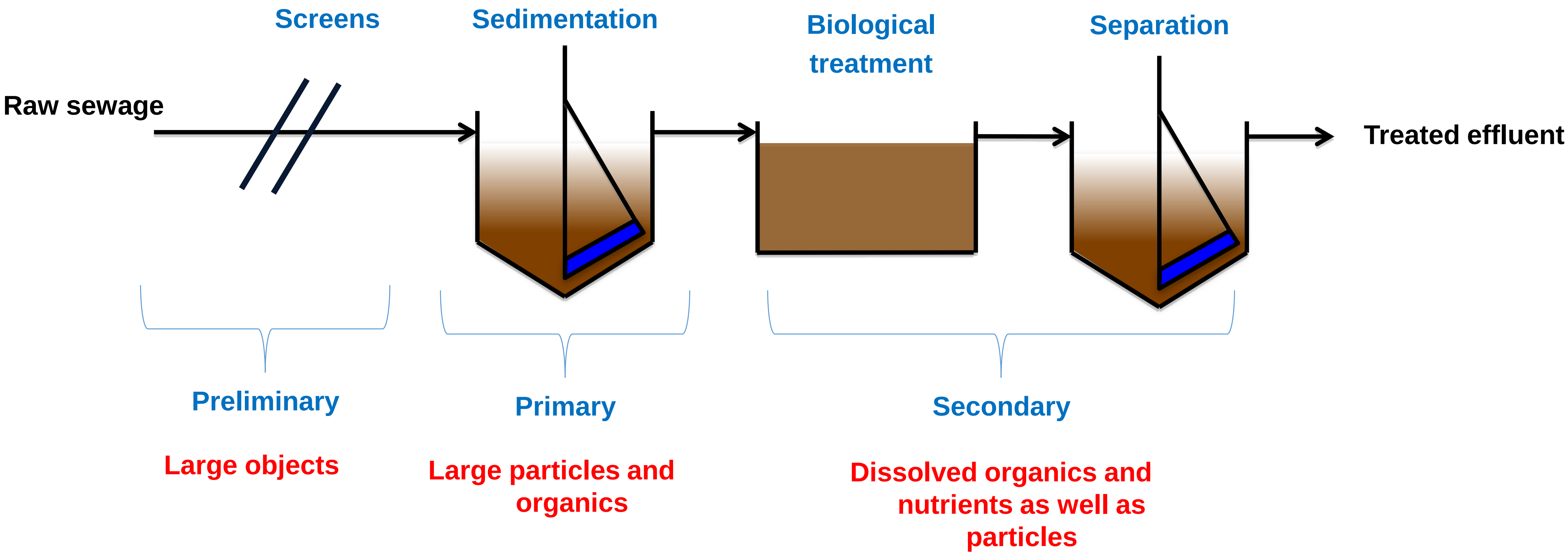
Water recycling technologies

Dr Marc Pidou

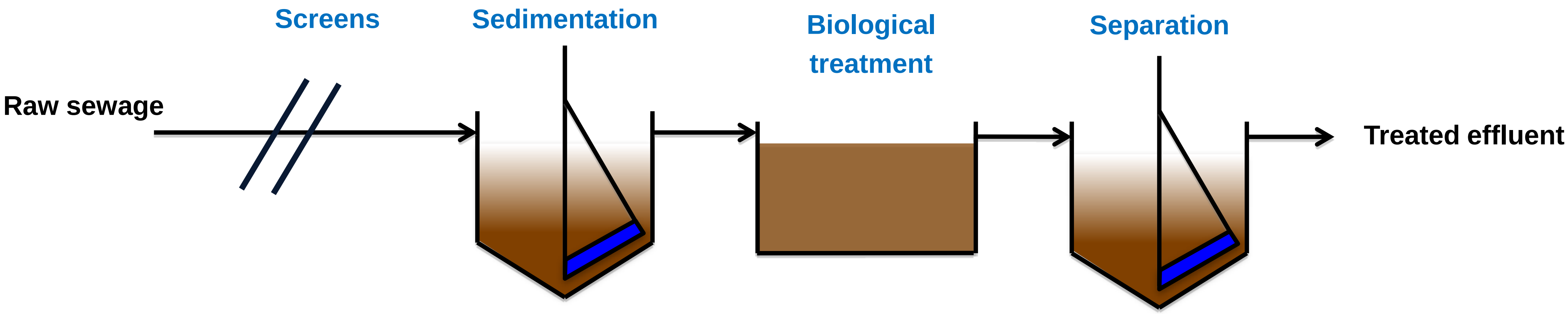
Wastewater treatment plant



Urban wastewater treatment directive

Biochemical oxygen demand (BOD_5)	25 mg/L
Chemical oxygen demand (COD)	125 mg/L
Total suspended solids	35 mg/L for more than 10 000 p.e. 60 mg/L for 2 000-10 000 p.e.
Total phosphorus	1 mg/L for more than 100 000 p. e. 2 mg/L for 10 000 - 100 000 p. e.
Total nitrogen	10 mg/L for more than 100 000 p.e. 15 mg/L for 10 000 - 100 000 p. e.

Wastewater treatment plant



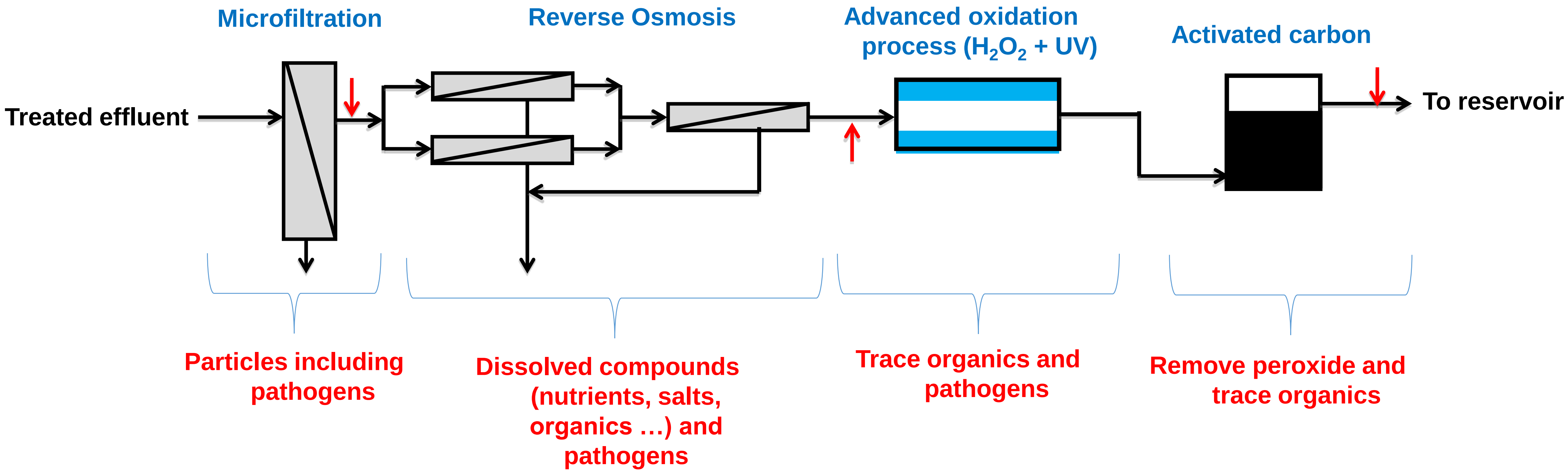
Typical raw sewage characteristics

	Units	Low	Medium	High
BOD_5	mg/L	110	190	350
COD	mg/L	250	430	800
Total suspended solids	mg/L	80	140	260
Total nitrogen	mg/L	20	40	70
Total phosphorus	mg/L	4	7	12
Total coliforms	No./100 mL	10^6 - 10^8	10^7 – 10^9	10^7 - 10^{10}

