Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations

An Introduction to Industrial Wastewater Treatment Technologies

Policies, Best Available Techniques and Membrane Processes in a Nutshell

Laurence Palmowski & Team

Presented by Sarah Müller

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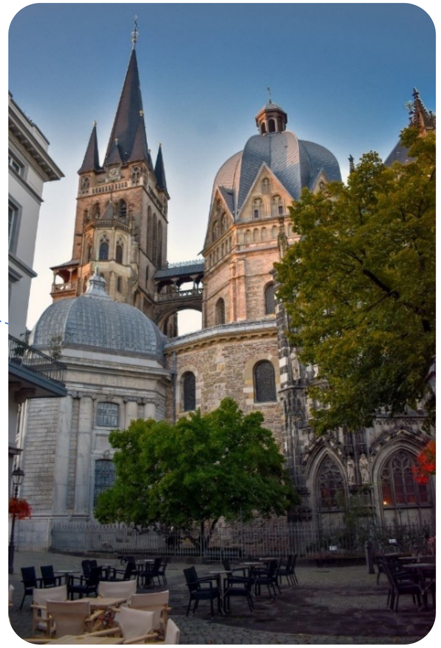
AquaSPICE @ RWTH Aachen University

Institute of Environmental Engineering

Univ.-Prof. Dr.-Ing. habil. Thomas Wintgens



AquaSPICE @ RWTH Aachen:

Dr.-Ing. Laurence Palmowski
palmowski@isa.rwth-aachen.de

Sarah Isabell Müller
mueller@isa.rwth-aachen.de

Stephan Dai
dai@isa.rwth-aachen.de

Sarah Müller
s.mueller3@isa.rwth-aachen.de

Research and Teaching @ ISA

RWTH Aachen University

industrial wastewater treatment

energy efficiency & sustainability

water quality management

wastewater treatment

urban drainage

water supply & water reuse

sewage sludge treatment

resources management

environmental analysis

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Interactive Session

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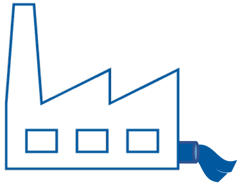
Outline

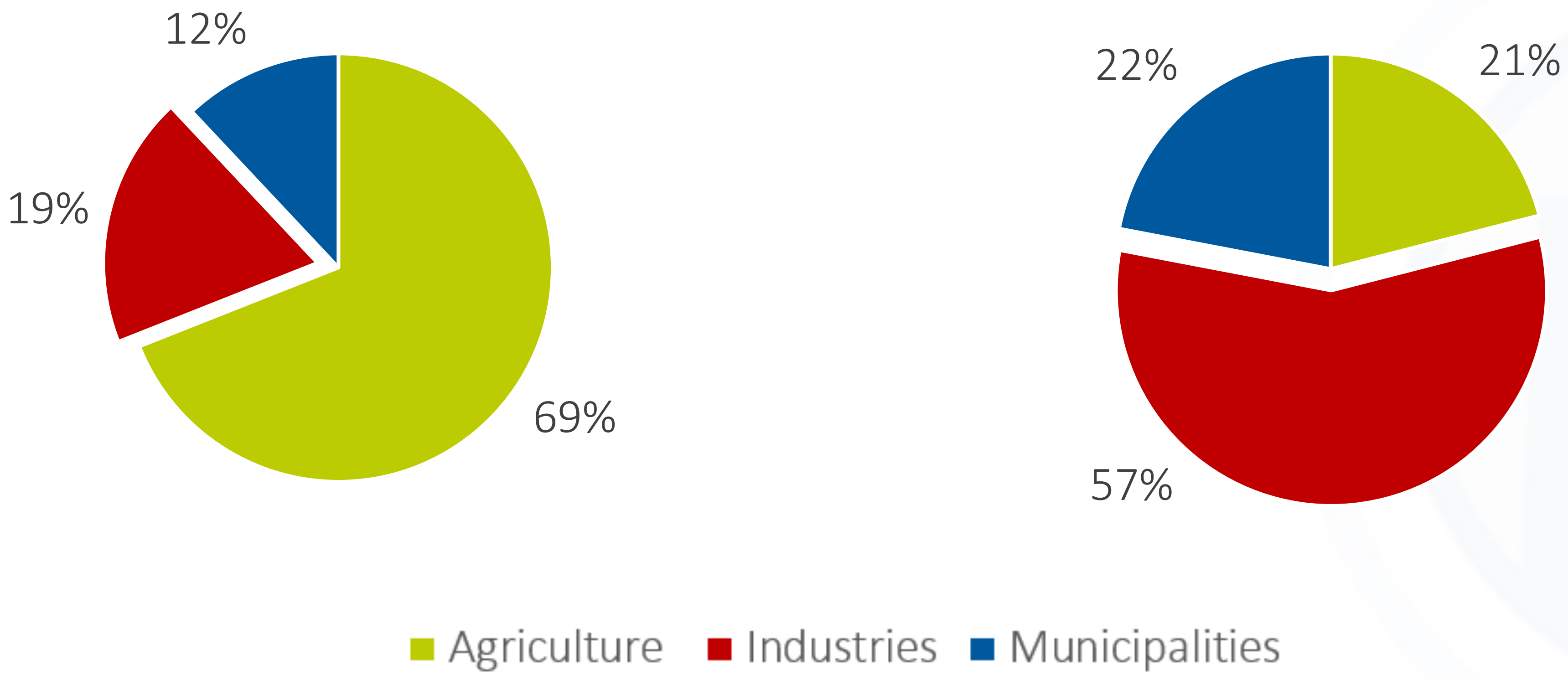
- Industrial Wastewater Fundamentals
- Technologies Mentioned in BAT
- Membrane Processes
- AquaSPICE @ DOW Boehlen

Industrial Wastewater Fundamentals



Water Use

- Global water use
- European water use



(AQUASTAT, 2015)

AquaSPICE

Use of Water in the Industrial Sector

Reaction medium/solvent

Cooling Towers

Firefighting water

Integral part of the product

Cleaning

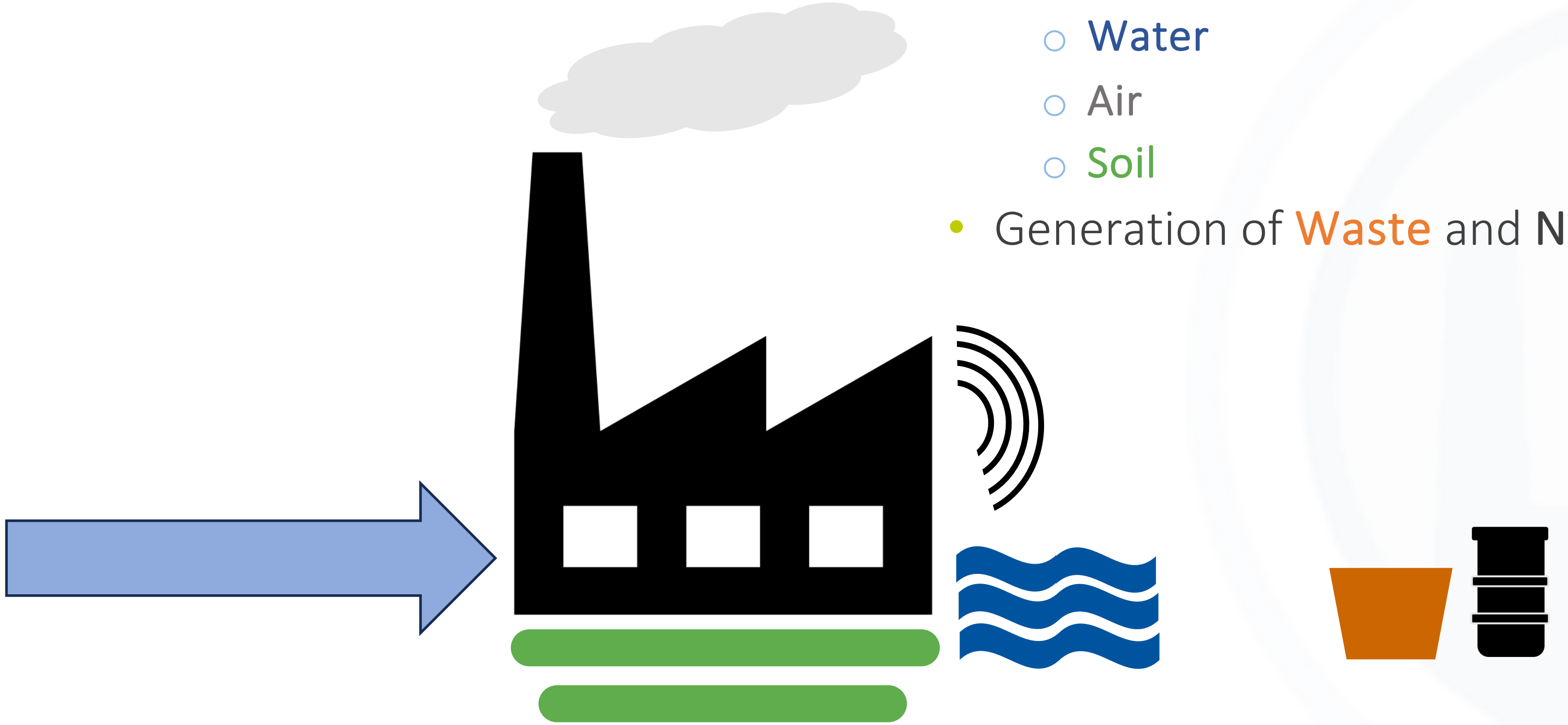
etc...

Environmental Challenges of Industrial Sector

Regarding Water

- Water/resource availability

- Water/environmental pollution
  - Emissions to:
    - Water
    - Air
    - Soil
  - Generation of Waste and Noise



Best Practices in Industrial Water Management

- Extensive **metering** and **water balances**
- **Leak detection**
- **Compliant water discharge** within **limit values**, specified in regulations
- Appropriate water and wastewater **treatment techniques** → Process Innovation
- **Water reuse** → Circular Innovation

\+ Digital Innovation

Pollutants in Industrial Wastewater I/II

Pollutants (depending on industry):

- Organic pollutants
  - Human and animal waste
- Inorganic pollutants
  - Heavy metals
  - Metal ions
  - Pesticides
- Suspended solids (e.g. sand, clay, colloids)
- Nutrients (e.g. phosphorus, ammonia)
- Pathogens (e.g. viruses, bacteria)
- etc.


[10]

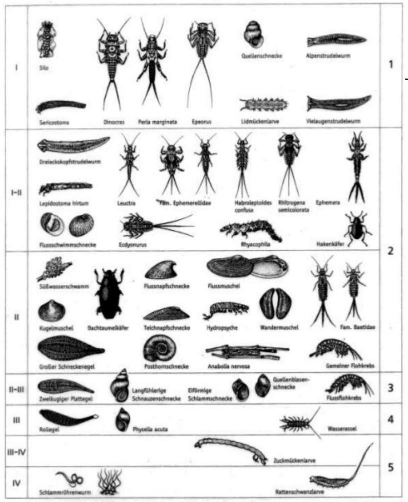
Pollutants in Industrial Wastewater I/II

Water quality parameters:

- Physical parameters (e.g. temperature, total suspended/dissolved solids (TSS, TDS), electrical conductivity, color, odor,…)
- Chemical parameters (e.g. pH, water hardness, dissolved oxygen, …)
- Biological parameters


[6]


[7]


[8]


[9]

Industrial Wastewater Policies

UN Sustainable Development Goals

Regarding Industrial Water Use

- Target 6.3:

  *"[…] **improve water quality** by **reducing pollution**, […] substantially increasing recycling and safe reuse globally.*

- Target 6.4:

  *"[…] **increase water-use efficiency** across all sectors […] to address water scarcity.*

- Target 12.4:

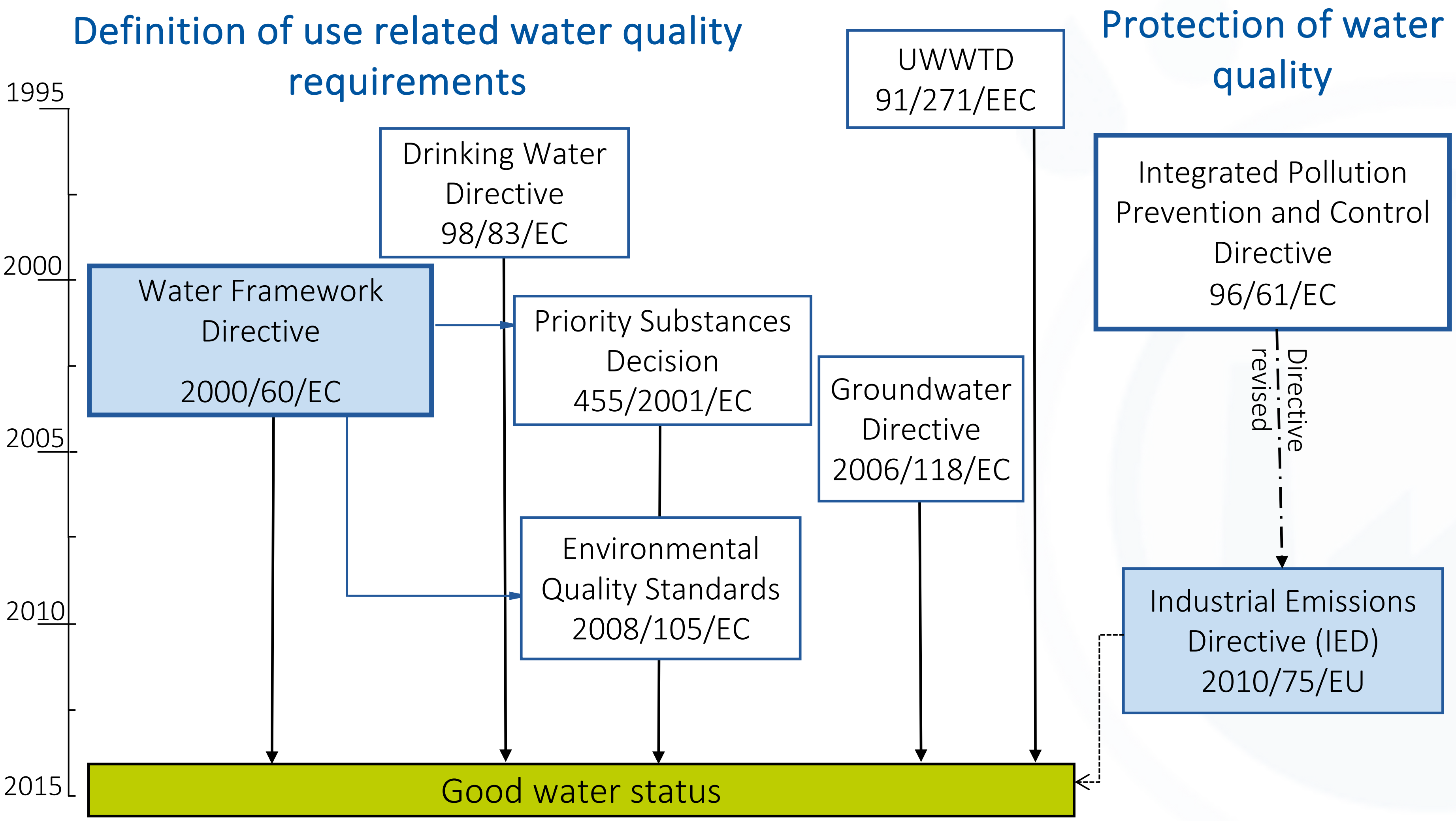
  *"[…] achieve the **environmentally sound management of chemicals** and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly **reduce their release to air, water and soil** […].*

Source: www.un.org

Levels of European Legislation

Level	Description	Legal form
Europe	Competence to issue a framing legislation defining minimum requirements	European Legal Acts
Member States	Enforcement of European Directives requires their transposition into national law	National Law Federal Law
Autonomous regions	Possibility to regulate issues which were not addressed in the national law, option to adopt more stringent standards	Regional Law

Overview – EU water legislation



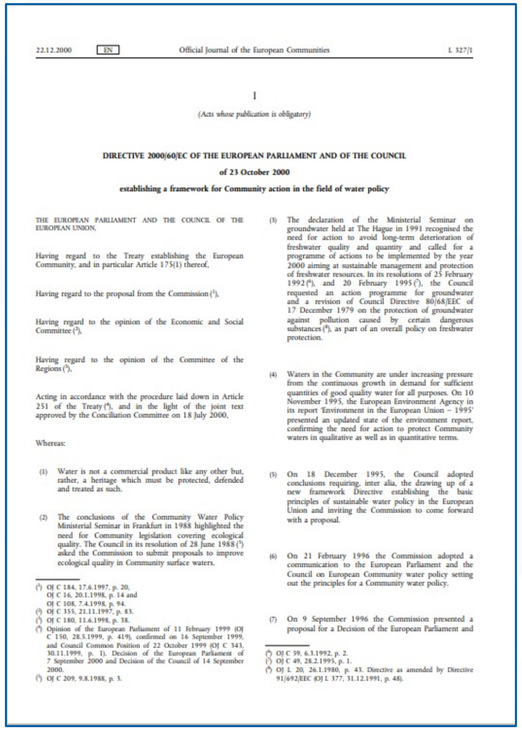
Source: Boymanns, 2001

Water Framework Directive (WFD)

WFD

Directive 2000/60/EC — EU Water Framework Directive

- Aim: Achieving "good status" for all EU ground and surface waters by 2015/2027
- Background:
  - Natural conditions and water management issues vary greatly across EU
  - WFD sets quality goals and methods to maintain good water quality
- Strategy: Water management based on river basins
  - Set reference conditions and monitor status of water
  - Assess impact of human activity
  - Full cost recovery of water services, polluters pay principle



22.12.2000 EN Official Journal of the European Communities L 327/1

I

(Acts whose publication is obligatory)

DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 23 October 2000

establishing a framework for Community action in the field of water policy

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 175(1) thereof,

Having regard to the proposal from the Commission (1),

Having regard to the opinion of the Economic and Social Committee (2),

Having regard to the opinion of the Committee of the Regions (3),

Acting in accordance with the procedure laid down in Article 251 of the Treaty (4), and in the light of the joint text approved by the Conciliation Committee on 18 July 2000,

Whereas:

(1) Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such.

(2) The conclusions of the Community Water Policy Ministerial Seminar in Frankfurt in 1988 highlighted the need for Community legislation covering ecological quality. The Council in its resolution of 28 June 1988 (5) asked the Commission to submit proposals to improve ecological quality in Community surface waters.

(3) The declaration of the Ministerial Seminar on groundwater held at The Hague in 1991 recognised the need for action to avoid long-term deterioration of freshwater quality and quantity and called for a programme of actions to be implemented by the year 2000 aiming at sustainable management and protection of freshwater resources. In its resolutions of 25 February 1992 (6), and 20 February 1995 (7), the Council requested an action programme for groundwater and a revision of Council Directive 80/68/EEC of 17 December 1979 on the protection of groundwater against pollution caused by certain dangerous substances (8), as part of an overall policy on freshwater protection.

(4) Waters in the Community are under increasing pressure from the continuous growth in demand for sufficient quantities of good quality water for all purposes. On 10 November 1995, the European Environment Agency in its report 'Environment in the European Union – 1995' presented an updated state of the environment report, confirming the need for action to protect Community waters in qualitative as well as in quantitative terms.

(5) On 18 December 1995, the Council adopted conclusions requiring, inter alia, the drawing up of a new framework Directive establishing the basic principles of sustainable water policy in the European Union and inviting the Commission to come forward with a proposal.

(6) On 21 February 1996 the Commission adopted a communication to the European Parliament and the Council on European Community water policy setting out the principles for a Community water policy.

(7) On 9 September 1996 the Commission presented a proposal for a Decision of the European Parliament and

(1) OJ C 184, 17.6.1997, p. 20,
OJ C 16, 20.1.1998, p. 14 and
OJ C 108, 7.4.1998, p. 94.
(2) OJ C 355, 21.11.1997, p. 83.
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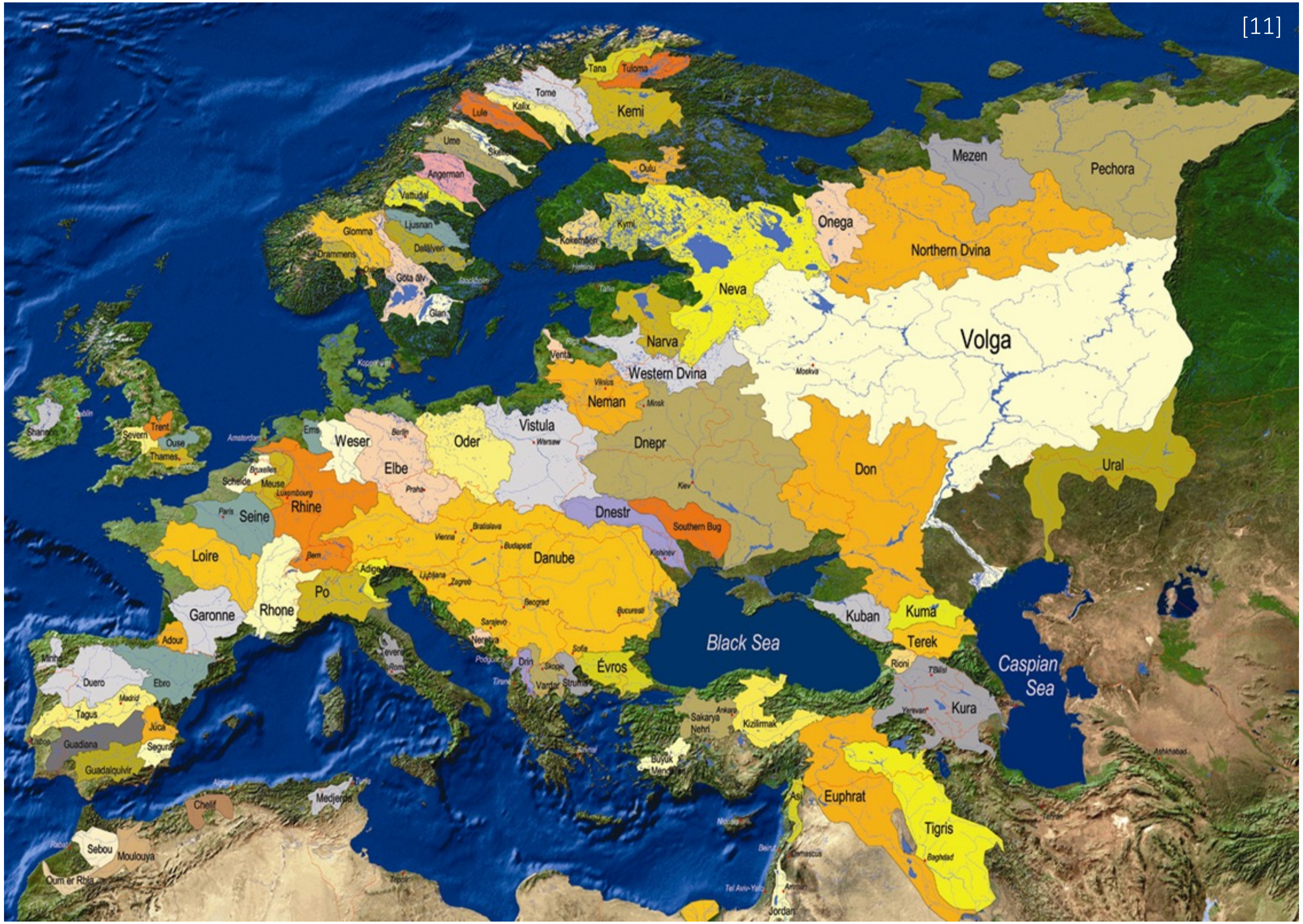
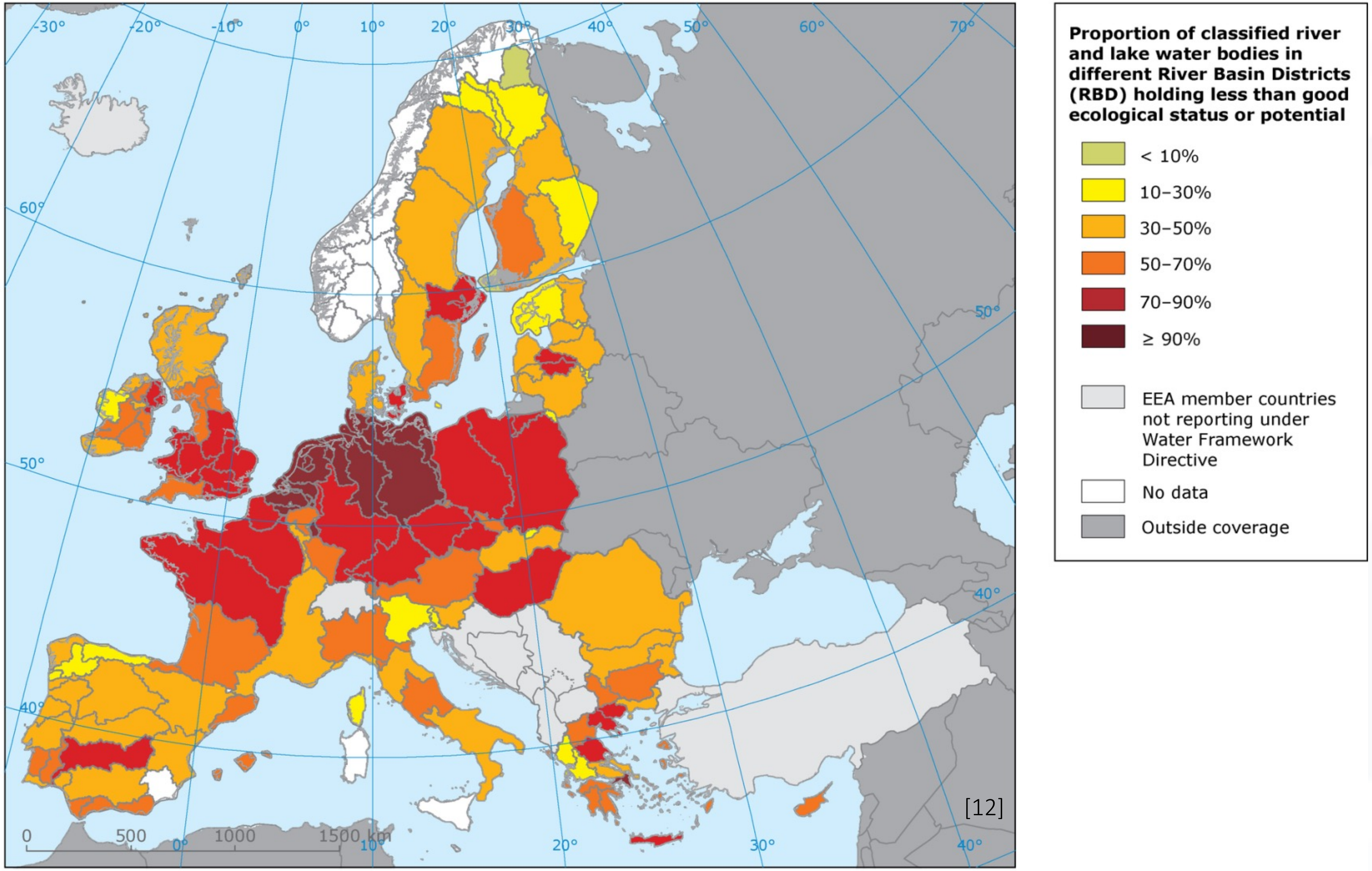
(8) OJ L 20, 26.1.1980, p. 43. Directive as amended by Directive 91/692/EEC (OJ L 377, 31.12.1991, p. 48).

