Soil Aquifer Treatment (SAT) as a Natural and Sustainable Wastewater Reclamation/Reuse Technology: General Concepts

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Outline

• Introduction
• Description of Representative Field Sites
• Selected Analytical Methods
• Results: Field Site Performance
• Summary and Implications

Introduction
What is SAT?

- **Soil Aquifer Treatment**
- Operated to use soil mantle and groundwater aquifer as treatment (and storage)
- **Three components:**
  - Surface infiltration
  - Percolation
  - Aquifer storage (and recovery)

Soil Aquifer Treatment (SAT)

- An advanced (beyond secondary) wastewater treatment process involving infiltration (percolation) of wastewater effluent through vadose (unsaturated) zone to recharge underlying groundwater aquifer
- Vadose and saturated zone treatment
- Long-term storage of renovated water
- Replenishment of diminished groundwater supplies
- Currently SAT renovated water is being used in USA as a non-potable resource (e.g., municipal and golf course irrigation) ⇒ Treated to Potable Levels
Soil Aquifer Treatment (SAT)

Treatment:
Aerobic → Anoxic?

SAT: Infiltration to Recovery
(Mekorot, 2004)

Reclaimed Wastewater
Infiltration Interface
Regional GW

Soil Percolation Zone
Vadose Zone
Treatment: Aerobic → Anoxic?

Infiltration basin
Observation wells
Recovery wells

GW Transport and Mixing Zone
Treatment and Storage

Sand layer for filtration

Vadose

Impregnable soil layer

Topographic height:
+40.0
+20.0
+8.0
-40.0
SAT: Infiltration to Recovery (Mekorot, 2004)

Montebello Forebay Infiltration Basins
Los Angeles, California USA

Land Requirements
Operating Conditions for SAT (Mekorot, 2004)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic loading</td>
<td>m/d</td>
<td>0.2 - 0.6</td>
</tr>
<tr>
<td>Wetting cycles</td>
<td>days</td>
<td>1 - 7</td>
</tr>
<tr>
<td>Drying cycles</td>
<td>days</td>
<td>2 - 7</td>
</tr>
<tr>
<td>Cleaning cycle</td>
<td>days</td>
<td>&lt; 15 - &gt; 30</td>
</tr>
<tr>
<td>Retention time in ground</td>
<td>months</td>
<td>&lt; 6 - &gt; 12</td>
</tr>
<tr>
<td>Depth to ground water</td>
<td>m.</td>
<td>5 - 30 (max. 100)</td>
</tr>
<tr>
<td>Recovery</td>
<td>%</td>
<td>up to 100 %</td>
</tr>
</tbody>
</table>

Key Factors:
- Time
- Distance
- Managing Redox
- Maintaining Infiltration

Comparison of Typical SAT Zones

<table>
<thead>
<tr>
<th>PROCESS/PARAMETER</th>
<th>INfiltration Interface</th>
<th>Soil-Percolation</th>
<th>Groundwater Transport</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment Mechanisms</td>
<td>Filtration ✓, Biodegradation</td>
<td>Biodegradation ✓, Adsorption</td>
<td>Biodegradation, Adsorption, Dilution ✓</td>
</tr>
<tr>
<td>Transport</td>
<td>Saturated</td>
<td>Unsaturated</td>
<td>Saturated</td>
</tr>
<tr>
<td>Residence Time</td>
<td>Minutes</td>
<td>Hours to Days</td>
<td>Months to Years</td>
</tr>
<tr>
<td>Travel Distance</td>
<td>Centimeters / Inches</td>
<td>3 - 30 m / 10 - 100 ft</td>
<td>Variable</td>
</tr>
<tr>
<td>Mixing</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Oxygen (O₂) Supply</td>
<td>Recharge Water</td>
<td>Unsaturated Zone</td>
<td>Regional G.W.</td>
</tr>
<tr>
<td>Biodegradable Org. Carbon Availability</td>
<td>Excess</td>
<td>Excess/Limiting</td>
<td>Limiting</td>
</tr>
<tr>
<td>Redox Conditions</td>
<td>Aerobic</td>
<td>Aerobic to Anoxic</td>
<td>Anoxic to Aerobic</td>
</tr>
</tbody>
</table>
Tracers

