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Onsite and Decentralized Wastewater Systems: Advances from a Decade of Research and Educational Efforts

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Southwest Onsite Wastewater Conference ~ January 29-30, 2014

Laughlin, Nevada

Introduction

- To help support the widespread application of modern onsite and decentralized systems, the Small Flows Program was established at CSM in Golden, Colorado
  - During the past 15 years, research and educational efforts have been carried out by a team of faculty, staff, and students
    - Research – fundamental and applied laboratory studies, controlled field research, field investigations, and mathematical modeling
    - Education – university courses and teaching materials
  - The overall goal has been to help answer key questions and support advances…

Small Flows Program
sustainable clean water and sanitation

- What do we mean by advances?
  - Improved scientific understanding
  - Improved ability to make predictions
  - New devices and technologies
  - More rational design procedures
  - Translation of research findings into improved practices
  - Education and capacity development
- Advances have occurred in several areas, including:
  - Advanced characterization of modern wastewater streams
  - Performance dynamics in reactor-based and soil-based systems
  - Modeling and decision support tool development
  - Mainline university course development and delivery

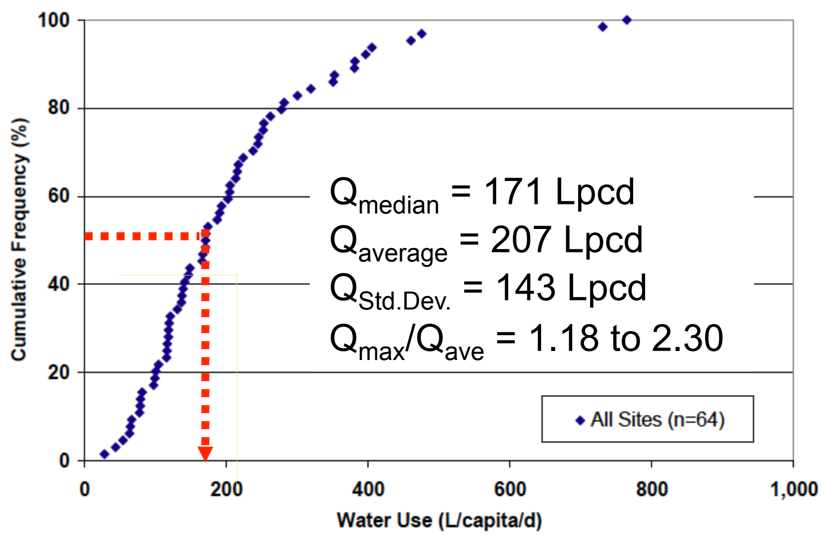
Research: Wastewater Characteristics

- *What are the characteristics of modern wastewaters often handled by onsite and decentralized systems?*
  - During a CSM project sponsored by the Water Environment Research Foundation (WERF), an advanced characterization study was completed
    - Comprehensive literature review and analysis
      - Raw wastewater and primary treated effluent (i.e., STE)
      - Domestic (single and multiple), food, medical, non-medical
      - Conventional pollutants and microorganisms
    - Field monitoring using a specialized apparatus
      - Raw wastewater and primary effluents
      - 17 domestic sources in 3 regions of the U.S.
      - Conventional pollutants, microorganisms, plus organic compounds of emerging concern

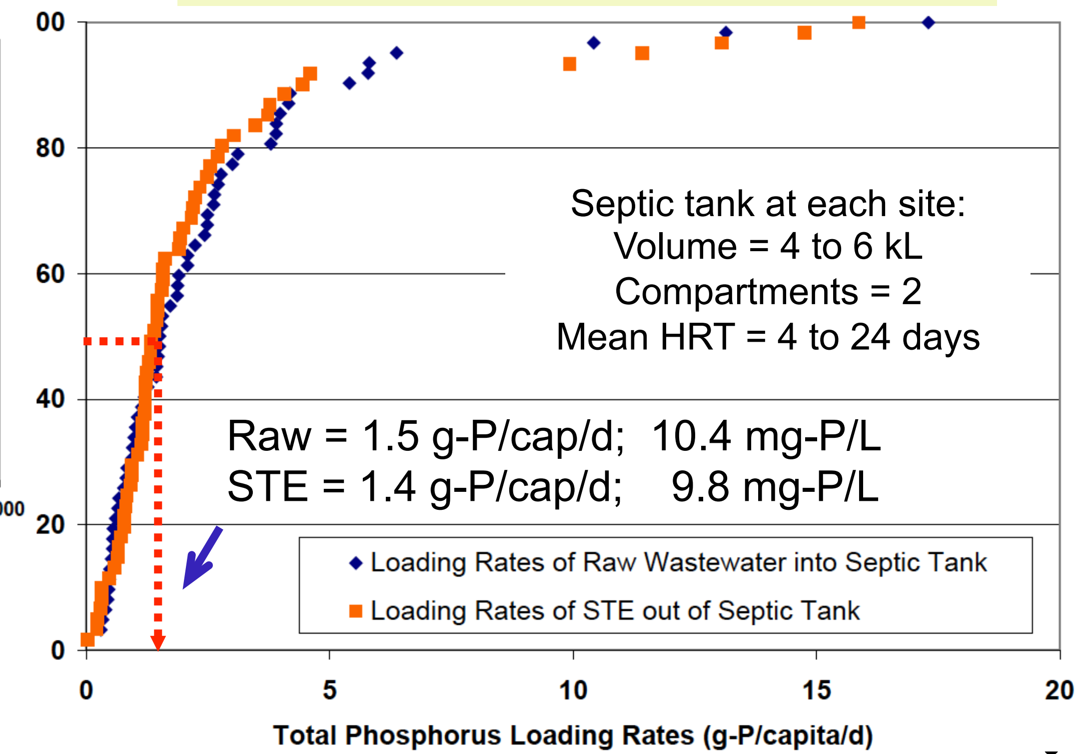
Source: Lowe *et al*. 2006; Lowe *et al.* 2009.

- Flow rates and conventional pollutants were characterized
  - Statistical tabulations, cumulative frequency distributions (CDFs)
  - Analysis of source features, geographic effects, and temporal trends

Daily flow rates from houses

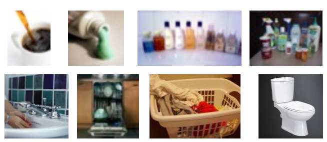


Total P in raw wastewater and STE



Source: Lowe *et al.* 2006, 2009.

- Monitoring of domestic sources yielded data on consumer product chemicals, pharmaceuticals, pesticides and flame retardants



  - Consumer product chemicals were pervasive
  - Other organics were less frequently present and at lower levels

Consumer product chemical organic compound	Compound function	Frequency of detection (%)	Concentration (µg/L)	
			Median	Max.
Bisphenol A	Plasticizer	1/12 (8%)	18	18
Caffeine	Stimulant	13/13 (100%)	93	E 1800 [1]
Ethylenediaminetetraacetic acid (EDTA)	Metal chelating agent	4/4 (100%)	33	E 720 [1]
Nitrilotriacetic acid (NTA)		1/4 (25%)	4.5	4.5
4-Nonylphenol (NP)	Surfactant metabolite	9/13 (69%)	6.8	66
4-Nonylphenolethoxylates (NPEO)		13/13 (100%)	7.5	23
5-chloro-2-(2,4-dichlorophenoxy)phenol (Triclosan)	Antimicrobial	13/13 (100%)	19	230

Source: Lowe *et al.* 2009.

[1] E = estimated, concentration exceeded maximum value of standard curve.

- Another CSM project was completed in collaboration with the U.S. Geological Survey
  - Monitoring at 30 operating onsite wastewater systems in CO
    - Residential, commercial, institutional sources
    - Water use ranged from 34 (vac. home) to 3570 gpd (restaurant)
    - Occupants or visitors per day varied widely
      - 2 (single-family home) to 1,100 (convenience store)
      - Also up to 40 animals (veterinary kennel)
  - Sampling of septic tank influent 2 to 3 times over 2 years
    - Conventional pollutants and consumer product chemicals

Residence (n=16)

Human Institution (n=3)

Retail Stores (n=3)

