Sustainable Removal Mechanisms and Monitoring Requirements for Soil Aquifer Treatment Systems

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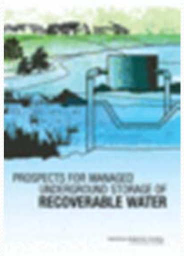
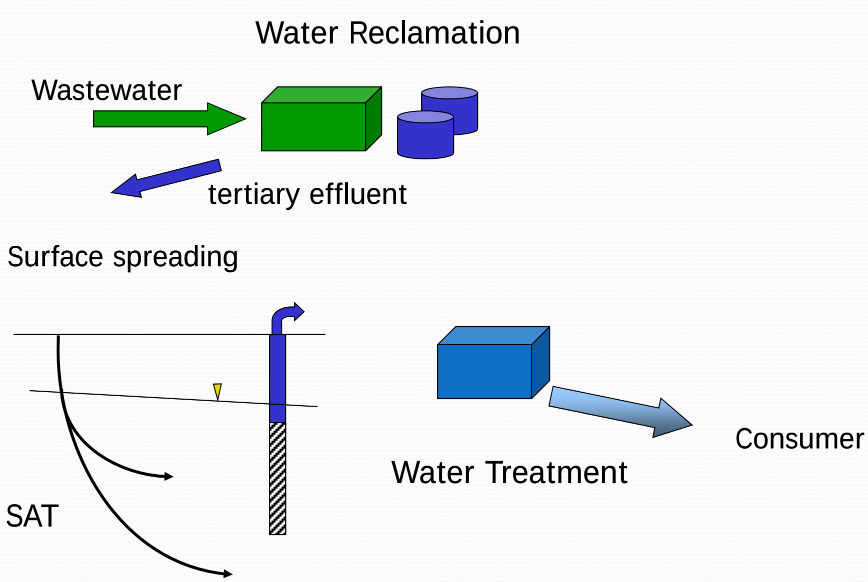
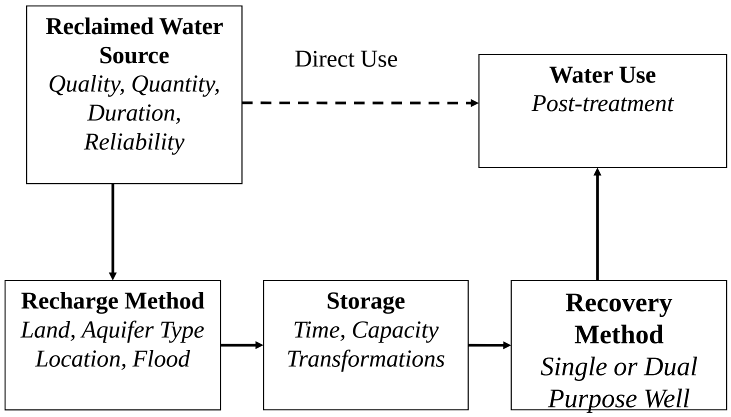