European River Catchments



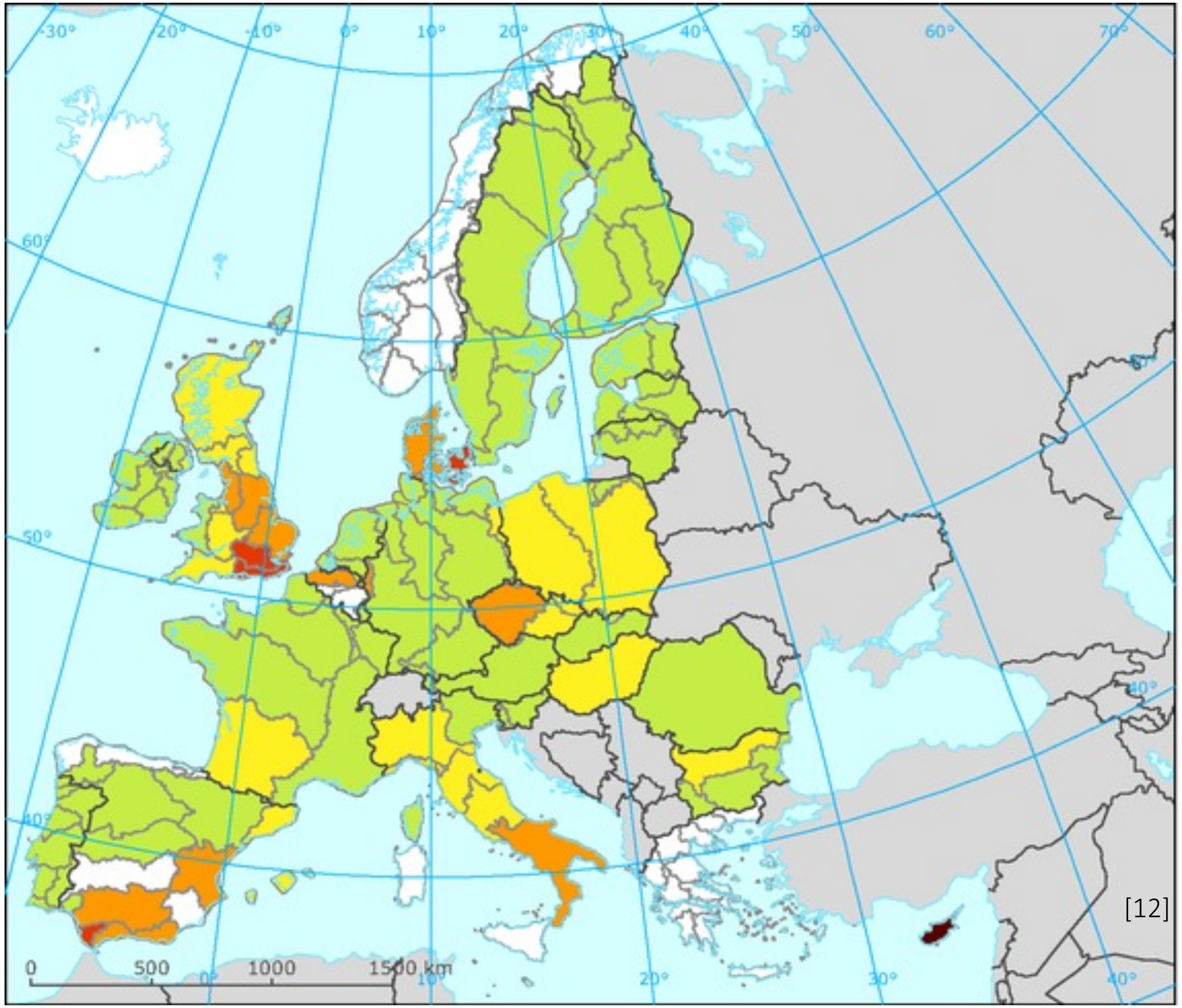
WFD

Ecological status of EU Surface Water Bodies

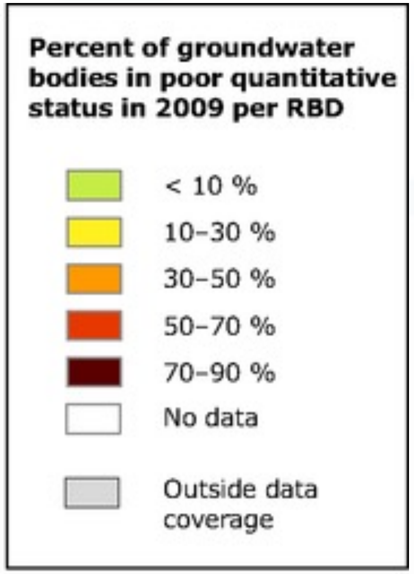


WFD

Ecological status of EU Groundwater Bodies



[12]



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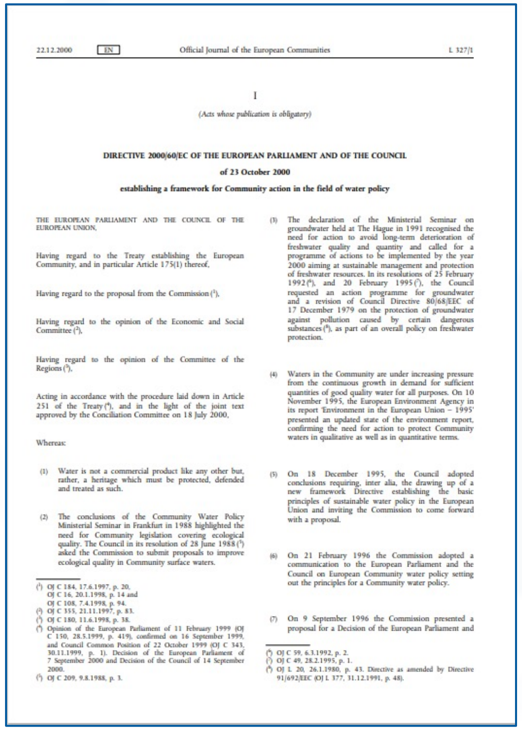
- Strategy: Water management based on river basins
  - Set reference conditions and monitor status of water
  - Assess impact of human activity
  - Full cost recovery of water services, polluters pay principle
- Review (December 2019)
  - Room for improvements (investments, implementation, …)
  - WFD achieved higher quality level of water bodies

  → contribute to achieving SDGs
- Proposal for revision (adopted in October 2022)
  - Updated list of pollutants



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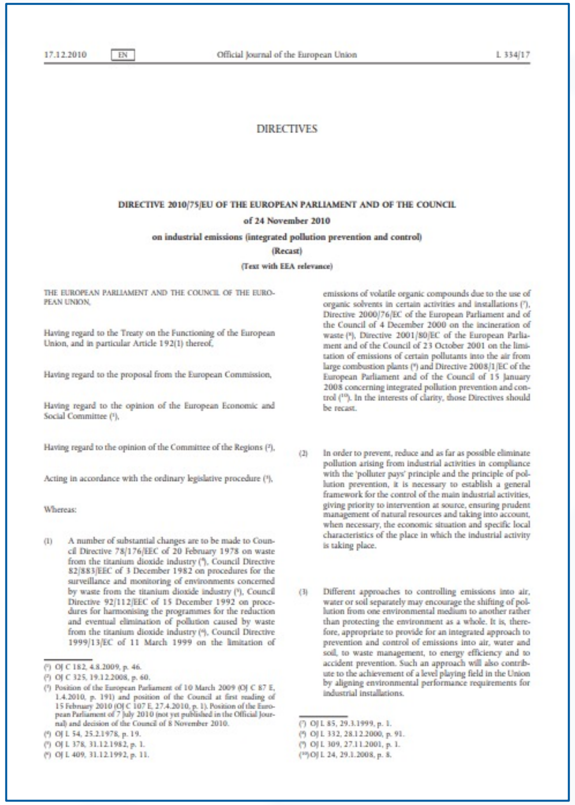
[8] OJ L 20, 26.1.1980, p. 43. Directive as amended by Directive 91/692/EEC (OJ L 377, 31.12.1991, p. 48).

Industrial Emissions Directive (IED)

IED

Directive 2010/75/EU — on Industrial Emissions

- Aim: Achieve a high level of environmental protection from industrial activities
- Sectors:
  - Energy
  - Chemicals
  - Metal production and processing
  - Waste management
  - Etc.
- Operator obligations:
  - Prevent/reduce industrial emissions into air, water and land
  - Avoidance of waste production, recycling where possible, disposal while avoiding any impact on the environment
  - Efficient use of energy


17.12.2010 EN Official Journal of the European Union L 334/17

DIRECTIVES

DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 24 November 2010

on industrial emissions (integrated pollution prevention and control)

(Recast)

(Text with EEA relevance)

→ All appropriate preventive measures are taken by applying the best available techniques (BAT)

Best Available Techniques

Best Available Techniques (BAT)

- Definition of the European Commission for Best Available Techniques (BAT)

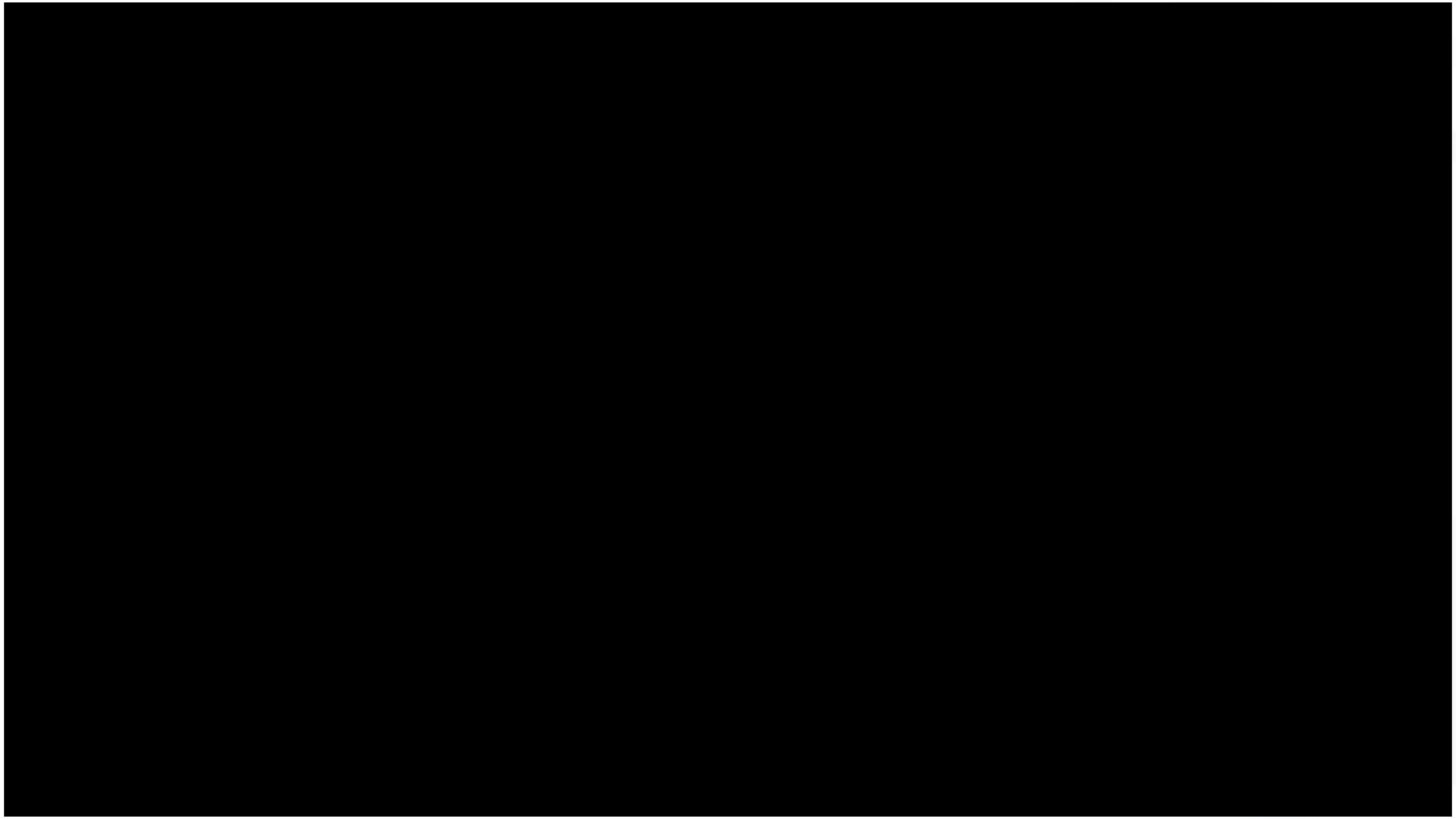
  - Most effective and advanced stage of operation methods which indicate the practical suitability of particular techniques to prevent or reduce emissions.

  - Best = Most effective in achieving a high level of protection of the environment as a whole.

  - Available = Implementation in relevant industrial sector feasible under economically and technically viable conditions.

  - Techniques = Both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned.

BAT-Video



https://www.youtube.com/watch?v=d2kprBd8Tk0

Goals of BAT Concept

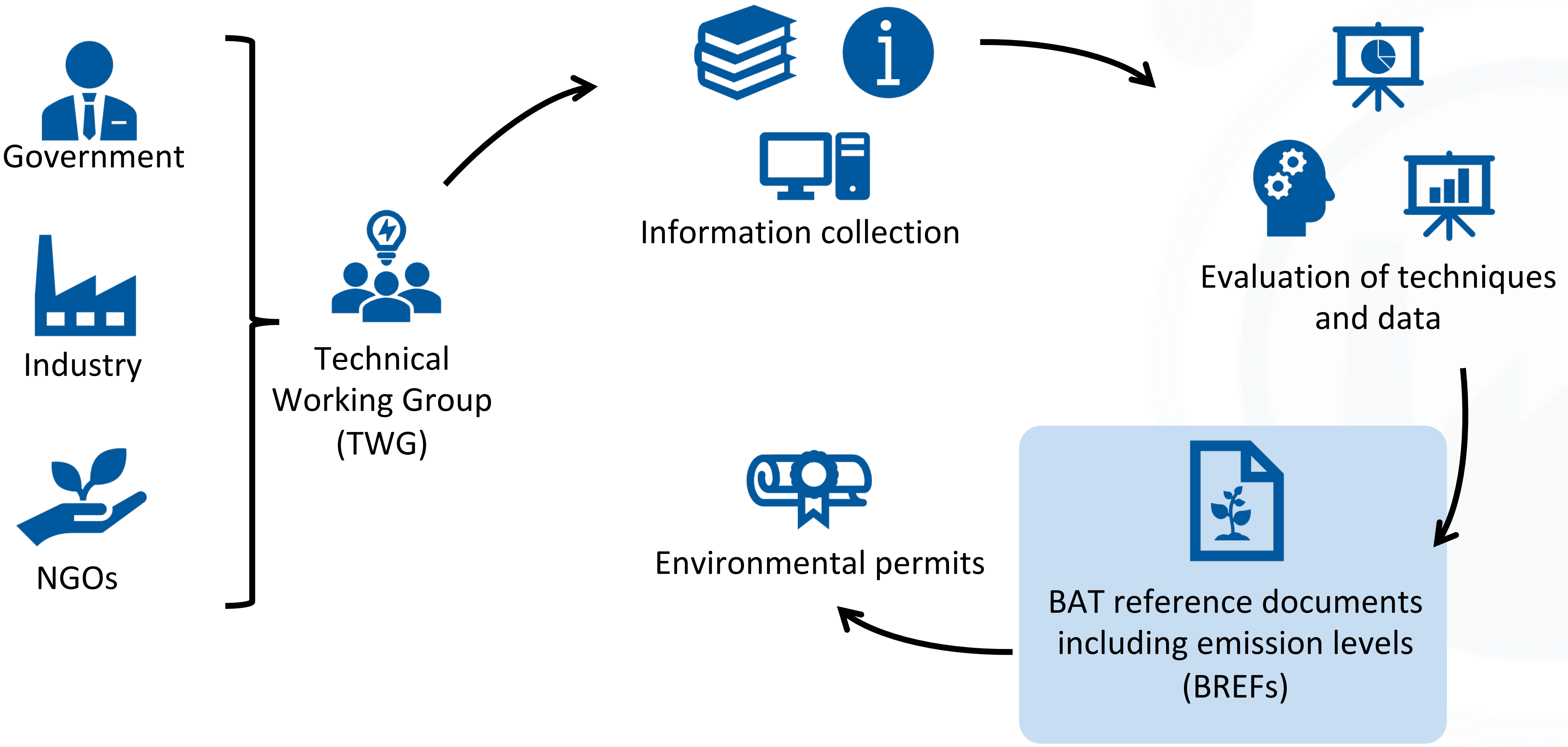
Prevention and control of industrial pollution to protect **human health** and the **environment across countries**

Global level goal: harmonize procedures and technologies

Local level goal: provide guidance for governments to identify permit conditions for industry (BAT-based permitting), e.g.:

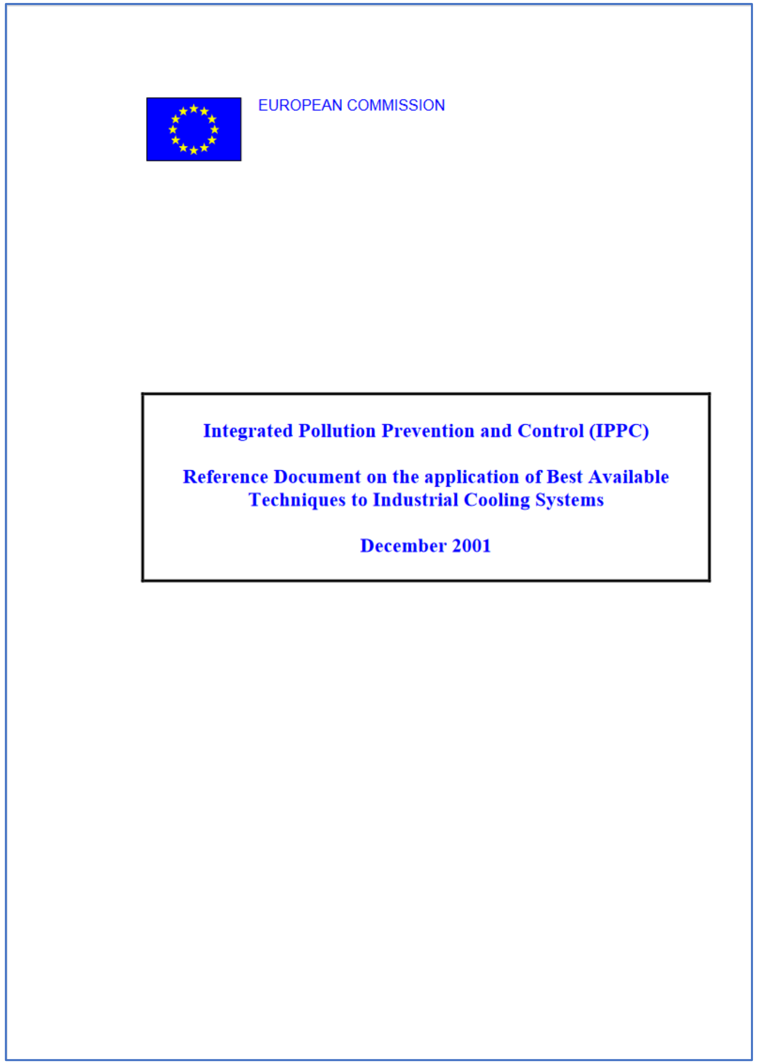
- Emission level values (obtained under normal operating conditions using BAT or a combination of BAT)
- Technical requirements
- Plant/production management requirements
- Plant/production monitoring requirements (for emissions, consumption of resources and waste generation)

How to Determine BATs in the EU - Sevilla Process



Exemplary BREFs for Industrial Water Treatment

Depending on Sector/Topic

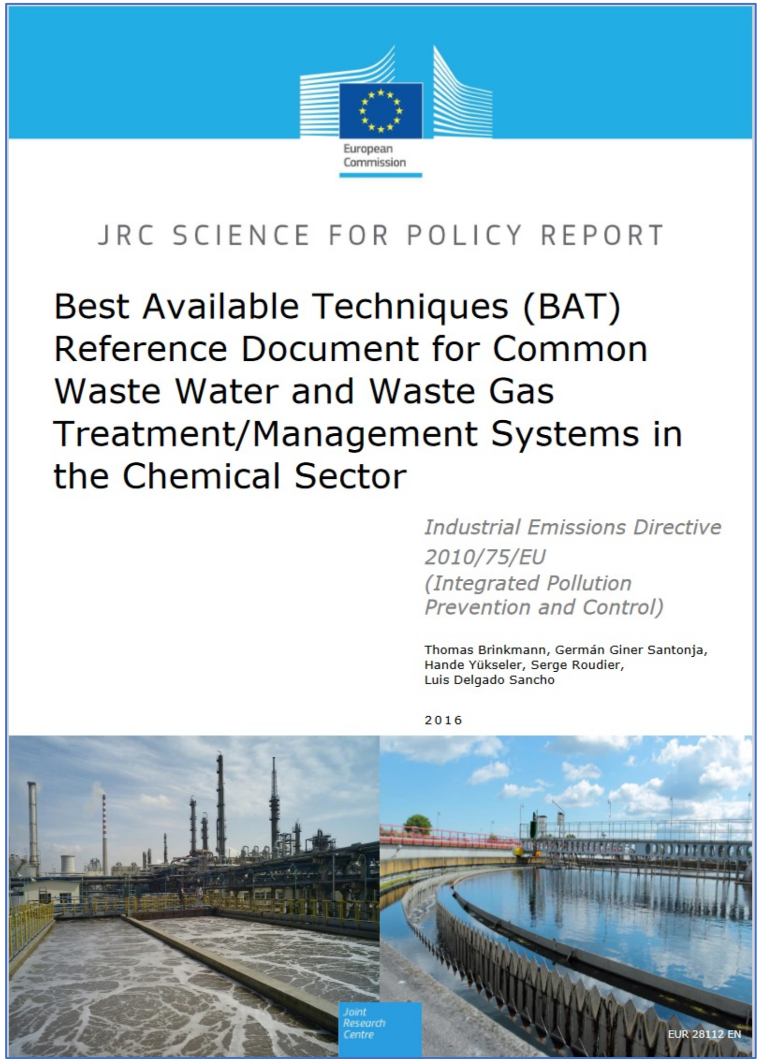

EUROPEAN COMMISSION

Integrated Pollution Prevention and Control (IPPC)

Reference Document on the application of Best Available Techniques to Industrial Cooling Systems

December 2001

Industrial Cooling Systems (2001)


European Commission

JRC SCIENCE FOR POLICY REPORT

Best Available Techniques (BAT) Reference Document for Common Waste Water and Waste Gas Treatment/Management Systems in the Chemical Sector

Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)

Thomas Brinkmann, Germán Giner Santonja, Hande Yükseler, Serge Roudier, Luis Delgado Sancho

2016

Joint Research Centre

EUR 28112 EN

Chemical Sector (2016)


European Commission

JRC SCIENCE FOR POLICY REPORT

Best Available Techniques (BAT) Reference Document for Waste Treatment

Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)

Antoine Pinasseau, Benoit Zerger, Joze Roth, Michele Canova, Serge Roudier

2018

Joint Research Centre

EUR 29362 EN

Waste Treatment (2018)

Example: BREF on Waste Treatment (WT)

Wastewater treatment

BREF WT content:

- Scope
- General Information
  - Types of wastewater in EU
  - Economics of waste treatment sector
  - …
- Processes and techniques commonly used for waste treatment

- **BAT conclusions**, including
  - BAT for wastewater treatment
  - BAT-associated limit values (BAT-AEL)

BAT Conclusions

- BAT for wastewater treatment

BAT 20. In order to reduce emissions to water, BAT is to treat waste water using an appropriate combination of the techniques given below.

	Technique (1)	Typical pollutants targeted	Applicability
Preliminary and primary treatment, e.g.			
a.	Equalisation	All pollutants	Generally applicable.
b.	Neutralisation	Acids, alkalis	
c.	Physical separation, e.g. screens, sieves, grit separators, grease separators, oil-water separation or primary settlement tanks	Gross solids, suspended solids, oil/grease	
Physico-chemical treatment, e.g.			
d.	Adsorption	Adsorbable dissolved non-biodegradable or inhibitory pollutants, e.g. hydrocarbons, mercury, AOX	
e.	Distillation/rectification	Dissolved non-biodegradable or inhibitory pollutants that can be distilled, e.g. some solvents	
f.	Precipitation	Precipitable dissolved non-biodegradable or inhibitory pollutants, e.g. metals, phosphorus	

...

- BAT-associated emission levels (BAT-AEL)

Table 6.1: BAT-associated emission levels (BAT-AELs) for direct discharges to a receiving water body

Substance/Parameter	BAT-AEL (1)	Waste treatment process to which the BAT-AEL applies
Total organic carbon (TOC) (2)	10–60 mg/l	• All waste treatments except treatment of water-based liquid waste
	10–100 mg/l (3) (4)	• Treatment of water-based liquid waste
Chemical oxygen demand (COD) (2)	30–180 mg/l	• All waste treatments except treatment of water-based liquid waste
	30–300 mg/l (3) (4)	• Treatment of water-based liquid waste
Total suspended solids (TSS)	5–60 mg/l	• All waste treatments
Hydrocarbon oil index (HOI)	0.5–10 mg/l	• Mechanical treatment in shredders of metal waste • Treatment of WEEE containing VFCs and/or VHCs • Re-refining of waste oil • Physico-chemical treatment of waste with calorific value • Water washing of excavated contaminated soil • Treatment of water-based liquid waste

...

