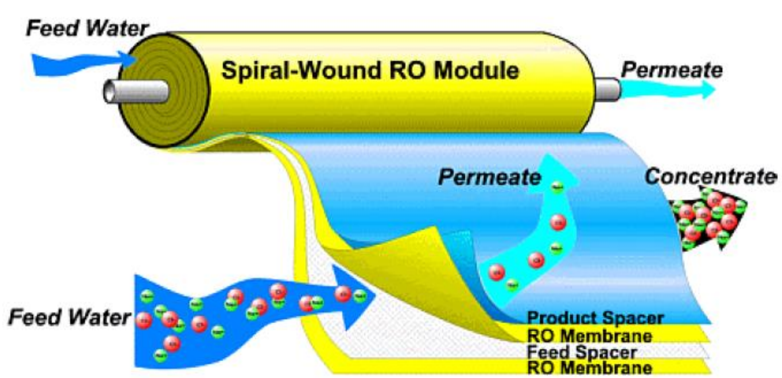
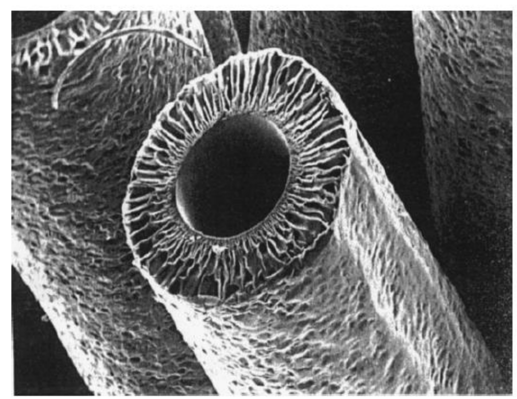
RO Membranes