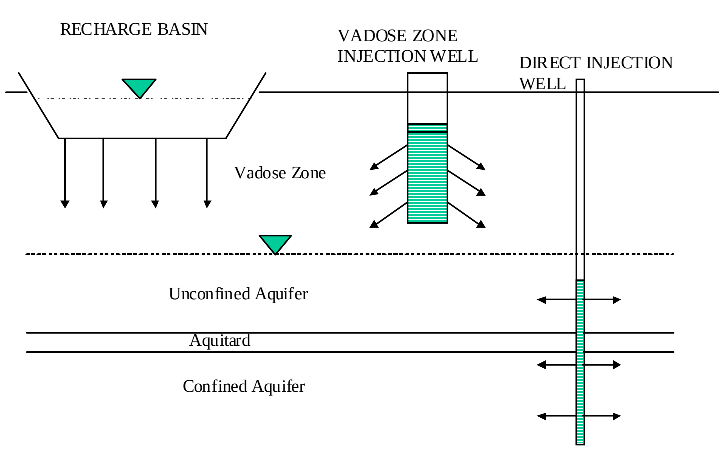
Indirect potable reuse



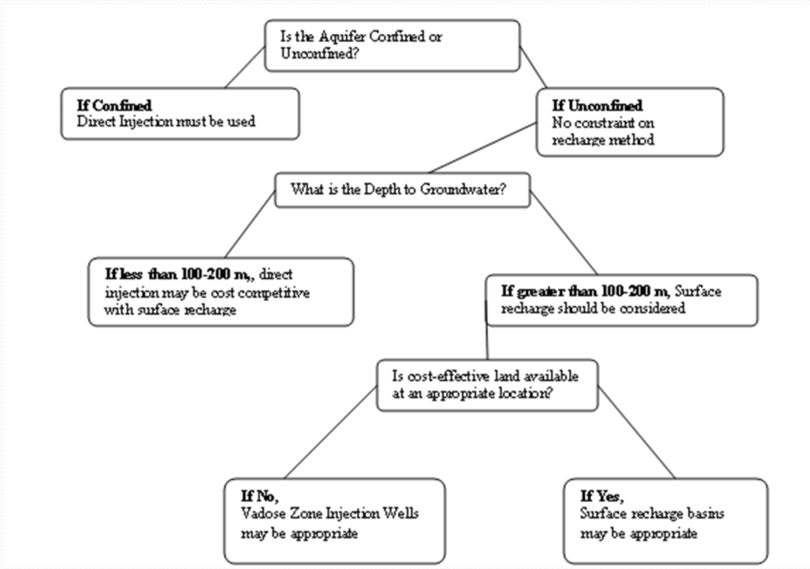
Major Components and Criteria



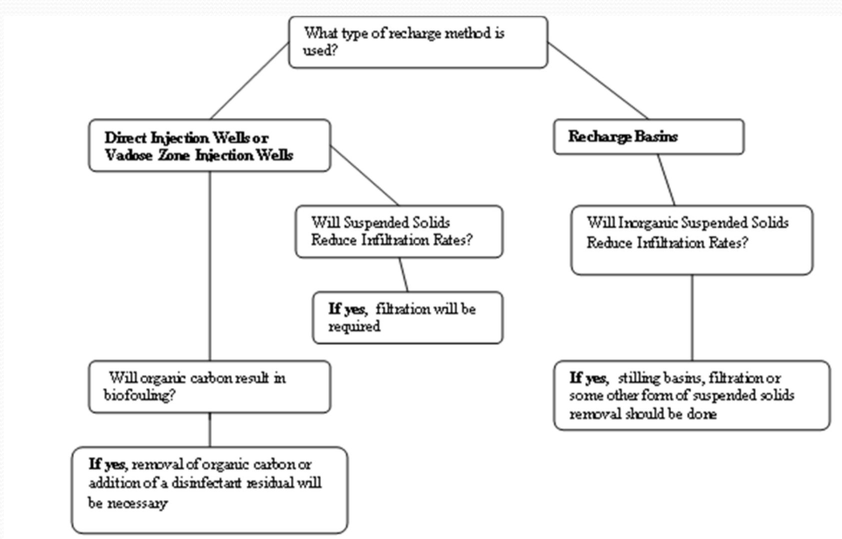
Methods for Aquifer Recharge



Types of Groundwater Recharge Systems

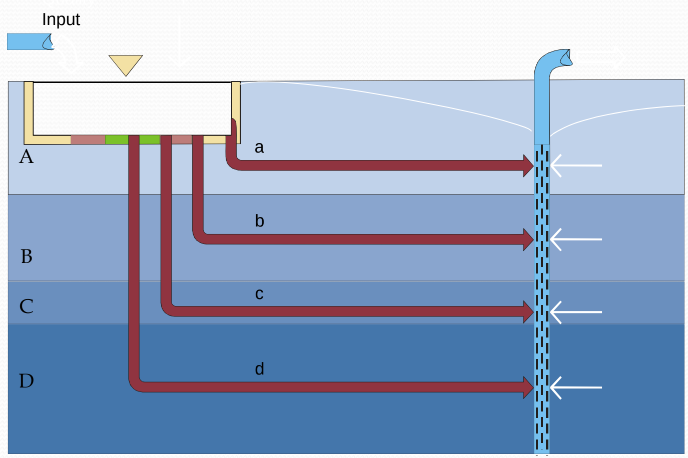


Decision Tree for Pre-Treatment



Recharge Basins

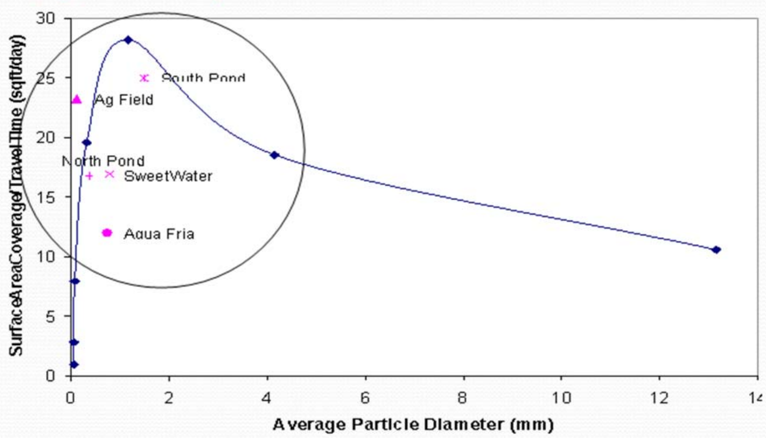
A Large Biological Filter? Sustainable



Why Do So Many Systems Work?

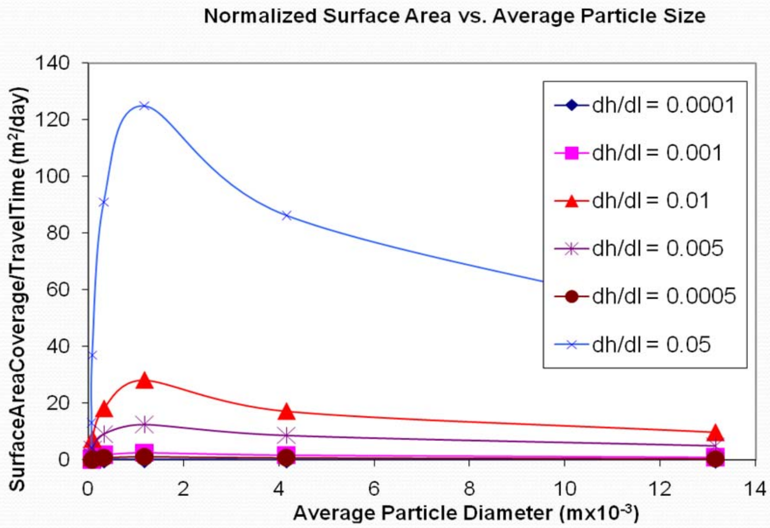
- Flow in alluvial deposits is predictable and provides consistent surface area
- Sustainable transformations are related to surface area
- Travel Time often used as regulatory criteria - correlates with surface area