Budds Farm WwTW Treated Effluent

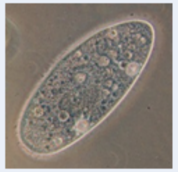
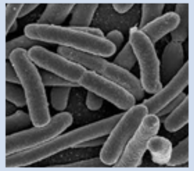
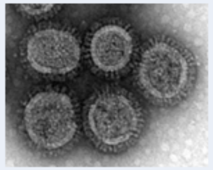
		Minimum	Maximum	Average	95^{th} Percentile	Count
BOD_5	mg/L	ND	25.6	3.25	7.63	238
COD	mg/L	14.7	318	57.4	92.7	244
TSS	mg/L	ND	94.3	13.2	27.3	249
TN	mg/L as N	5.6	11	7.75	10.2	27
TP	mg/L as P	0.622	4.97	2.89	4.57	248

Advanced treatment for indirect potable water recycling



Important parameters for water recycling

Micro-organisms: seen as the most significant risk

Organisms		Size	Comments
	Helminths (parasitic worms)	1-60 µm	Very resistant to environmental stresses but easily removed by conventional treatment
	Protozoa	1-20 µm	Very infectious but found in low numbers in secondary treated effluent
	Bacteria	0.2-10 µm	Found in very high concentrations in wastewater but not all are pathogenic
	Viruses	10-300 nm	Persistent and very infectious

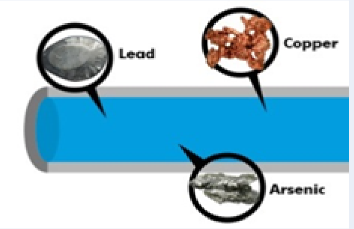
Important parameters for water recycling

Micro-organisms: seen as the most significant risk

USEPA (2012)

Type of Microorganism	Indicator microorganisms			Pathogenic microorganisms				
	Escherichia coli (indicator bacteria)	*Clostridium perfringens*	Phage (indicator virus)	Enteric bacteria (e.g., *Campylobacter*)	Enteric viruses	*Giardia lamblia*	*Cryptosporidium parvum*	Helminths
Bacteria	X	X		X				
Protozoa and helminths						X	X	X
Viruses			X		X			
Indicative Log Reductions in Various Stages of Wastewater Treatment[1]								
Secondary treatment	1 - 3	0.5 - 1	0.5 - 2.5	1 - 3	0.5 - 2	0.5 - 1.5	0.5 - 1	0 - 2
Dual media filtration[2]	0 - 1	0 - 1	1 - 4	0 - 1	0.5 - 3	1 - 3	1.5 - 2.5	2 - 3
Membrane filtration (UF, NF, and RO)[3]	4 - >6	>6	2 - >6	>6	2 - >6	>6	4 - >6	>6
Reservoir storage	1 - 5	N/A	1 - 4	1 - 5	1 - 4	3 - 4	1 - 3.5	1.5 - >3
Ozonation	2 - 6	0 - 0.5	2 - 6	2 - 6	3 - 6	2 - 4	1 - 2	N/A
UV disinfection	2 - >6	N/A	3 - >6	2 - >6	1 ->6	3 - >6	3 - >6	N/A
Advanced oxidation	>6	N/A	>6	>6	>6	>6	>6	N/A
Chlorination	2 - >6	1 - 2	0 - 2.5	2 - >6	1 - 3	0.5 - 1.5	0 - 0.5	0 – 1

Important parameters for water recycling

Chemicals		Hazard	Treatment
	Salts	Negative impact on fresh waters, soils and crops Cause scaling and /or corrosion	Advanced treatment required such as reverse osmosis, distillation or electro-dialysis
	Metals	Toxic to plants, animals and humans	Significant removal by conventional systems Advanced treatment required for high-risk application (potable uses)
	Nutrients	Contribute to eutrophication Help micro-organisms growth	Removed in conventional treatment

Important parameters for water recycling

Organic matter

Impact	Treatment
Aesthetic: odour and colour Help micro-organisms growth Reduce efficiency of disinfection systems	Significant removal by conventional treatment

Trace organics:
pharmaceuticals, pesticides, personal care products, endocrine disrupting compounds (EDCs) and disinfection by-products (DBPs)

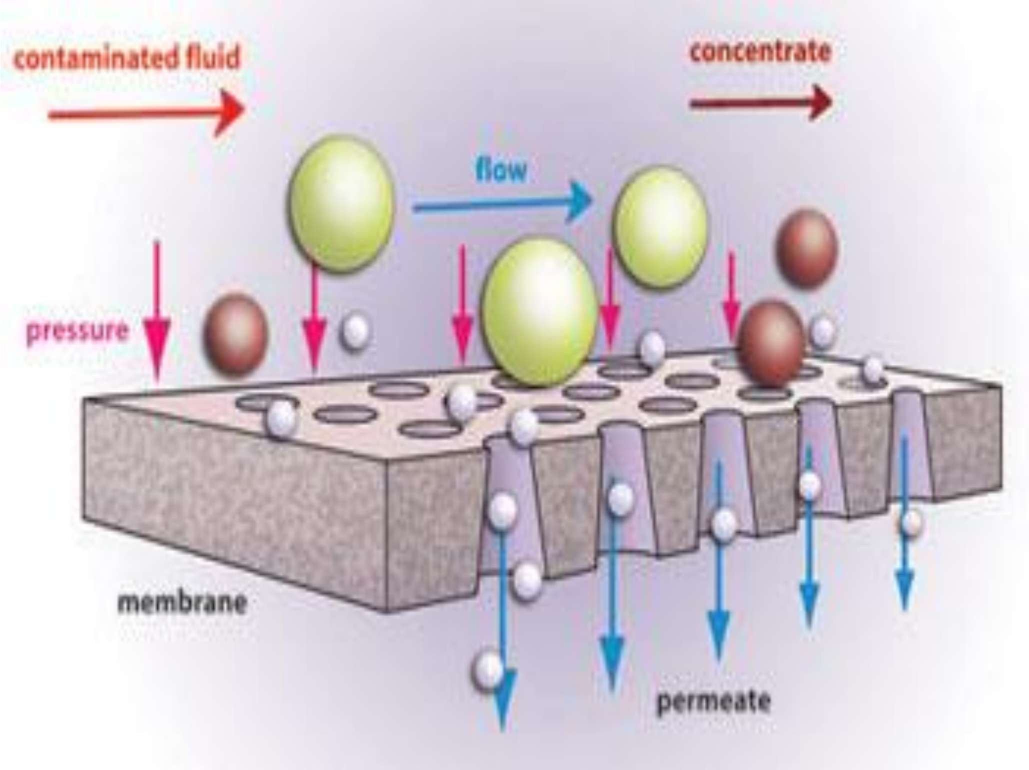
Advanced treatment required such as RO, advanced oxidation processes (AOPs) and/or adsorption