Membrane Modules

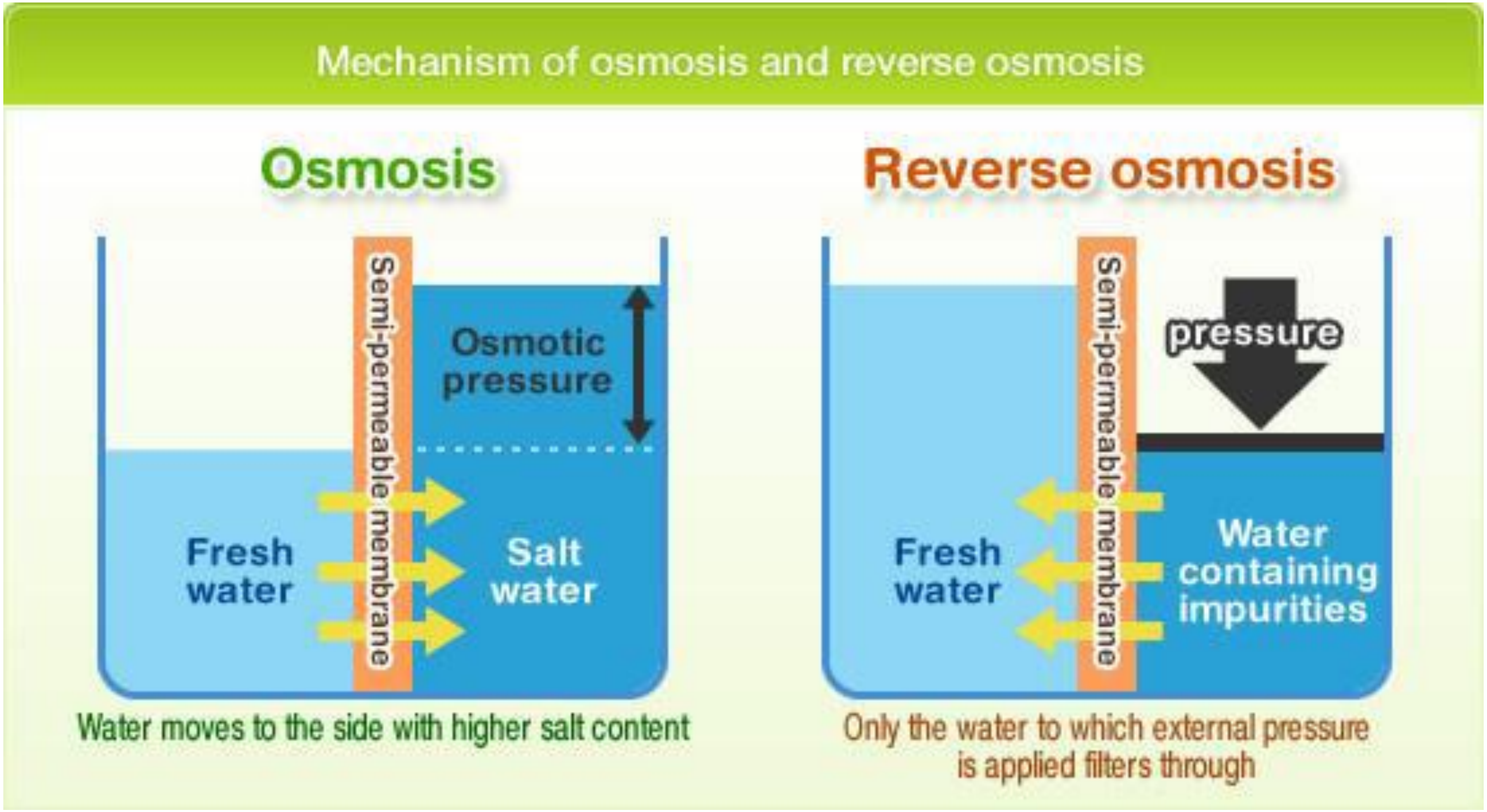
- Spiral Wound
- Hollow Fiber



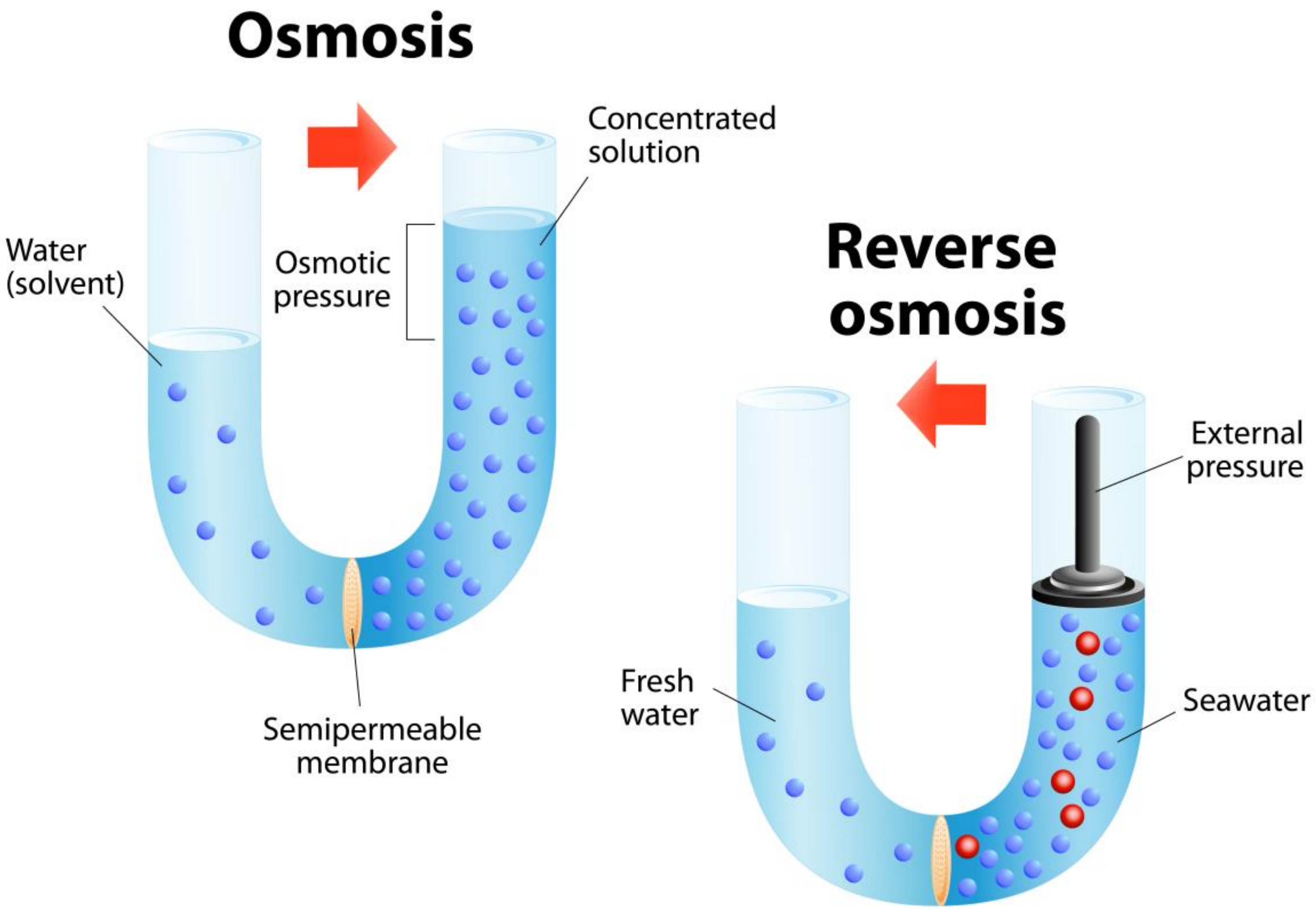


https://www.youtube.com/watch?v=aVdWqbpbv_Y

Mechanism of Reverse Osmosis



Mechanism of Reverse Osmosis



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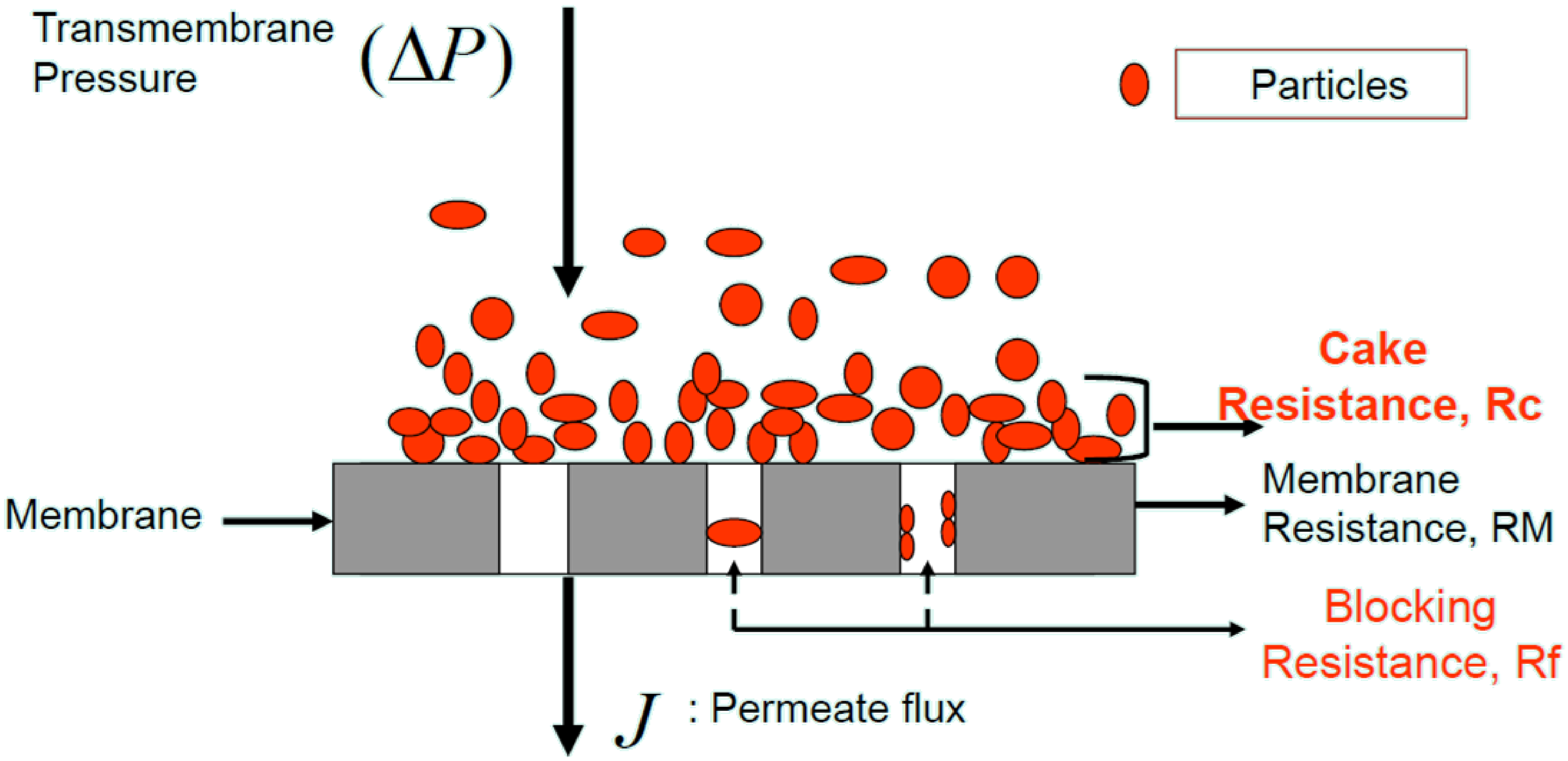
Reverse Osmosis facility

RO video

- https://www.youtube.com/watch?v=_H8EDLFNDtI (6 min)

Fouling



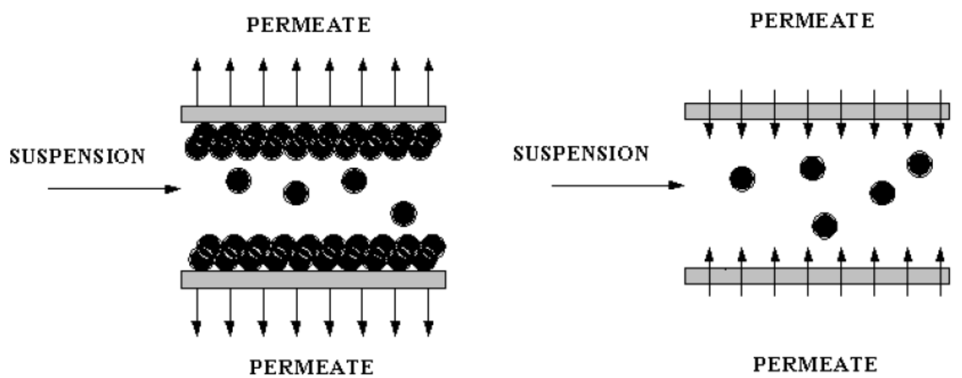
Transmembrane Pressure
(ΔP)
Particles
Cake Resistance, Rc
Membrane
Membrane Resistance, RM
Blocking Resistance, Rf
J : Permeate flux

Degrees of Fouling

- Reversible fouling
  - removed by backwash and/or chemical cleaning of membrane
  - flux restored
  - surface fouling
- Irreversible fouling
  - Permanent
  - pore fouling

How to Control Fouling

- Pre-treatment
- Increased cross-flow velocity and turbulence on concentrate side of membrane
- Chemical cleaning
- Back pressure
  - Alternate pressuring and de-pressuring and by changing the flow direction at a given frequency
  - After a given period of time, the feed pressure is released and the direction of the permeate reversed



Energy Consumption and Pressure

	Bar	Kwh/m^3	Heat
UF/MF	0.5 - 2	0.1 - 0.2	-
NF	5 - 10	0.3 - 0.5	-
RO Brackish	10 – 20	0.5 - 1	-
RO Seawater	50 – 90	2 - 4	-

Advantage and Disadvantages of different Desalination Technologies

Desalination Technology	Advantage	Disadvantage
MSF	• Simple • Produces high quality water • Cost drops at large capacity • Can be semi-operational so limiting down time	• High energy consumption • Air pollution • Slow response to water demand fluctuations • Scaling in tubes
MED	• Wide selection of feed water • Produces high quality water • Less energy consumption than MSF • Requires lower temperature operation; thus reducing scaling and energy costs	• Higher energy requirements than RO • Slow response to water demand fluctuations • Lower capacity than MSF
VCD	• Low energy consumption	• Expensive form of energy (electricity) is required • High capital cost (compressors)
RO	• Less energy consumption compared to MSF and MED • Low thermal impact of discharges • Less problem with corrosion • High recovery rates (about 45% of seawater) • Removal of unwanted contaminants such as pesticides and bacteria • Small plant footprint • Flexible to meet fluctuations in water demand	• Sensitive to feed water quality • Membrane fouling requiring for chemical cleaning thus loss of productivity • Complex to operate • Lower product water purity

Desalination Challenges

- High initial cost
- Know-how of membrane Technology
- High energy consumption
- Membrane fouling
- Brine Disposal

Typical RO Initial Components Cost

Item	Cost sharing
High pressure pump	36.8%
Membrane (element & vessel)	15.8
High pressure piping	2.6%
Controllers	4%
Design, construction & testing	5.3%
Containers	10.5%
Pre-treatment (pumps, filters, network piping and controllers)	22.4%

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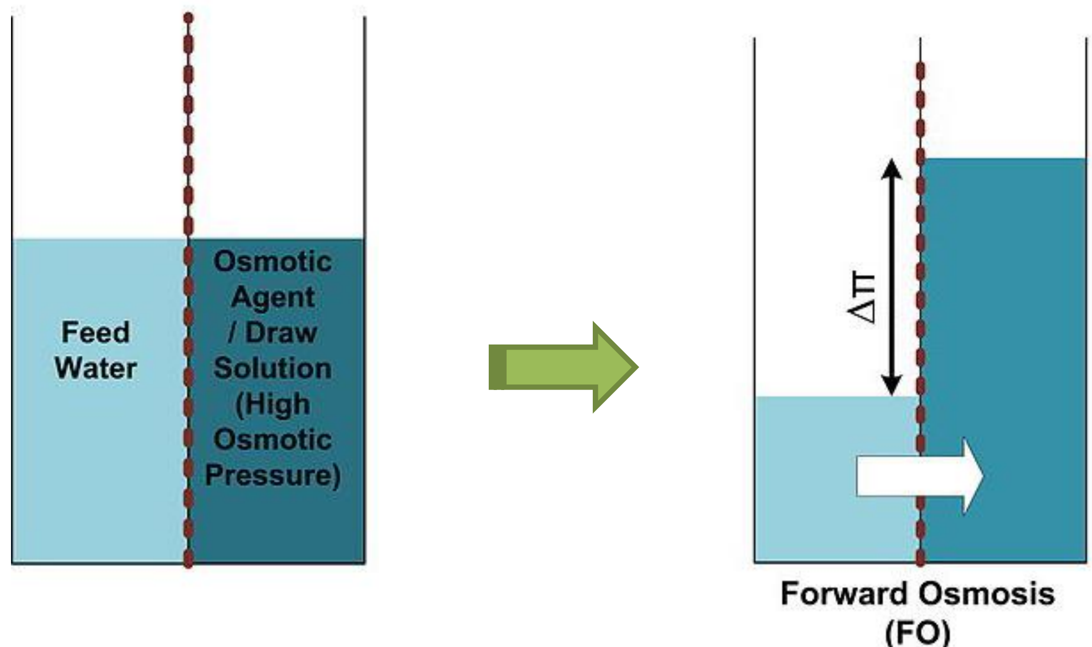
Natural Forward Osmosis

Forward osmosis is the predominant method of water transport across cells of all living organisms. **Root cells of mangrove trees** are a great example of a naturally occurring FO process. The cells utilize a **highly concentrated internal solution of sugars** to extract fresh water from the surrounding seawater.