Surface Area correlates with travel time in sand/gravel aquifers



Makam and Fox, 2009

Effect of Hydraulic Gradient



Makam and Fox, 2009

Travel Time

- Well defined for alluvial aquifers with separate recharge and recovery points
- Can be unpredictable for other aquifers (fractured flow, etc)
- Highly variable for dual purpose wells-last water injected is first water recovered

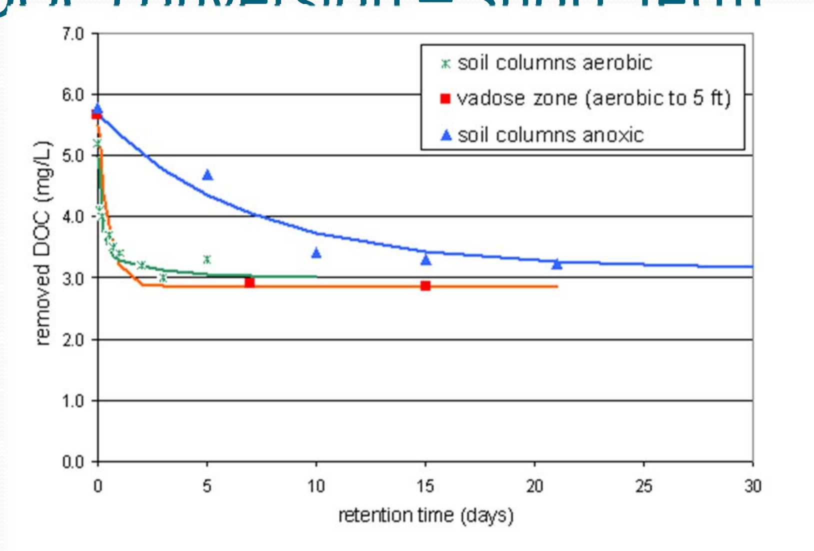
Why do viruses drive travel time criteria?

- Survival – possibly six months at low temperature
- Bacteria and parasites are removed by filtration along with other mechanisms
- Netherlands and Germany, 50 to 70 days no disinfection required
- California – 6 months+

What is Reclaimed Water Organic Carbon?

- Natural Organic Matter (mgC/L)
- Soluble Microbial Products (mgC/L)
- Easily Biodegradable Compounds (mgC/L)
- Anthropogenic Compounds (ugC/L and ngC/L)
- NOM and SMPs are persistent along with select anthropogenic compounds

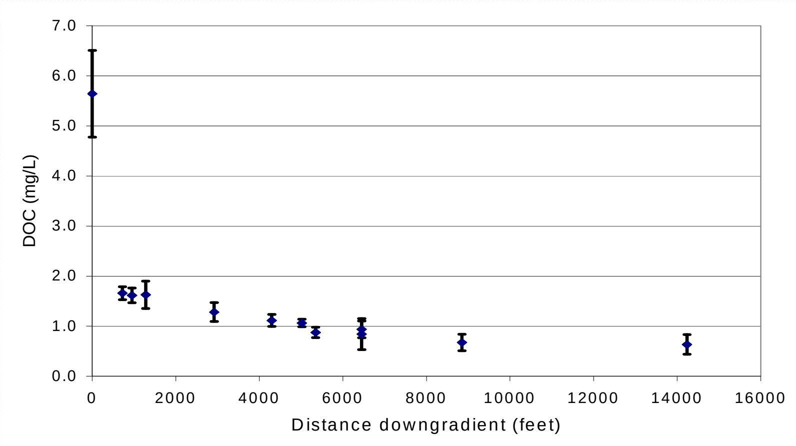
DOC conversion – Short Term



Vadose Zone vs Saturated Zone

- Vadose Zone
  - Variable Flow Path/Travel Time
  - Aerobic/Anoxic Cycle
- Saturated Zone
  - Consistent Flow Path/Travel Time
  - Anoxic if Oxygen Depleted in Vadose Zone

DOC Conversion – Long Term (5 Years)