BREF for Waste Treatment 2018

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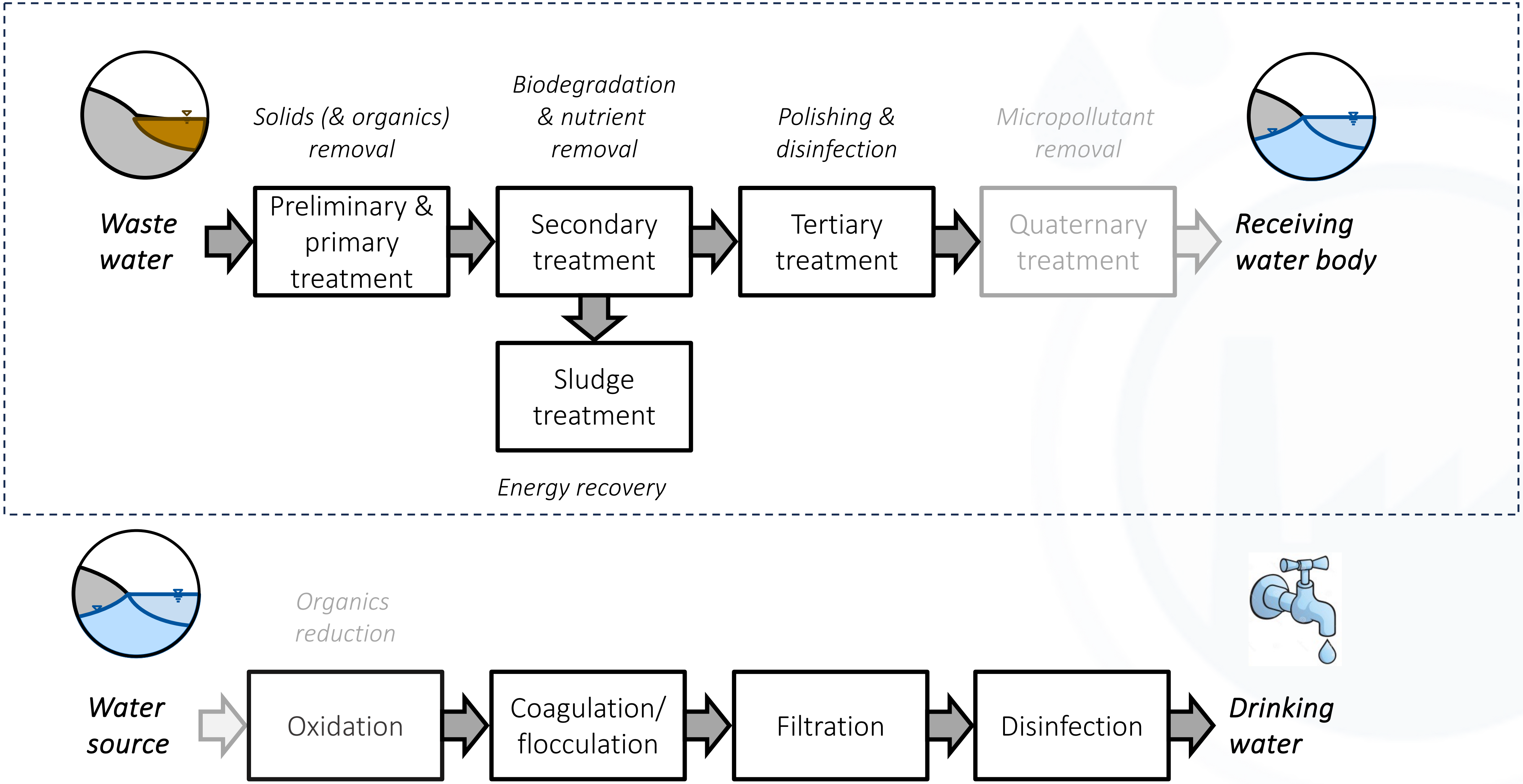
e.	Distillation/rectification	Dissolved non-biodegradable or inhibitory pollutants that can be distilled, e.g. some solvents	
f.	Precipitation	Precipitable dissolved non-biodegradable or inhibitory pollutants, e.g. metals, phosphorus	
g.	Chemical oxidation	Oxidisable dissolved non-biodegradable or inhibitory pollutants, e.g. nitrite, cyanide	
h.	Chemical reduction	Reducible dissolved non-biodegradable or inhibitory pollutants, e.g. hexavalent chromium (Cr(VI))	
i.	Evaporation	Soluble contaminants	
j.	Ion exchange	Ionic dissolved non-biodegradable or inhibitory pollutants, e.g. metals	
k.	Stripping	Purgeable pollutants, e.g. hydrogen sulphide (H_2S), ammonia (NH_3), some adsorbable organically bound halogens (AOX), hydrocarbons	
Biological treatment, e.g.			
l.	Activated sludge process	Biodegradable organic compounds	Generally applicable.
m.	Membrane bioreactor		
Nitrogen removal			
n.	Nitrification/denitrification when the treatment includes a biological treatment	Total nitrogen, ammonia	Nitrification may not be applicable in the case of high chloride concentrations (e.g. above 10 g/l) and when the reduction of the chloride concentration prior to nitrification would not be justified by the environmental benefits. Nitrification is not applicable when the temperature of the waste water is low (e.g. below 12 °C).
Solids removal, e.g.			
o.	Coagulation and flocculation	Suspended solids and particulate-bound metals	Generally applicable.
p.	Sedimentation		
q.	Filtration (e.g. sand filtration, microfiltration, ultrafiltration)		
r.	Flotation		

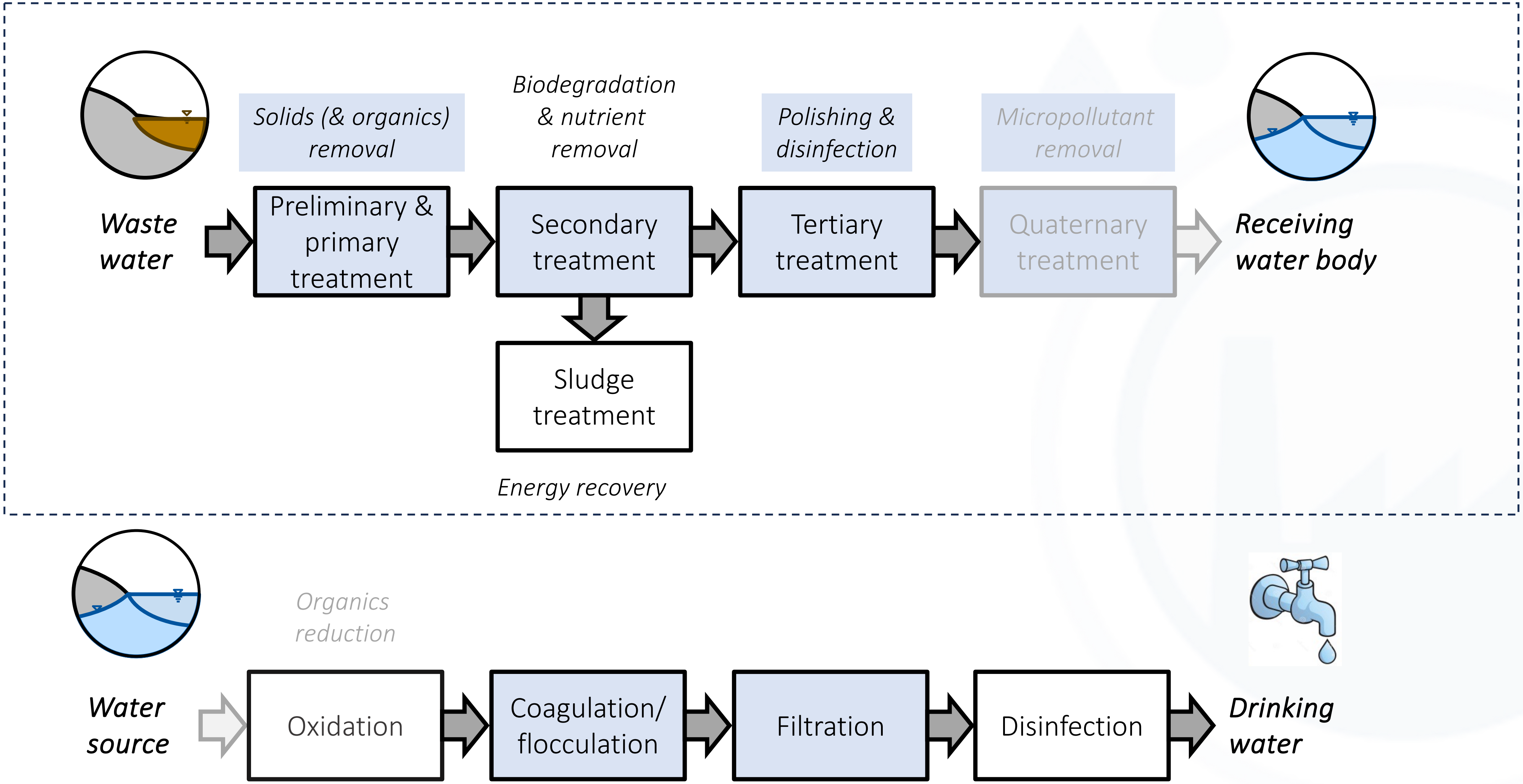
([1]) The descriptions of the techniques are given in Section 6.6.3.

How Does (Waste)Water Treatment Work?

Typical Treatment Schemes

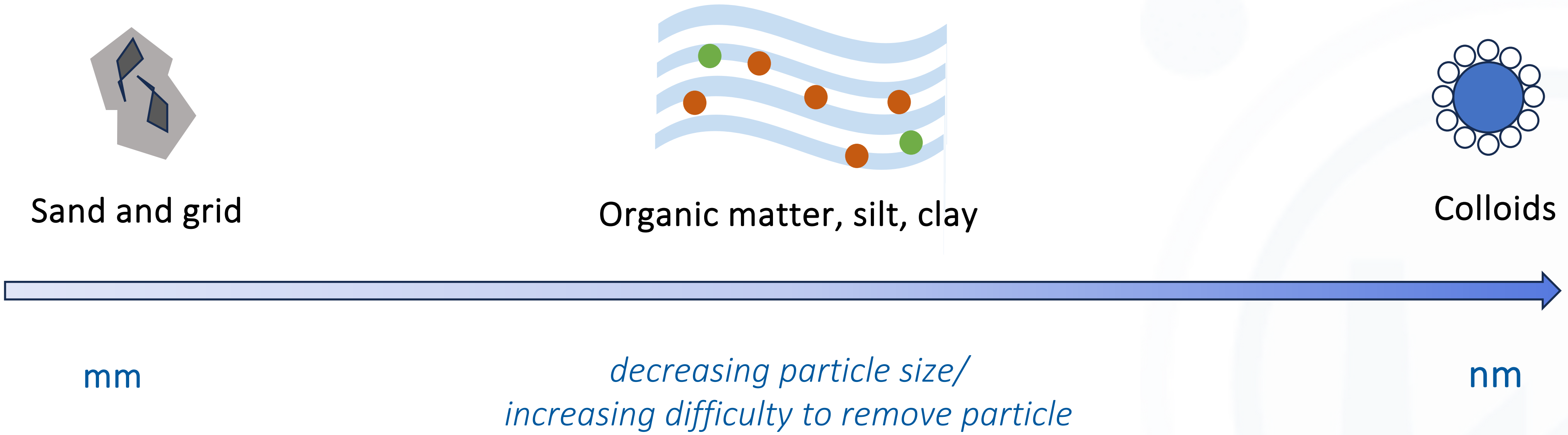


Solids Removal and Physical Separation in Typical Water Treatment Schemes



Suspended Solids in Wastewater

Pollutant particle sizes



The smaller a particle the harder it is to remove from water!

→Idea: Clumping of small particles (colloids) to create bigger agglomerates that are easier to remove

→ Done in preliminary treatment step: Coagulation/Flocculation

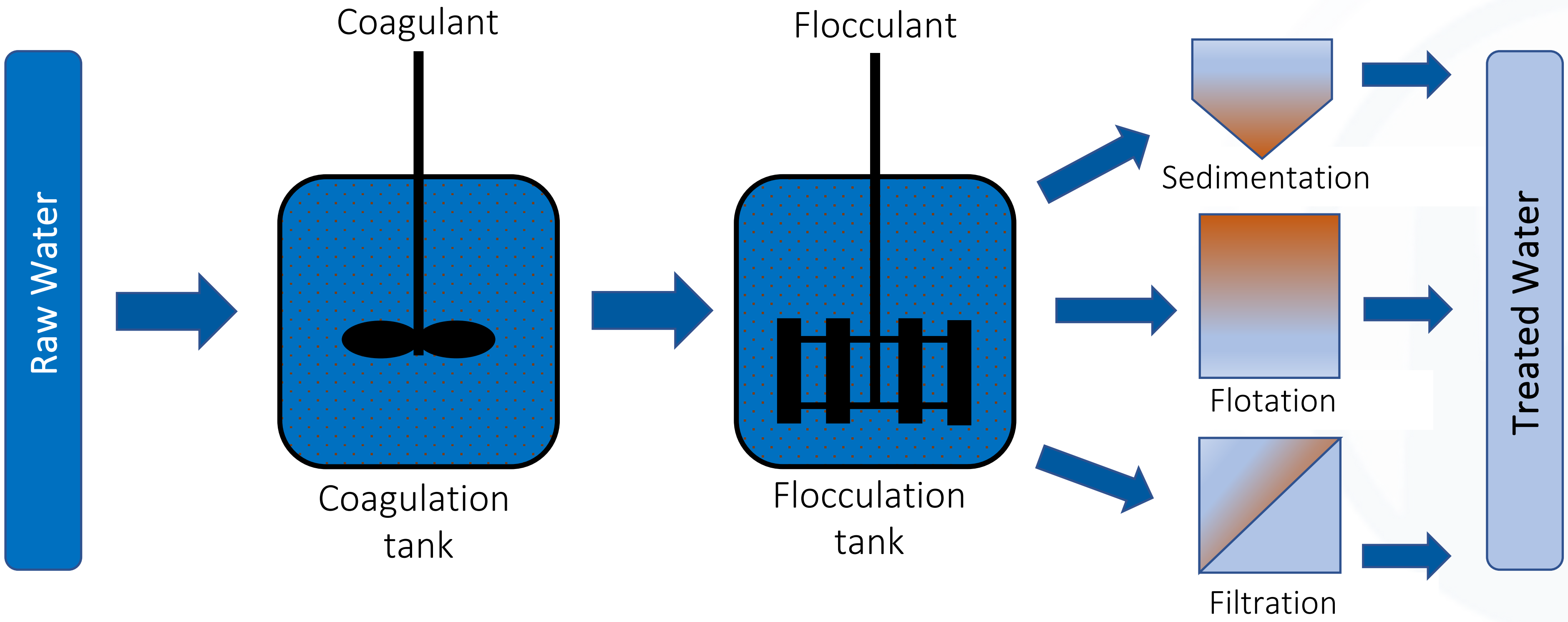
Coagulation/Flocculation

Suspended colloids | Agglomeration | Flocculation/ Sedimentation | Treated Water

[13]

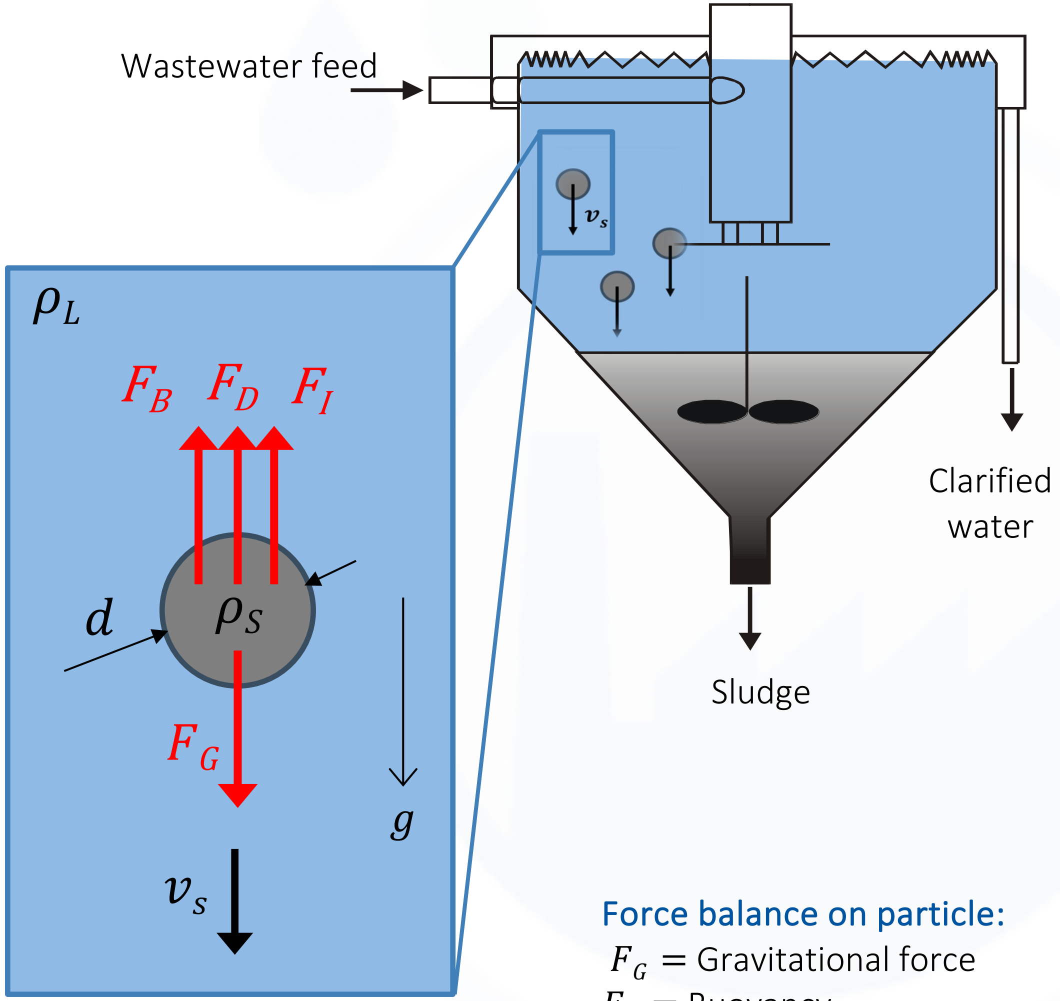
Coagulation/Flocculation within General Treatment Scheme

- Basic steps: Coagulation → Flocculation → Solid-liquid-separation



Sedimentation

- Separation principle: **Density difference**
  - …between suspended solids and liquid phase
- Driving force: **Gravitation**
  - Separation occurs when: $t_{residence} > t_{sedimentation}$
  - Crucial parameter: **terminal sedimentation velocity $\boldsymbol{v_s}$**
- Minimal particle size: 100 µm
  - Economically feasible separation of smaller particles by flotation or deep bed filtration
- Used for pre- and post clarification basins



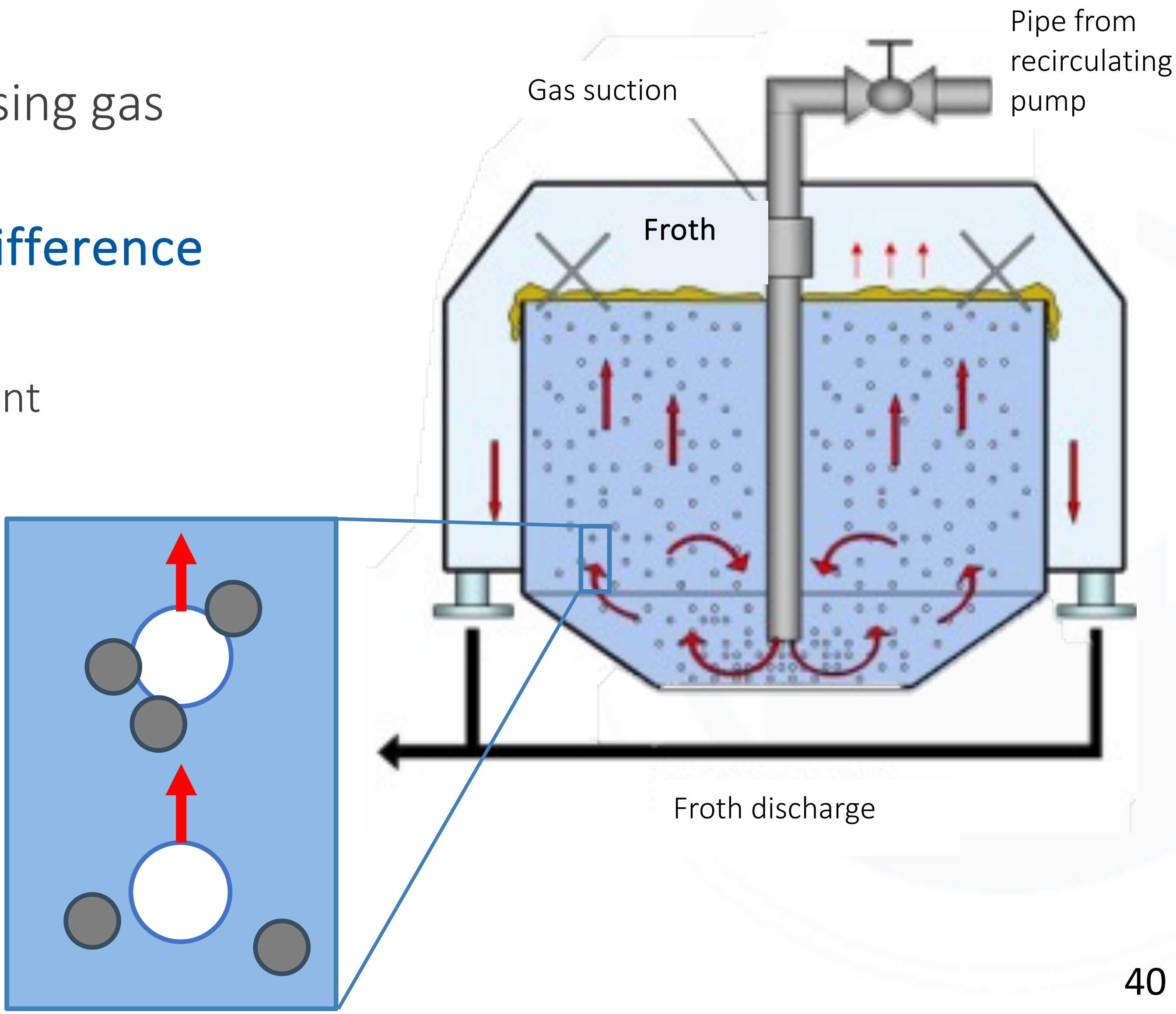
Force balance on particle:
F_G = Gravitational force
F_B = Buoyancy
F_D = Drag (or resistance)
F_I = Inertial force

Flotation

- Adhesion of suspended on rising gas bubbles

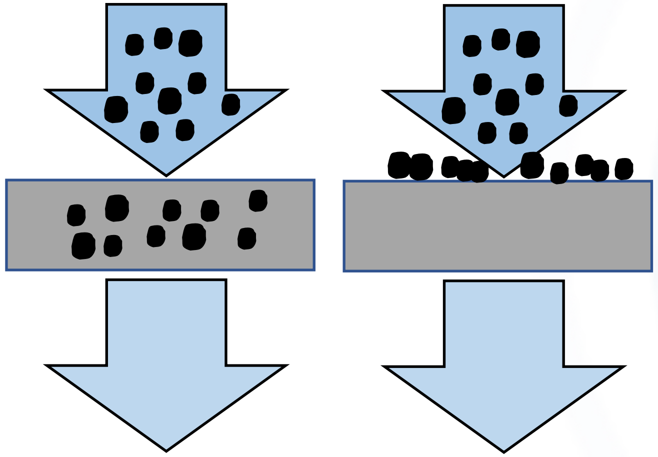
→ Separation due to density difference

- Precondition:
  - Hydrophobic surface of pollutant
  - Gas insoluble in water
- For particles < 100 µm



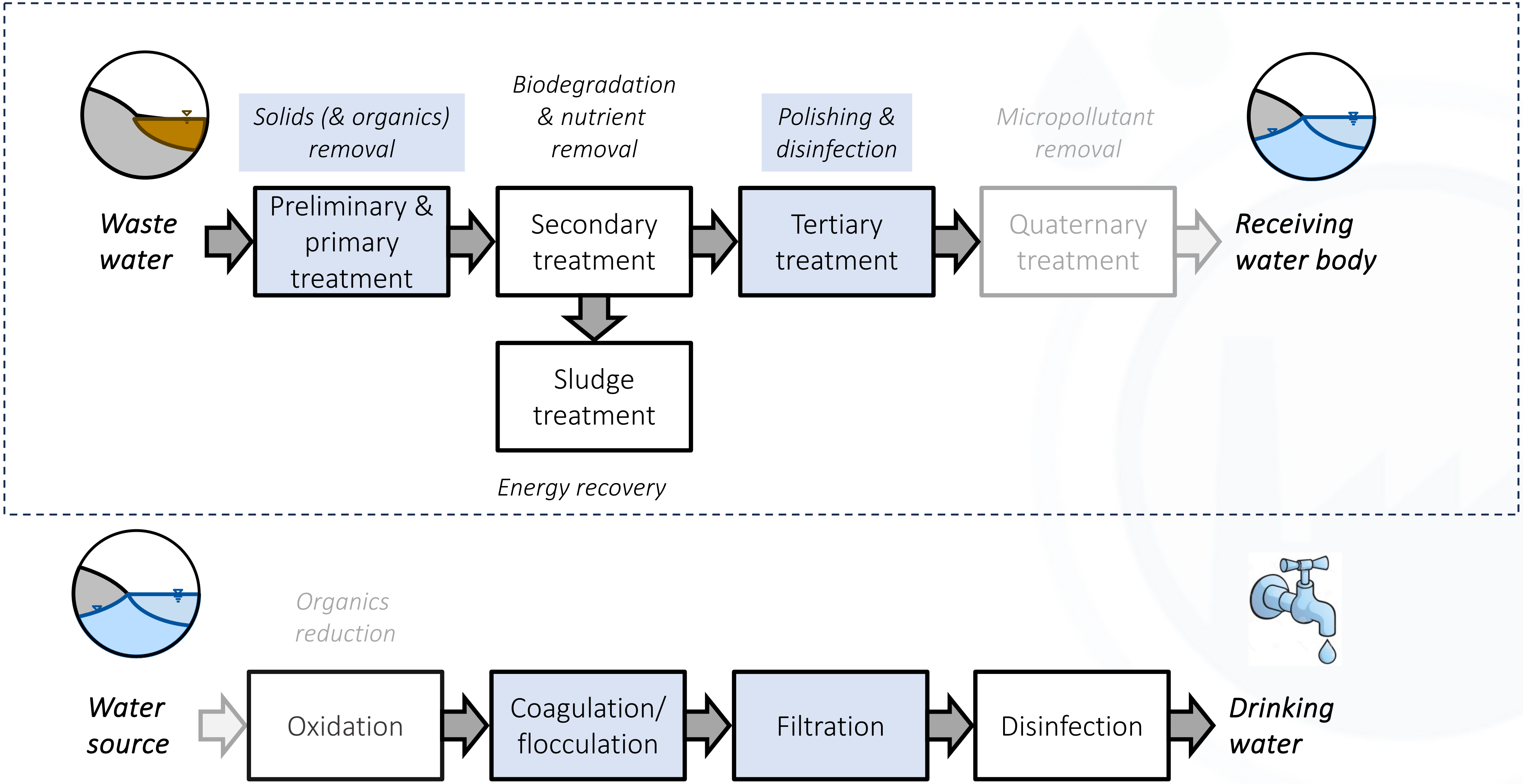
Filtration

- Separation based on **particle size** and resulting steric hindrance by a **liquid-permeable filter medium**
- Types of filtration
  - Depth-filtration
  - Surface filtration: additional retention by the filter cake
- Filter media examples:
  - Sand, Gravel, Anthracite,…
  - Cloth, woven fibres,..
  - (Biologically activated) carbon
  - Multimedia filtration



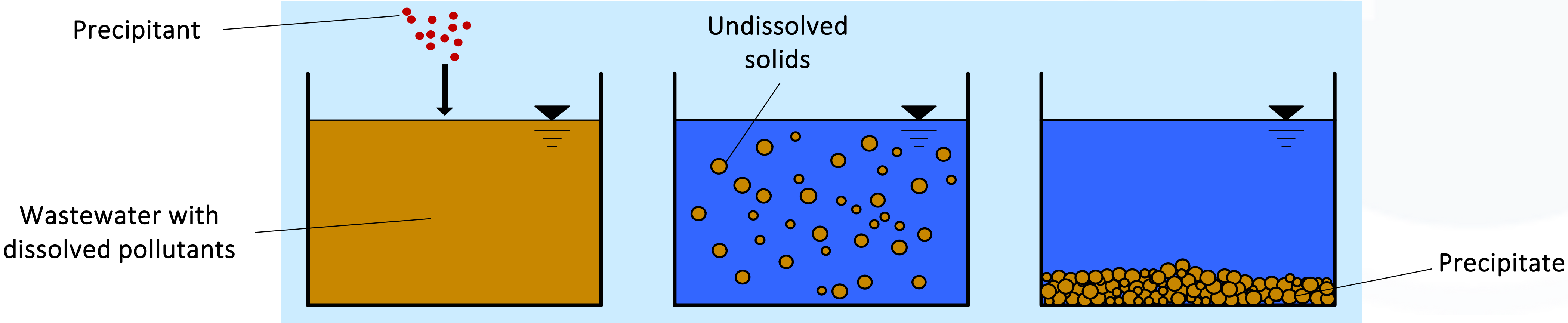
How Does (Waste)Water Treatment Work?