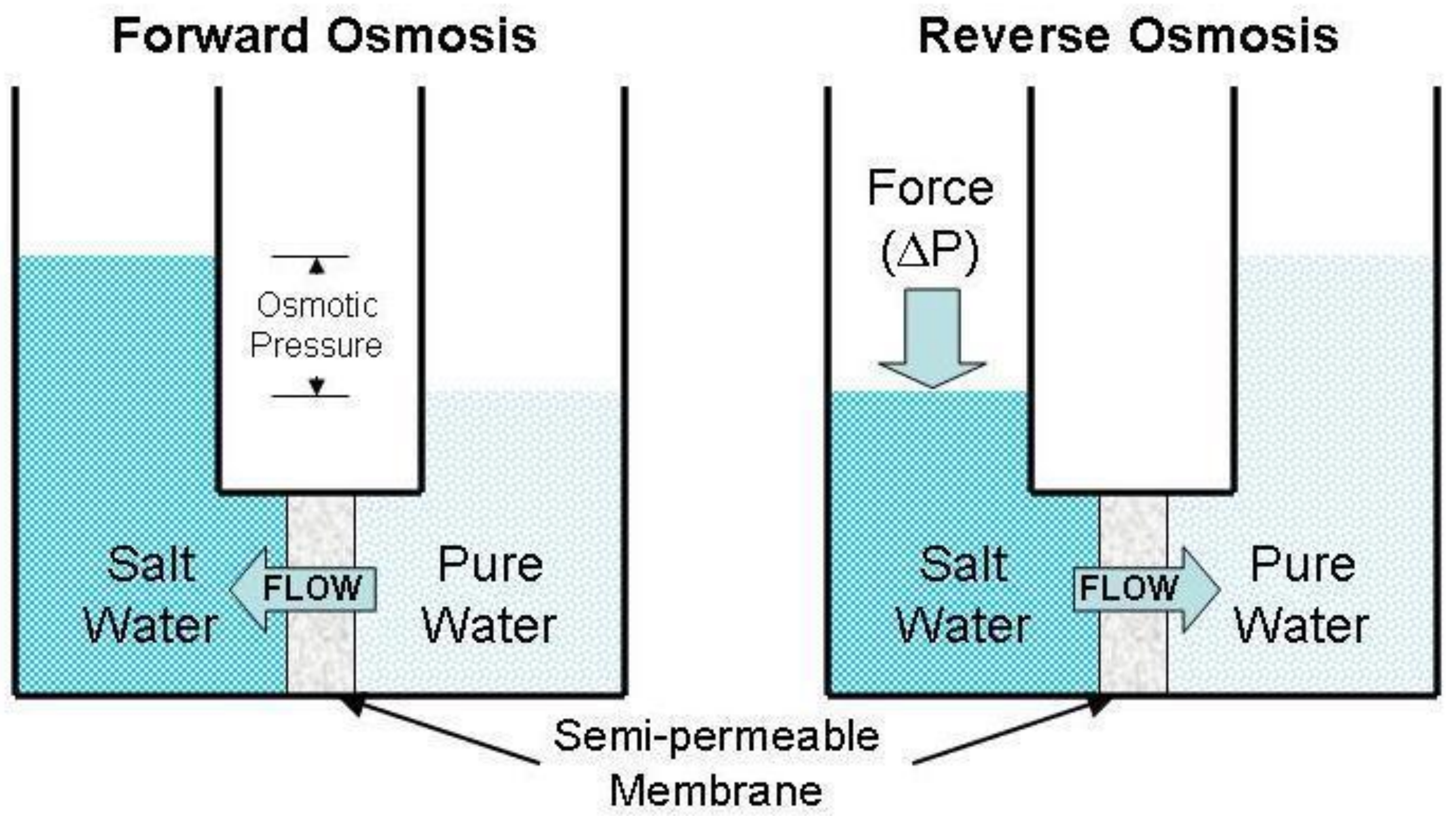
What is Forward Osmosis (FO)?

Osmosis is defined as “the natural diffusion of solvents or water through a semipermeable membrane while preventing the passage of solutes”

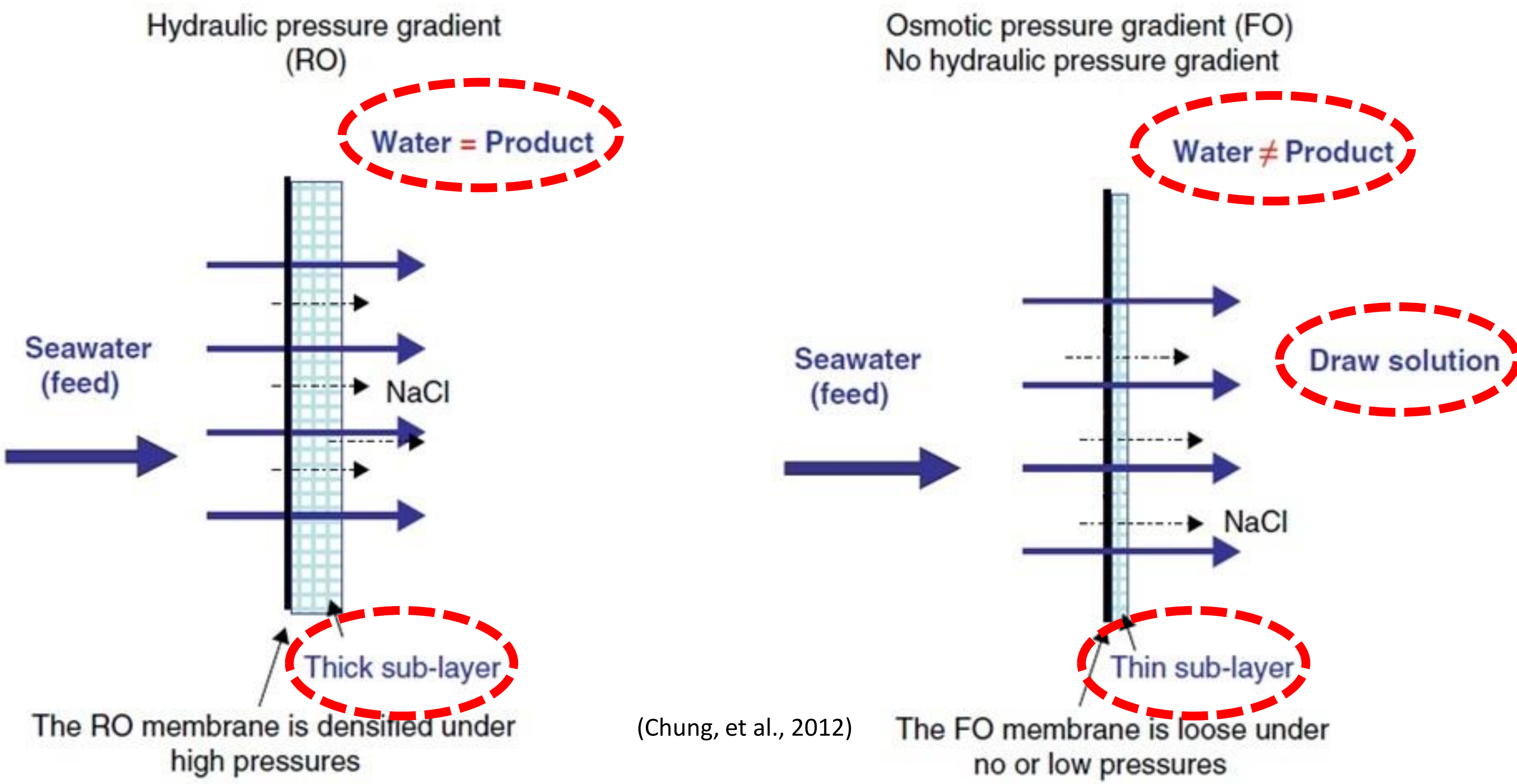


(Coday et al., 2014)

FO vs. RO


Forward Osmosis
Osmotic Pressure
Salt Water
FLOW
Pure Water
Reverse Osmosis
Force (ΔP)
Salt Water
FLOW
Pure Water
Semi-permeable Membrane

FO vs. RO



(Chung, et al., 2012)

FO vs. RO

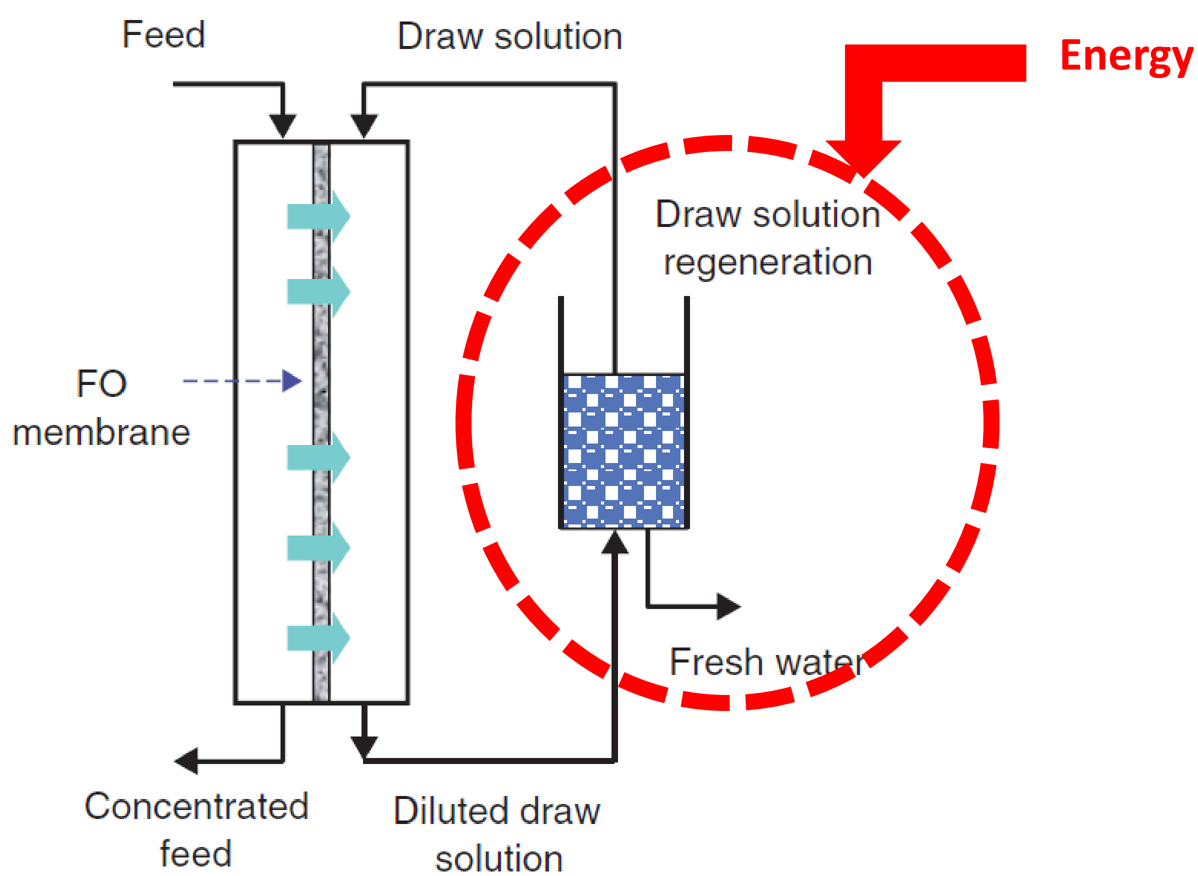
RO

- Energy intensive
- Significant irreversible membrane fouling
- High operation pressure

