Groundwater Aquifer Recharge and Recovery (ARR):
An Adaptation Strategy for Climate Change-Induced Water Scarcity in the KSA/GCC Region

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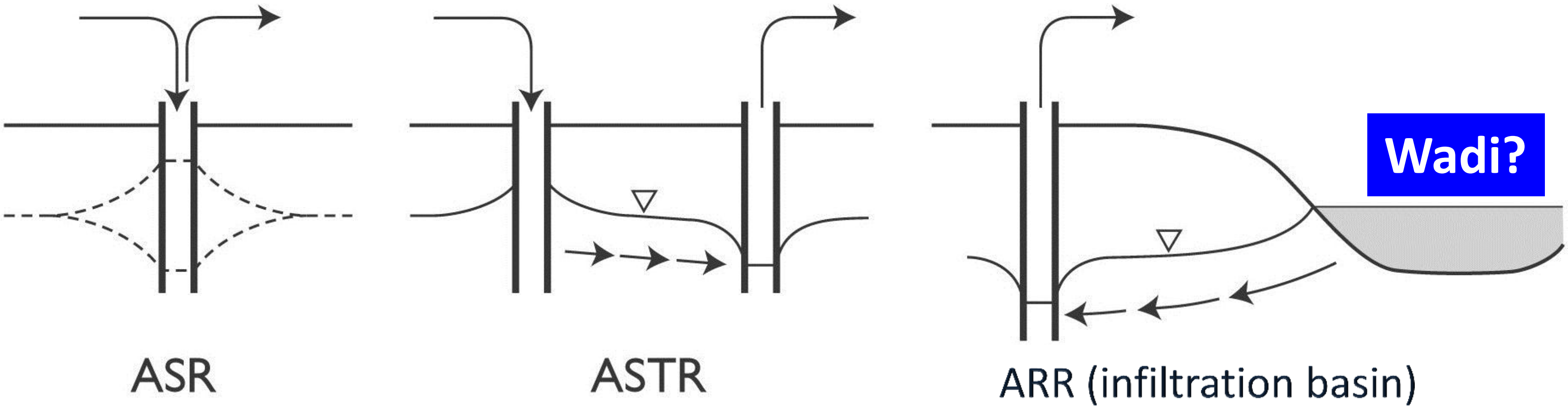
Aquifer Recharge and Recovery (AAR): Variations on a Theme

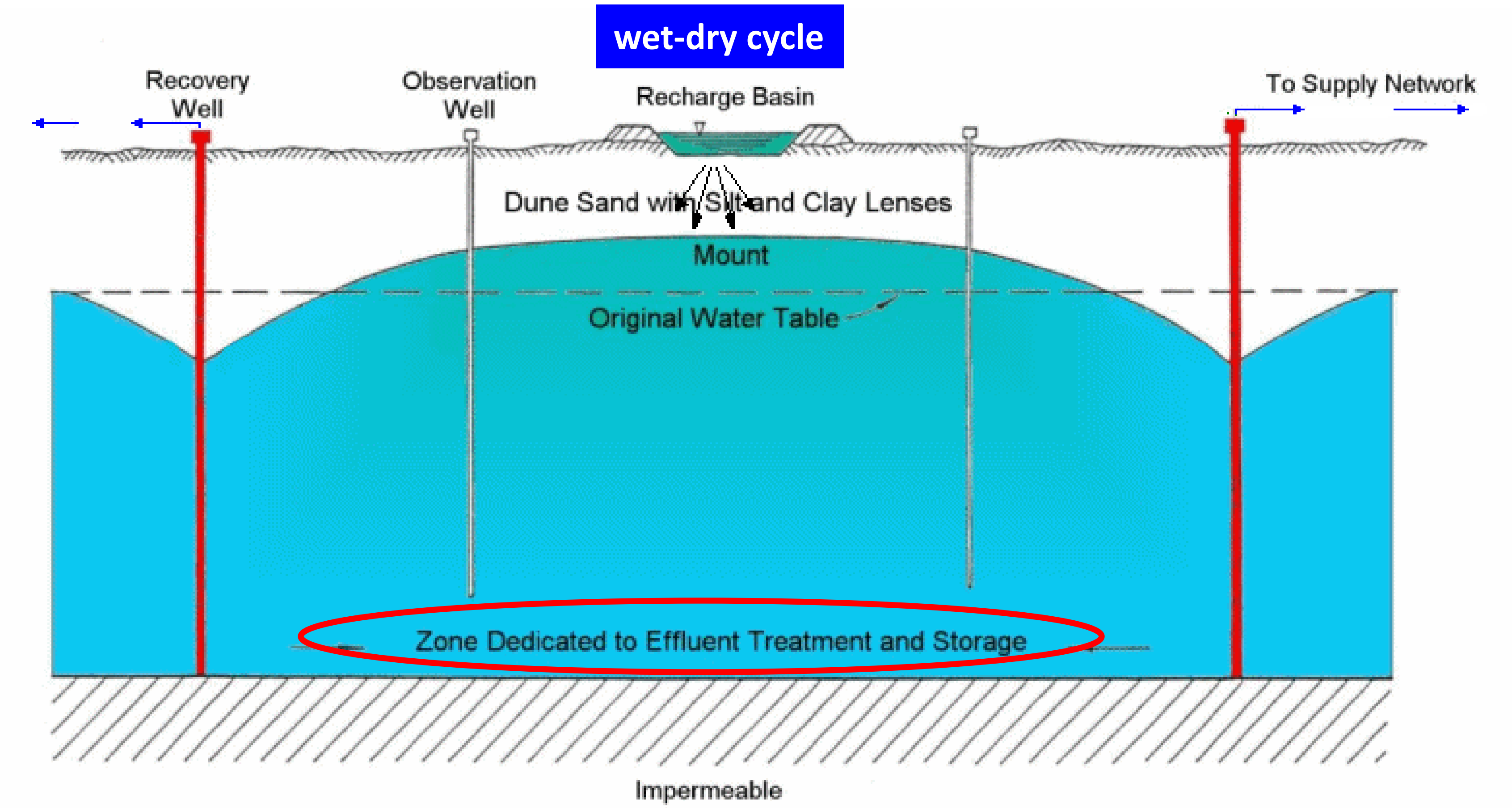
- ARR = Aquifer Recharge and Recovery;
  Infiltration Basin ⇨ Recovery Well
  - ASR = Aquifer Storage and Recovery ⇨ one well (injection and recovery)
  - ASTR = Aquifer Storage Transfer and Recovery ⇨ two wells



- Can Manage Travel Distance ✓, Travel (Residence) Time ✓, Redox ?
- Suitable (Geo)Hydrology and Storage ?
- Dissolution of Natural Contaminants (e.g., As) ?