Typical Treatment Schemes



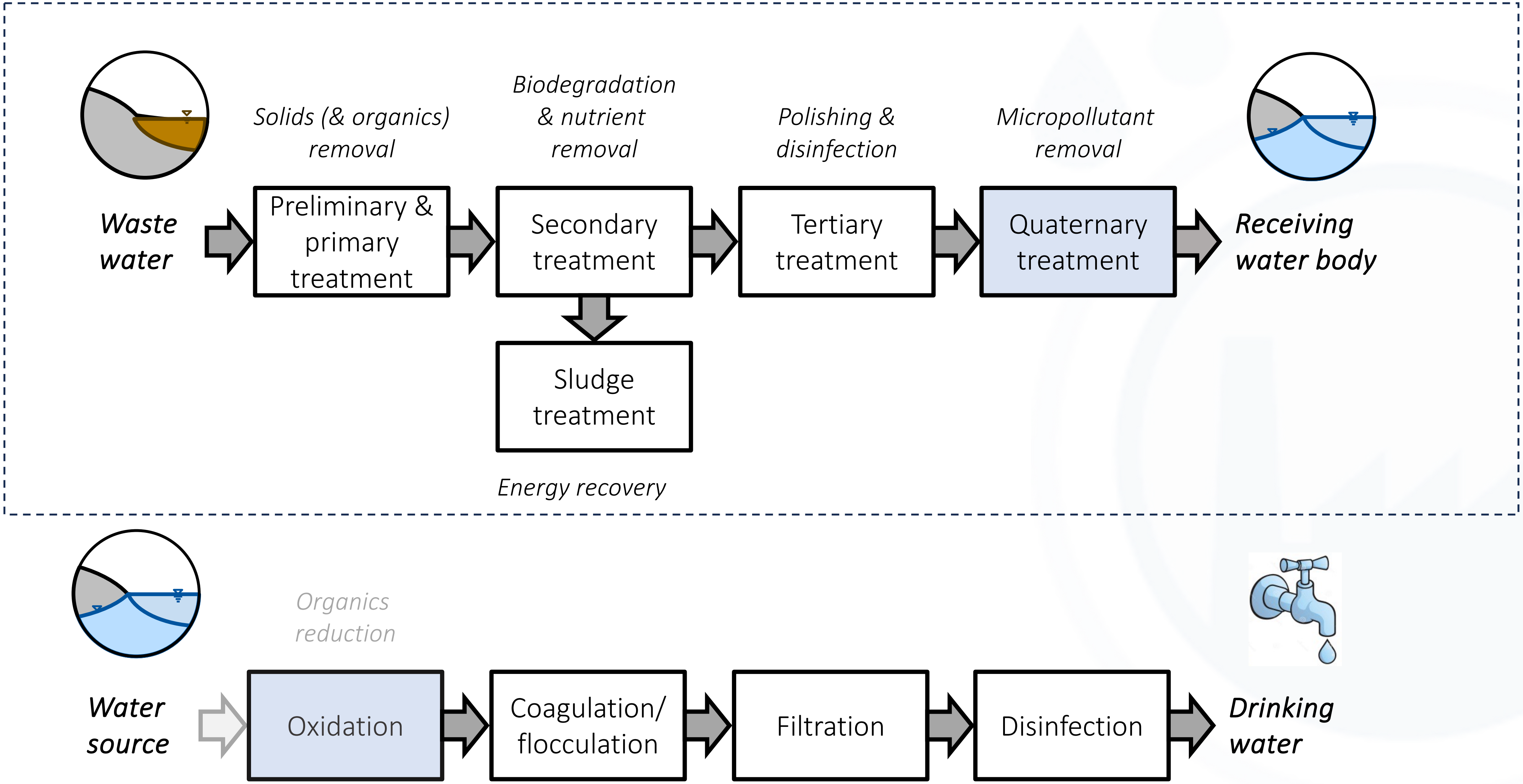
Precipitation

- Goal: removal of **dissolved** pollutants, e.g. heavy metals or nutrients like phosphate:
    1. Chemical reactants, so called **precipitants**, are added to wastewater to have a **chemical reaction** with the dissolved pollutants
    2. The resulting compounds have a **low solubility** in water and are therefore present in an undissolved, solid state
    3. The solid product, called **precipitate**, can then be removed by mechanical processes (e.g. filtration)



How Does (Waste)Water Treatment Work?

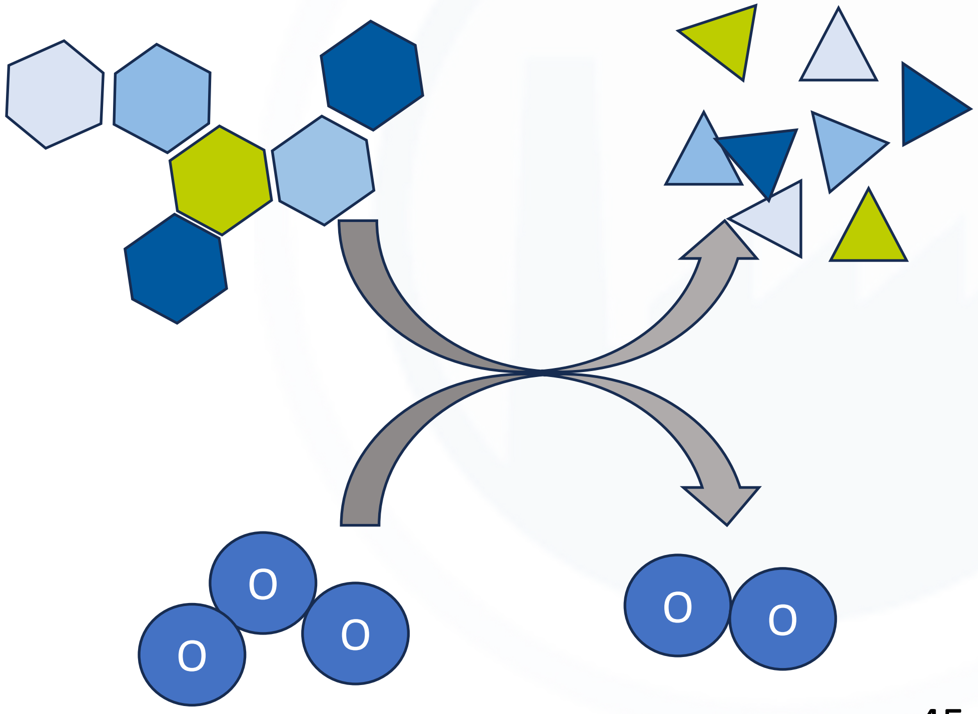
Typical Treatment Schemes



Oxidation

- Oxidation = chemical reaction
  - Powerful oxidizing agents **break down** suspended or dissolved, mostly organic pollutants (reducing agents) into simpler, less harmful forms.
- Pollutant examples:
  - Pharmaceutical residues, Biocides, …
- Oxidizing agents:
  - O_3, H_2O_2 (, O_2)
- Technologies:
  - Ozonation, Advanced Oxidation Processes
  - Wastewater Incineration

→Oxidation ≠ complete removal



More Technologies

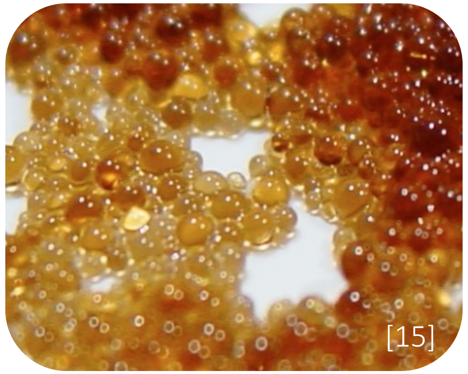
Biological Processes

Activated Sludge

Membrane Bioreactor

Adsorption Processes

Activated Carbon Filtration



Ion Exchange

Thermal Processes

Distillation, Rectification

Membrane Processes

In a Nutshell…

[21]

The choice of industrial (waste)water treatment technologies and the combination thereof depends on the (waste)water **composition** and characteristics, (waste)water **volume**, the desired **quality** of the treated water, **regulations**, **resuse and recycling goals**, **feasibility**, etc.

AquaSPICE

Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations

Membranes

Summer School 2024

Laurence Palmowski & Team

The AquaSPICE project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958396.

Content

- Membrane Fundamentals
- Membrane Processes
- Economic Considerations
- AquaSPICE Case Study 1: Dow Boehlen

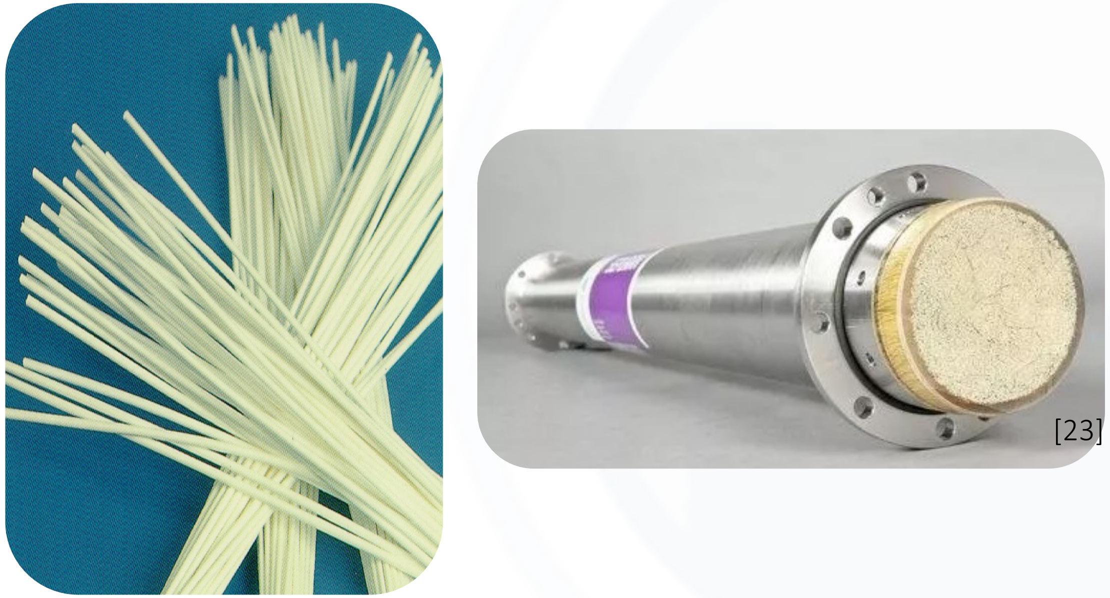
Membrane Fundamentals

What are Membranes?

- **Membranes :**
  - Thin **selective barriers** designed to **separate** or **filter** substances based on size, charge, or other specific properties
  - Synthetic membranes can be made of organic and inorganic materials, mostly **polymers**

[22]

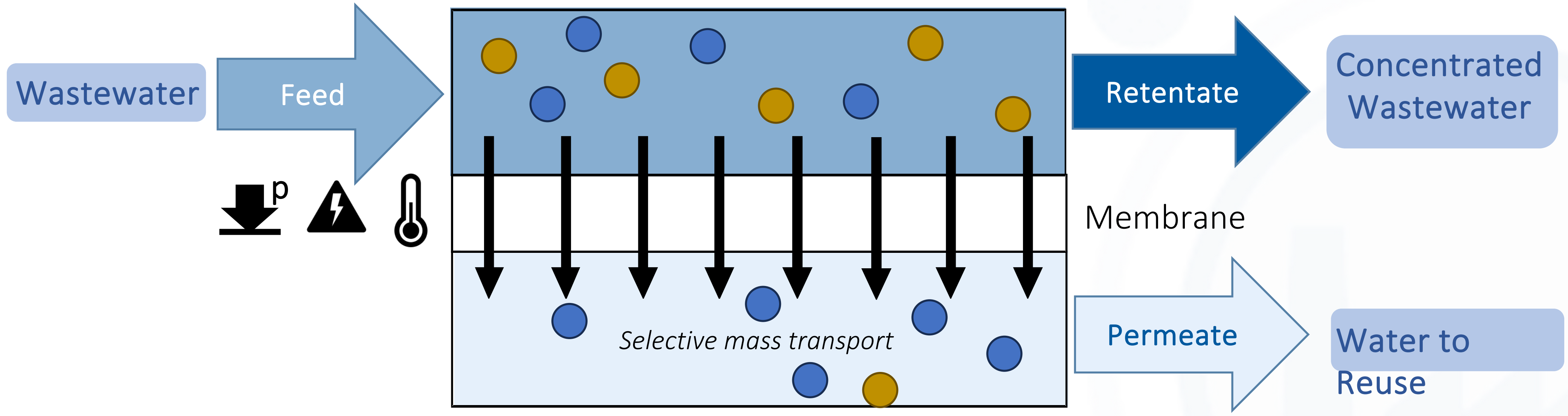
Electrodialysis membrane (left) and electrodialysis stack (right)



[23]

Hollow fibre membranes (left) and hollow fibre membrane module (right)

Membrane Process Terminology



- Different **driving forces** for mass transport through membrane
  - **Pressure** Δ_p driven membrane processes, e.g. Micro-, Nano-, Ultrafiltration, Reverse Osmosis
  - **Electrochemically** Δ_U driven membrane processes, e.g. Electrodialysis
  - **Temperature** Δ_T driven membrane processes, e.g. Membrane Distillation

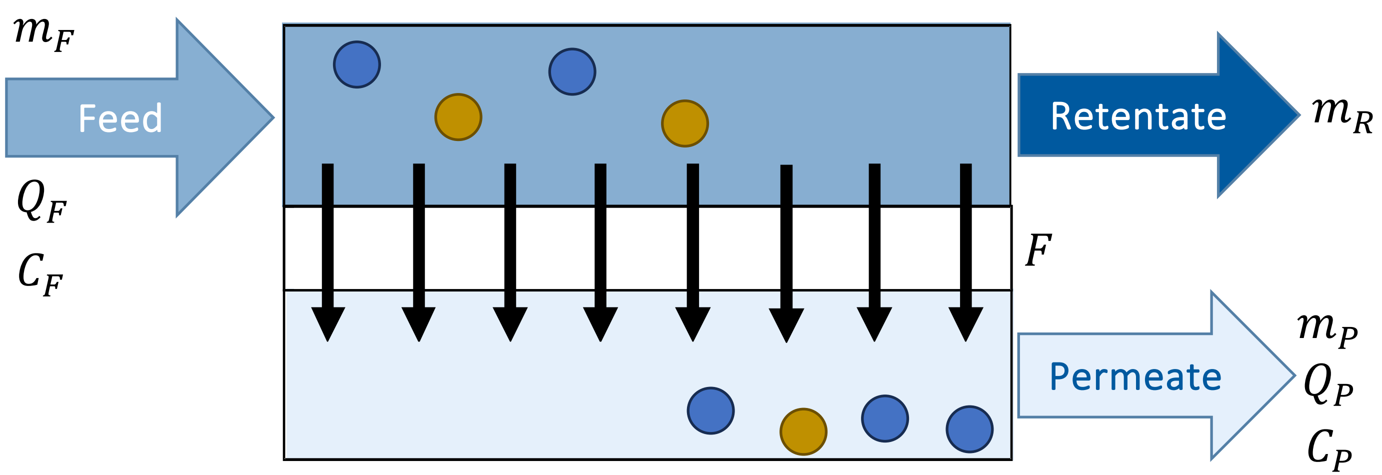
Membrane Applications in Industry

Preventing or **mitigating emissions** from industrial processes (wastewater treatment)

Enabling the **recovery of valuable resources** from industrial process streams (water, heat, solvents or other raw materials)

Promoting **energy savings** in industry

Important Parameter for Membrane Processes I/II



Mass Balance $\dot{m}_F = (\dot{m}_R + \dot{m}_P) \left[\frac{kg}{h}\right]$

Membrane Flux $F = \frac{Q_P}{A} \left[\frac{L}{m^2 * h}\right]$

(Water) Recovery $r = \frac{Q_P}{Q_F} * 100\ [\%]$

(Solute) Rejection $R = \frac{C_F - C_P}{C_F} * 100\ [\%]$

Selectivity $S_{ij} = \frac{C_{iP}/C_{jP}}{C_{iF}/C_{jF}}$

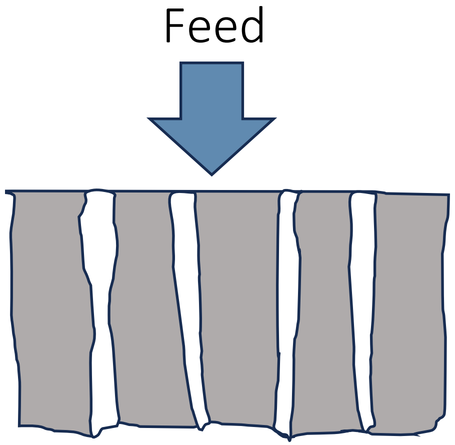
Parameter:

m – mass flow rate [kg/h]
Q – volumetric flow rate [L/h]
A – membrane surface area [m^2]
C – solute concentration [g/L]

Indices:

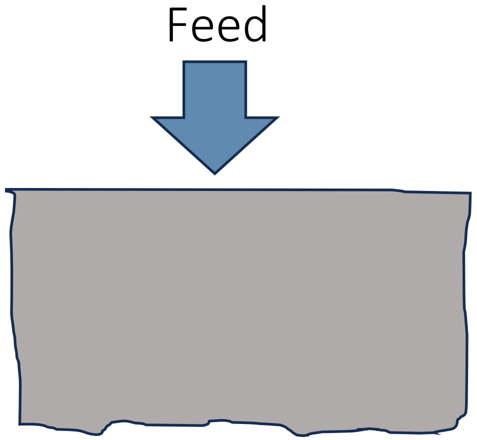
F – feed
P – permeate
R – retentate
i – substance i
j – substance j

Membrane Structures



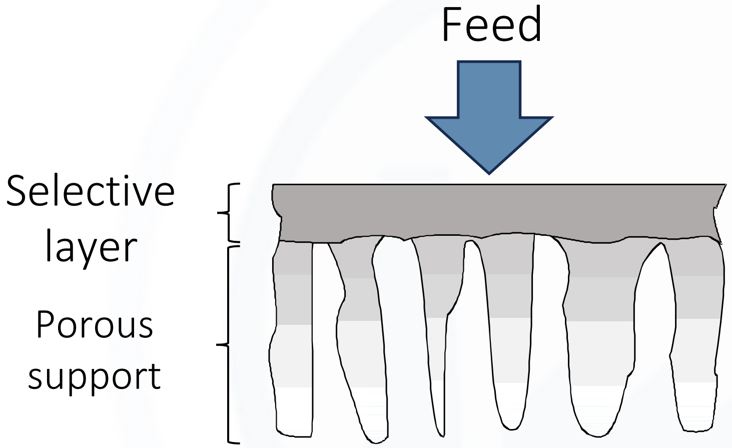
Porous

Separation by Sieve Effect



Dense

Separation by Solution-Diffusion Mechanism



Asymmetric

Membrane Morphology

Asymmetric Membranes

Why asymmetric membranes?

Requirement → High permeate flow

Consequences → Thin selective layer

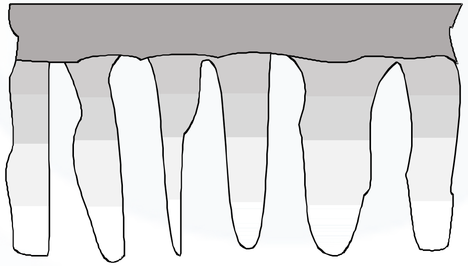
$$\mathit{Flux} \sim \frac{1}{\mathit{Membrane\ thickness}}$$

Problem → Low mechanical stability

Solution

→ **Asymmetric membrane**

= very thin and selective layer **+** thick and porous supporting layer



Membrane Configurations

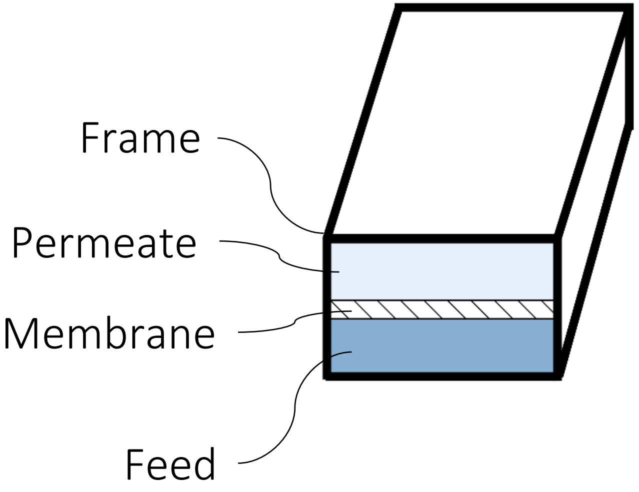
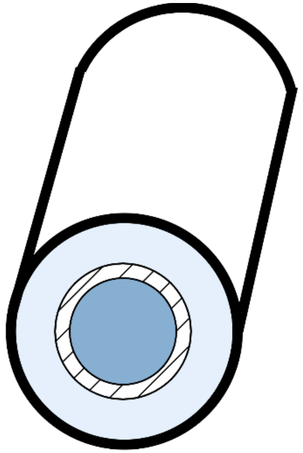
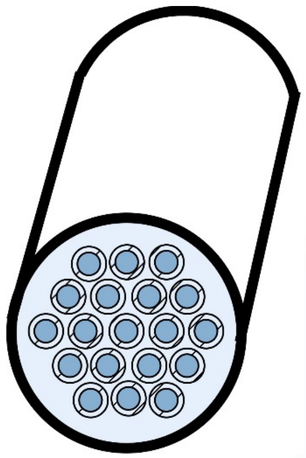


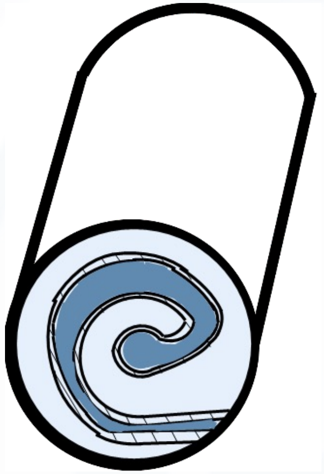
Plate and Frame



Tubular



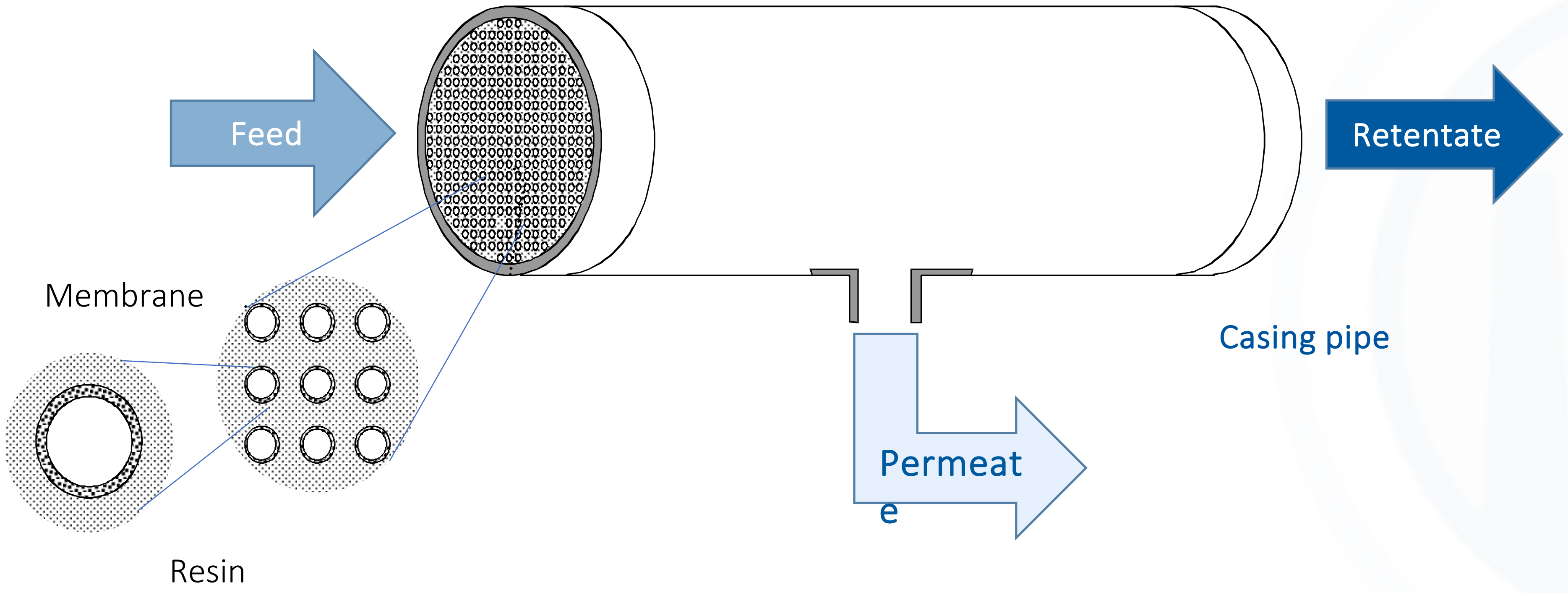
Capillary/Hollow fiber



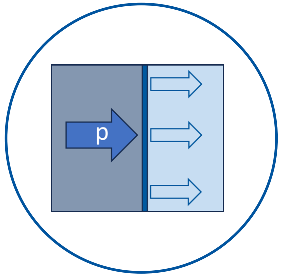
Spiral wound

Membrane Module

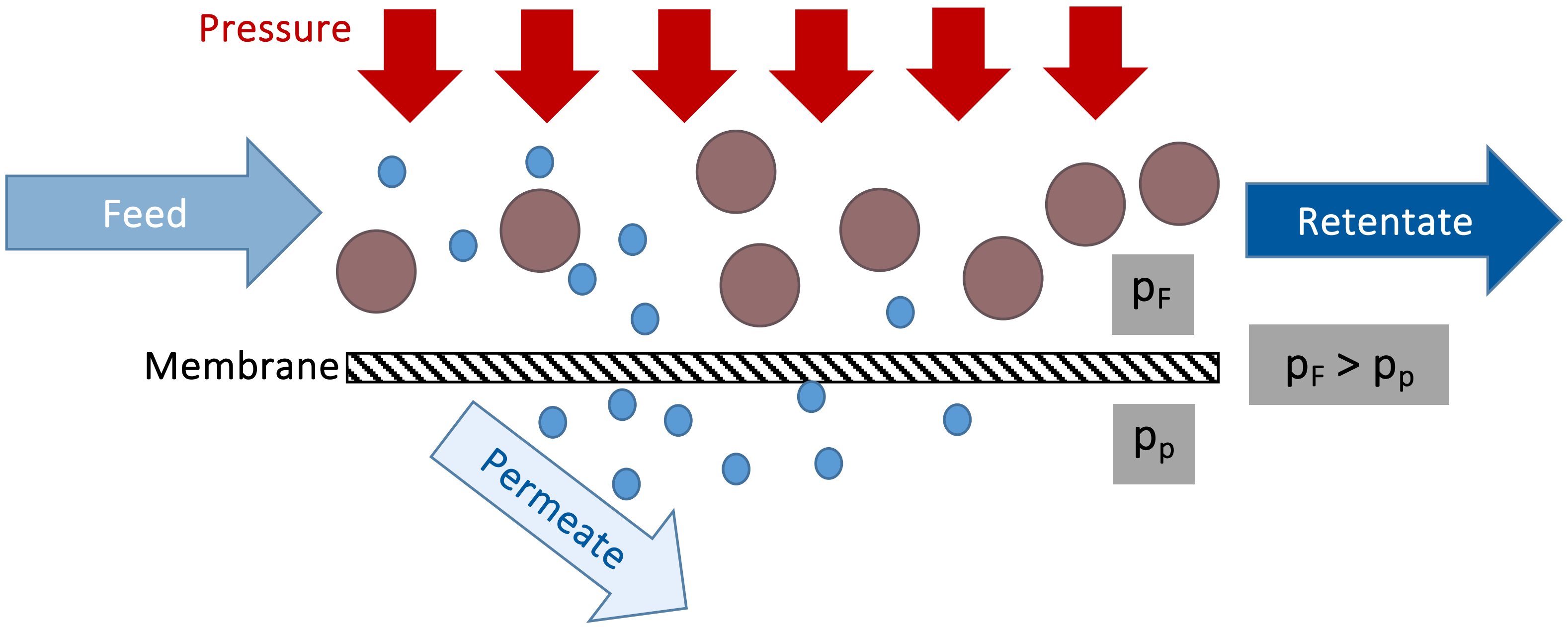
Scheme of a Capillary Module



Pressure Driven Membrane Processes



Principle of Pressure Driven Membrane Processes



Microfiltration:

