Soil Treatment Units used for Effluent Infiltration and Purification

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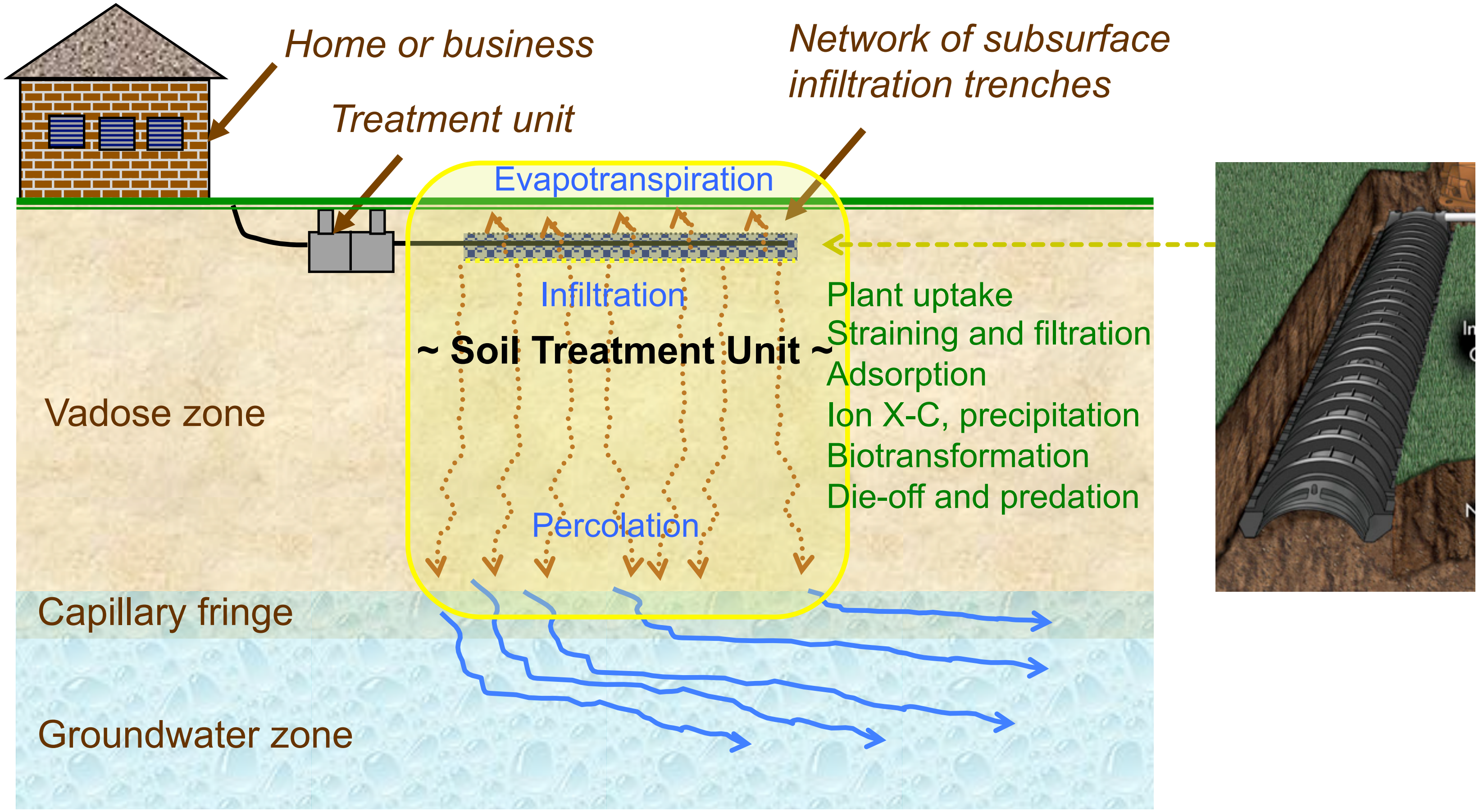
Introduction

- Most onsite wastewater systems in the USA include a unit operation involving a soil profile within a landscape
- Historically, soil was used for simple waste disposal
- A modern design goal is to achieve long-term treatment
  - Terminology has evolved to reflect this goal
    - Historical = Leachfield, Drainfield, Soil Absorption System
    - Contemporary = Dispersal Area, Soil Treatment Area (STA), Soil Treatment Unit (STU)
- We now have the knowledge and tools to support a rational design process for a modern STU
  - To achieve tertiary treatment with natural disinfection

Technology Overview

- Illustration of a modern “Soil Treatment Unit” (STU)
  - Design for long-term tertiary treatment with natural disinfection



Treatment performance expectations

- Expect tertiary treatment with natural disinfection
- By 3-ft depth, it is reasonable to expect soil pore water to reflect the following pollutant and pathogen removals:
  - BOD_5 and TSS = 95% removal (C = 5 to 10 mg/L)
  - Nitrogen = 20% removal of total N (C = 45 mgN/L)
  - Phosphorus = 99% removal (C = <0.1 mg/L)
  - Pathogens = ≥99.99% removal
  - Organic chemicals = 90 to 100% removal
- Further treatment occurs during deep percolation, assimilation into the groundwater, and migration away from the site

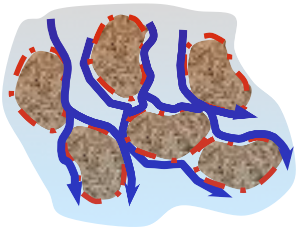
Principles and Processes

- Major processes affecting treatment performance
  - Effluent infiltration into soil pore networks
  - Effluent water movement within a soil profile
    - Percolation – movement within the pore network
    - Groundwater recharge – transport into groundwater
    - Evapotranspiration – transport up and out of the soil
  - Effluent pollutant and pathogen removal reactions
    - Kinetic reactions (e.g., biodegradation)
    - Capacity-based reactions (e.g., filtration, sorption)
    - Plant-based reactions (e.g., nutrient uptake)
- These processes can interact in a dynamic manner as the soil treatment unit matures

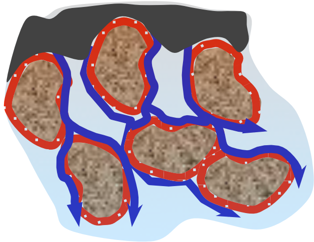
Effluent Infiltration …

- Infiltration of effluent into a soil pore network depends on the same factors that govern infiltration of clean water
- However, there are important differences in three areas
  - Expandable clay minerals - *avoidable*
    - If a soil profile has expandable clay minerals, addition of effluent water can cause swelling and a reduced Ksat
    - Water chemistry interactions can also cause dispersion of clays and reduce Ksat
    - Both effects can reduce the infiltration capacity of the soil
  - Damage during construction - *avoidable*
    - If construction is done poorly, soil compaction and smearing can cause soil pores to be blocked /sealed and this can greatly reduce the infiltration capacity compared to that of undisturbed native soil