ARR: Infiltration (Recharge) to Recovery

(Cikurel, 2004)



- **Unsaturated (Vadose) Zone: Treatment (Oxic → Anoxic)**
- **Saturated Zone: Treatment (Oxic) + Storage**

Attributes of ARR

- A Physico-Biological Process
  - Filtration and Biodegradation
  - Biodegradation (Sustainability) ✓ vs. Sorption
- A Sustainable Process
  - Low Cost, Low Energy, low GHGs, Minimal Chemicals
- Provides Both Treatment and (Subsurface) Storage

Potential Source Waters

- Wastewater (Effluent)
  - Secondary
  - Primary? (advanced primary: SS ↓)
- Stormwater
  - Urban Runoff
  - Natural Catchment Runoff
- Desalinated Water
  - *Storage* for Water Security

Treatment & Storage

Potential Roles for ARR (and ASR)

- Wastewater Reuse
  - Aquifer Recharge and Recovery (ARR)
    as Robust, Multi-Contaminant Treatment Barrier
- Engineered ARR for Urban Runoff Infiltration
  - Infiltration Basin Amendments or
    Permeable Treatment Bed
    Targeting Inorganic Micropollutants (e.g., Zn, Cu, Cr)
    (e.g., Iron Oxide Layer)
- Desalination
  - Aquifer Storage and Recovery (ASR)
    for (Seasonal) Excess Desalination Production
    (being implemented in Qatar and Abu Dhabi)

Factors Affecting Performance of ARR System

- Site Specific Conditions
  - Source Water (WW effluent, stormwater)
  - Geology and Soils
  - Geohydrology
    - Alluvial, *Unconfined Aquifer* ✓ vs. Confined Aquifer
    - Aquifer Depth (Depth to Water Table) ⇨ *Vadose Zone*
    - *Aquifer Thickness* (water table to bedrock)
    - *Permeability* (Hydraulic Conductivity) !
  - Travel Distance
    - Well Placement and Spacing between Wells
  - Travel (Residence) Time
    - Well Placement and Operation (Pumping Rate)
    - Permeability (Hydraulic Conductivity)

Design/Operation Considerations: ARR

- Travel Distance (to recovery wells)
  - <10 m to > 100 m
- Residence (Travel) Time
  - <10 d to > 100 d
- Dilution/Mixing: Percent (%) Infiltrate
  - Defined by Conservative Tracer (vs. native groundwater)
- Soil Permeability
  - 10^{-4} to 10^{-2} m/s
- Water Quality
  - Temperature, pH
  - Dissolved Oxygen (DO), Nitrate (NO_3^-), Redox (Oxidation-Reduction Potential)
- Soil Components
  - Iron and Manganese (possible reductive dissolution)
  - Also, As and F^-

Summary of Operating Conditions (Guidelines) for ARR (Cikurel, 2004)

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Parameter	Units	Value
Hydraulic loading rate (HLR)	m/d	0.2 to 0.6
Wetting cycles	days	1 to 7
Drying cycles	days	2 to 7
Cleaning cycle	days	< 15 to > 30
Retention time (in ground)	months	< 1 to > 12
Depth to ground water	m	5 to 30
Travel distance	m	< 10 to > 100
Recovery	%	up to 100 %

Key Design/Operational Parameters/Conditions:

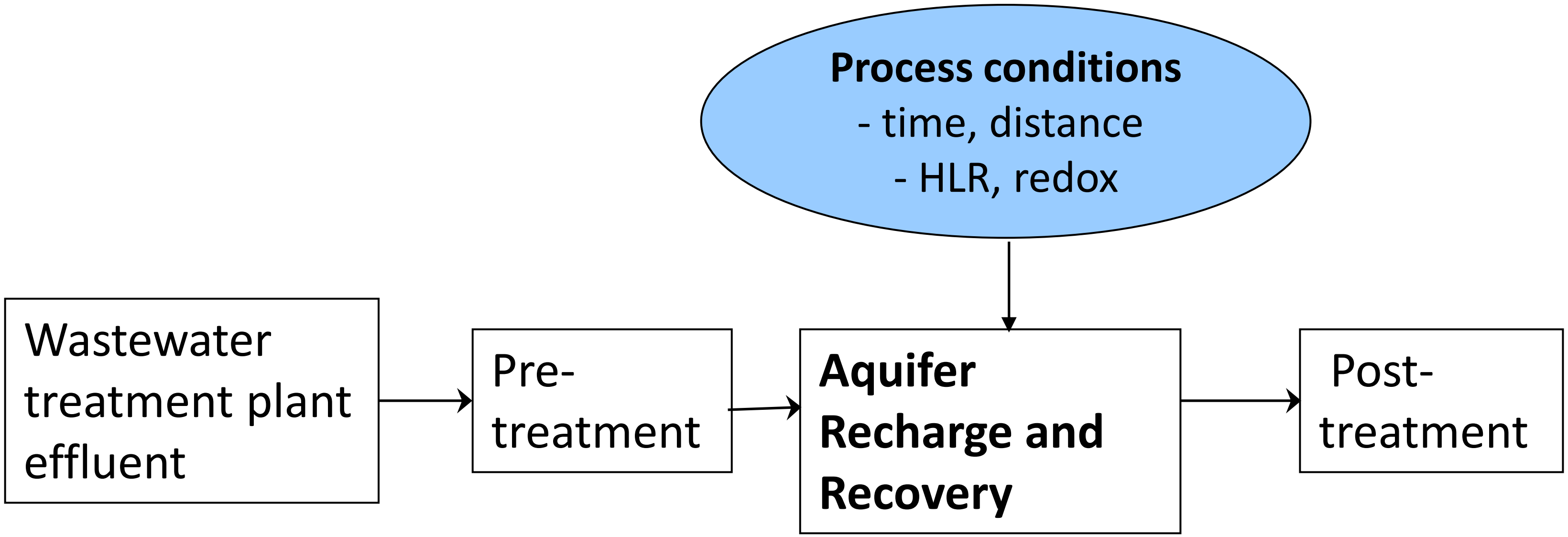
- (Travel) Distance ⇨ > 10 m
- (Residence) Time ⇨ > 10 days
- Managing Redox ⇨ oxic and anoxic zones
- Managing Infiltration ⇨ wet-dry cycles

Water Quality Benefits of ARR: Removals of…

- Turbidity
- Dissolved Organic Carbon (DOC)
- Bacteria, Protozoa, and Viruses
- Organic Micropollutants (OMPs)
    - Pharmaceutically Active Compounds (PhACs)
    - Personal Care Products (PCPs)
    - Endocrine Disrupting Compounds (EDCs)
    - Pesticides
- Nitrogen (ammonia and nitrate)
- Taste and Odor
- Algal Toxins

Multi-Objective (-Contaminant) Process:
⇨ A Total Treatment System (or central feature)

ARR for Wastewater Reclamation: Potential Pre- and Post-Treatments



Wastewater treatment plant effluent

1. Primary
2. Secondary
3. Tertiary ?

Pre-treatment

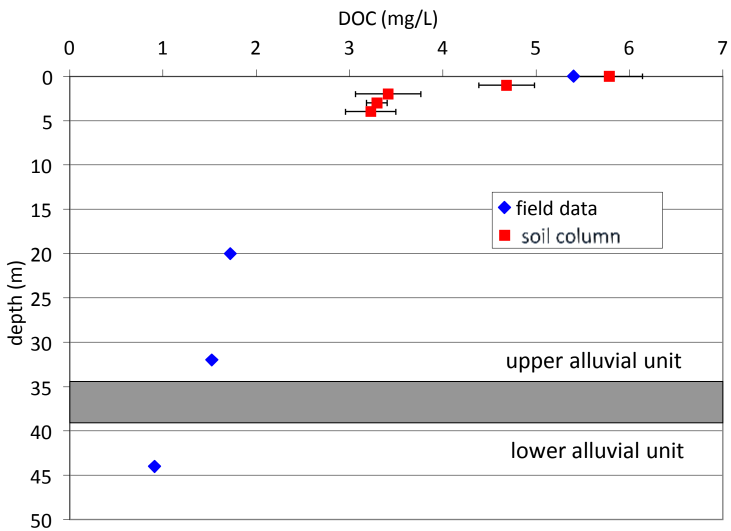
1. None
2. Oxidation (O_3 , AOP)
3. Membrane Filtration (MF)

