WATER REUSE – A PILLAR OF CIRCULAR ECONOMY

ROADMAP OF INNOVATION IN WATER REUSE

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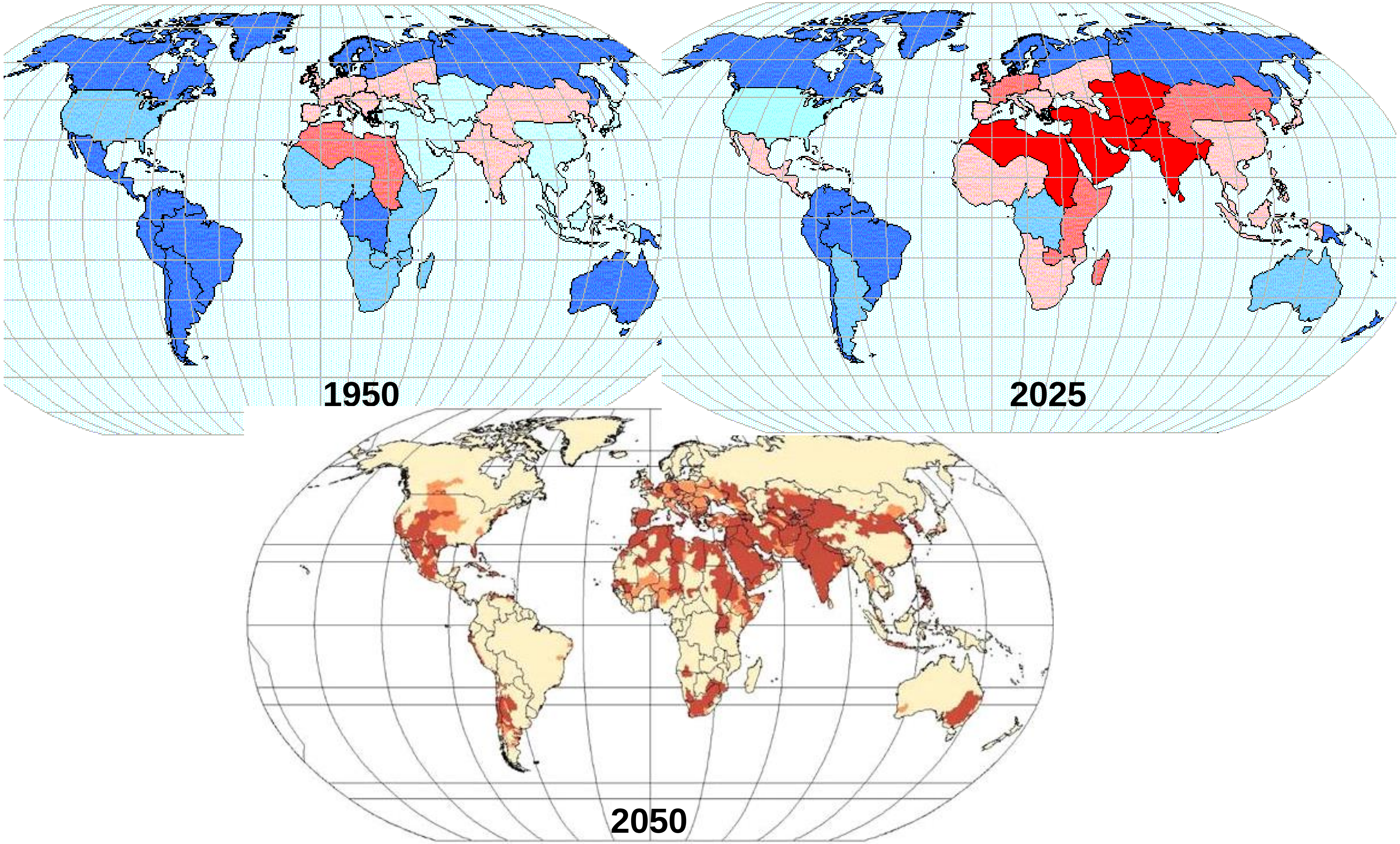
Major impacts of climate change on water resources

Thirsty Planet

Currently almost half of the world's population — some 3.6 billion people — live in areas vulnerable to water scarcity and more than 5 billion people could suffer water shortages by 2050 (UN, 2018)

- **Longer and more severe dry seasons**
- Widespread changes in the distribution of precipitation with **more frequent drought and flooding events**, leading to an overall long-term reduction in river flows and aquifer recharge rates
- **Deterioration of the quality of all freshwater sources** due to higher temperatures and diminishing flows
- Increased water use for irrigation

Projected risk of water scarcity
Status of water availability per capita

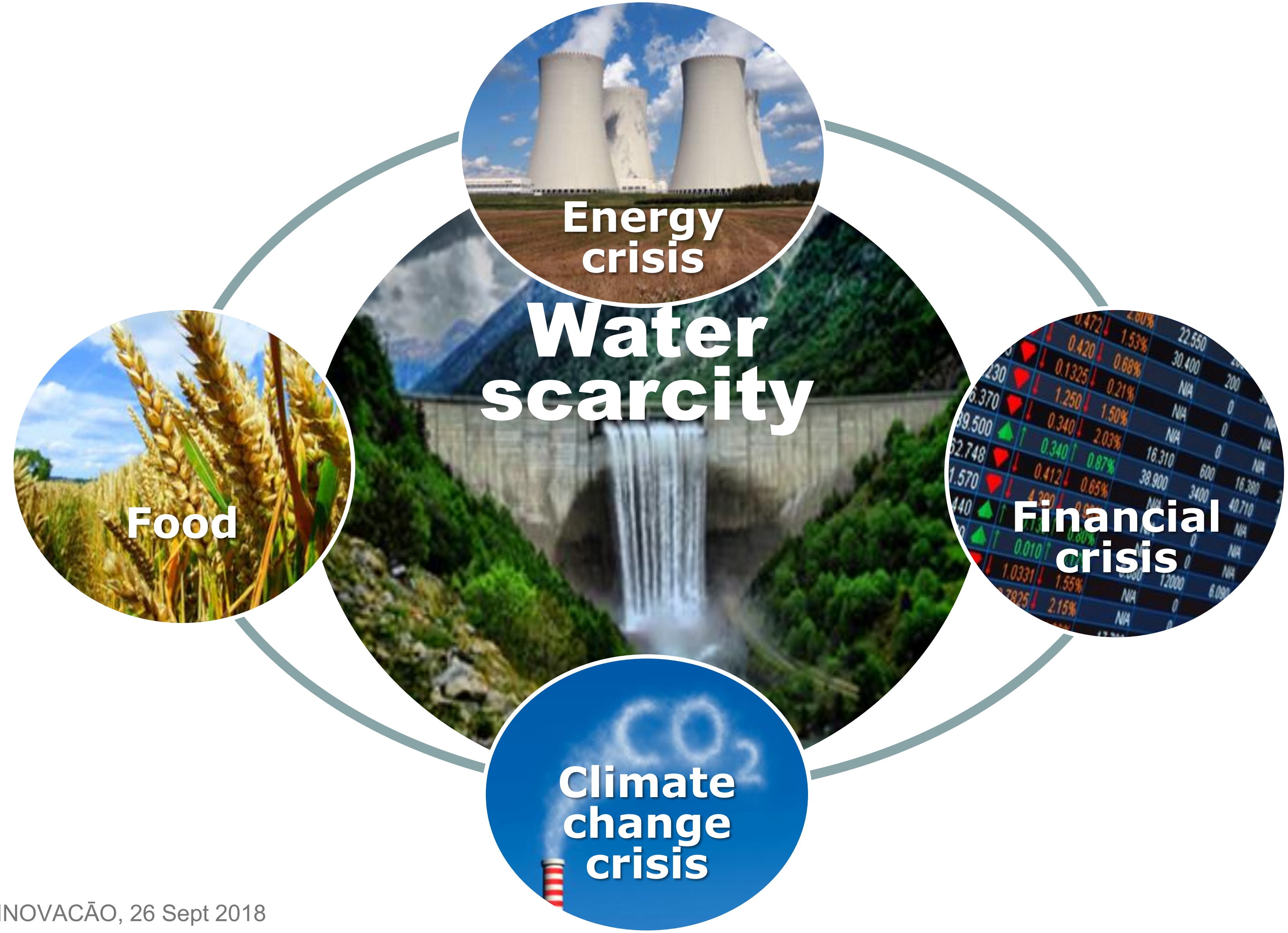


Forecasted risks

Increasing water demand, unsustainable water supply and declining water quality

- **Higher water costs**
  - Higher water tariffs
  - Increase in cost of wastewater treatment to meet more stringent future regulations
  - Elevated costs for pretreatment to obtain target water quality
- **Stringent policies and regulations**
  - Regulatory restrictions for water use and withdrawals
  - Impact on future economic growth and license to operate
  - Regulatory restrictions for specific industrial activities and waste discharges
- **Impeded business development**
  - Disruption of water supply and associated financial loss
  - Conflicts between countries, sectors, local communities and other large users

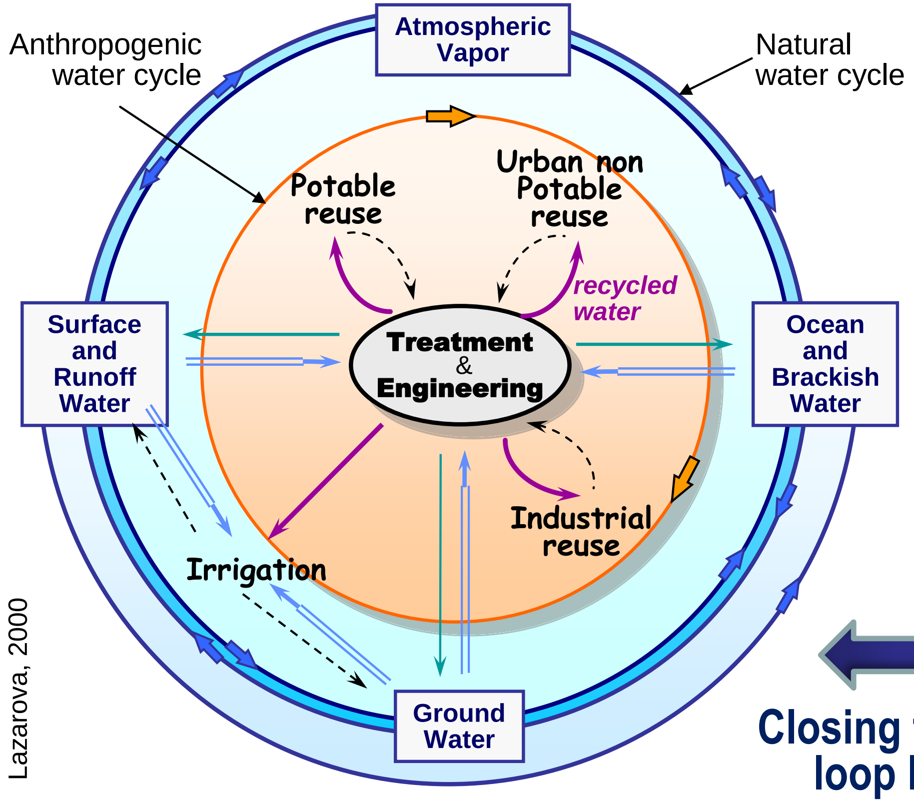
Water is a critical resource and a pillar of circular economy



Reuse Water = A Pillar of Circular Economy

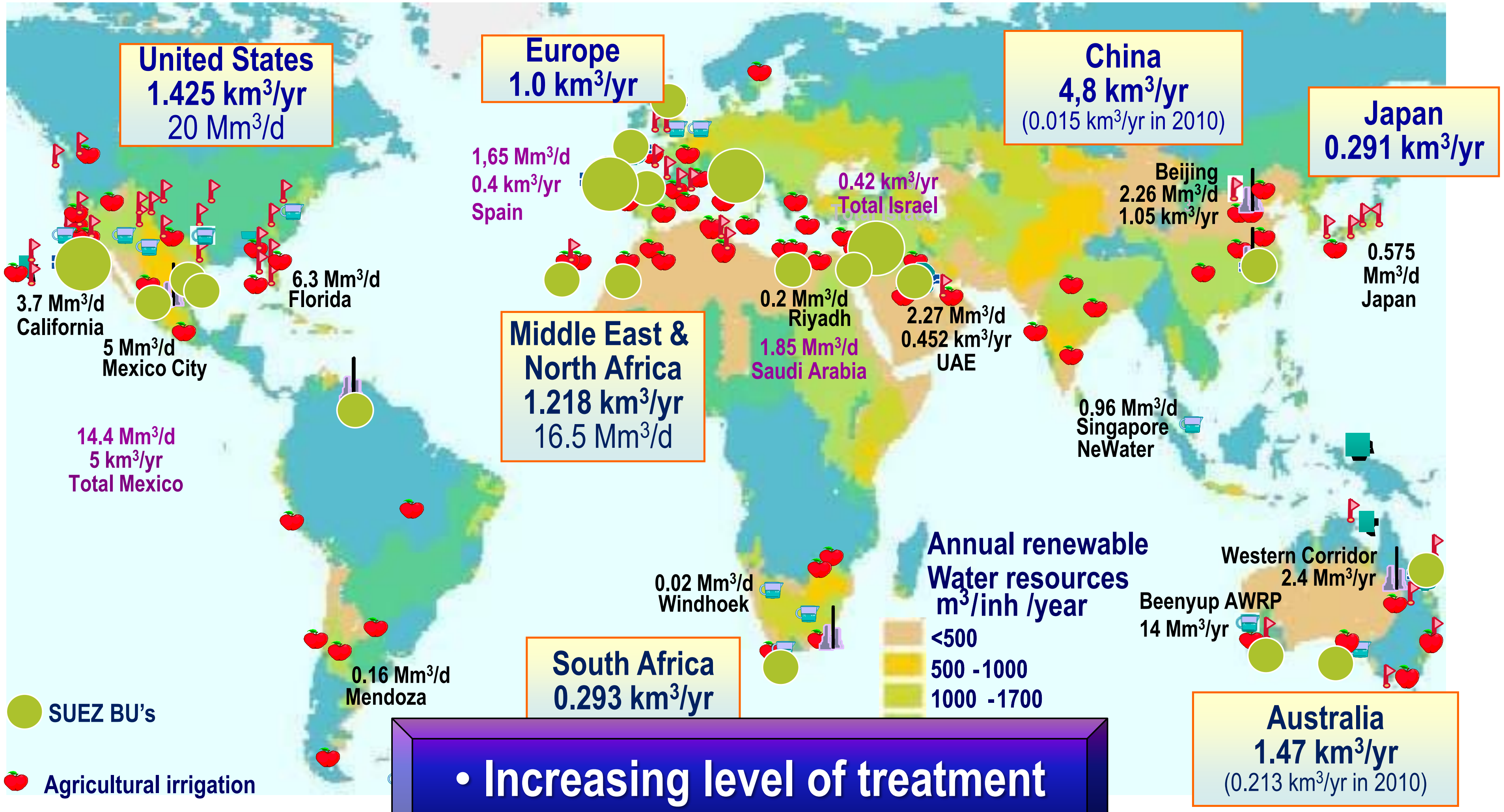
A Concern for Sustainability

- Adaptation to Climate Change & Growing Urbanization
- Increasing Role of Water Reuse in Water Management and Urban Planning