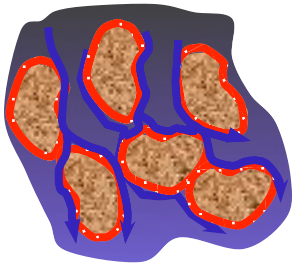
- Effluent effects on an infiltrative surface (IS) zone - *manageable*



  - I. Biofilms within the soil pores (~6 to 12 in. depth)
    - Biofilms form as water, nutrients & microbes enter the soil pore network
    - Biofilm biomass may die off and be degraded



  - II. A biomat on the infiltrative surface (~1 to 4 in. height)
    - Suspended solids can be filtered out and form a biomat on top of the soil infiltrative surface
    - Some of the filtered solids may be biodegradable and slowly decay



  - III. Pore-filling beneath the infiltrative surface (~1 to 2 in. depth)
    - Humic substance like materials can evolve over time
    - Yield a ‘glue’ that retains water and matter in soil pores at and just below the effluent infiltration location

- Infiltration capacity declines during longer-term operation
  - Declines are due to biomat formation (II) and pore-filling (III) at and near the location where effluent enters the soil pore network
    - Concept of 3 phases and a long-term acceptance rate (LTAR)
      - For long-term operation, the HLR$_D$ is set at or near the LTAR

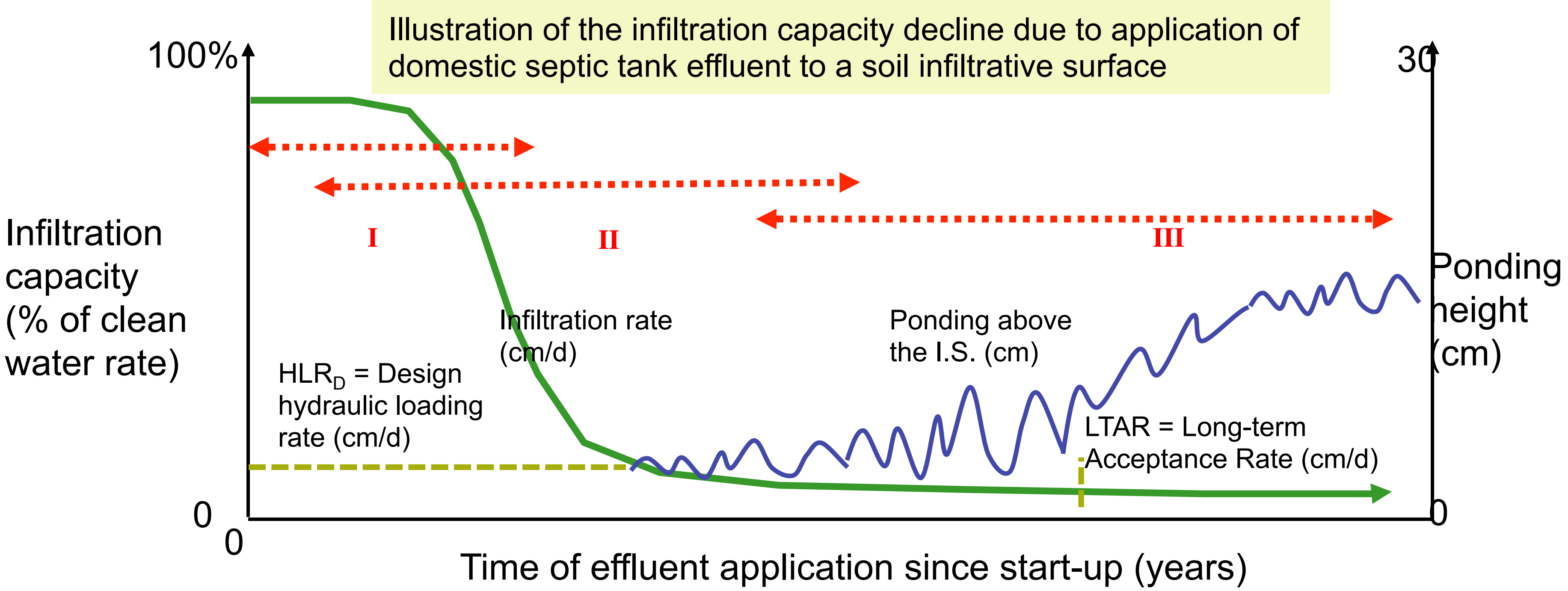


Illustration of the infiltration capacity decline due to application of domestic septic tank effluent to a soil infiltrative surface

- Key factors that affect infiltration capacity and a LTAR
  - Soil properties and site conditions - *given*
    - Soil texture and structure in and near the dispersal zone
    - Soil profile lithology and hydrogeology
    - Site climatic and hydrologic conditions
  - Design and operation - *chosen*

Interactions

    - Effluent application rate and method
      - Hydraulic loading rate (HLR)
      - Frequency, uniformity, and continuity of effluent application
    - Effluent quality
      - BOD, Kjeldahl N, Suspended Solids
    - Infiltrative surface architecture
      - Geometry and depth
      - Infiltrative surface features

- Infiltration capacity as affected by HLR and effluent quality
  - Infiltration rate decline caused by effluent application is most strongly impacted by HLR and effluent composition
    - IR decline = f (mass loading of long-term BOD (carbonaceous plus total Kjeldahl nitrogen) and total suspended solids)

$$\frac{IR_t}{IR_o} = \frac{\exp\left[2.63 - 5.70\left(\text{tBOD}\right) + 41.08\left(\text{TSS}\right) - 0.048\left(\text{tBOD x TSS}\right)\right]}{1 + \exp\left[2.63 - 5.70\left(\text{tBOD}\right) + 41.08\left(\text{TSS}\right) - 0.048\left(\text{tBOD x TSS}\right)\right]}$$

Where,

IR_t = infiltration rate after a period of operation (cm/d)

IR_o = infiltration rate at startup (cm/d)