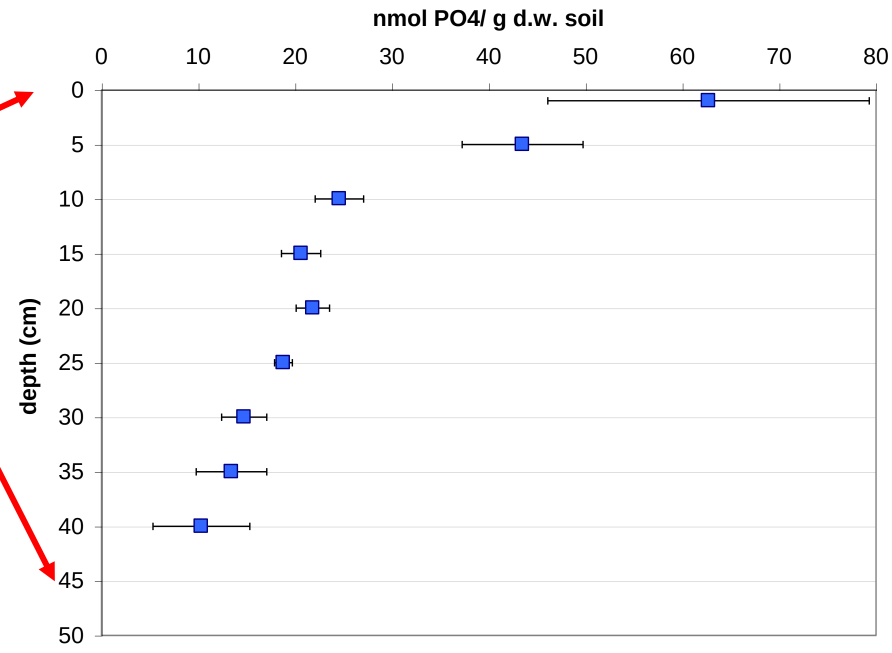
Post-treatment

1. UF (viruses)
2. NF (trace organics)
3. GAC (trace organics)
4. Post disinfection (Chlorination or UV)

- Potential Hybridizations
- Multi-Barrier Approach
- ARR: Central Feature of Process Train

DOC and Biomass Profiles

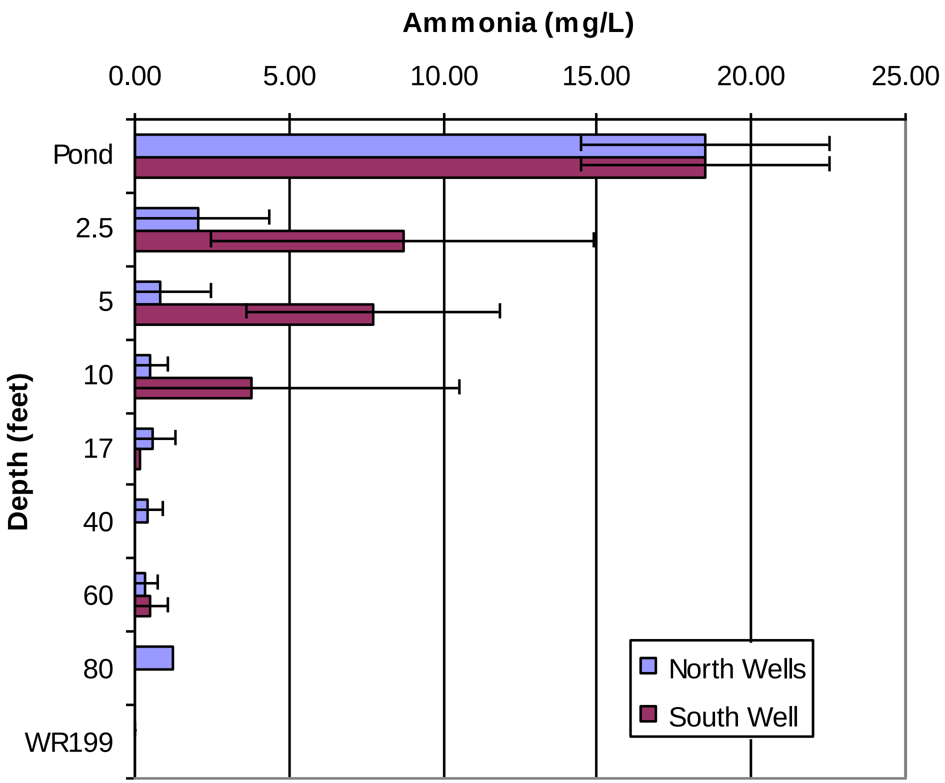




Biomass (Phospholipid) Profile
⇨ DOC Removal Profile
⇨ Sustainable Biodegradation

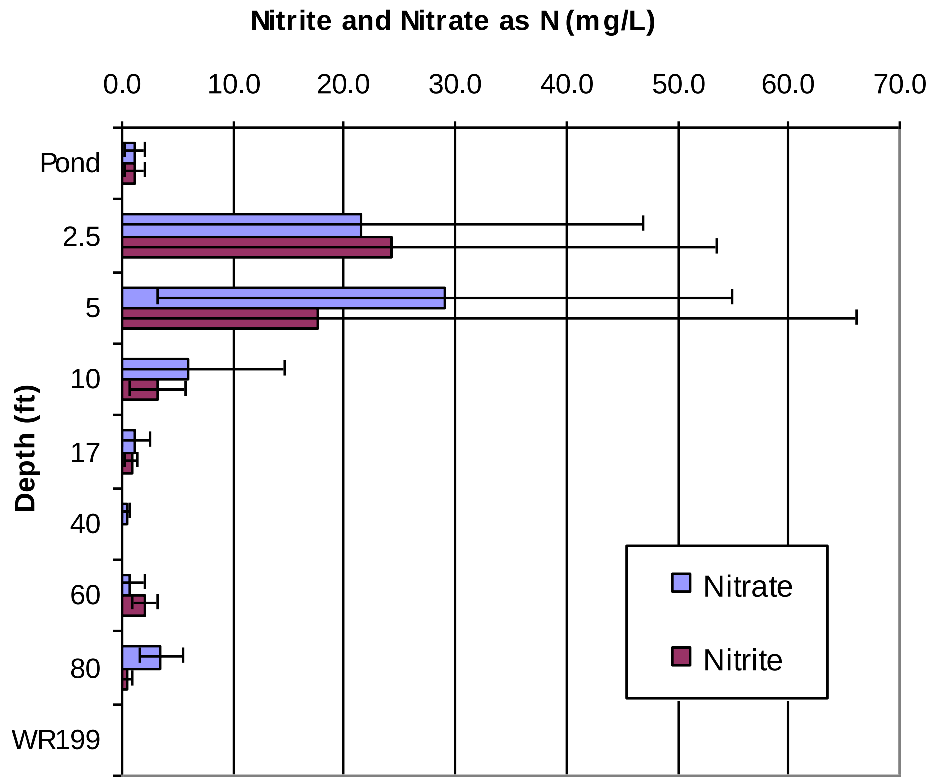
Nitrogen Removals at ARR Site (II-Effluent, Arizona USA)

Ammonia



⇧
Evidence of Nitrification & Denitrification ⇨

Nitrate and Nitrite



OMP Elimination by ARR Under Varying Redox Conditions (adapted from Jekel)

Compound	Anoxic		Oxic (aerobic)	
	Removal	Percentage	Removal	Percentage
FAA	high	>60 %	high	>60 %
AAA	high	>60 %	high	>60 %
Phenazone	moderate	30 – 60 %	high	>60 %
Carbamazapine	high	>60 %	moderate	30 – 60 %
Propyphenazone	moderate	30 – 60 %	moderate	30 – 60 %
DP	low	< 30 %	low	< 30 %
EDTA	low	< 30 %	low	< 30 %
AOX	low	< 30 %	moderate	30 – 60 %
AOI	moderate	30 – 60 %	low	< 30 %
AOBr	high	>60 %	low	< 30 %
Diclofenac	high	>60 %	n/a	n/a
Clofibric Acid	low	< 30 %	n/a	n/a
TCIPP	high	>60 %	n/a	n/a
TCEP	high	>60 %	n/a	n/a