Particles, algae, protozoa, bacteria

Ultrafiltration:

Viruses, colloids, macromolecules

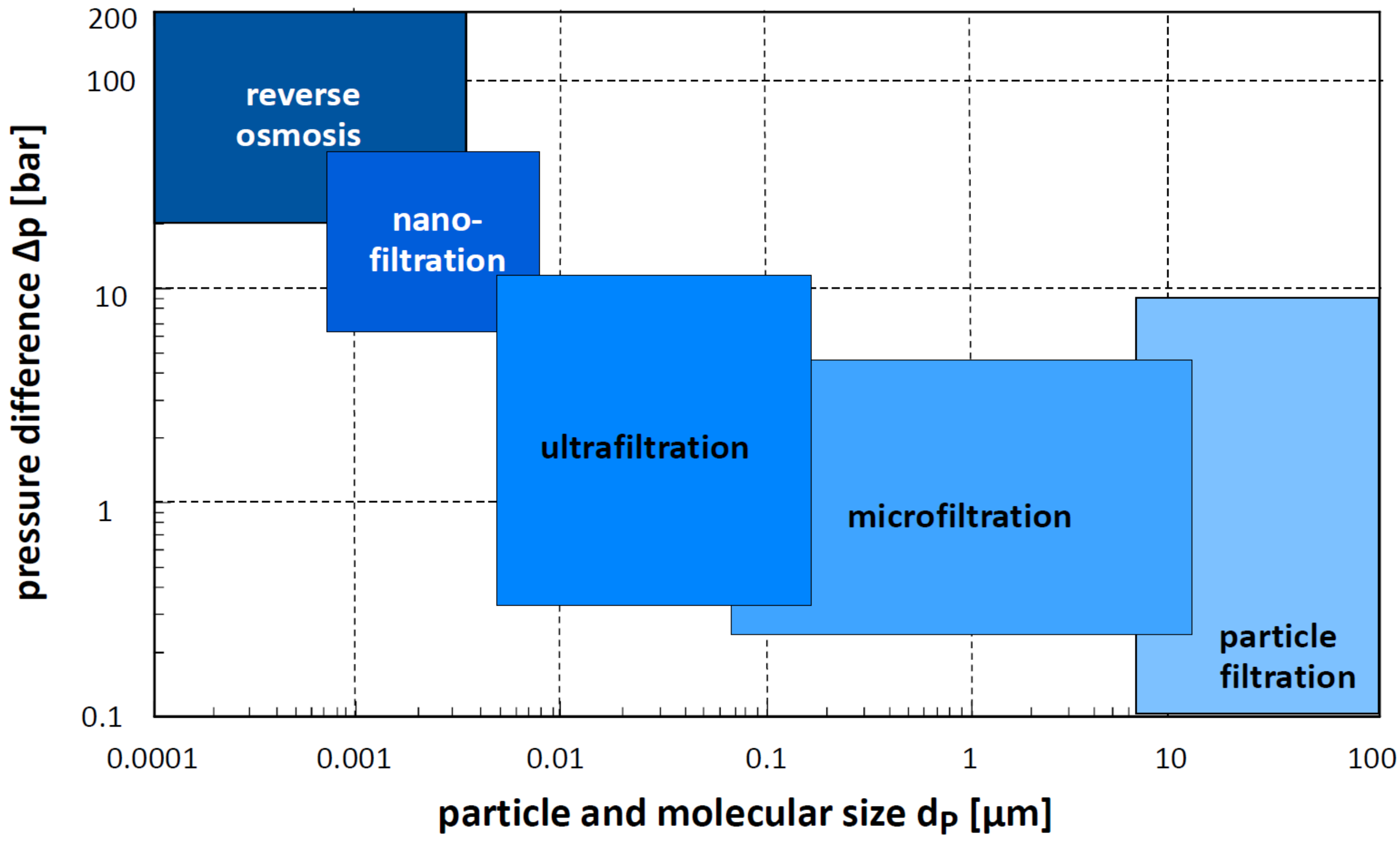
Nanofiltration:

Dissolved, org. substances, divalent ions

Reverse Osmosis:

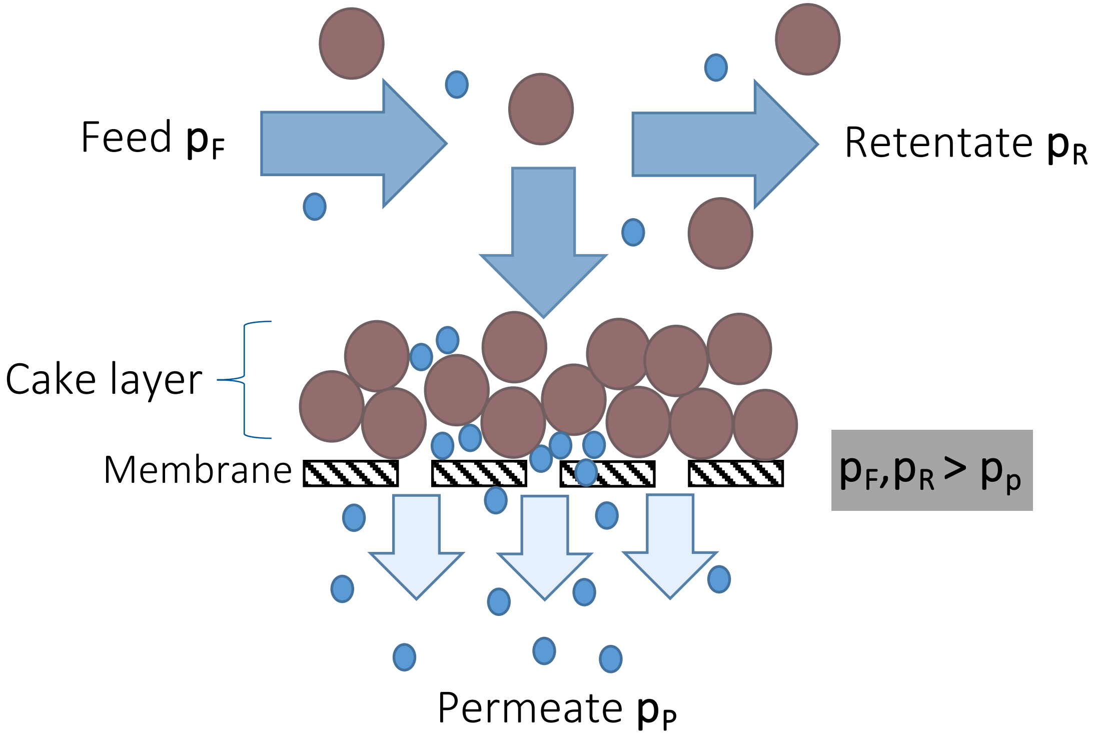
monovalent ions, small molecules

Classification of Pressure Driven Membrane Process



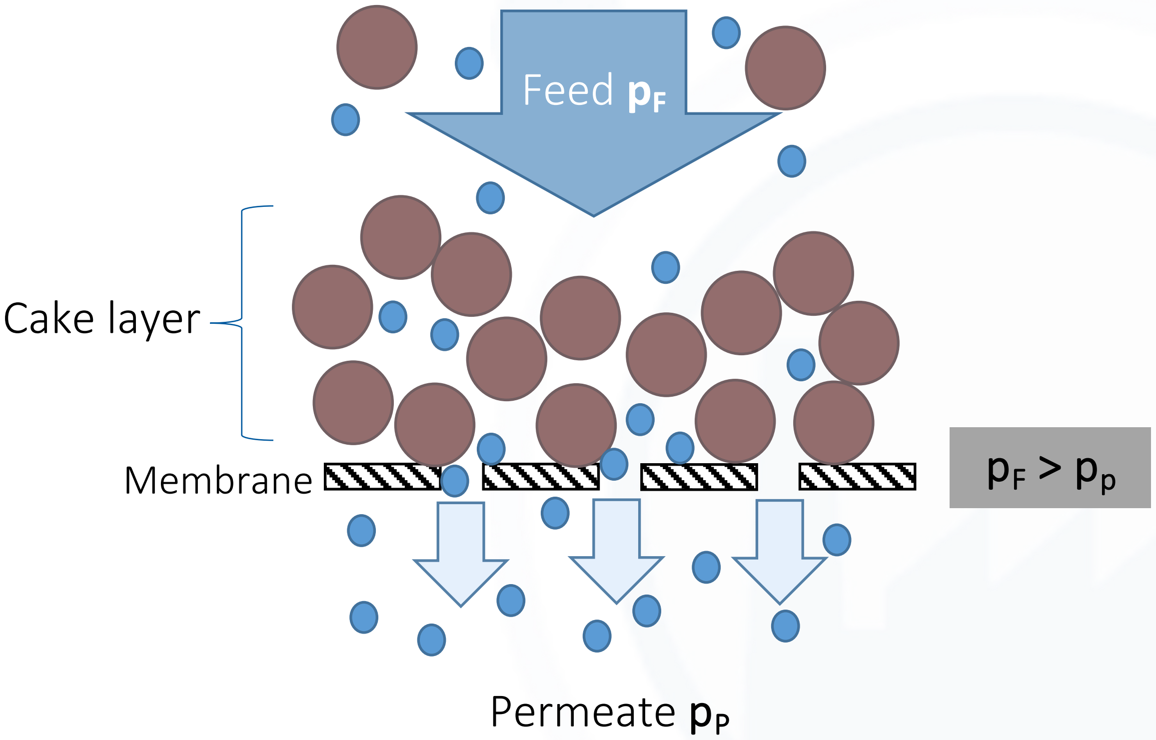
Operational Modes

Crossflow ||



$$\Delta p_{Transmembrane} = \left(\frac{p_F - p_R}{2}\right) - p_P$$

Dead-End ⊥

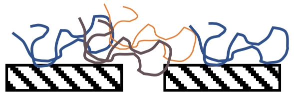


$$\Delta p_{Transmembrane} = p_F - p_P$$

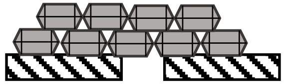
Performance Limiting Phenomena

- Membrane Fouling is the buildup of undesirable substances or particles on the membrane, impeding its filtration efficiency
- Classification of fouling

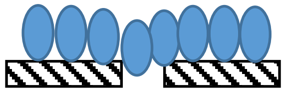
Organic fouling



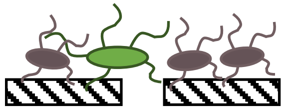
Inorganic fouling



Collodial fouling

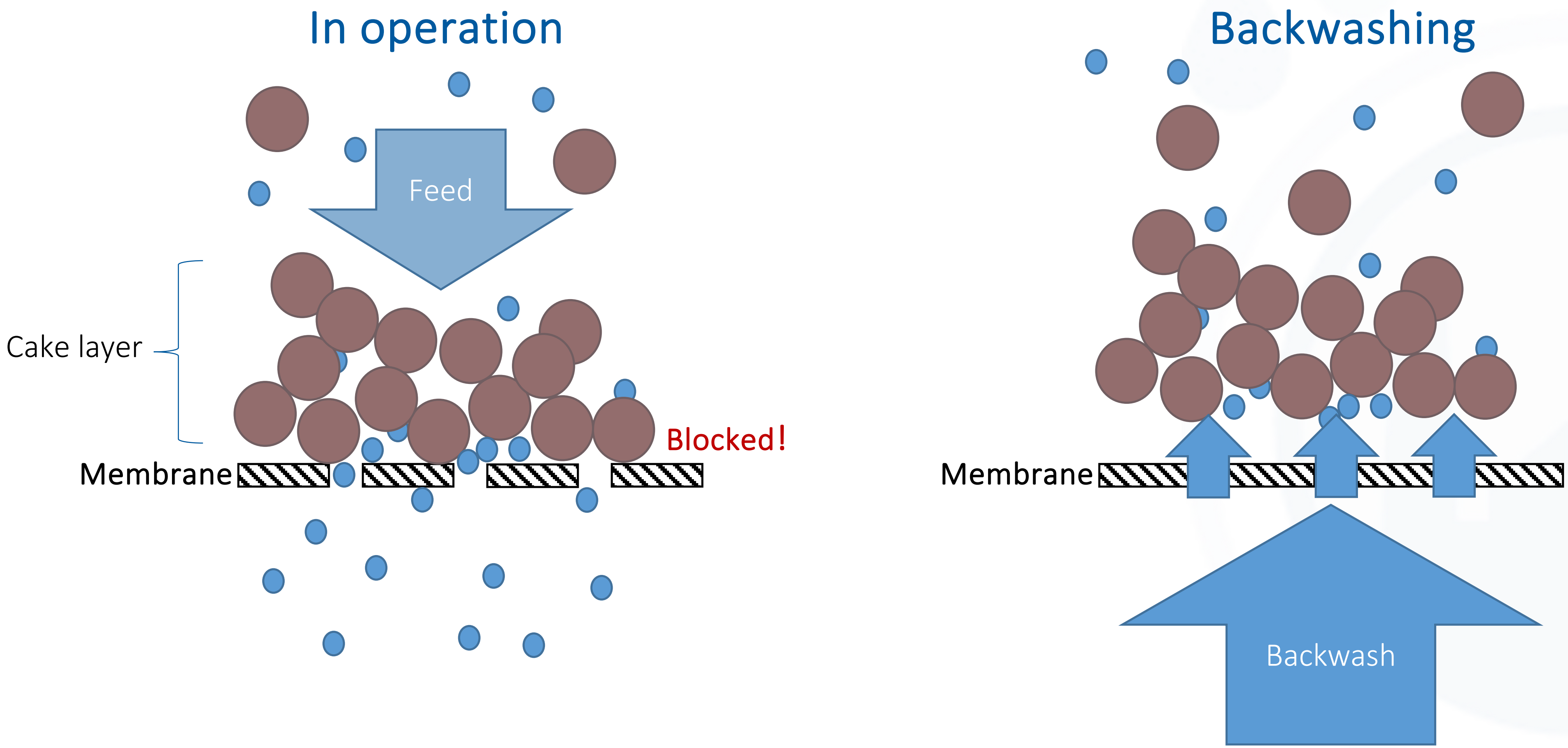


Biofilms



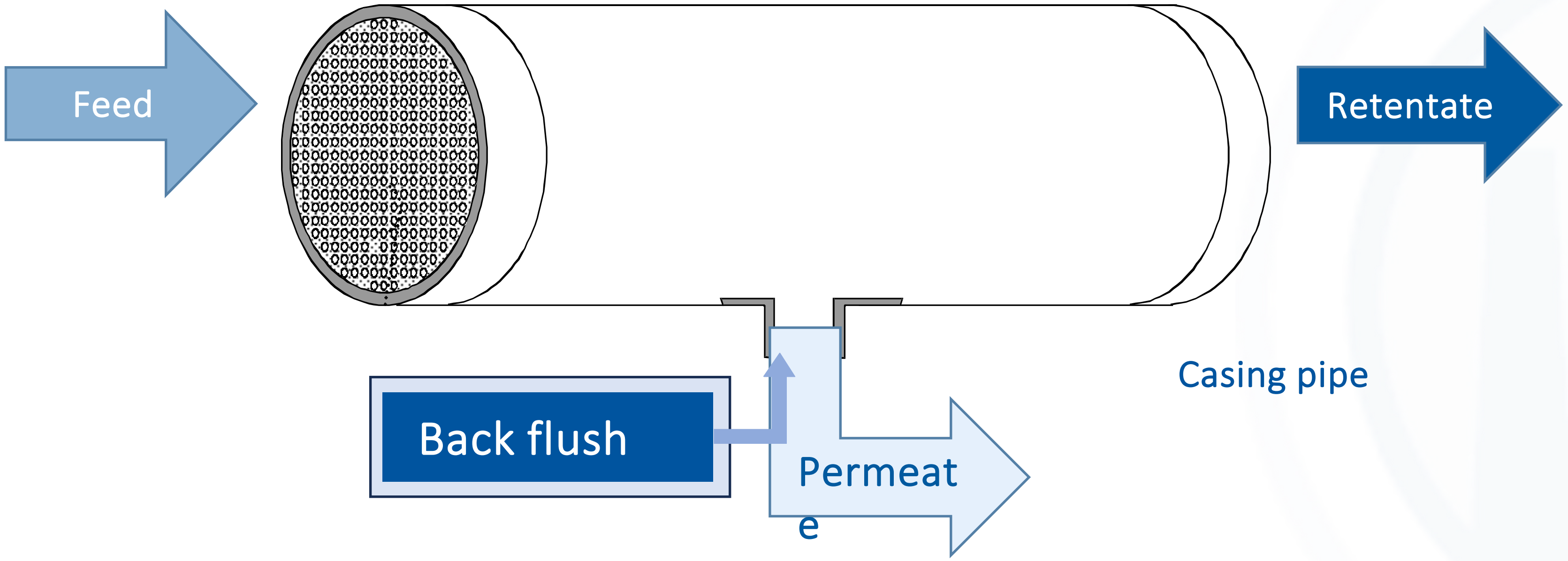
Backwashing, Chemical Cleaning

Backwashing I/II

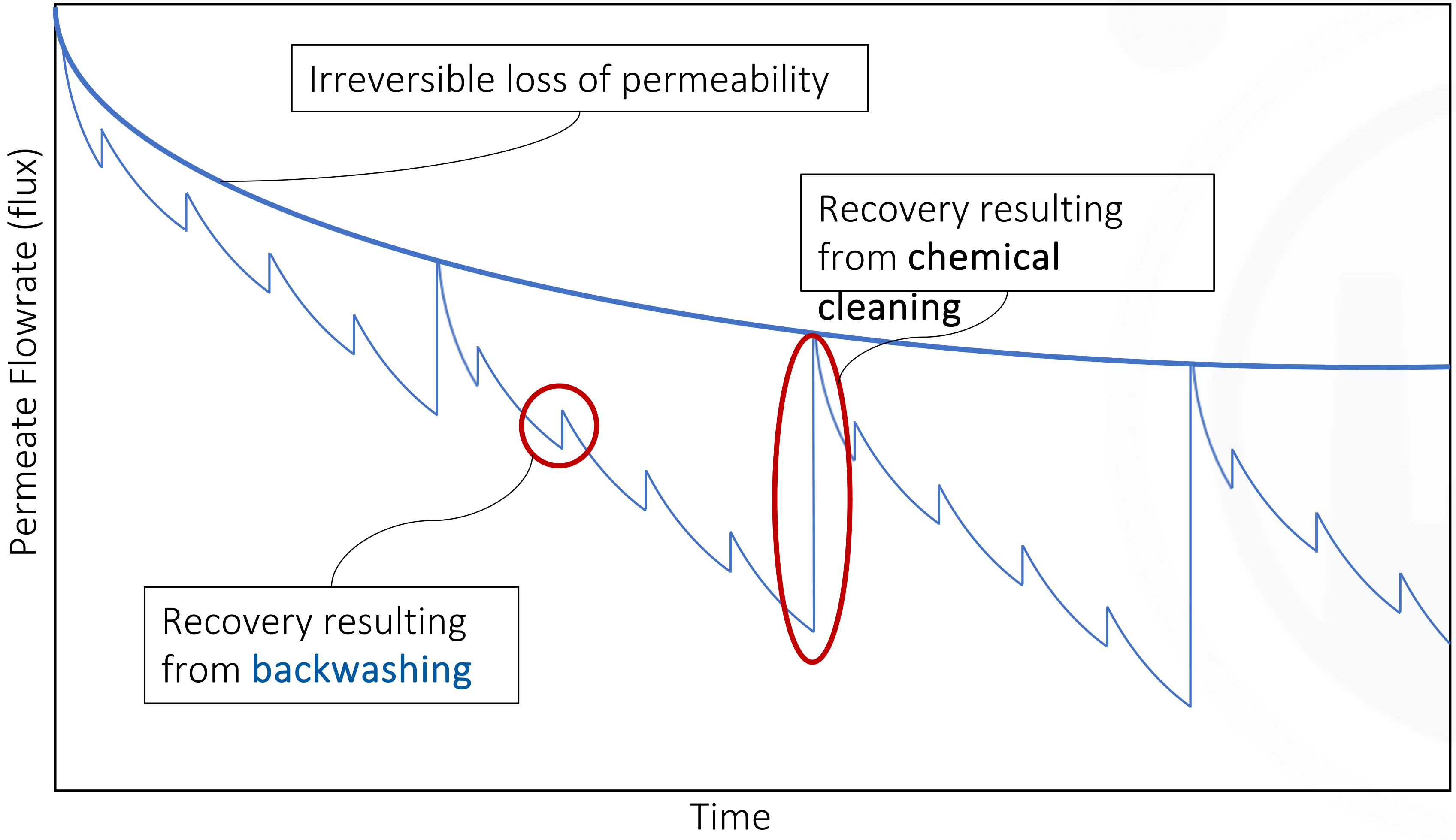


Backwashing II/II

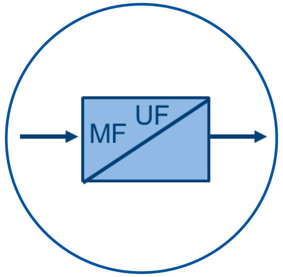
Module-scale Backwashing



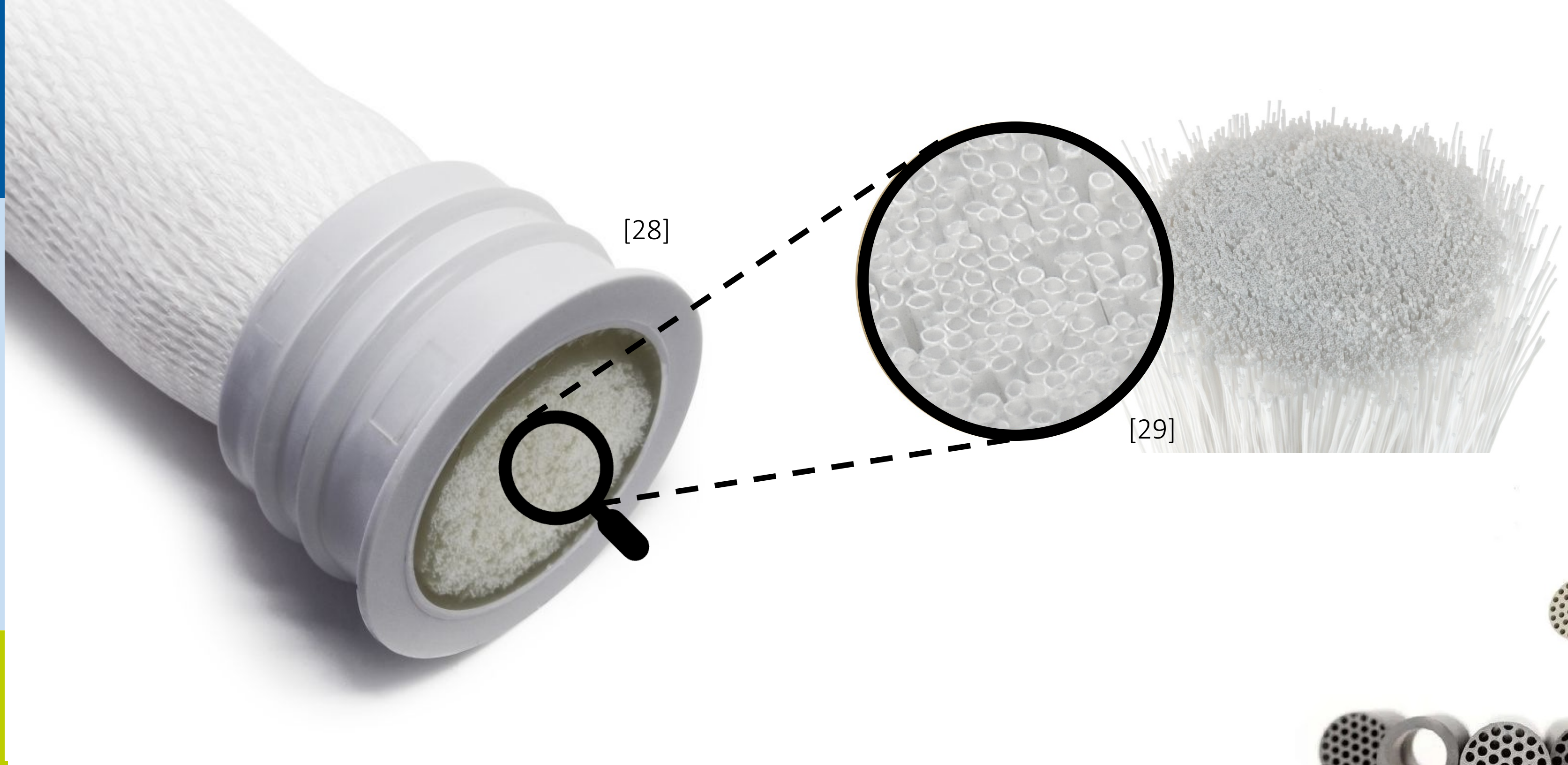
Membrane Cleaning

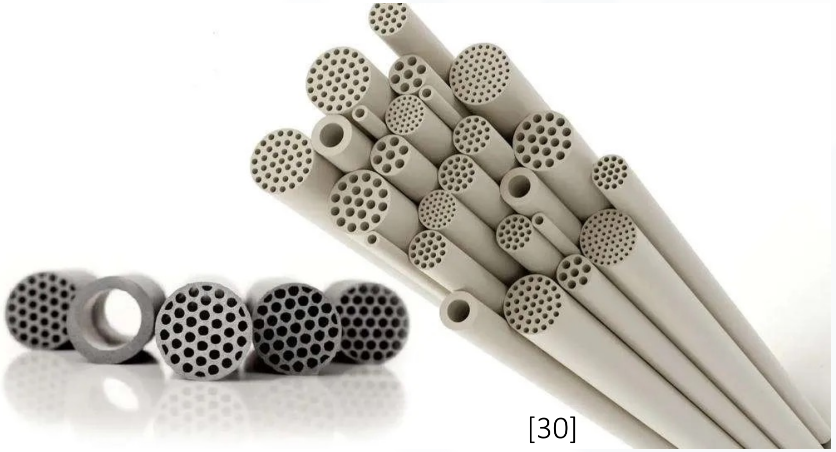


Micro- and Ultrafiltration



Micro- and Ultrafiltration





Main Applications of Micro- and Ultrafiltration

Examples

- Leachate treatment
- Concentration of aqueous coating from spray booth water

Environmental engineering

Metalworking industry

- Concentration of oil/water emulsion
- Treatment of degreasing baths

- Concentration of gelatin and chicken proteins
- Clarifying filtration of wine

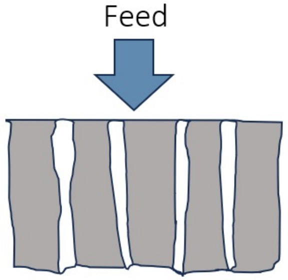
Pharmaceutical industry

Food industry

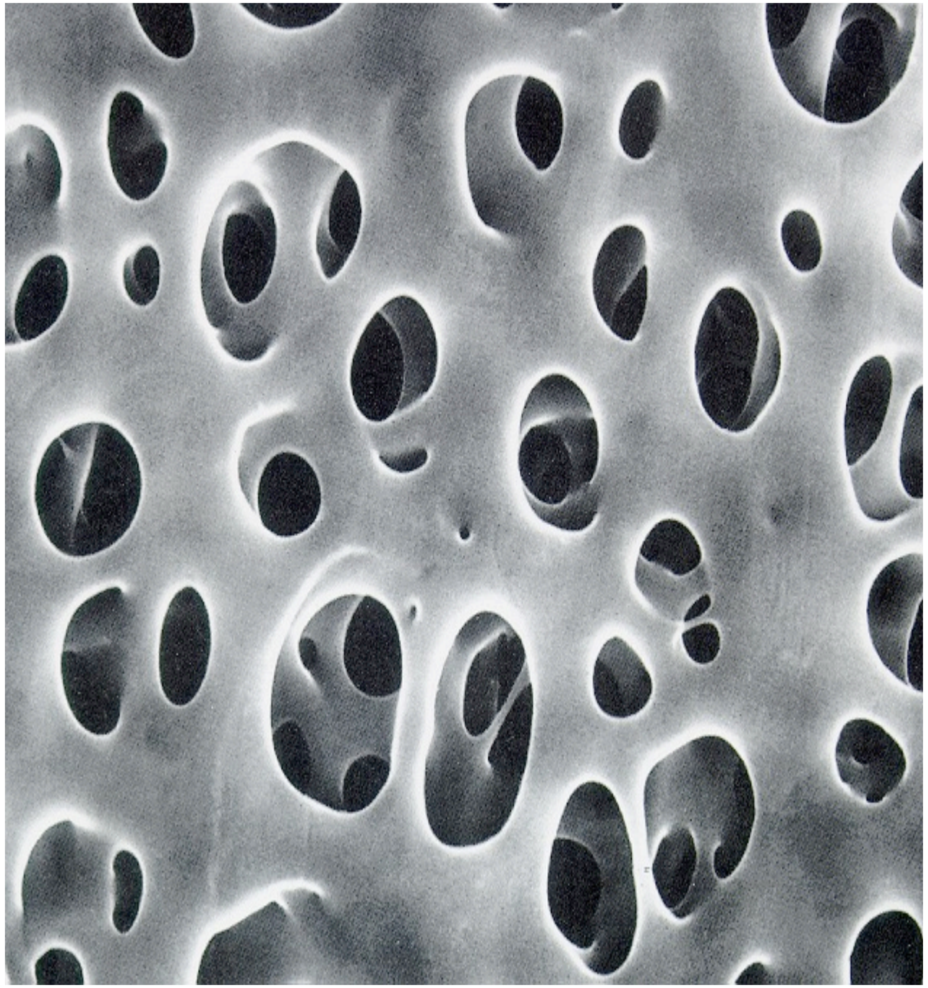
- Purification of antibiotics
- Concentration, separation and purification of vaccines and enzymes