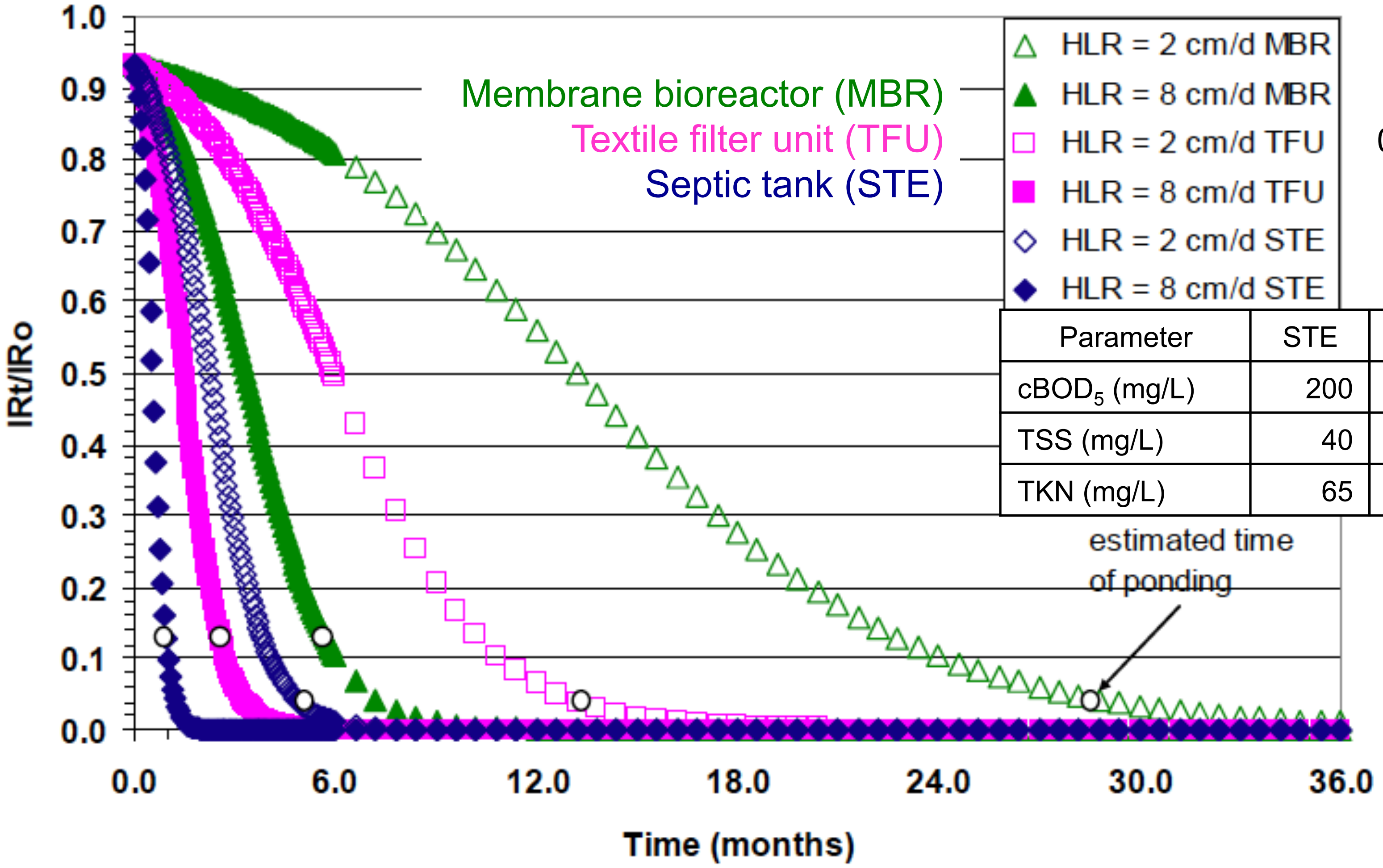
tBOD = cumulative mass loading of tBOD applied to the infiltrative surface after a period of operation (kg/m^2)

= ultimate cBOD plus nBOD

TSS = cumulative mass loading of TSS applied to the infiltrative surface after a period of operation (kg/m^2)

Source: Siegrist 1986, Siegrist and Boyle 1987.

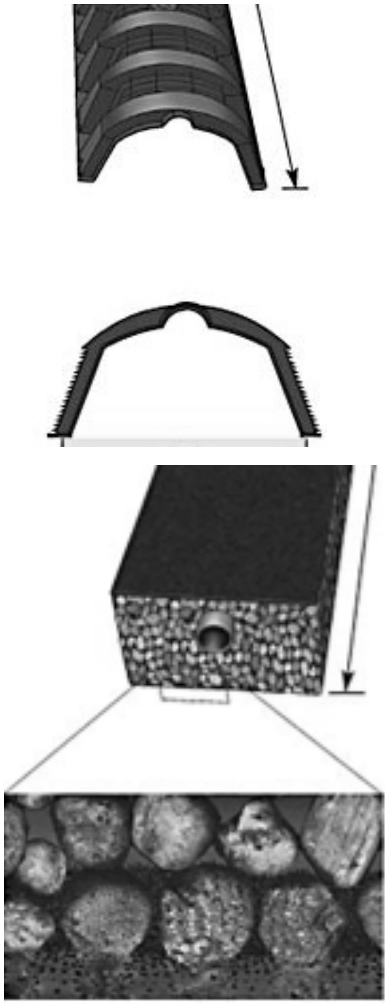
- Illustration of infiltration rate declines



1 cm/d =
0.245 gal/d/ft^2

Parameter	STE	TFU	MBR
cBOD$_5$ (mg/L)	200	10	2
TSS (mg/L)	40	10	2
TKN (mg/L)	65	40	15

Simulated infiltration capacity decline as affected by effluent quality and loading rate in a sandy loam soil in Colorado.
Source: Van Cuyk *et al.* 2005 with simulations based on the model of Siegrist and Boyle 2007.



- Infiltration capacity as affected by infiltrative surface architecture
  - Narrow, short trenches placed shallow in the soil profile can:
    - Benefit from higher porosity, organic matter, aeration,…
  - Chambers (without buried stones or similar media) can:
    - Avoid compaction and fines from ‘dirty’ gravel media
    - Avoid pore entry blockage and embedment
    - Enable inspection and maintenance as needed
  - Hydraulic loading rates to the soil infiltrative surface
    - For STE
      - LTAR for open surface > object laden surface
    - For TFE and similar higher quality effluents
      - LTARs for open surface ≅ object laden surface

Source: Walsh 2006, Siegrist 2007, Lowe and Siegrist 2008.