Closing the water loop locally

Water Reuse – a Global Trend Towards Sustained Growth

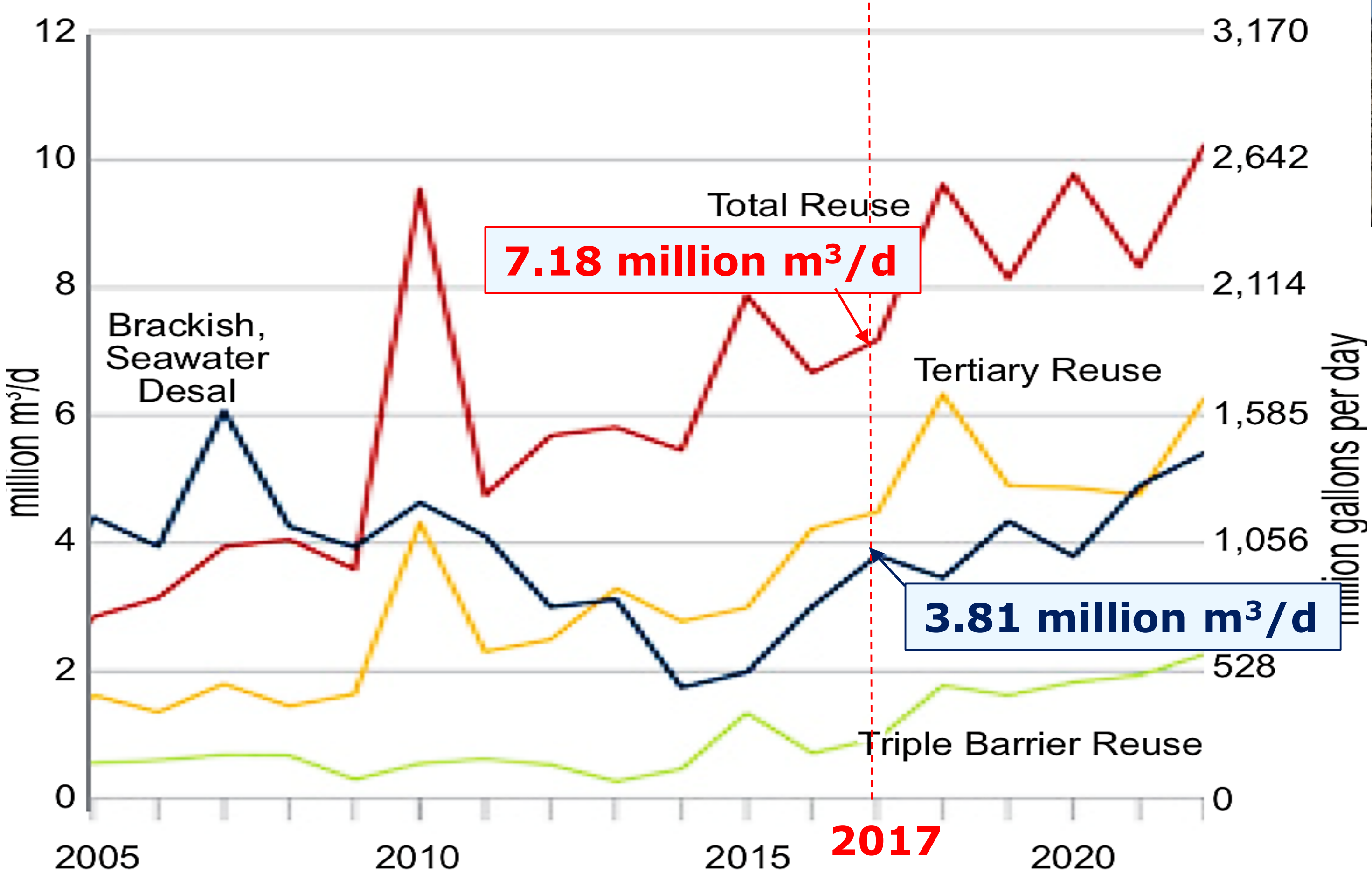


- Increasing level of treatment
- Public-private partnership

1 km³ = 1 billion m³

Water Reuse Market Trends

Water Reuse Will Likely Have Faster Growth than Desalination in the Next 5 Years

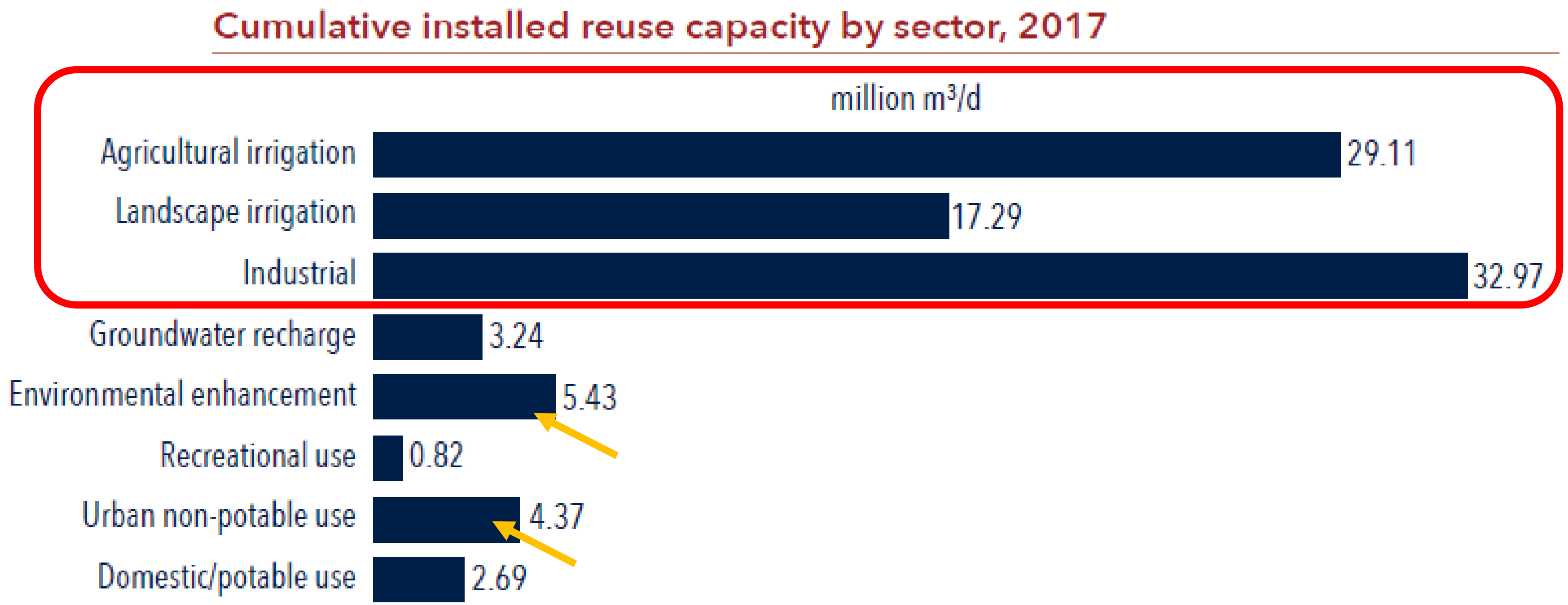


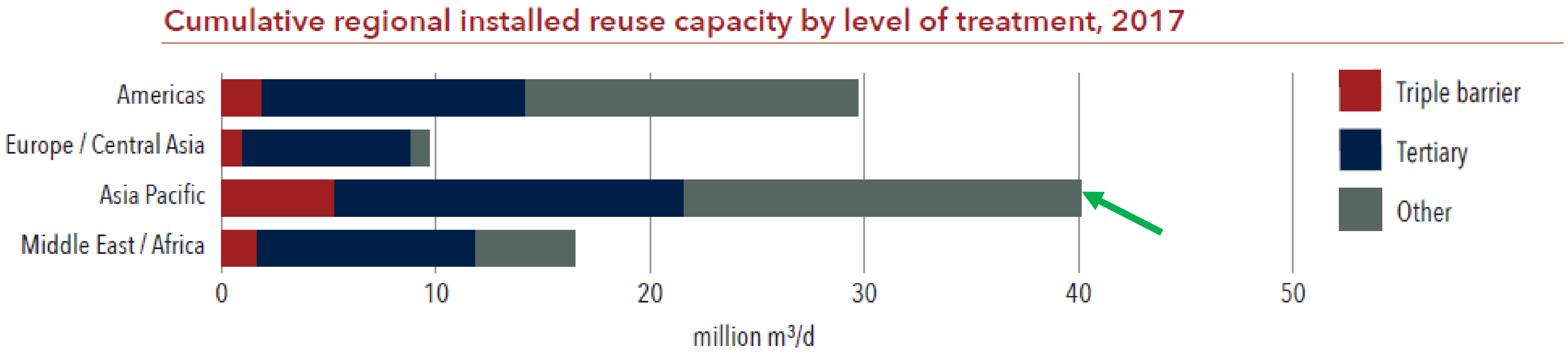
Incremental Contracted Desal & Reuse Capacity, 2005-2022

adapted from GWI's Global Water Market Report in 2018, https://tinyurl.com/yafhy36b

Water Reuse Market Trends

Cumulative Installed Reuse Capacity in 2017





Source: GWI 2017

Key Factors for Sustainable Growth of Water Reuse

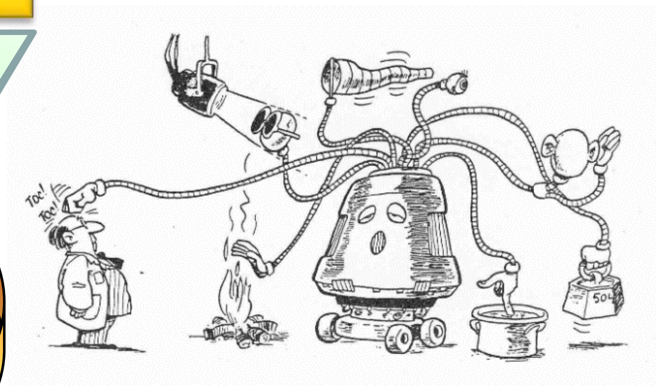
Economics
Capex + Opex of treatment & distribution of recycled water

Financing
Tariffs and water pricing, cost recovery, market value

Socio-psychological
Public perception & attitudes; communication & education

Policy, regulations, administration
Incentives, good practices

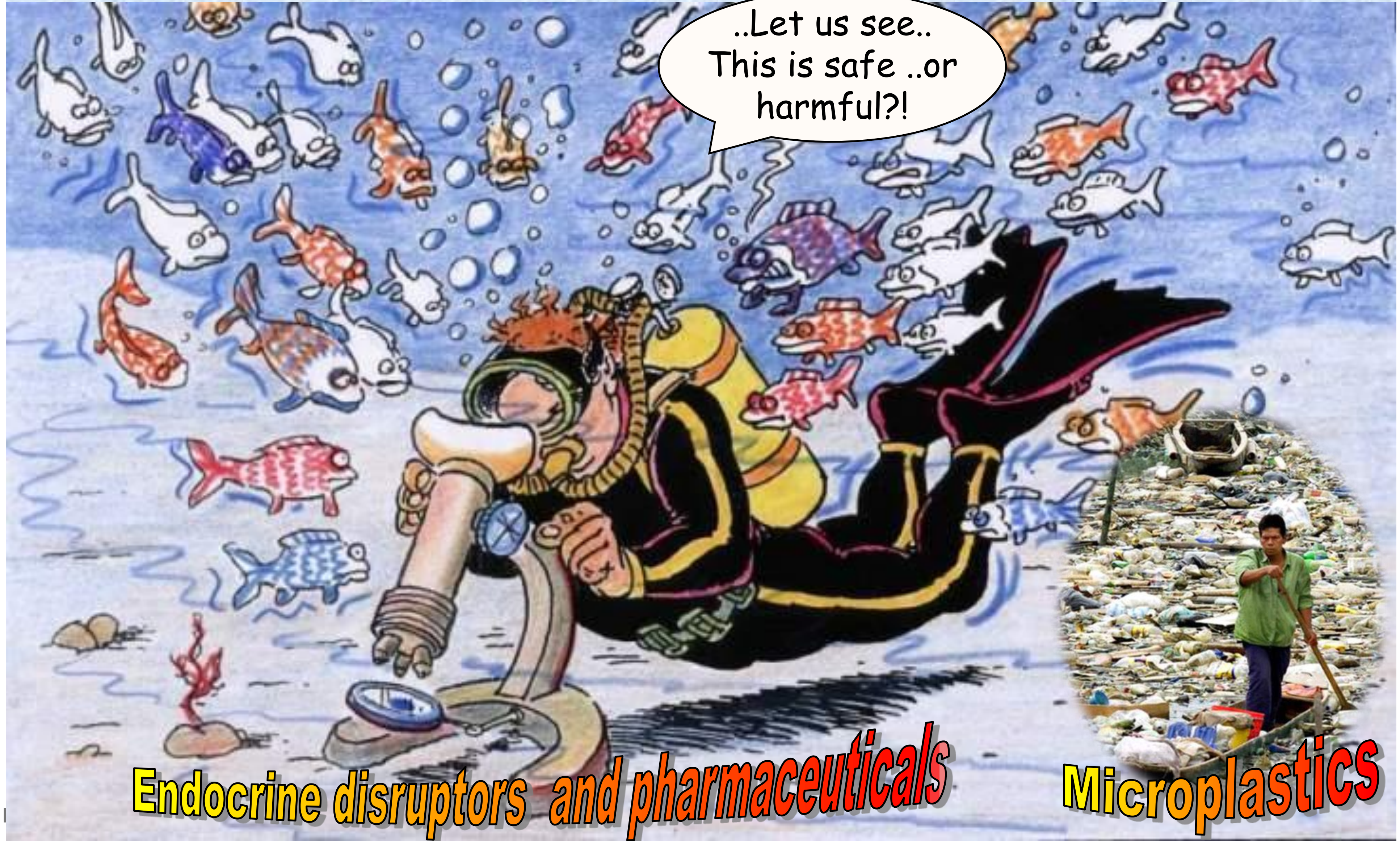
Technical issues



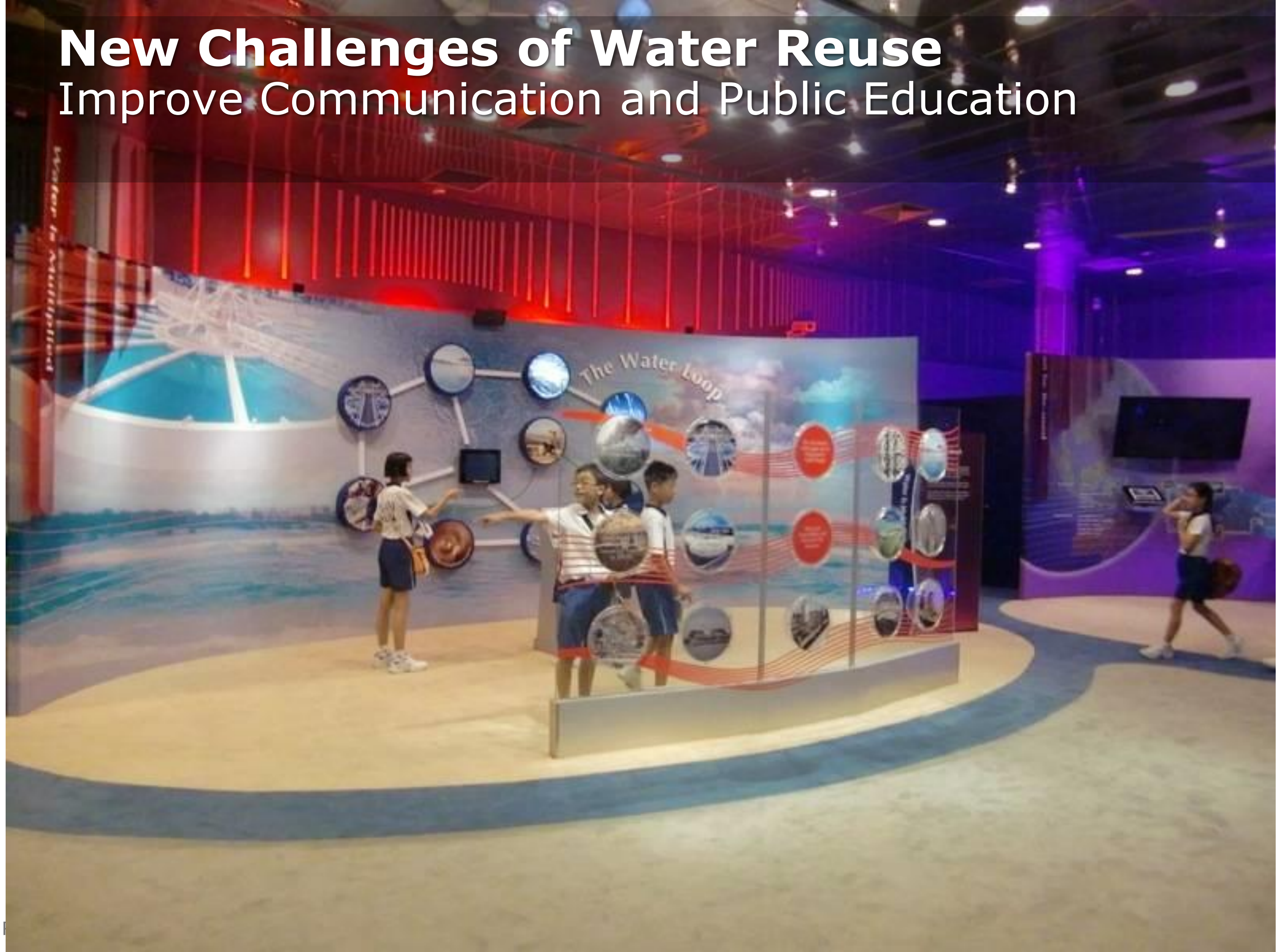
Key Issues and Challenges for Sustainable Growth of Water Reuse

1. **New policies and regulations**
   - ❖ Provide **incentives for water reuse** and reform water rights
   - ❖ Frame best management practice and **feasible regulatory frameworks**
2. **Implementation of Innovative technologies & tools**
   - ❖ Advance in **engineering and technology**
     - ✓ Scale-up and long-term efficiency of full-scale installations
     - ✓ Compatibility with existing technologies and infrastructure
     - ✓ Failure risk management
     - ✓ Monitoring: sensor reliability, calibration and data analysis
   - ❖ **Energy and cost efficiency**
     - ✓ Water & energy nexus
     - ✓ **Cost & risk nexus**
3. **Soft science development**
   - ❖ public perception & education, health & environmental risk assessment, cost/benefits & LCA analysis…

Water Reuse Regulations: New Challenges with the Advance in Science and Analytical Chemistry



New Challenges of Water Reuse
Improve Communication and Public Education

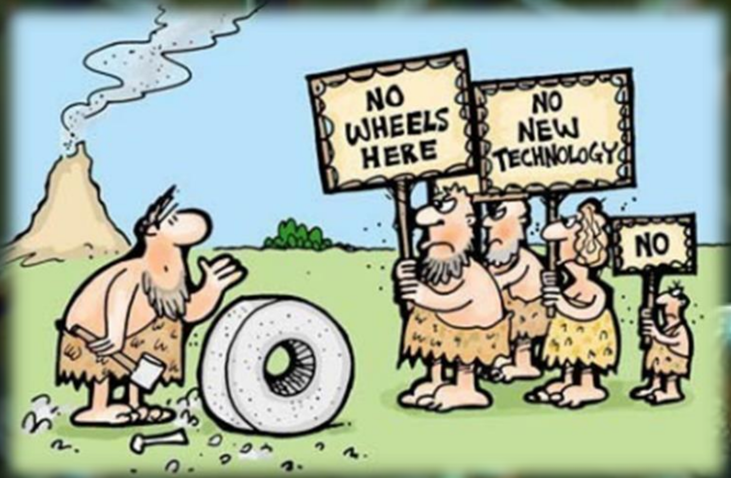


Technical Challenges ?!?

New Challenges

Why make it simple when you can make it complicated?

The Oldest Challenge



Protesting against new technology : the early days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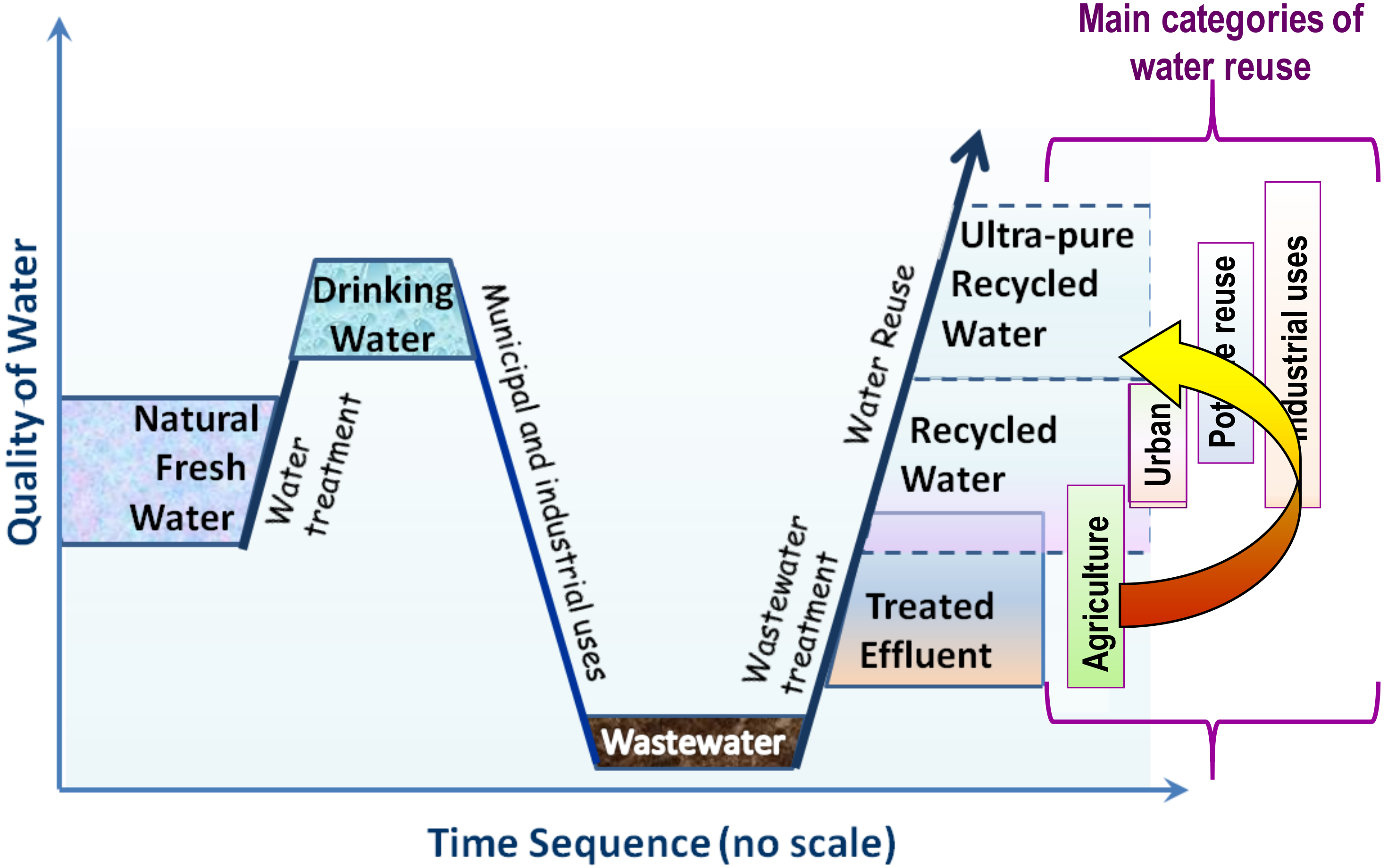
Technology as Enabler
of Water Reuse