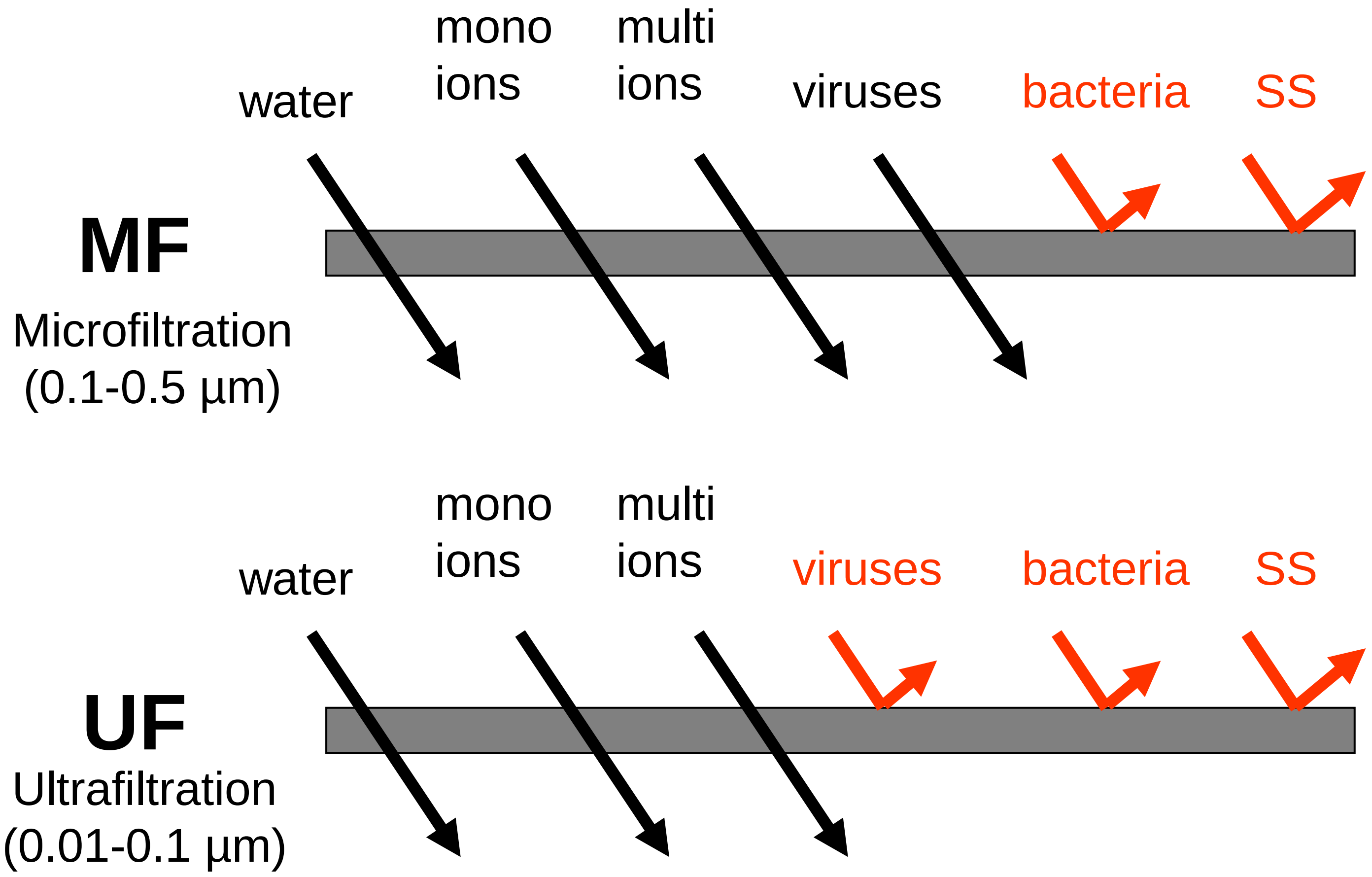
Important parameters for water recycling

Parameters	Impact	Treatment
Suspended solids Turbidity	Aesthetic: odour and colour Help micro-organisms growth Reduce efficiency of disinfection systems	Significant removal by conventional treatment
pH	Can promote scaling and /or corrosion	Adjustment at any stage

Microfiltration

Porous membranes





Separation by size exclusion
(removes things bigger than pore size)

Microfiltration

Why do we use membranes?

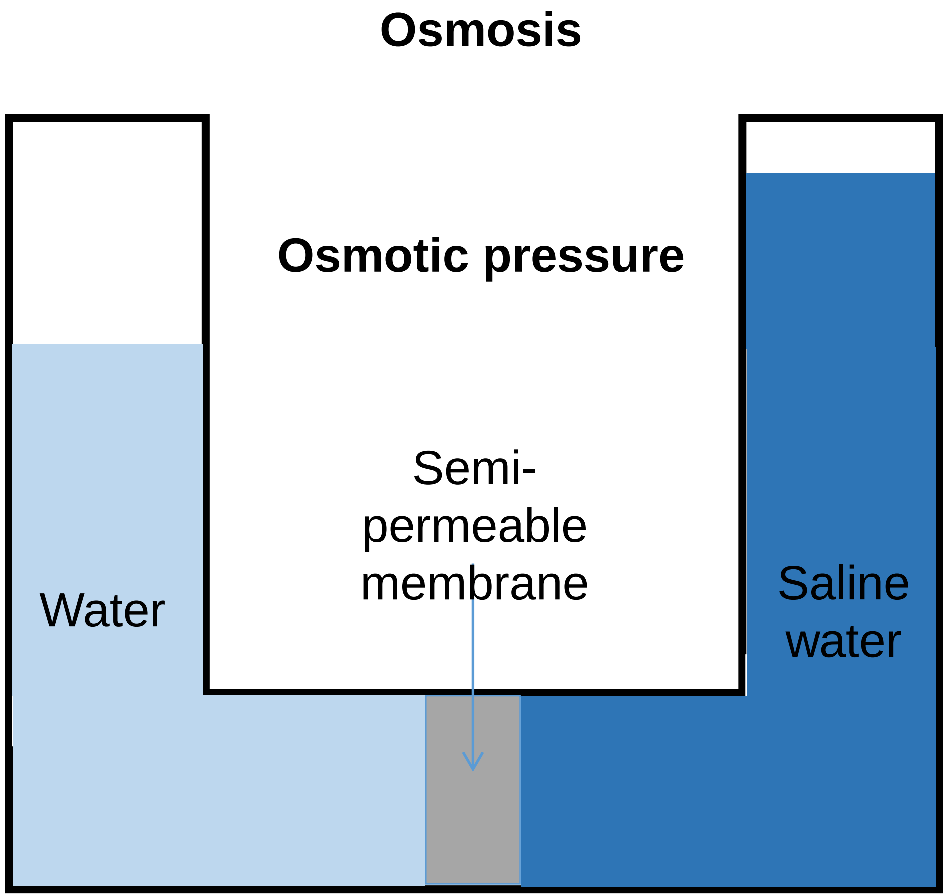
Physical barrier to pollutants (effective removal of particulate matter and pathogens)

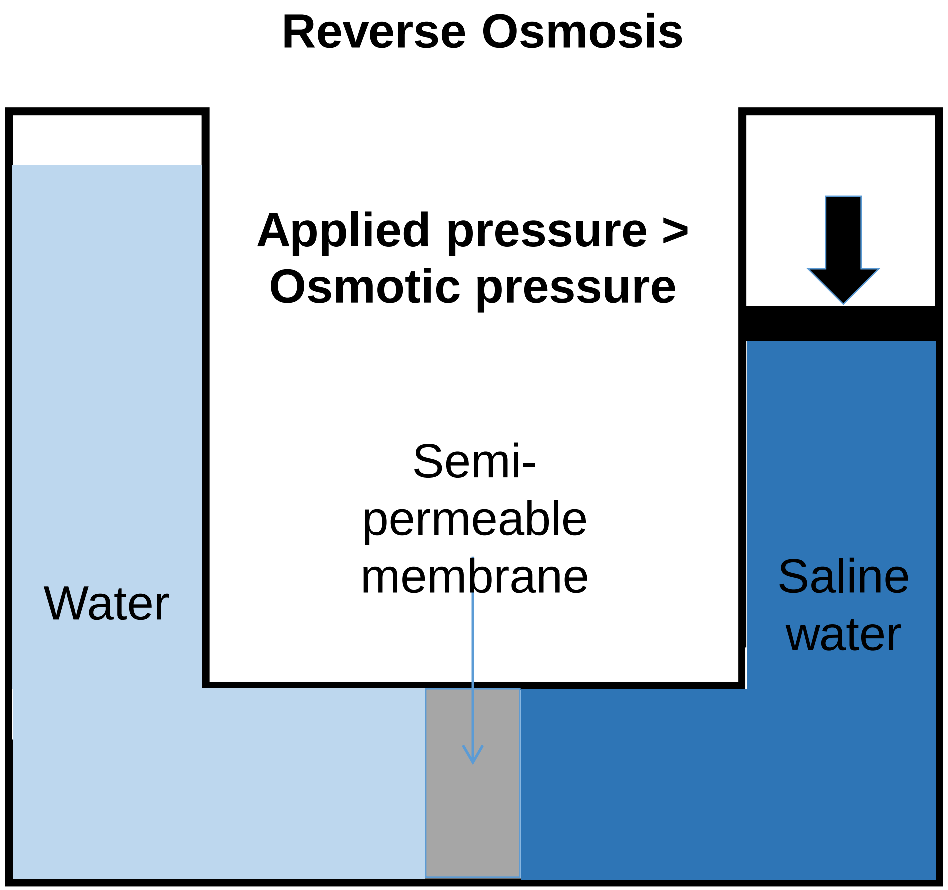
Small footprint

Easily automated

Reverse osmosis membranes

	Osmotic pressure (bar)	Process pressure (bar)
Sea water	23-32	40-80
Treated effluent	0.4-4	2-17