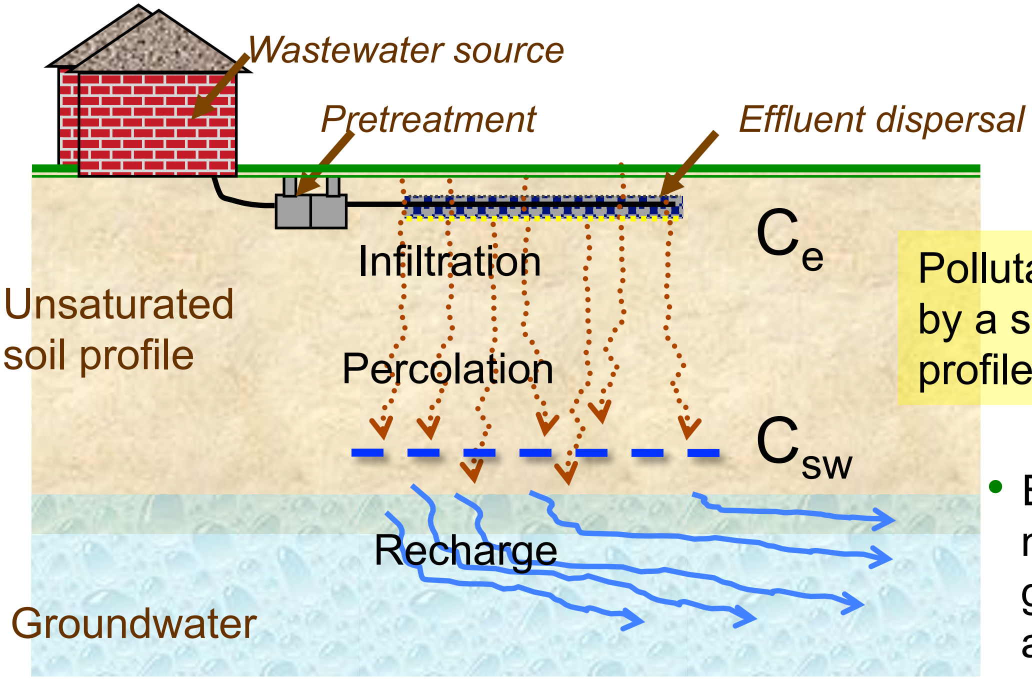
Effluent Pollutant & Pathogen Removal …

- Soil profile attributes need to be favorable to treatment
  - Adequate hydraulic conductivity for water movement
    - Native soil K_{sat} > 1 to 2 gpd/ft^2
  - Adequate soil profile depth
    - Depending on effluent loading rate and quality, only 2 to 4 ft. of unsaturated soil is typically needed
  - Conditions conducive to pollutant and pathogen removal
    - Unsaturated soil with film flow over soil grains and long travel times for kinetic processes (e.g., BOD and NH_4^+ removal, virus inactivation)
    - Adequate volume of soil to provide grain surface area for biofilms and sorption reactions (e.g., P removal)
    - Properties conducive to treatment (e.g., circumneutral pH, high Eh, moderate temperatures, no biotoxins)

- For treatment, design factors control the types and rates of reactions plus the hydraulic retention time (HRT)
  - Hydraulic loading rate (HLR) and effluent quality
    - HLR and effluent quality can affect infiltration capacity, uniformity of infiltration and HRT in the soil profile
  - Method of effluent delivery and application
    - The application method can affect uniformity of infiltration, unsaturated flow conditions, and HRT
  - Infiltration depth and unsaturated zone properties
    - Depth affects aeration and plant-based processes
    - Unsaturated zone thickness affects aeration and HRT
    - Soil properties can affect reactions and rates (e.g., pH, Eh, mineralogy, natural organic matter content)

- Assessing pollutant and pathogen removal
  - Unlike a tank-based unit, with effluent dispersal in soil there is not an outlet pipe discharging a treated effluent
    - Treatment is often based on concentrations in soil pore water at a specified depth (C_{SW}) compared to the effluent applied (C_E)

$$\%\text{Removal} = \left[\frac{C_E - C_{SW}}{C_E}\right] \text{x } 100\%$$



Pollutant and pathogen removals by a specified depth in the soil profile (e.g., 3 ft.)

- But…Treatment also occurs by natural attenuation during groundwater recharge and flow away from the site

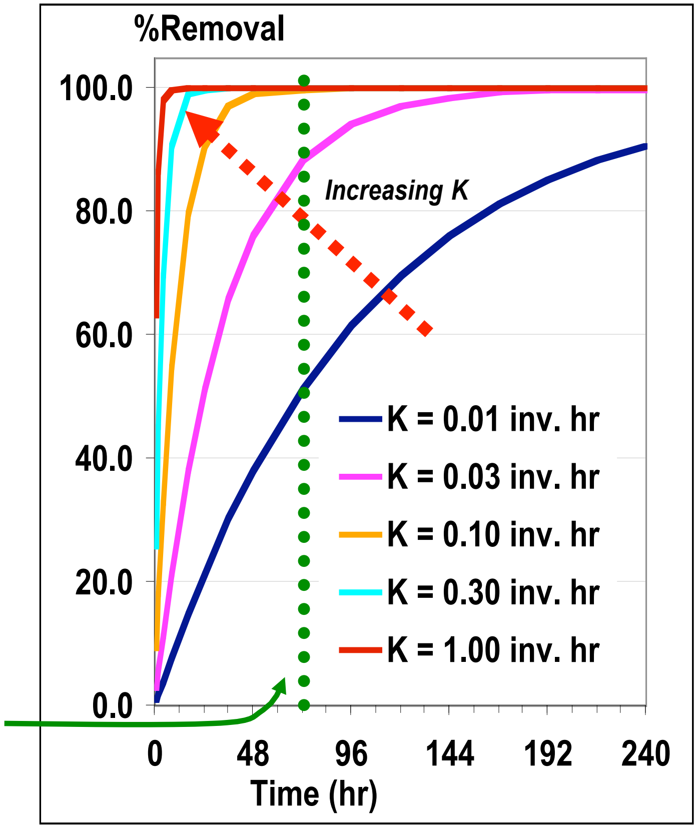
- Assessing treatment *efficiency* by concentration (Δ C)
  - Purification of many effluent constituents is achieved by kinetic reactions (e.g., BOD removal, bacterial die-off)
  - For unsaturated plug flow and 1st-order kinetics

$$\%\text{Removal} = \left(1 - e^{-Kt}\right) \times 100$$

$$t = \frac{(d)(n_e)}{q}$$

where,

K = 1st-order reaction rate (hr^{-1})
t = retention time for reaction (hr)
d = unsaturated soil depth (cm)
n_e = effective porosity (v/v)
q = hydraulic loading rate (cm/hr)



t = 72 hr for d = 60 cm, n_e = 0.2, q = 4 cm/d

Source: Siegrist 2007.

- Assessing treatment *effectiveness* by mass discharge (M_d)