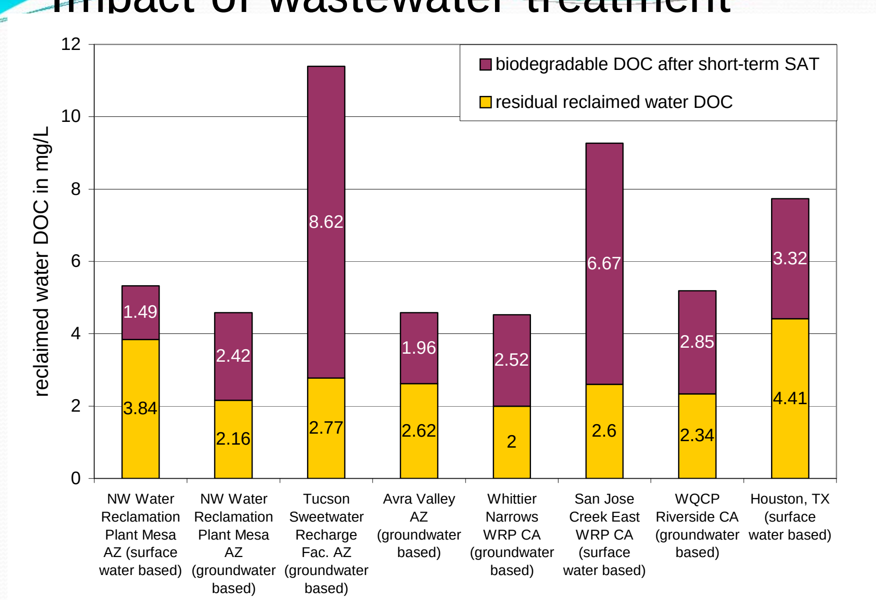


Investigated types of wastewater treatment

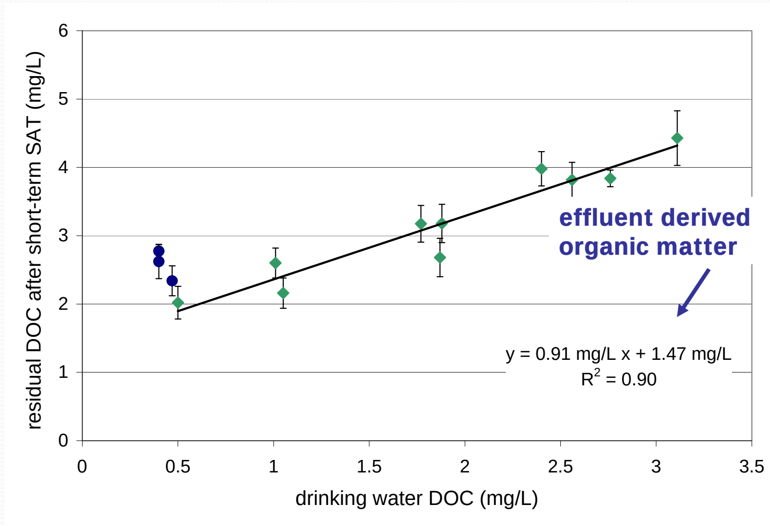
- Activated sludge including nitrification/denitrification
- Activated sludge with partly nitrification
- Trickling filter, no nitrification
- Oxidation ditch including nitrification/denitrification

Investigated field sites

Impact of wastewater treatment



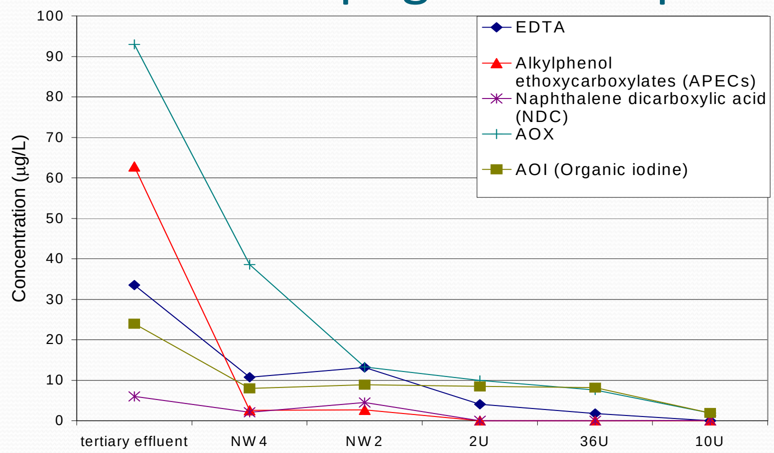
Correlation between drinking water DOC and residual reclaimed water DOC
(Residual DOC = NOM + EfOM)



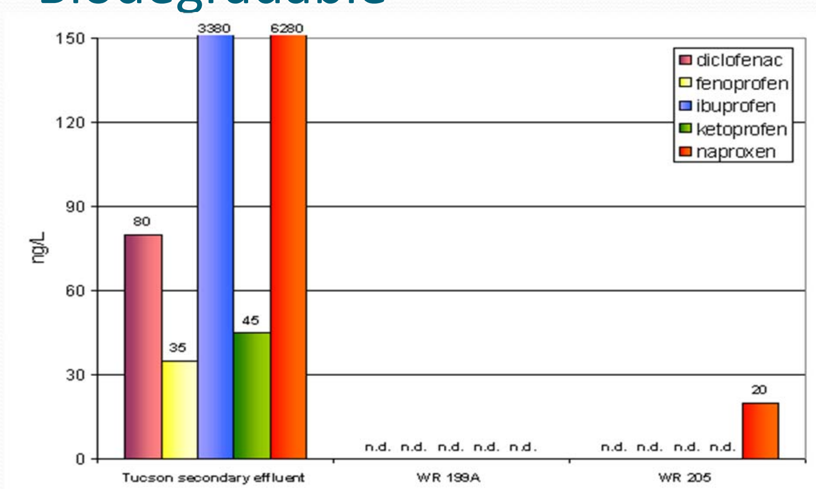
One Exception – Alice Springs, Australia

- Soil Aquifer Treatment was not Effective
- Pre-treatment with lagoons with months of retention time
- Organic Carbon was Algal-derived and had very little biodegradable organic carbon

