Aalto University
School of Engineering

WAT-E2120 - Physical and Chemical Treatment of Water and Waste

Membrane filtration

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Content / Learning outcomes

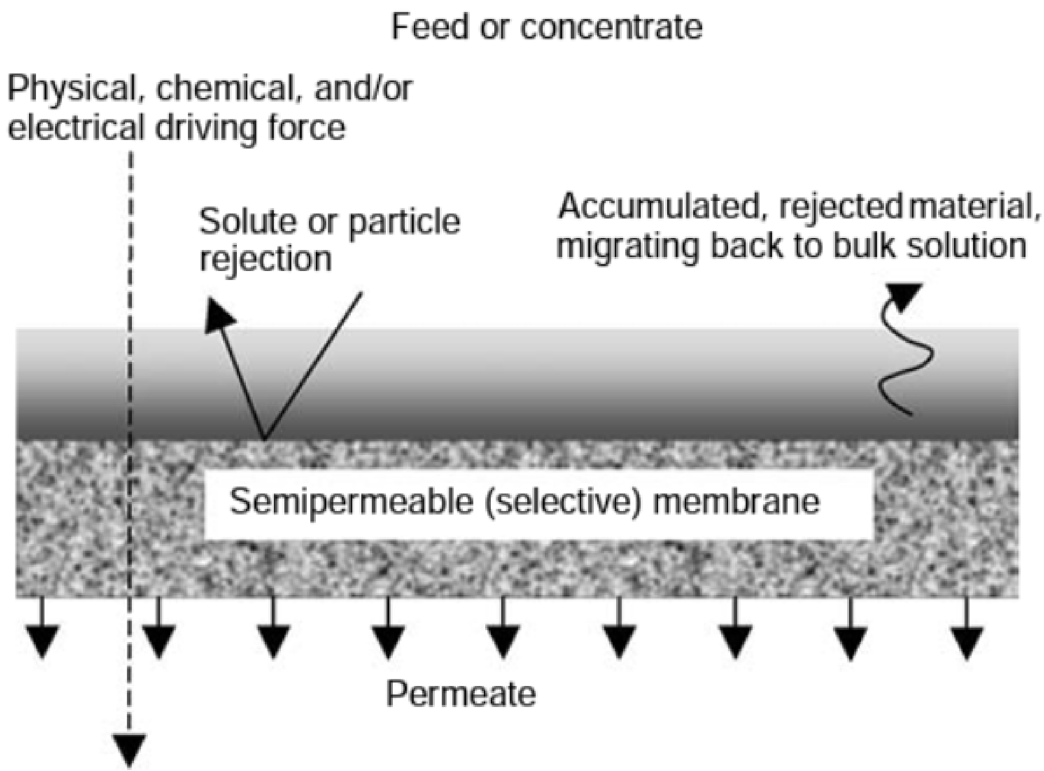
- Overview of membrane process
- Membranes, modules and arrays
- Parameters of the membrane process
- Applications in water treatment

- After the lesson you should
  - Know the principles and appliances of membrane filtration
  - Understand the parameters affecting membrane filtration
  - Know some applications of membrane filtration in water treatment
  - Be able to calculte flux, recovery and rejection of the membrane system

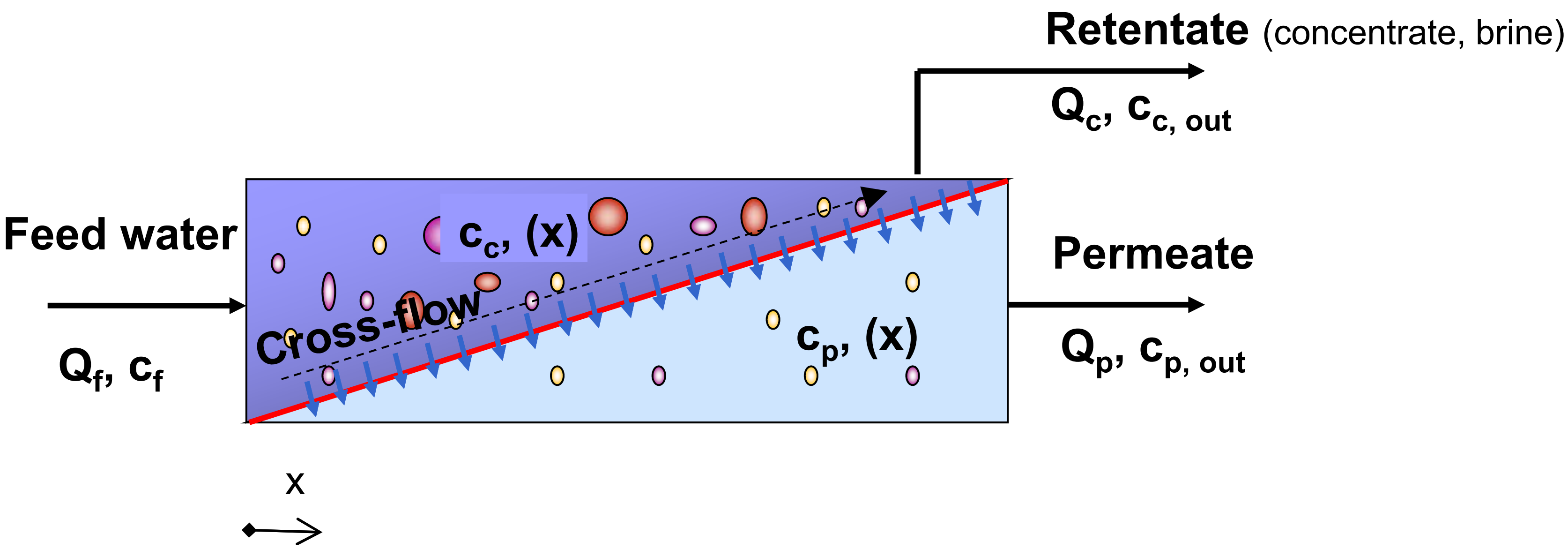
Membrane filtration

- In membrane filtration a thin layer of semipermeable material (membrane) separates substances based on their physical or chemical properties when a driving force is applied → mechanical process
- Driving forces in membrane filtration are
  - Pressure gradient,
  - Difference in concentration gradient (dialysis)
  - Gradient in electrical potential (electrodialysis)
- Most membrane processed used in water treatment are driven by an imposed transmembrane pressure (TMP) differential.

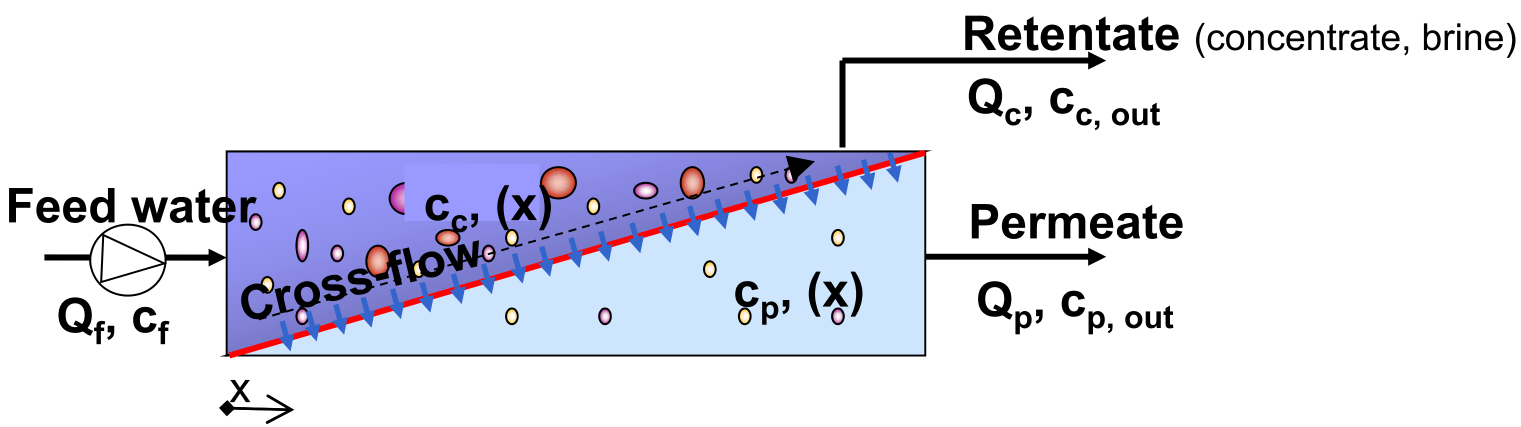
Key Processes in Membrane filtration



Flows in Membrane Process



Parameters of Membrane Process



Driving pressure, Trans membrane pressure: hydraulic pressure difference between the feed and permeate sides of the membrane [bar, Pa]

Flux (J): the permeate flow through the membrane area [L/m^2.h]

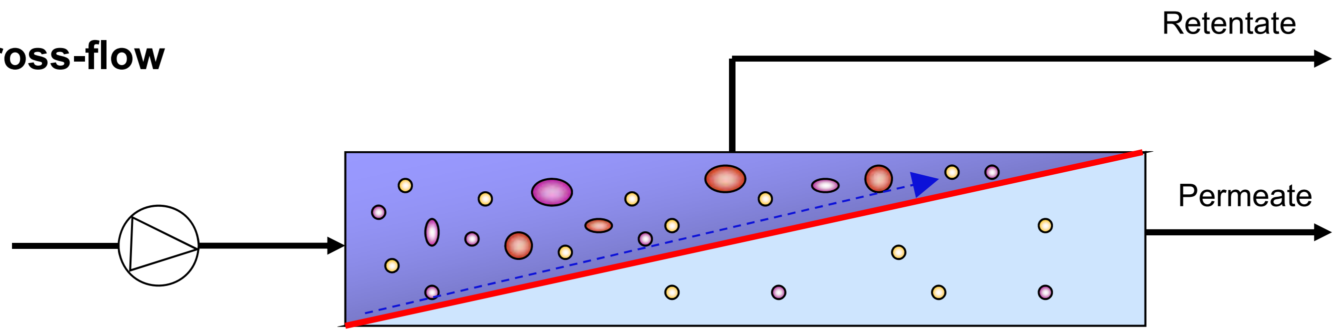
$$\hat{J}_w = \frac{Q_p}{A_m} = v_w \qquad (15\text{-}2)$$