FO

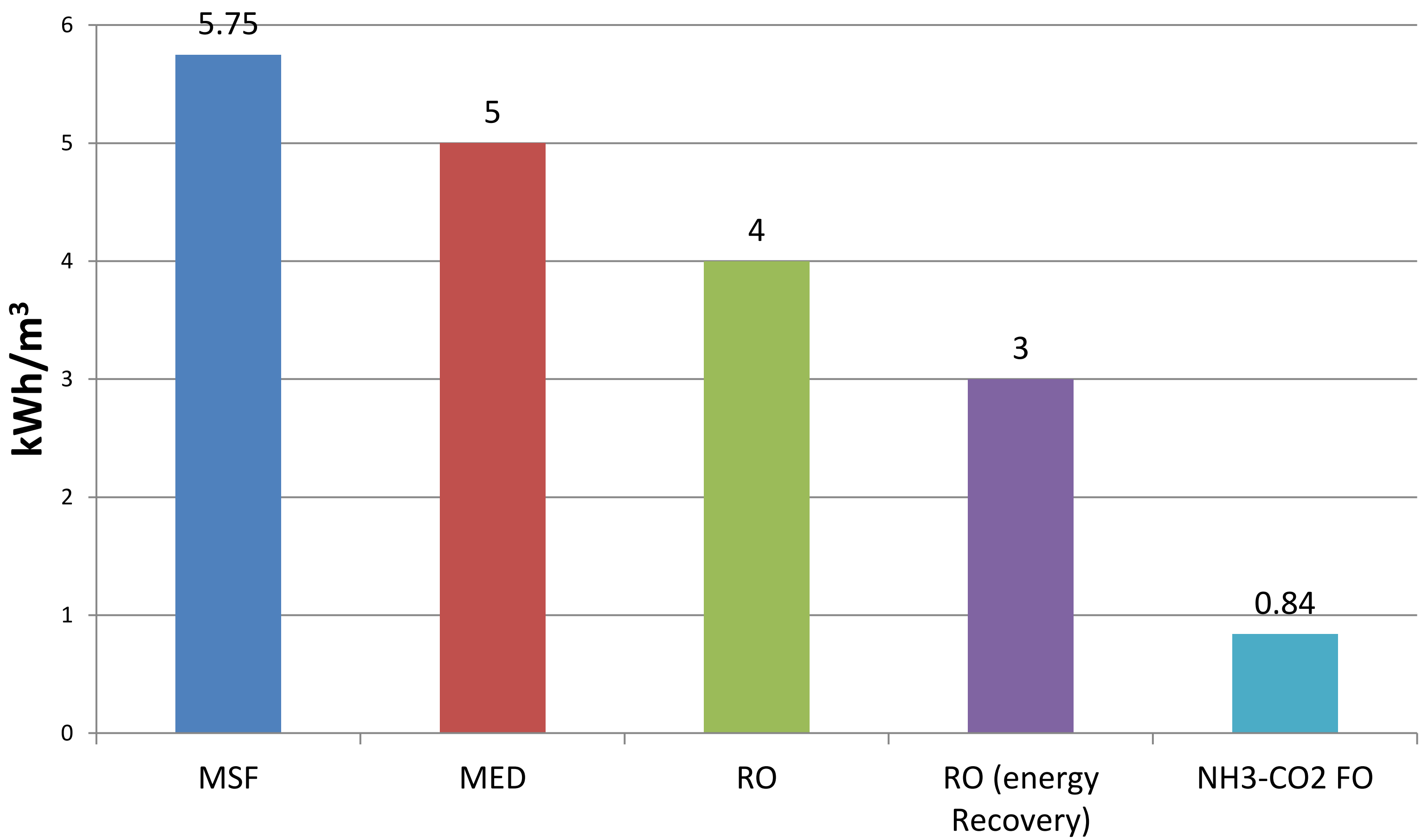
- Low energy requirement
- Low reversible fouling
- Low operation pressure
- Simple equipment
- Easy membrane support

Forward Osmosis



(McCutcheon et al., 2005)

Desalination Energy Requirements

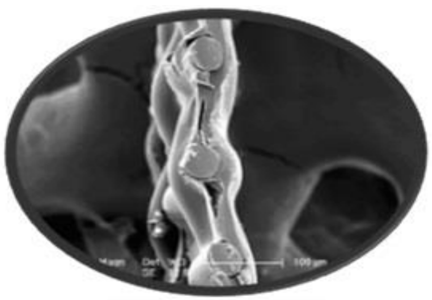


(Phuntsho, 2012)

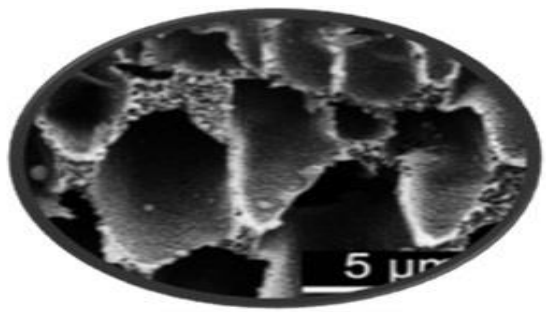
Forward Osmosis Membranes

FO Membrane

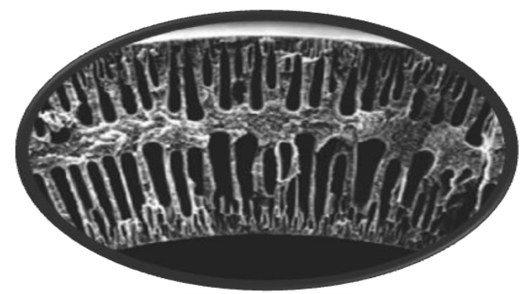
- Phase Inversion-Formed Cellulosic
- Thin Film Composite (TFC)
- Chemically Modified



(McCutcheon et al., 2005)



(Yip et al., 2010)



(Setiawan et al., 2011)

FO Application in Water Industry

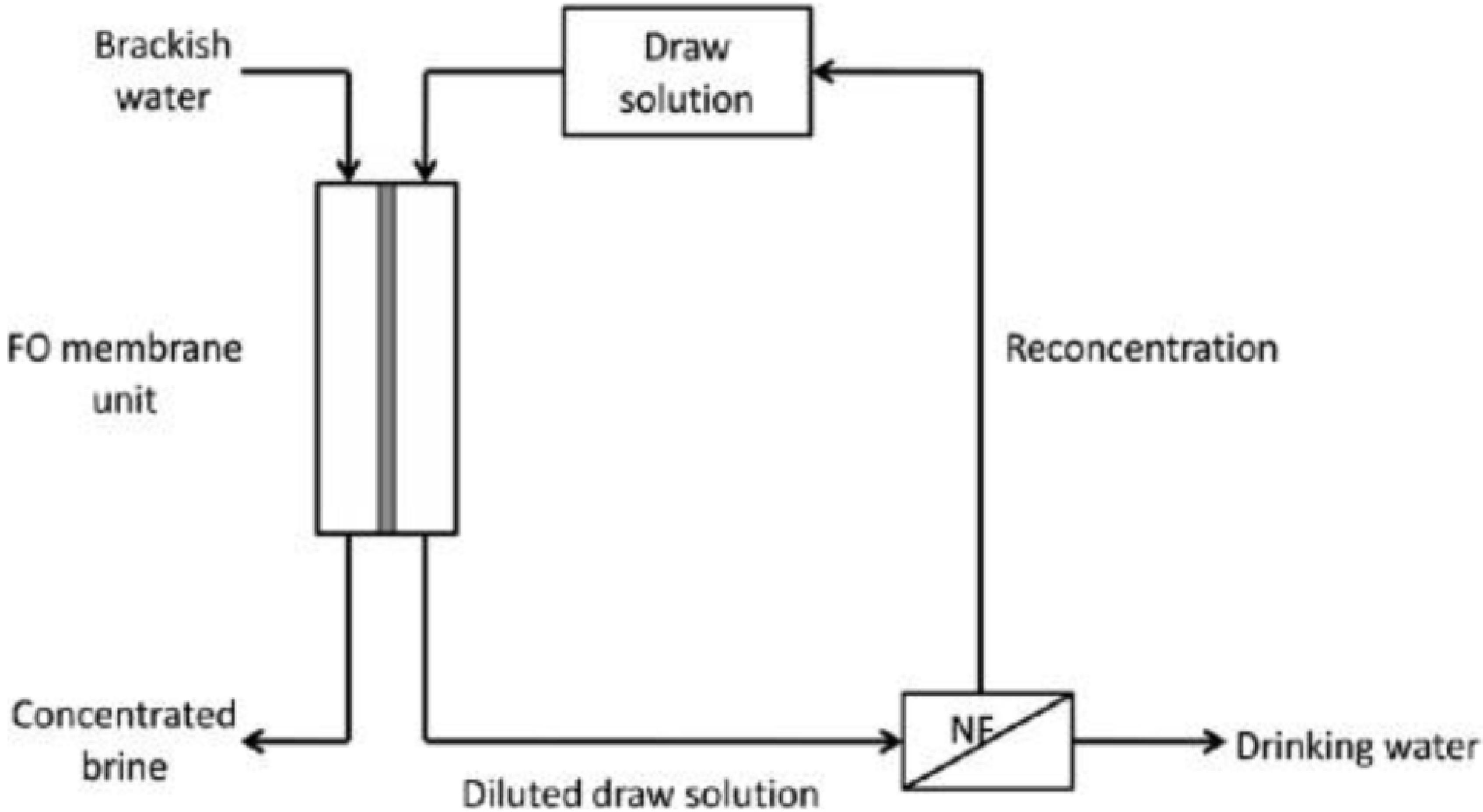
- **Desalination**
  - **Potable Water**
  - **Irrigation Water**
- **Water Reuse**
  - **WW Applications**
    - Osmotic Membrane Bioreactor (OSMBR)
    - Leachate Treatment
  - **Industrial Applications**
    - Oil and Gas
    - Pharmaceu-tical
    - Food and Beverage (F&B)