OMP Elimination by ARR Under Varying Redox Conditions (adapted from Jekel)

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TCIPP	high	>60 %	n/a	n/a
TCEP	high	>60 %	n/a	n/a

Removals of Micropollutants and Electron Acceptors under Varying Redox Conditions (Stuyfzand, 2011)

Redox	Removal (%)										
	0		20		40		60		80		100
Oxic	NO_3^-										NH_4^+
				Chloroform				Benzene, Mecoprop			
	Atrazine, Diurone										
	Sulfamethoxazole										

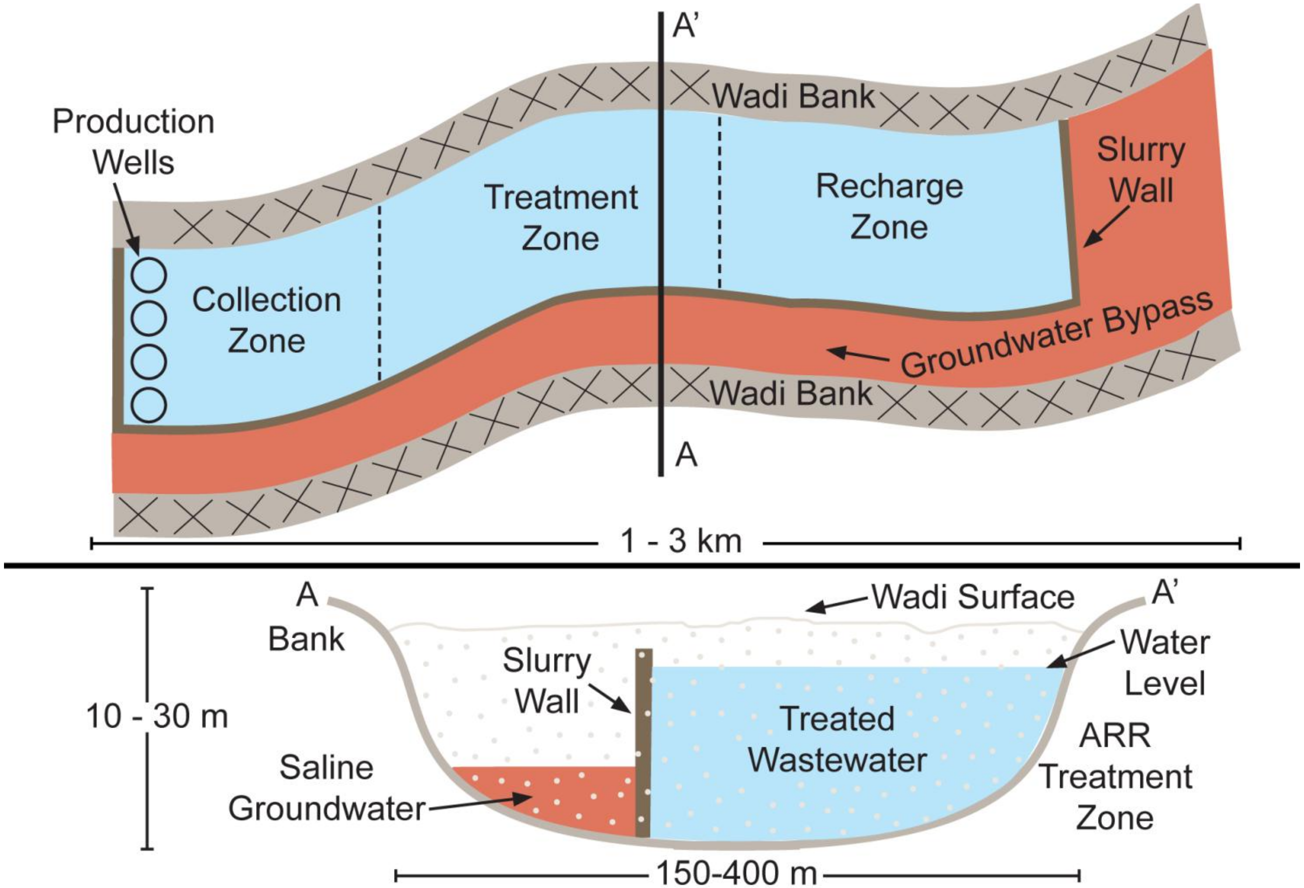
Other Recharge Options (besides infiltration/recharge basin)

- Injection Well
  - If confining layer (no vadose zone attributes)
  - Possibly, a vadose zone (gravel pack) well
- Sink Hole (Italy)
- Dune Infiltration (Belgium)
- (Intermittent) River Bed Infiltration (Spain)
  - *Wadis* in KSA and GCC Region ✓

(Potential) Wadi Aquifer System ARR

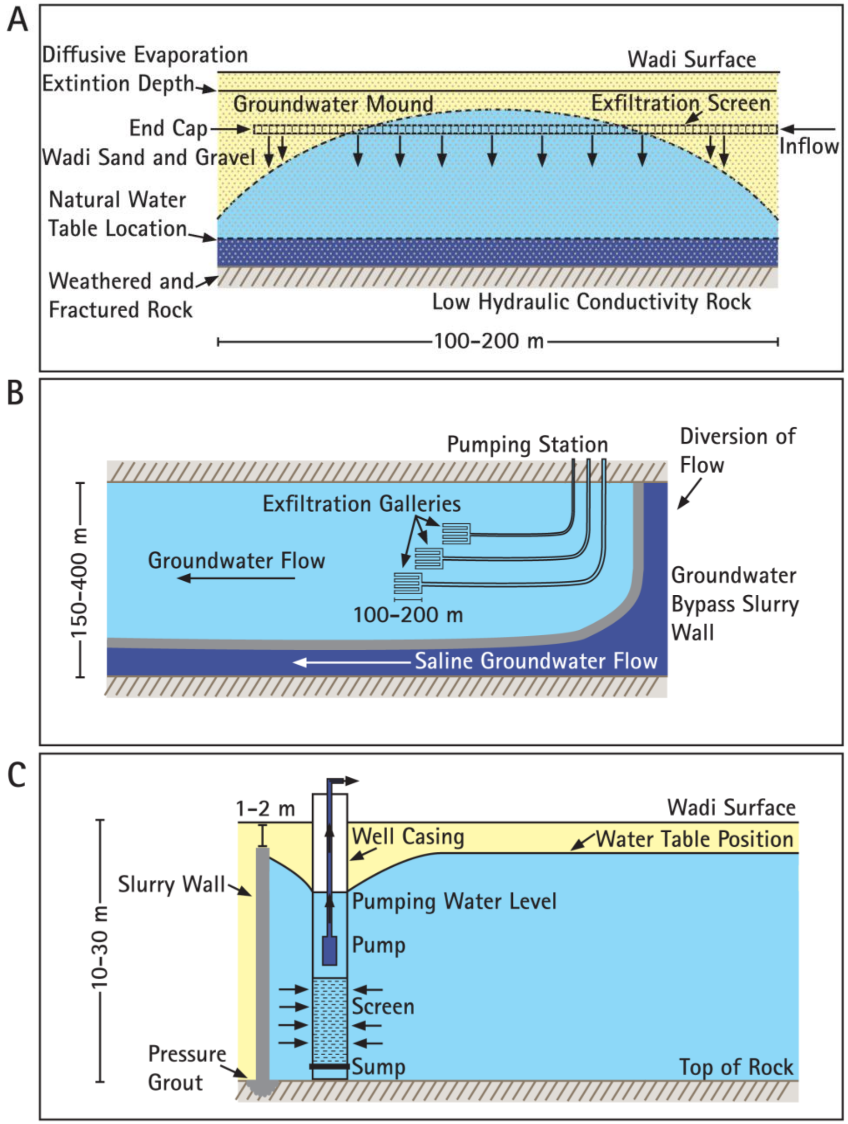
From Missimer et al., 2012. Restoration of Wadi Aquifers by Artificial Recharge with Treated Wastewater: Ground Water (in press)