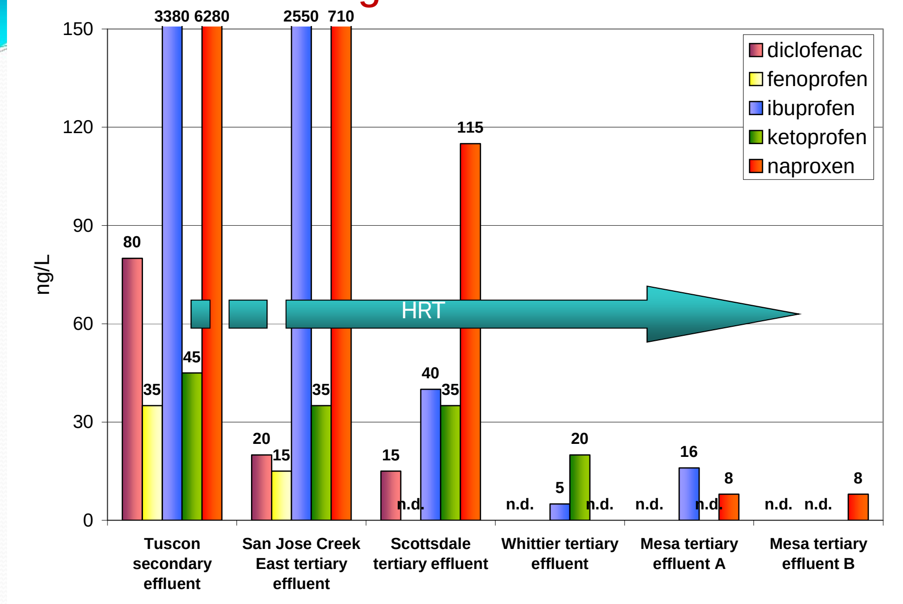
Fate of Anthropogenic Compounds



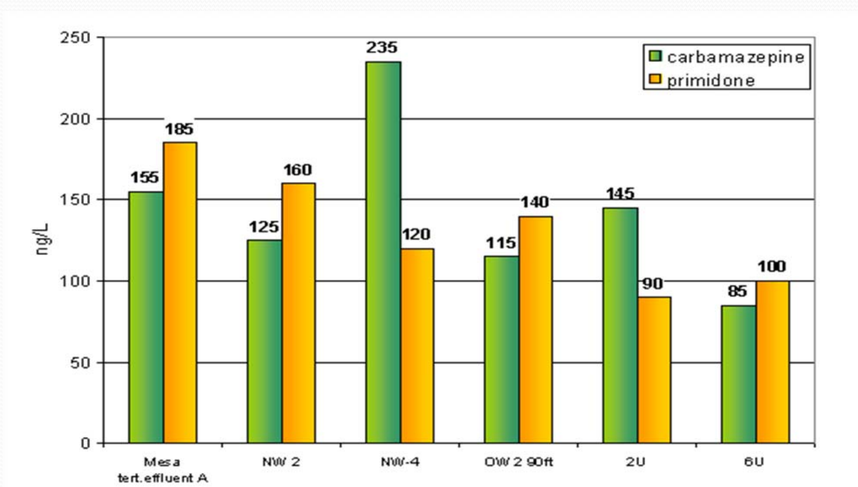
Many Pharmaceuticals are Biodegradable



Occurrence of analgesics in wastewater effluents



Some Pharmaceuticals are Persistent



A Co-Metabolic Story

- Nanogram/L concentrations cannot support growth
- Co-metabolism is the transformation of a compound by an enzyme with no benefit to the microbe
- Appears to be major mechanism of removal during SAT for trace organics

Why co-metabolism during SAT but not at WWTP?