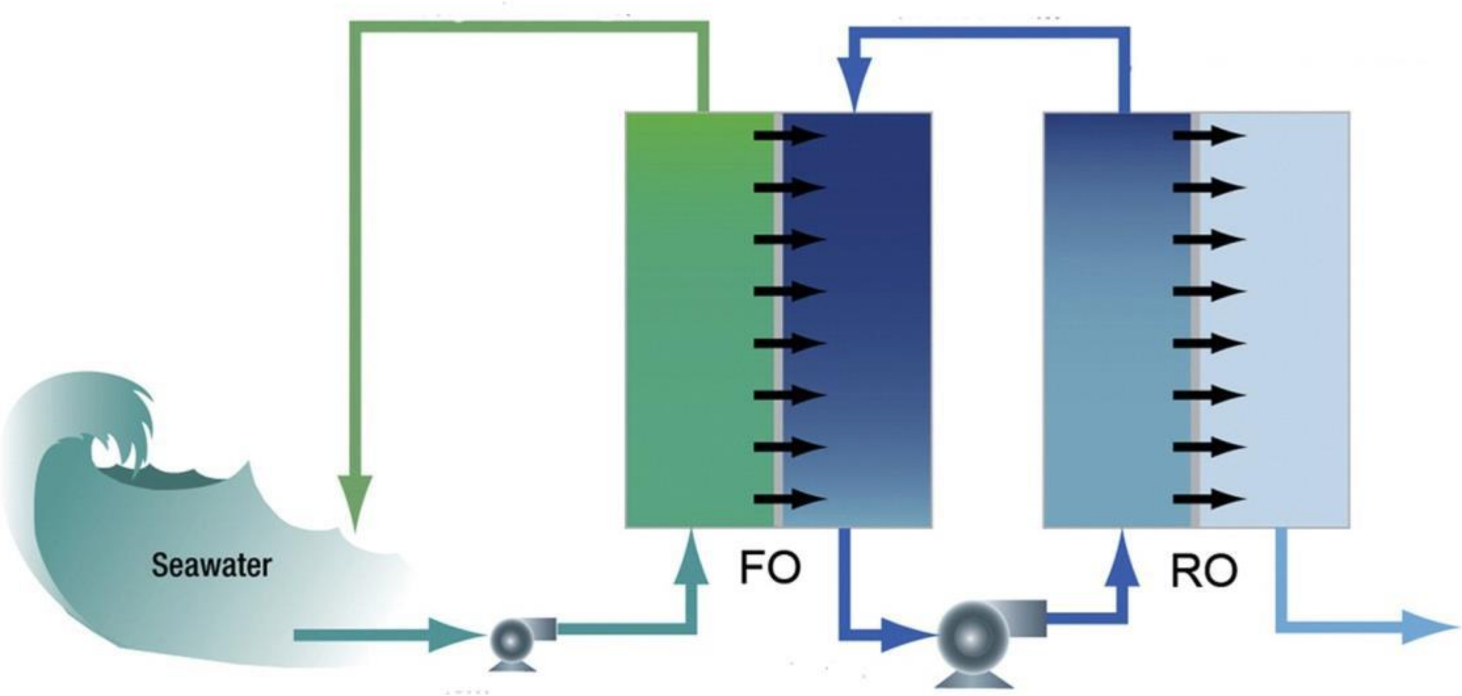




FO for Potable Water



FO for Potable Water

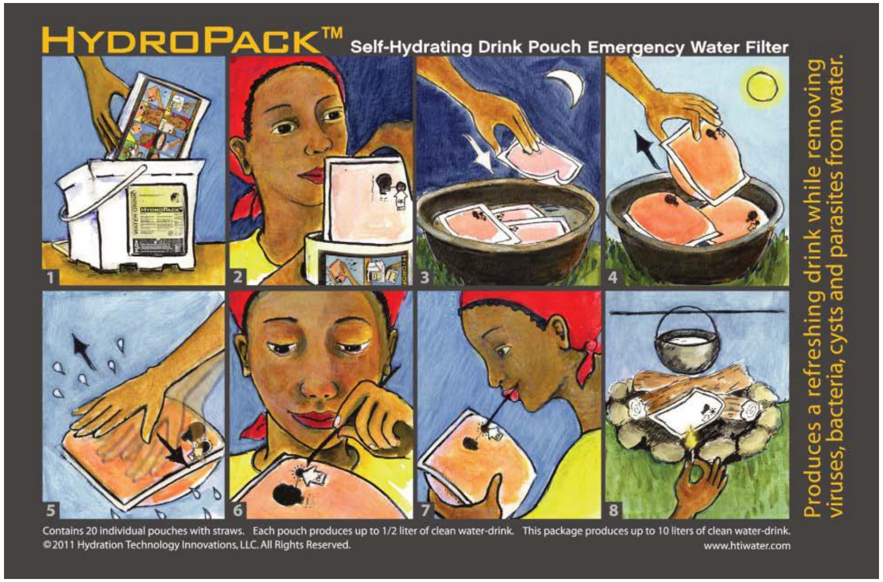


https://www.youtube.com/watch?v=ZGhyeIwTPyg

FO for Potable Water - Hydration Bags

HTI company has commercialized **hydration bags** for military, recreational and emergency relief situations to provide drinking water that contains a nutrient rich solution when potable water becomes inaccessible.

FO for Potable Water - HydroPack™



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FO for Potable Water - Emergency Hydration

Mission Atlantis - STS 135

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DESALINATION FOR IRRIGATION

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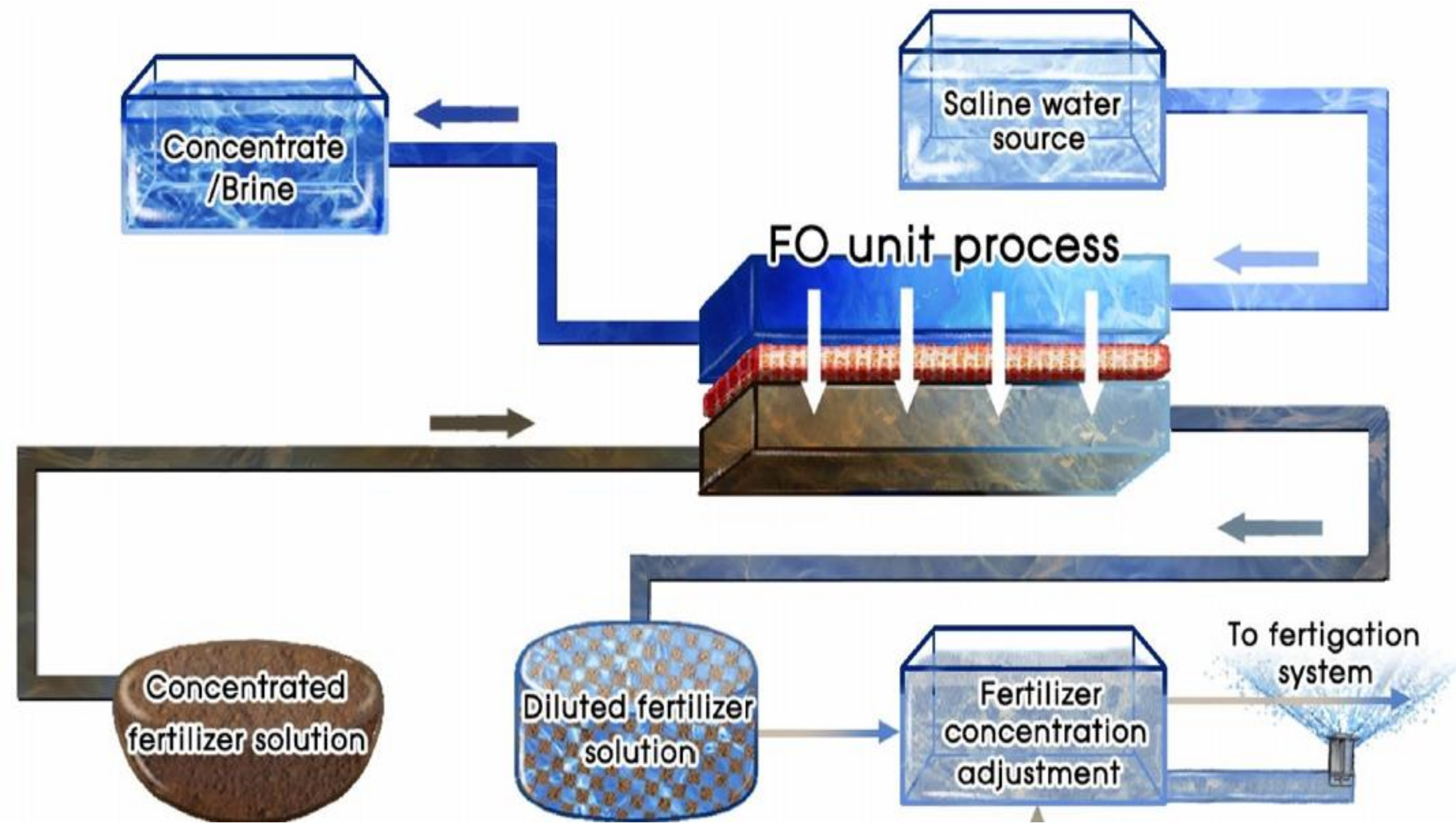
FO for Irrigation - Fertilizer Drawn Forward Osmosis (FDFO)

- Concentrated fertilizer solution is used as the draw solute
- Diluted fertilizer solution after desalination can be directly applied for fertigation
- No need for separation and recovery of the draw solution

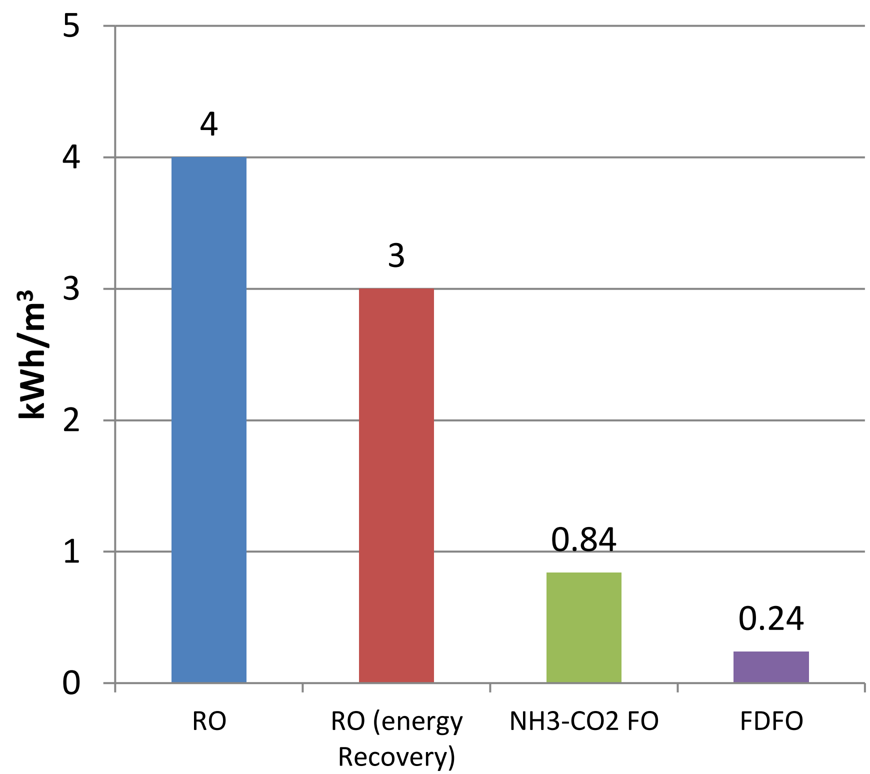
FO for Irrigation - Typical FDFO Setup



(Phuntsho et al., 2011)