Engineered Wadi Aquifer ARR



From Missimer et al., 2012. Restoration of Wadi Aquifers by Artificial Recharge with Treated Wastewater: Ground Water (in press)

Engineered Wadi Aquifer ARR - cont



Engineering issues
- distance from source to site
- evaporation rate vs. surface infiltration
- aquifer heterogeneity

From Missimer et al., 2012. Restoration of Wadi Aquifers by Artificial Recharge with Treated Wastewater: Ground Water (in press)

Role of ARR in
Urban Storm Water Runoff Exploitation

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- Non-Point (Diffuse) Source
  - Impacts of Vehicle Traffic, Urban Irrigation, Land Use
  - Surface Sources: Streets, Parking Lots, Roofs
- Contaminants
  - Trace Metals, Nutrients (P & N),
    Oil and Trace Organics, Pesticides, Road Salts
  - Improved Quality After *First Flush*
- Exploitation as Impaired Quality Source
  - Aquifer Recharge and Recovery ⇨ Infiltration Basins
  - Permeable Treatment Beds/Basin Amendment Layer
  - Pervious Pavements vs. Infiltration Basin
  - ARR as a Form of Storm Water Harvesting
  - *Potential* Constraint: Combined Sewers ⇨ CSOs

ARR *Hybrids* for Wastewater Reclamation/Reuse

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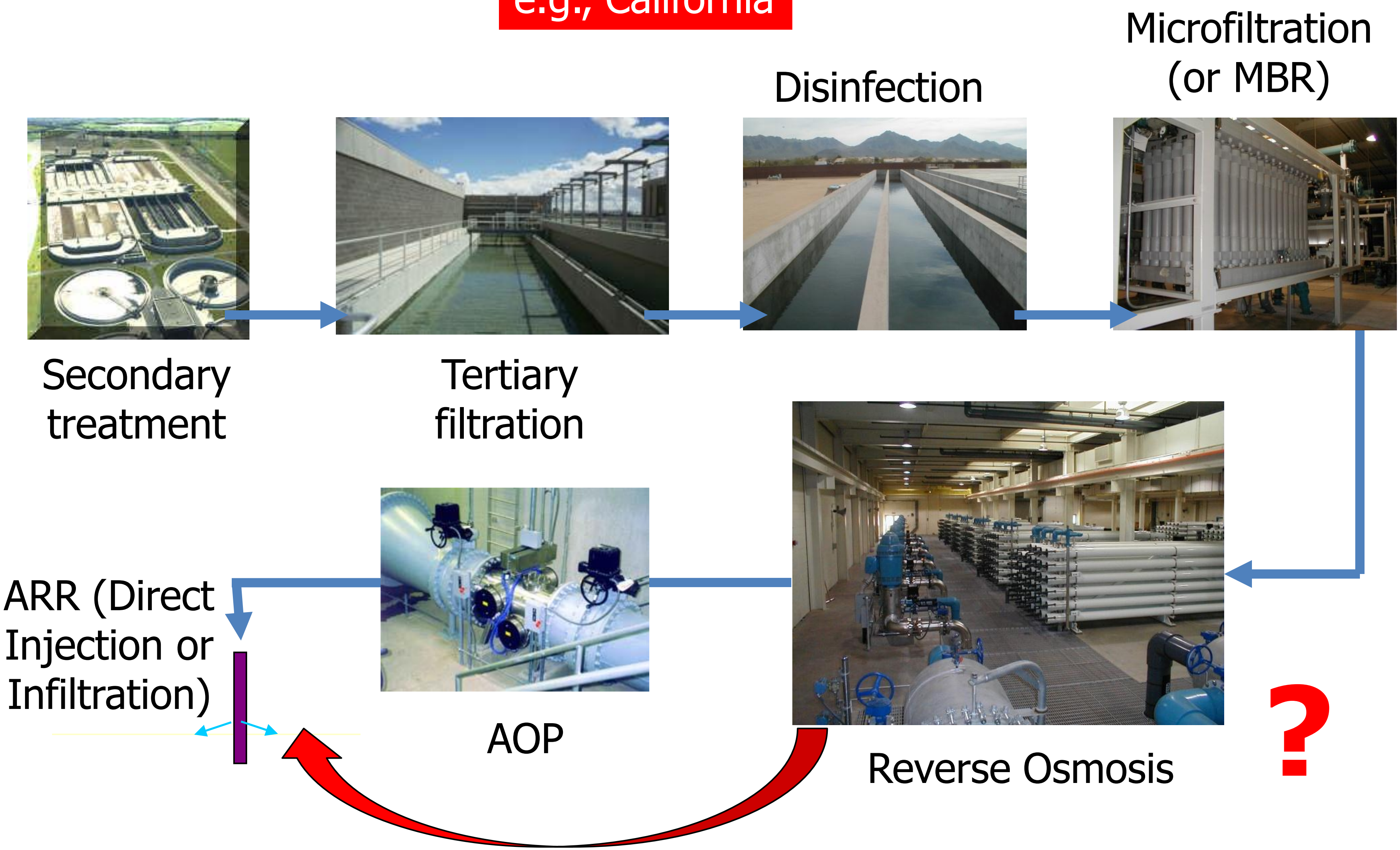
- ARR → Nanofiltration (NF)
  - Double Barrier for OMPs (NF)
  - OMP Biodegradation plus Membrane Rejection (NF)
  - Membrane Fouling Reduction by ARR (Synergistic)
  - Also, Effective DOC Removal (NF)
- Oxidation (Disinfection) → ARR
  - Double Barrier for OMPs (and Microbes)
  - OMP Oxidation plus Biodegradation
  - ARR Biodegradation of Oxidation By-Products (Metabolites)
- ARR → Granular Activated Carbon (GAC)
  - Double Barrier for OMPs
  - ARR Reduction of NOM Loading onto GAC

ARR – NF Membrane Hybrid

The Water Industry Standard for to Indirect Potable Reuse

e.g., California



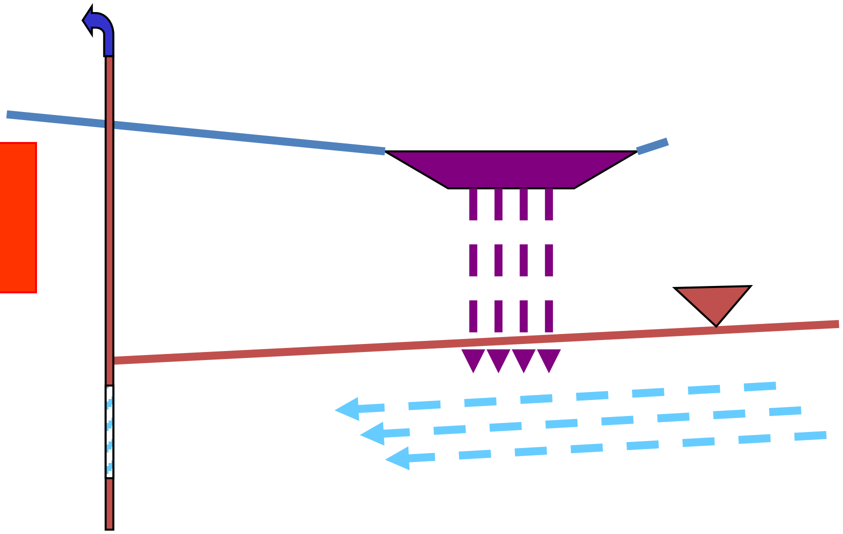
Hybrid Process:
NF Post-Treatment for Persistent OMP Removal