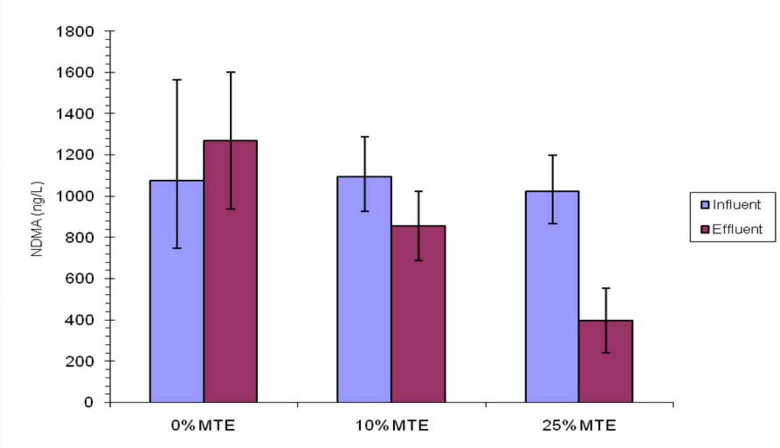
- Abundant Food

WWTP

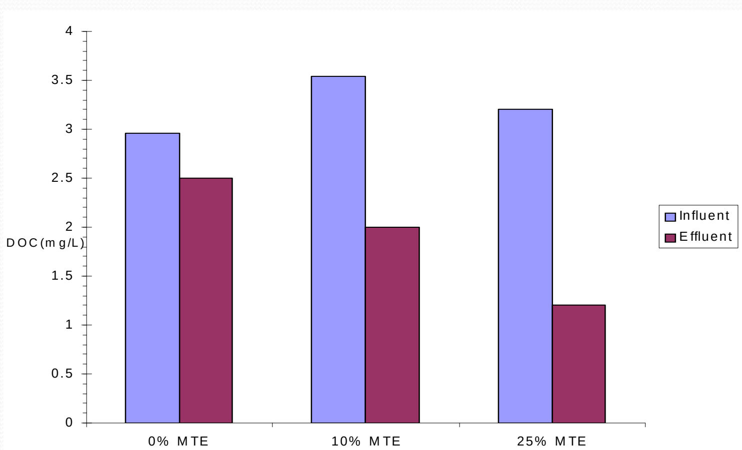
Living on the Scraps

SAT

Implications for SAT
No BDOC = No Co-metabolism



DOC removed by CAP Column



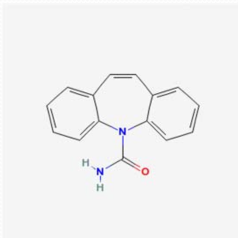
Reverse Osmosis(RO) vs SAT without RO

- RO eliminates BDOC and limits soil as a treatment barrier – thus NDMA and 1,4 Dioxane persist
- RO plus AOP is solution
- Compounds are concentrated in reject – ½ life in oceans?
- SAT with no RO – a list of compounds are persistent – depends on Redox conditions

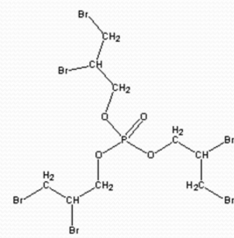
Scottsdale Water Campus

- RO treatment and injection with Vadose Zone Wells
- NDMA detected in Groundwater
- Plans on by-passing the RO with 20% of flow – hope to stimulate NDMA removal in subsurface

SAT persistent compounds water soluble and tend to resist oxidation – Do we need an alternative to advanced oxidation?

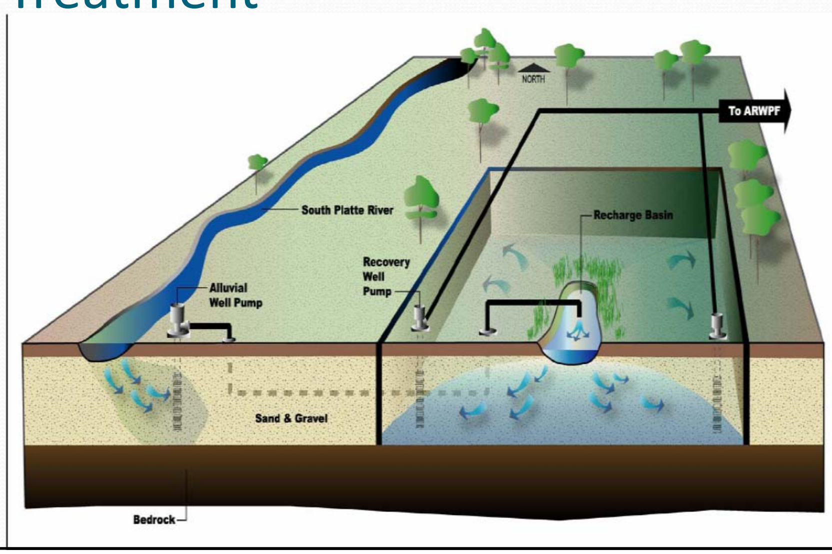


Carbamezapine

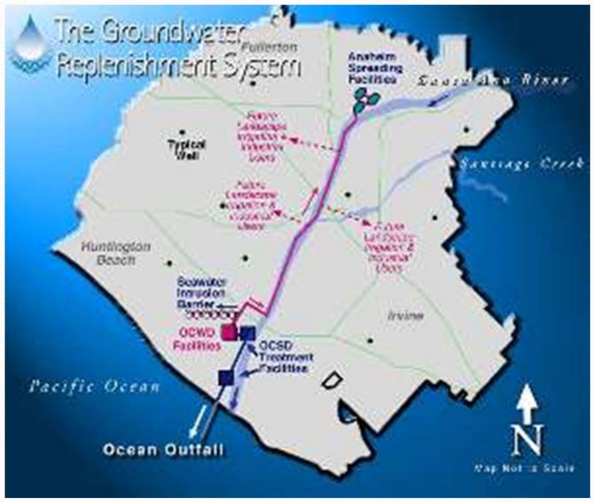


Tris (2,3-Dibromopropyl) Phosphate

Praire Waters – SAT with post Treatment



Orange County, CA – RO followed by SAT



Indirect Potable Reuse – What is Sustainable?

Orange County (Ocean Discharge RO reject)

MF=>RO=>AOP=>SAT=>Potable

Prairie Waters - Aurora Colorado (Inland)

=>Bank Filtration=>SAT=>AOP=>GAC=>Potable

Operation – Wet/Dry Cycle

- Operate Wet Until Clogging Layer Limits Infiltration
- Stop Adding Water and Allow to Drain
- Allow clogging layer (Suspended Solids and Algae/Bacteria to Dessicate) – potato chips

Continuous Wetting

- Must have continuous clogging layer removal
- Orange County Submarine
- Can have unforeseen consequences – what happens to aquatic life when it is drained

Recharge Basins-Maintenance

- Clogging Layer will eventually require removal – unless Conductivity of Soil is Lower than Clogging Layer
- Best to remove Top Layer
- Ripping puts clogging materials in deeper - temporary solution that requires future removal of more material