- **Intrinsic (Internal) Tracers**
- **Estimation of % Reclaimed Water**
  - Target Anions
    - Sulfate ($\text{SO}_4^{2-}$)
    - Bromide ($\text{Br}^-$)
    - Boron (B)
  - Wastewater Indicators
    - EDTA
    - Caffeine
- **Estimation of Travel Time**
  - Isotopes (Isotope Hydrology)
    - Boron ($^{11}\text{B}/^{10}\text{B}$)
    - Oxygen ($^{18}\text{O}/^{16}\text{O}$)

Dissolved Oxygen/Redox

- **Aerobic Conditions ✓**
  - Recharge Basin and Upper Vadose Zone
  - Organic Carbon Degradation and Nitrification ($\text{O}_2$ as Electron Acceptor)
- **Anoxic (Facultative) Conditions ✓**
  - Lower Vadose Zone and Saturated Zone
  - Organic Carbon Degradation and Denitrification ($\text{NO}_3^-$ as Electron Acceptor);
  - $\text{O}_2$ Replenishment by Regional Groundwater
- **Anaerobic Conditions:**
  - Limited Evidence; Organic Carbon Degradation
    - ($\text{SO}_4^{2-}$ as Electron Acceptor)
- **Beyond NO$_3^-$ Reduction:**
  - Fe/Mn Reductive Dissolution; As?
Aquifer Storage, Transfer (Treatment) and Recovery ASTR

- GS
- WT
- Confining layer
- Time/Distance
- Bedrock

Other Recharge Options

- (Intermittent) River Bed Infiltration (Spain)
- Sink Hole (Italy)
- Dune Infiltration (Belgium)
- Injection Well (China, after SSF (“vadose zone”) above confining layer)
SAT in Indirect potable reuse

Water Reclamation

Wastewater

Surface spreading or deep injection

Reservoir

Water Treatment

Consumer

Applicability of SAT

• Eliminate additional treatment; an alternative to advanced/tertiary wastewater treatment:
  - Reclaimed/recycled (waste)water ✓
  - Storm water
  - Surface water

• Potential worldwide application, depending on geology, soils, hydrology, etc. (presently in USA, Israel, Australia, Europe)
Pretreatment

- **Secondary Treatment**
  - Conventional WW Biotreatment (non-nitrified) ✓
  - Advanced Biological (BNR) ×
- **Primary Treatment**?
  - Advanced Primary?
- **Disinfection**
  - Chlorination ×
  - UV ?
  - None ✓

Post-Treatment

- **Membranes**?
  - A Secondary Barrier (Multiple Barriers)
  - UF: Viruses;
    SAT Reduces Fouling Potential
  - NF: Viruses; DOC;
    Some NO₃⁻ and Trace Organics
- **Chemical Disinfection**
  - CT Requirements (C (mg/L) x T (min))
    (Ground Water Disinfection Rule (GWDR) in USA)
  - x-log inactivation of viruses;
    credit for subsurface filtration
Regulatory Considerations

- Source Control (Industrial WW)
- (Degree of) Wastewater Treatment
- Treatment Standards
- Recharge Method
- Recharge Area/Well Proximity
- Vadose Zone Depth
- Maximum Infiltration Rate
- Time/Distance Travel Requirements
- DOC of WW-Origin ✓
- Monitoring

SAT Treatment Objectives

- Bulk Organic Matter
  - Natural Organic Matter (NOM)
  - Effluent Organic Matter (EfOM)
- Nitrogen Species
  - Ammonia (NH₃)
  - Nitrate (NO₃⁻)
- Microbes
  - Viruses as Controlling (most mobile) organism
- Effluent-Derived Organic Micropollutants
  - Pharmaceuticals Active Compounds (PhACs)
  - Endocrine Disrupting Compounds (EDCs)
Field Sites
### Representative SAT Field Sites in USA

#### City of Mesa, AZ
- **Ground** Water
- **SAT** Source
- **WW Treatment**: Short- & intermediate-term SAT
- **Vadose Zone**: Anoxic w/ 1st 2 – 3 m aerobic
- **Sample Set**: SAT

#### City of Tucson, AZ
- **Ground** Water
- **WW Treatment**: Secondary (Trickling Filter w/o Nitrification + Cl₂)
- **Vadose Zone**: Anoxic w/ 1st 2 – 3 m aerobic
- **Sample Set**: Short- & intermediate-term SAT

### Field Sites

<table>
<thead>
<tr>
<th>SAT Facility</th>
<th>DW Source</th>
<th>WW Treatment</th>
<th>Vadose Zone</th>
<th>Sample Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tucson WRP</td>
<td>Ground Water (low DOC)</td>
<td>Secondary (Trickling Filter w/o Nitrification + Cl₂)</td>
<td>Anoxic w/ 1st 2 – 3 m aerobic</td>
<td>Short- &amp; intermediate-term SAT</td>
</tr>
</tbody>
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### Field Sites