$$M_d = \Sigma J_i A_i$$

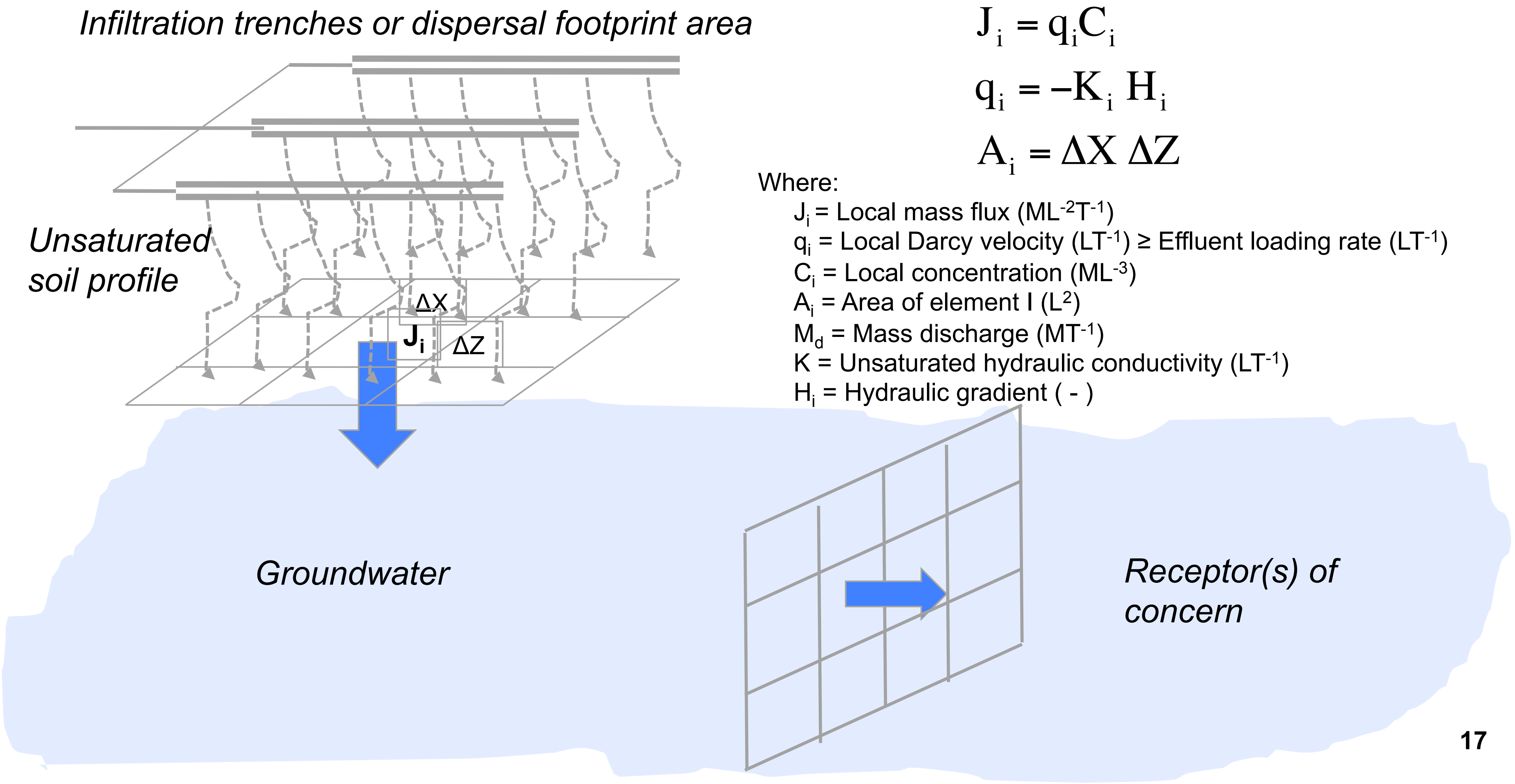
$$J_i = q_i C_i$$

$$q_i = -K_i H_i$$

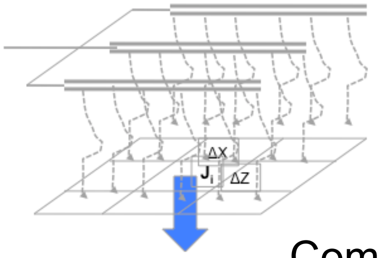
$$A_i = \Delta X \, \Delta Z$$

Where:

J_i = Local mass flux ($ML^{-2}T^{-1}$)
q_i = Local Darcy velocity (LT^{-1}) ≥ Effluent loading rate (LT^{-1})
C_i = Local concentration (ML^{-3})
A_i = Area of element I (L^2)
M_d = Mass discharge (MT^{-1})
K = Unsaturated hydraulic conductivity (LT^{-1})
H_i = Hydraulic gradient (-)



- Mass discharge can be assessed by different methods
  - ❍ Illustration of a spreadsheet model – STUMOD



Complex flow and transport equations are used to estimate pollutant levels with depth

Required input values:
Soil type: Sandy loam
HLR: 3 cm/d
C_o-NH_4: 60 mg-N/L
C_o-NO_3: 1 mg-N/L
T: 15°C
Depth: 90 cm


STUMOD

Soil types
○ Clay
○ Clay Loam
○ Loam
○ Loamy Sand
○ Sand
○ Sandy Clay
○ Sandy Clay
● Sandy Loam
○ Silt
○ Silty Clay
○ Silty Clay
○ Silty Loam

HLR 3
a1 0.051
a2 0.027
Ks 38.25
q1 0.039
q2 0.387
n 1.448
m 0.31
l 0.5
ho 2.35
cf 1

Biomat params
Kb 0.4
BT 2

Carbon function
a 0

Effluent concentration
Co-NH4 60
Co-NO3 1

Nitrifcation params
Kr-max 56
Km-nit 5
e2 2.267
e3 1.104
b1 0.347
fs 0
fwp 0
swp 0.154
sl 0.665
sh 0.809