Keep it Light-Avoid Compaction

Recharge Basins- Water Quality Specifics

- Organic Carbon – Lowers Redox – Primary Effluent will increase clogging
- Trace Organics – Majority Removed but some persist
- Nitrogen – Ammonia Removal with wet/dry cycles – nitrified effluent not good
- Suspended Solids – Clogging
- Pathogens – Public Health/Exposure

Dual Function Basins – A deep channel shelters aquatic life during drying

Wet/Dry Cycles Redox

- Wetting – oxygen is consumed by organics
- Drying – oxygen enters soil as wetted front moves to groundwater
- Adsorbed Ammonia consumes oxygen during drying and nitrate is produced
- Wet/Dry Cycle times = varying redox conditions

Water Quality Relationships

- Organic Matter – Almost Independent of Pre-treatment – Easily Biodegradable Removed
- Redox – The Aquifer Becomes Anoxic – no way to reaerate
- Nitrogen – removal requires varying redox conditions

Pre-treatment -Hydraulic Capacity

- Suspended Solids are Major Factor
- Cannot remove nitrogen low enough to prevent algae – solar radiation is abundant and water is continuously added
- Phosphorous accumulates in calcerous soils – removed from water but abundant
- Algae can cause pH fluctuations resulting in $CaCO_3$ precipitation – very bad

Tucson, AZ – Is it Green – STOP!

Deeper is Not Better

- The Equations say increase depth and infiltration rate increases but----
- Depth compresses the clogging layer making conductivity decrease
- Furthermore, depth increases intragranular pressure
- Compression = intragranular pressure*thickness/eslasticity
- A deep clogged basins can take months to drain – not desirable

Deeper is not Better

- Decrease of Hw from 1m ot 0.2m increased infiltration rates from 20m/yr to 100m/yr
- Basins must be graded with a slope so difficult to get depths less than 0.2m

Nitrogen Removal Common Explanation

- **Autotrophic nitrification and heterotrophic denitrification**
- **Requiring cBOD:N ratio of 3:1**
- **Most SAT systems cBOD:N ratios of 1:1**
  - **Result in 30% nitrogen removal efficiencies**
- **Field SAT observations have been higher**

Different Effluents = Different Oxygen Demands

- Secondary Effluent –cBOD<20 mg/L Nitrogenous BOD >80 mg/L
- Nitrified Effluent – cBOD < 20 mg/L, Nitrogenous BOD < 5 mg/L
- Nitrified/Denitrified Effluent cBOD<10 mg/L, Nitrogenous BOD 2-3 mg/L

Different Effluents = Potentials for Sustaining Nitrogen Removal

- Secondary Effluent – Sustain by Anaerobic Ammonia Oxidation
- Nitrified Effluent – no electron donor and negligible removal
- Nitrified/Denitrifed Effluent – removal is possible but no relevant

Summary of Nitrogen Removal at Applicable SAT Sites

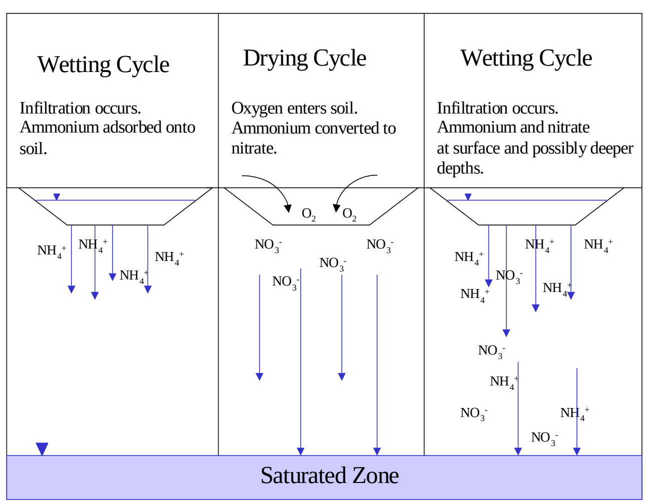
Site	Years of Operation	Pretreatment	Average NH_4^+ Conc.	Average Percent Nitrogen Removal
[1]Flushing Meadows	1967 – 1978	Secondary activated sludge, No chlorination	21 mg N/L	65 %
[2]23rd Avenue Phoenix, AZ	1974 – 1983	Secondary activated sludge, No chlorination prior to 1980 Chlorination after 1980	18 mg N/L	69 %
[3]TTSA	1978 - current	Advanced treatment, Ion exchange for NH_4^+ removal, Chlorination	7 mg N/L	70-90 %
[4]Sweetwater	1986 - current	Secondary treatment, Chlorination	20 mg N/L	75 %

[1]Bouwer and Rice (1974), [2]Bouwer and Rice (1984), [3]Woods et al., 1999, [4]Wilson et al., 1995