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</thead>
<tbody>
<tr>
<td>Tucson WRP Tucson, AZ USA</td>
<td>Ground Water (low DOC)</td>
<td><strong>Secondary</strong> (Trickling Filter w/ Nitrification + Cl_2)</td>
<td>Anoxic w/ 1st 2 – 3 m aerobic</td>
<td>Short- &amp; intermediate-term SAT</td>
</tr>
<tr>
<td>Mesa WRP Mesa, AZ USA</td>
<td>Surface Water</td>
<td><strong>Tertiary</strong> (Nitrification/Partial Denitrification + Filtration + UV)</td>
<td>Anoxic w/ 1st 2 – 3 m aerobic</td>
<td>Short-, intermediate, &amp; long-term SAT</td>
</tr>
</tbody>
</table>

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### Tucson WRP: Sweetwater Recharge and Storage Facility

- **Treatment plant**
- **RB-1**

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Sampling Location Descriptions at Tucson WRP

<table>
<thead>
<tr>
<th>Sample</th>
<th>Travel Distance (meters)</th>
<th>Travel Time (days)</th>
<th>Reclaimed Water (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB1 (Recharge Basin)</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>MW5 (Shallow Monitoring Well)</td>
<td>6</td>
<td>11</td>
<td>100</td>
</tr>
<tr>
<td>WR199a (Deep Recovery Well)</td>
<td>35</td>
<td>35</td>
<td>100</td>
</tr>
</tbody>
</table>

Mesa WRP: Northwest Water Reclamation Facility
The Mesa Northwest site

Mesa WRP Site

Short Term SAT
Intermediate Term SAT
Long Term SAT

Northwest Water Reclamation Plant
Infiltration ponds
Multi-depth sampler
UPPER ALLUVIAL
MIDDLE ALLUVIAL
## Sampling Location Descriptions at Mesa WRP

<table>
<thead>
<tr>
<th>Sample</th>
<th>Travel Distance (meters)</th>
<th>Travel Time (months)</th>
<th>Reclaimed Water (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>P15</td>
<td>negligible</td>
<td>Short</td>
<td>100</td>
</tr>
<tr>
<td>NW4</td>
<td>388</td>
<td>6-18</td>
<td>100</td>
</tr>
<tr>
<td>NW3</td>
<td>655</td>
<td>6-19</td>
<td>86</td>
</tr>
<tr>
<td>NW2</td>
<td>885</td>
<td>6-20</td>
<td>99</td>
</tr>
<tr>
<td>10u</td>
<td>1950</td>
<td>12-96</td>
<td>61</td>
</tr>
<tr>
<td>26u</td>
<td>1950</td>
<td>12-96</td>
<td>71</td>
</tr>
<tr>
<td>44u</td>
<td>2700</td>
<td>12-96</td>
<td>39</td>
</tr>
</tbody>
</table>

## Analytical Methods
### Bulk EfOM Measurements

- Dissolved Organic Carbon (DOC)
- UV Absorbance @ 254 nm ($\text{UVA}_{254}$)
- Specific UV Absorbance
  
  ($\text{SUVA} = \text{UVA}_{254}/\text{DOC}$)
- Dissolved Organic Nitrogen (DON)

### Trace Organic Compounds

- Pharmaceutically Actives Compounds (PhACs)
- Endocrine Disrupting Compounds (EDCs)
- Adsorbable Organic Iodine (AOI)
  - Iodinated X-Ray Contrast Agents (e.g., iopromide)
Results: EfOM