FO for Irrigation - Advantages

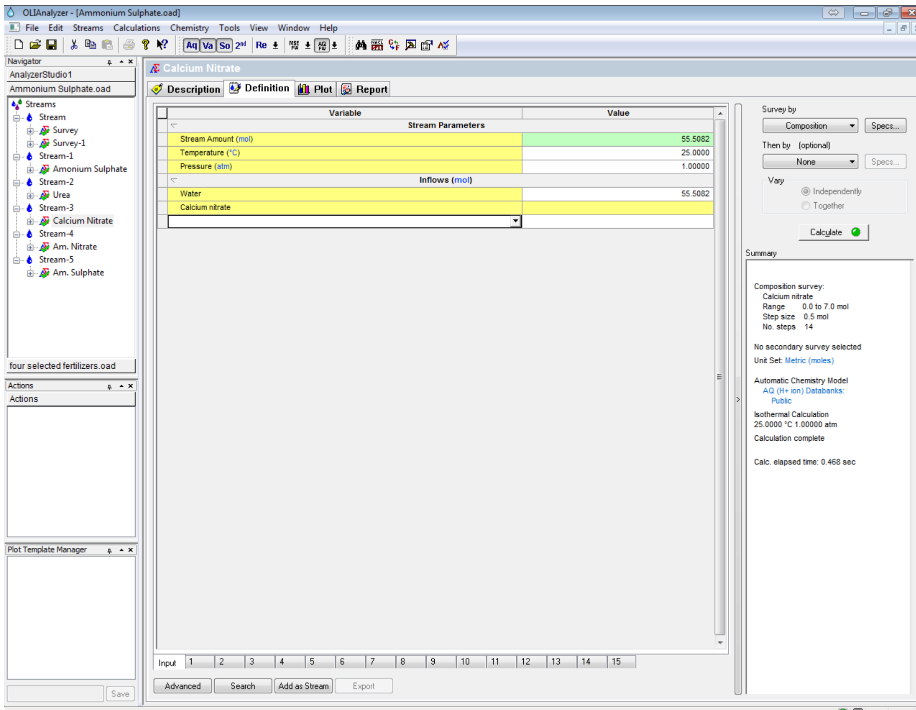
- Low energy desalinating process
- Fertilized irrigation
  - minimum loss due to leaching,
  - optimizing the nutrient balance,
  - control of nutrient concentration in the soil solution,
  - savings in labor and energy

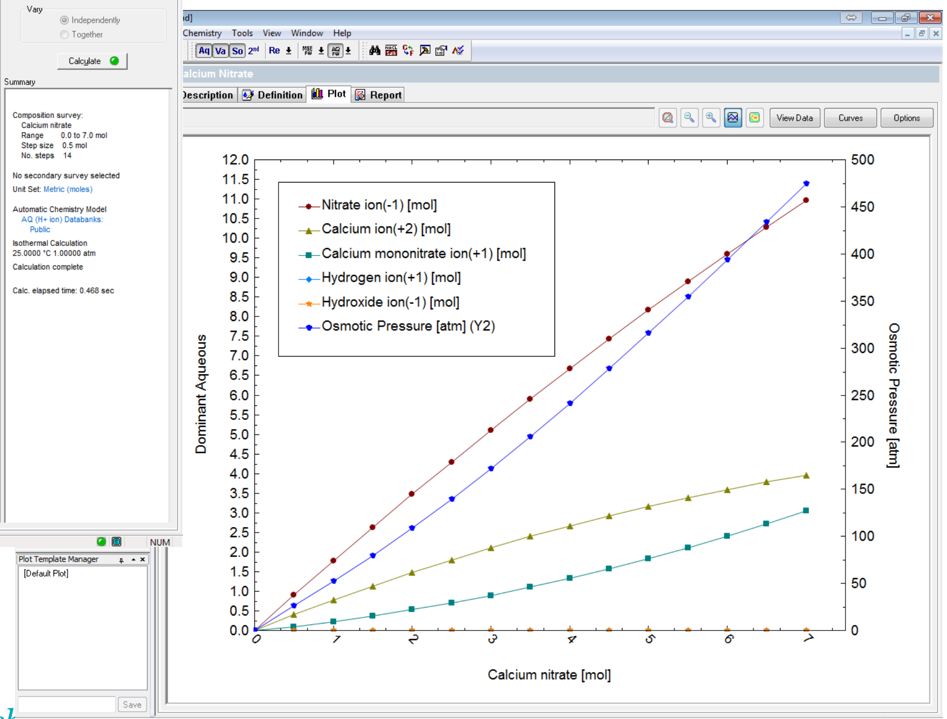


(Phuntsho, 2012)

Fertilizers Performance as DS

OLI Stream Analyzer Software

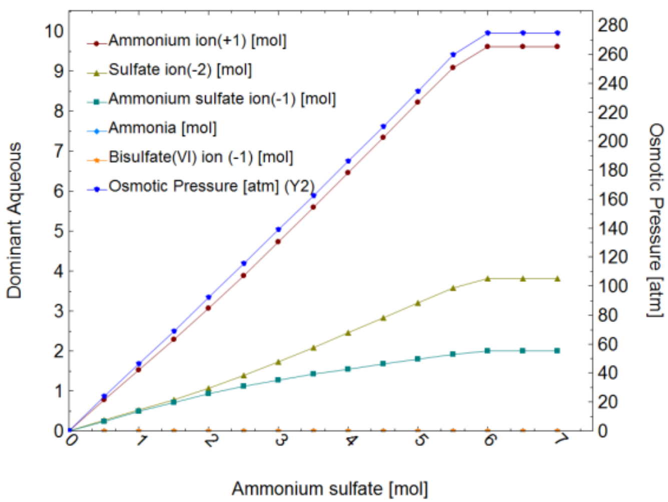


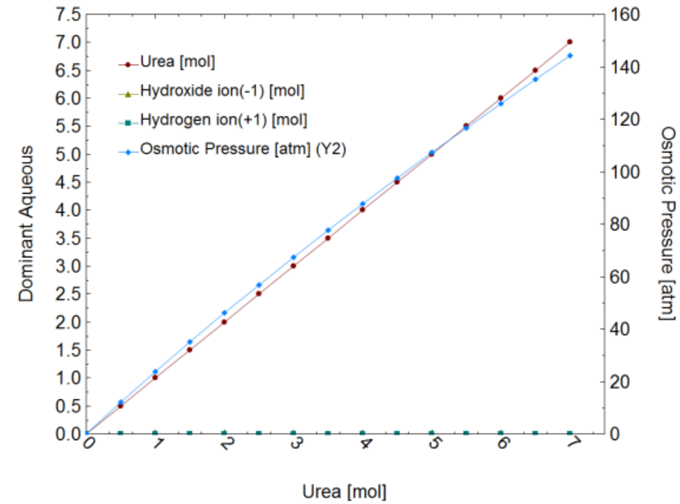


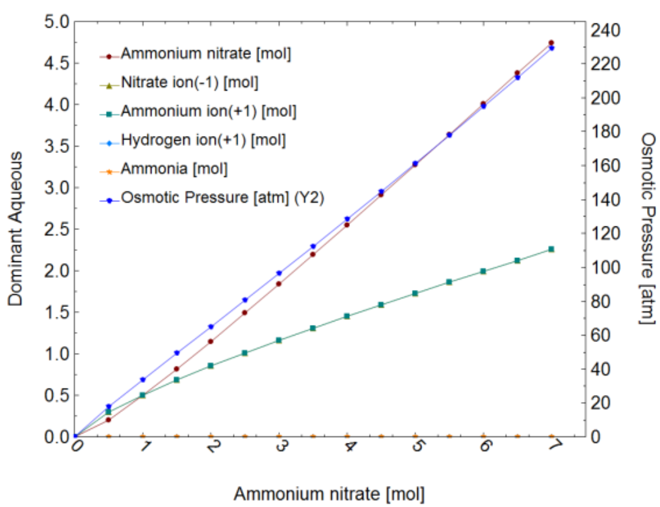
(OLI Systems, 2015)

Fertilizers Performance as DS

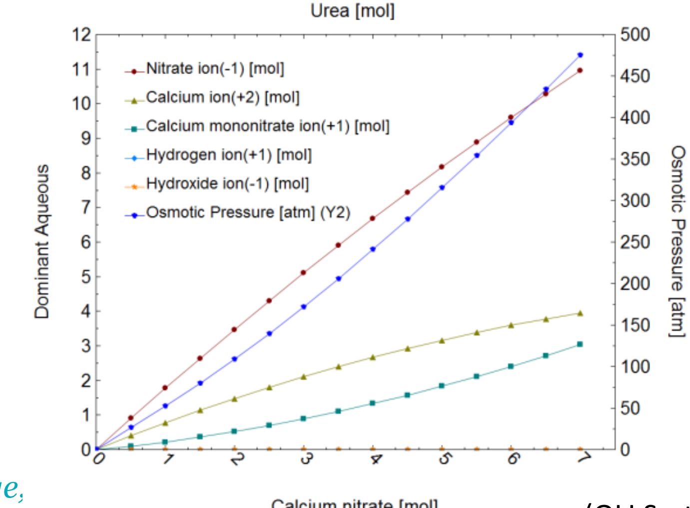
Osmotic Pressure and Speciation







ter - Exchange,



(OLI Systems, 2015)