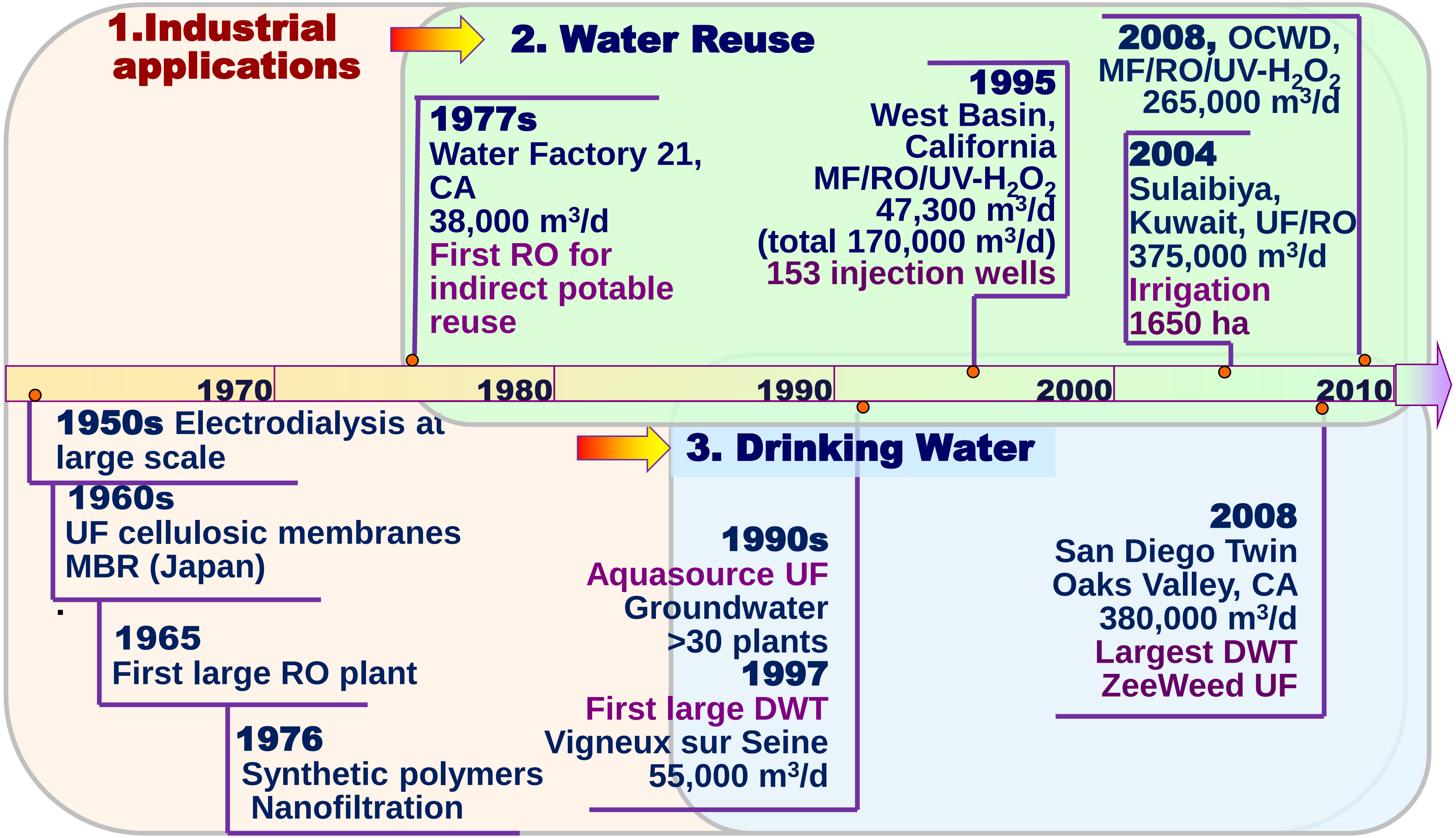
Technology as Enabler of Sustainable Water Cycles – Water Quality ≠ Source of Water

- With current technologies, source water quality no longer dictates product water quality

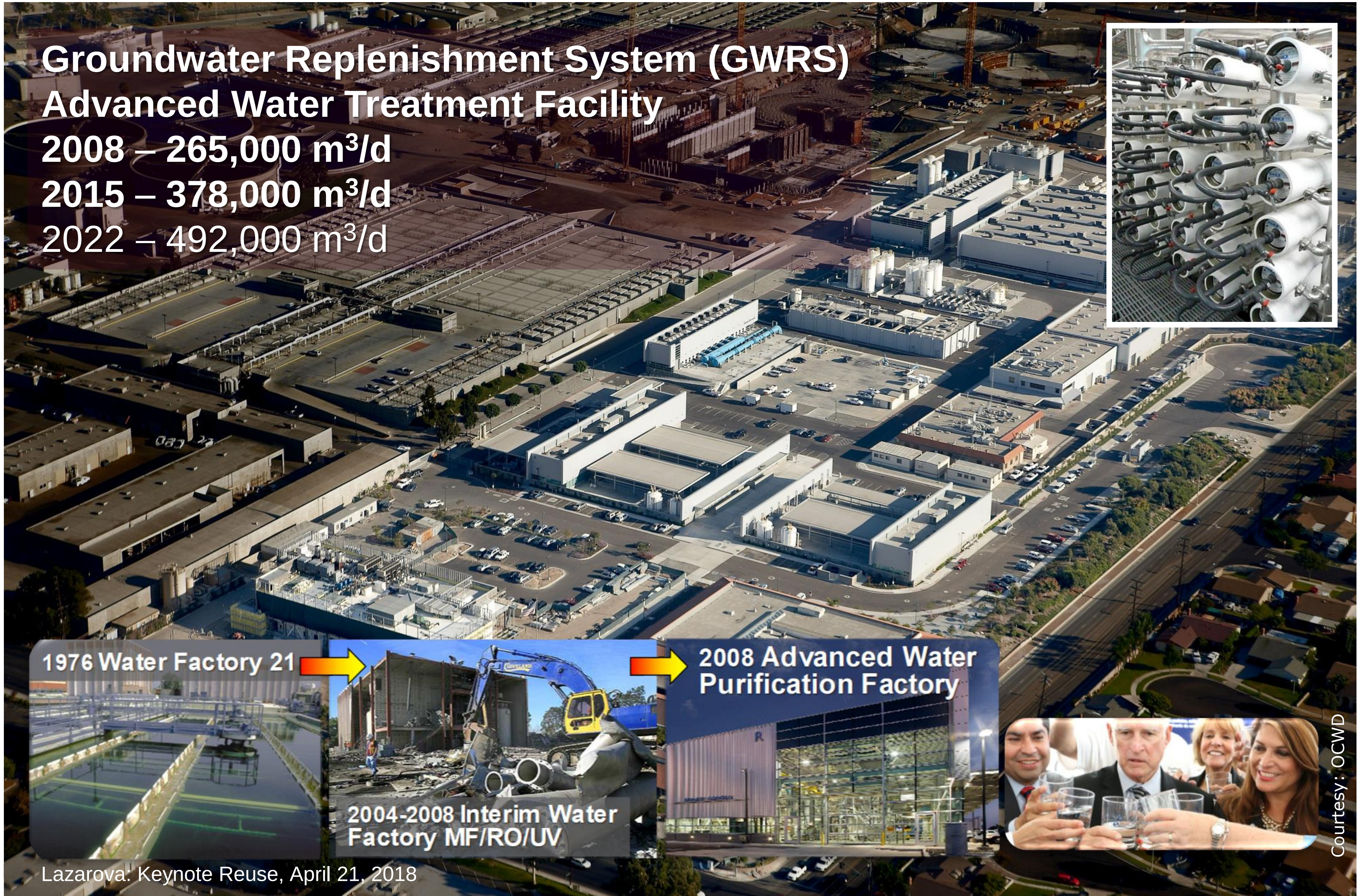


Source: Asano 2002; Lazarova et al. 2013

Technology as Enabler of Sustainable Water Cycles – The Role of Membranes



Technology as Enabler of Water Reuse –
The Example of Orange County, CA



Technology as Enabler of Water Reuse –
The Example of Orange County, CA

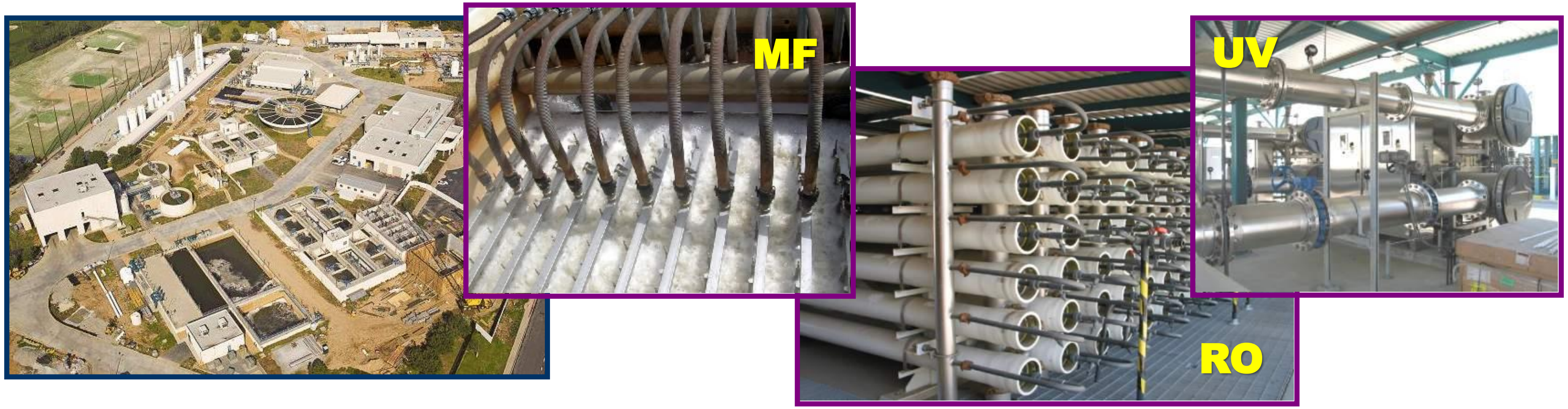
Highlights

- **1976:** Water Factory 21 for seawater barrier (1976-2004), 57,000 m^3/d, 23 injection wells, **first RO in 1977**, 67% recycled water
- 2004-2008 Interim Water Factory MF/RO/UV (19,000 m^3/d)
- **2008**: Groundwater replenishment system, 265,000 m^3/d
  - ✓ **Advanced Water Purification**: **MF / 3 stage TFC RO / UV+H_2O_2** / on-line monitoring
  - ✓ Extension of the seawater barrier with 100% recycled water and replenishment of existing spreading basins

Technology as Enabler of Water Reuse –
The Example of West Basin, CA

Highlights

- **1995:** West Basin WRP (The Edward C. Little WRP), **One of the first MF/RO**, 47,300 m^3/d (five types of "designer" water, total 170,000 m^3/d) 153 injection wells
- **Step-by-step implementation** with permits for injection of 35% initially to currently 100% of recycled water
  - ✓ Advanced Water Treatment MF/RO/UV+H_2O_2/ on-line monitoring
  - ✓ Pilot studies and evolution of membrane technologies
  - ✓ Economic viability (subsidiaries + diversification)



Sustainable Water Cycles with Water Reuse

Technology as Enabler – The NeWater Story

- **Step by step process**

Gaining public perception

Full-scale implementation (2003 – present)

Demonstration Plant Study (1998 – 2002)

Pilot Plant Study

Learning from overseas experience (Water Factory 21, etc)

Initial Ground Breaking Research

- Test of reliability and robustness of MF/RO, UF/RO, UV…
- Operational experience used for the design of full-scale plants
- Lessons learned applied to new plants and expansions

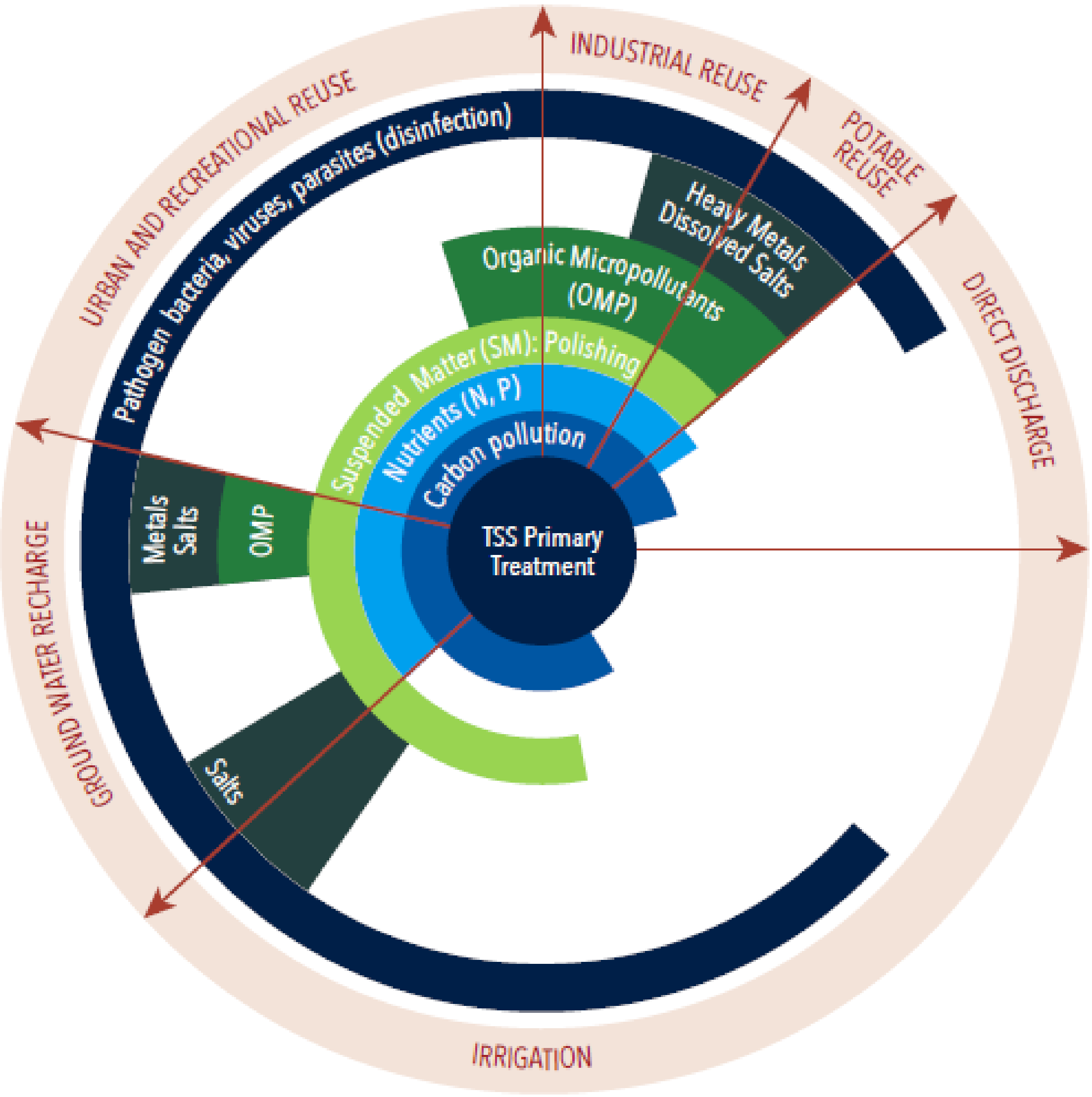
Source: Courtesy of PUB


Roadmap on Technology Innovation in Water Reuse

Global Water Reuse Technology Innovation Trends

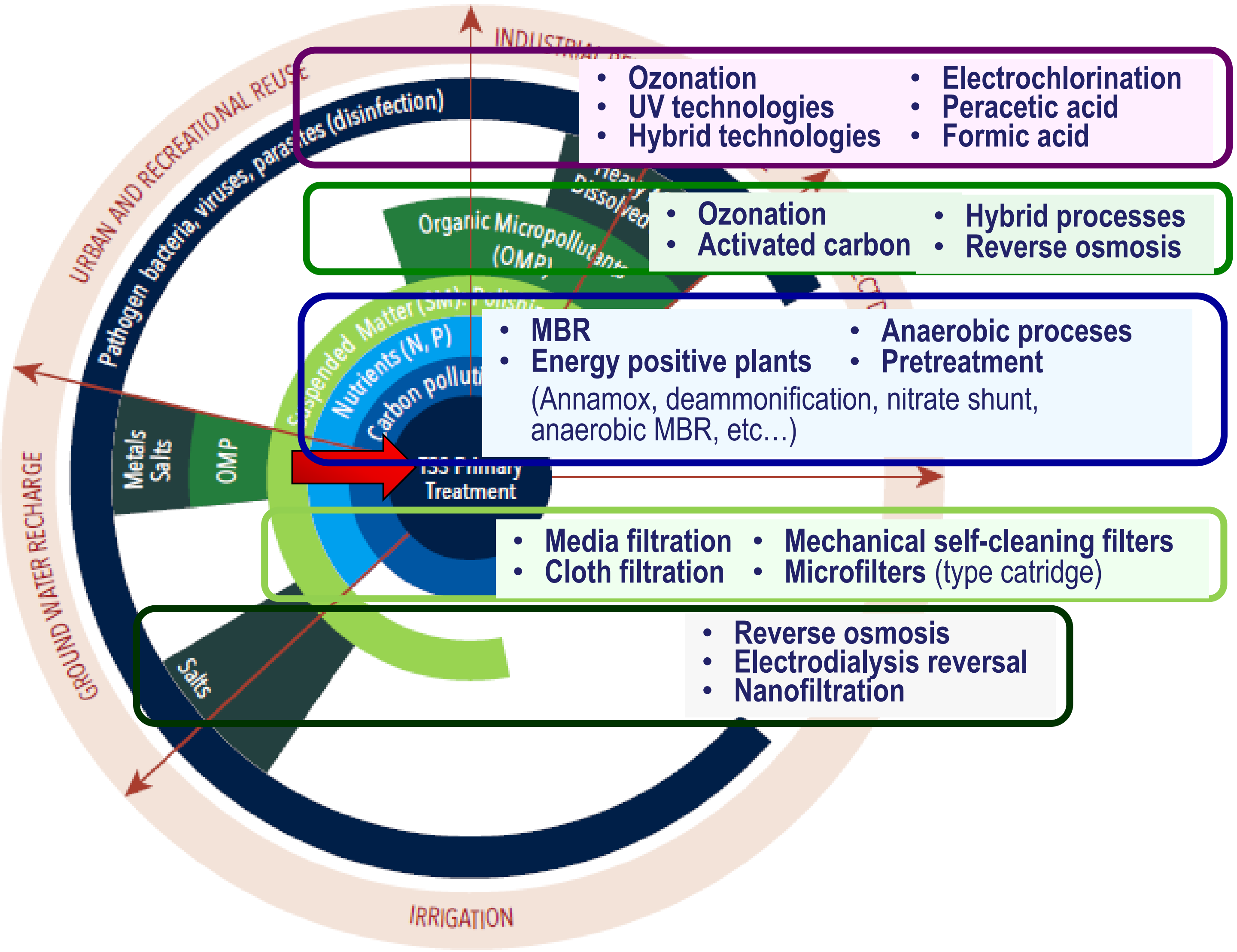
- **Improvement** of reliability, performance, flexibility and robustness **of existing technologies**
  - ✓ MBR, biofiltration, advanced oxidation, disinfection….
  - ✓ Multi-barrier membrane treatment (MF/RO, UF/RO)
- **New cost and energy efficient technologies** for conventional and advanced treatment
  - ✓ C&N removal, removal of trace organics…
  - ✓ Nano-technologies, new membranes…
- **Improved** water quality and process performance **monitoring**
  - ✓ On-line monitoring and new surrogate parameters
  - ✓ Broad-spectrum analysis of pathogens, emerging contaminants, toxicity, bioassays…
  - ✓ Analytical methods for trace organics, nanoparticles, antibiotic resistance…