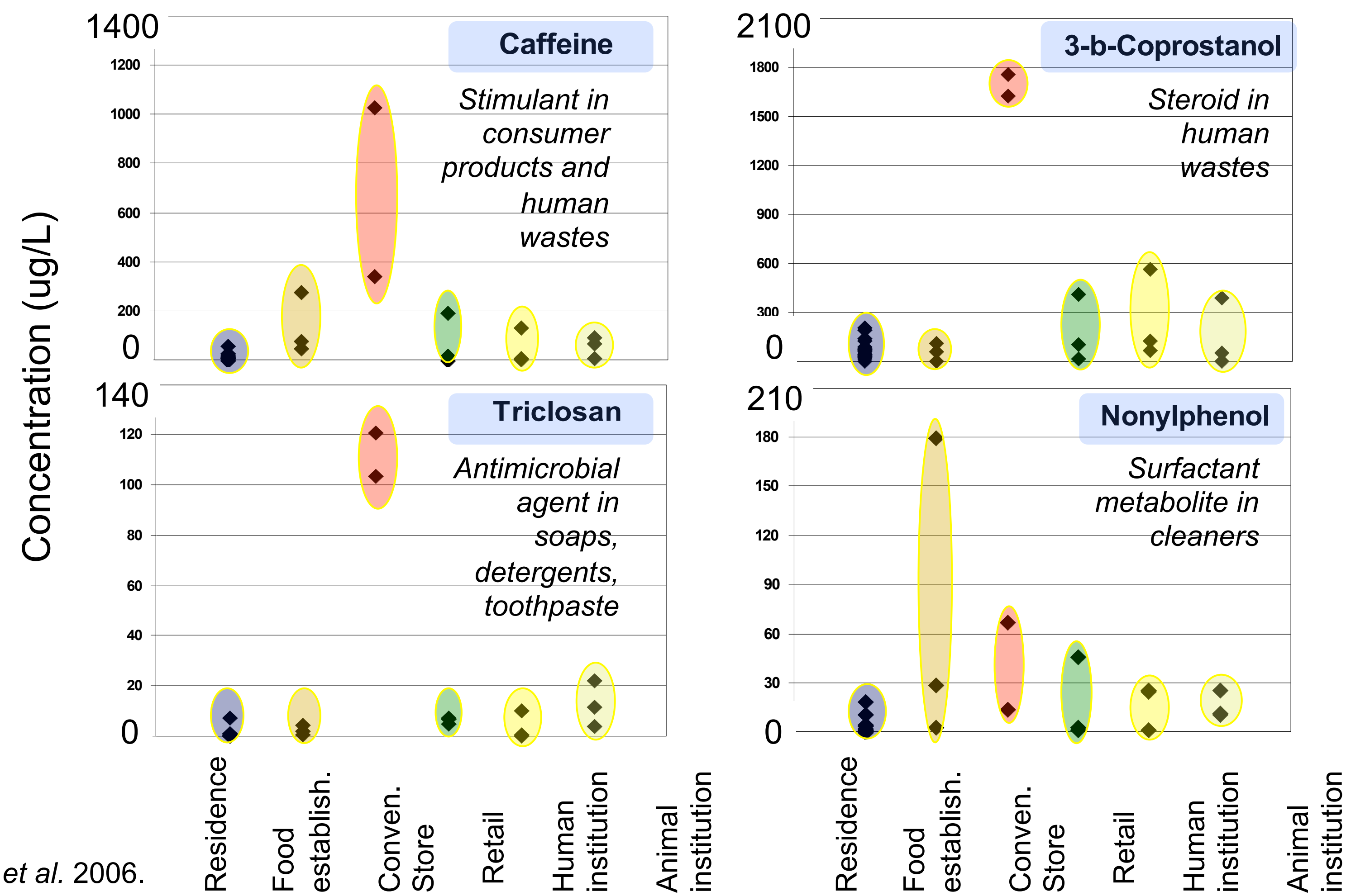
Convenience Store (n=2)

Restaurant (n=3)

Veterinary Hospital (n=3)

Source: Conn *et al.* 2006.

- Consumer product chemicals were commonly found
  - Occurrence of organics varies by type of source, e.g.:

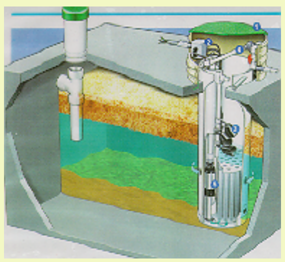


Source: Conn *et al.* 2006.

Research: Bioreactors & Biofilters

- *How do tank-based unit operations with contrasting processes perform and how robust and reliable are they?*

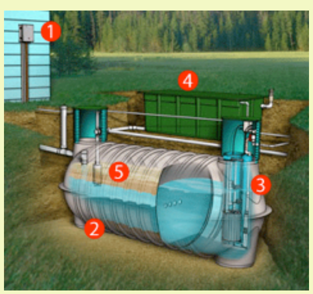
Untreated wastewater → *Septic tank w/ effluent screen* → *Packed bed textile filter* → *Ultraviolet light disinfection* → *Stream or landscape discharge*



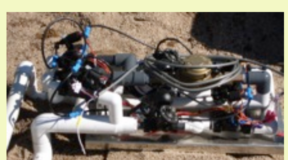
Source: Orenco Systems Inc.

SCG Enterprises Inc.

Septic tank w/ biofilter and recycle → *Spin-disk filter* → *Shallow subsurface drip dispersal for turf irrigation*

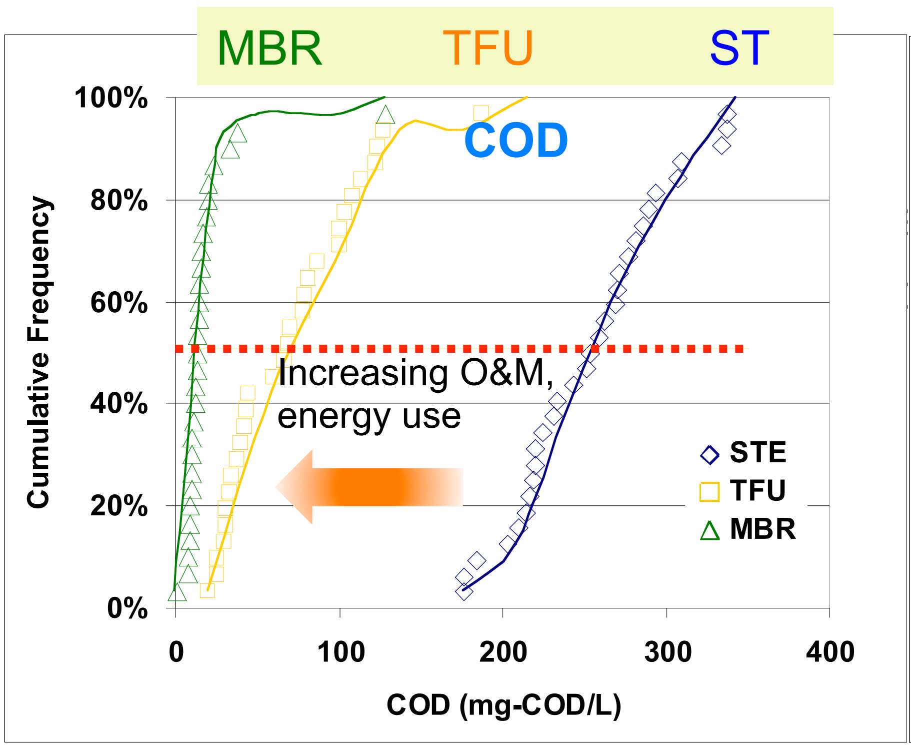


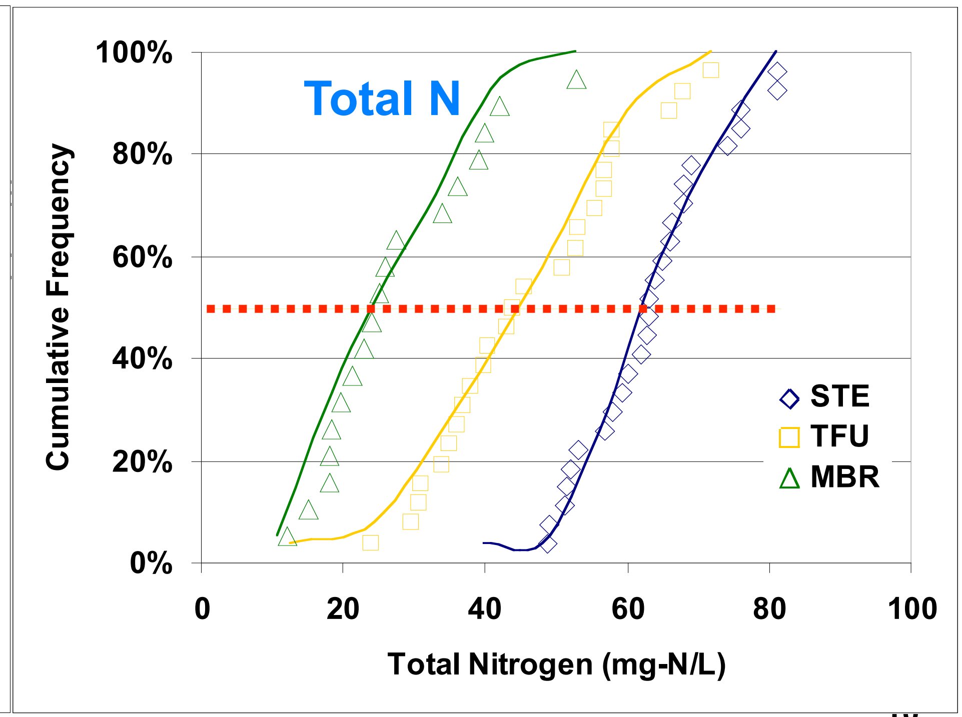
Source: Orenco Systems, Inc.



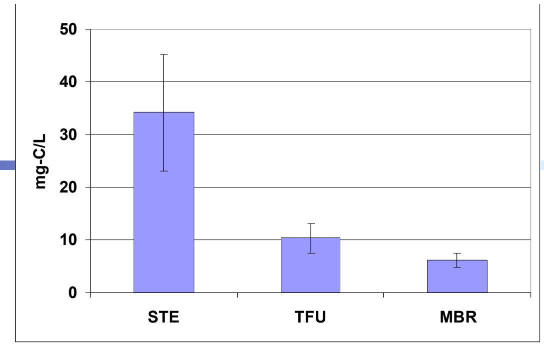
AMC at the CSM Mines Park Test Site

- During a CSM project sponsored by USEPA, domestic wastewater from an apartment building was treated in:
  - Septic tank, Textile biofilter, or Membrane bioreactor
  - Effluents were monitored for treatment efficiency and consistency
  - Systems were monitored for O&M requirements





Source: Van Cuyk *et al.* 2005, Lowe *et al.* 2008.