Recovery (r): the fraction of the feed water that becomes product water [%]

$$r = \frac{Q_p}{Q_f} = 1 - \frac{Q_c}{Q_f} \qquad (15\text{-}1)$$

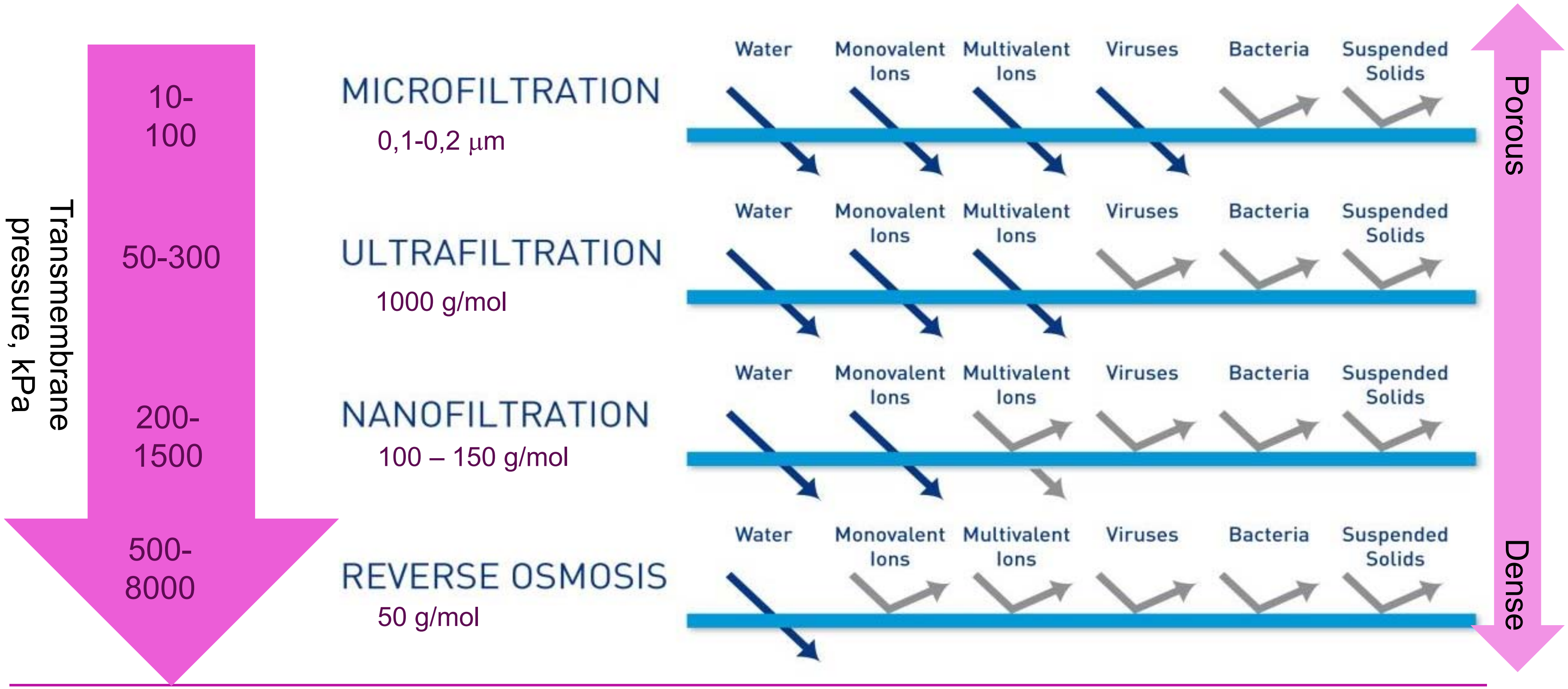
Modes of Operation

Cross-flow



Dead-end

Pressure-Driven Membrane Processes



Retention Mechanisms in Membrane Filtration

- Particles and colloids by physical sieving (main mechanism in MF and UF)
- Dissolved contaminants by chemical and electrical interactions between contaminant and membrane (main mechanism in RO and NF)
- Retention is affected by
  - Membrane: pore size, charge, surface roughness, hydrophobicity
  - Contaminant: size, charge, conformation, etc.
  - Feed water characteristics: pH, ionic strength etc.
  - Hydraulics: flow, trans membrane pressure

Membranes

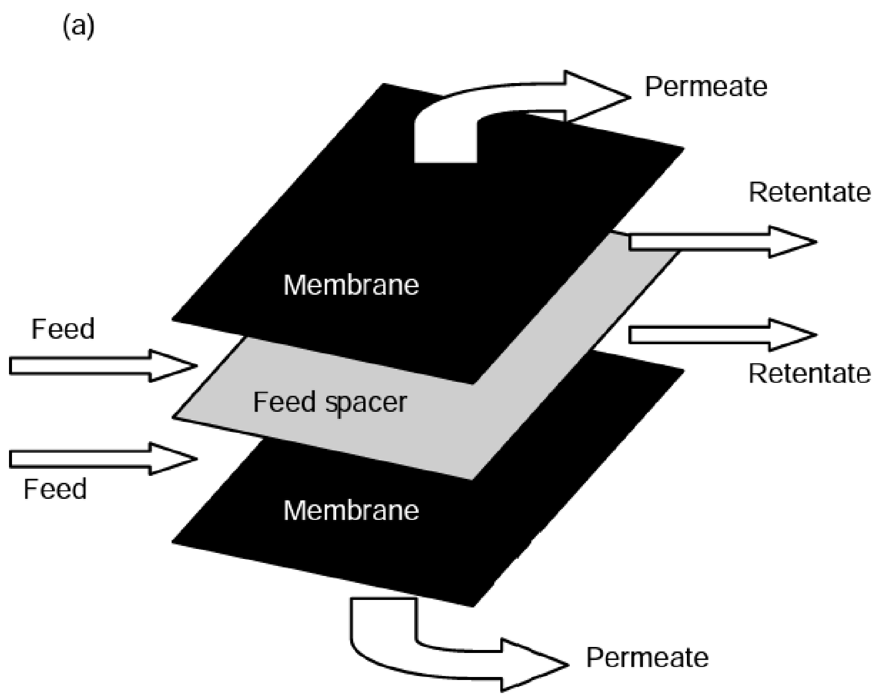
- Membranes should be durable, permeable for water and selective for removed parameters.
- The most membranes are made of organic polymers.
  - Hydrophilic and negatively charged in water treatment
- Ceramic membranes are used in specific applications.
- Membrane integrity is imperative for efficient treatment
  - Indirect methods to assess: particle, turbidity or conductivity metering, microbiological surveillance
  - Direct methods to assess: air holding capacity (offline), acoustic surveillance of hydraulic changes (online)

Membrane Elements and Modules

- Membrane material is packed in membrane elements.
- Optimal membrane element
  - High packing density
  - Low foulung tendency
  - Low energy consumption
  - Easy to clean
  - Easy to attach with other elements
- Membrane element units caontaining several elements are called modules (pressure vessels).