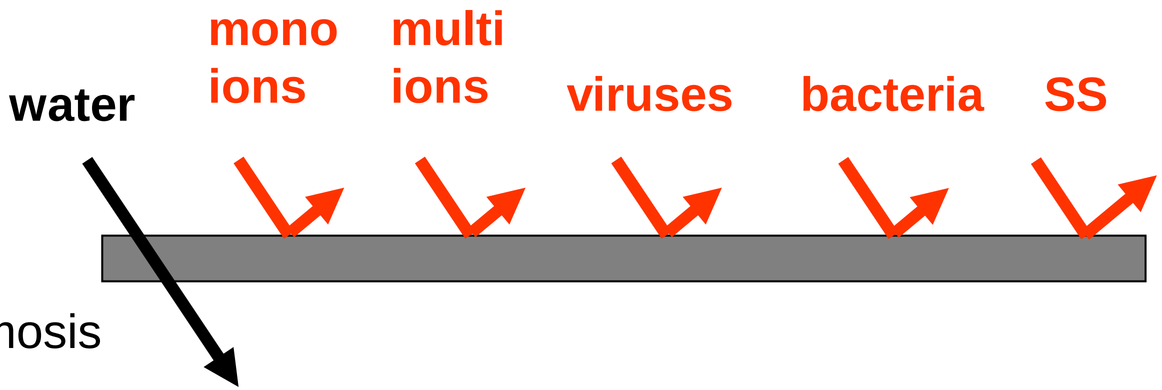




Reverse osmosis membranes

RO

Reverse Osmosis



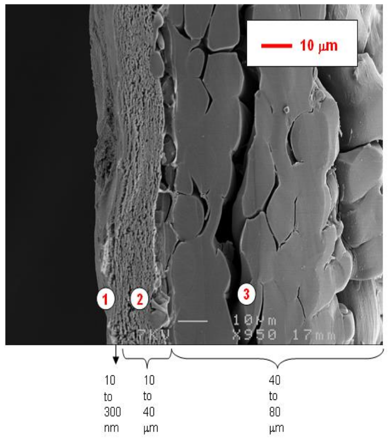
Separation by diffusion/selectivity

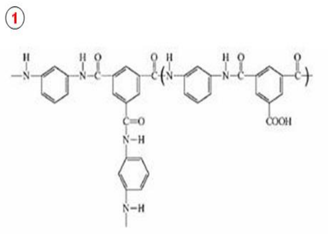
Commonly used for desalination

Will produce deionised water (>90% removal of salts and other dissolved compounds)