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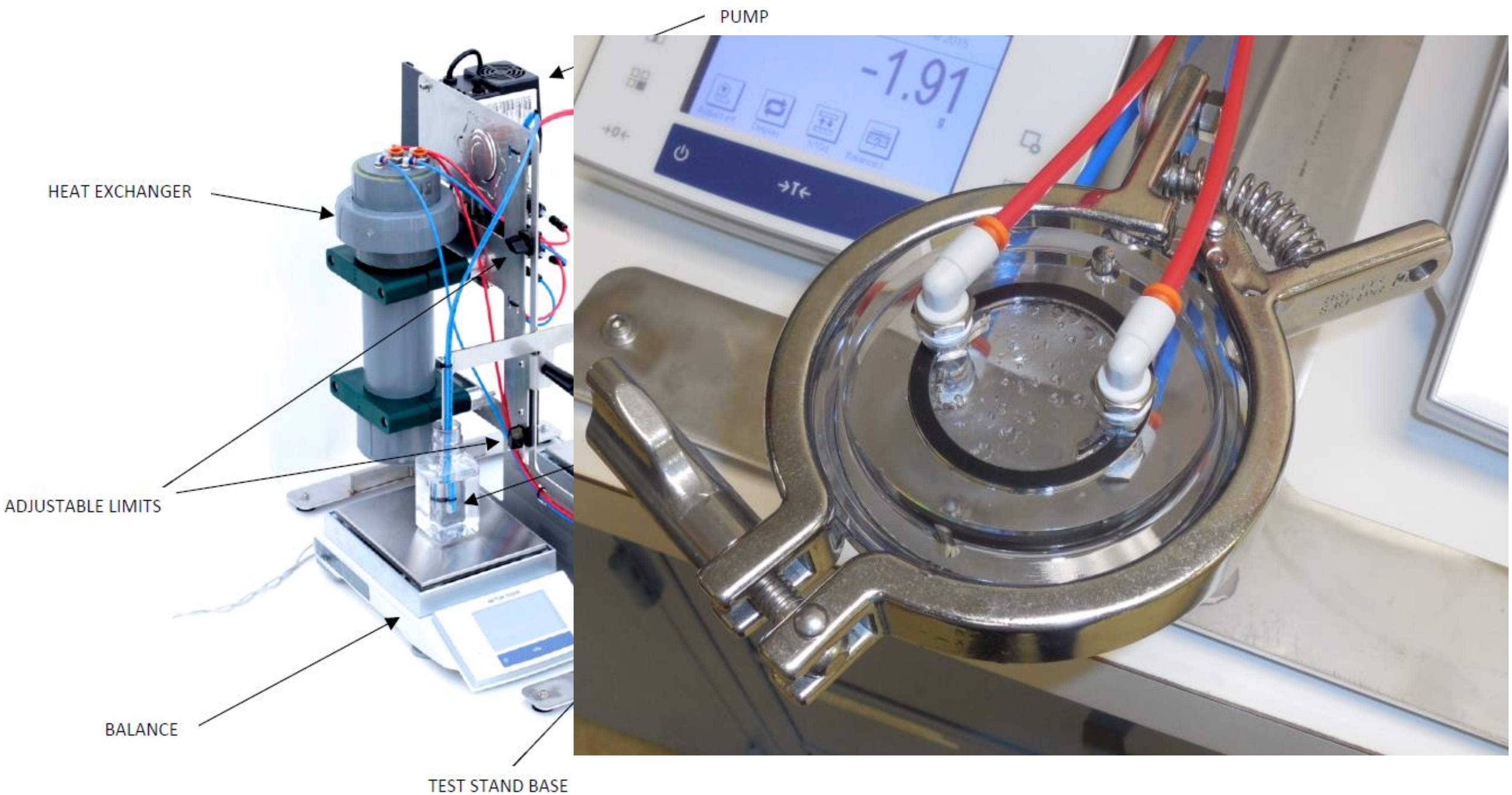
Experimental Bench-scale Setup



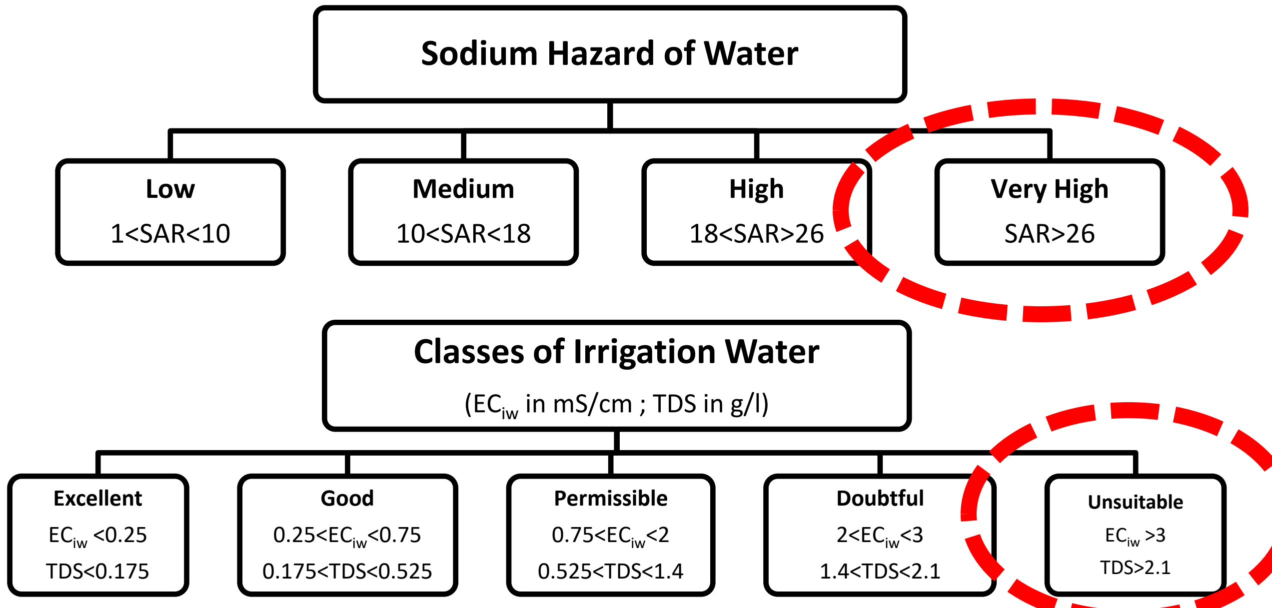
(Porifera Inc., 2015)

Brackish GW sample as FS

Ion	Concentration
Na^+	669.99 mg/l
Cl^-	1,041.25 mg/l
NH_4^+	2.1 mg/l
SO_4^{2-}	2,224.8 mg/l
Ca^{2+}	564.8 mg/l
Mg^{2+}	215.4 mg/l
K^+	41.73 mg/l
Fe^{3+}	0.036 mg/l
Mn^{2+}	0.016 mg/l
NO_3	29.75 mg/l
HCO_3^-	17.08 mg/l
CO_3^{2-}	0 mg/l
pH	6.5
EC	7.32 mS/cm
TDS	3.66 g/l
SAR	33.9

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

(Fipps, 2003)



*Water is **unsuitable for irrigation** due to a **very high Sodium Adsorption Ratio (SAR)**. If such water is used without proper treatment will cause **sodium toxicity** and **loss of soil structure** which will eventually lead to **soil degradation and poor crop yield.***

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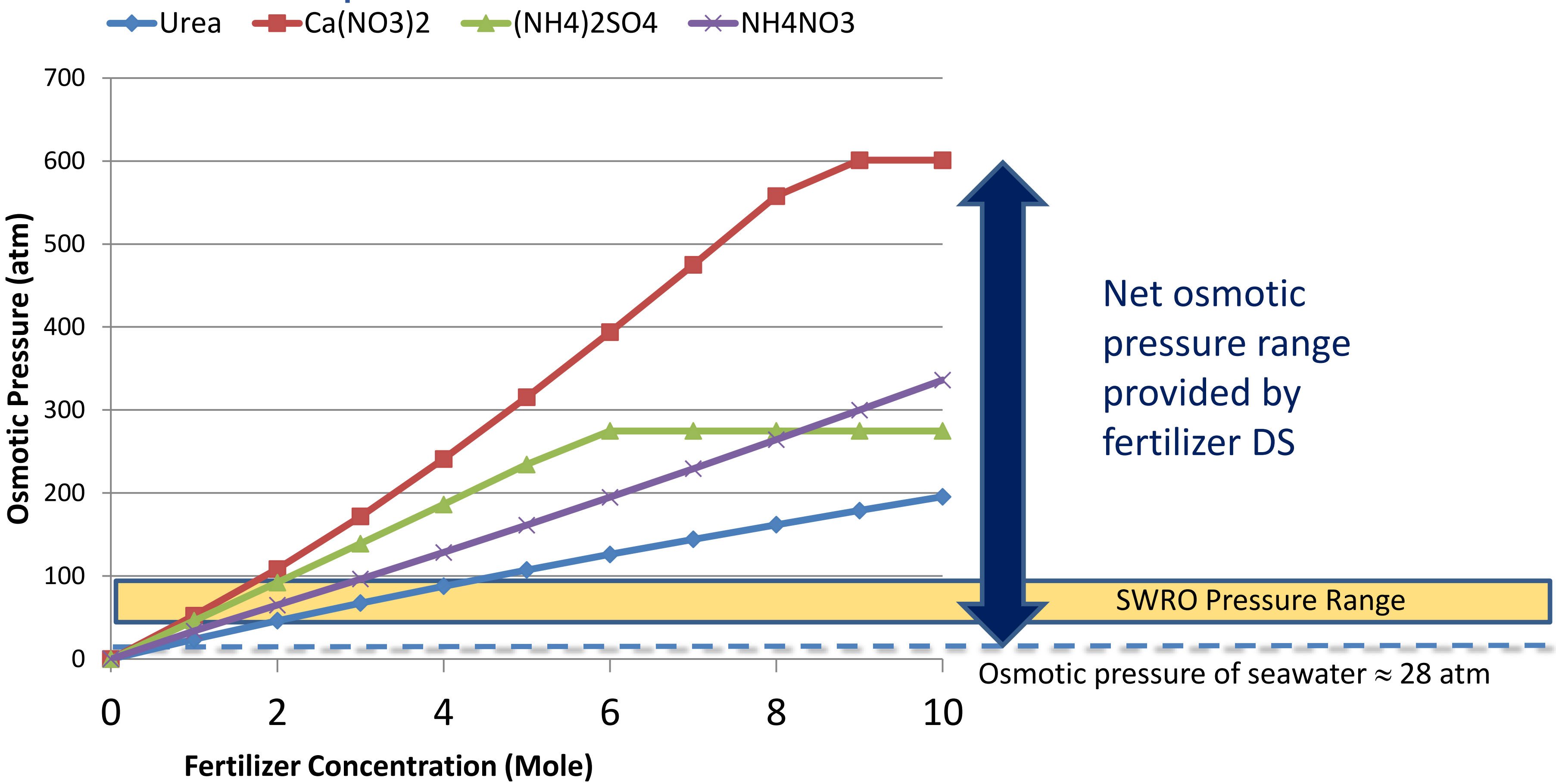
Salt affected Soils and Crops

(WateReuse Foundation, 2007)