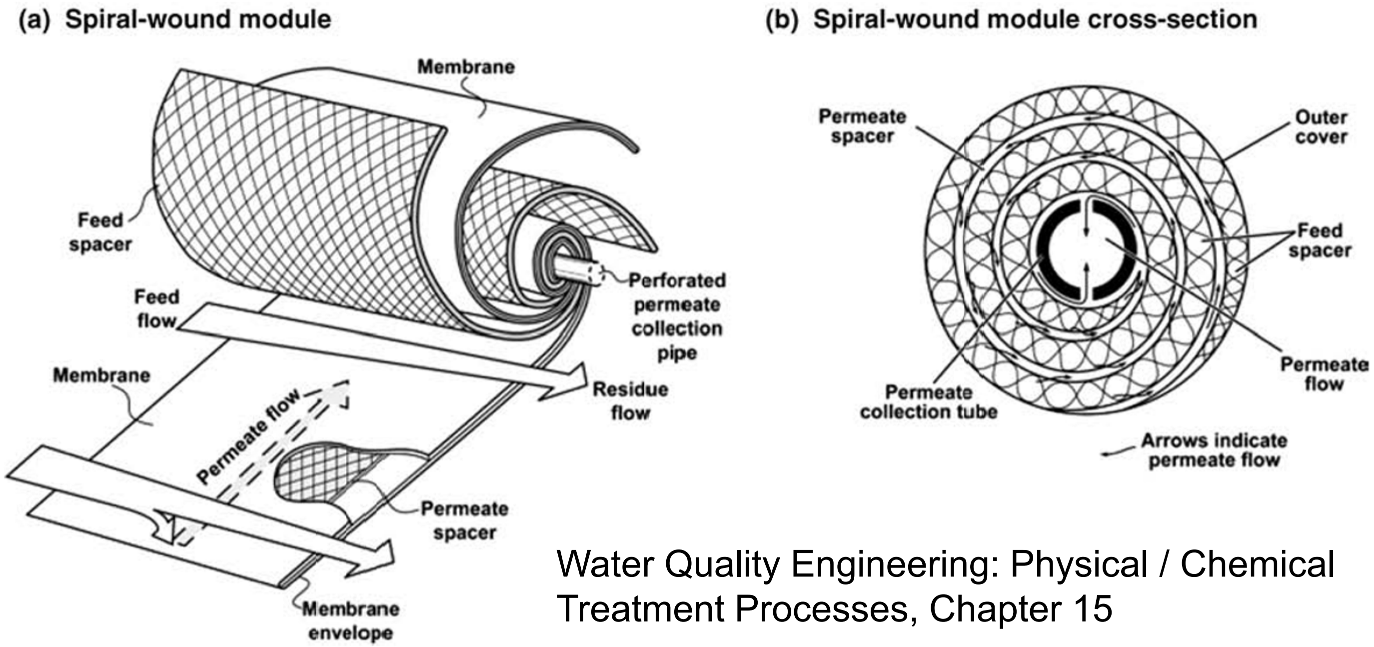
Membrane Elements: Plate and frame

- Packing density 200-500 m^2/m^3



Membrane Elements: Spiral-wound

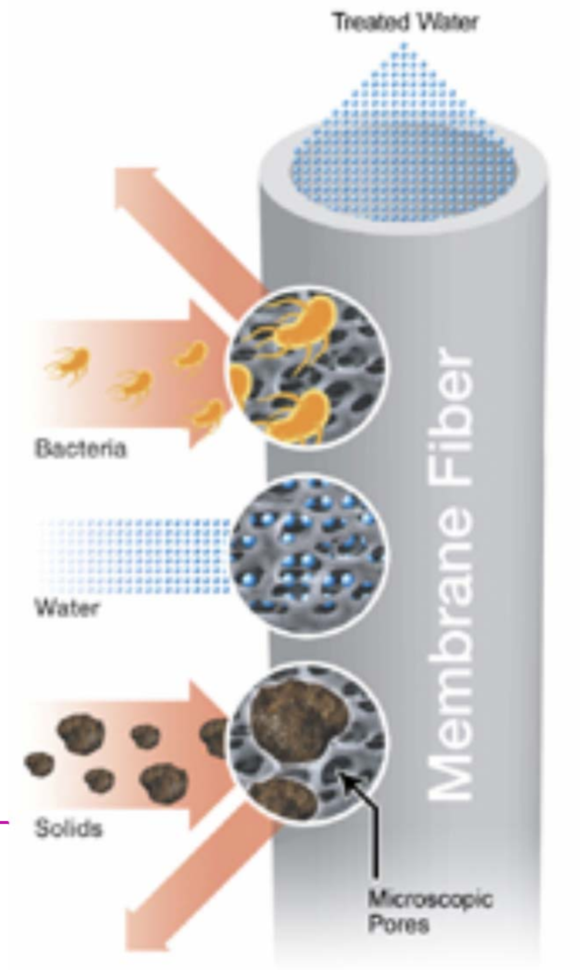
- Most common element in RO and NF applications
- Packing density 700-2000 m^2/m^3
- Feed spacers get easily clogged requires feed water of good quality
- Back flushing not possible



Water Quality Engineering: Physical / Chemical Treatment Processes, Chapter 15

Membrane Elements: Hollow fibre / tubular

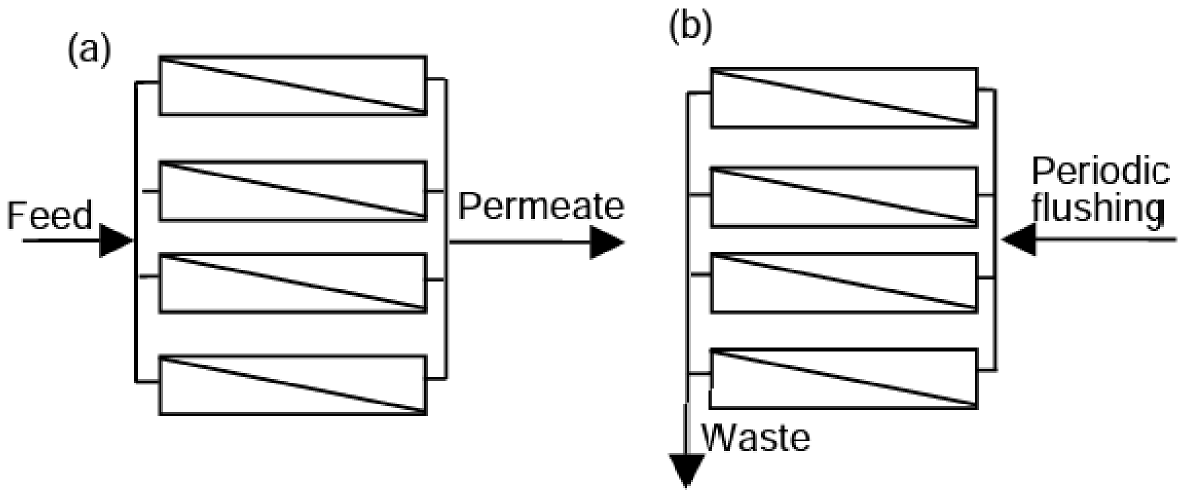
- Permeate flow either inside-out or outside-in mode
- Dead-end or cross-flow
- Packing density 1000-2000 m^2/m^3 in hollow fibre, 100-300 m^2/m^3 in tubular



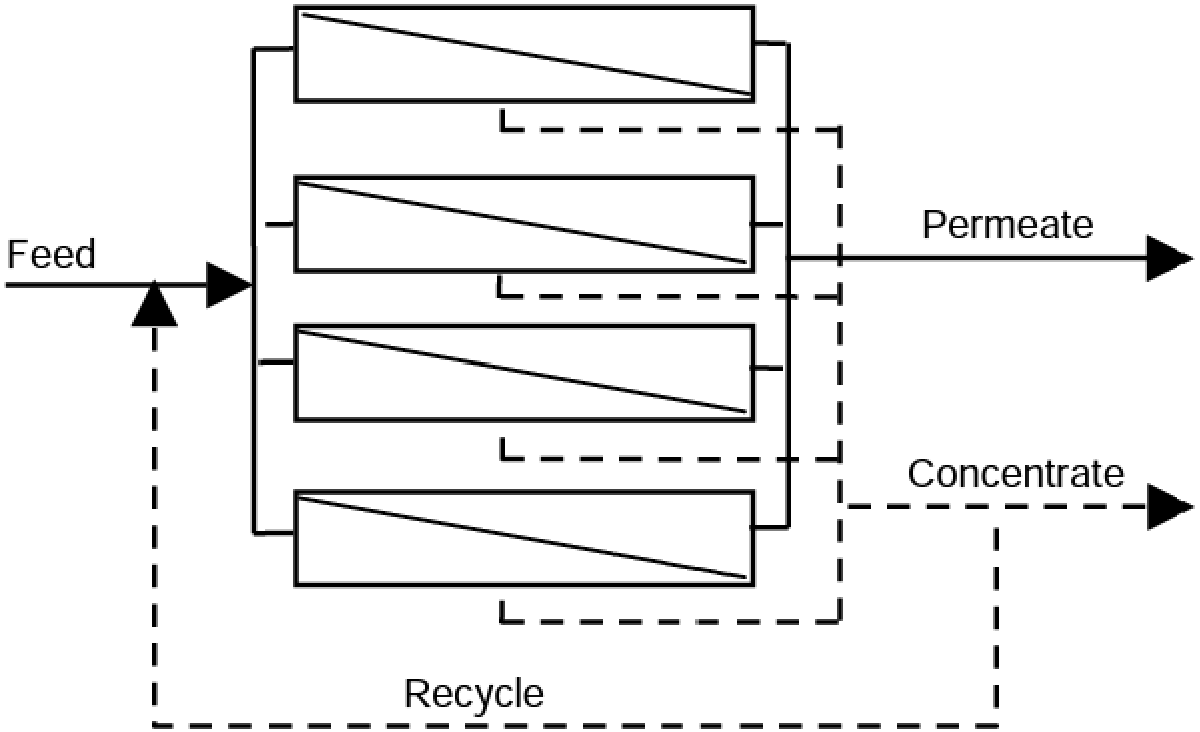
Membrane Arrays and Systems

- Multiple modules are connected by piping to form an independent processing unit, array.
- One or more membrane arrays are combined to form full-scale membrane system.
- Capacity of the system can be increased by installing more modules or arrays in parallel.
- Recovery of the system can be increaced by recycling the retentate or by installing more stages to the process.
- https://www.youtube.com/watch?v=aVdWqbpbv_Y