DOC and SUVA Profiles at Tucson WRP

Steady-State
 (>10 Years)
 Profiles
 Sustainability
### Bulk DOC, SUVA and DON for Tucson WRP Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>DOC (mg/L)</th>
<th>SUVA (L/m-mg)</th>
<th>DON (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RB1</td>
<td>14.1</td>
<td>1.26</td>
<td>9.4</td>
</tr>
<tr>
<td>MW5</td>
<td>4.84</td>
<td>2.38</td>
<td>BDL</td>
</tr>
<tr>
<td>WR199A</td>
<td>0.98</td>
<td>2.46</td>
<td>BDL</td>
</tr>
<tr>
<td>Drinking Water</td>
<td>~0.5</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### Bulk DOC, SUVA and DON for Mesa WRP Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>DOC (mg/L)</th>
<th>SUVA (L/m-mg)</th>
<th>DON (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin (Mesa III Effl)</td>
<td>6.10</td>
<td>1.62</td>
<td>2.1</td>
</tr>
<tr>
<td>NW4</td>
<td>1.47</td>
<td>1.63</td>
<td>1.8</td>
</tr>
<tr>
<td>NW3</td>
<td>1.76</td>
<td>1.25</td>
<td>1.7</td>
</tr>
<tr>
<td>NW2</td>
<td>1.52</td>
<td>1.45</td>
<td>1.1</td>
</tr>
<tr>
<td>10u</td>
<td>1.14</td>
<td>1.67</td>
<td>0.2</td>
</tr>
<tr>
<td>26u</td>
<td>0.75</td>
<td>1.46</td>
<td>n/a</td>
</tr>
<tr>
<td>44u</td>
<td>1.08</td>
<td>1.48</td>
<td>n/a</td>
</tr>
<tr>
<td>Drinking Water</td>
<td>~2.0</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Biomass Profiles: Mesa WRP

EfOM Removal ⇒ Sustainable Biodegradation

Results: Nitrogen
Nitrogen Trends at Tucson WRP Site

Ammonia

Nitrate and Nitrite

Results: Trace Organics
### Removal of Selected Pharmaceutically Active Compounds (PhACs) through SAT at Mesa WRP and Tucson (WRP) (Drewes, 2004)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Antiepileptics (ng/L)</th>
<th>Analgesics (ng/L)</th>
<th>Lipid Regulators (ng/L)</th>
<th>Wastewater Indicators (ng/L)</th>
<th>X-ray Contrast Agents (ng/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbazepine</td>
<td>Primidone</td>
<td>Ibuprofen</td>
<td>Naproxen</td>
<td>Gemfibrozil</td>
</tr>
<tr>
<td>Mesa eff</td>
<td>175</td>
<td>202</td>
<td>16</td>
<td>8.0</td>
<td>n.d.</td>
</tr>
<tr>
<td>NW4</td>
<td>235</td>
<td>120</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>NW2</td>
<td>125</td>
<td>160</td>
<td>16</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>2U</td>
<td>145</td>
<td>90</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>6U</td>
<td>85</td>
<td>100</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
<tr>
<td>Tucson WRP</td>
<td>n.d.</td>
<td>110</td>
<td>3,380</td>
<td>6,280</td>
<td>1,240</td>
</tr>
<tr>
<td>Tucson eff</td>
<td>n.d.</td>
<td>110</td>
<td>3,380</td>
<td>6,280</td>
<td>1,240</td>
</tr>
<tr>
<td>WR199</td>
<td>610</td>
<td>155</td>
<td>n.d.</td>
<td>n.d.</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

### Fate of Analgesics during short-term SAT at Tucson WRP (Drewes, 2004)

Eliminated
Over Several m
Or Several days
Fate of Antiepileptics during long-term SAT at Mesa WRP (Drewes, 2004)

Persist over Several km & Several Years

Removal of Selected Endocrine Disrupting Compounds (EDCs) through SAT at Mesa WRP and Tucson WRP (Drewes, 2004)

<table>
<thead>
<tr>
<th>Sample</th>
<th>17-β Estradiol (ng/L)</th>
<th>Estriol (ng/L)</th>
<th>Testosterone (ng/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesa WRP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basin</td>
<td>4.2</td>
<td>4.9</td>
<td>3.0</td>
</tr>
<tr>
<td>P5</td>
<td>0.5</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>NW2</td>
<td>&lt;0.4</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>NW4</td>
<td>&lt;0.4</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>2U</td>
<td>&lt;0.4</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>6U</td>
<td>&lt;0.4</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Tucson WRP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RB1</td>
<td>7.2</td>
<td>21.3</td>
<td>11.5</td>
</tr>
<tr>
<td>MW5</td>
<td>1.8</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>WR199</td>
<td>&lt;0.4</td>
<td>&lt;0.6</td>
<td>&lt;0.5</td>
</tr>
</tbody>
</table>

Effective Removal: Biodegradation or Adsorption?