FO for Irrigation - Fertilizers Performance

Osmotic pressure



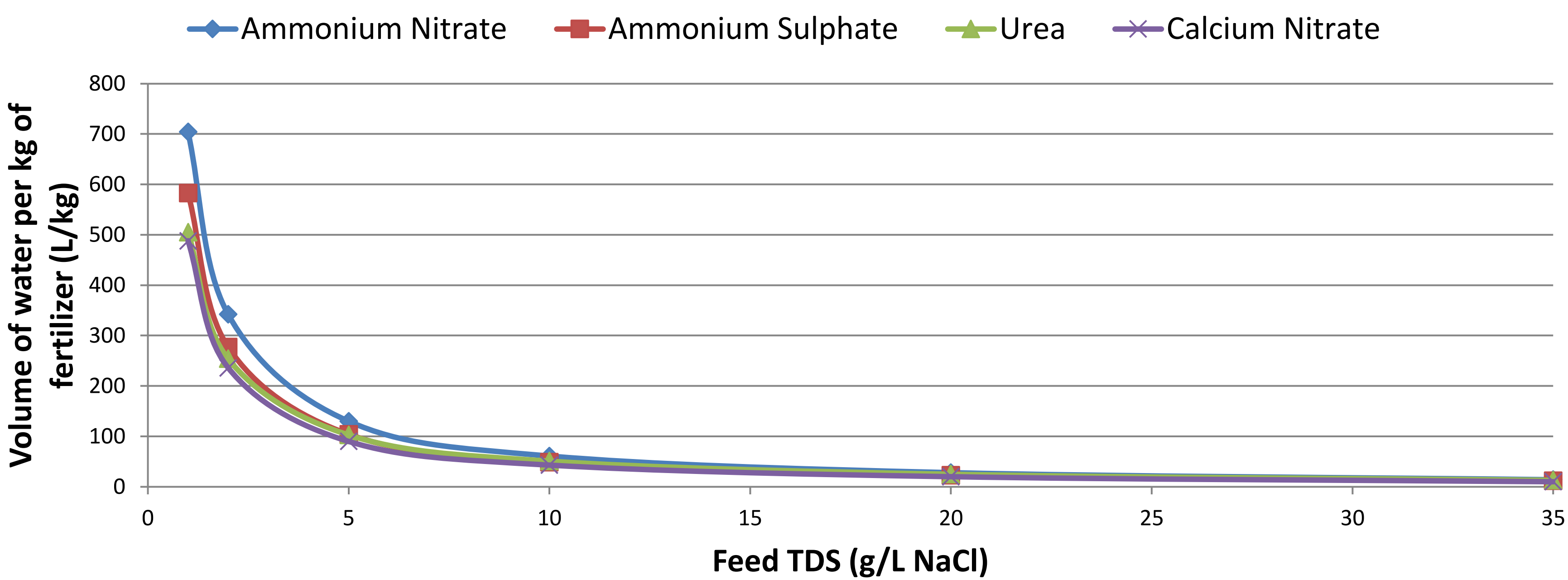
(OLI Systems, 2015)

Fertilizers Performance as DS

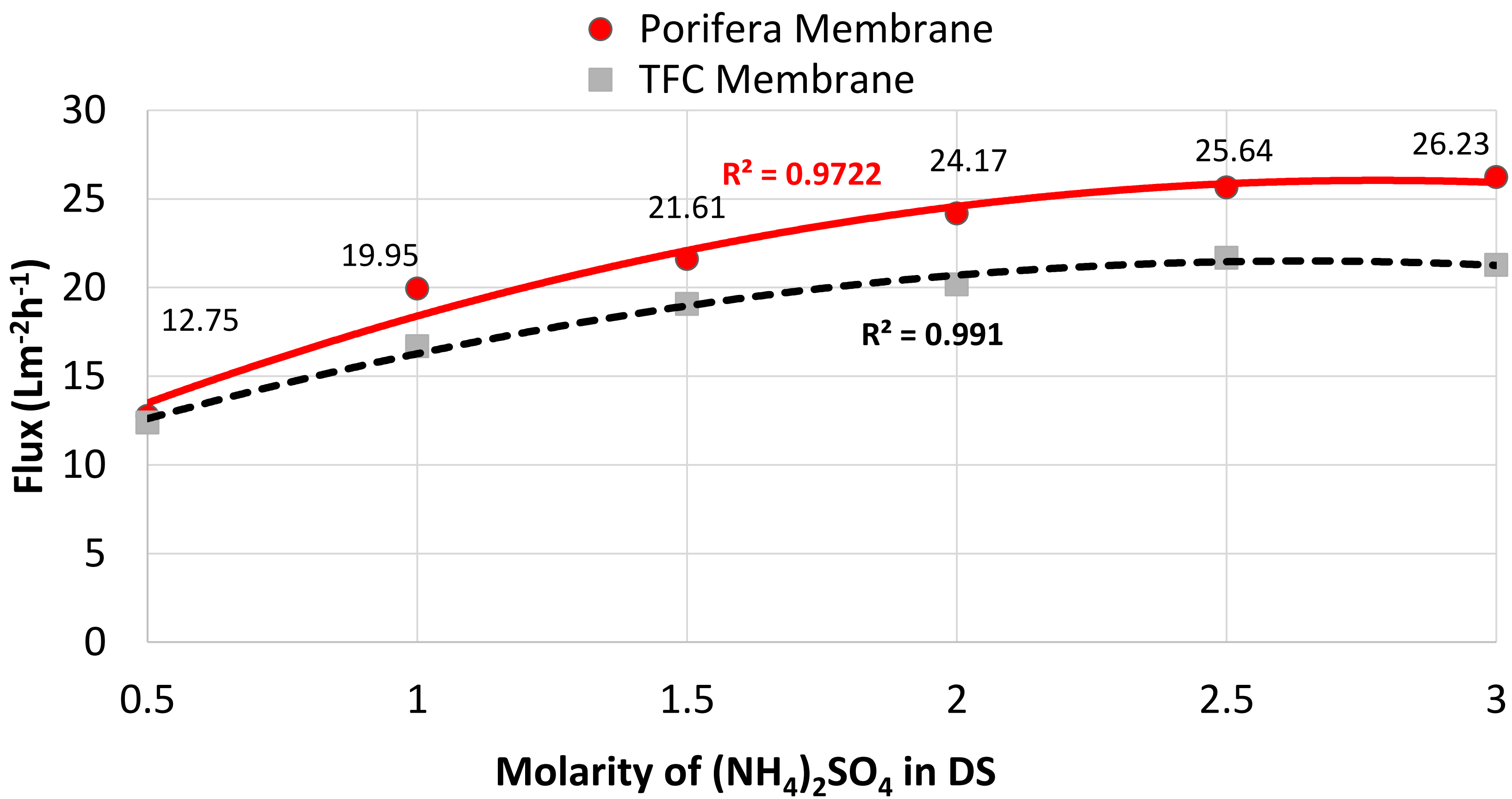
Water Extraction Capacity,

$$V = \frac{1000}{M_w}\left[\frac{1}{C_{D,E}} - \frac{1}{C_{D,Max}}\right]$$

- M_w : molecular weight of draw solute
- $C_{D,E}$: the molar concentration of the DS that generates same bulk osmotic pressure as that of the FS (mol)
- $C_{D,Max}$: maximum solubility of the draw solute (mol)

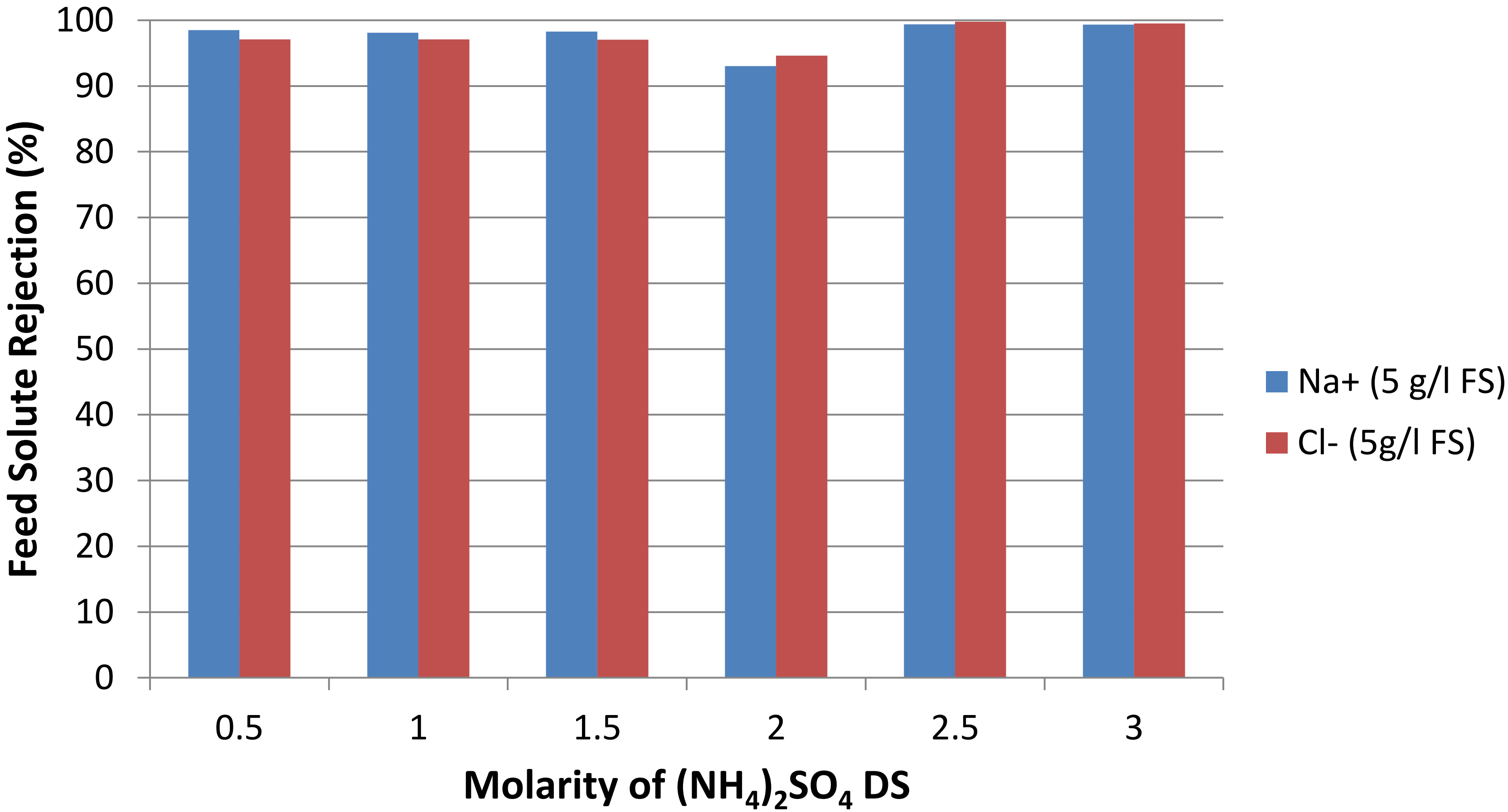


Water flux using GW as FS



Experimental Conditions: FS: GW, DS: $(NH_4)_2SO_4$, Temperature: 25 C, Membrane: Porifera and TFC, crossflow velocity: 12.9 cm/s

Feed Ion Rejection



(Nasr & Sewilam, 2016)

FO for Irrigation - FDFO Challenges

FDFO has some challenges

- Availability of efficient FO membranes
- Choice of a suitable fertilizer DS
- Lower-than-expected water flux
- Reverse movement of draw solutes (reverse permeation)
- Meeting irrigation water quality standards

Center of Excellence for Water Partners:

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