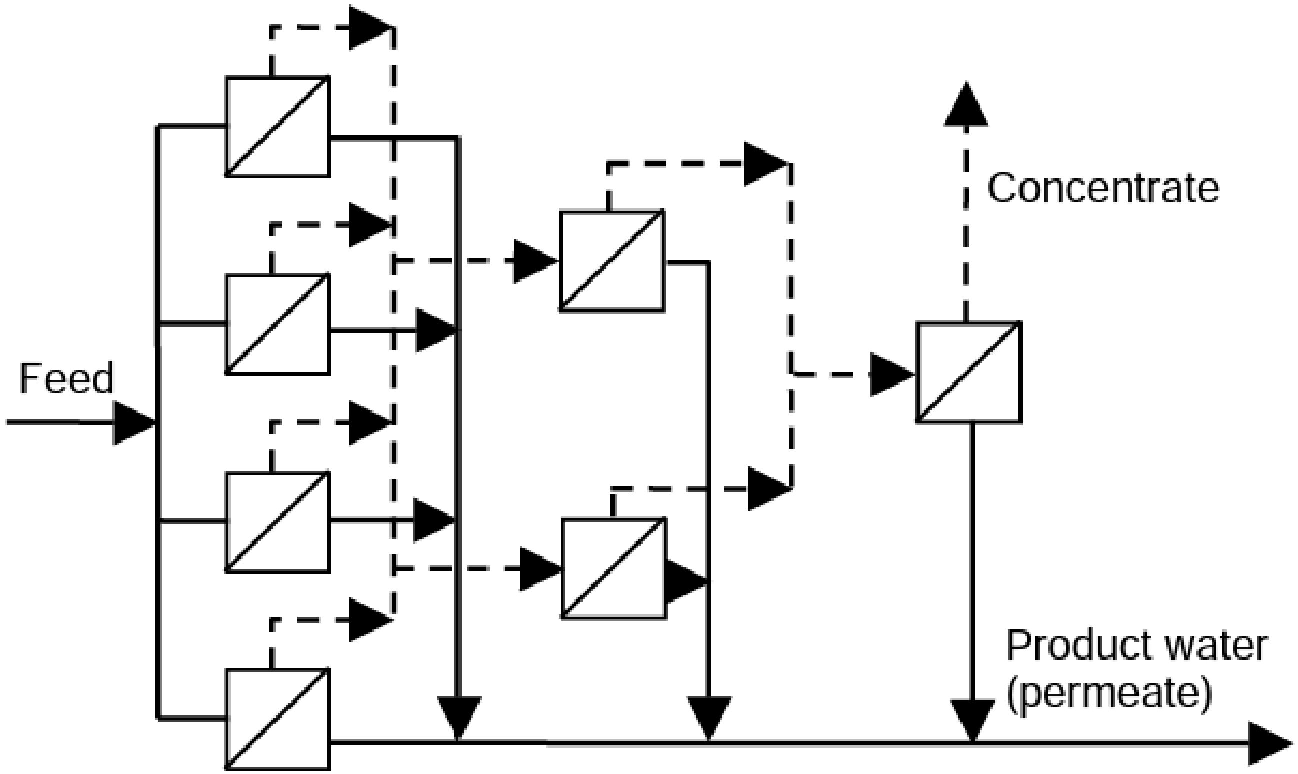
Membrane arrays: dead end



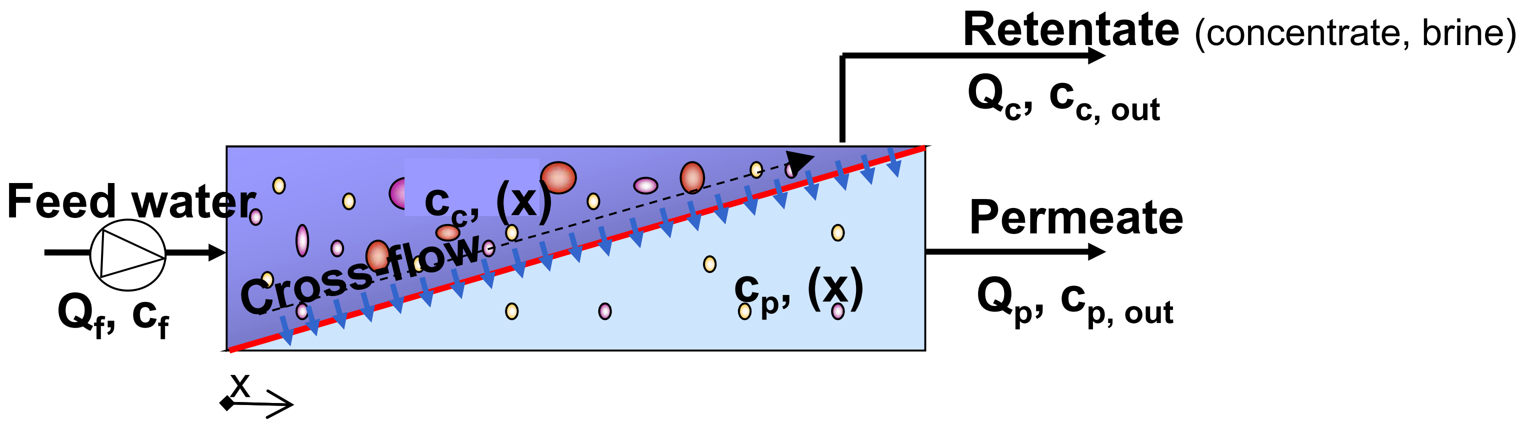
Membrane arrays: feed and bleed



Membrane arrays: staged (cascade)



Parameters of Membrane Process



Driving pressure, Trans membrane pressure: hydraulic pressure difference between the feed and permeate sides of the membrane [bar, Pa]

Flux (J): the permeate flow through the membrane area [L/m^2.h]

$$\hat{J}_w = \frac{Q_p}{A_m} = v_w \qquad (15\text{-}2)$$

Recovery (r): the fraction of the feed water that becomes product water [%]

$$r = \frac{Q_p}{Q_f} = 1 - \frac{Q_c}{Q_f} \qquad (15\text{-}1)$$

Example 1

EXAMPLE 15-2. A test system containing a single spiral-wound element with 30 m^2 of membrane area receives a constant feed flow of 5m^3/h and is operated at a permeate flux of 25 L/m^2.h.

a) Calculate the recovery for this module.

Example 1

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a) Calculate the recovery for this module.

$$Q_p = \hat{J}_V A_m = (25\,\mathrm{L/m^2\,h})30\,\mathrm{m^2} = 750\,\mathrm{L/h}$$

$$r_{el} = \frac{Q_p}{Q_f} = \frac{750\,\mathrm{L/h}}{(5\,\mathrm{m^3/h})(1000\,\mathrm{L/m^3})} = 0.15 = 15\%$$

Example 1

EXAMPLE 15-2. A test system containing a single spiral-wound element with 30m^2 of membrane area receives a constant feed flow of 5m^3/h and is operated at a permeate flux of 25 L/m^2.h.

b) Calculate the average velocity of the water toward the membrane.

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b) Calculate the average velocity of the water toward the membrane.

The velocity of water toward the membrane equals the volumetric flux. Converting the given flux into more conventional units of velocity, we find

$$\hat{J}_V = 25\,\mathrm{L/m^2\,h}\left(\frac{1\,\mathrm{m^3}}{1000\,\mathrm{L}}\right)\left(100\,\frac{\mathrm{cm}}{\mathrm{m}}\right)$$
$$= 2.5\,\mathrm{cm/h}$$

Example 1

EXAMPLE 15-2. A test system containing a single spiral-wound element with 30m^2 of membrane area receives a constant feed flow of 5m^3/h and is operated at a permeate flux of 25 L/m^2.h.

c) Calculate the recovery for a pressure vessel with three such elements in series, assuming that the recovery is identical in each element.

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c) Calculate the recovery for a pressure vessel with three such elements in series, assuming that the recovery is identical in each element.

The 2nd and 3rd elements also recover 15% of the flow entering to them.

$$Q_{p,2} = 0.15 Q_{in,2} = 0.15\left[(1.0 - 0.15) Q_{in,1}\right]$$
$$= 0.13 Q_{in,1}$$

$$Q_{p,3} = 0.15 Q_{in,3} = 0.15\left[(1.0 - 0.15) Q_{in,2}\right]$$
$$= 0.15\left[(1.0 - 0.15)^2 Q_{in,1}\right] = 0.11 Q_{in,1}$$

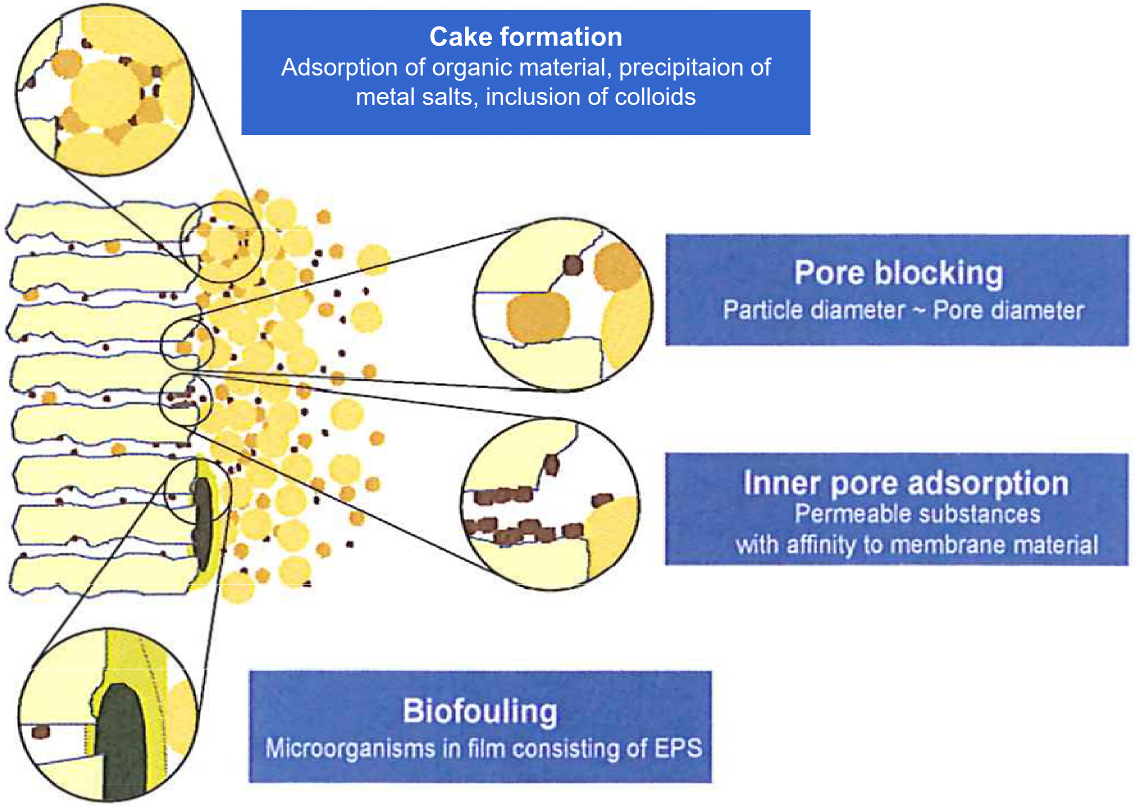
The overall recovery is 0,15+0,13+0,11 = 0,39 = 39%