They can’t remove very small uncharged inorganic and organic molecules

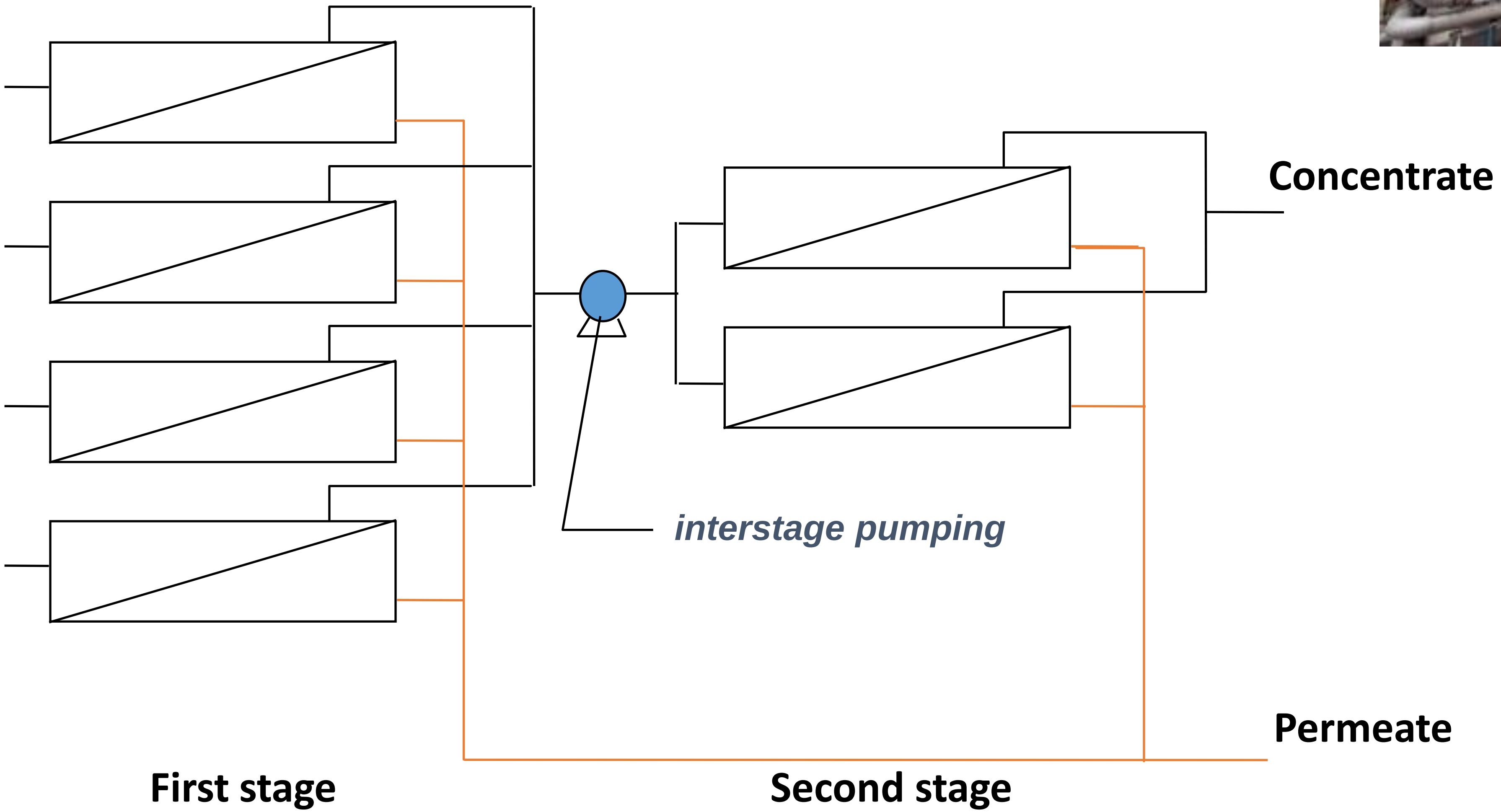
Dense membranes





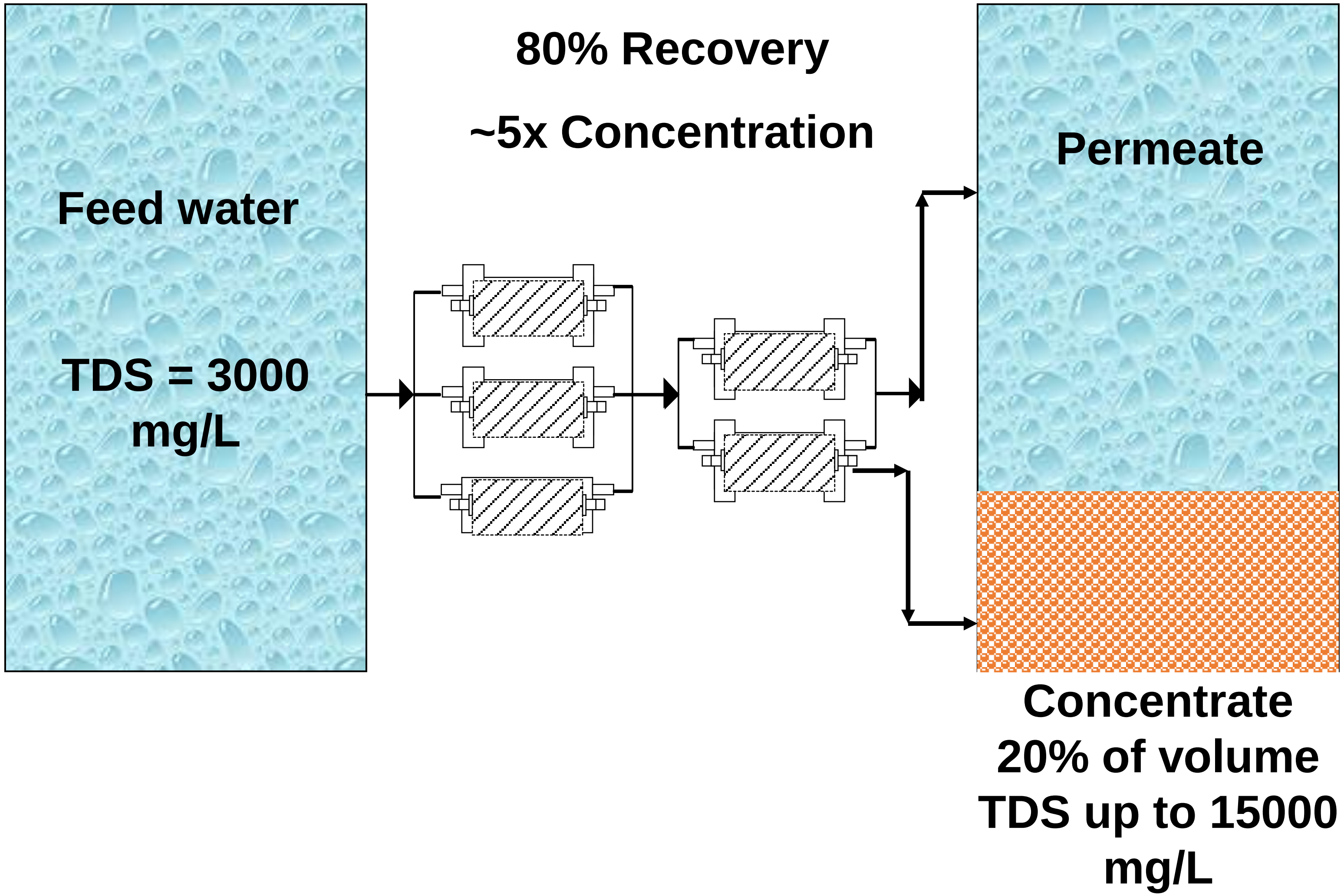
Reverse osmosis membranes

Staging to increase recovery



Reverse osmosis membranes

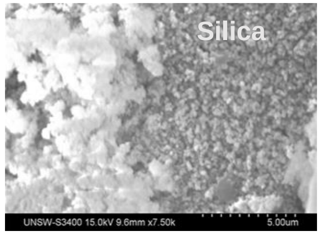
Concentration



Membrane operation

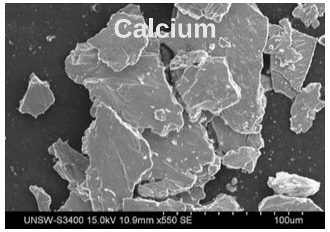
Membrane fouling = reduce flow and/or increase pressure

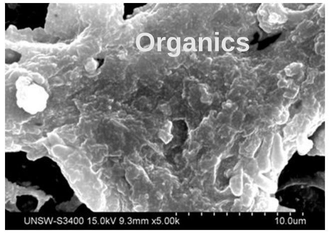
undesired adsorption and deposition of material present in the feed on the membrane surface



Particulate fouling

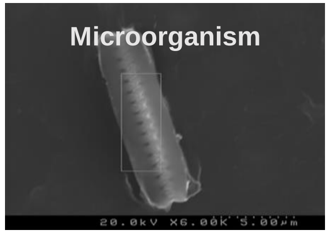
Inorganic fouling





Organic fouling

Biofouling



Membrane operation

Fouling control

- Remove material in pretreatment (e.g. particles with MF membrane)
- Control during operation (chemical dosing: disinfection for biofouling and anti-scalant for inorganic fouling)
- Remove periodically:
  - Physical cleaning (backwash – only for MF/UF)
  - Chemical cleaning (acid and alkaline chemicals)

Reject streams

Backwash from MF

Concentrate from RO

↓

Will contain the compounds rejected by the membranes which would have been discharged with the effluent

The risk is associated with the concentration (rapid dispersion needed)

Anything else?

Chemical cleaning solutions (they have to be neutralised)

Antiscalant

Polishing steps

Advanced oxidation processes: Hydrogen peroxide (H_2O_2) + UV

Hydrogen peroxide reacts with UV light to form a very strong oxidant ($OH^{\cdot}$) which will decompose the trace organics remaining in the water

Activated carbon

Removal of hydrogen peroxide and any trace organics remaining by adsorption

Remineralisation

To reduce the corrosivity of the water

- Aggressiveness index
- Ryznar index
- Langelier Saturation Index

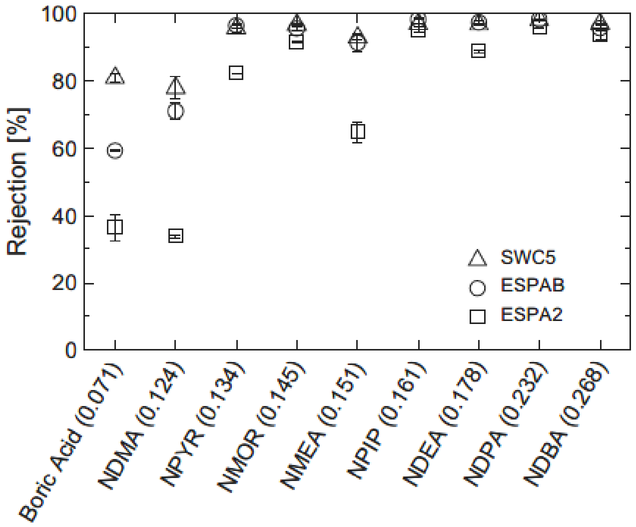
Dosing of salts/minerals

- Carbon dioxide
- Calcium carbonate
- Lime
- Sodium chloride

- Possible disinfection

Trace organics – RO rejection

Impact of molecule size



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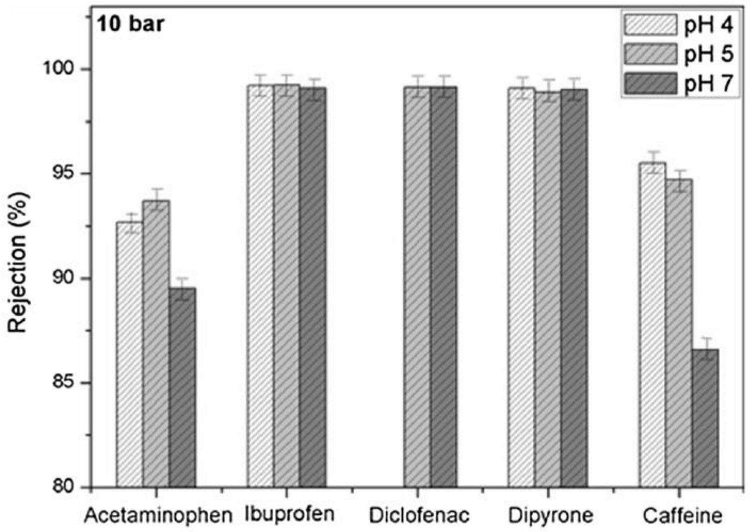
Pharmaceuticals



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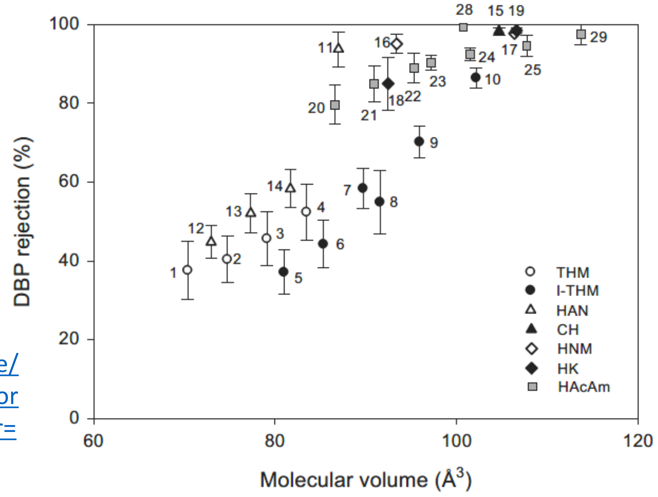
Pesticides