Global Water Reuse Technology Innovation Trends – Treatment Levels Required for Water Reuse



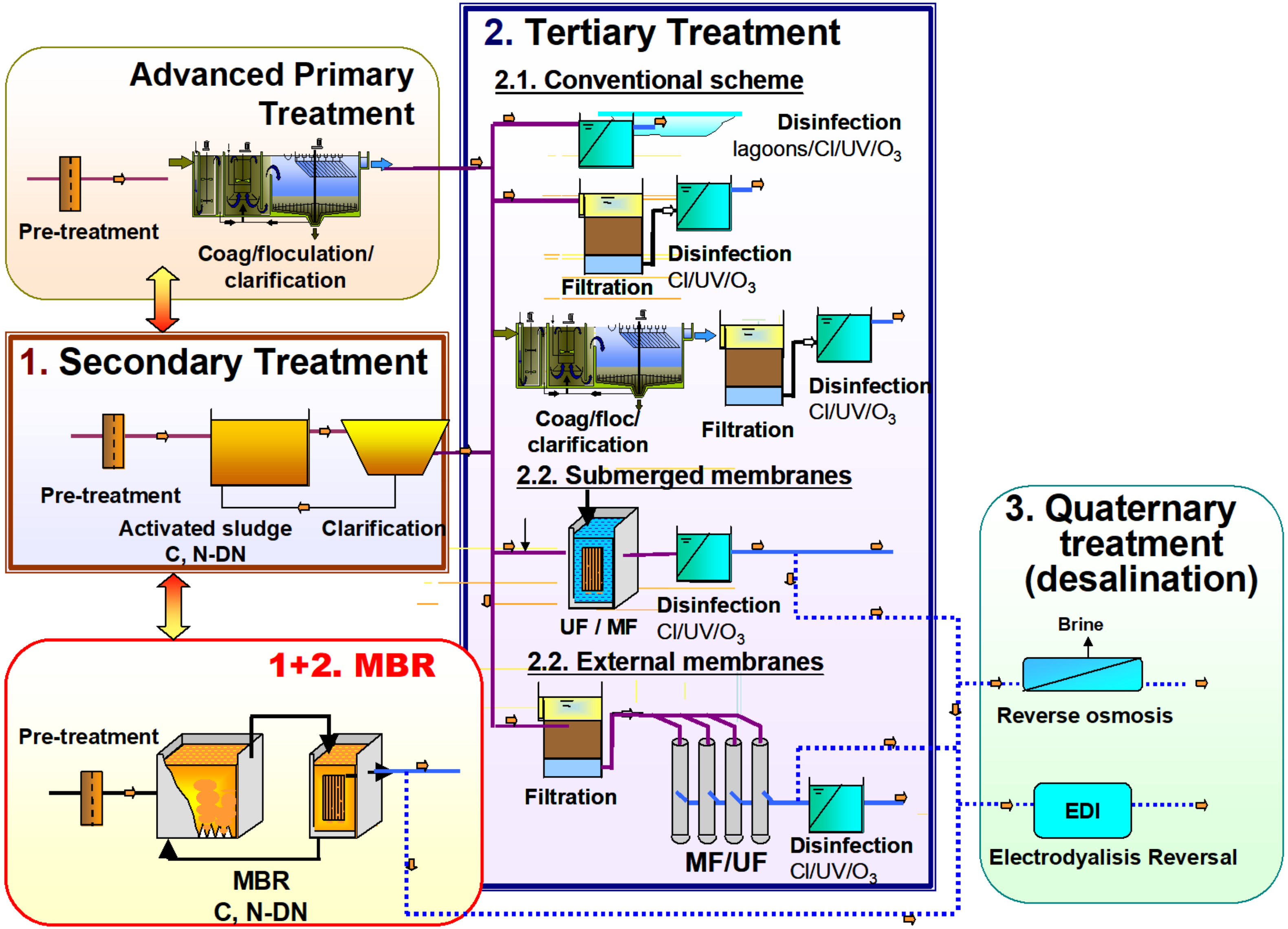
Source: Lazarova et al, 2000

Global Water Reuse Technology Innovation Trends – Treatment Levels Required for Water Reuse



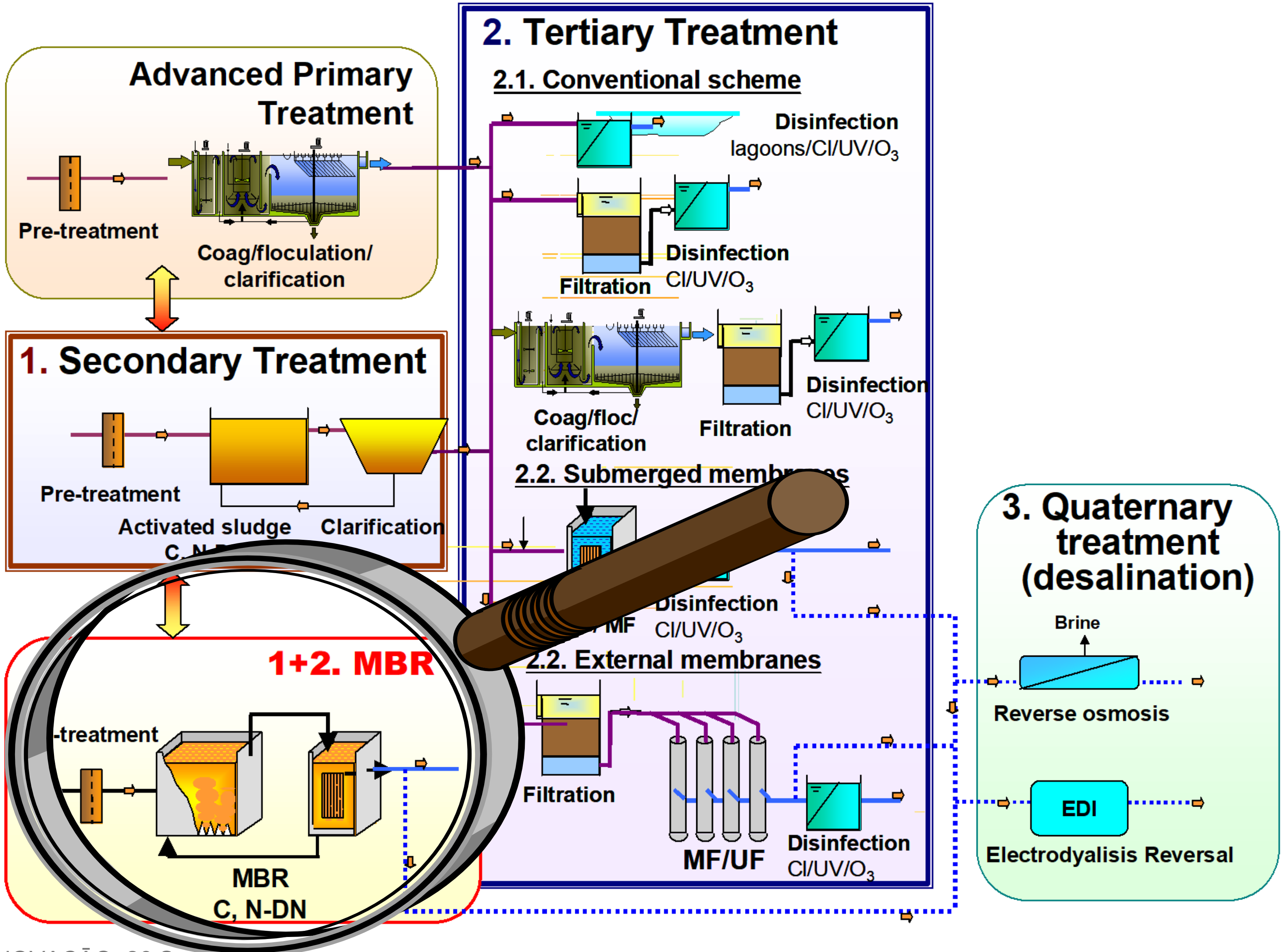
Source: Lazarova et al, 2000

Global Water Reuse Technology Innovation Trends – Typical Treatment Trains for Water Reuse




Improvement of
Existing Technologies

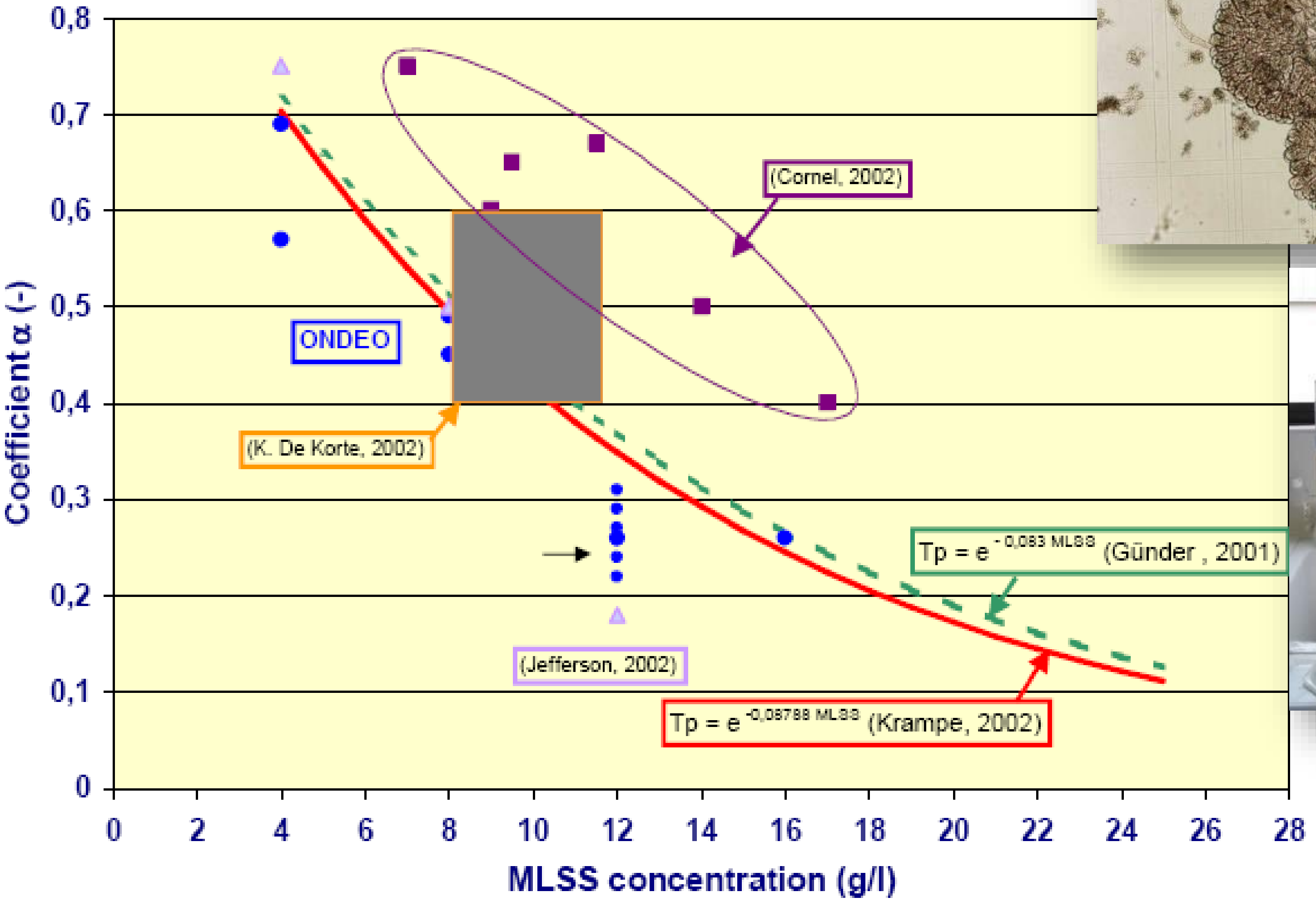
Global Water Reuse Technology Innovation Trends – Typical Treatment Trains for Water Reuse

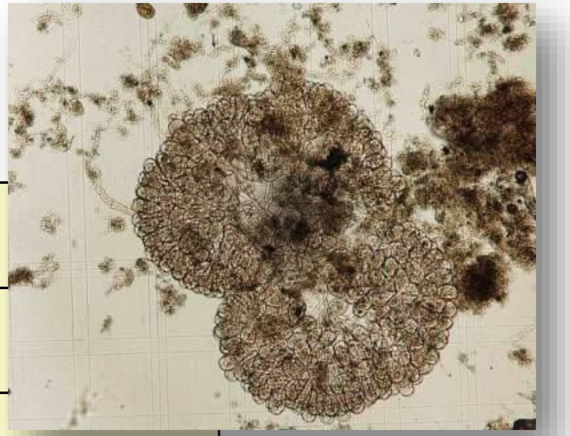


Advanced Biological Treatment
Membrane Bioreactors (MBRs)

- Two major types
  - ✓ Submerged membranes (mostly for urban wastewater)
  - ✓ Side stream membranes (mostly for industrial wastewater)
- Major advantages
  - ✓ Low footprint and modular design
  - ✓ High effluent quality, solids free, SDI<3, enhanced C & N removal, disinfection
  - ✓ Reliability & automation
- Key challenges
  - ✓ Scale-up for very large plants
  - ✓ Pre-treatment
  - ✓ Capex 400 to 6600 €/m^3
  - ✓ Energy & Opex 0.44-1.32 €/m^3
  - ✓ Membrane commodization
  - ✓ MBR-RO coupling
  - ✓ Performance evaluation: LRVs and integrity tests (pressure decay…)

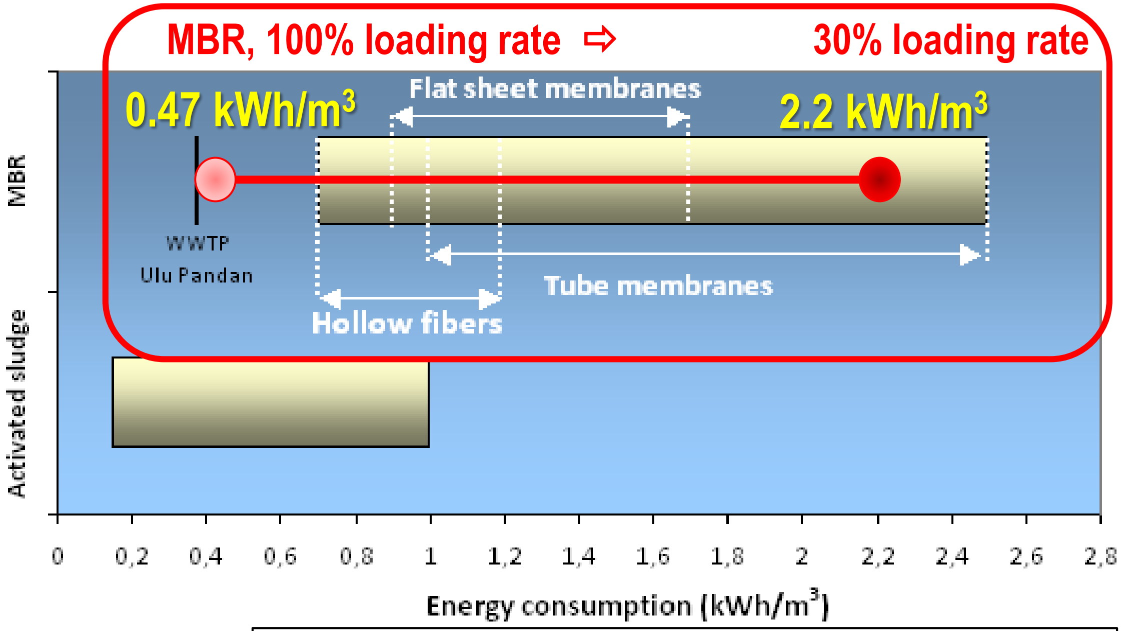
Key Challenges of MBR –
Oxygen Transfer Efficiency