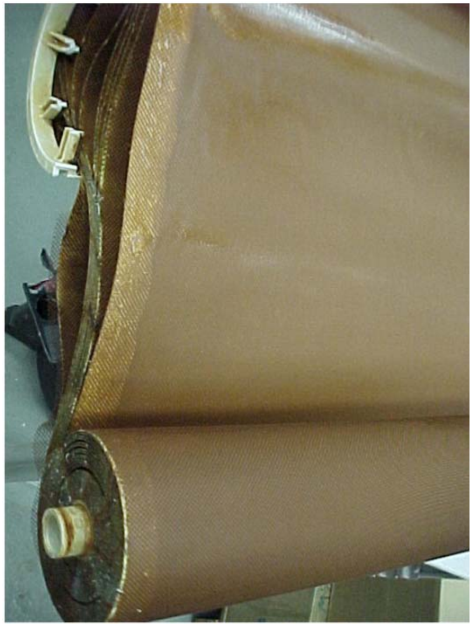
Homework 1

Effect of fouling on flux

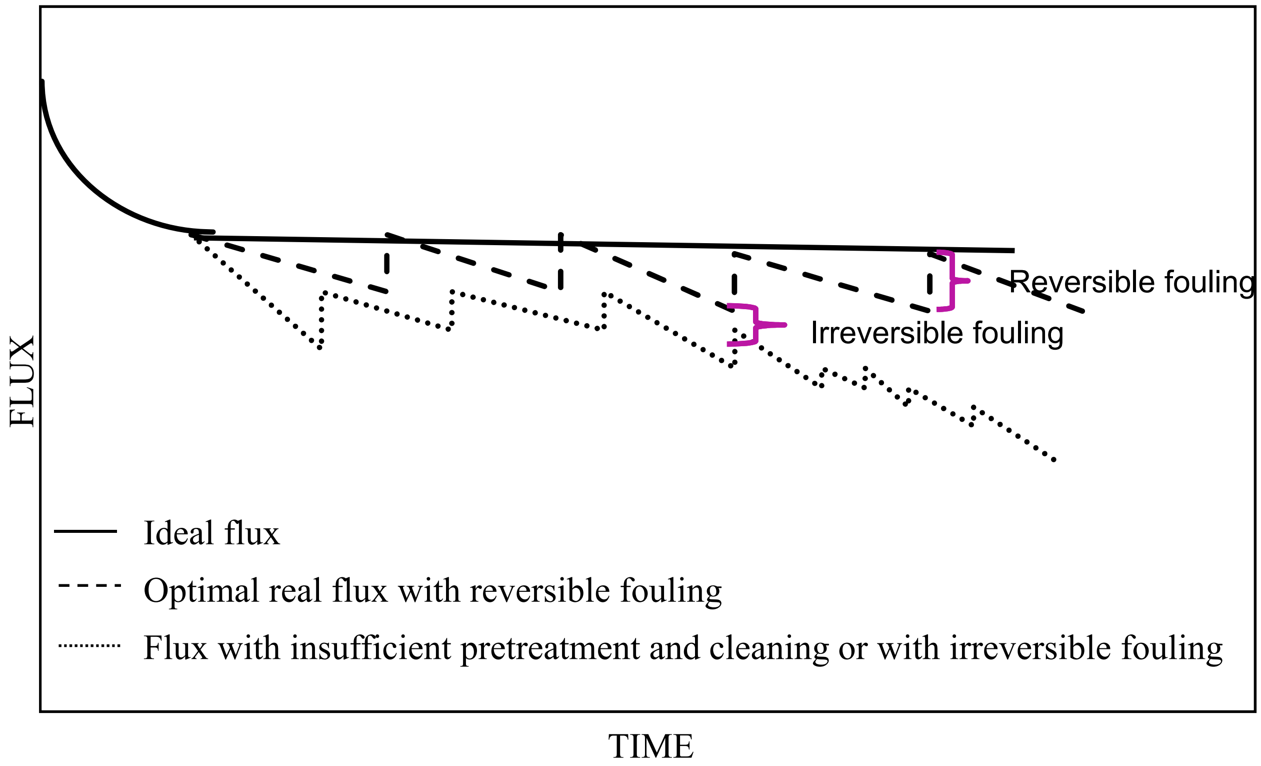
Membrane: NF 255 (ppz), spiral-wound module, A = 30.8 m^2
Feedwater: chemically coagulaied and sandfiltered water from Dämman water treatment plant
Driving pressure = 7.5 bar, Recovery = 80 %, T = 25 ^{o}C

Mechanisms of membrane fouling





Reversible and irreversible fouling



Darcy's law in pressure-driven membrane processes

$$J = (\Delta P - \Delta \Pi) / \mu (R_m + R_f)$$

,where

J = volumetric flux [m.s $^{-1}$]

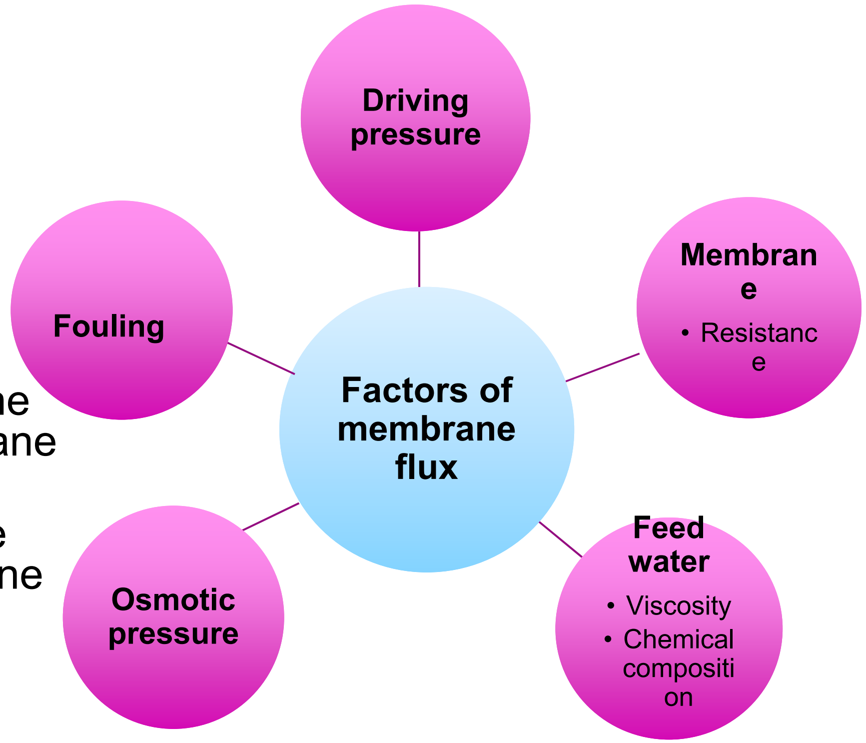
ΔP = hydraulic pressure difference between the feed and permeate sides of the membrane [Pa]

$\Delta \Pi$ = osmotic pressure difference between the feed and permeate sides of the membrane [Pa]

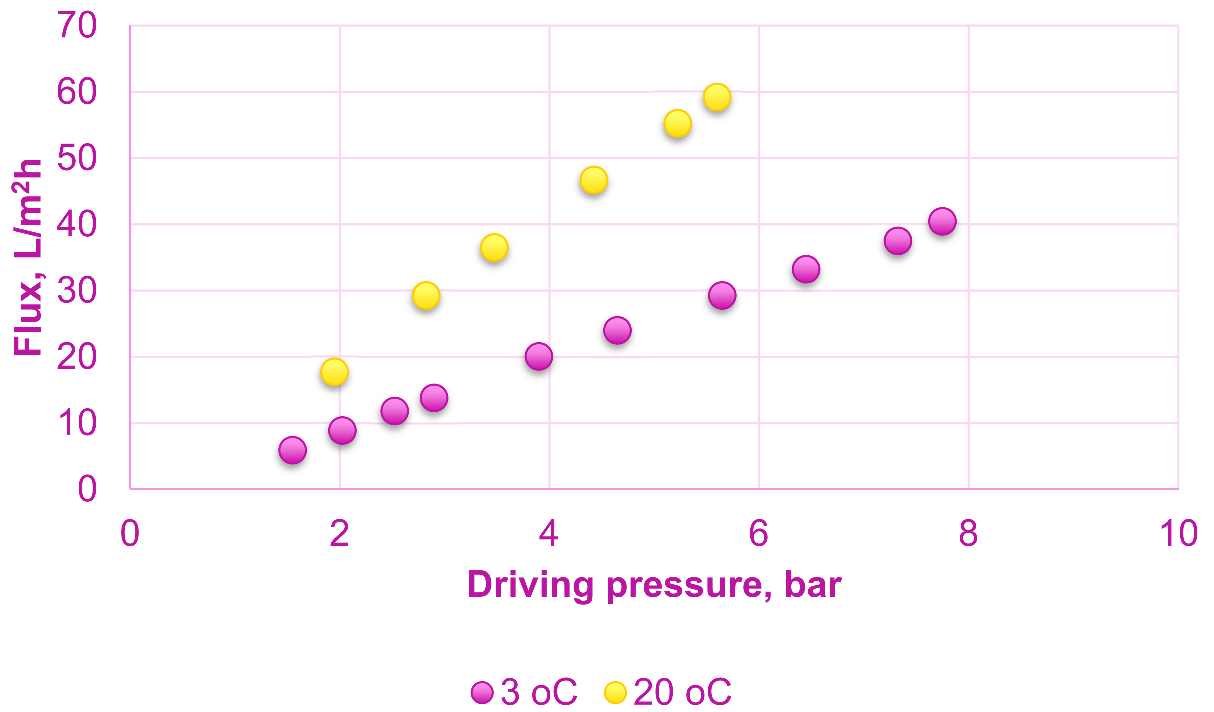
μ = viscosity of the water [Pa.s]