Pesticide	Input [µg/dm³]	Permeate [µg/dm³]	Retention factor [%]	Concentrate [µg/dm³]
α-HCH	135	0.8	99.4	1430
β-HCH	67.2	0.6	99.1	723
γ-HCH	37.2	0.6	98.4	402
HCB	9.0	< 0.2	> 97.8	98.0
2,4´-DDE	0.7	< 0.2	–	7.3
4,4´-DDE	3.5	< 0.2	–	33.4
2,4´-DDD	39.1	< 0.2	>99.5	415
4,4´-DDD	0.8	< 0.2	–	8.5
2,4´-DDT	63.3	0.2	99.7	625
4,4´-DDT	201	0.6	99.7	2130
Total	556.8	3.0	99.5	5872.2

https://app.amanote.com/v4.1.9/research/note-taking(modal:authentication-modal/modal/login)

Disinfection byproducts



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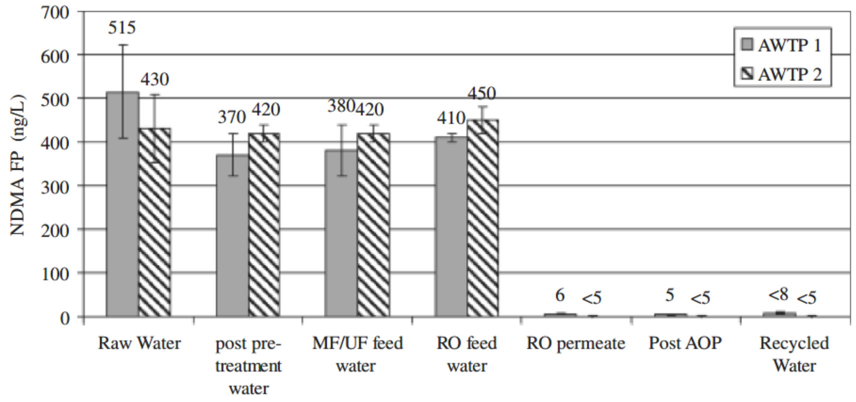
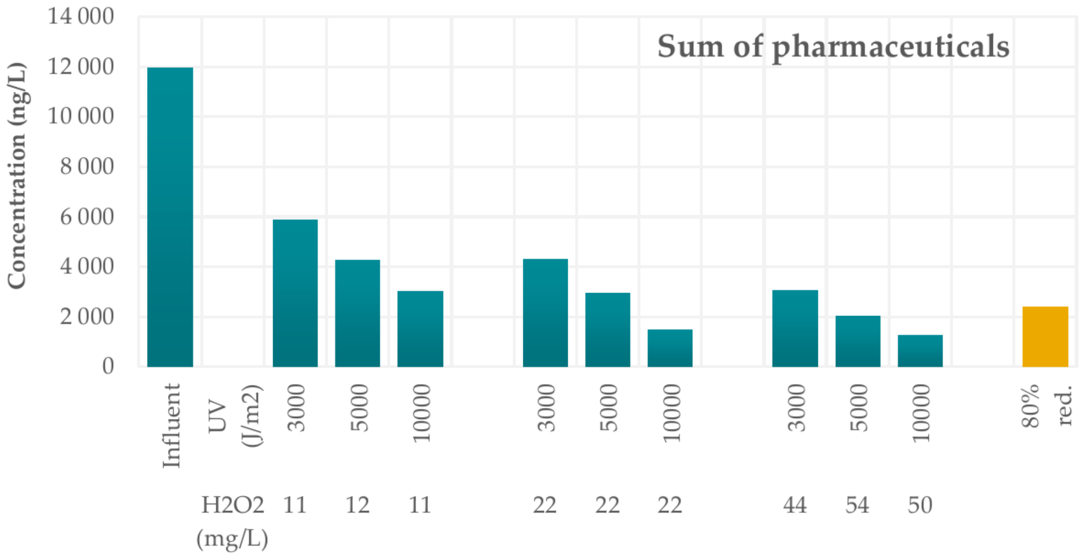


https://iwaponline.com/wst/article/63/4/605/16161/Occurrence-of-N-nitrosodimethylamine-precursors-in

Hydrogen peroxide/UV

Pharmaceuticals



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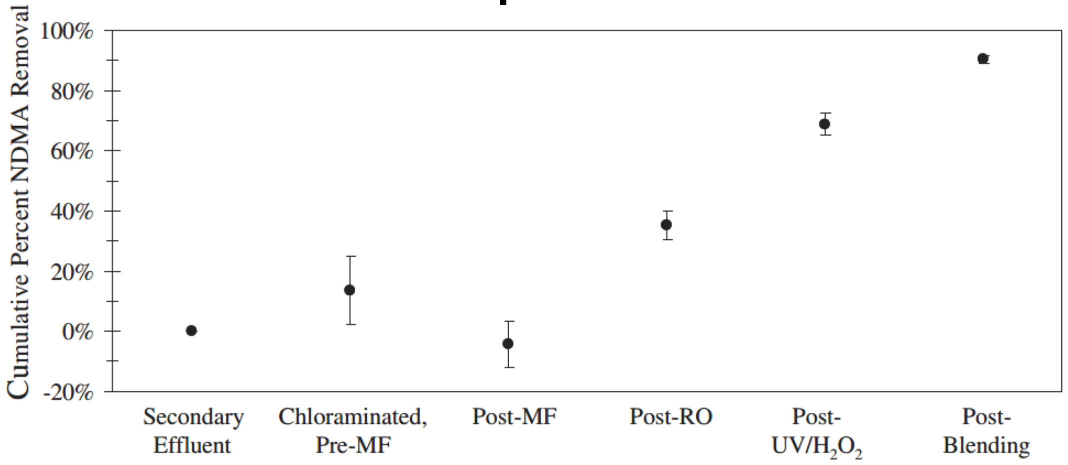
Example of NDMA



https://www.sciencedirect.com/science/article/pii/S0043135407004976?via%3Dihub

Activated carbon

Concentration of TOPs (ng/L) and the removal of TOPs at 30 g/L shell GAC dose.

Category	Chemicals	GAC dosage (g/L)						Removal (%)
		0	2.5	5	10	20	30	
Pesticides	Atrazine	5.8	4.6	3.7	2.9	1.7	1.2	80.00
	Prometryn	0.2	0.2	0.1	–	–	–	100.00
	Chlorpyrifos	3.5	2.8	1.7	1.8	1.7	–	100.00
	Dipterex	6	4	3.1	2.5	1.6	0.4	93.33
	Acetamiprid	18.6	14.5	11.7	9.1	4.9	2.8	84.95
	Imidacloprid	2.2	1.5	1.2	0.7	0.2	0	100.00
	Thiamethoxam	5.8	4.6	4.8	3.4	1.8	1.6	72.41
	Azoxystrobin	6.3	4.7	3.8	2.7	1.3	0.7	88.89
	Carbendazim	284.8	199.2	149.6	93.9	38.8	20.5	92.80
	Dimethomorph	5.4	4.1	3.5	2.7	1.4	0.9	83.33
	Difenoconazole	1.5	0.9	0.7	0.3	–	–	100.00
	Prochloraz	1.2	0.7	0.4	0.2	–	–	100.00
Pharmaceuticals	Diclofenac acid	521.1	476.5	405.4	342	209.1	160.1	69.28
	Ibuprofen	22.1	15.1	17.2	15.6	11.3	8.3	62.44
	Mefenamic Acid	112.5	93	80.6	61	28.5	22.7	79.82
	Clarithromycin	4.4	3.9	3.1	2.5	1.5	1.1	75.00
	Roxithromycin	28	24.5	20	15.4	9.2	6.3	77.50
	Sulfamethoxazole	16	12.6	10.9	9.2	6.2	3.95	75.31
	Trimethoprim	7.5	5.5	4.4	2.9	1.2	0.7	90.67
	Carbamazepine	27.5	21.6	16.8	12.5	7.6	4.3	84.36
	Diphenhydramine hydrochloride	71.6	48.2	36.5	23.8	10.1	5.7	92.04

https://www.sciencedirect.com/science/article/pii/S0048969720351408?via%3Dihub

Microplastics

Definition:

Plastic particles/debris of size ranging from 1 to 5000 µm and 1–1000 nm are referred to as micro plastics (MPs) and nanoplastics (NPs), respectively.