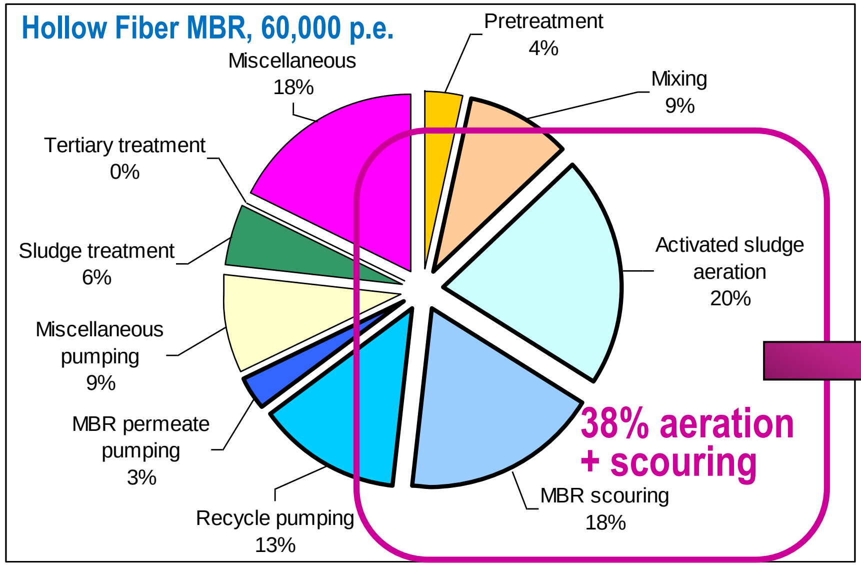


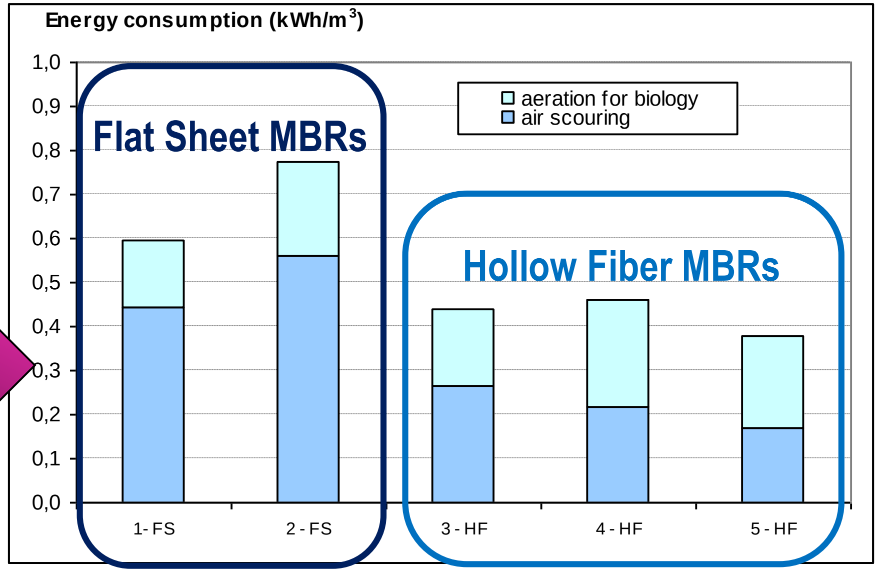


Key Challenges of MBR – Energy Use

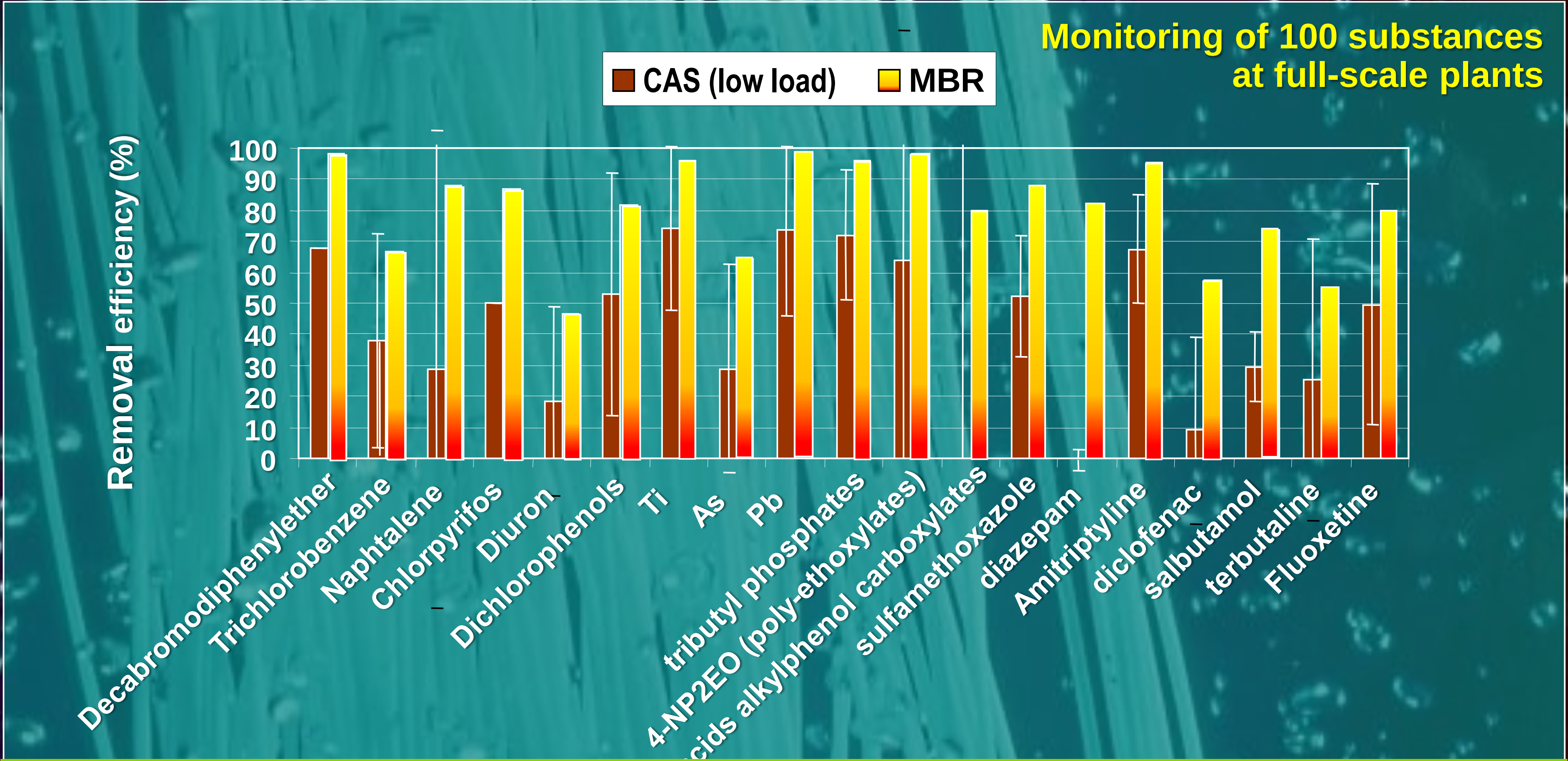
- High energy use than activated sludge
- High influence of hydraulic loading
- 38 to 80% of energy for aeration and scouring







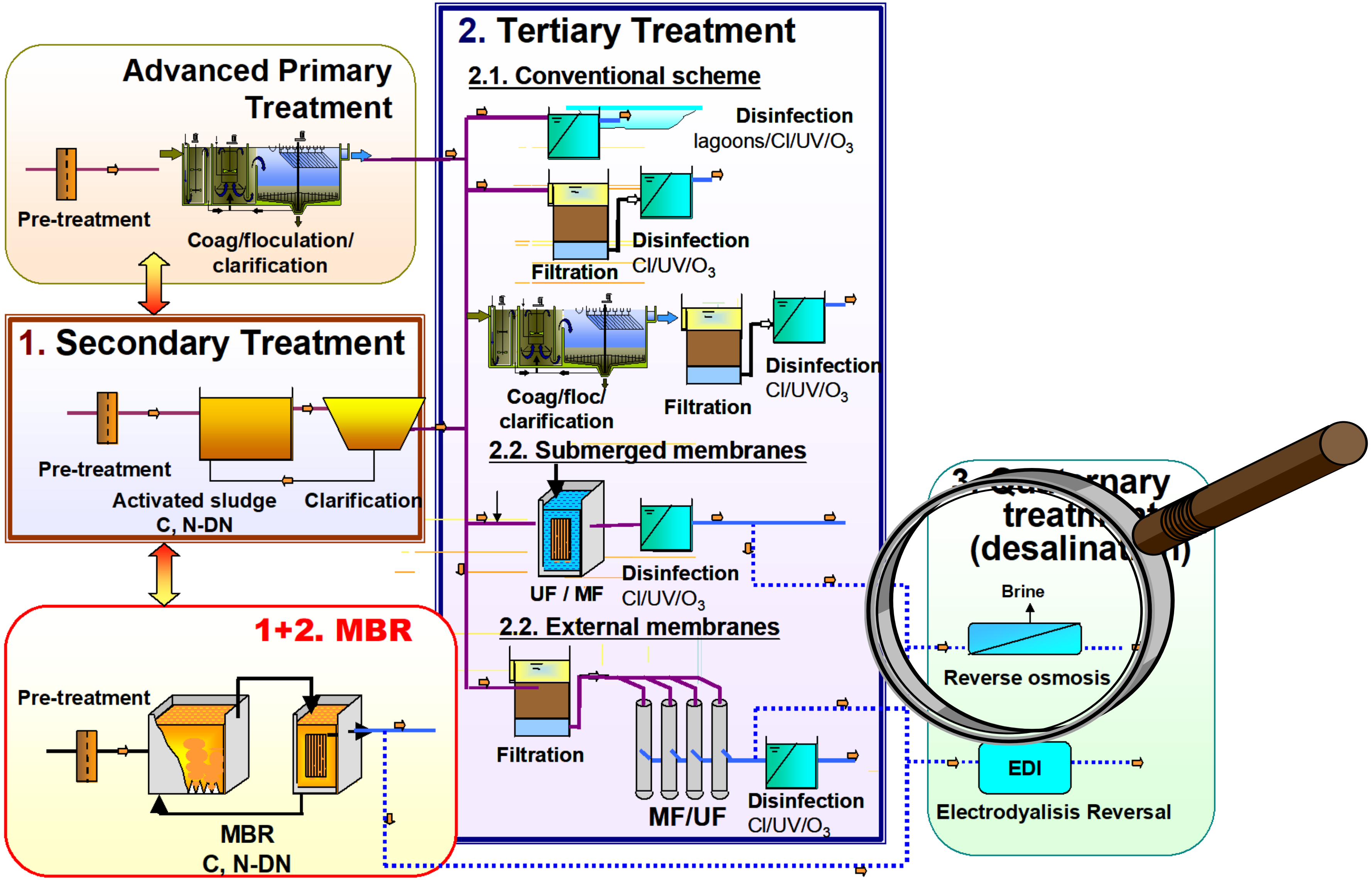
Main Advantages of MBRs – Enhanced Removal of Organic Micropollutants



MBR allows improvement of removal efficiencies for:

- ✓ **Polar substances** partially removed in CAS (higher biodegradation)
- ✓ **Adsorbable compounds** (beneficial effect of high sludge concentration)

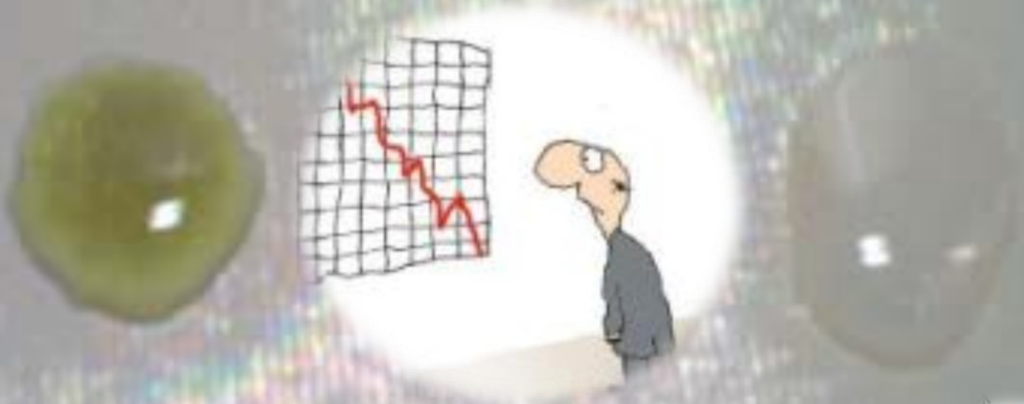
Global Water Reuse Technology Innovation Trends – Typical Treatment Trains for Water Reuse



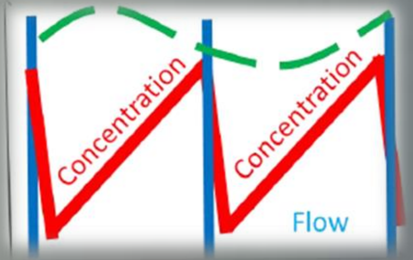
RO Application in Water Reuse

RO Fouling Control

- Efficient pre-treatment processes with increasing use of MF/UF and MBR technologies
- Good operation practices (pH control, chloramination, P removal)



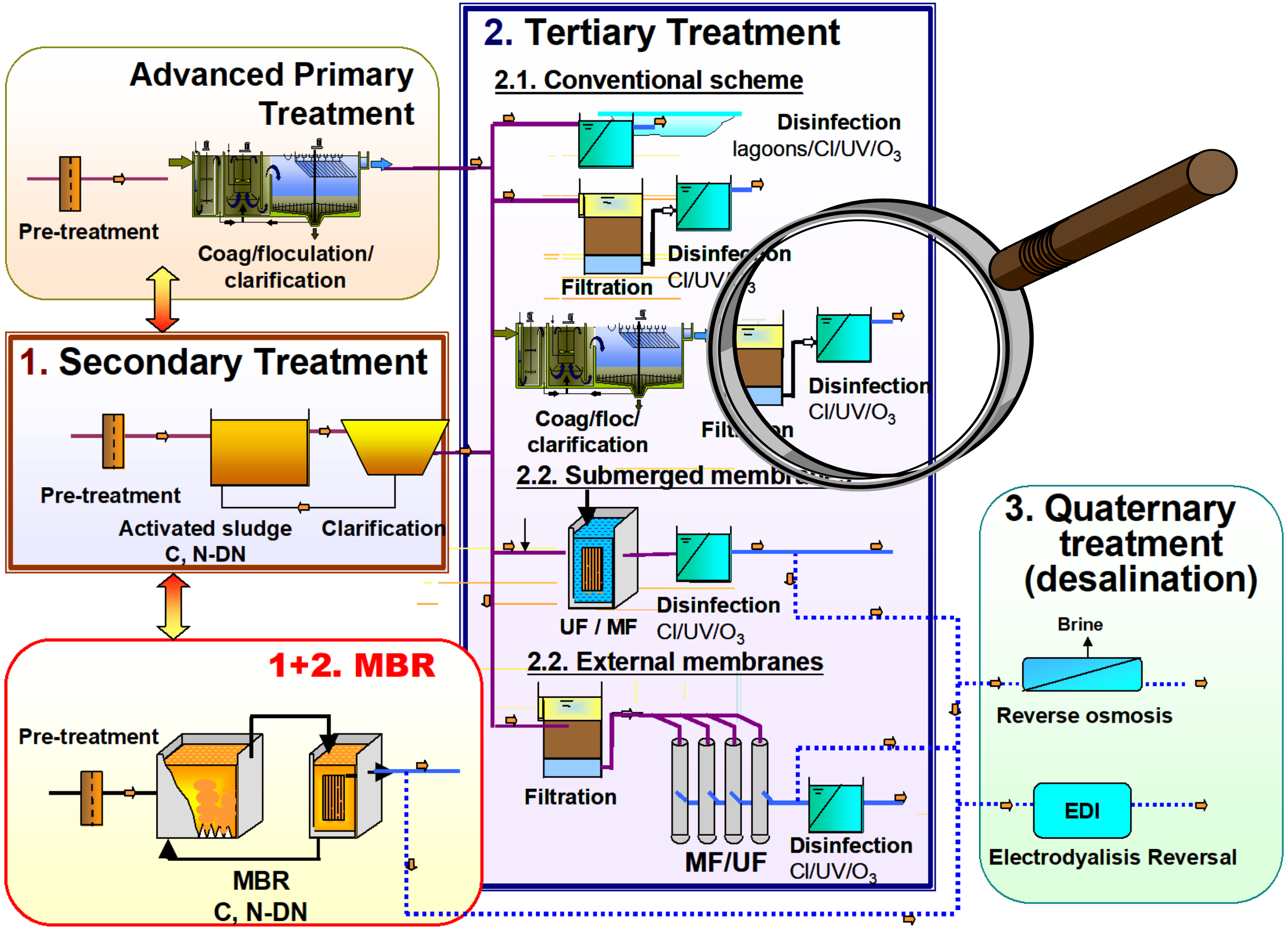
- Use of low-fouling / low differential pressure membranes and large 16'' elements



Reject valve closed

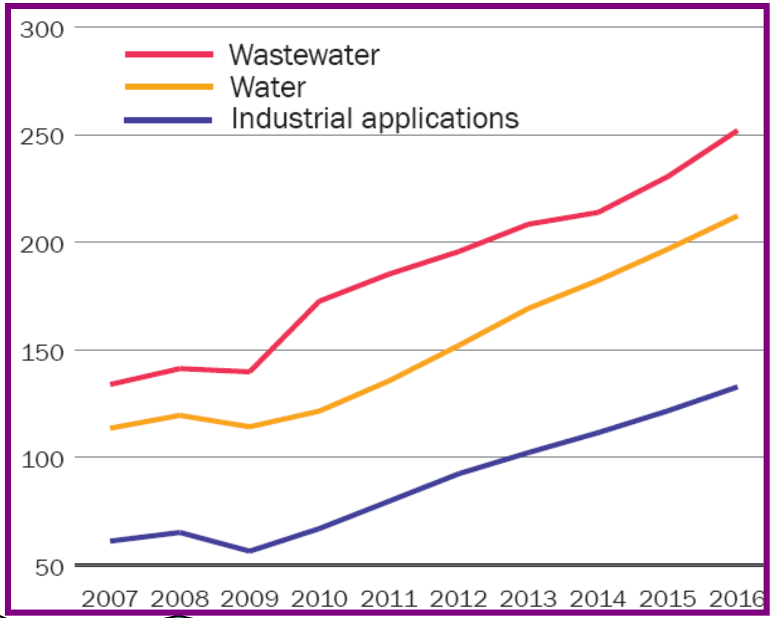
- New cleaning procedures (IDE PROGREEN™ physical online pulse flow cleaning; direct forward osmosis high salinity osmotic backwash…)

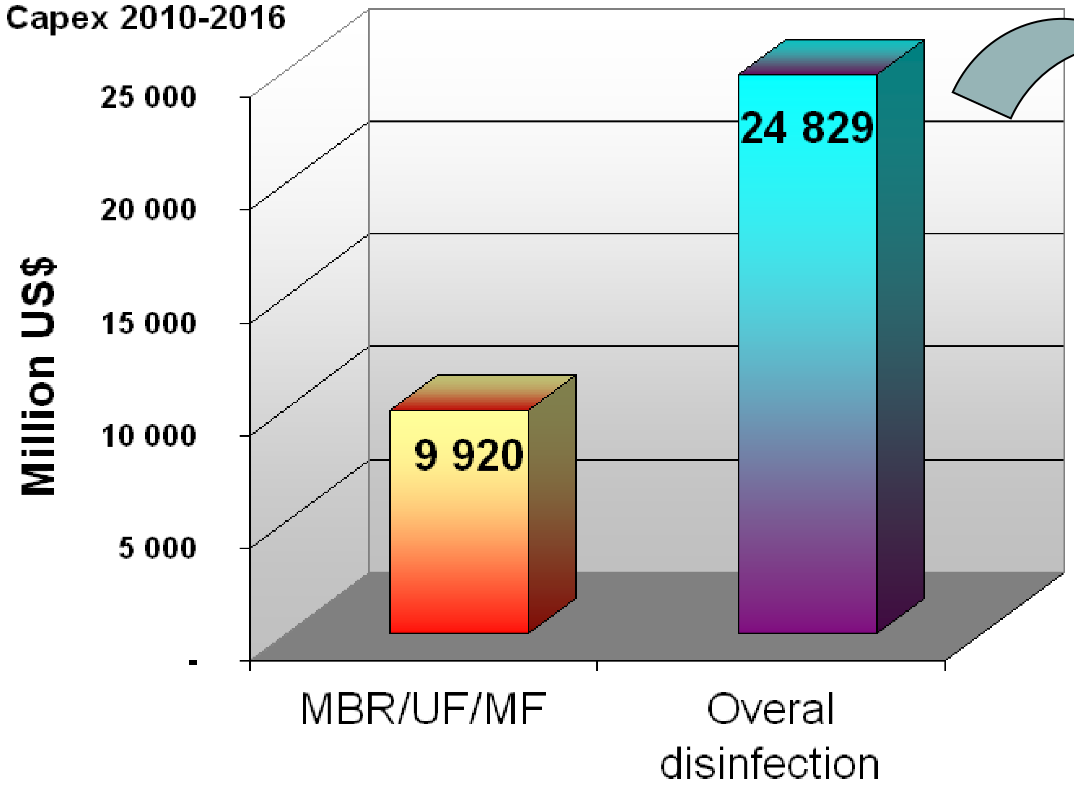
Global Water Reuse Technology Innovation Trends – Typical Treatment Trains for Water Reuse