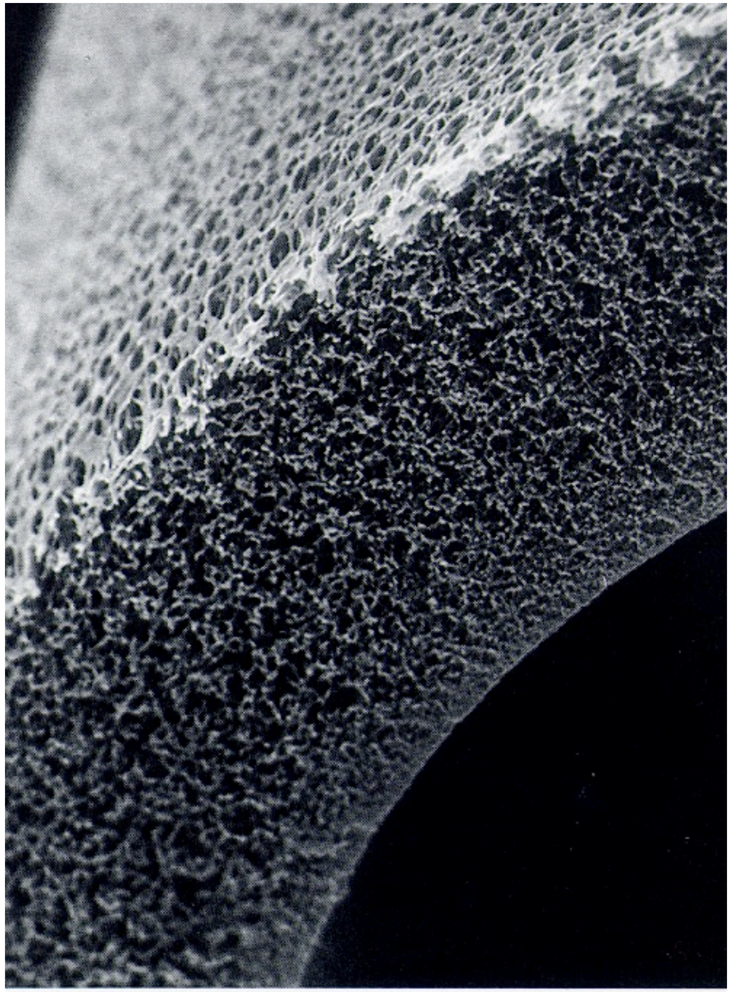
Membranes for Microfiltration

SEM Images



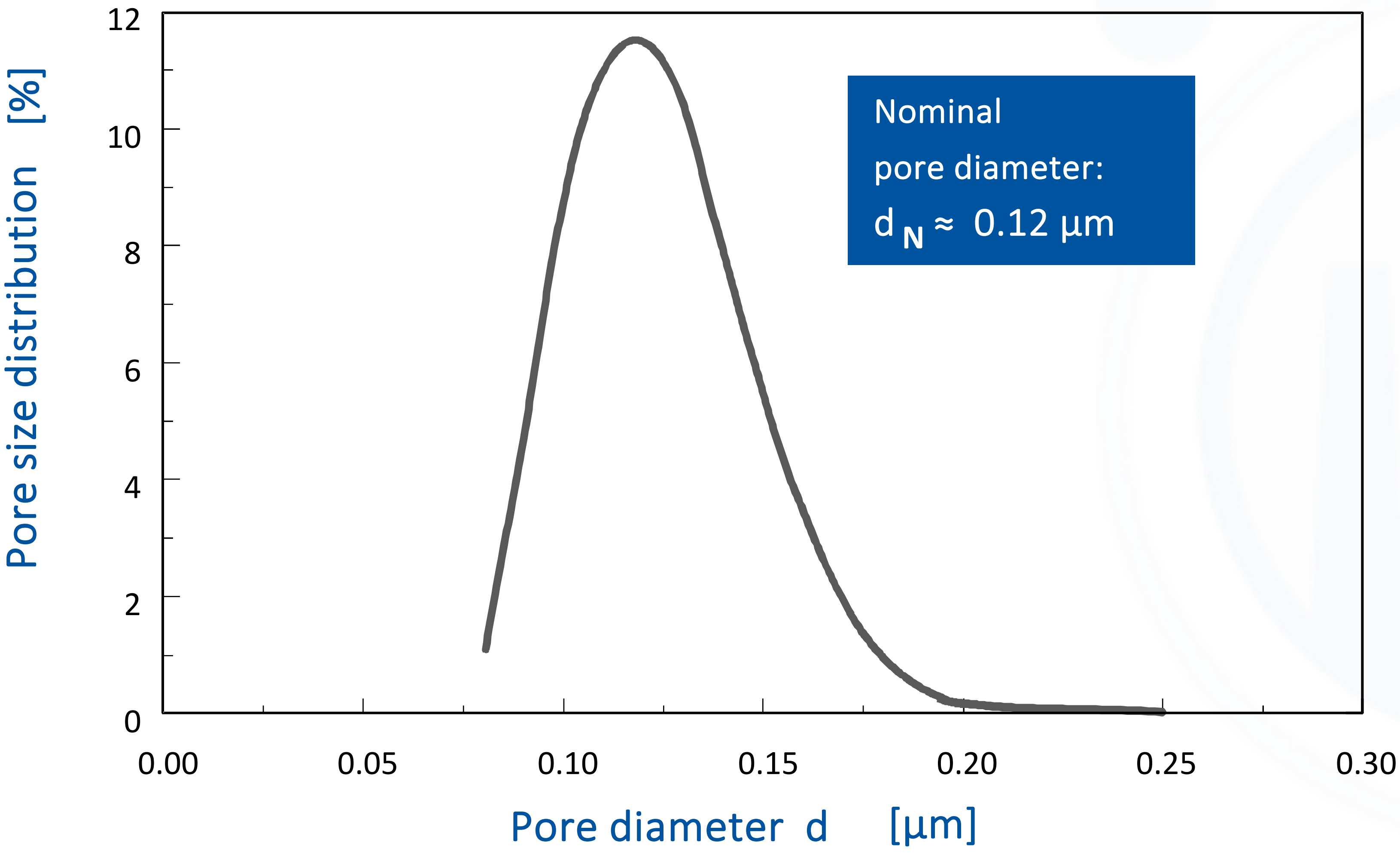
Symmetric polysulfone membranes: pore structure





Membranes for Microfiltration

Exemplary pore size distribution of microfiltration membranes

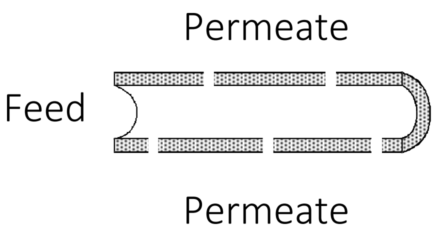


Module Design for Micro- and Ultrafiltration

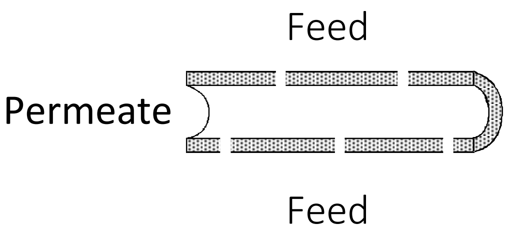
Capillary/ Hollow Fiber Module

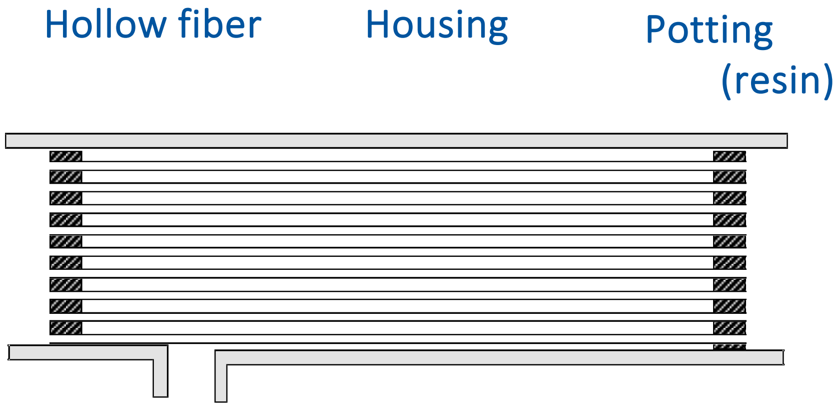
- Hollow fiber module

Feed: lumen side



Feed: shell side





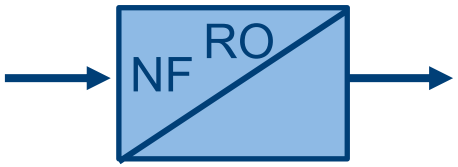
Plants for Micro- and Ultrafiltration

Drinking water treatment 300 m³/h using ultrafiltration in Grundmühle waterworks

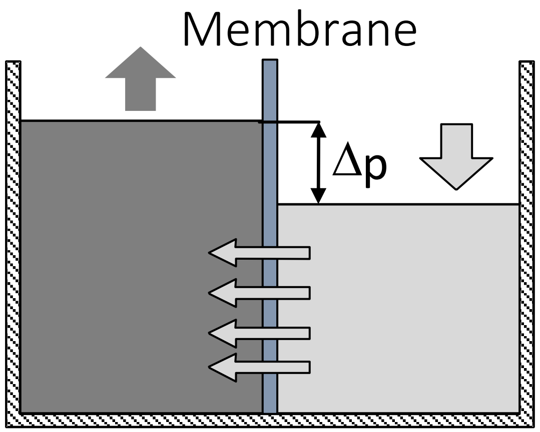
[19]

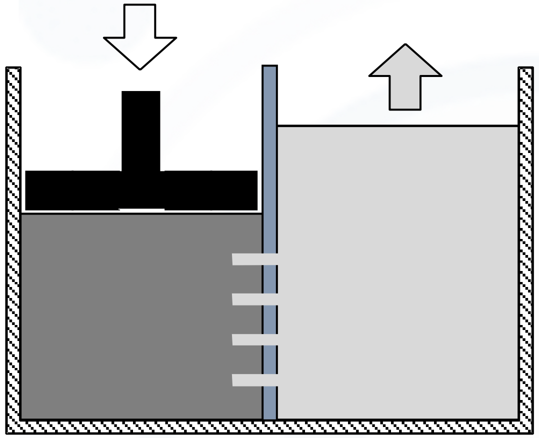
Many modules are assembled to so called racks or stages.

Nanofiltration (NF)
and Reverse Osmosis (RO)



Principles of Reverse Osmosis





high concentration

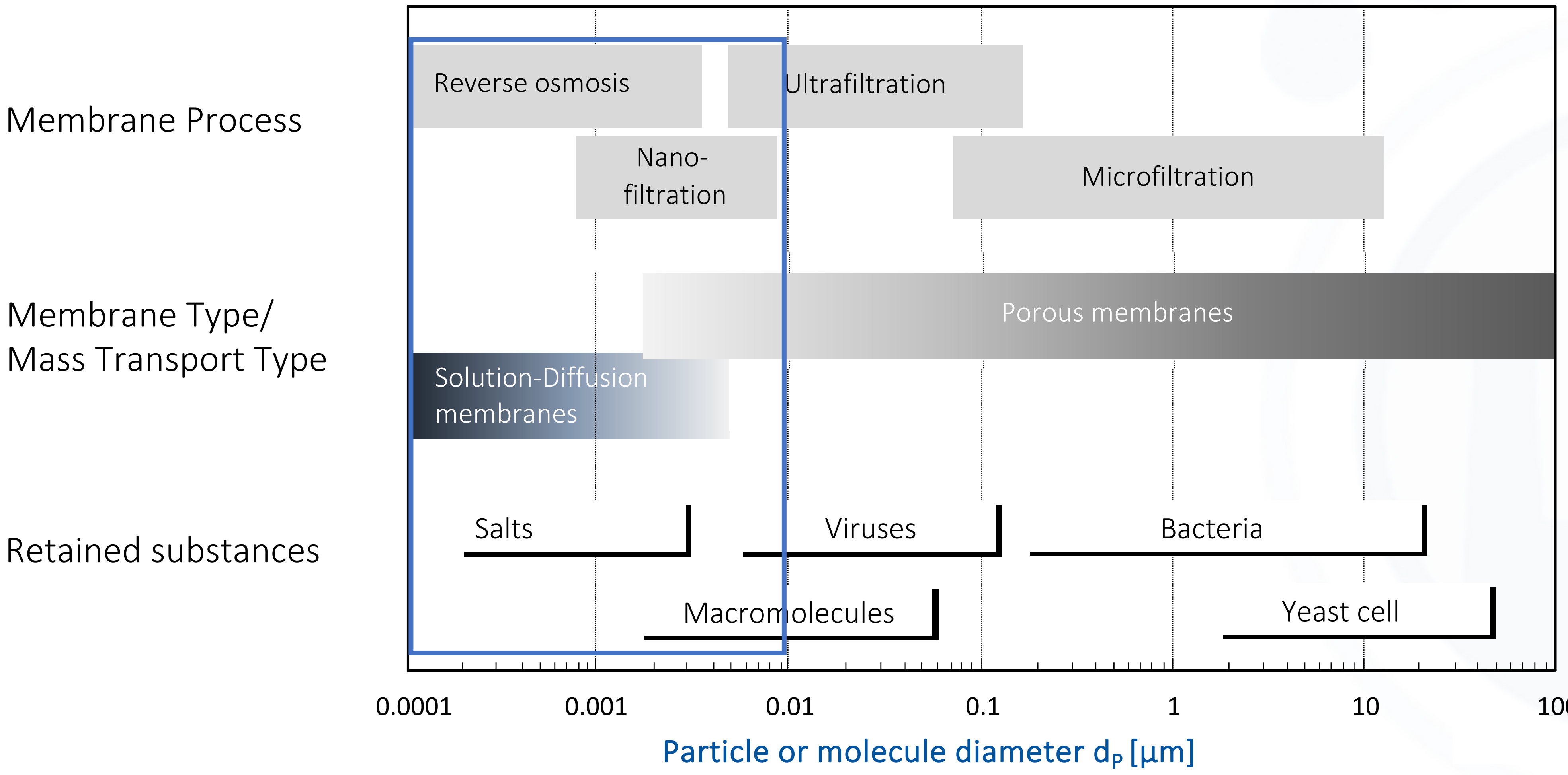
low concentration

Osmosis : $\Delta p < \Delta\pi$

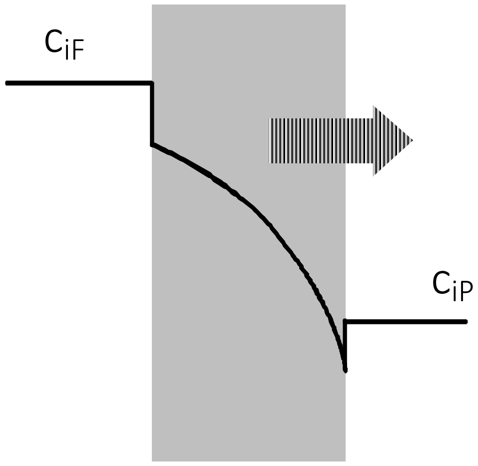
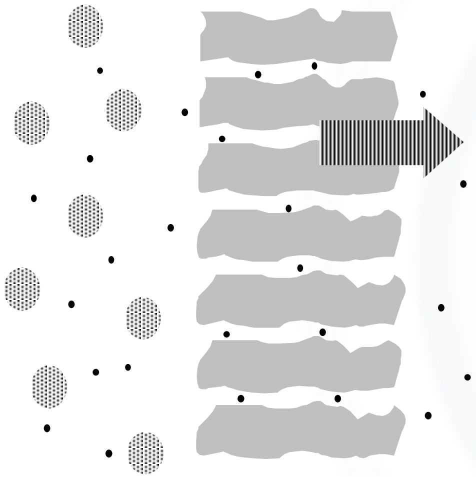
Reverse osmosis: $\Delta p > \Delta\pi$

$\Delta\pi$ Osmotic pressure
Δp Hydrostatic pressure

Modeling of the Mass Transport in Membranes

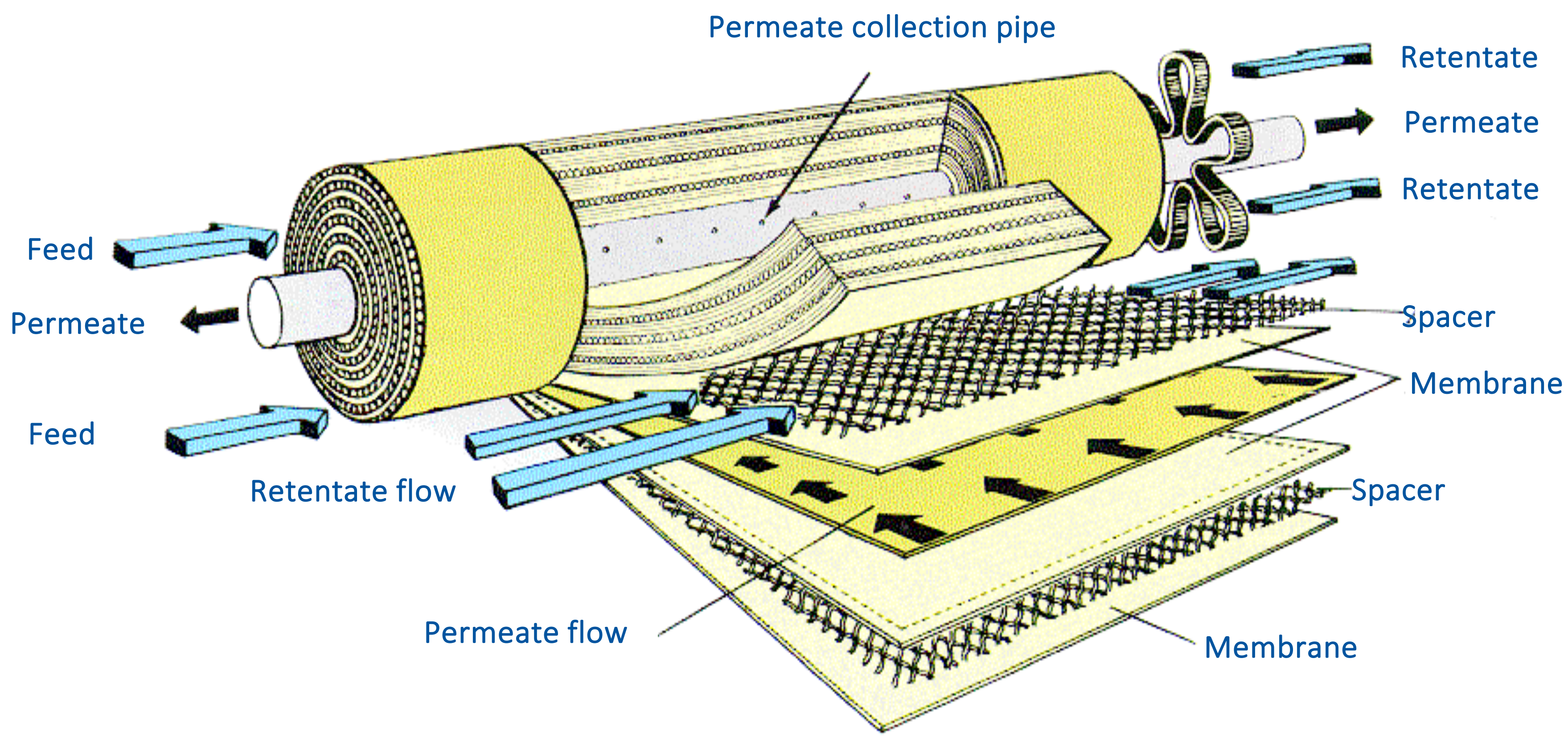


Models for the Mass Transport Through Membranes

Solution-diffusion membrane	Porous membrane
	
• Reverse osmosis • Electrodialysis • Pervaporation	• Microfiltration • Ultrafiltration • Nanofiltration

RO/NF Modules: Spiral Wound Membrane Module

Design of a Spiral Wound Membrane Module



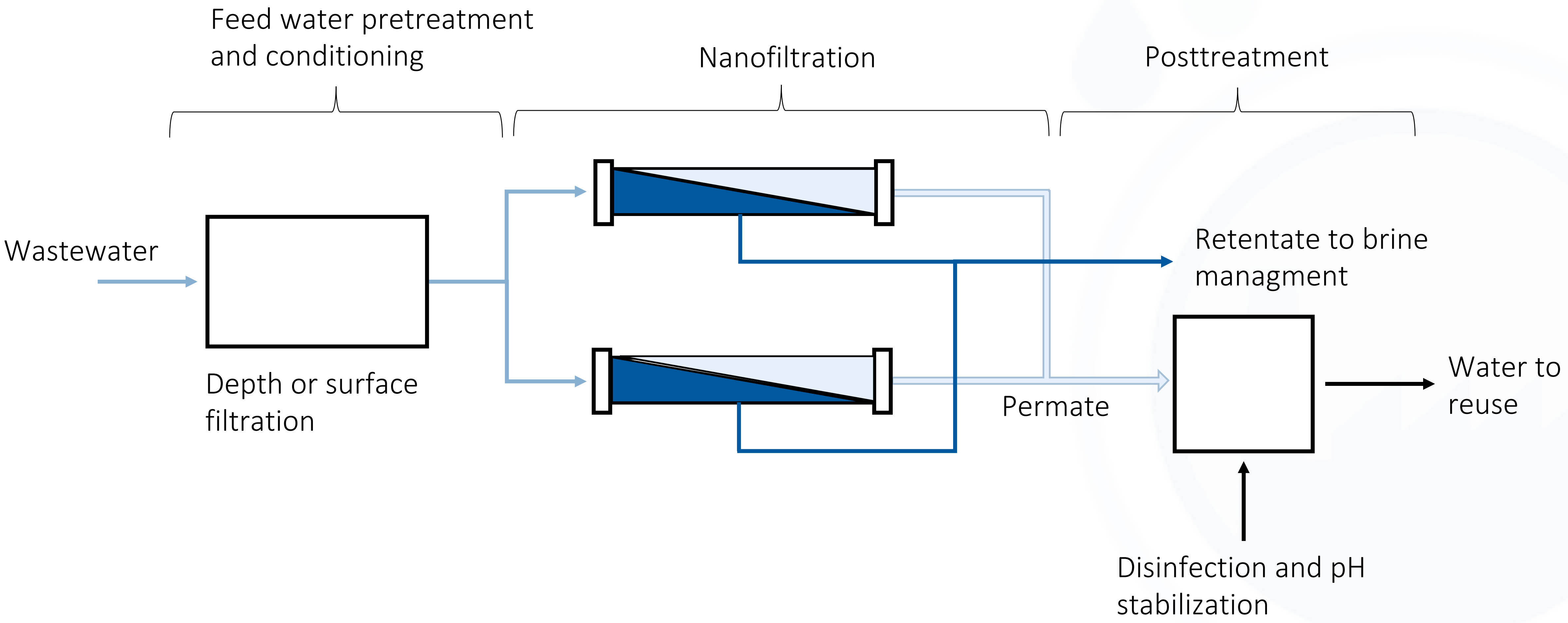
Height of feed channel fixed due to spacer: 0.5 - 1.0 mm

Example: RO for Seawater Desalination


[35]

- NAQA’A Desalination Plant (UAE)
- Desalination capacity > 600 000 m^3/day

Exemplary Membrane Process Flow Chart



Factors Influencing the Performance of Membrane Modules

Characteristics of membrane module

Characteristics of membrane

- Morphology and structure
- phys.-chem. properties
- chem./mech./therm. stability

Module design

- Feed-side hydrodynamics
- Packing density/Dead zone
- Backwash ability

Performance of membrane modules

Membrane permeability

- Reversible cake layer
- Membrane fouling
- Membrane aging

Filtering membrane area

- Module blocking due to high particulate concentration
- Blocking/Accumulation of sludge

Chemical cleaning

- Cleaning agents
- Cleaning frequency
- Cleaning parameter

Plant design

- Operation parameter
- Module rinsing
- Chemically supported cleaning

Feed (pretreatment)