Secondary treatment

ARR

Nanofiltration (refractory OMPs)

Fouling Reduction By ARR



Removal of Organic Micropollutants : ARR (Biodegradation) and/or Membrane Rejection

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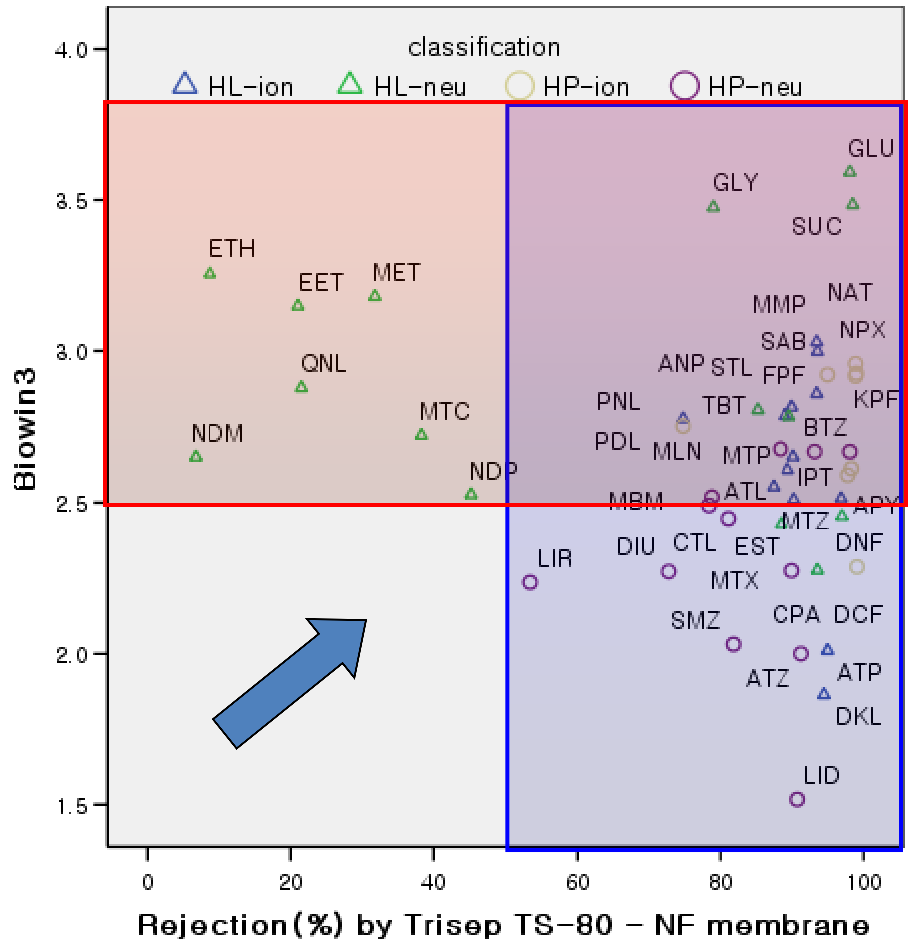
ARR (relative biodegradability)

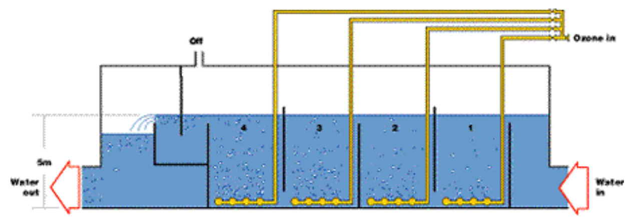


NF Membrane Rejection →

Oxidation – ARR Hybrid

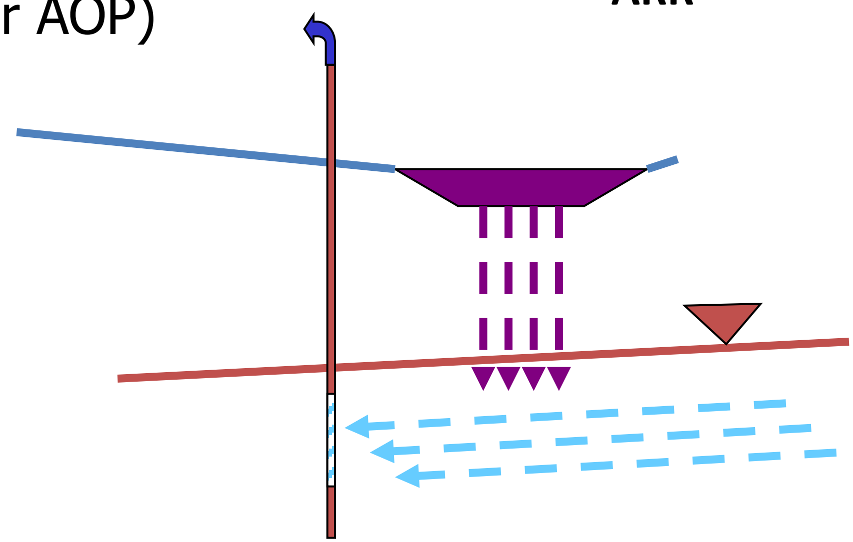
Hybrid Process: Oxidation Pre-Treatment for Enhanced Biodegradation of OMPs

Secondary treatment



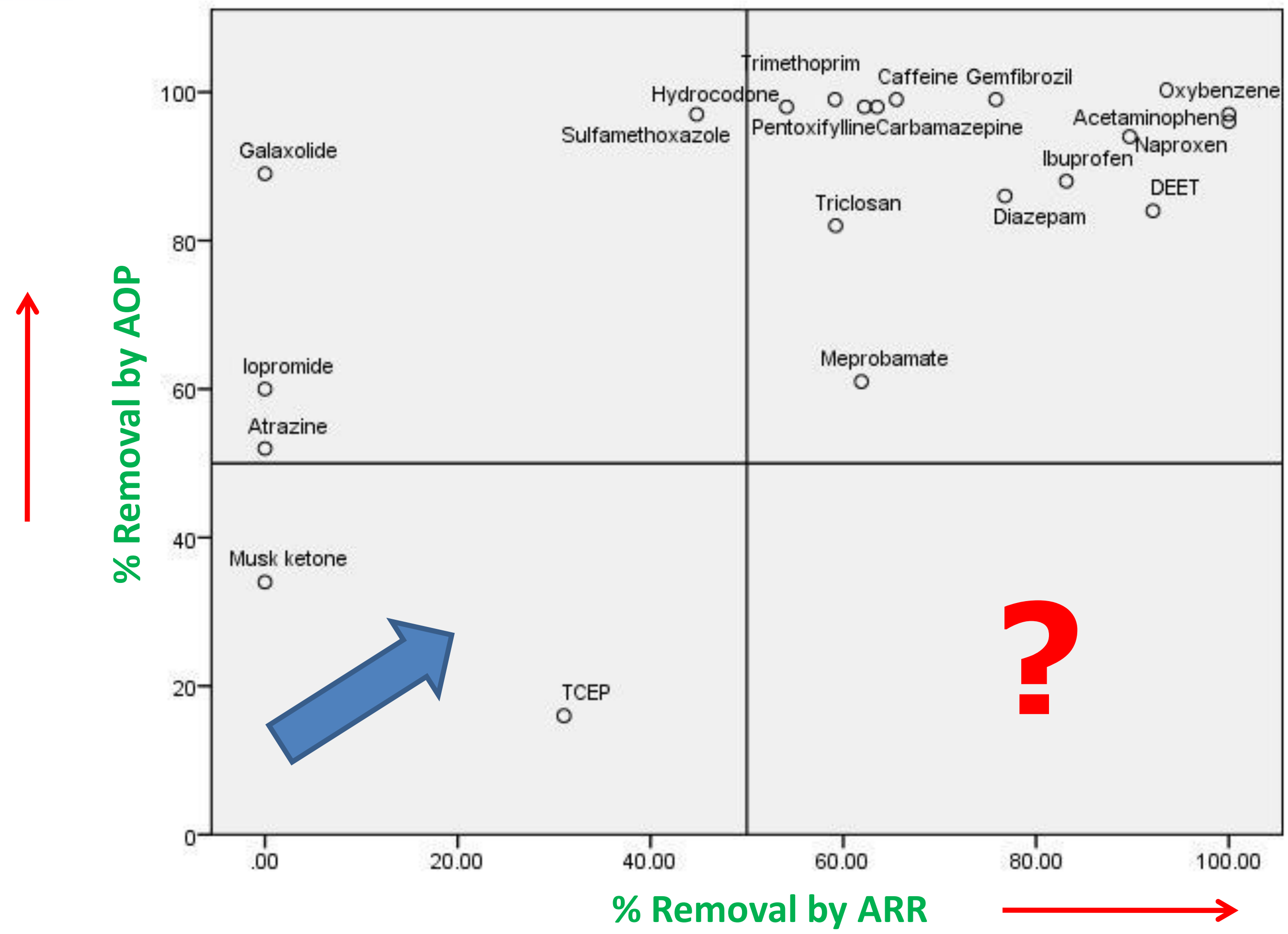
Ozonation (or AOP)