- Advanced characterization revealed the effluent organic matter is chemically different

Less biodegradable

ST – saturated organic compounds with low to high M.W.

TF – buildup of humic and fulvic acids, more aromatic in character

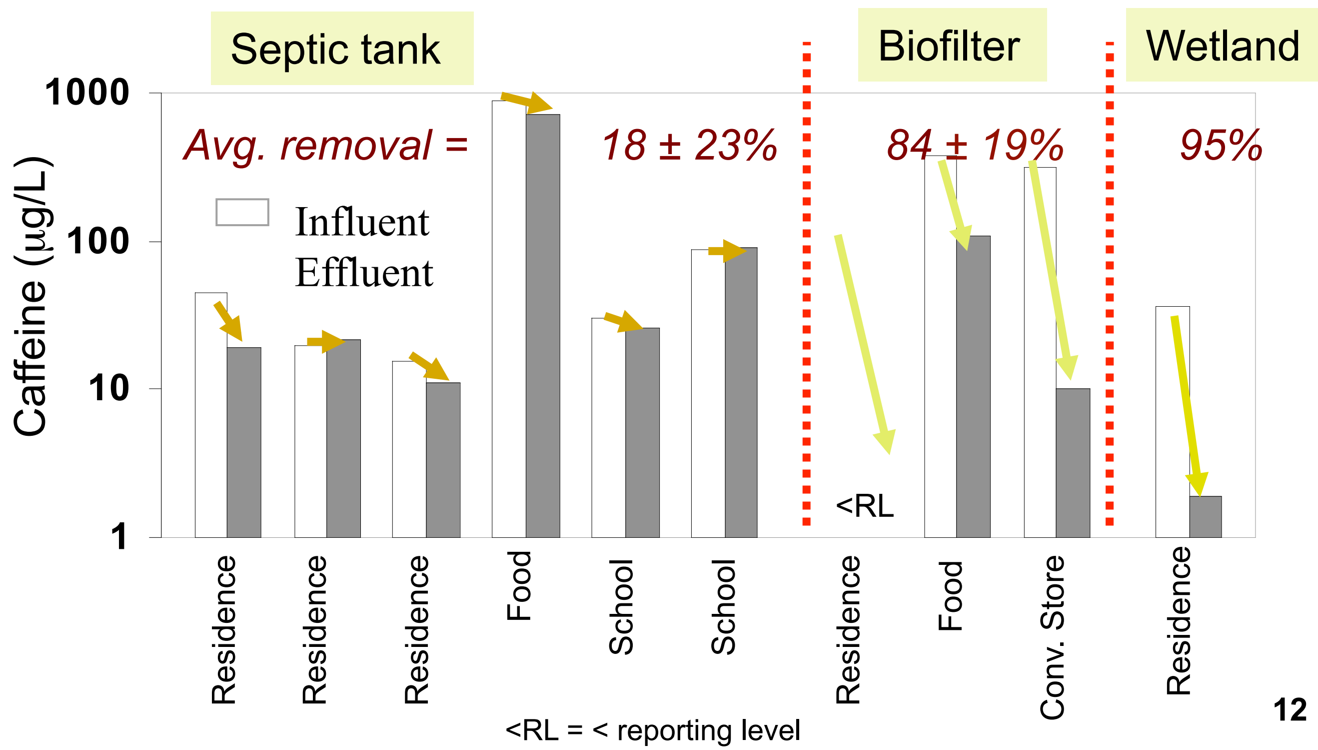
MBR – similar to TF but with more developed humic and fulvic acids

Parameter	ST		TF		MBR	
	mgC/L	%	mgC/L	%	mgC/L	%
Bulk sample DOC	33.0	100.00	9.4	100.0	6.3	100.0
Colloidal DOC	4.9	15.0	3.0	32.0	0.4	7.0
Hydrophilic carbon DOC	17.1	51.8	2.4	25.6	2.0	31.8
Hydrophobic acids DOC	10.7	32.3	4.1	43.2	3.4	54.2
Hydrophobic neutrals DOC	0.3	0.85	0.0	0.0	0.4	6.9
DOC	33.0 mg-C/L		9.4 mg-C/L		6.3 mg-C/L	
UV absorbance	24.0 L/m		16.8 L/m		10.9 L/m	
Specific UV absorbance	0.73 L/m-mg		1.79 L/m-mg		1.72 L/m-mg	

Source: Van Cuyk *et al.* 2005, Lowe *et al.* 2007.

- In a project sponsored by the U.S. Geological Survey, treatment of consumer product chemicals was studied
  - Monitoring of field systems with different treatment processes
    - Caffeine removal is enhanced by aerobic biotransformation
      - Triclosan, dichlorobenzene, *et al.* behave similarly

- Septic tanks
  Sorption, anaerobic biotransformation
- Biofilters
  Sorption, volatilization, aerobic biotransformation
- Constructed wetlands
  Sorption, aerobic or anaerobic biotransformation, plant uptake



Source: Conn *et al.* 2006.

- During research at the Mines Park Test Site
  - A Textile biofilter achieved higher removals for caffeine, 4-nonylphenols, and Triclosan - aerobic biotransformation
  - But no additional removal occurred for EDTA and NTA - Not amenable to aerobic biotransformation

Parameter	Units	Septic tank (anaerobic)	Textile biofilter (aerobic)
DOC	mg/L	30 (8.4)	16 (4.2)
NH_4	mg-N/L	34 (7.5)	3.8 (1.1)
NO_3	mg-N/L	0.85 (0.48)	19 (3.8)
Caffeine	µg/L	34 (8.7)	0.87 (0.49)
EDTA	µg/L	24 (1.0)	33 (13)
Nitrilotriacetic acid (NTA)	µg/L	3.7 (2.3)	4.0 (1.9)
4-Nonylphenol	µg/L	3.3 (1.4)	<RL of 2
4-NP1EC	µg/L	63 (23)	7.3 (3.6)
4-NP1EO	µg/L	1.6 (0.97)	<RL of 1
Triclosan	µg/L	9 (3.3)	<RL of 0.2

Source: Conn *et al.* 2010.

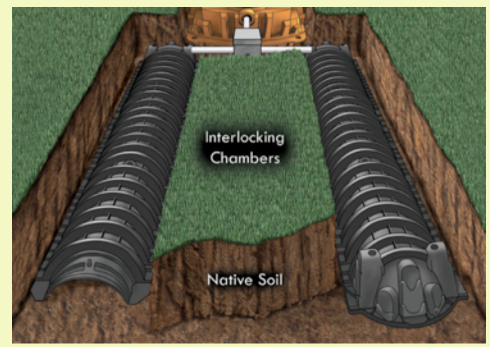
Effluent concentrations (average (std. dev.), n=14 over 13 mon.

Research: Soil Infiltration & Dispersal

- *What level of treatment can be achieved during infiltration or drip dispersal? What are the benefits of pretreatment?*

Septic tank w/ effluent screen

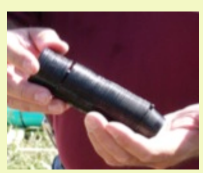
Subsurface infiltration trenches with groundwater recharge

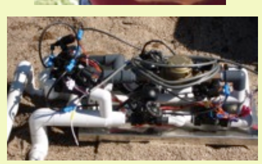


Source: Infiltrator Systems Inc.