- Feed components and concentrations
- Dissolved substances, colloids
- pH-Value, conductivity
- Pretreatment, Flocculation

Operation and feed parameter

Common Properties of Membrane Processes

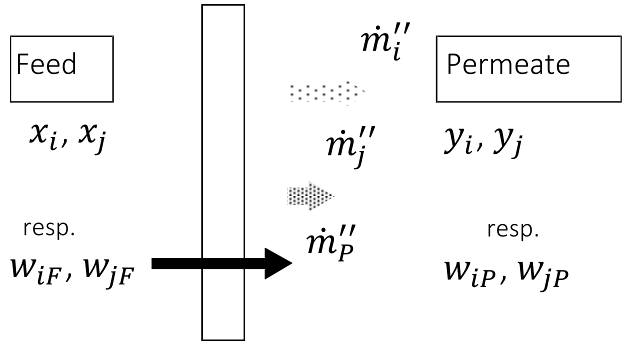
- Limited selectivity (effective for large classes of compounds)
- Modular construction
  - Scalable and easily expandable
- Relatively compact compared to sedimentation
  → Low footprint
- Only separation, no elimination of pollutants
  → Treatment/disposal of pollutant-rich concentrate is needed
- Moderate energy demand
  - Yet critical for cheap products, such as water
- Large contact surface
  → Membrane fouling and durability are critical aspects

Economic Considerations

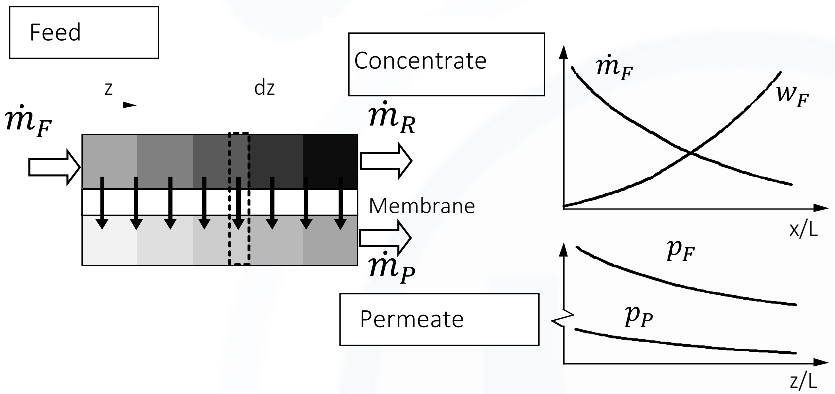
Technical and Economic Aspects

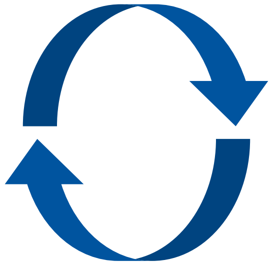
Different Levels of Process Development

Membrane element

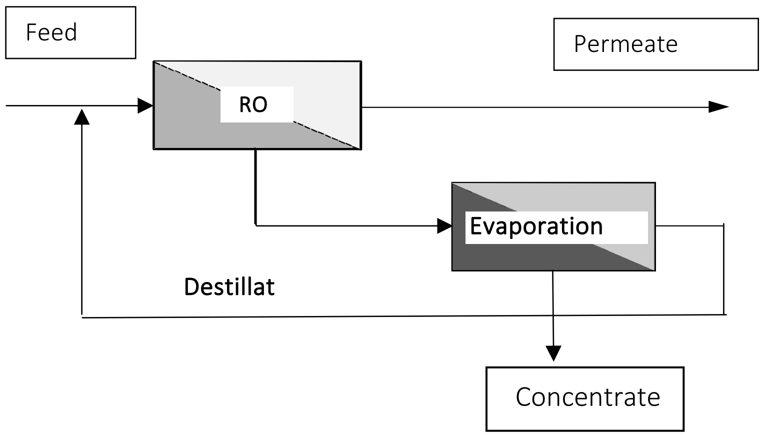


Module

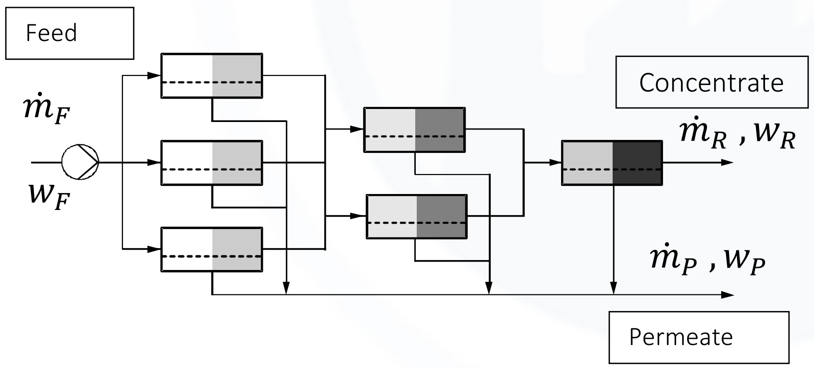




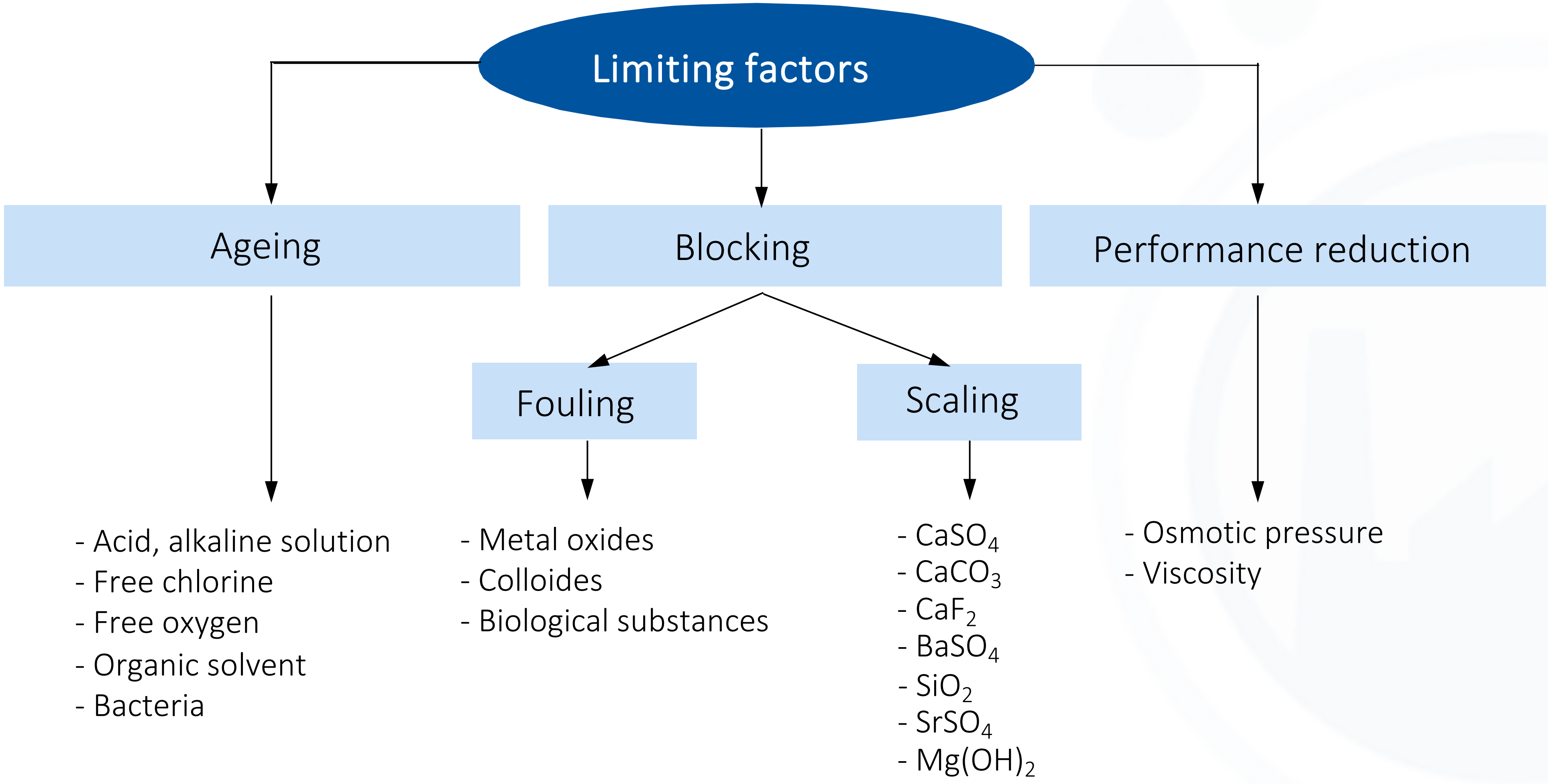
Full process



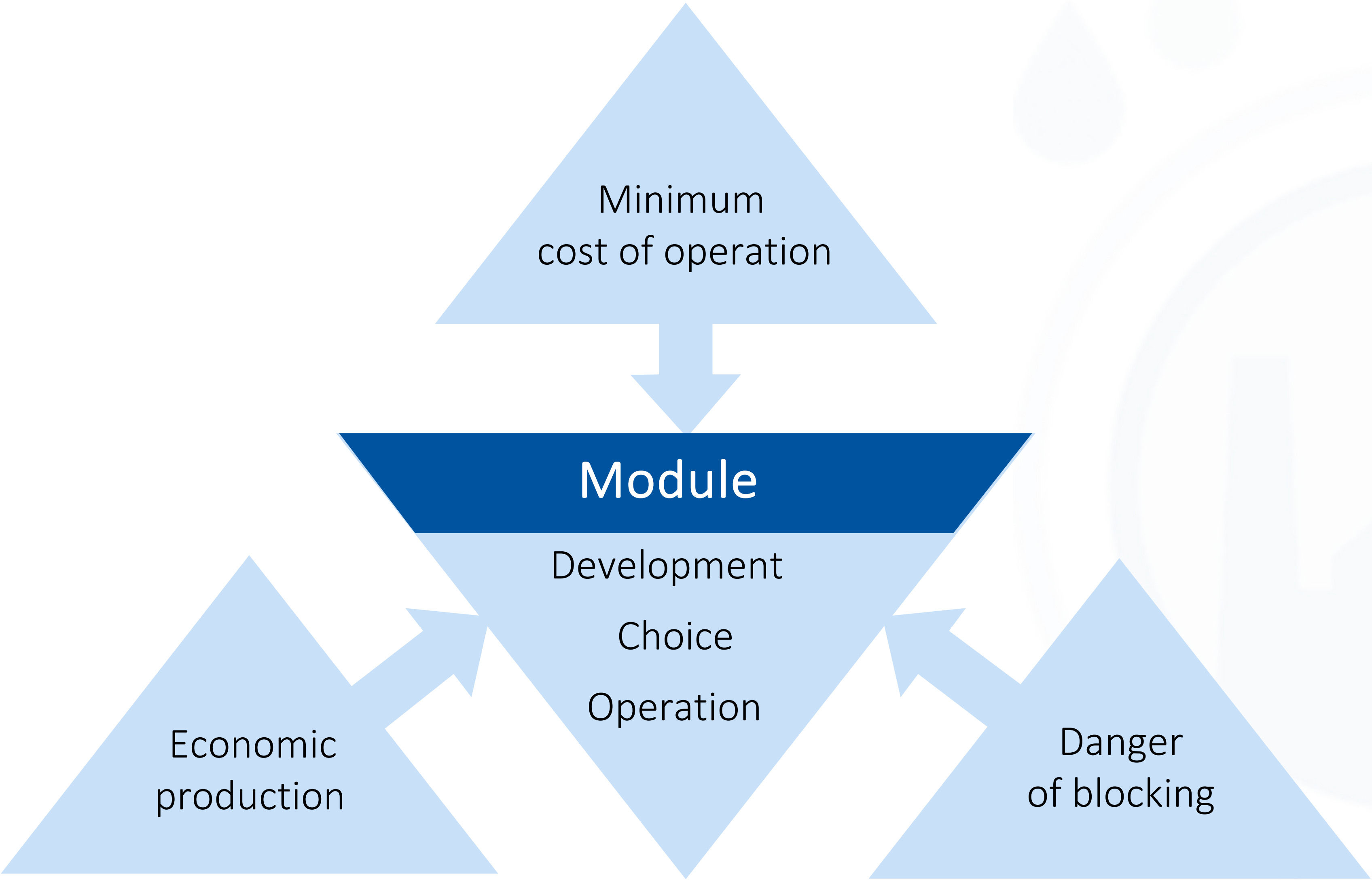
Module arrangement



Limiting Factors of Membrane Processes



Viewpoints of Module Development, Choice and Operation



Demands on Module Construction

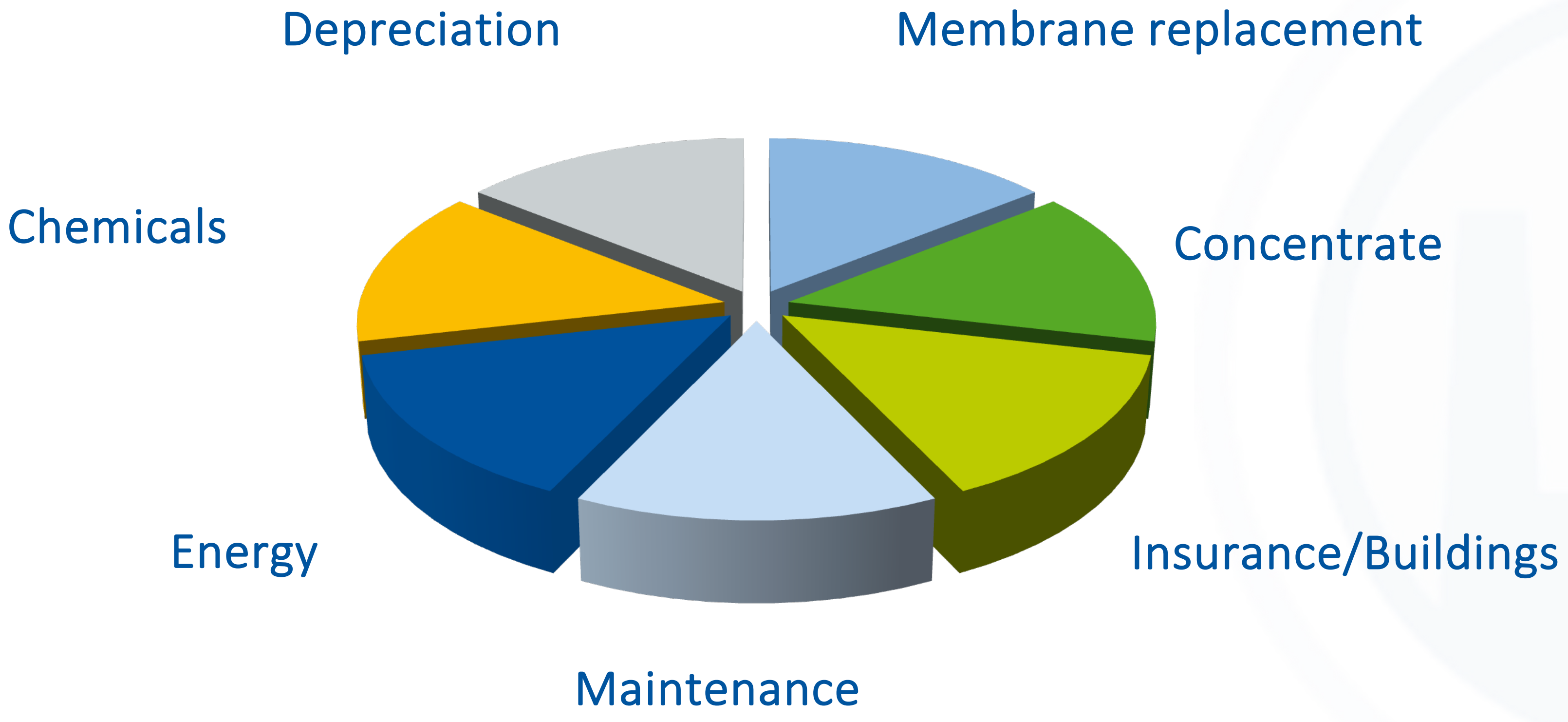
- **Economic production:**
  - High packing density
  - Low-cost materials that guarantee sufficient thermal, chemical and mechanical stability

- **Minimum cost of operation:**
  - Low pressure drop
  - Low energy demand
  - Good cleaning performance
  - Cost-efficient membrane change

- **Low danger of blocking:**
  - High load capacity for solids
  - Steady flow
  - Prevention of dead zones
  - Prevention of channeling

Technical and Economic Aspects

- Shares of **operation cost** of membrane plants



Literature Reference: Membrane Processes

The material on membrane processes presented is partially based on the book „Membranverfahren“
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Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations

Assessment of Cooling Tower Blowdown Reuse Feasibility at Chemical Industrial Site

Sarah Isabell Müller, Eduard de las Heras García, Lies Hamelink, David Moed, Lisa Wyseure, Ivaylo Hitsov, Gergana Chapanova, Thomas Diekow, Christian Kaiser, Laurence Palmowski, Thomas Wintgens

The AquaSPICE project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 958396.

Dow Chemical Company Introduction

Quick Facts

- Dow Chemical Company
  - Founded in 1897
  - Multinational corporation, headquarters in Midland, Michigan (USA)
  - Products:
    - Basic and performance plastics
    - Basic and performance chemicals
    - …
  - Target industries/applications:
    - Automotive
    - Construction
    - Pharmaceutical
    - Agriculture
    - …

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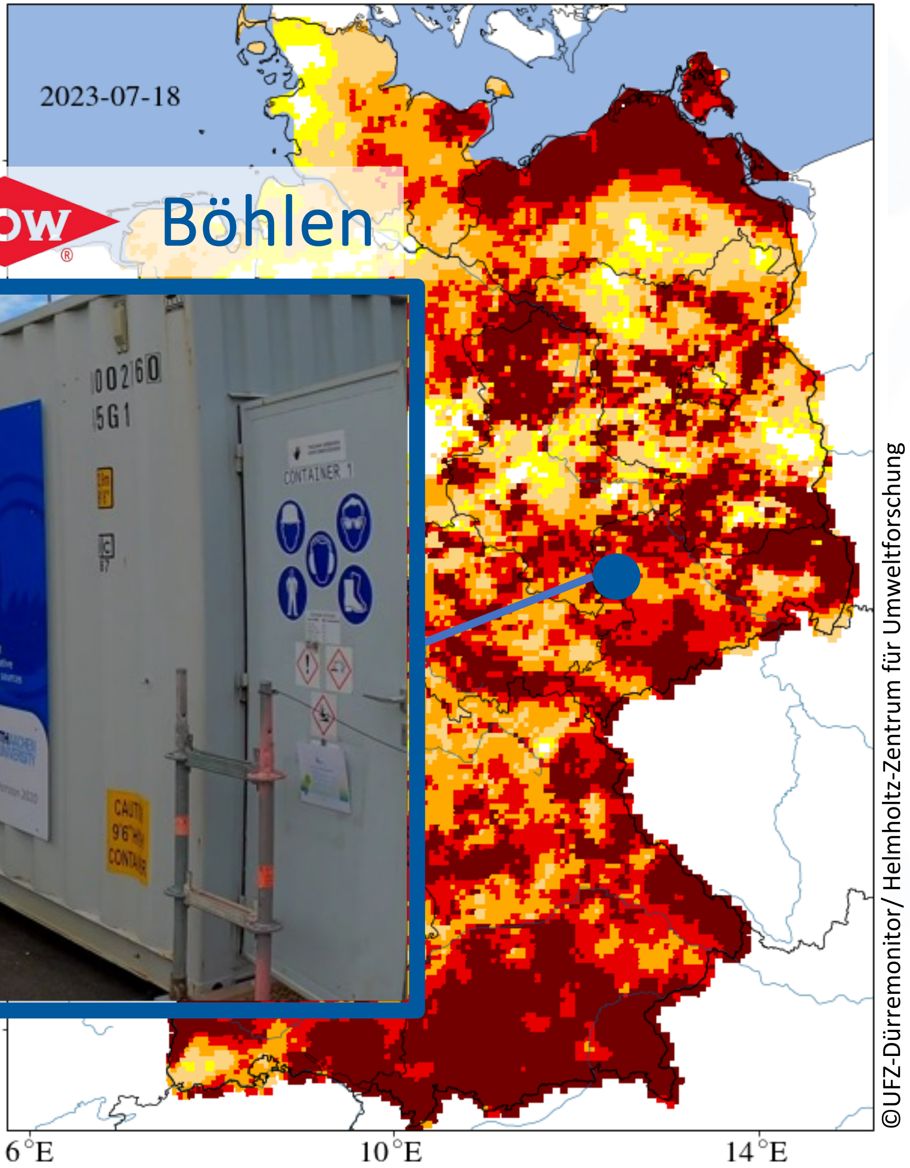
@ Terneuzen, The Netherlands
@ Boehlen, Germany

AquaSPICE

Water Stress in Germany

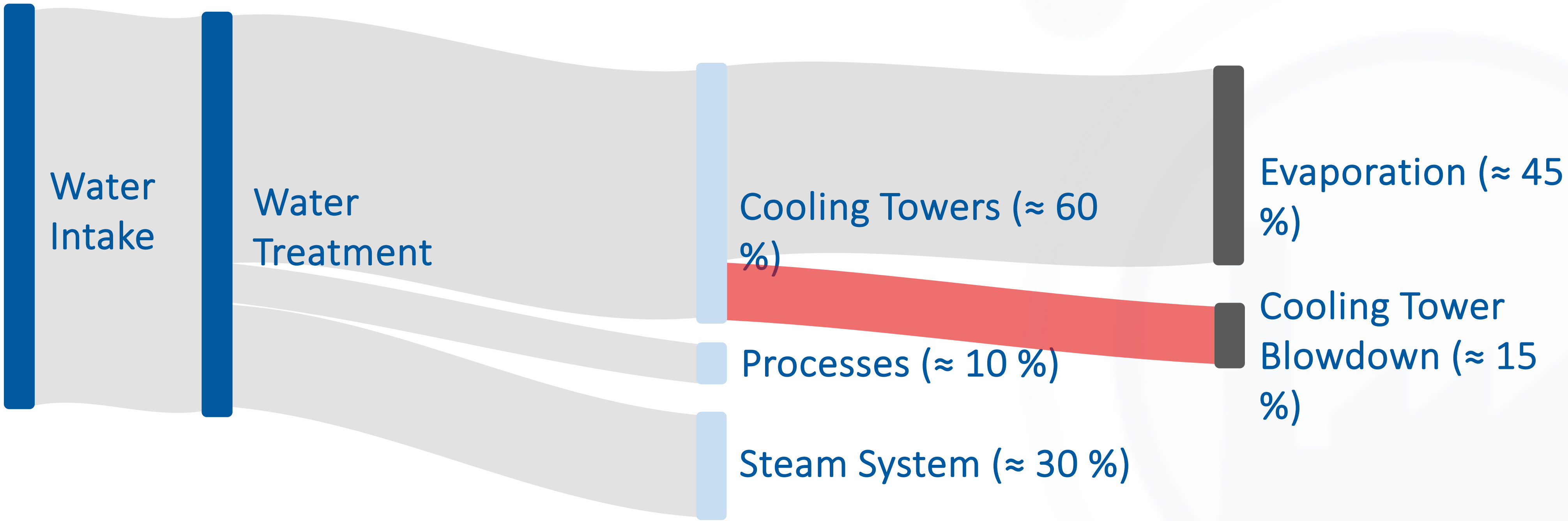
Current Drought Map of July 2023

Pilot Trials at Dow Böhlen



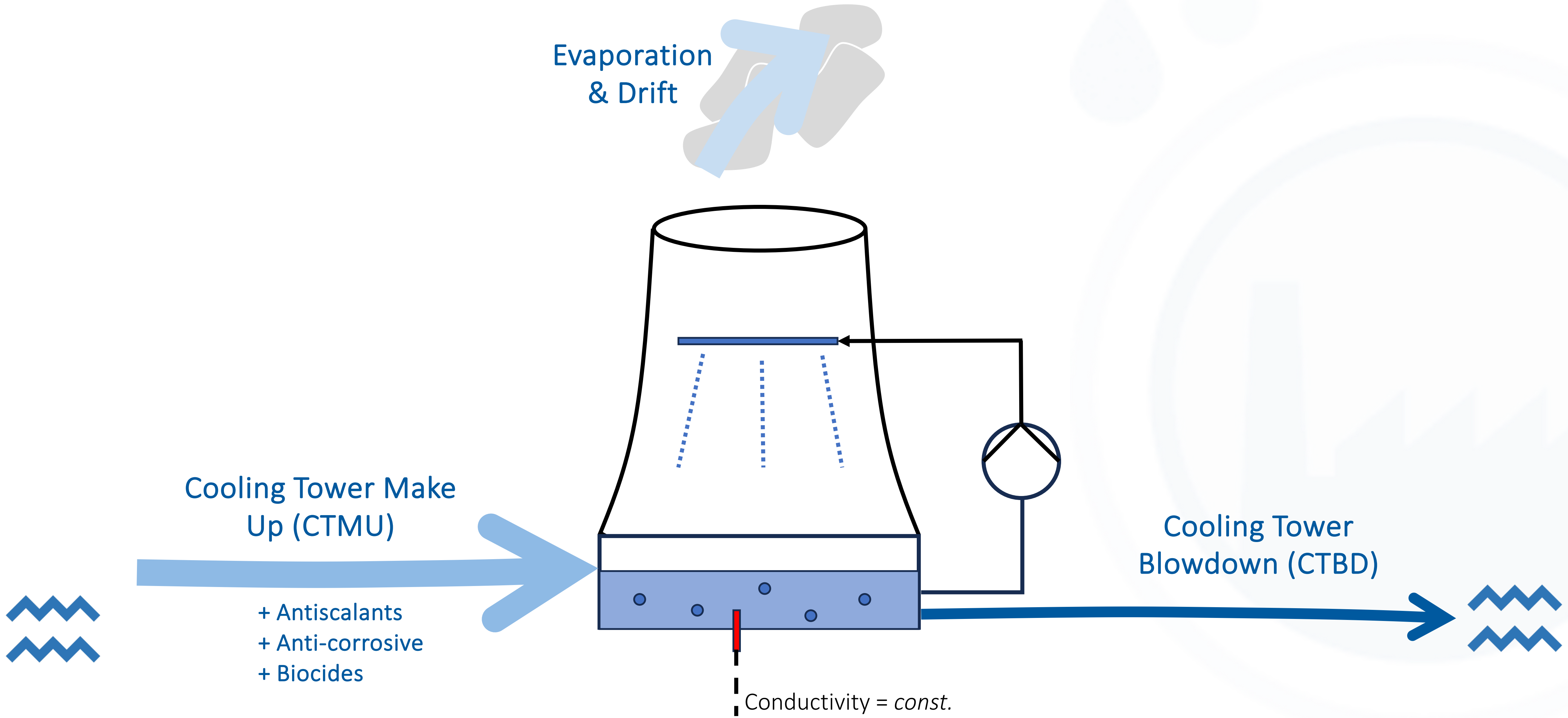
- Abnormally dry
- Moderate Drought
- Severe Drought
- Extreme Drought
- Exceptional Drought