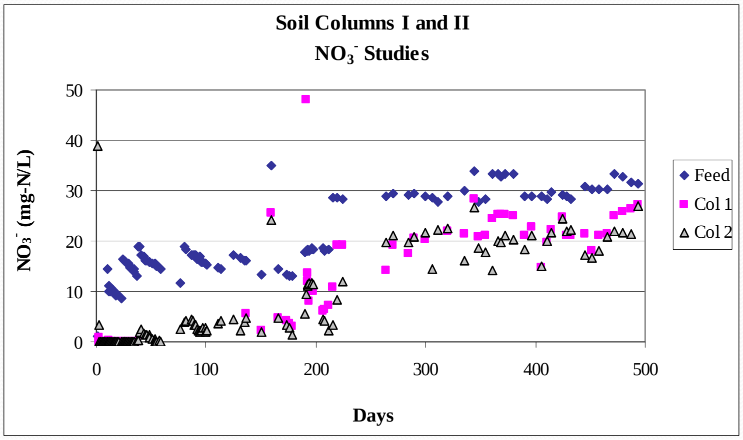
Proposed Mechanism

- Anaerobic ammonium oxidation
- Microbial process of oxidation of ammonium with a nitrogen compound (NO_3^- or NO_2^-) serving as the electron acceptor in the absence of molecular oxygen
- $NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O$
- $5NH_4^+ + 3NO_3^- \rightarrow 4N_2 + 9H_2O + 2H^+$

Nitrogen During SAT



Nitrate Removal in Soil Columns – Tucson, AZ



Anaerobic Ammonia Oxidation

- Conversion of nitrate to nitrite appears to be rate limiting step – unsure how it is mediated
- Slow Growing but Ubiquitous
- Certainly present in ocean sediments

Nitrogen Manganese Interactions

$$2NH_3 + 3MnO_2 + 6H^+ \rightarrow 3Mn^{2+} + N_2 + 6H_2O$$

ΔG_f^o = -658.6 kJ/mole (2.3)

$$2NO_3^- + 5Mn^{2+} + 4H_2O \rightarrow 5MnO_2 + N_2 + 8H^+$$

ΔG_f^o = -14.2 kJ/mole

Luther, 1999

Nitrate Spikes

- High Nitrate Concentrations may be observed in vadose zone samples
- Localized phenomena where ammonia became concentrated and oxidized
- Problem with regulators – we appear to be making nitrogen!!
- Peaks will dilute and attenuate
- Long drying cycles could result in oxidation of large mass of adsorbed ammonia

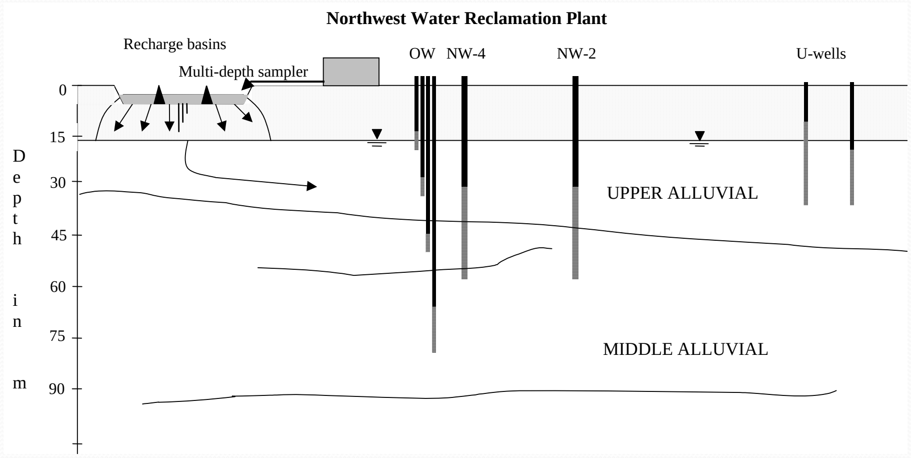
Objectives of Monitoring

- Does the groundwater sample contain reclaimed water?
  - Ionic Composition
  - Isotopic Ratios - Boron/Oxygen
  - Fluorescence and Recalcitrant Organics (Iodine)

Objectives of Monitoring

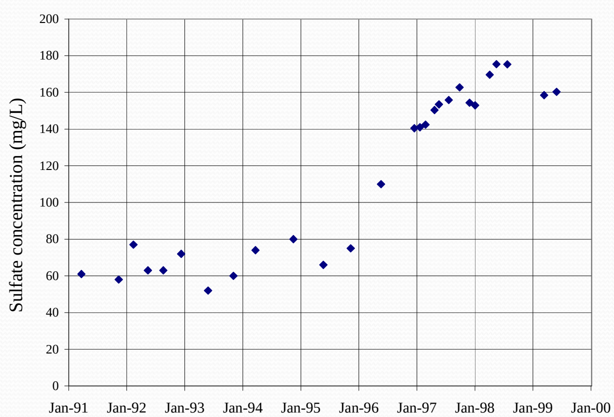
- Have natural processes attenuated contaminants in the reclaimed water?
  - Organics
    - Bulk Organics - DOC as a surrogate?
    - Trace Organics
  - Nitrogen
  - Pathogens

Monitoring – multiple depth down gradient



not to scale

Sulfate Breakthrough Curve



Reclaimed Water Dominates Upper Alluvial Unit 2000 m downgradient

Mixing and Dilution

- Typical Recharge Rates - 2-4 orders of magnitude greater than natural recharge (Recharge 0.5-5 ft/d vs Precipitation 0.5-2 ft/yr)
- Dilution/Mixing in Saturated Flow Relatively slow
- ZONE/PLUME DOMINATED BY RECHARGE WATER

Why Dilution??

- Most drinking water wells are screened over 100 meters
- The reclaimed water is in the top portion of the aquifer only

QUESTIONS?

Terra Preta – Man can improve soil!