R_m = resistance of the membrane [m $^{-1}$]

R_f = resistance of the fouling [m $^{-1}$]



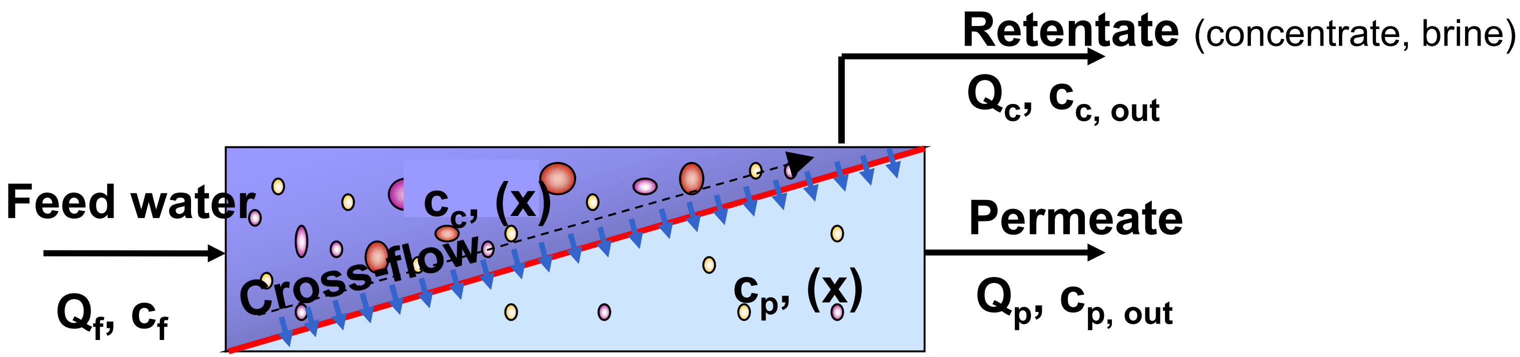
Effect of pressure and temperature on flux



Membrane: NF 255 (ppz), spiral-wound module, A = 30.8 m^2
Feedwater: chemically coagulated and sandfiltered water from Dämman water treatment plant

Homework 2

Mass Balance in Membrane Processes

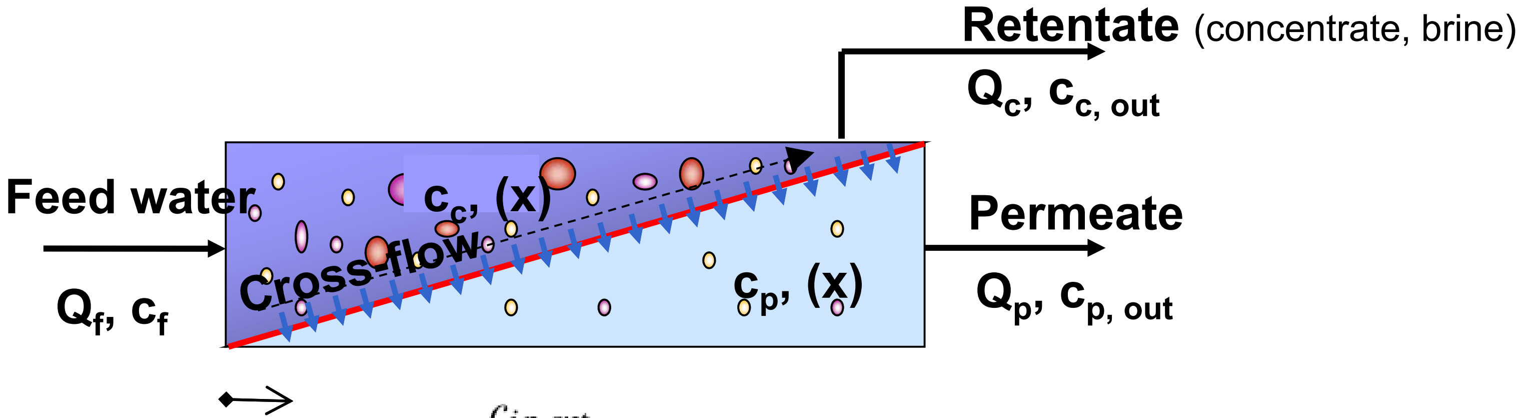


$$\begin{pmatrix}\text{Rate of change of}\\ \text{mass of contaminant}\\ \text{stored in system}\end{pmatrix} = \begin{pmatrix}\text{Rate at which}\\ \text{contaminant enters}\\ \text{in feed}\end{pmatrix} - \begin{pmatrix}\text{Rate at which}\\ \text{contaminant leaves}\\ \text{in permeate}\end{pmatrix} - \begin{pmatrix}\text{Rate at which}\\ \text{contaminant leaves}\\ \text{in concentrate}\end{pmatrix}$$

$$0 = Q_f c_f - Q_p c_{p,out} - Q_c c_{c,out} \quad (15\text{-}25)$$

$$c_{c,out} = \frac{Q_f c_f - Q_p c_{p,out}}{Q_c} \quad (15\text{-}26)$$

Rejection (R) in Membrane Processes



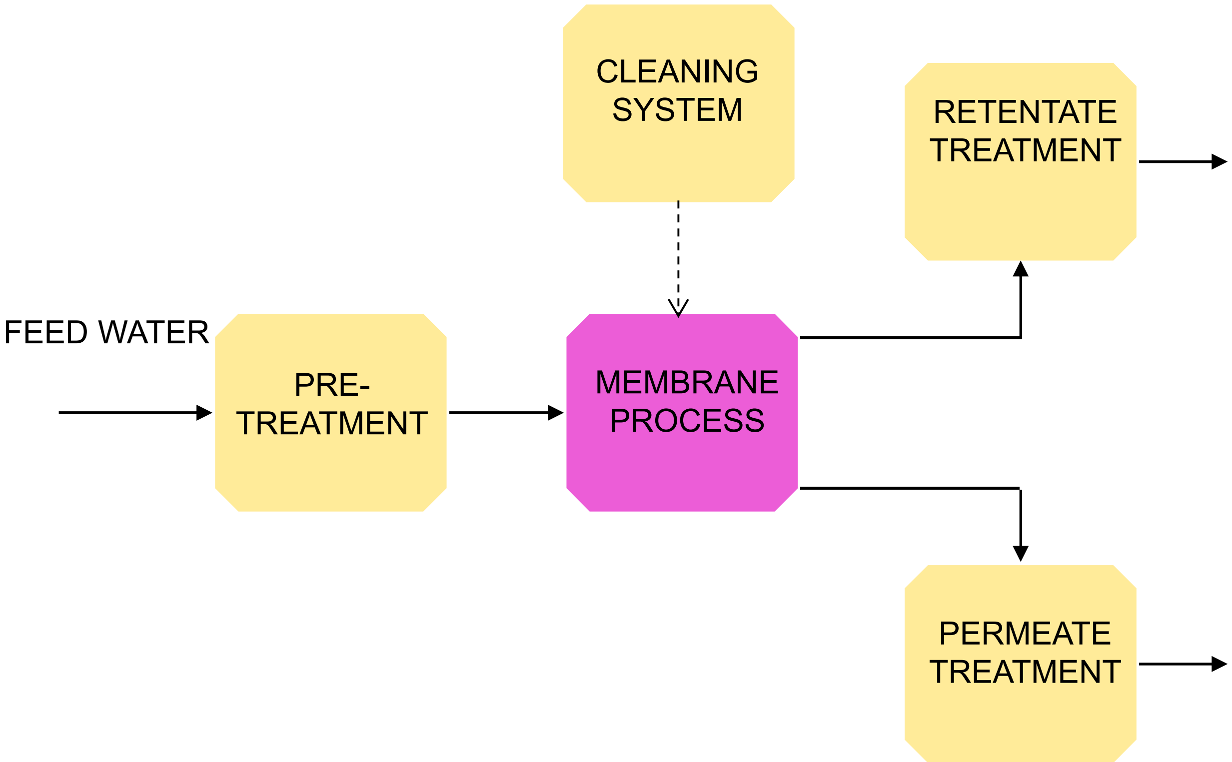
$$R_i \equiv 1 - \frac{c_{i,\mathrm{p,out}}}{c_{i,\mathrm{f}}} \qquad (15\text{-}24)$$

$$R_{\text{mass}} = \frac{Q_\mathrm{c} C_\mathrm{c,out}}{Q_\mathrm{f} C_\mathrm{f}} = 1 - \frac{Q_\mathrm{p} C_\mathrm{p,out}}{Q_\mathrm{f} C_\mathrm{f}} = 1 - r\frac{C_\mathrm{p,out}}{C_\mathrm{f}} = 1 - r(1-R)$$

(15-28)

$$c_\mathrm{c,out} = \frac{Q_\mathrm{f} c_\mathrm{f} - r Q_\mathrm{f}(1-R)c_\mathrm{f}}{(1-r)Q_\mathrm{f}} = c_\mathrm{f}\frac{1-r(1-R)}{1-r} \qquad (15\text{-}27)$$

Membrane Process



Operational monitoring of a membrane processe?