ARR



O_3 or OH• Oxidation of OMPs
+
ARR Biodegradation of Metabolites

Removal of Organic Micropollutants: ARR (Biodegradation) and/or (Advanced) Oxidation



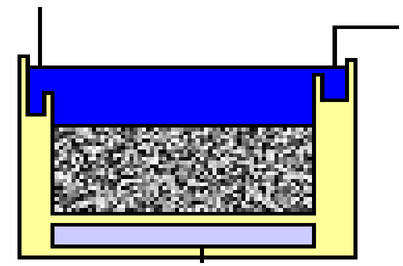
Why not AOP alone? ⇨ Metabolites (by-products)

ARR – GAC Hybrid

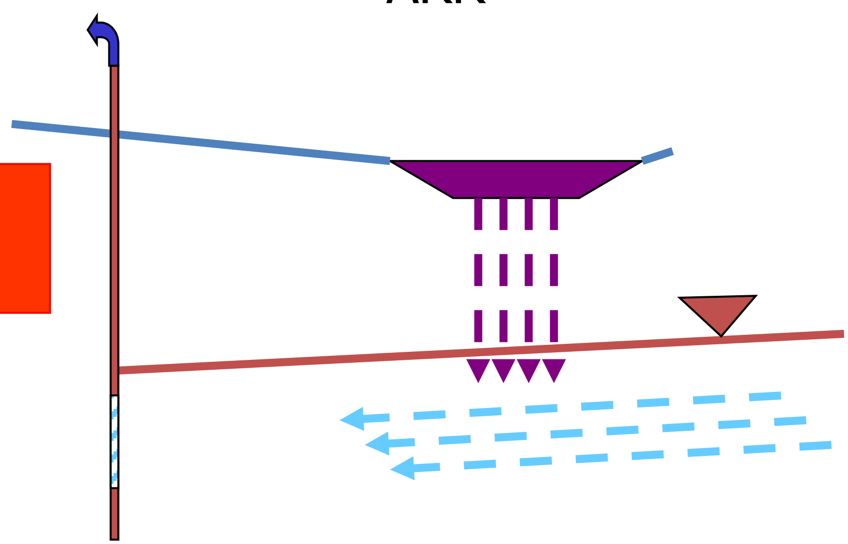
Hybrid Process:
Post-Treatment for Persistent OMP Removal

Secondary treatment

ARR

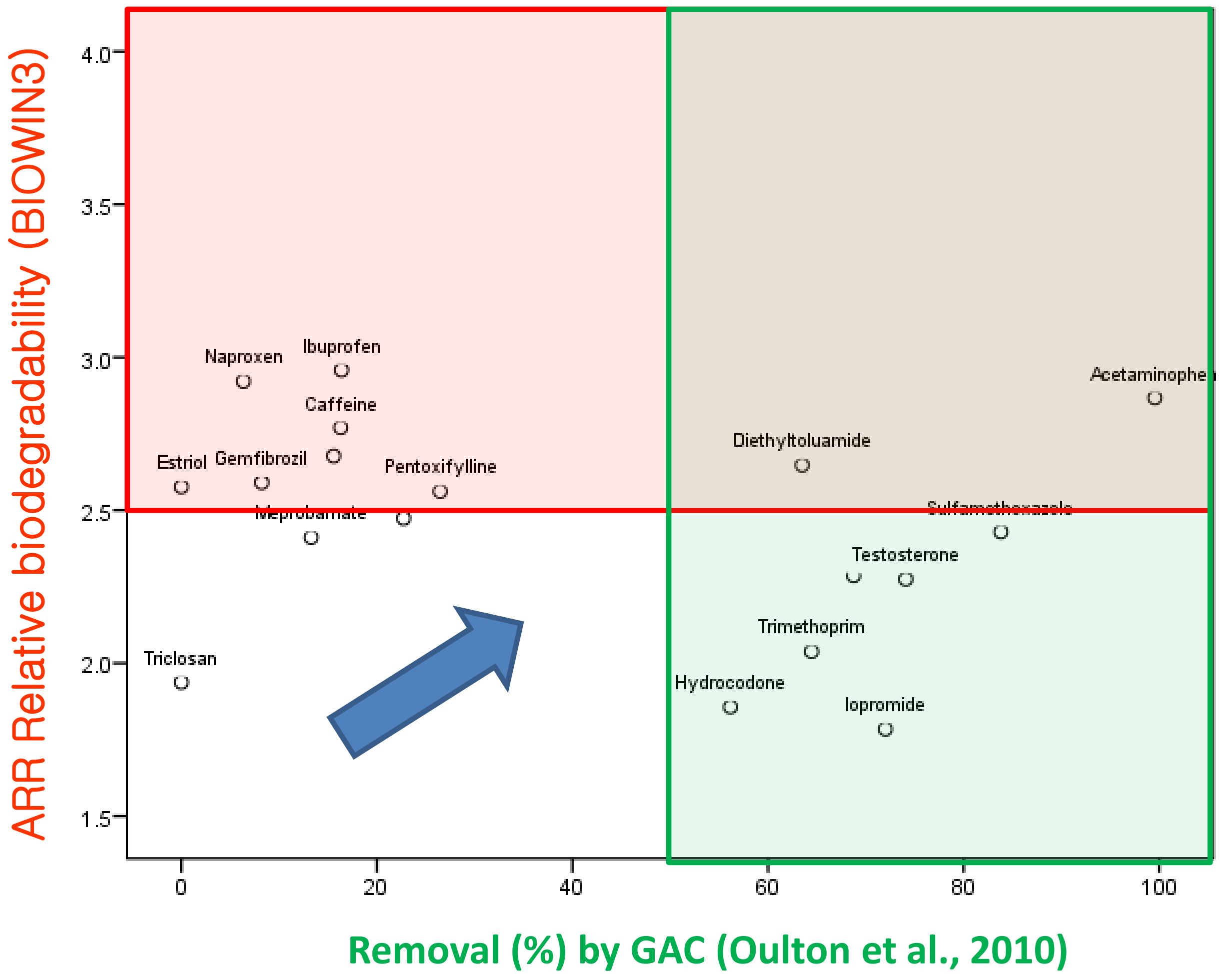


GAC
(refractory OMPs)



DOC Loading Reduction By ARR

Innovative System for Removal of Micropollutants – RBF and GAC



What About Microbial Removals?