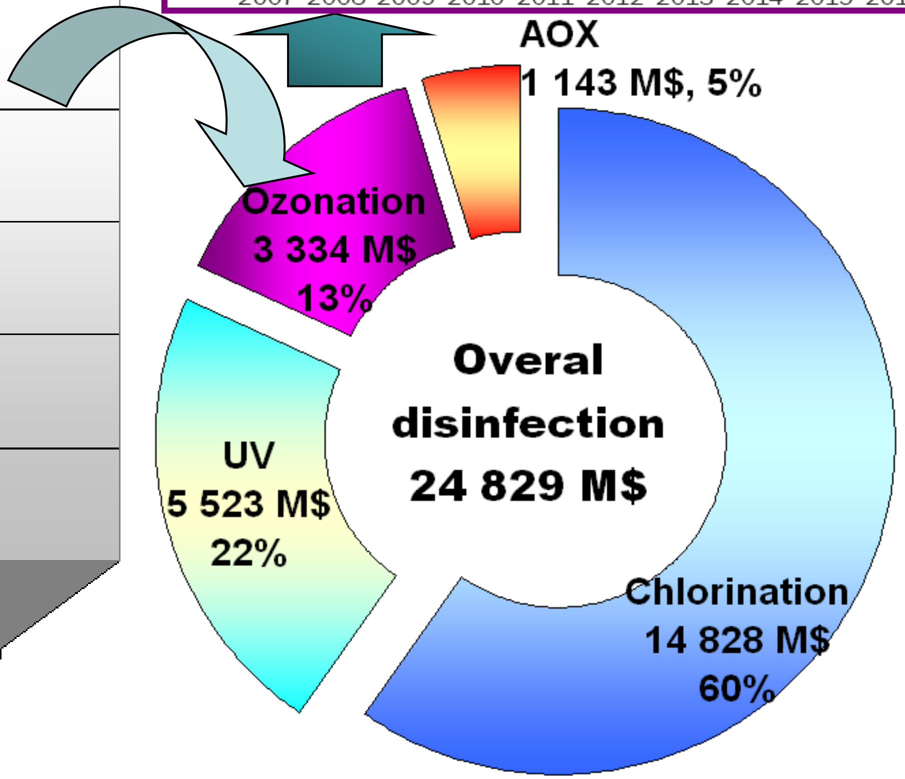


Wastewater Disinfection

- Ozonation shares only **13%** of the total disinfection market in 2016
- **High market growth** is expected for all applications







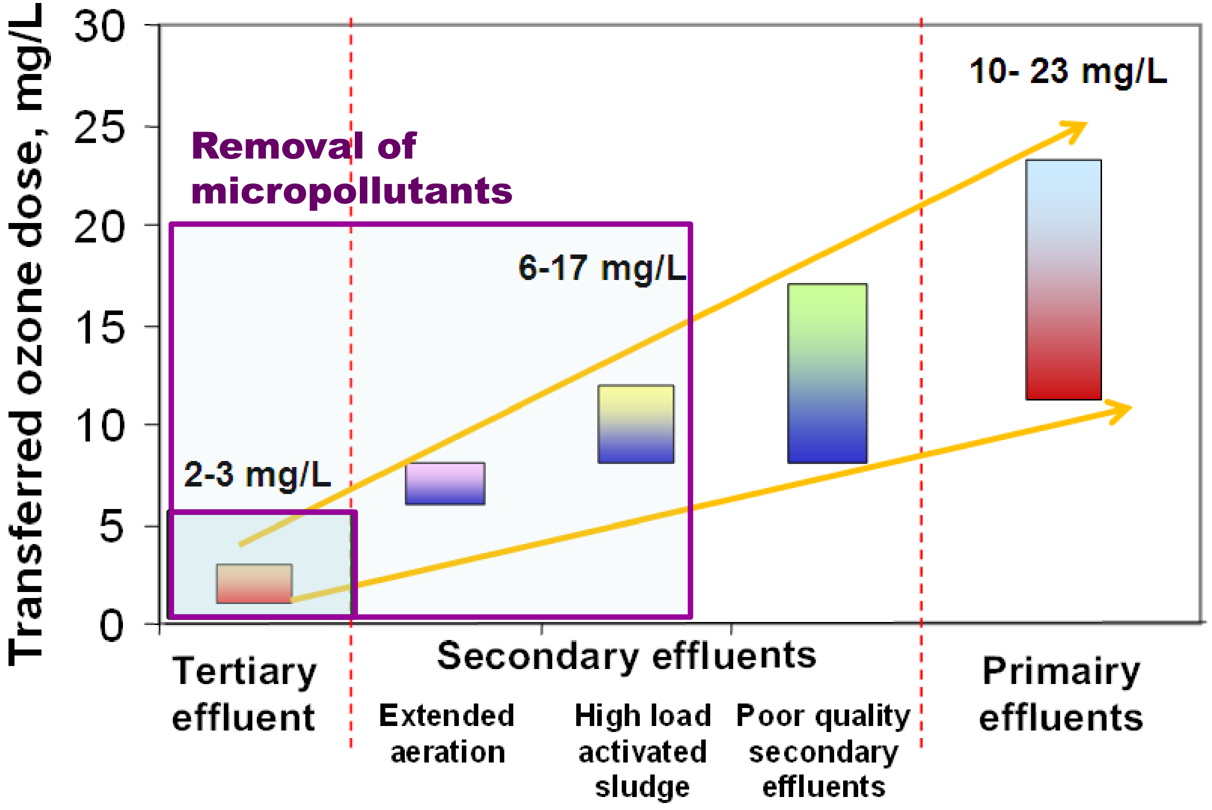
*Source: GWI, Municipal Water Reuse Markets 2010

Ozonation – Major Advantages

- Suitable for all microorganisms: viruses, bacteria and protozoa cysts
- Yields additional water quality improvement: removal of colour, odour and **refractory organics**
- Efficient for low quality effluents
- Near-complete removal of
  emerging organic micropollutants

Ozone Application for Wastewater Treatment – Lessons Learned

- Ozone disinfection is **very efficient for wastewater disinfection** with low HRT (<4 min) and dosage depending on water quality

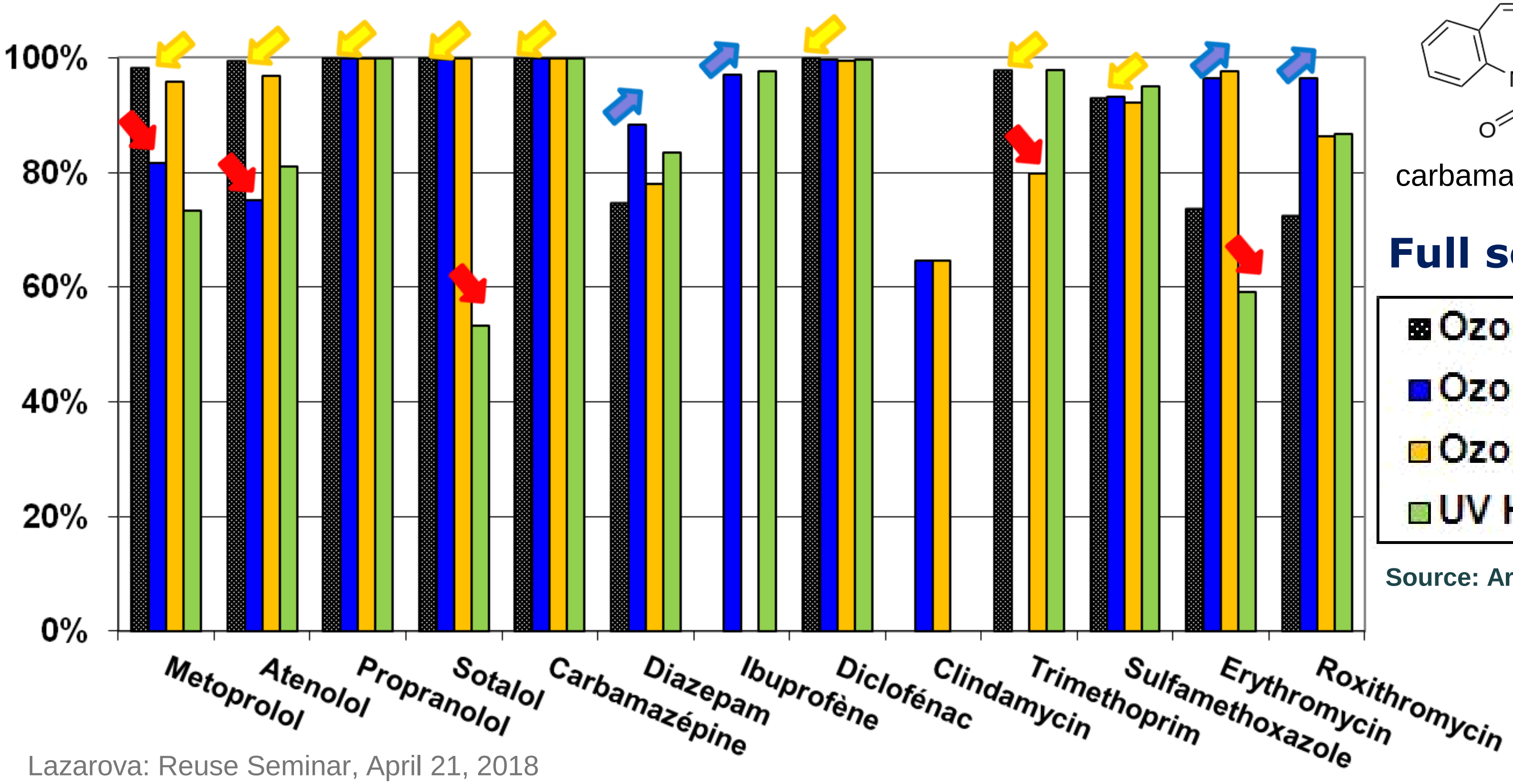


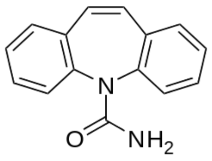
- At such low HRT, ozone dose plays **important role for removal of organic micropollutants**
  - completion of the 1st kinetic stage of oxidation
  - *e.g.* 5-20 mgO_3/L transferred ozone dose

Micropollutants Removal
Comparison of Ozone with Other AOP Processes

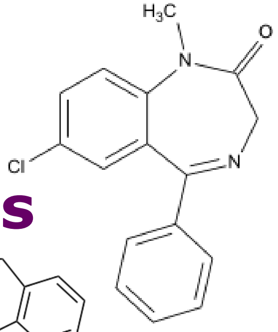
- Betablockers, carbamazepine, diclofenac, sulfamethoxazole, etc. **– very high removal (>98%) with ozone alone at low dose (5 mg/L)**
- Removal may increase ( ) or decrease ( ) with H_2O_2 addition or UV irradiation

☺ Coexistence of **radical and molecular pathways**





carbamazepine



diazepam

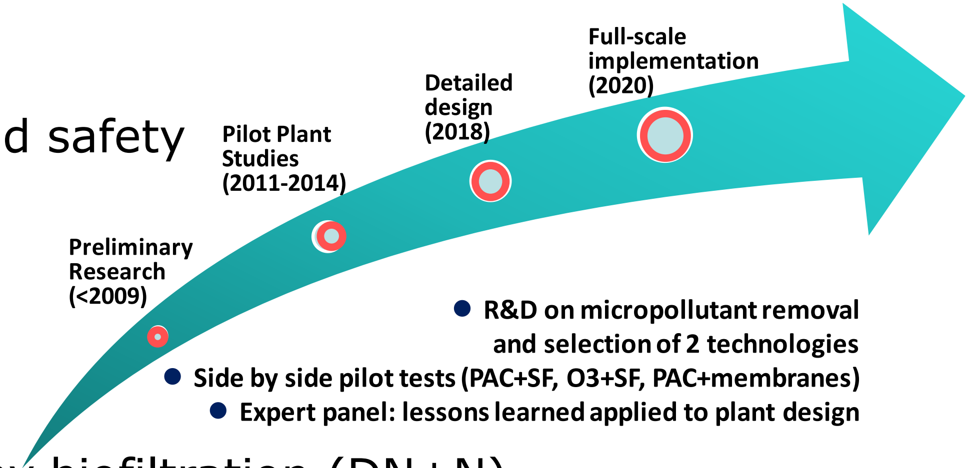
Full scale results

Ozone
Ozone H2O2 1/0,5
Ozone UV 795
UV H2O2 10

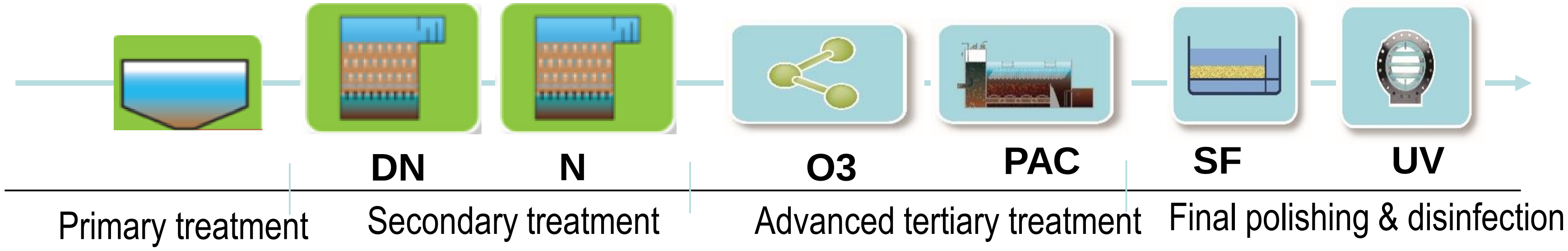
Source: Armistiq project

Production of High-Quality Recycled Water
The case of Lausanne

- **Objectives**
  - ✓ Leman Lake health protection and safety
  - ✓ Control of Capex and Opex
  - ✓ High reliability of operation and treatment flexibility

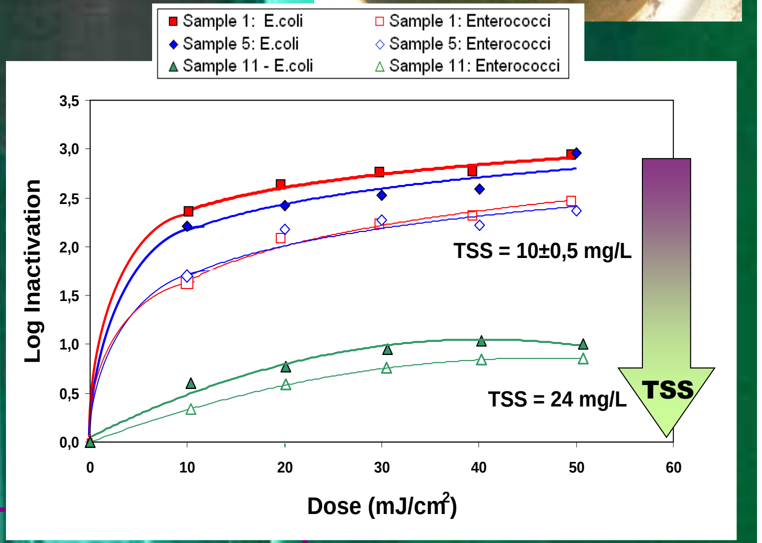


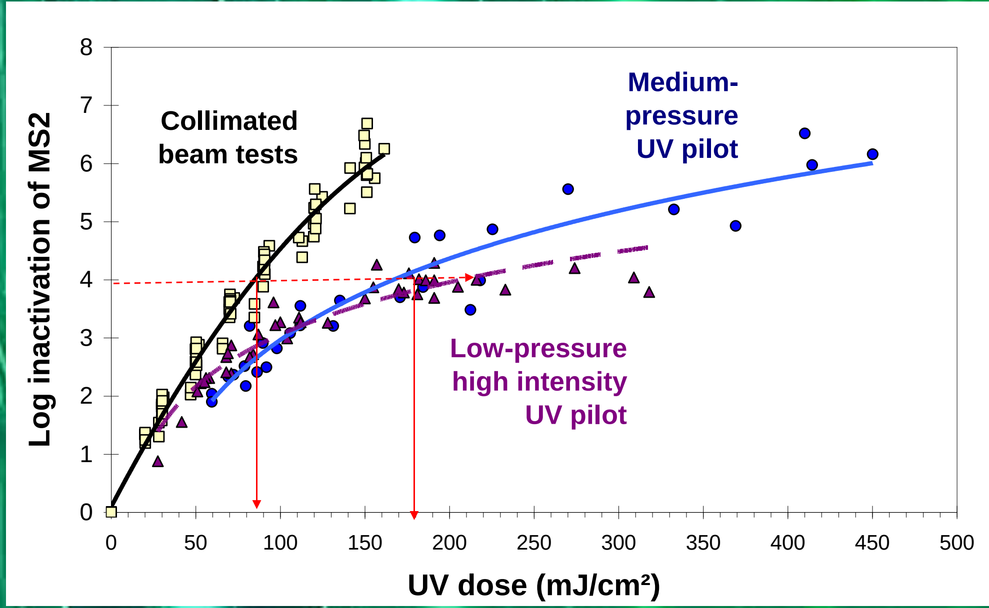
- **Treatment solution**
  - ✓ Enhanced primary treatment
  - ✓ Enhanced secondary treatment by biofiltration (DN+N)
  - ✓ Advanced tertiary treatment by ozonation, powdered activated carbon, sand filtration and final UV disinfection
    - Design capacity 8640 m^3/d
    - Water quality: <10 mgDOC/L, <100 *E.coli*/100 mL, <100 Enterococci/100 mL, 12 micropollutants (pharmaceuticals, additives, pesticides)