- Trans membrane pressure
- Conductivity / turbidity / particle count / microbial quality of permeate
- Feed flow
- Permeate flow

RO applications

- Sea water or brackish water desalination is the most common membrane process at the moment
- Wastewater reuse
- Similar uses in drinking water productions as with NF
- Treatment of landfill leachates
- Treatment and recycling of process waters in industry
- Production of ultrapure water

Desalination with RO

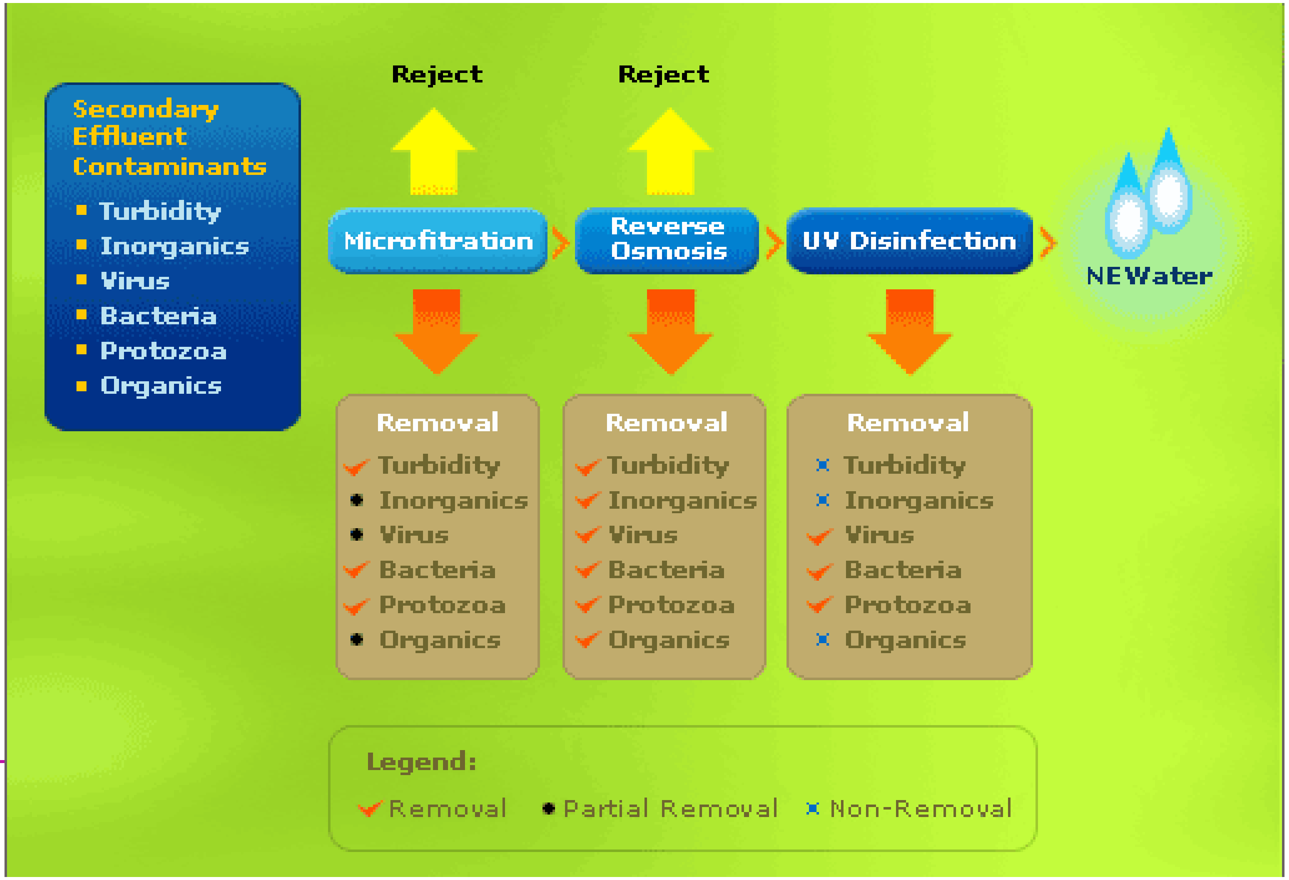
- The most common membrane process at the moment
- The most cost effective technique for seawater desalination
- Houtskär, FInland
  - – Remineralisation and pH adjustmet after RO
  - – Production capacity 90 m^3/d

Fluoride removal with RO

- Only part of the steam treated with RO to achieve the required fluoride level (1,5 mg/l) in drinking water
- Kuivala, Finland
  - Treats artificially produced ground water, approximately 30% of the production capacity
  - Biggest membrane filtration plant in Finland, production capacity 9.000 m^3/d
  - Fluoride removal efficiency 98 %

Wastewater treatment for reuse

- Singapore NEWater
- https://www.pub.gov.sg/watersupply/fournationaltaps/newater

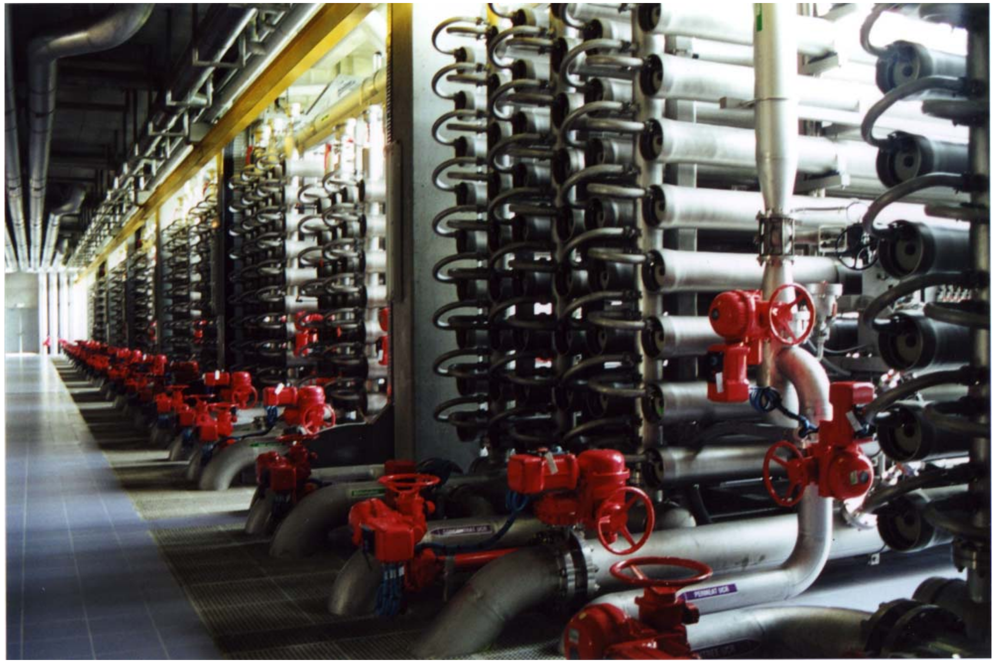


NF applications

- Removal of organic matter, above 90 %
- Disinfection, removal efficiency 100 %
- Removal of turbidity 100 %
- Removal of hardness
- Removal of multivalent dissolved salts

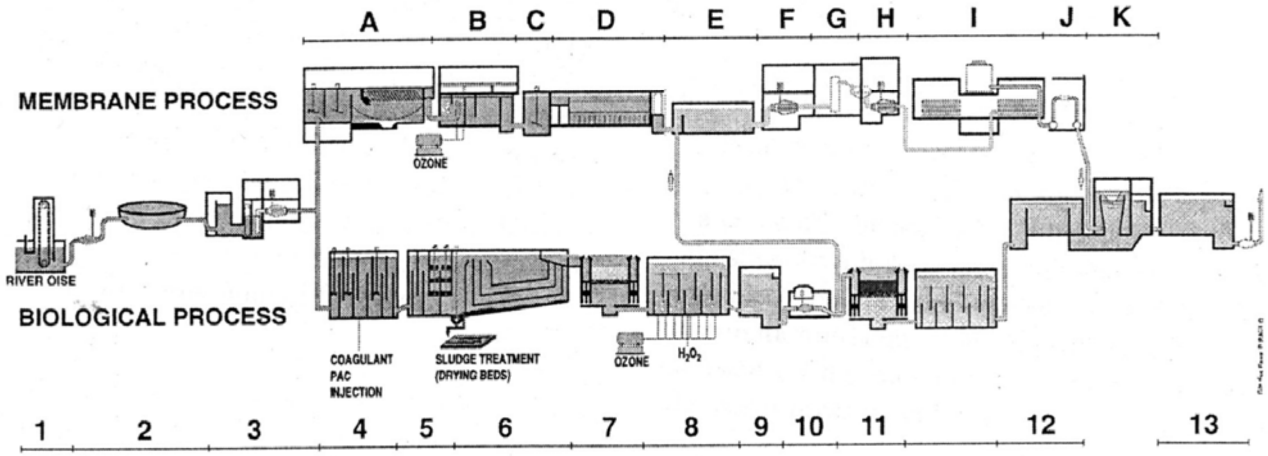
Mery-sur-Oise, Paris

- One of the biggest NF treatment plant in the world.
- Removal of humic substances and atrazine (pesticide) from polluted river water
- Production capacity 140.000 m^3/d, 9.120 NF200 modules
- Recovery 85%



Mery-sur-Oise Drinking Water Treatment Plant

A - Actiflo clarifiers
B - Ozone contact basins
C - Coagulant flash mixers
D - Dual layer filters
E - Intermediate tank
F - Low pressure pump
G - Cartridge prefilters
H - High pressure pumps
I - Nanofiltration skids
J - UV reactor
K - Mixing