Removal of Hormones during SAT at Tucson WRP (Drewes, 2004)

Effectively eliminated over several m or several days

Results: Microbials (Viruses as Controlling Organism)
Bacteriophage Tracer Study at Arizona Field Site # 1

• Attenuation rate over first 3 meters:
  - MS2 - 0.85 log
  - PRD1 - 1.5 log
• Extrapolation ⇒ 7 log removal in less than 30 m
• No positives in groundwater monitoring well
• Detectable Enteric Viruses in Effluent
• Supporting Soil Column Experiments:
  - ≈ 1-log reduction of Bacteriophage over 1 m
  - up to 2-log reductions of Poliovirus

Results: Disinfection By-Products (DBPs)
Disinfection By-Products (DBPs)

- Role of Disinfection in an SAT System:
  - Disinfection of Original Drinking Water Source (DBPs in Drinking Water Source; Watershed Perspective)
  - Disinfection (Chlorination) of Wastewater Effluent (DBPs Present in Recharge Basin; Loss of Volatile DBPs)
  - Disinfection (Chlorination of SAT-Treated Water (DBPs Formed Upon Recovery/Subsequent Disinfection)

- Regulated (Chlorination) DBPs (in USA)
  - Trihalomethanes (THMs) and Haloacetic Acids (HAAs)

- DBP Precursors:
  - Organic (DOC) and Inorganic (Br⁻)
  - \( \text{DOC} + \text{Cl}_2 \rightarrow \text{CHCl}_3 \Rightarrow \text{TOCl} \) (AOCl)
  - \( \text{Br}^- + \text{Cl}_2 \rightarrow \text{Br}_2; \ \text{DOC} + \text{Br}_2 \rightarrow \text{CHBr}_3 \text{ etc.} \Rightarrow \text{TOBr} \) (AOBr)

Fate of Cl⁻/Br⁻-DBPs and AOI during SAT: AZ Site # 1

![Bar chart showing the fate of Cl⁻/Br⁻-DBPs and AOI during SAT: AZ Site # 1](chart.png)
Fate of Cl-/Br-DBPs and AOI during SAT: AZ Site # 2

Summary and Implications
## General Performance

<table>
<thead>
<tr>
<th>Parameter/Condition</th>
<th>SAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth/Travel Distance</td>
<td>&gt; 10 m in vadose zone; 0 to several km in aquifer</td>
</tr>
<tr>
<td>Residence Time</td>
<td>&gt; 10 days in vadose zone; 0 to several years in aquifer</td>
</tr>
<tr>
<td>Hydraulic Loading/Infiltration Rate</td>
<td>&lt; 1 m/day</td>
</tr>
<tr>
<td>Schmutzdecke/Clogging Layer</td>
<td>yes</td>
</tr>
<tr>
<td>Flow Regime</td>
<td>unsaturated and saturated</td>
</tr>
<tr>
<td>Redox</td>
<td>oxic (aerobic) ✓ and anoxic</td>
</tr>
</tbody>
</table>

## General Performance - cont

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity (NTU)</td>
<td>≤ 1 NTU</td>
</tr>
<tr>
<td>DOC Removal</td>
<td>≥ 50 %</td>
</tr>
<tr>
<td>Biostability: BDOC Removal</td>
<td>&lt; MDL</td>
</tr>
<tr>
<td>Trace Organics Removal</td>
<td>≥ 50 % (except for few persistent PhACs)</td>
</tr>
<tr>
<td>(Total) Nitrogen Achievable</td>
<td>≤ 2 mg/L</td>
</tr>
<tr>
<td>Microbial Removal (Viruses)</td>
<td>≥ 4-log</td>
</tr>
</tbody>
</table>
Attributes vs. Constraints

• Attributes:
  - Robust Barrier
  - Multi-Objective (-Contaminant) Process
  - Sustainability
  - Biologically Driven (vs. Physically/Chemically Driven)

• Constraints:
  - Low Permeability Soils (<10^-4 m/s)
  - Possible Preferential Flow Patterns
  - Arsenic Dissolution
  - Calcite Dissolution/Soil Collapse (permeability ↓)
  - Difficult to Control Operating Conditions
  - Lack of Framework/Models for Technology Transfer

Other Considerations

• Relevance to Both Developed and Developing Countries
• Opportunity for Indirect Potable Reuse
• Possible Hybrids
  - Anaerobic Treatment → SAT
• Limits of Technologies?
  - SAT of I Effluents
Questions

• Should soil passage, if properly designed and operated, be considered as a robust buffer in indirect potable reuse
  ⇒ yes (GLA)
• Is WW (pre)treatment beyond non-nitrified secondary treatment necessary?
  ⇒ no (GLA)
• Is only primary treatment realistic?
  ⇒ in developing countries (GLA)
• Should WW be disinfected before soil passage?
  ⇒ no chlorine!; UV OK but unnecessary (GLA)

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Questions?

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