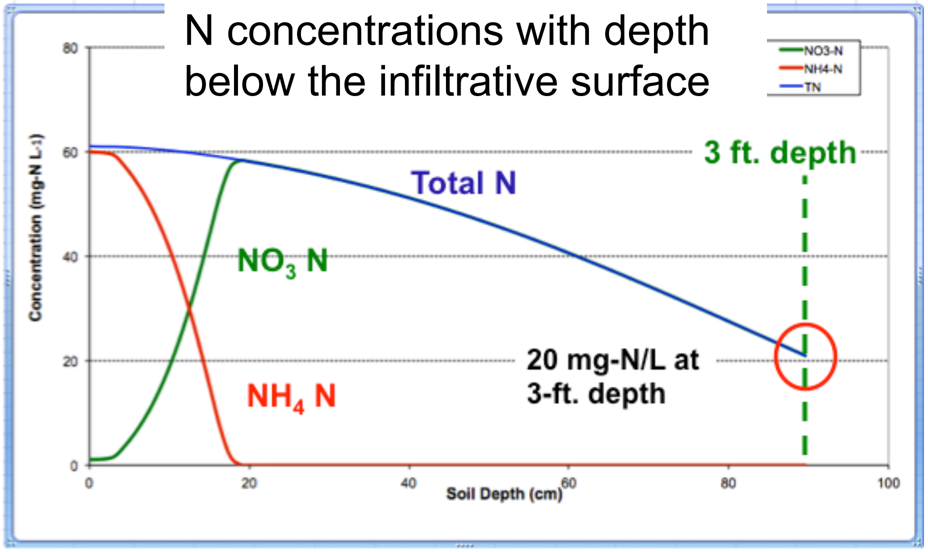
T 15
Topt1 25
Topt2 25

Denitrification params
Vmax 2.58
Km-dnt 5
e-dnt 2.865
b2 0.347
sdn 0

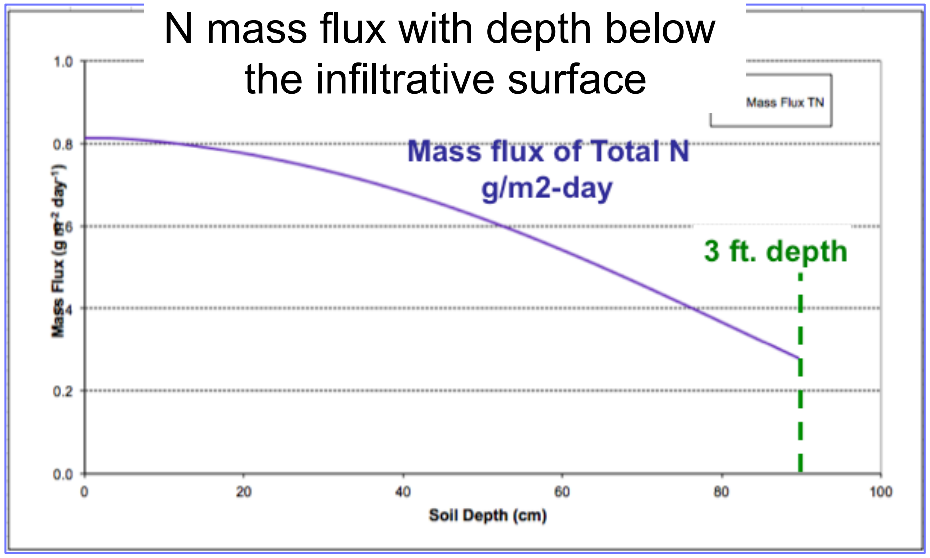
Adsorption params
kd 0.35
fr 0
r 1.5

D 90

Outputs
C/Co NH4 1
C/Co TotN 1


N concentrations with depth below the infiltrative surface

20 mg-N/L at 3-ft. depth

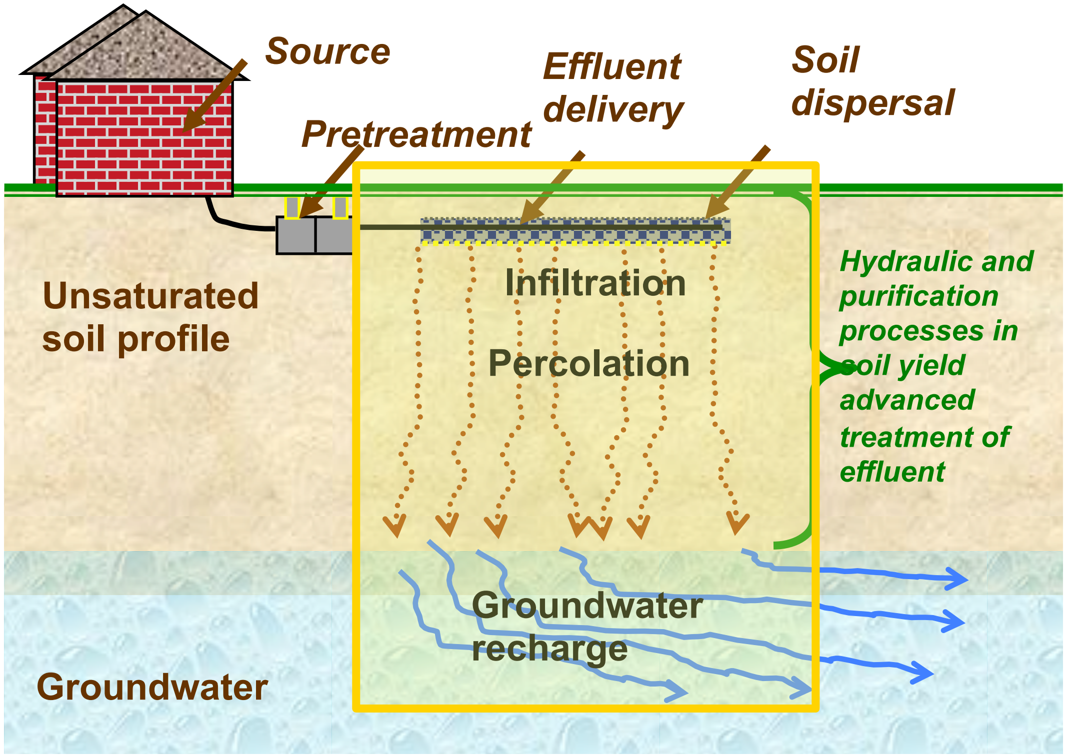

N mass flux with depth below the infiltrative surface

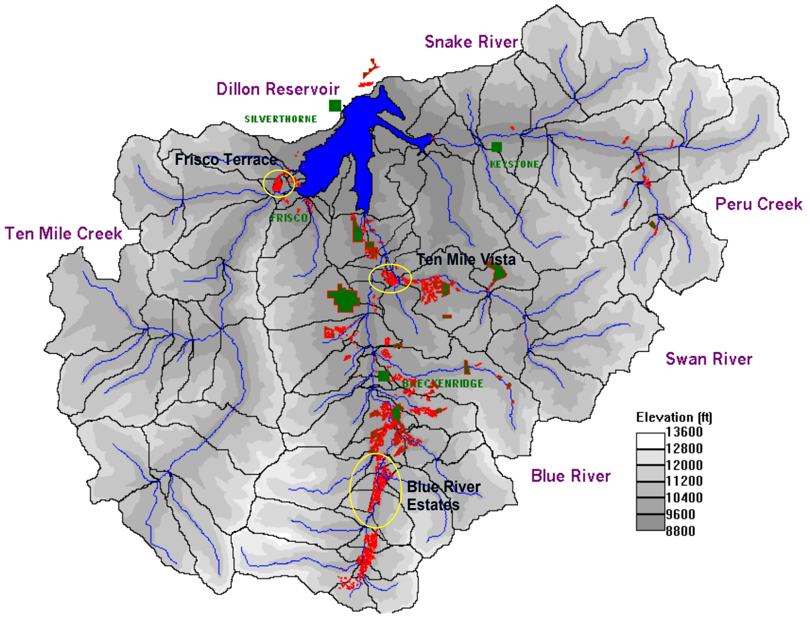
Source: Geza *et al.* 2009, 2010, 2012; McCray *et al.* 2010.

Design and Implementation

- Design and implementation of a soil treatment unit
  - Requires careful consideration of the wastewater source and pretreatment options, along with the soil and site conditions, and treatment goals

Single site scale …..➔…..Development scale …..➔…..Watershed scale





- Key elements to address during rational design of a soil treatment unit for a particular site
  - Treatment goals and method of assessment
  - Suitability of site conditions and soil properties
  - Treatment required prior to application to the soil
  - Architecture of the soil infiltrative surface
  - Effluent application rates for infiltration area sizing
  - Depth of soil required beneath the infiltrative surface
  - Geometry and landscape placement
  - Effluent application and distribution
  - Options for long-term service
  - Installation, startup and operation
  - Monitoring and performance assuranc

Evolving Prescriptive- to Performance-based design:

Challenges and opportunities for science-based design and implementation…

- Research findings ➔ Regulatory reform in Colorado
  - Pre-Modern era onsite regulations in Colorado

    “Guidelines on Individual Sewage Disposal Systems”
    Colorado Dept. Public Health and Environment, Water Quality Control Division
    - 5 CCR 1003-6 62 pp.
    Effective: November 30, 2004; October 30, 2000; …
  - CDPHE ISDS Steering Committee

    “Recommendations of the Individual Sewage Disposal System Steering Committee” February 14, 2002 30 pp.
  - Modern era onsite regulations in Colorado – Reg. 43

    “On-Site Wastewater Treatment System Regulation”
    Colorado Dept. Public Health and Environment, Water Quality Control Division
    - 5 CCR 1002-43 Regulation #43 91 pp.
    Effective: June 30, 2013
  - Highlights of aspects related to *soil treatment area* design