https://www.sciencedirect.com/science/article/pii/S0048969723052749

	Treatment plant type/Location	Membrane characteristics	MP abundance in effluent (MP/L)	Removal efficiency (%)	Reference
MF	Laboratory	Material: PVDF and Pore size: 0.1 µm	–	Up to 91%	Pramanik *et al.* (2021)
MF	Laboratory	Material: PC and pore size: 5 µm Material: CA and pore size: 5 µm Material: PTFE and pore size: 5 µm	33,000–127,000 8,000–27,000 46,000–47,000	96.8–99.6[a] 94.3–99.8[a] 96–99.6[a]	Pizzichetti *et al.* (2021)
MF	WTP/Indonesia	Pore size: 0.05 µm	5	81.5	Marsano *et al.* (2022)
MF	Laboratory	Material: SiC support and SiC membrane, maximum pore size: 604 nm	1,250	98.5	Luogo *et al.* (2022)
MF	WWTP/Germany	Pore size: 0.1 µm	0.67 µg/L	>94	Bitter *et al.* (2022)
MF	WWTP/Iran	Material: PVDF and PET, pore size: 0.1 µm	0–2	98.1–100	Yahyanezhad *et al.* (2021)
UF	Laboratory	Material: PES, MWCO: 100 kDa	–	Up to 96	Pramanik *et al.* (2021)
UF	LLTP/China	–	~0.1	75	Zhang *et al.* (2021)
UF	Laboratory	Material: SiC support and ZrO_2 membrane, maximum pore size: 74 nm	450	99.2	Luogo *et al.* (2022)
UF	WTP/Indonesia	Pore size: 0.07 µm	22	37.1	Marsano *et al.* (2022)
UF	Laboratory	Material: PVDF, Pore size:30 nm, module: flat sheet	0	100	Ma *et al.* (2019)
UF	WWTP/Thailand	Material: PES/PVP blend, pore size: 0.1 µm	2.33	78.16	Tadsuwan & Babel (2022)
UF	LLTP/Turkey	–	6.5	96	Kara *et al.* (2023)
UF NF	LLTP/Turkey	–	~10 2	96 99	Kara *et al.* (2023)
NF	DWTP/France	Material: polypiperazine-amide and PSf MWCO: 400 Da, Pore size: ~ 1 nm	0–0.018	–	Barbier *et al.* (2022)
RO	DWTP/Spain	–	0.06	54 ± 27	Dalmau-Soler *et al.* (2021)
RO (permeate) RO (retentate)	LLTP/China	Pore size: 0.1 nm	0.4 9.5	~ 99.8 –	Sun *et al.* (2021)
RO	WWTP/Australia	–	0.21	–	Ziajahromi *et al.* (2017)
MBR sludge	WWTP/Italy	Pore size: 0.04 µm module: hollow fiber submerged UF	81.1×10^3 (MP/ kg)	–	Di Bella *et al.* (2022)
MBR	LLTP/China	–	~0.5	50	Zhang *et al.* (2021)
MBR	WWTP/Spain	Module: flat sheet submerged membrane	1.21	79	Bayo *et al.* (2020)
MBR	WWTP/China	Material: PVDF, pore size: 0.1 µm, module: hollow fiber submerged membrane	–	82.1	Lv *et al.* (2019)
MBR (permeate) MBR (sludge) (27.3 (±4.7) MP/g dw	WWTP/Finland	Pore size: 0.4 µm, module: flat sheet submerged membrane	0.4 27.3 (MP/g)	99.4 –	Lares *et al.* (2018)

(Continued.)

https://iwaponline.com/wst/article/88/1/199/95676/A-review-of-microplastic-removal-from-water-and

PFAS ("forever chemicals")

Membrane	Type	Feed water			PFAS Rejection (%)	Ref.
		pH	Concentration (μg·L^{-1})	Compositions		
		NA	1.0×10^3 (HFPO-DA)	500.0 mg·L^{-1} Na_2SO_4,100.0 mg·L^{-1} NaCl	99.5 (HFPO-DA)	[61]
	DK	5.0–6.0	150.0–400.0 (PFPnA,PFBS,PFHxA,PFHpA,PFHxS,PFOA,6:2 FTS,PFNA,PFOS,FOSA,PFDA,PFUnA,PFDS,PFDoA,PFTA)	DI water	chromatographically resolved (PFPnA), ≥95.0 (Others)	[44]
		4.0	1.0×10^4 (PFOS)	DI water	90.0–99.0 (PFOS)	[31]
	DL	5.0–6.0	150.0–400.0 (PFPnA,PFBS,PFHxA,PFHpA,PFHxS,PFOA,6:2FTS,PFNA,PFOS,FOSA,PFDA,PFUnA,PFDS,PFDoA,PFTA)	DI water	chromatographically resolved (PFPnA), 42.0 (FOSA), ≥95.0 (Others)	[44]
	NF200	5.0–6.0	150.0–400.0 (PFPnA,PFBS,PFHxA,PFHpA,PFHxS,PFOA,6:2FTS,PFNA,PFOS,FOSA,PFDA,PFUnA,PFDS,PFDoA,PFTA)	DI water	chromatographically resolved (PFPnA), ≥95.0 (Others)	[44]
	XN45	NA	1.0×10^2-1.0×10^6 (PFOA)	DI water	58.0–90.0 (PFOA)	[66]
	2540-ACM5-TSF	NA	100.0 (PFOA)	spiked groundwater	98.8–99.2 (PFOA)	[67]
				DI water	99.1–99.9 (PFOA)	
	HYDRACORE	NA	100.0 (PFOS)	DI water	48.0–60.0 (PFOS)	[59]
				20.0 mg·L^{-1} HA	40.0–55.0 (PFOS)	
	NE70	6.5	1.0 (PFOS,PFOA)	DI water	71.0 (PFOA),42.0 (PFOS)	[69]
		7.1		Surface water	79.0 (PFOA),65.0 (PFOS)	
		7.0		Groundwater	80.0 (PFOA,PFOS)	
	NTR7450	3.3,7.0,10.0	1.0×10^5-2.0×10^6 (PFHxA)	DI water	>96.0 (PFHxA)	[52]
	ESNA1-K1	7.0	100.0 (PFOS)	0.1–2.0 mM of Fe^{2+}, Mg^{2+}, Na^+, SO_4^{2-}, PO_4^{3-} and Cl^-	92.1–99.1 (PFOS)	[73,74]
	NFG	NA	100.0 (PFHxA,PFOA,PFBS,PFHxS,PFBA,PFOS)	DI water	40.0 (PFHxA),60.0 (PFOA),94.0 (PFBS), 65.0 (PFBA),25.0 (PFHxS),30.0 (PFOS)	[60]
Lab-synthesized NF	TFC[b]	3.2–9.5	100.0 (PFOS)	DI water	89.0–97.0 (PFOS)	[75]
		7.0		0.1–2.0 mM Ca^{2+}	94.0–99.5 (PFOS)	
	PAC[c]-NF	NA	3.0×10^3 (PFOA)	non-settleable powder activated carbon	55.0 (PFOA)	[66]
	HT[d]-NF			non-settleable (within 1 h) hydrotalcite	86.0 (PFOA)	
	TFC	7.0	1.0×10^3 (PFOA)	5.0 mg·L^{-1} $CaCl_2$ 5.0 mg·L^{-1} Na_2SO_4	89.0–92.0 (PFOA)	[39,45]
			25.0,50.0,100.0,150.0 (PFOS,PFBS)	DI water	88.0–92.5 (PFOS),48.0–50.5 (PFBS)	
			50.0 (PFOS,PFBS)	10.0,50.0 and 100.0 mM NaCl	89.6–91.9 (PFOS),48.9–20.5 (PFBS)	
			50.0 (PFOS,PFBS)	10.0 mg·L^{-1} BSA or SA	91.4–95.6 (PFOS),46.3–68.6 (PFBS)	
	TFC	7.0	1.0×10^3 (PFOA)	5.0 mM NaCl,$CaCl_2$,Na_2SO_4 DI water	86.0–89.0 (PFOA)	[39]
	4 wt% OOMT nanocomposite membranes	7.0	20.0–200.0 (PFOS)	DI water	72.5–92.5 (PFOS)	[91]
			100.0 (PFOS)	10^{-2},0.1 mM SO_4^{2-}, PO_4^{3-}, and Cl^-	91.0–97.0 (PFOS)	
			100.0 (PFOS)	0.0–100.0 ug/L Pb^{2+}	83.0–95.0 (PFOS)	
	PEM[e]	7.0	1.0×10^3 (PFOS,PFOA)	5.0 mg·L^{-1} NaCl, $CaCl_2$, Na_2SO_4	35.0–90.0 (PFOA),65.0–90.0 (PFOS)	[54]
	SG	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	LFC1	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
Commercial RO	LFC3	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	BW30	4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.1 (PFOS)	[60]
		3.5–7.1	1.0×10^5 (PFHxA)	DI water	96.0->99.9 (PFHxA)	[53]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	ESPA3	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	ESPA-2540	7.0 ± 0.4	0.3–58.4 (PFPeA,PFHxA,PFHpA,PFOA,PFPrS, PFBS, PFPeS,PFHxS,PFHpS,PFOS)	AFFF Spiked water	>99.0 (ALL)	[32]
			0.1–2.7 (PFPeA,PFHxA,PFHpA,PFOA,PFPrS,PFBS,P FPeS,PFHxS,PFHpS,PFOS)	AFFF ground water		
	XLE	3.5–7.1	1.0×10^5 (PFHxA)	DI water	>97.5 (PFHxA)	[53]
	SW30XLE	3.5–7.1	1.0×10^5 (PFHxA)	DI water	>96.0 (PFHxA)	[53]