Septic tank

Spin-disk filter

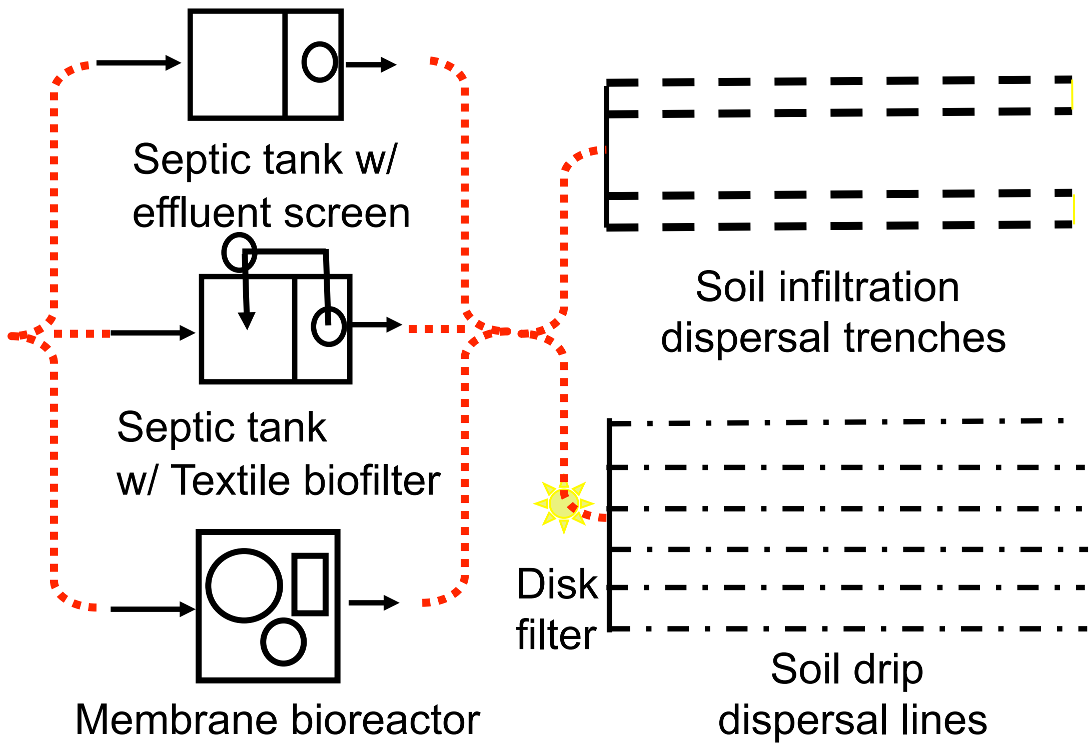


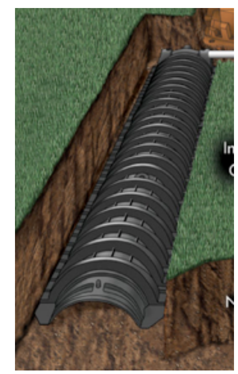


Shallow subsurface drip dispersal for turf irrigation

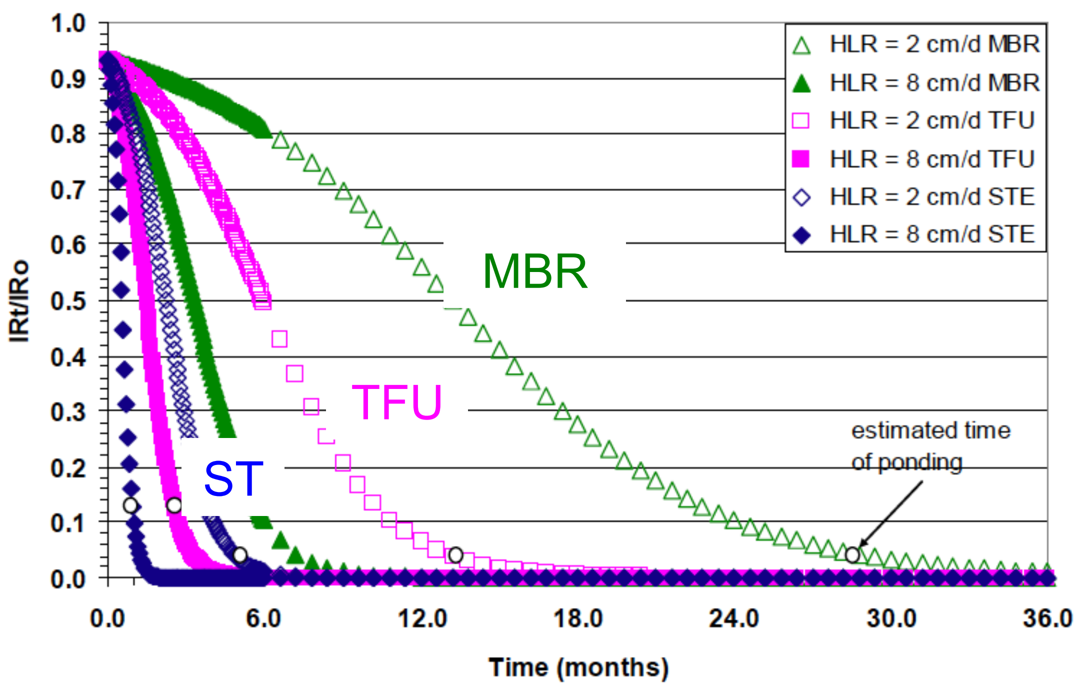
- Within CSM projects sponsored by USEPA, WERF, USGS, and private industry, lab experiments, field studies, and modeling have examined:
  - Effluent quality & loading, system features, soil properties,…
  - Flow & transport processes, treatment of pollutants and pathogens

Source: Tackett *et al.* 2004, Dimick 2005, VanCuyk *et al.* 2005, Parzen *et al*. 2007, Lowe and Siegrist 2008, Lowe *et al.* 2008, Tillotson 2009, Siegrist et al. 2013.





- Effluent infiltration into subsurface trenches
  - At the infiltrative surface, effluent causes development of a “biozone” due to: 1) biofilms, 2) biomat, and 3) pore filling by humic substances
  - Biozone development impacts infiltration and purification
  - Higher quality effluents retard biozone formation & sustain higher IR
    - IR over time for different effluent qualities and loading rates:



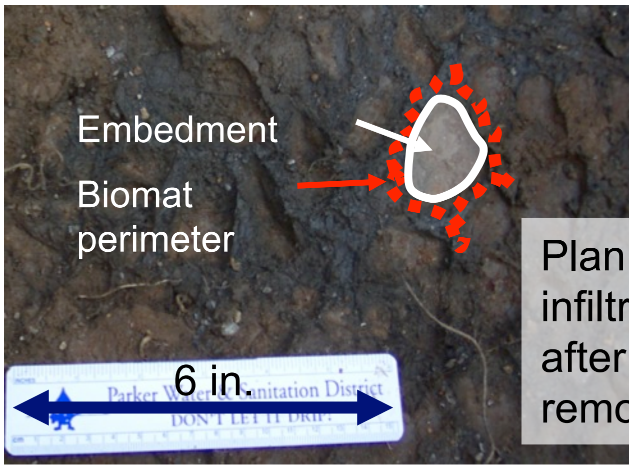
Parameter	ST	TFU	MBR
$cBOD_5$ (mg/L)	200	10	2
TSS (mg/L)	40	10	2
TKN (mg/L)	65	40	15

$10\ L/m^2/d = 1\ cm/d = 0.245\ gal/d/ft^2$

Source: Van Cuyk *et al.* 2005, McKinley and Siegrist 2010, 2011.

Characterization of the "biozone" generated in soil

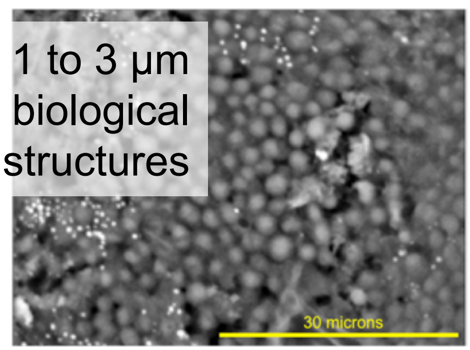
- Macro- and micromorphology, geochemistry, microbiology



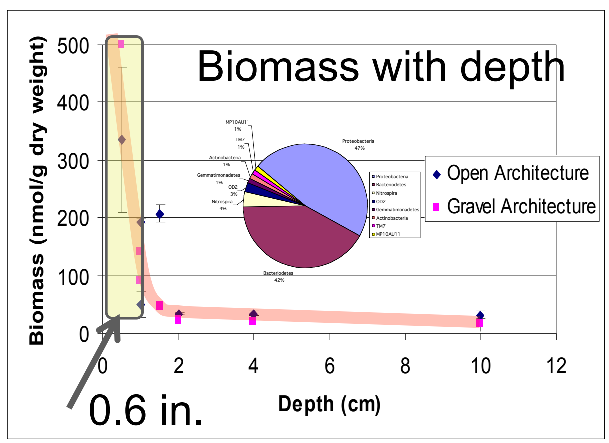
Plan view of the soil infiltrative surface after gravel was removed by hand

Organic matter with depth

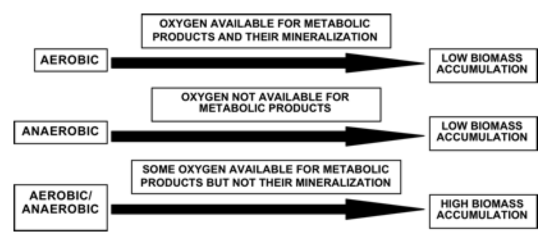
Parameter	0 – 0.2 in.	0.2 – 0.4 in.	0.4 - 0.6 in.
Water content	72%	39%	30%
TOC (g/kg d.w.)	26.9	11.3	6.2
Humins	60 – 80% of TOC		
Humic acids	25 – 33% of TOC		
Fulvic acids	17 – 21% of TOC		
Polysaccharides	9 – 18% of TOC		