Efficacy of ARR vs. Other Processes

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Microbe	ARR	MF Membrane	UF Membrane	Ozonation
Total Coliforms	100 % (nd)	4.8 – 5.9 log	100 % (nd)	2.3 – 4.1 log
	24 m	0.2 um	100 kD	0.3 – 6.3 mg/L-min
	Weiss, 2005	Farahbakhsh, 2004	Bourgeous, 2001	Owens, 2000
Giardia Cysts	>1.9 log	4.6 – 5.2 log	4.7 – 5.2 log	1.5 – 2.7 log
	24 m	0.1 – 0.2 um	100 – 500 kD	0.3 – 1.0 mg/L-min
	Weiss, 2005	Jacangelo, 1997	Jacangelo, 1997	Owens, 2000
Crypto Occysts	>1.5 log	> 7 log	> 7 log	0.6 – 2.7 log
	24 m	0.25 um	13 kD	2.6 – 7.2 mg/L-min
	Weiss, 2005	Hirata, 1998	Hirata, 1998	Owens, 2000
MS2 Phage	8 log	0.2 – 1 log	1.7 - > 7 log	3 log
	30 m	0.1 – 0.2 um	100 – 500 kD	0.03 mg/L-min
	Medema, 2002	Jacangelo, 1997	Jacangelp, 1997	Oh, 2007

ARR: Equivalent to Other Processes if Adequate Time/Distance

Log Removals of Microorganisms during Bank Filtration (≈ ARR) Field Sites (Tufenkji et al., 2002)

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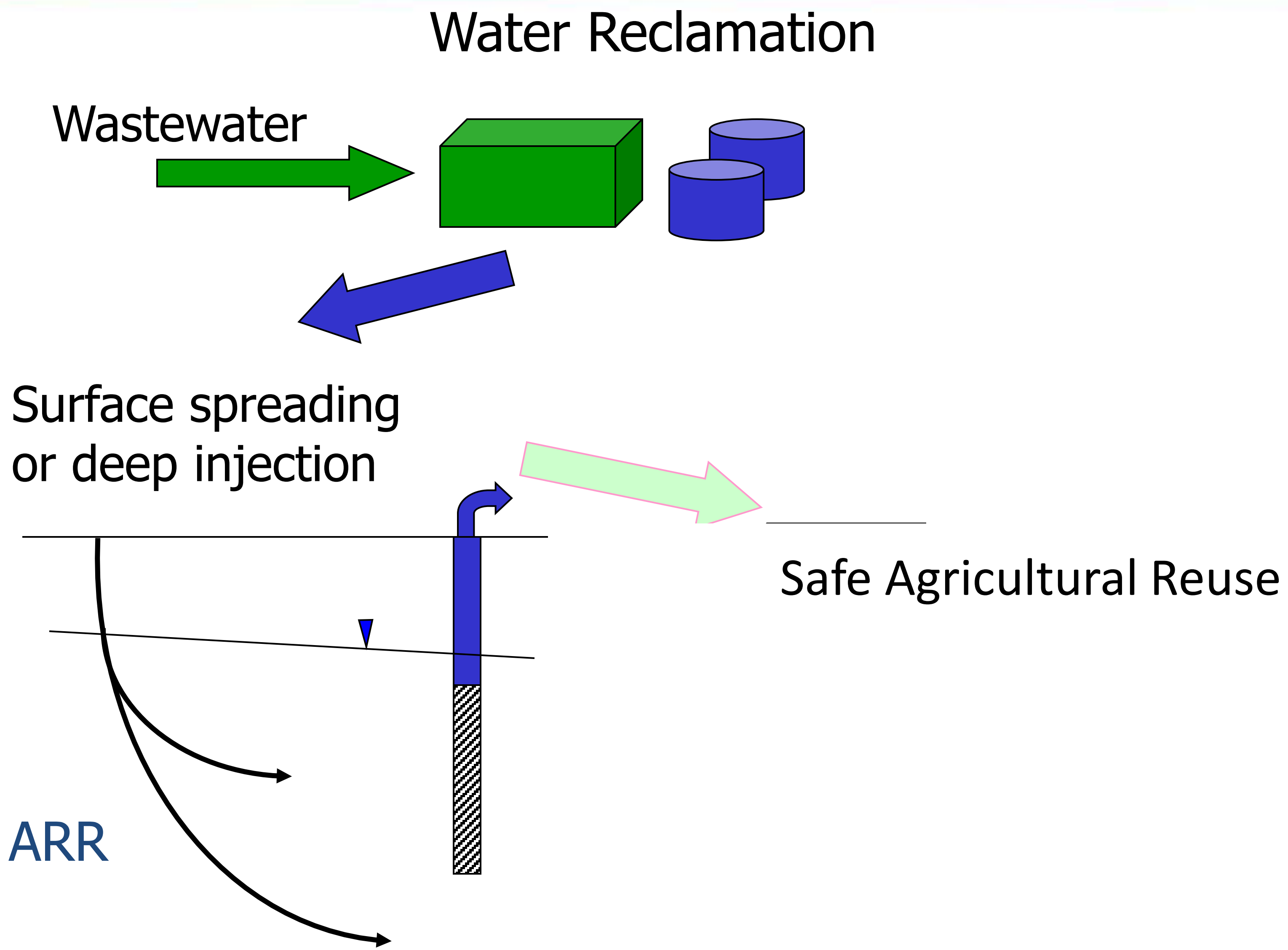
Parameter	Rhine River at Remmerden	Meuse River at Zwijndrecht	Meuse River at Roosteren		
Travel Distance (m)	30	25	13	25	150
Travel Time (days)	15	63	7	18	43
Total Coliforms	5.0	5.0	-	-	-
Fecal Streptococci	3.2	3.5	-	-	-
Enteric Viruses	4.0	4.0	3.7	-	-
Bacteriophages (Type 1)	6.2	5.7	3.9	6.0	-
Bacteriophages (Type 2)	-	-	3.8	5.1	7.8

ARR in Indirect (Potable) Reuse (effective microbial and OMP removals)



Cost, Energy, GHGs, and Constraints

Cost of ARR Systems

Comparison of total annual costs for ARR and other secondary treatment technologies (Source: Nema *et al*., 2001)

Treatment system	**Indicative cost ratio (Based on total annual costs)**
Soil Aquifer Treatment (I Effl)	1.00
Activated Sludge	1.65
Trickling Filter	1.70
Anaerobic Filter	1.35
Upflow Anaerobic Sludge Blanket (UASB)	1.17

But what about *transmission* costs?

Adaptation to Climate Change: Specific Energy Consumption and GHG Emissions

- Energy (kWh/m^3)
  - 0.10 kWh/m^3 for Stormwater ASR (Dillon, 2010)
  - Mainly pumping costs
    (recovery; gravity feed to infiltration?)
  - But what about *transmission* costs?
- GHGs (kg CO_2-eq/m^3)
  - Lower Energy Implies Lower GHG Emissions
  - No Definitive Study as of yet

ARR Constraints

- Persistence of a Few OMPs
  (Berlin Study: only 5 or 6 of 50 monitored OMPs) ⇨ *Risk?*
- Low Permeability Soils (<10^{-4} m/s) ⇨ *Vadose Zone Wells?*
- Possible Preferential Flow Patterns
  ⇨ Need for Subsurface (Geophysical) Characterization
- Fe/Mn Dissolution (anoxic conditions) ⇨ *Fe/Mn Removal*
- Arsenic or Fluoride Dissolution
- Calcite Dissolution/Soil Collapse (permeability ↓)
- Non-Sustainable Removals of Trace Metals (urban runoff)
- (More) Difficult to Control Operating Conditions
- Lack of Framework/Models for Technology Transfer ✓

Thank you...