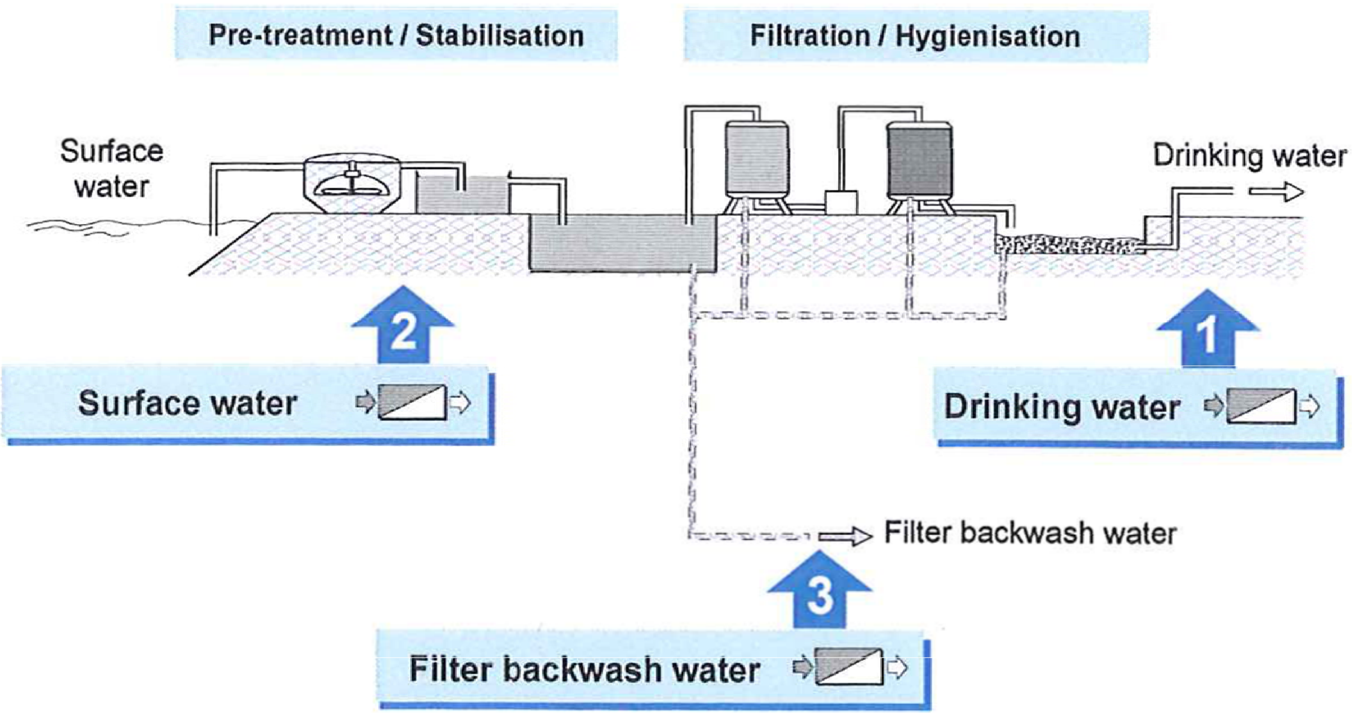


1 - Water intake
2 - Raw water storage
3 - Intake tank
4 - Flash mixers
5 - Flocculators
6 - Sedimentation tanks
7 - Sandfilters
8 - Ozone contact basins
9 - Intermediate tanks
10 - Pumps
11 - Biological activated carbon filters
12 - Chlorine contact reservoir
13 - Storage reservoir - Pumping station

UF and MF applications

- For removal of particulate matter, bacteria, colloids and high molecular weight soluble matter.
- To replace the traditional chemical treatment in drinking water production
- Preatreatment for RO
- In membrane bioreactors
- In combination with chemical flocculation and powdered activated carbon to advanced organic matter removal.

UF applications in water treatment



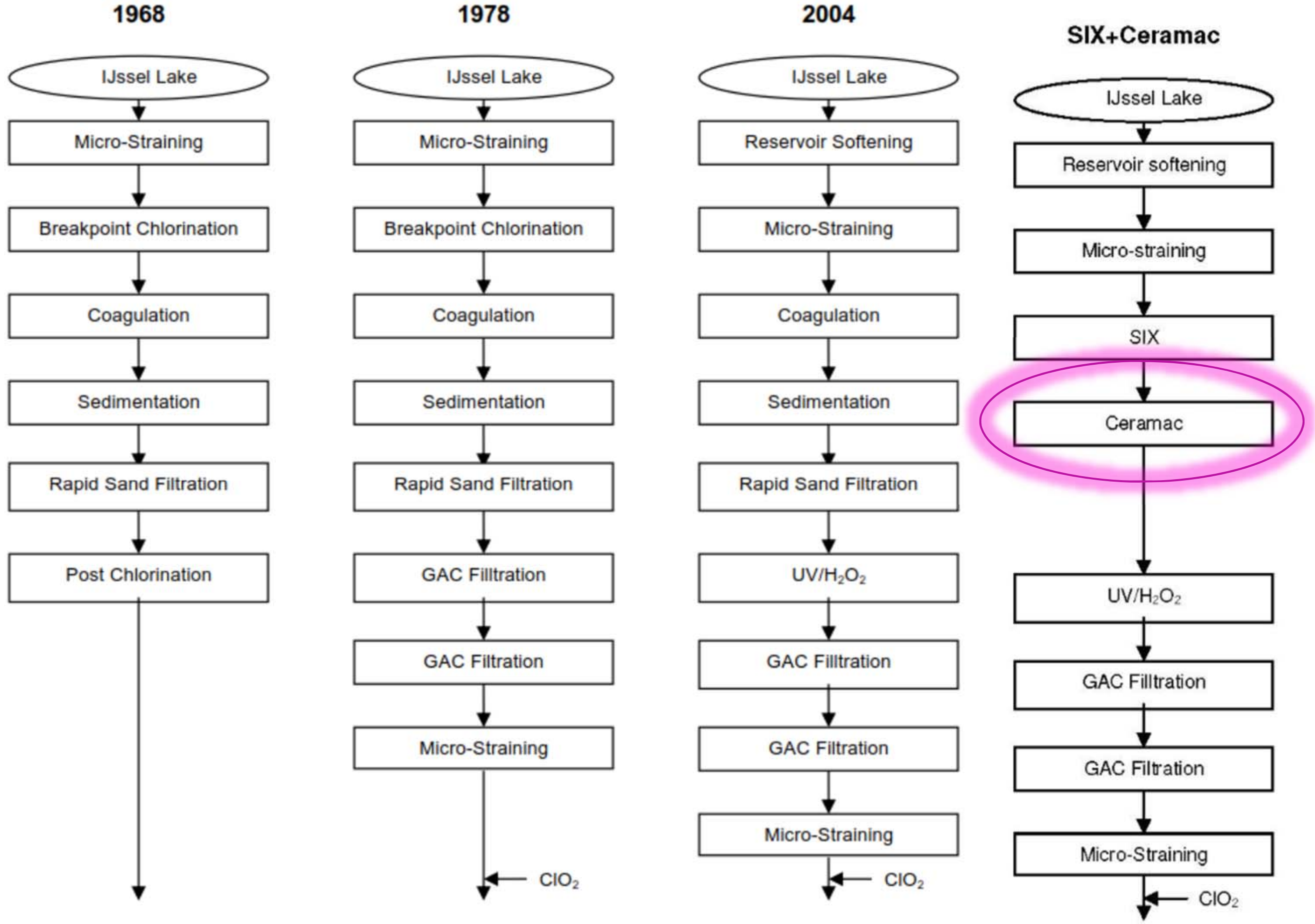
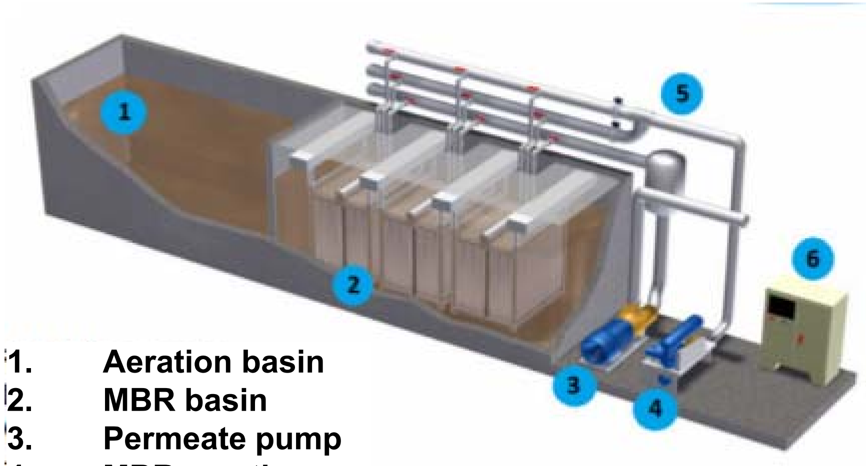


Figure 4: Technologic progression of WTP Andijk from 1968-2004

GaljaardG et al. (2011) Performance evaluation six ® -ceramac® in comparison with conventional pre-treatment techniques for surface water treatment. Water Practice & Technology 6(4)

Membrane Bioreactor MBR

- MBR combines activated sludge process for organic matter removal and membrane process for mechanical sludge removal
- Taskila, Oulu, Finland
  - Operation started October 2018
  - production capacity 216 m^3/h (T < 10 ^oC) / 288 m^3/h (T > 10 ^oC)
  - Effluent organic matter, phosphorus and suspendid solids concentrations remarkably lower than environmental permission, nitrogen concentration didn't comply in the beginning, microbial quality of the effluent excellent



1. Aeration basin
2. MBR basin
3. Permeate pump
4. MBR aeration compressor
5. Permeate and air lines
6. Control panel