Spherical 1 to 3 µm gray biological structures

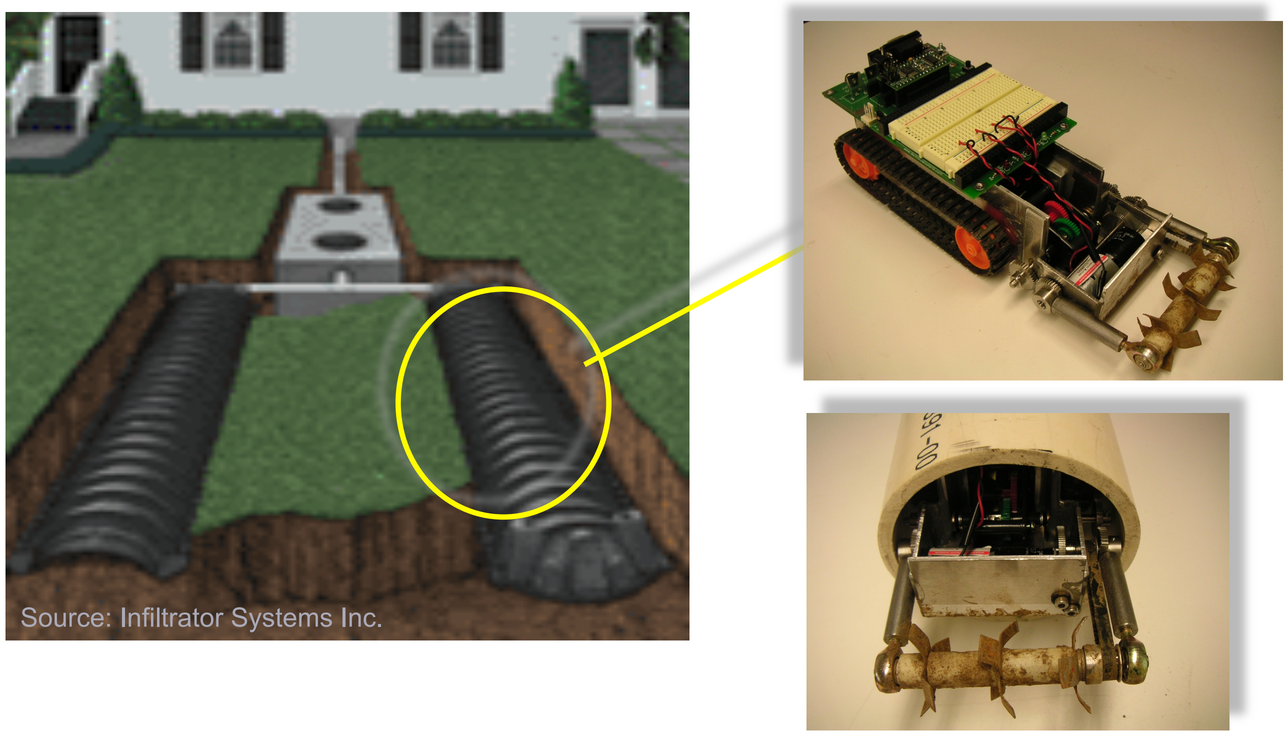


Biomass accumulation as affected by O_2 availability



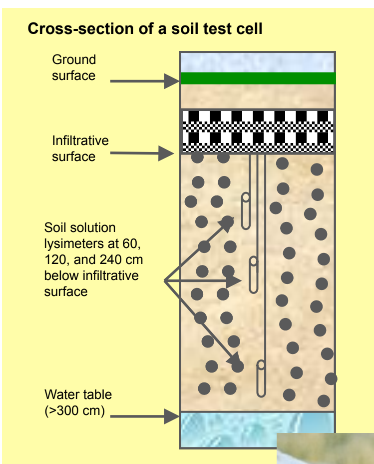
Source: McKinley and Siegrist 2010, 2011, Tomaras *et al.* 2009.

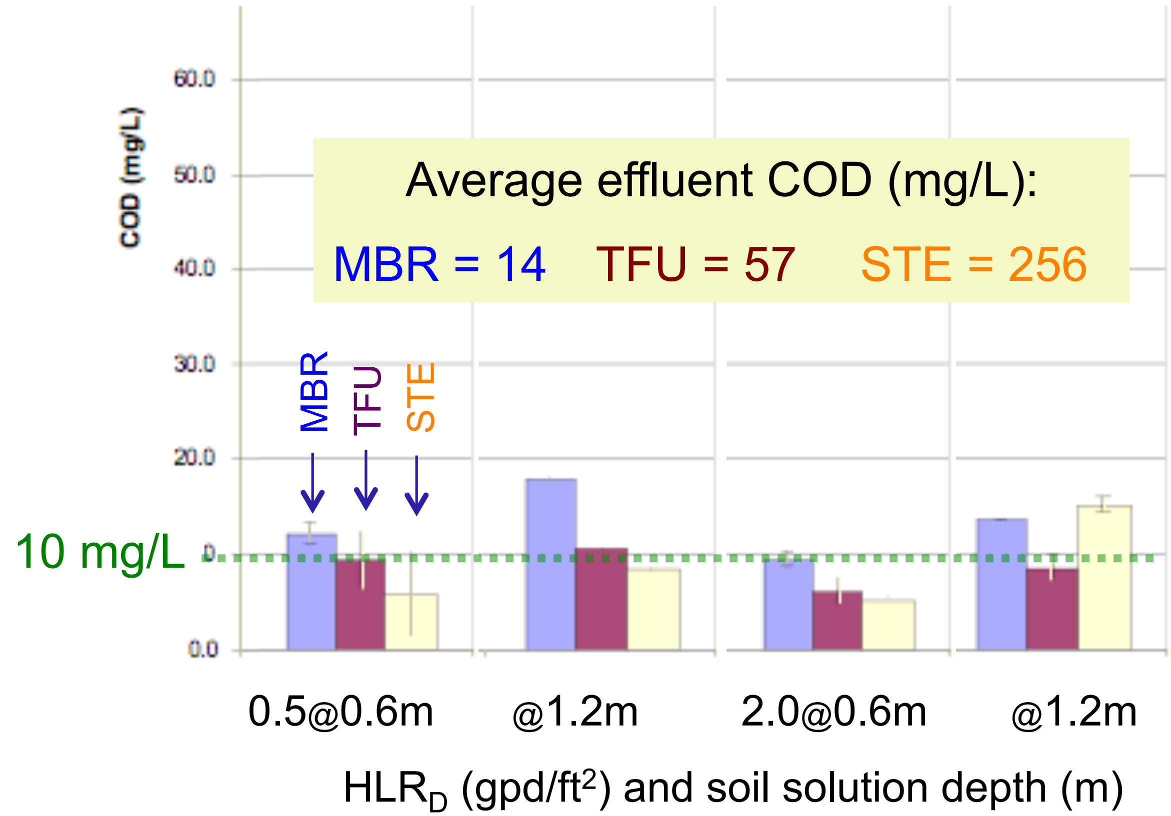
- With an understanding of the genesis and character of a biozone, cost-effective approaches and technologies may be applied to maintain and manipulate it, such as:
  - Controlling or amending effluent quality or loading rate
  - Robotic tools to “maintain” the infiltrative surface zone



Source: Infiltrator Systems Inc.

- Pollutant and pathogen removal during effluent infiltration
  - Treatment is often insensitive to the applied effluent quality or HLR
    - Results for COD are shown for treatment in sandy loam soil
    - Results for N, P, and virus are similar

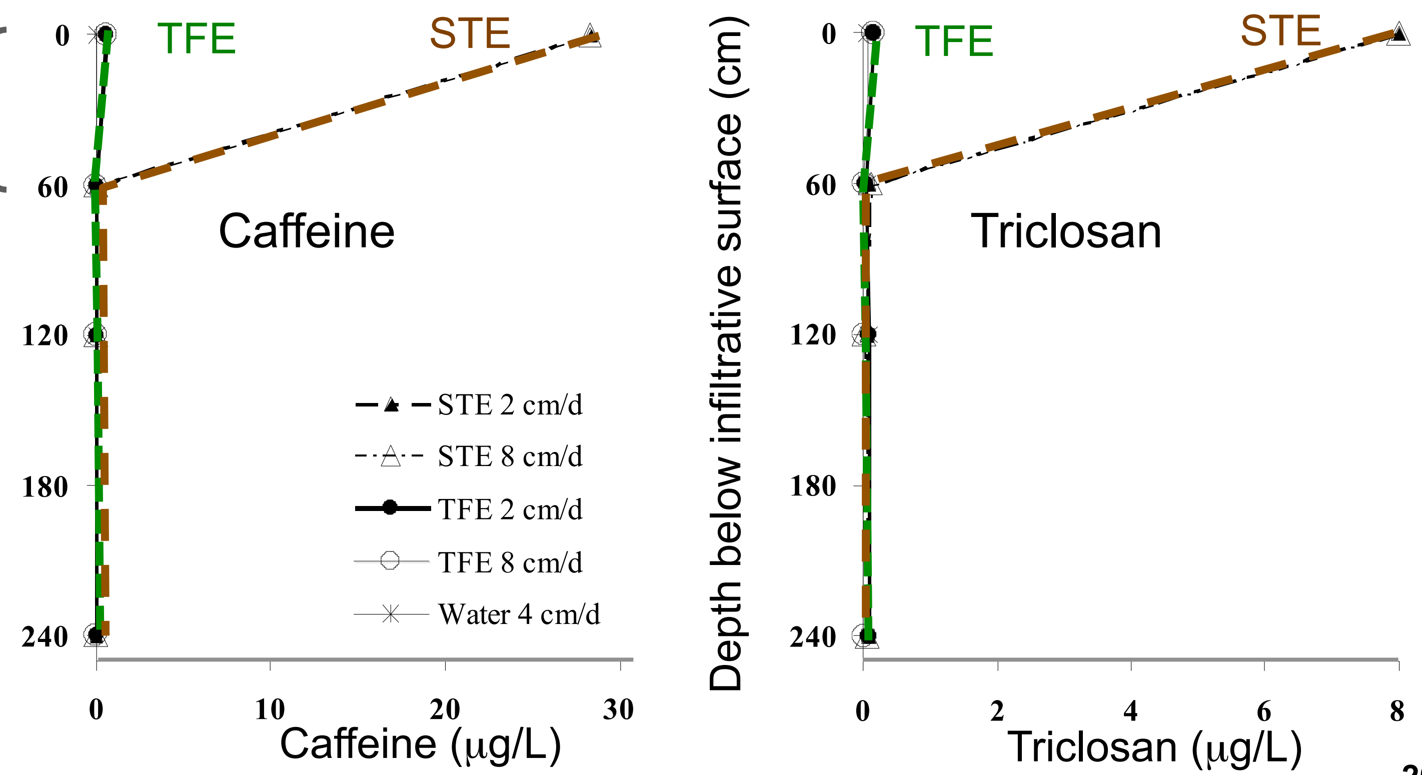




Source: Dimick 2005, Van Cuyk *et al.* 2005, Lowe and Siegrist 2008.