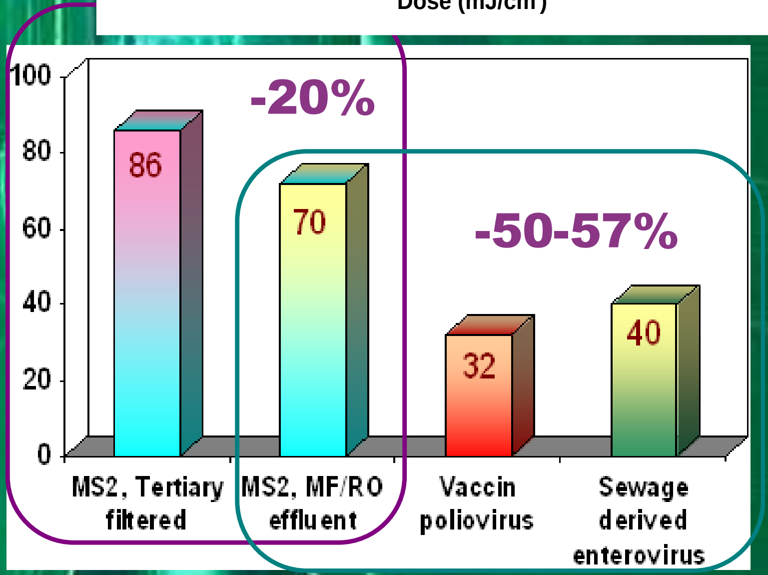


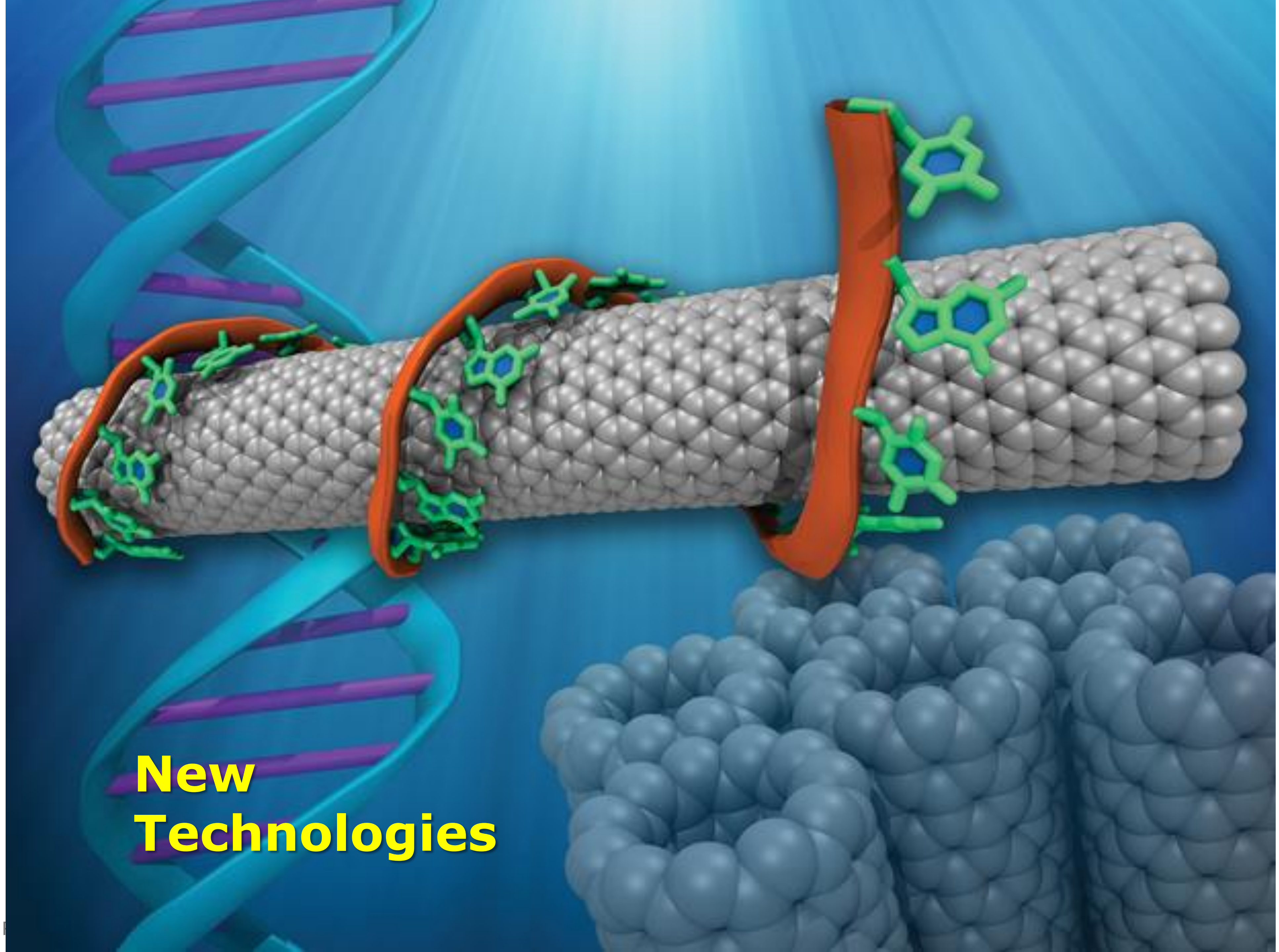
UV Disinfection – Major Challenges

- UV dose control
- High influence of water quality
- Influence of type of microorganism
- High influence of hydrodynamic conditions



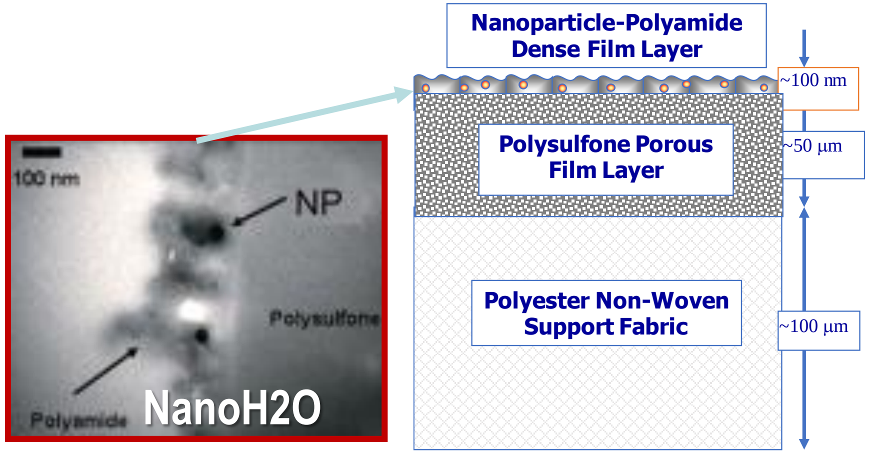




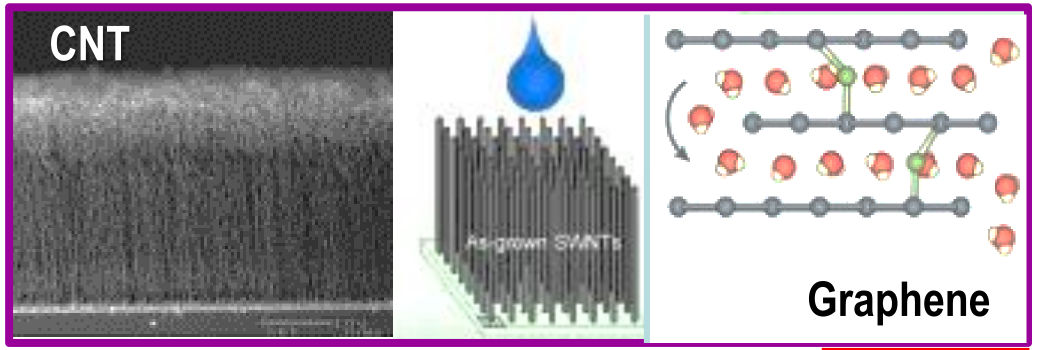

New
Technologies

New Technologies
Nano-engineered Membranes

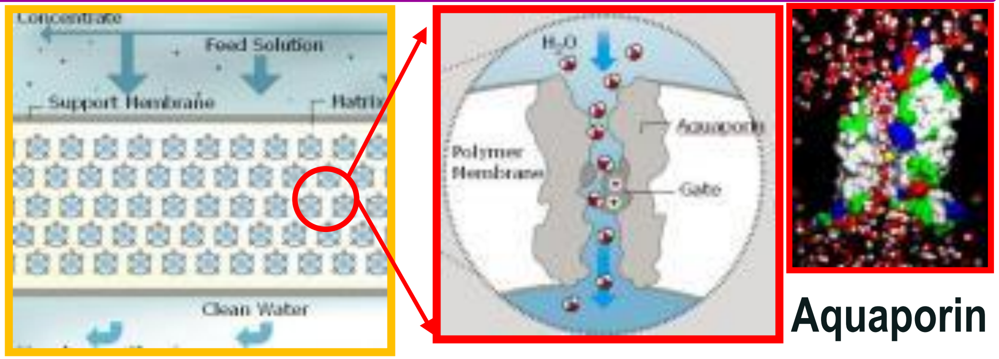
- **New nanomaterial** membranes
  - ✓ Thin film **nanocomposites** (e.g. NanoH2O QuantumFlux)
  - ✓ Self-cleaning/catalytic
  - ✓ Mixed matrix membranes (e.g. hybrid TiO_2/polymer…)



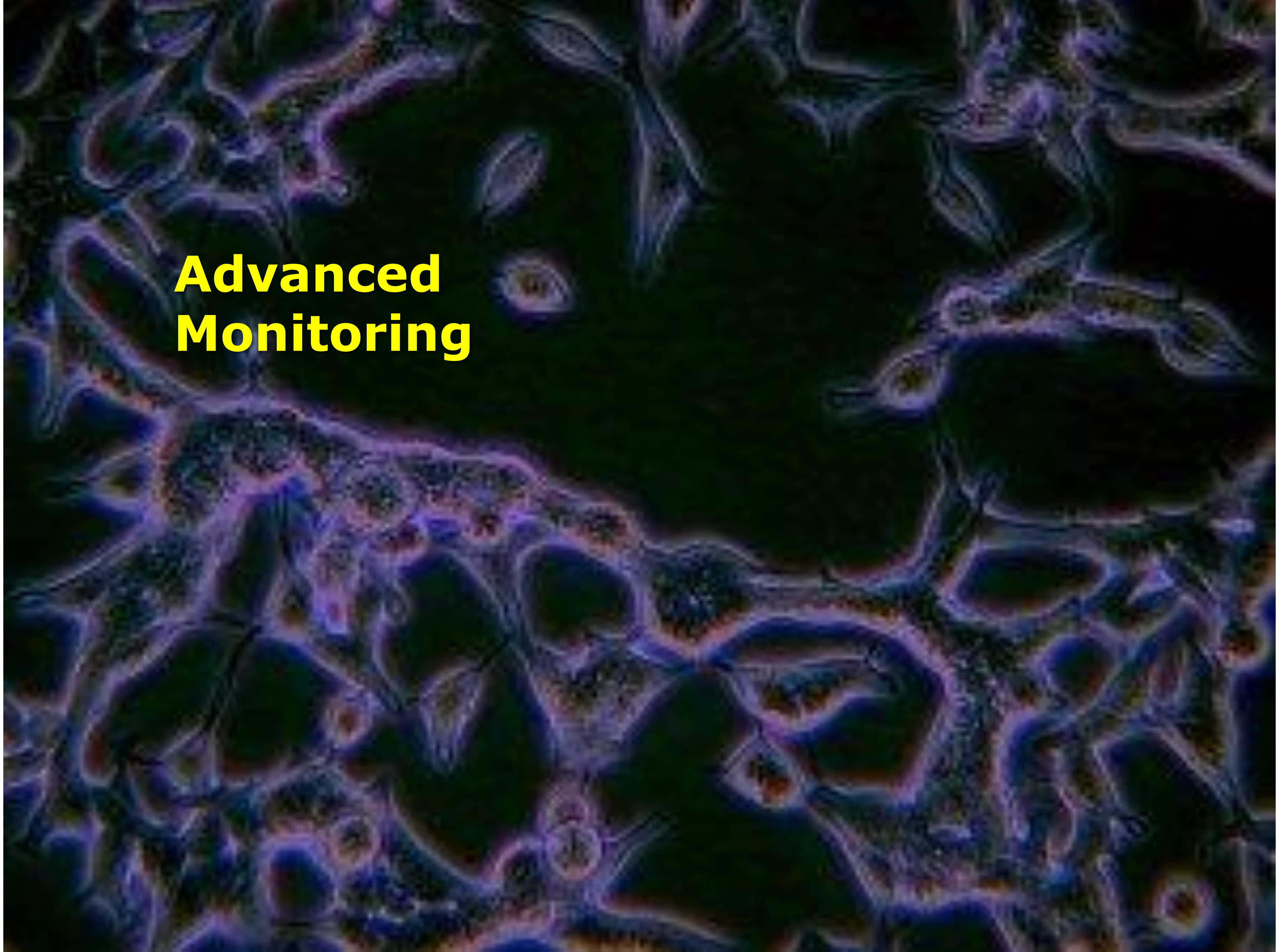
- **Carbon based** membranes
  - ✓ Carbon nanotubes (CNT)
  - ✓ Graphene



- **Biomimetic** membranes
  - ✓ Aquaporin



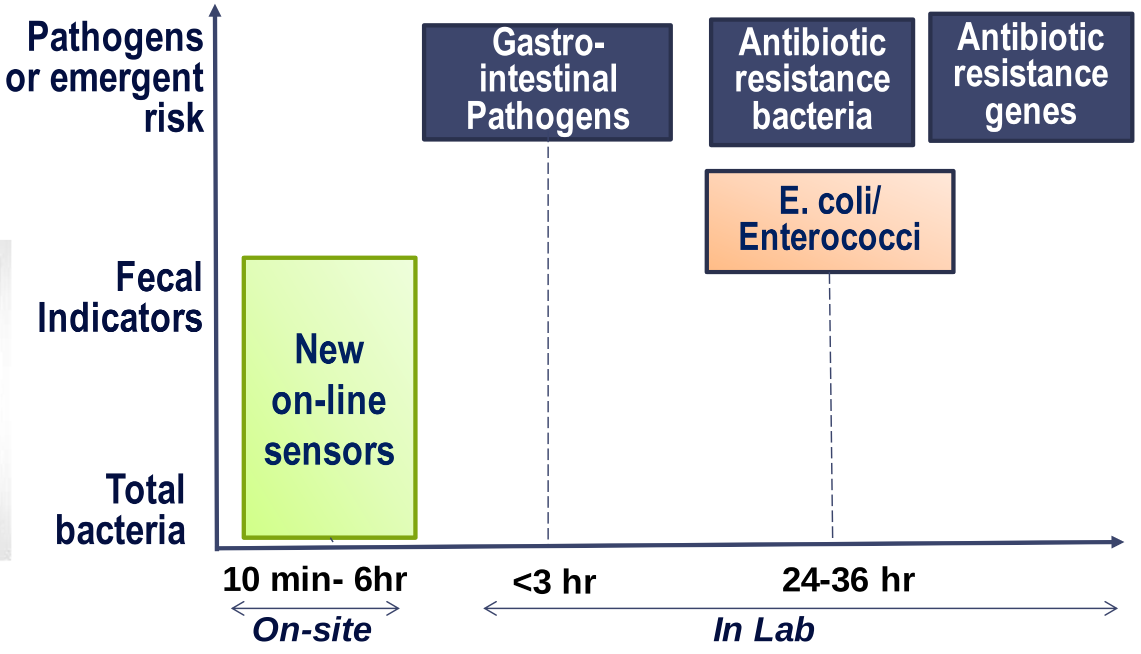
Expected flux increase x 10-20


Advanced
Monitoring

Technology Advance in Monitoring

- Two **main categories**
  - ✓ Analytical (compliance) monitoring of physico-chemical parameters, microorganisms & pathogens, trace organics and emerging pollutants, antimicrobial resistance….)
  - ✓ Performance monitoring (e.g. membrane integrity testing, on-line monitoring, sensors & data management….)

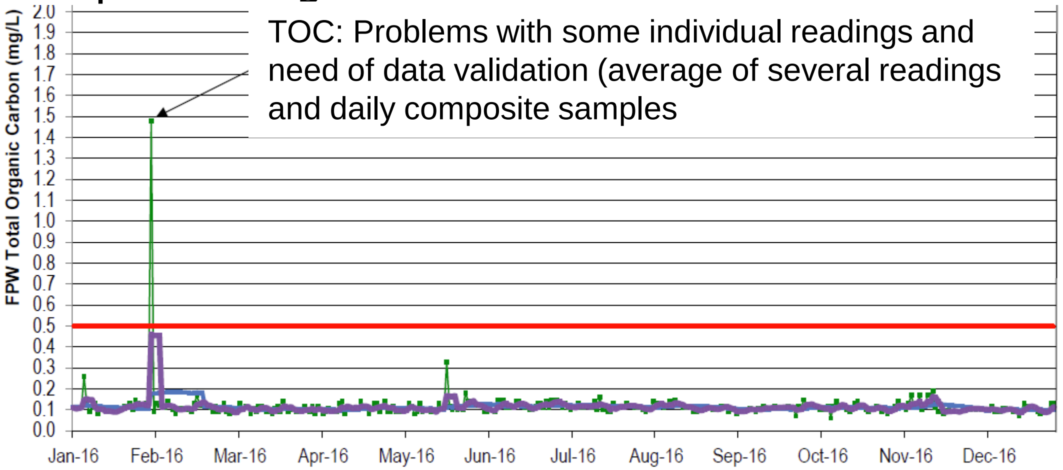
Example: Innovation in microbial monitoring

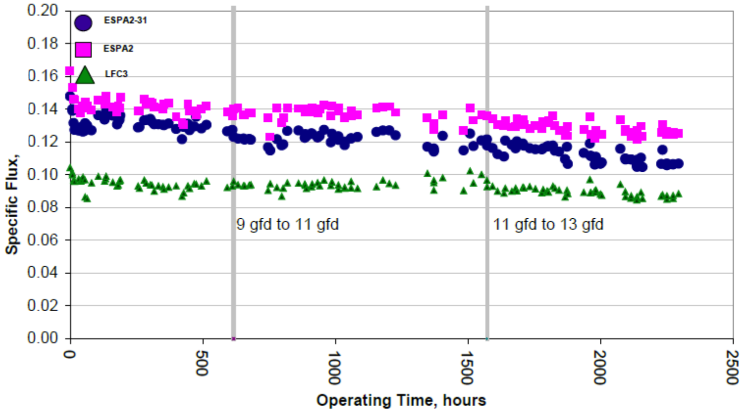


Source: Courtesy of SUEZ

On-line Process Monitoring of Advanced Treatment Schemes – MF&UF/RO/AOP

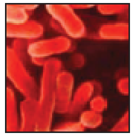
- List of **typical parameters** for on-line monitoring (IPR&DPR)
  - ✓ Turbidity through MF/UF
  - ✓ Pressure decay test with MF/UF
  - ✓ Conductivity through RO
  - ✓ TOC through RO
  - ✓ UVT into UV AOP
  - ✓ UV power delivered
  - ✓ pH through decarbonation
  - ✓ pH through lime addition





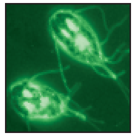
Broad Spectrum Analysis of Pathogens

- Detection of 22 fecal pathogens in less than 3 hours
  - ✓ Automated analysis, useful for Sanitation Safety Plans and control monitoring
  - ✓ Proprietary technology with cost of 500 €/analysis (22 € per pathogen)



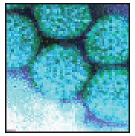
Bacteria

Campylobacter (jejuni, coli and upsaliensis)
Clostridium difficile (toxin A/B)
Plesiomonas shigelloides
Salmonella
Yersinia enterocolitica
Vibrio (parahaemolyticus, vulnificus and cholerae)
Vibrio cholerae
Diarrheagenic E. coli/Shigella
Enteroaggregative *E. coli* (EAEC)
Enteropathogenic *E. coli* (EPEC)
Enterotoxigenic *E. coli* (ETEC) *lt/st*
Shiga-like toxin-producing *E. coli* (STEC) *stx1/stx2*
E. coli O157
Shigella/Enteroinvasive *E. coli* (EIEC)