- Reg. 43 recognizes different effluent qualities
  - 5 treatment levels based on $cBOD_5$, TSS, Total N

Treatment level	$cBOD_5$* (mg/L)	TSS (mg/L)	Total Nitrogen (mg/L)
TL 1 **	145	80	60 – 80 mg/L
TL 2	25	30	60 – 80 mg/L
TL 2N	25	30	>50% reduction ***
TL 3	10	10	40 – 60 mg/L
TL 3N	10	10	20 mg/L

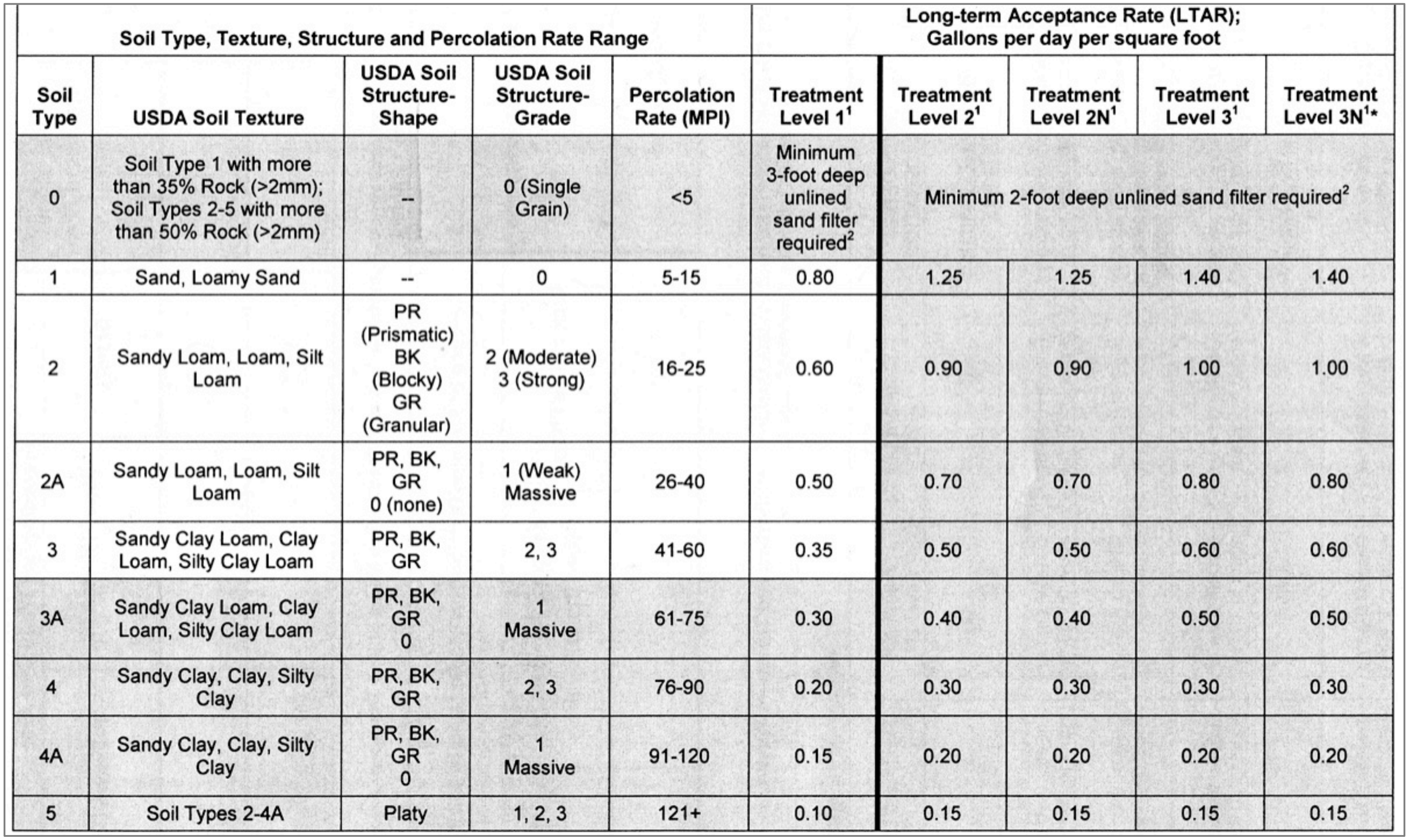
* $cBOD_5$ can be estimated as 0.85 x total BOD_5 .

** Values for TL 1 are typical but design must account for site-specific information.

*** NSF/ANSI Standard 245 – Wastewater Treatment Systems – Nitrogen Reduction requires reduction of 50% rather than achieving a specific value.

Table 6-3. Colorado Reg. 43. June 2013.

- LTARs are based on soil properties and treatment levels
    - LTARs for 5 soil types and 5 treatment levels; 0.10 - 1.40 gpd/ft^2



Soil Type, Texture, Structure and Percolation Rate Range					Long-term Acceptance Rate (LTAR); Gallons per day per square foot				
Soil Type	USDA Soil Texture	USDA Soil Structure-Shape	USDA Soil Structure-Grade	Percolation Rate (MPI)	Treatment Level 1[1]	Treatment Level 2[1]	Treatment Level 2N[1]	Treatment Level 3[1]	Treatment Level 3N[1]*
0	Soil Type 1 with more than 35% Rock (>2mm); Soil Types 2-5 with more than 50% Rock (>2mm)	--	0 (Single Grain)	<5	Minimum 3-foot deep unlined sand filter required[2]	Minimum 2-foot deep unlined sand filter required[2]			
1	Sand, Loamy Sand	--	0	5-15	0.80	1.25	1.25	1.40	1.40
2	Sandy Loam, Loam, Silt Loam	PR (Prismatic) BK (Blocky) GR (Granular)	2 (Moderate) 3 (Strong)	16-25	0.60	0.90	0.90	1.00	1.00
2A	Sandy Loam, Loam, Silt Loam	PR, BK, GR 0 (none)	1 (Weak) Massive	26-40	0.50	0.70	0.70	0.80	0.80
3	Sandy Clay Loam, Clay Loam, Silty Clay Loam	PR, BK, GR	2, 3	41-60	0.35	0.50	0.50	0.60	0.60
3A	Sandy Clay Loam, Clay Loam, Silty Clay Loam	PR, BK, GR 0	1 Massive	61-75	0.30	0.40	0.40	0.50	0.50
4	Sandy Clay, Clay, Silty Clay	PR, BK, GR	2, 3	76-90	0.20	0.30	0.30	0.30	0.30
4A	Sandy Clay, Clay, Silty Clay	PR, BK, GR 0	1 Massive	91-120	0.15	0.20	0.20	0.20	0.20
5	Soil Types 2-4A	Platy	1, 2, 3	121+	0.10	0.15	0.15	0.15	0.15

Table 10-1. Colorado Reg. 43. June 2013.