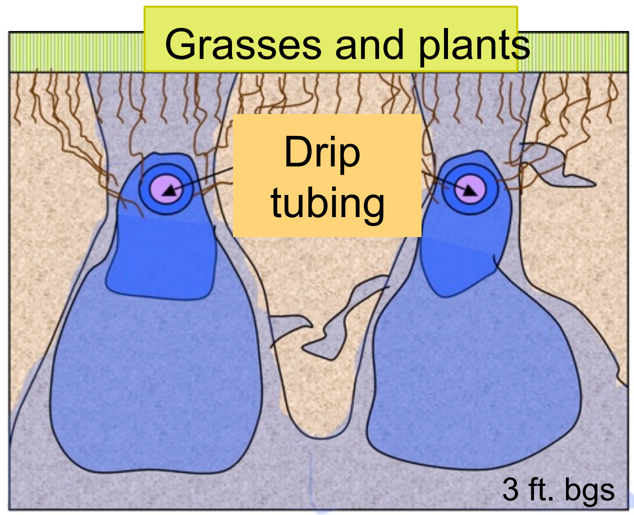
- Consumer product chemical removal Is dependent on soil properties and profile conditions as well as compound properties
  - e.g., Caffeine and Triclosan removal occurs by ≤ 2 ft. (60 cm) below the infiltrative surface if aerobic conditions are present

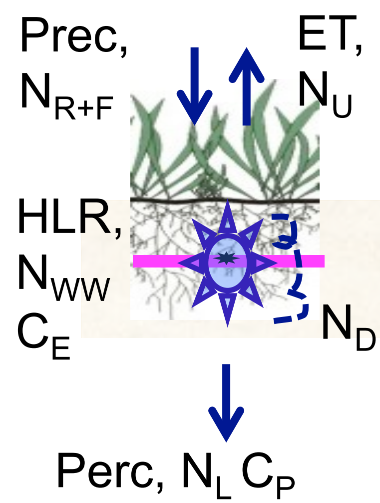
Removal by 60 cm depth



Source: Conn *et al.* 2010.

- Effluent dispersal into the shallow subsurface
  - Drip dispersal can enable effective onsite treatment plus beneficial reuse of wastewater resources in a semi-arid climate





During 2 yr. of dispersal of STE in a sandy loam in CO:

HLR @ 0.24 gpd/ft^2 ➔ Perc = 64%

HLR @ 0.12 gpd/ft^2 ➔ Perc = 34%

Water filled porosity in profile was >85% v/v

Removal of effluent N dispersed = 51%

NO_3-N in soil water at 3 ft. avg. 24 mg-N/L

Fecal coli. and *E. coli.* were eliminated

$$HLR = (ET - Prec) + Perc$$

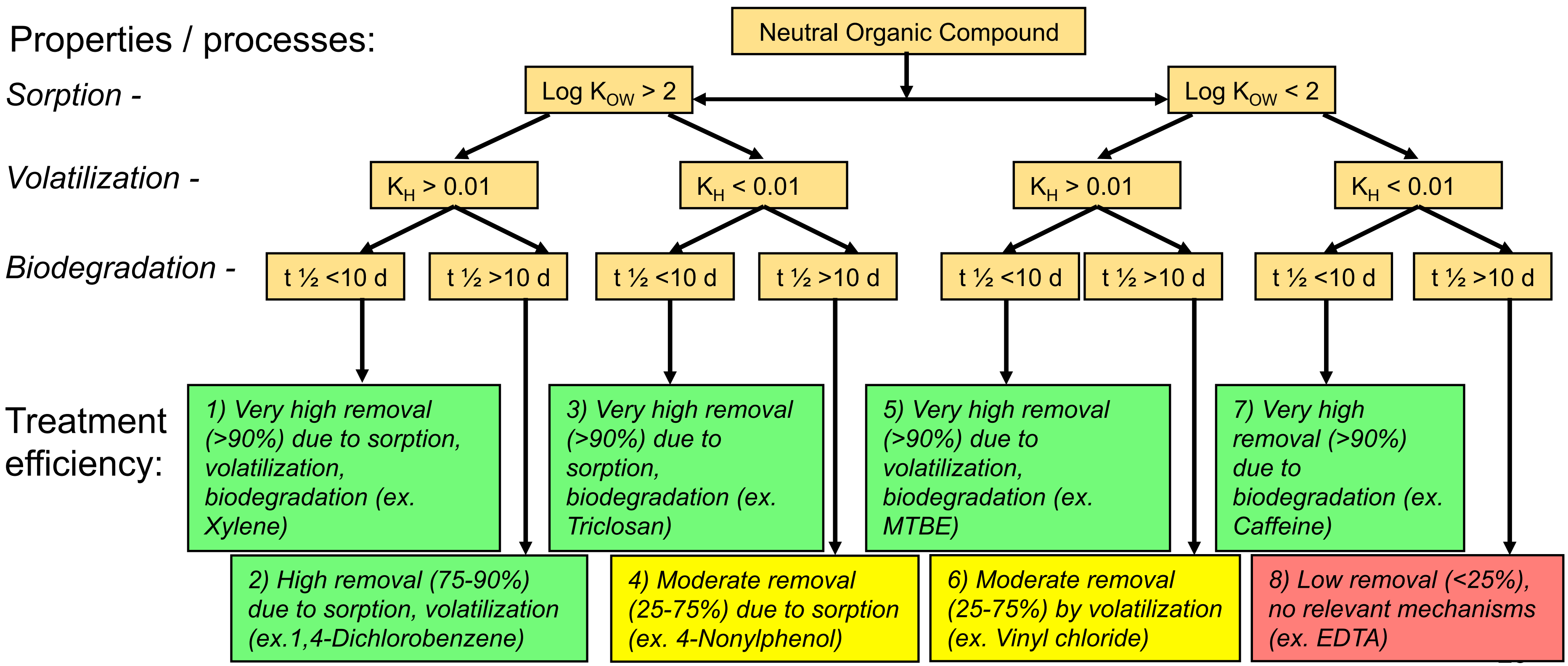
$$= (N_{WW} + N_{R+F}) - (N_U + N_D)$$

Source: Parzen *et al.* 2007, Siegrist *et al.* 2014.

Research: Modeling and Decision Support

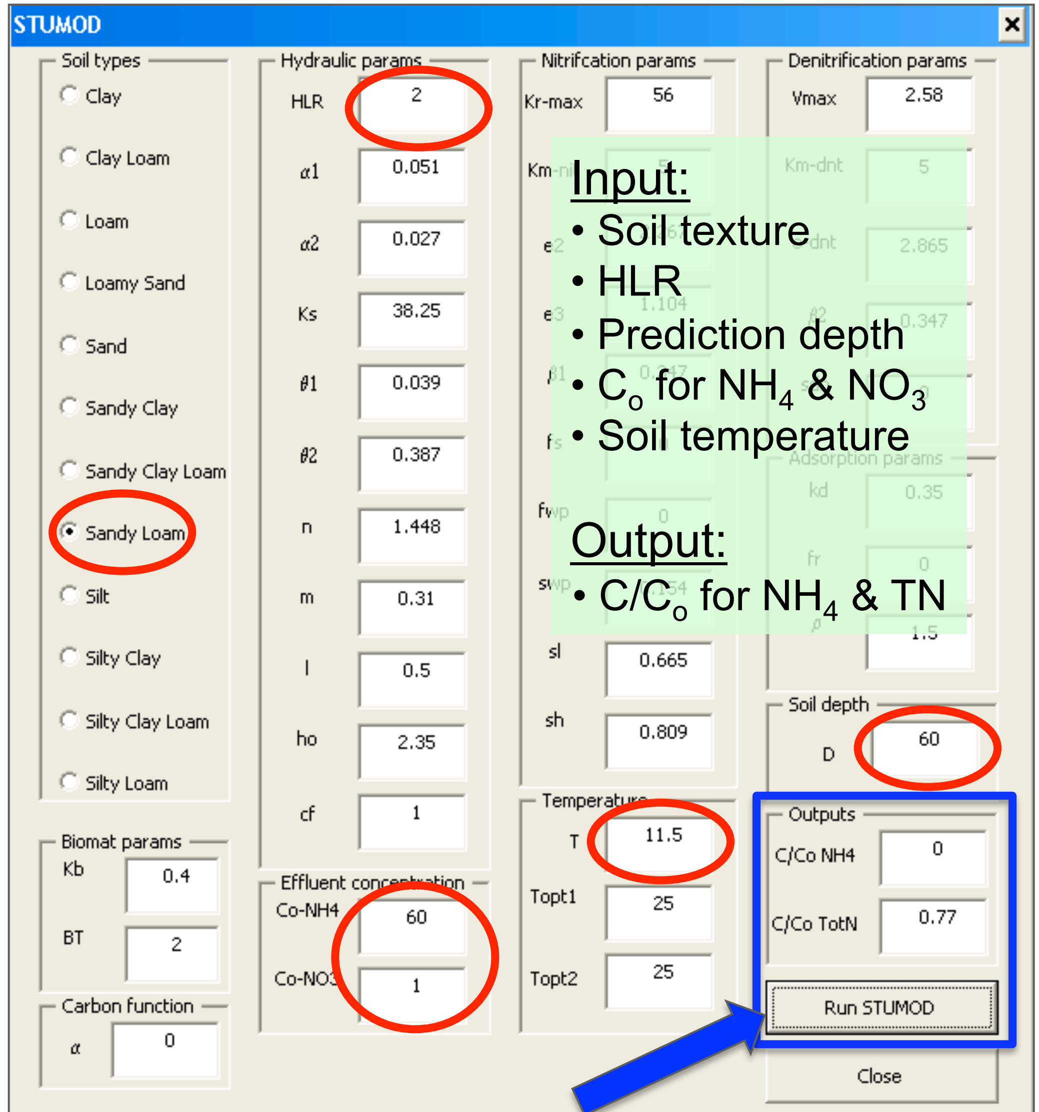
- *Can mathematical models and other tools be developed and made useful for decision-making?*
  - CSM projects sponsored by U.S. EPA, WERF, and private industry have examined, adapted, and developed different types of models and tools for different purposes
    - Decision diagrams for system selection
    - Analytical models of unit operations for system design
      - Design equations
      - Spreadsheet calculators
    - Numerical models to demonstrate and examine system performance based on design and environmental conditions
    - Watershed-scale models to link onsite and decentralized systems with the environment and other sources of pollutants

- A CSM project completed for USGS developed decision support for the occurrence and treatment of organic chemicals
  - Source activities ➔ occurrence
  - Compound properties & treatment processes ➔ removal efficiencies



Source: Conn 2008, Conn and Siegrist 2008.