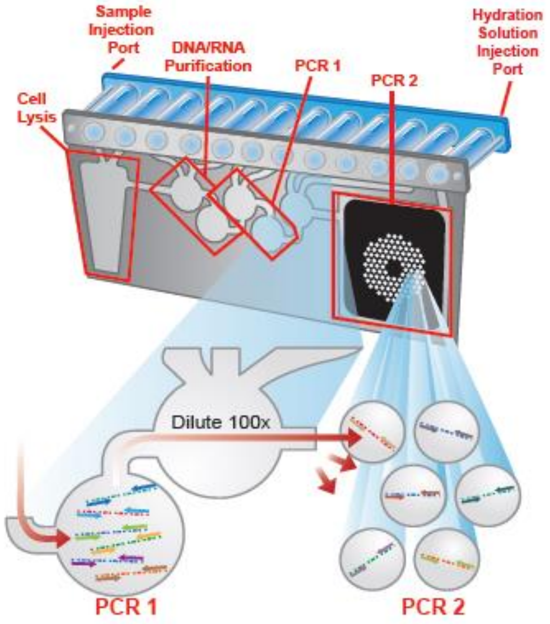
Parasites

Cryptosporidium
Cyclospora cayetanensis
Entamoeba histolytica
Giardia lamblia



Viruses

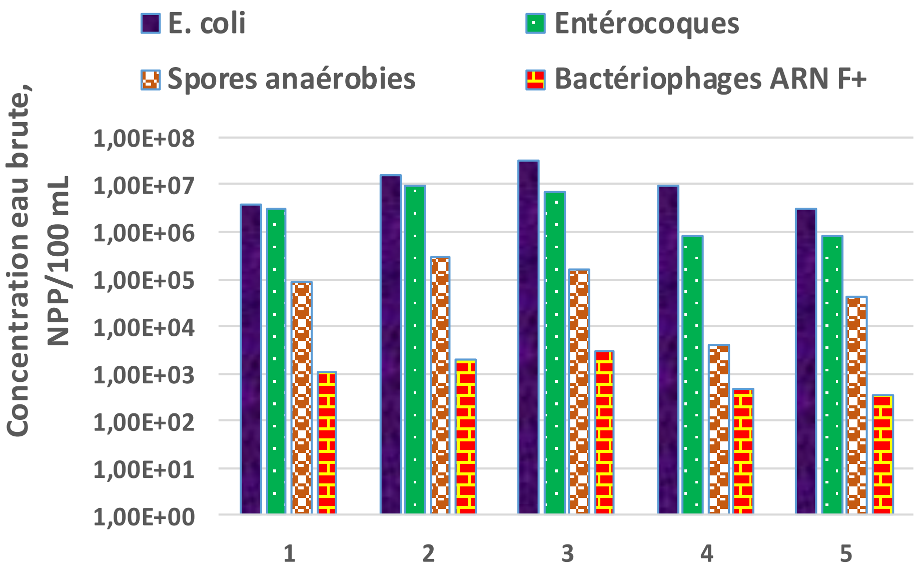
Adenovirus F 40/41
Astrovirus
Norovirus GI/GII
Rotavirus A
Sapovirus (I, II, IV and V)



Source: Courtesy of SUEZ

Indicators vs Pathogens in raw wastewater

- **Indicator content in raw sewage**
  - ✓ *E. coli:* 6-7 log
  - ✓ Enterococci: 5-6 log
  - ✓ Bacteriophages F+: 2-3 log
  - ✓ Anaerobic spores: 3-5 log
- **Pathogen content in raw sewage**
  - ✓ *Bacteria:* 5-6 log
  - ✓ Giardia: 4-3 log
  - ✓ Viruses: 6-7 log
- **MBR permeat**
  - ✓ Not detected indicators & pathogens

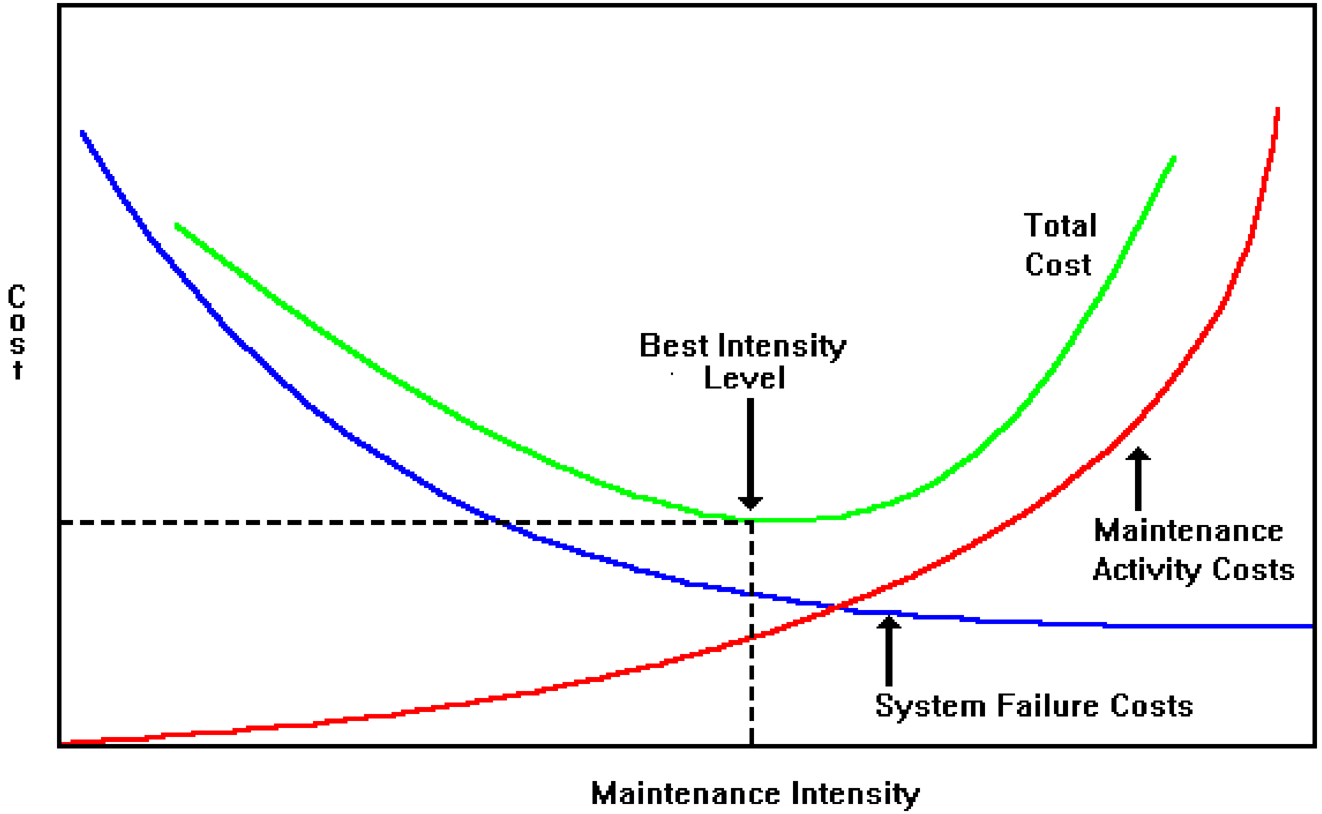


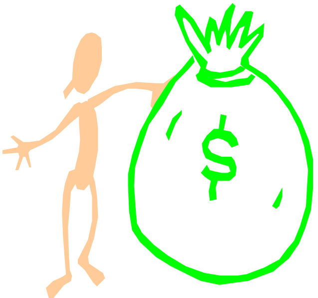
Pathogens (FilmArray Test)	Results
Bacteria	
Campylobacter (C. jejuni / C. coli / C. upsaliensis)	**$1{,}7.10^5 < X < 1{,}7.10^6$**
Clostridium difficile (toxines A/B)	**$500 < X < 1{,}7.10^5$**
Plesiomonas shigelloides	< 500
Salmonella	**$500 < X < 1{,}7.10^5$**
Vibrio (*V. parahaemolyticus / V. vulnificus/ V. cholerae*)	<500
Vibrio cholerae	<500
Yersinia enterocolitica	**$1{,}7.10^5 < X < 1{,}7.10^6$**
E. coli enteroagregative (EAEC)	**$>1{,}7.10^6$**
E. coli enteropathogen (EPEC) **	NA
E. coli enterotoxin (ETEC)	**$1{,}7.10^5 < X < 1{,}7.10^6$**
E. coli de type Shiga producing toxins (STEC)	**$1{,}7.10^5 < X < 1{,}7.10^6$**
E. coli O157*	**$500 < X < 1{,}7.10^5$**
Shigella/E. coli enteroinvasive (EIEC)	**$500 < X < 1{,}7.10^5$**
Parasites (protozoa)	
Cryptosporidium	<20
Cyclospora cayetanensis	<20
Entamoeba histolytica	**$20 < X < 6{,}7.10^3$**
Giardia lamblia	**$6{,}7.10^3 < X < 6{,}7.10^4$**
Viruses	
Adenovirus F 40/41	**$> 3{,}3.10^7$**
Astrovirus	**$> 3{,}3.10^7$**
Norovirus GI/GII	**$3{,}3.10^6 < X < 3{,}3.10^7$**
Rotavirus A	**$3{,}3.10^6 < X < 3{,}3.10^7$**
Sapovirus (Genogroups I, II, IV et V)	**$3{,}3.10^6 < X < 3{,}3.10^7$**


Cost-Risk Nexus

Towards Zero Health and Process Failure Risk

- Increasing health risk requirements (theoretical basis)
- **Risk of failures should be minimised with reasonable O&M costs**





EU Microbial Performance Targets for Agricultural Irrigation

- WHO 2006: theoretical credit
- Australia 2006: impossible to measure inlet-out of the reclamation plant, includes the addition barriers
- France 2010: 4 log removal inlet-outlet of the reclamation plant, impossible to demonstrate

Reclaimed water quality class	Indicator microorganisms (*)	Performance targets for the treatment chain (log_{10} reduction)
A	*E. coli*	≥ 5.0
	Total coliphages/ F-specific coliphages/somatic coliphages/coliphages(**)	≥ 6.0
	Clostridium perfringens spores/spore-forming sulfate-reducing bacteria(***)	≥ 5.0

(*) The reference pathogens Campylobacter, Rotavirus and Cryptosporidium can also be used for validation monitoring purposes instead of the proposed indicator microorganisms. The following log_{10} reduction performance targets should then apply: Campylobacter (≥ 5.0), Rotavirus (≥ 6.0) and Cryptosporidium (≥ 5.0).

(**) Total coliphages is selected as the most appropriate viral indicator. However, if analysis of total coliphages is not feasible, at least one of them (F-specific or somatic coliphages) has to be analyzed.

(***) Clostridium perfringens spores is selected as the most appropriate protozoa indicator. However sporeforming sulfate-reducing bacteria is an alternative if the concentration of Clostridium perfringens spores does not allow to validate the requested log10 removal.

EU Minimum Quality for Agricultural Irrigation

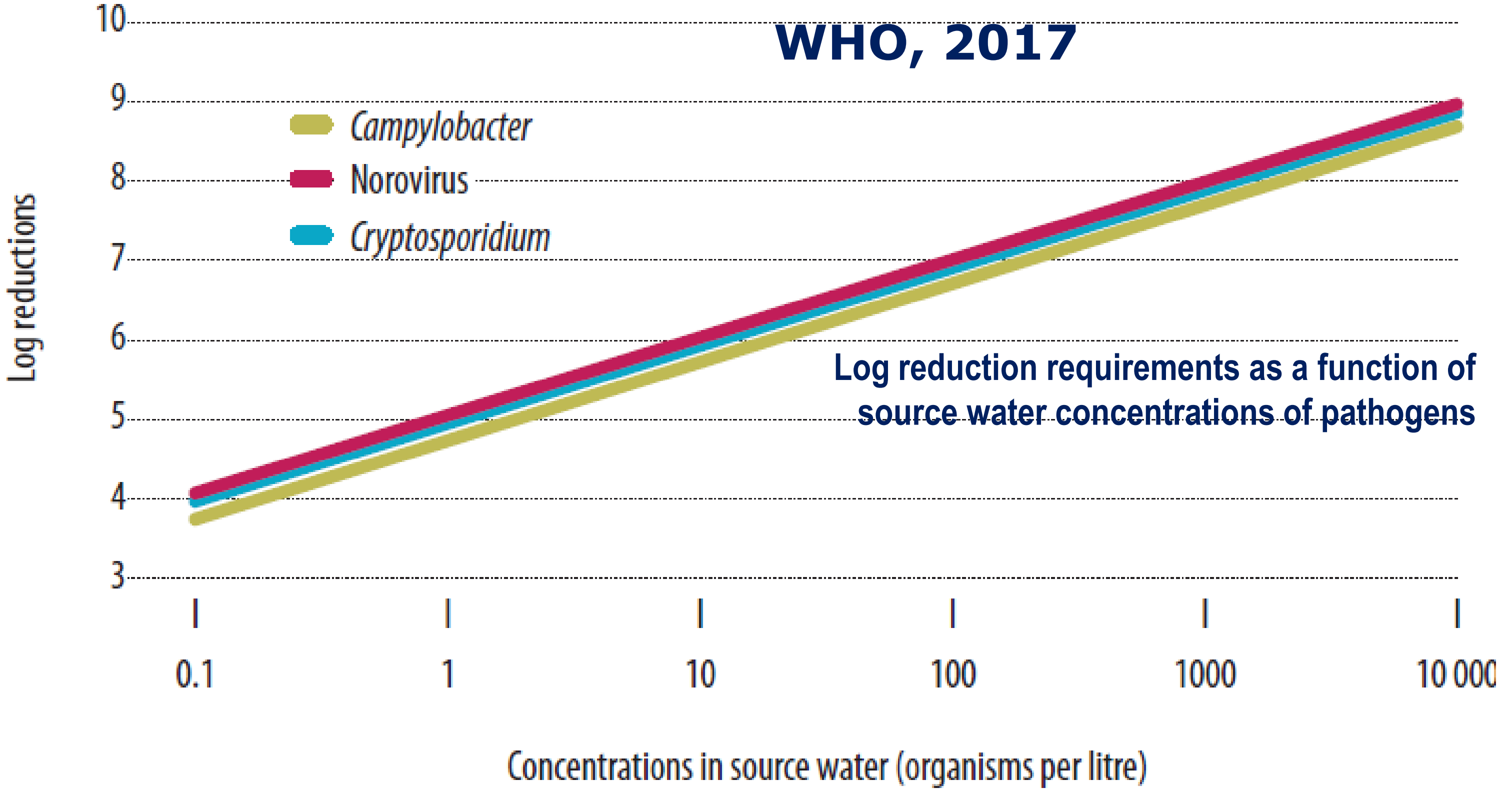
Minimum reclaimed water quality class	Crop category	Irrigation method
A <10 E.coli/100mL	All food crops, including root crops consumed raw and food crops where the edible part is in direct contact with reclaimed water	All irrigation methods
B <100 E.coli/100mL	Food crops consumed raw where the edible part is produced above ground and is not in direct contact with reclaimed water, processed food crops and non-food crops including crops to feed milk- or meat-producing animals	All irrigation methods Alfafa, corn….
C <1000 E.coli/100mL		Drip irrigation* only
D	Industrial, energy, and seeded crops	All irrigation methods

- **Class A&B for all type of crops**
- **Corn, potatoes irrigation…..& maturation ponds are excluded**

Impossible in practice:
Drip irrigation needs filtration

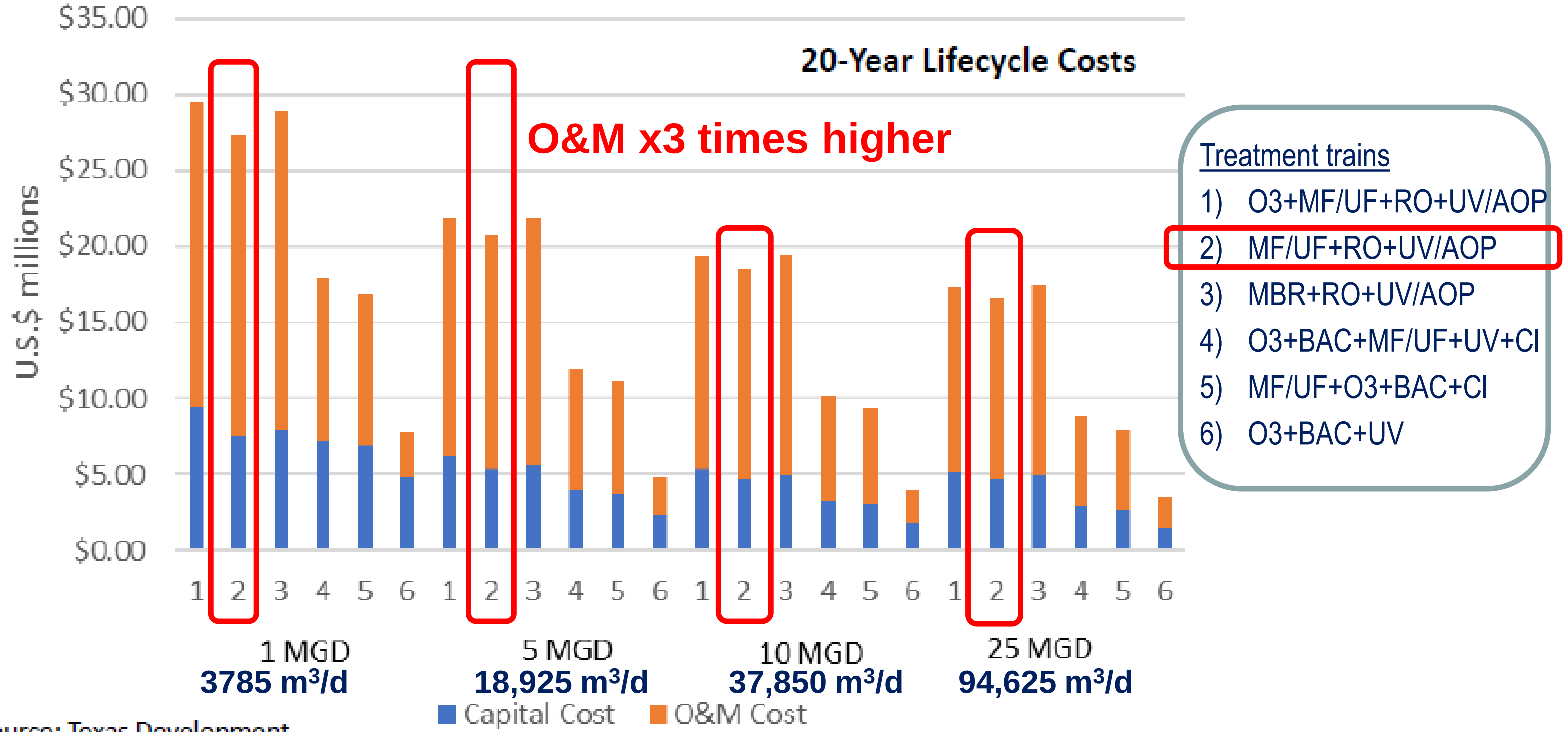
Microbial Risk Assessment
Microbial Performance Targets for Potable Reuse

- **Different methods** used to calculate health-based targets
- Numerous **uncertainties**
- **High** associated **costs**



O&M Costs of Advanced Water Reuse

- O&M costs increase with increasing treatment intensity
  - ✓ California: 1,22-1,78 \$/m³ for DPR plant capacity <34,000 m³/d; 0.89-1.3 \$/m³ for large plants
  - ✓ Texas: 0.105-1.00 \$/m³ depending on size and treatment with O&M costs representing 39 to 82% of lifecycle costs



Source: Texas Development Board, 2015.


Concluding Remarks

Concluding Remarks

- Water reuse is becoming an important part of the water management portfolio in water scarce regions and many urban areas, creating **enhanced opportunities for innovation and building a circular economy**
- The safety of water reuse can be secured by **innovative tools and technologies**
  - ✓ Improving the performance, robustness and reliability of water reclamation facilities and implementing new monitoring tools
  - ✓ **Safeguarding the economic viability** of recycled water
- **Holistic approach** should be applied to develop water reuse
  - ✓ Promote “fit to purpose” treatment and macroeconomic long-term benefits
  - ✓ Provide incentives, education and improved communication
  - ✓ Bridge the gap between practice, research and regulations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