- Soil treatment area size is adjusted for:
  - System type and effluent application method

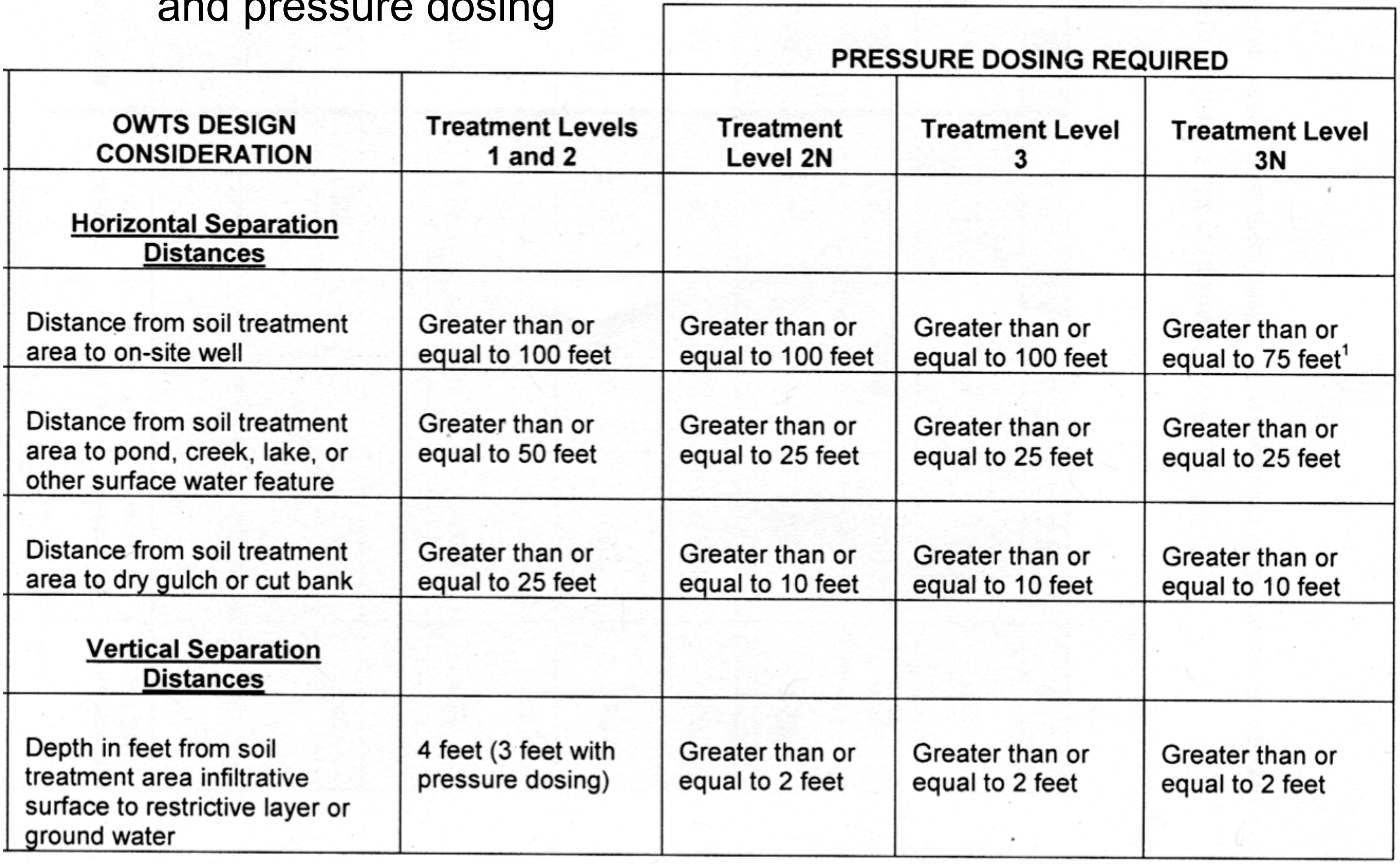
Type of Soil Treatment Area	Method of Effluent Application to Soil Treatment Area		
	Gravity	Dosed (Siphon or Pump)	Pressure Dosed
Trench	1.0	0.9	0.8
Bed	1.2	1.1	1.0

  - Distribution media type (Treatment Level 1)

Type of Soil Treatment Area	Type of Storage/Distribution Media Used		
	Rock or tire chips	Manufactured media other than chambers	Chambers
Trench or Bed	1.0	0.9	0.7

Table 10-2 and 10-3. Colorado Reg. 43. June 2013.

- Separation distances are adjusted based on treatment levels and pressure dosing



		PRESSURE DOSING REQUIRED		
OWTS DESIGN CONSIDERATION	**Treatment Levels 1 and 2**	**Treatment Level 2N**	**Treatment Level 3**	**Treatment Level 3N**
Horizontal Separation Distances				
Distance from soil treatment area to on-site well	Greater than or equal to 100 feet	Greater than or equal to 100 feet	Greater than or equal to 100 feet	Greater than or equal to 75 feet[1]
Distance from soil treatment area to pond, creek, lake, or other surface water feature	Greater than or equal to 50 feet	Greater than or equal to 25 feet	Greater than or equal to 25 feet	Greater than or equal to 25 feet
Distance from soil treatment area to dry gulch or cut bank	Greater than or equal to 25 feet	Greater than or equal to 10 feet	Greater than or equal to 10 feet	Greater than or equal to 10 feet
Vertical Separation Distances				
Depth in feet from soil treatment area infiltrative surface to restrictive layer or ground water	4 feet (3 feet with pressure dosing)	Greater than or equal to 2 feet	Greater than or equal to 2 feet	Greater than or equal to 2 feet

Table 7-2. Colorado Reg. 43. June 2013.

Closing Remarks

- A soil treatment unit can serve as an excellent unit operation within an onsite wastewater system
  - Effluent water movement and pollutant and pathogen removal processes are generally well understood
  - Models and decision aids enable a more rational design process
- Modern soil treatment units can now be relied on to:
  - Achieve tertiary treatment of primary or secondary effluents and accomplish natural disinfection,
  - Provide a receiving environment for reclaimed water, and
  - Provide cost-effective, robust, and sustainable service
- Improved understanding has supported regulatory reform

- Findings are published in peer-reviewed sources, e.g.:

Siegrist RL, Parzen R, Tomaras J, Lowe KS. 2013. Water Movement and Fate of Nitrogen during Drip Dispersal of Wastewater Effluent into a Semi-Arid Landscape, *Water Research*. doi: 10.1016/j.watres.2013.12.031.

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Lowe KS, VanCuyk SM, Siegrist RL, Drewes JE. 2008. Field Evaluation of the Performance of Engineered Onsite Wastewater Treatment Units. *J. Hydrologic Eng.*, 13(8):735-743.

Associated Research Publications

Conn KE, Siegrist RL, Barber LB, Meyer MT. 2010. Fate of Trace Organic Compounds during Vadose Zone Soil Treatment in an Onsite Wastewater System. *J. Env. Tox. and Chemistry.* 29(2):285-293.

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