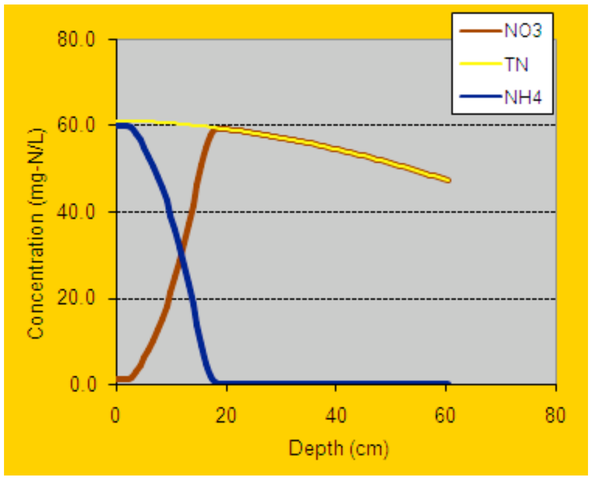
- A CSM project funded by WERF supported development of STUMOD – a model for soil treatment
  - Analytical modeling using complex flow and transport equations is implemented via a spreadsheet
  - Input data on system conditions and output for pollutant removal with depth



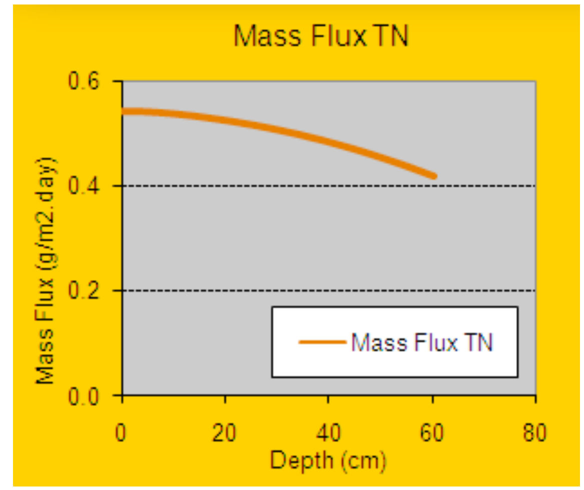
Source: Geza *et al.* 2011, McCray *et al.* 2010.

- Example output from a STUMOD simulation of nitrogen removal

Concentration of N species with depth (mg-N/L)

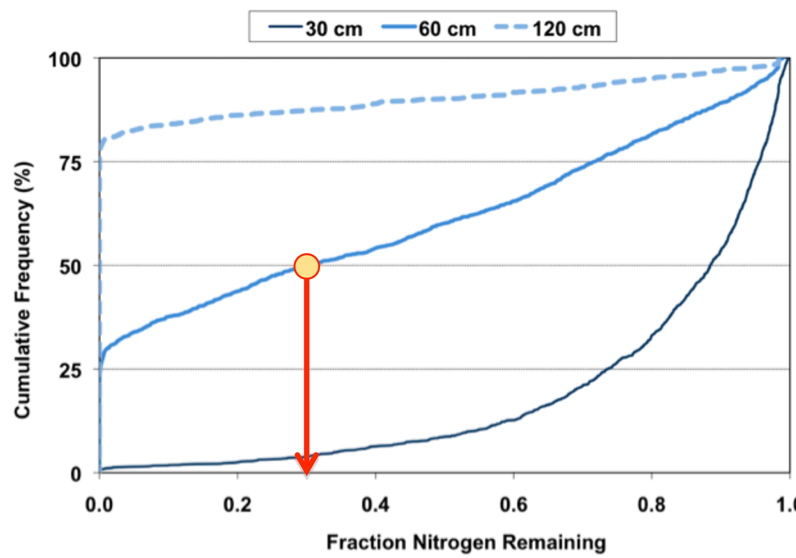


Mass per time per footprint area (g-N/m²/day)

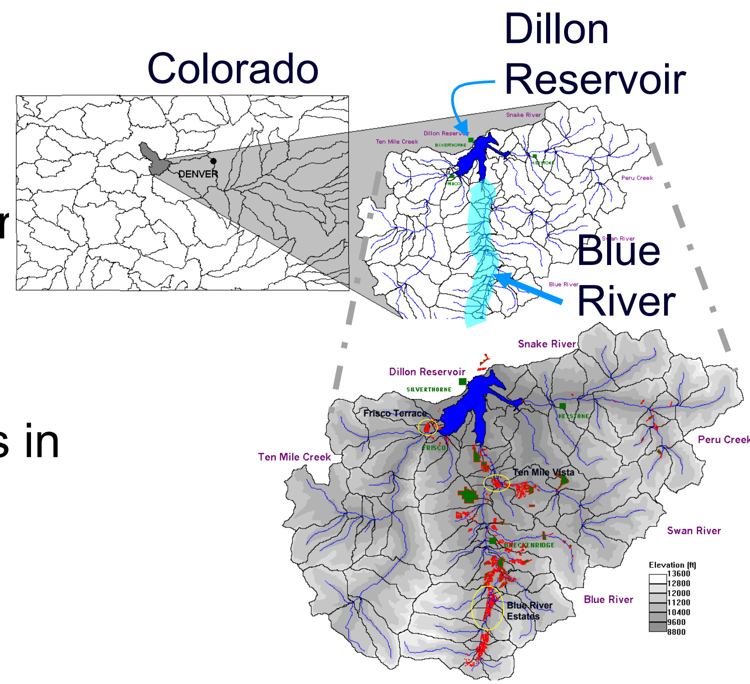


Probability distribution that a given removal will occur under specified conditions

e.g., there is a 50% probability of 70% nitrogen removal at 60-cm depth



- A CSM project funded by USEPA examined watershed-scale modeling
  - Link onsite systems at single sites or developments with the environment and other sources of pollutants
  - Comparative application of 3 models in the Blue River basin
    - MANAGE, SWAT and WARMF
    - A focus was on WARMF
      - Five linked modules including Consensus and TMDL modules
      - Physically based, dynamic model
        - Driven by meteorology, land use, point sources, fertilizer, air quality data,...
        - Simulates temperature, DO, TSS, N, P, fecal coli., Chl-a, etc.



Source: Siegrist *et al*. 2005, McCray *et al*. 2009.

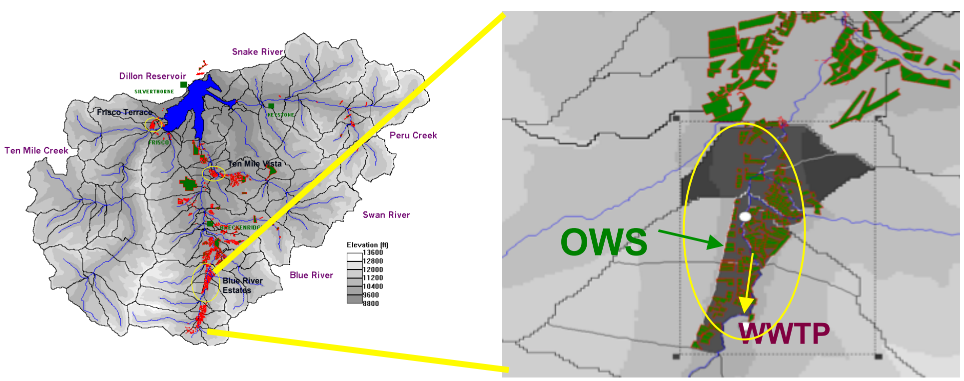
- Example decision that watershed modeling can help inform
  - Benefits to water quality by converting 906 residents from onsite (362 onsite systems) to an existing centralized plant?
  - Results of model simulations revealed that there would be little or no benefit to water quality in the Blue River by centralization
  - But there would be known and potential costs