				DI water		
	SG	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	LFC1	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
Commercial RO	LFC3	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	BW30	4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.1 (PFOS)	[60]
		3.5–7.1	1.0×10^5 (PFHxA)	DI water	96.0->99.9 (PFHxA)	[53]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	ESPA3	4.0	1.0×10^4 (PFOS)	DI water	>99.0 (PFOS)	[31]
		4.0	5.0×10^2-1.6×10^6 (PFOS)	DI water	>99.0 (PFOS)	[77]
	ESPA-2540	7.0 ± 0.4	0.3–58.4 (PFPeA,PFHxA,PFHpA,PFOA,PFPrS, PFBS, PFPeS,PFHxS,PFHpS,PFOS)	AFFF Spiked water	>99.0 (ALL)	[32]
			0.1–2.7 (PFPeA,PFHxA,PFHpA,PFOA,PFPrS,PFBS, P FPeS,PFHxS,PFHpS,PFOS)	AFFF ground water		
	XLE	3.5–7.1	1.0×10^5 (PFHxA)	DI water	>97.5 (PFHxA)	[53]
	SW30XLE	3.5–7.1	1.0×10^5 (PFHxA)	DI water	>96.0 (PFHxA)	[53]

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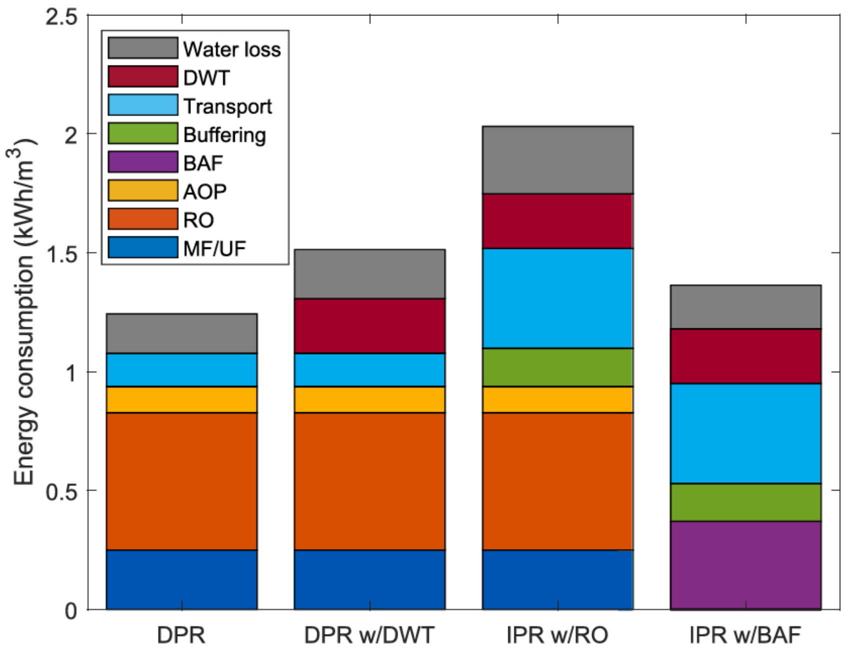
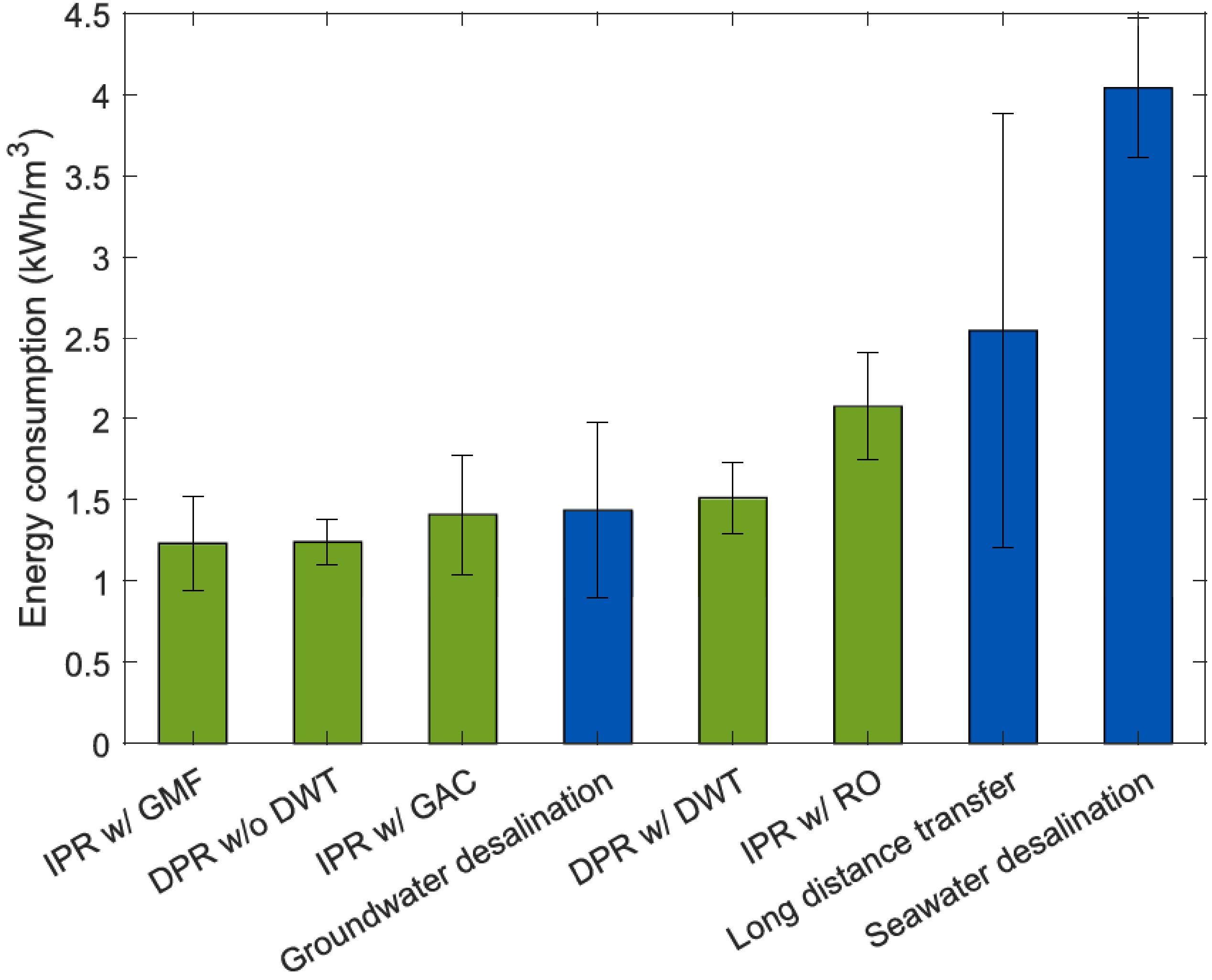
Energy use





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