Water Usage in the Chemical Industry

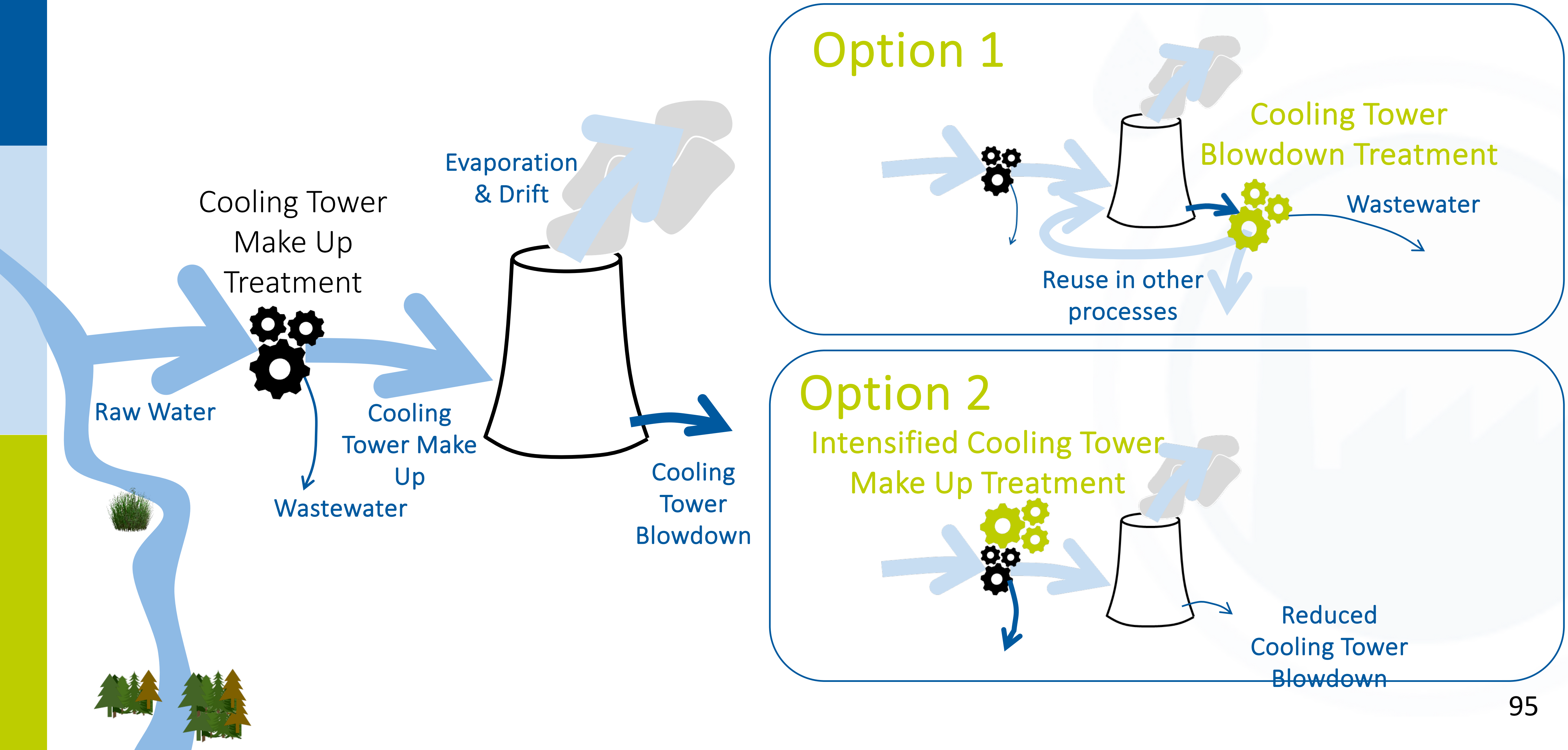


According to AquaSPICE D2.2 (2021)

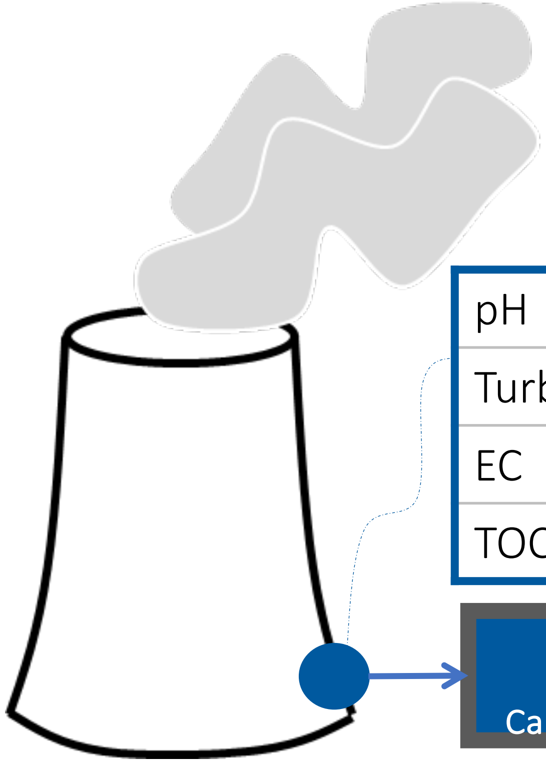
Cooling Tower Blowdown



Options for Water Use Minimization



Trials: Cooling Tower Blowdown (CTBD)



Average CTBD

pH	7
Turbidity	7 NTU
EC	1950 µS/cm
TOC	22 mg/L

Biologically Activated Carbon Filtration → Ultrafiltration → Reverse Osmosis → Mixed Bed (Ion Exchange)

Reuse

Targets:

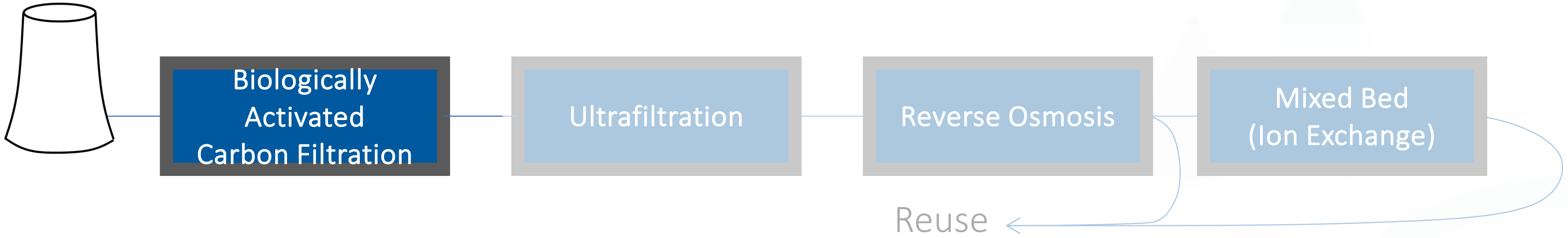
Water Quality

Water Efficiency

Cooling Tower Make Up Water:
TOC < 3 mg/L
EC < 500 µS/cm

Boiler Feed Water:
TOC < 0.2 mg/L
EC < 0.2 µS/cm

Trials: Pre-Treatment



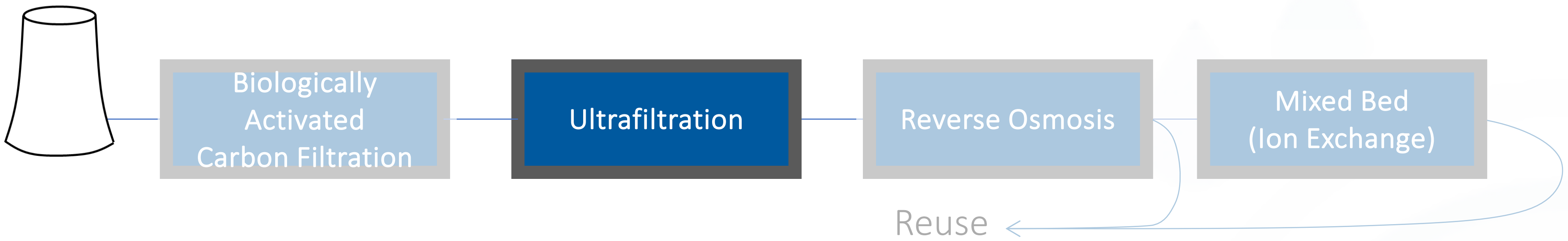
- 3 cylindrical columns operated in series (50 L), top down
- Biologically activated GAC (NORIT GAC 830 W)
- Volume Flow: 500 L/h
- Filtration Velocity: 15 m/h
- EBCT: 5 min per column

	Average Quality	Rejection
TOC	16 mg/L	≈ 20 %
EC	2 mS/cm	-
Turbidity	3 NTU	≈ 55 %

Specific Energy Consumption: ≈ 0.04 kWh/m^3

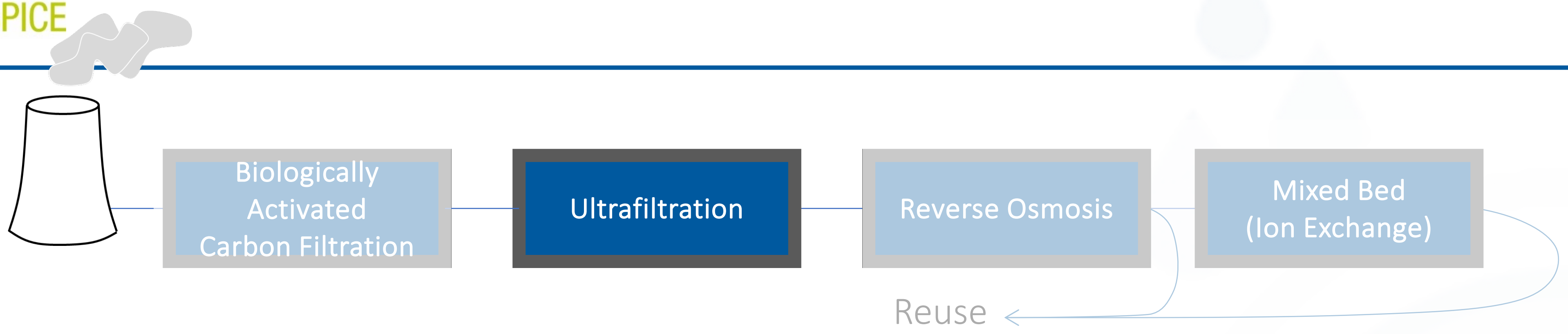
Water Recovery: 99.9 %

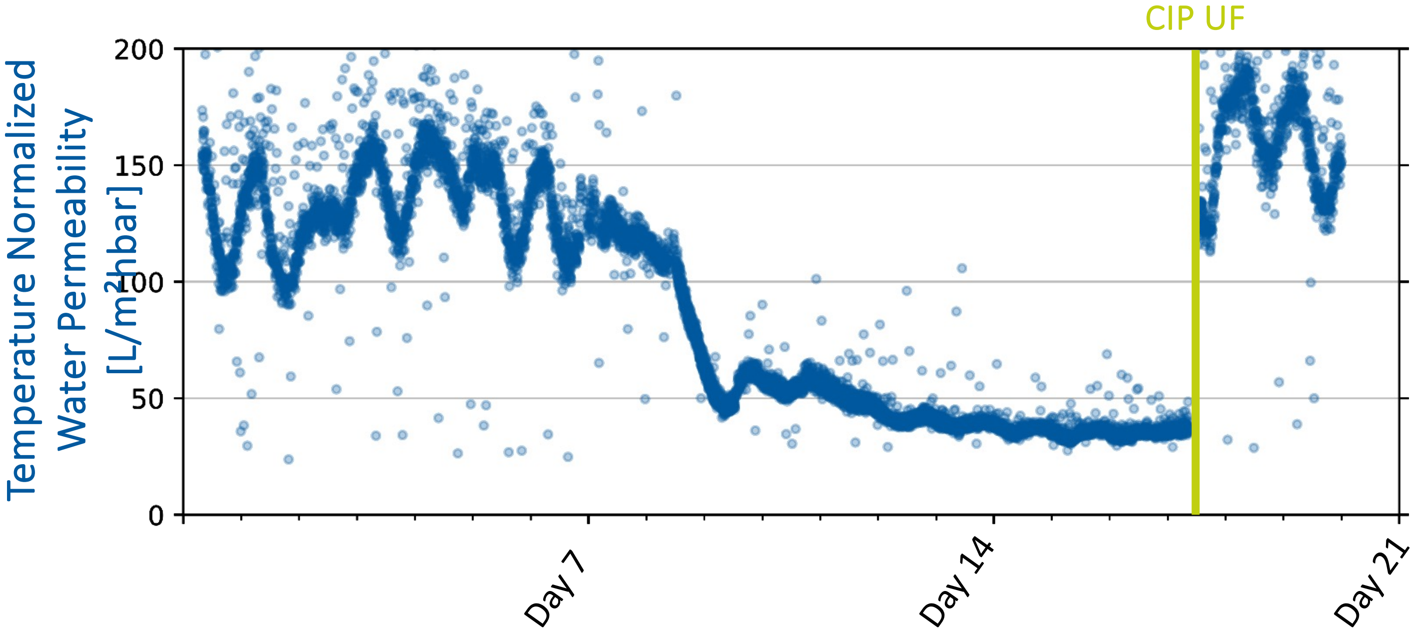
Trials: Pre-Treatment



- 2 modules of 4“ inge dizzer® P Multibore® 0.9 membranes operated in parallel (dead-end)
- Permeate Flux: 35 LMH
- Filtration Time: 30 min
- Backwash Time: 15 s
- Forward Flush Time: 30 s

Trials: Pre-Treatment



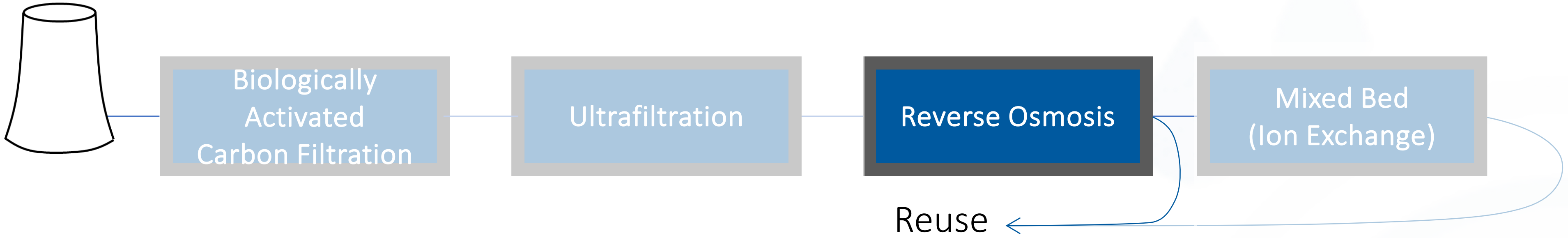


	Average Quality	Rejection
TOC	14 mg/L	≈ 10 %
EC	n.a.	-
Turbidity	0.5 NTU	≈ 80 %

Specific Energy Consumption: ≈ 0.04 kWh/m³

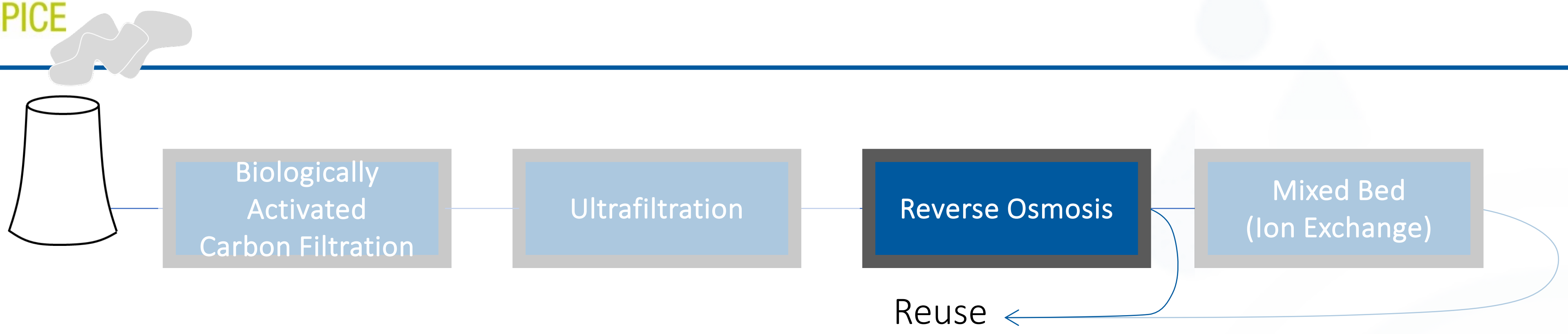
Water Recovery: 95.4 %

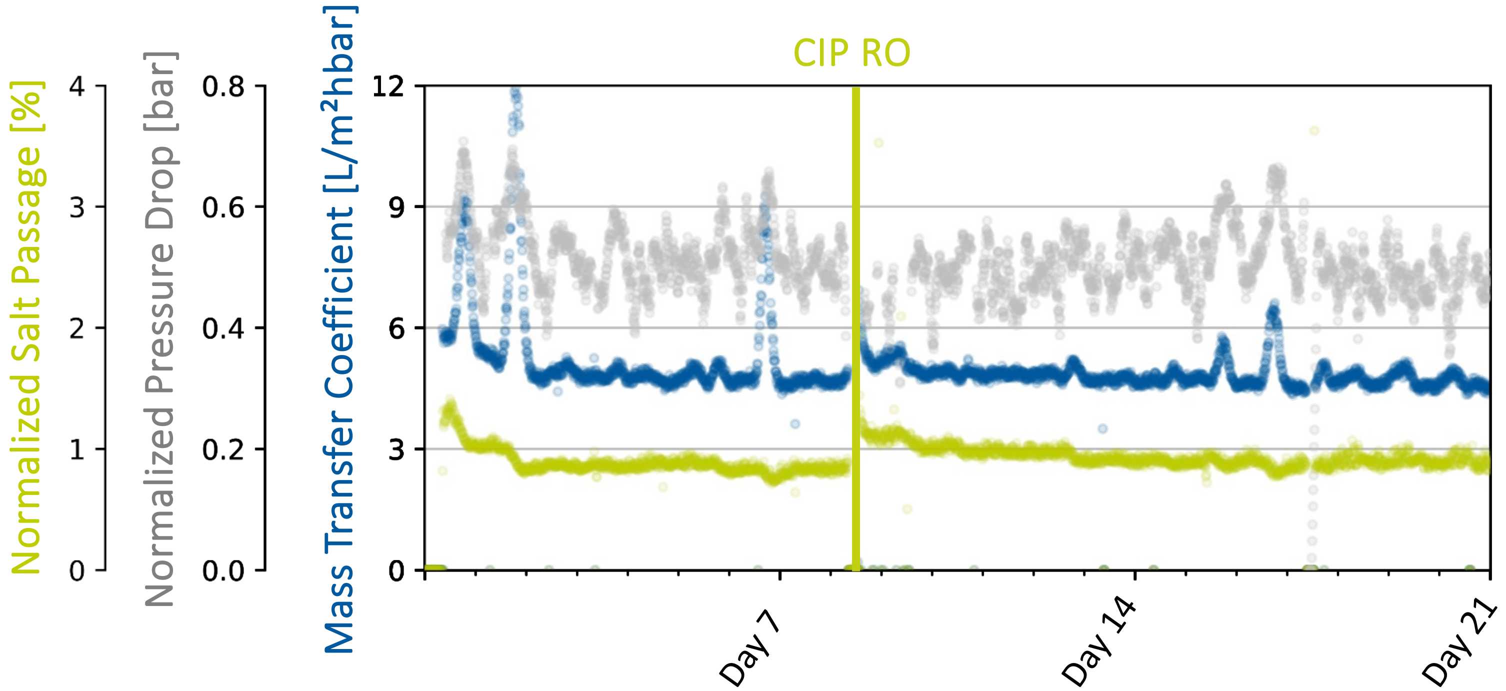
Trials: Desalination



- 4" module DuPont FilmTec™ LCLE-4040 (8.7 m²):
  - Partial Recirculation of Concentrate: higher system recovery
- Module Feed Flow: ~ 1100 L/h
- Permeate Flux: 20 LMH
- Feed adjustments:
  - 20 w-% HCl for pH (pH = 6.1)
  - Antiscalant (Genesys LF: 4 mg/L to Feed)

Trials: Desalination



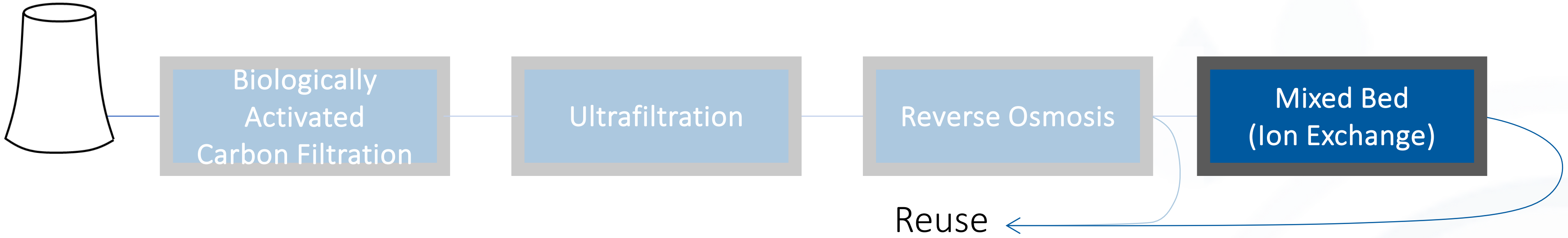


	Average Quality	Rejection
TOC	0.1 mg/L	≈ 99.3 %
EC	80 µS/cm	≈ 96 %
Turbidity	0.2 NTU	≈ 60 %

Specific Energy Consumption: ≈ 2 kWh/m³

Water Recovery: 75 %

Trials: Desalination



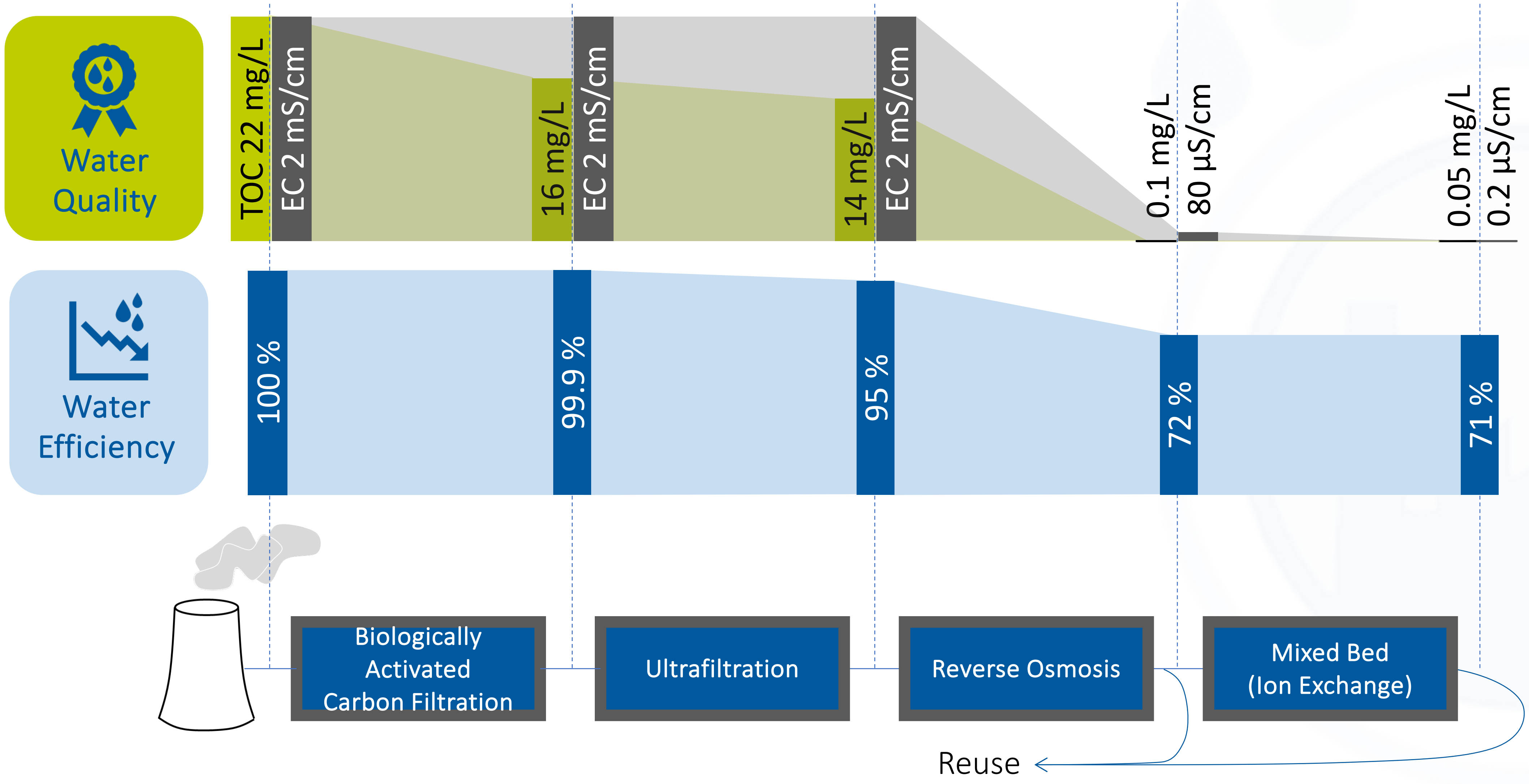
- Resin: Amberlite™ MB20
- 1 day operation (till exhaustion)
- Throughput: 16 BV/h
- Filtration velocity: 22 m/h

	Average Quality	Rejection
TOC	0.05 mg/L	≈ 50 %
EC	0.2 µS/cm	≈ 99 %
Turbidity	n.a.	-

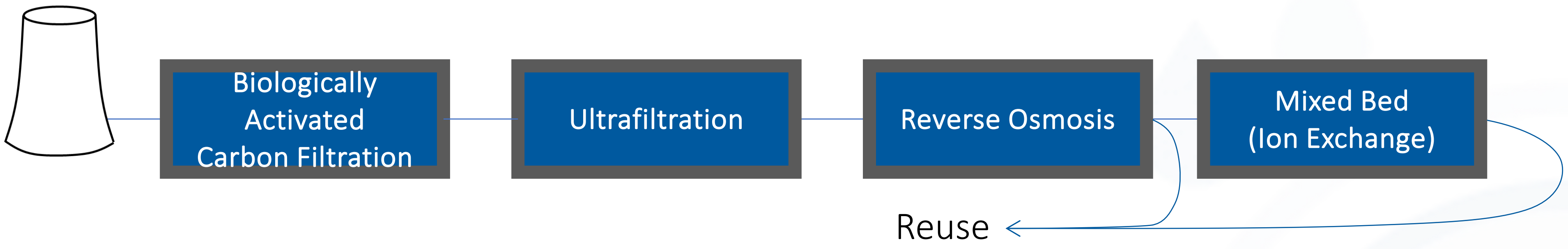
Specific Energy Consumption: ≈ 0.02 kWh/m³

Water Recovery: 99 %

Summary: Targets



Conclusion



Water Efficiency

- Total treatment train operated with **71 % Water Recovery**
  - Cooling tower‘s water footprint reduction of > 15 %

Water Quality

- **Recommendation:** Reuse of treated water as boiler feed water (high quality even of RO permeate→ boiler feed water (deionate) is more valuable)
- Good **operational stability** of all technologies was shown
- **Barrier for implementation:** Effects of reduced and more concentrated water amount on receiving water bodies need to be studied

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Advancing Sustainability of Process Industries through Digital and Circular Water Use Innovations

Thank you!

info@aquaspice.eu www.aquaspice.eu aquaspice aquaspice

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