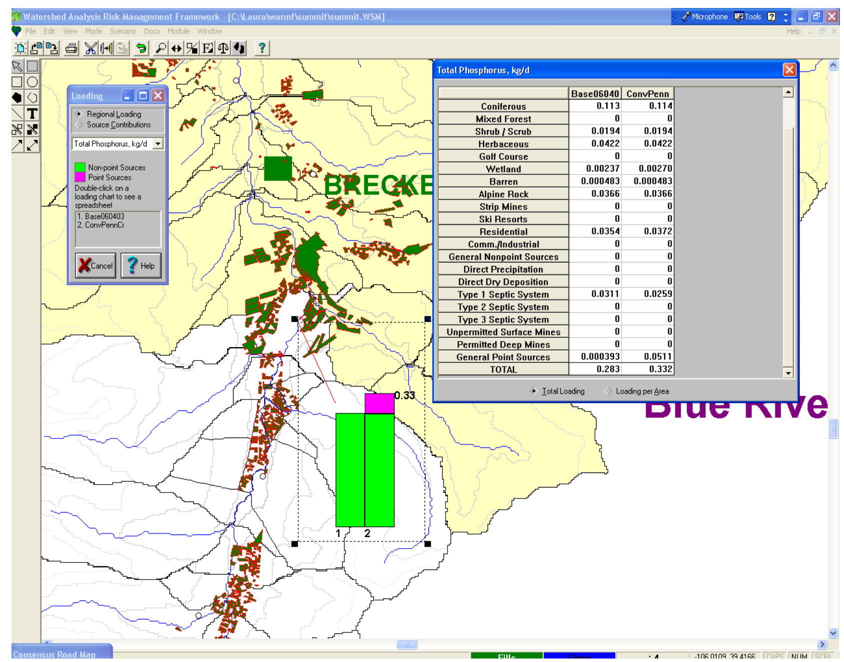
:Changes in P loading to the River:

Nonpoint P ⇓

Point P ⇑

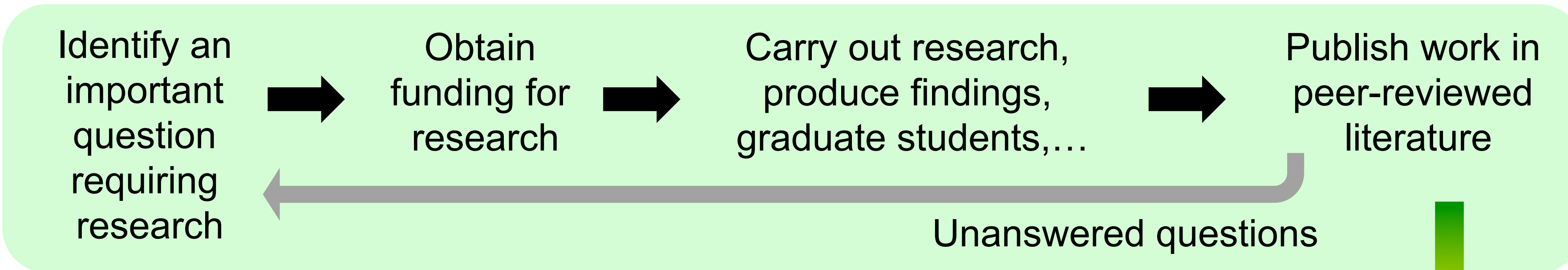
Total P load ⇑





Research Findings ➔ Practice?

- Research findings do not automatically yield advances



- Clear and compelling findings can foster advances
- But improved practices also require:
  - Translation of findings so they convey knowledge and know-how to designers, contractors, regulators, policy makers,…
  - Adoption of findings into modern regulations and requirements
  - Education of students who can help catalyze change

This can take a lot of effort and a long time…a generation or more…

Example of research findings being adopted into practice

Design hydraulic loading rates (HLR_D) that account for effluent quality when sizing the area required for soil infiltration

25+ years

1980 and before: Conflicting views and lack of evidence of how infiltration rates in soil might be affected by effluent quality

1980's: Field research initiated by Siegrist *et al.* in Wisconsin to examine effluent quality effects through longer-term controlled field research

1987: Journal papers were published documenting effects of effluent quality on infiltration rates (Siegrist and Boyle 1987; Siegrist 1987)

1998 – 2008: Research continued at CSM and elsewhere confirming and extending earlier findings (e.g., Van Cuyk *et al.* 2005, Lowe and Siegrist 2008)

2006 – 2008: Trade journal articles and conference papers were prepared describing a rational design process for soil treatment units, including how HLR_D could be selected to account for effluent quality (Siegrist 2006, 2007, 2008)

2013…: Major revision of Colorado regulations including different HLR_D for different types of effluent qualities (Colorado Reg. 43)

- Example of mainline university course development
  - During my years at UW Madison (1968 to 1987)…
  - Some course development efforts at UW and other universities
  - Curriculum development work by CIDWT
  - At CSM, development of a new course within degree programs
    - “CEEN472 - Onsite Water Reclamation and Reuse”
      - First delivered in Spring 2006 as a special topics course
      - Approved as a mainline course in March 2008
      - Delivered each spring semester as a 3-credit elective for upper level undergraduate and graduate students
      - Scope: source characteristics and manipulation, alternative sewers, reactor-based treatment and disinfection, landscape-based treatment and dispersal, monitoring and controls, performance assurance and management
      - Enrollments are 15 to 25 students – approx. 200 to date

CEEN472 – Onsite Water Reclamation and Reuse

Course Syllabus - Spring Semester, 2014

Time: 2:00 – 3:15 p.m., Tuesdays and Thursdays
Location: Coolbaugh Hall, Room 210
Instructor: Robert L. Siegrist, Ph.D., P.E., BCEE, Professor, CEE
Office: Coolbaugh 112A Telephone: 303.384.2158 Email: siegrist@mines.edu
Office Hours: Tuesdays and Thursdays, time to be determined

Course Purpose and Scope:

In the U.S. and most industrialized nations, infrastructure for water supply and wastewater management was built during the 20th Century without much concern for sustainability. However, as we entered the 21st Century, concerns emerged about wasteful use of drinking water, the impacts of leaking sewers and sewer overflows, the risks of and impacts from treatment plant failures, and the high costs of energy and chemical requirements. There was growing interest in onsite and decentralized wastewater systems and how they could be used to protect public health and maintain environmental quality while minimizing resource consumption, having low energy and chemical consumption, and enabling beneficial reuse of water and nutrients. This course covers the selection, design, and implementation of onsite and decentralized systems for wastewater treatment and localized water reclamation and reuse. Topics covered include: typical water use and wastewater generation, water use efficiency and source separation, effluent conveyance, engineered and natural treatment units, disinfection units, system monitoring and performance assurance, and resource efficient approaches and systems for common scenarios. The approaches, technologies and systems are targeted for the U.S. and similar industrialized nations, but also have wide applicability in the developing world.

Course Requirements:

The work requirements in this course consist of five homework assignments and a class project (some or all done in teams (e.g., 2 to 3 students)) and two in-class exams (completed individually). The class project is anticipated to involve a critical review of an approach or technology – or - selection and design of a system for a development complex. For the class project, each team will prepare a written report and give a presentation to the class. All work carried out must be neat, clear and understandable, include any supporting references and data analysis, and be submitted by the due date assigned (unless a pre-approved excuse is granted). All members of a team must contribute to completion of the team-based work and all are expected to understand all components of the work carried out and submitted. The final grade for the course will be based on the percentage of possible points earned (with ~40% associated with homeworks, 40% with exams, and 20% with the class project). It is anticipated that final grades will be assigned as: A = 90-100; A-=88-89; B+=86-87; B=80-85; B-=78-79; C+=75-77; C=70-74; C-=68-69; D+=65-67; D=60-64; F=<60. During the semester, there may be opportunities to earn extra credit and improve your grade.

Course Prerequisites:

CEEN301 (ESGN353) or consent of instructor.

Principal References:

Instructor lecture materials and other information distributed to students registered in CEEN472. Supplementary reference materials can be found in the list attached to this syllabus.

Closing Remarks

- Research and educational efforts during the past decade have helped advance the application of modern onsite and decentralized wastewater systems
- Advances will continue, with a growing impact on applications in urban areas
  - NSF ERC: "Reinventing the Nation's Urban Water Infrastructure"
    - The ERC has a broad array of research and educational thrusts
    - Onsite and decentralized systems are included in ReNUWIt

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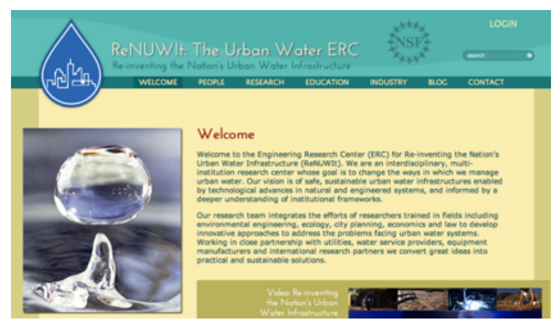

- Thank you for listening …!

Acknowledgements

- CSM Small Flows Program and the AQWATEC Center
  - Faculty and staff
    - Kathryn Lowe, John McCray, Jörg Drewes, Tzahi Cath, Mengistu Geza, John Spear, Jill Tomaras, Sheila Van Cuyk, *et al.*
  - Students and post-doctoral fellows
    - John Albert, Jan Benecke, Jennifer Bagdol, Debbie Huntzinger-Beach, Kathy Conn, Charlotte Dimick, Sarah Doyle, Kirk Heatwole, Jochen Henkel, Ryan Holloway, Shiloh Kirkland, Paula Lemonds, Andy Logan, Jim McKinley, Rebecca Parzen, Ana Prieto, Tanja Rauch, Nate Rothe, Kyle Tackett, Bryce Tillotson, Mia Tucholke, Dave Vuono, Ryan Walsh, Phillip Zelenak, *et al.*
  - Program Sponsors
    - CSM and its Research Foundation, USEPA, USGS, NSF, WERF, DoEd, along with contracts and philanthropic grants from private industry

Associated Research Publications

Cath TY. 2012. ReNUWIt Research highlights: Tailored Water Reuse. Presentation at the ReNUWit NSF Engineering Research Center Annual Review meeting, Stanford University, Palo Alto, CA. May 2012.

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