Soil Treatment Units Used for Effluent Infiltration and Purification within Onsite Wastewater Systems: Science and Technology Highlights

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Abstract

To develop a fundamental understanding of the principles and processes important to soil treatment units used within onsite and decentralized wastewater systems, a program of research has been ongoing for more than a decade within the Small Flows Program at the Colorado School of Mines in Golden, Colorado, USA. Recent and ongoing research concerning soil treatment and assimilation of effluents in the subsurface has been focused on two onsite system approaches: 1) effluent dispersal into a soil profile using shallow trenches outfitted with infiltration chambers and 2) effluent dispersal into the rhizosphere using drip tubing with pressure-compensating emitters. Research has included laboratory experiments, controlled field experiments with pilot-scale systems, field monitoring of full-scale systems, and mathematical modeling. This paper provides a summary of the research carried out. Due to space limitations this paper is focused on soil treatment using subsurface infiltration trenches. While many of the principles and processes are also applicable to soil treatment using drip dispersal of effluent into the rhizosphere, this soil treatment approach is not explicitly covered in this paper.

Keywords: Effluent dispersal in soil, pollutant and pathogen removal in soil.

Introduction

Today, the vast majority of onsite and decentralized systems in the U.S. include a unit operation involving soil to achieve tertiary treatment with natural disinfection (e.g., Siegrist *et al.* 2001, USEPA 2002). Similar to a confined treatment unit (e.g., septic tank, packed bed filter), an unconfined soil profile can be conceptualized as a *wastewater treatment unit operation* that is designed to: 1) hydraulically process and purify the effluent within the soil profile to the extent needed to protect public health and water quality; 2) provide a long service life with low operation and maintenance requirements; 3) enable resource recovery and reuse; and 4) have an affordable cost (Siegrist 2006, 2007). Using the terminology, Soil Treatment Unit, reflects this conceptualization (Figure 1).

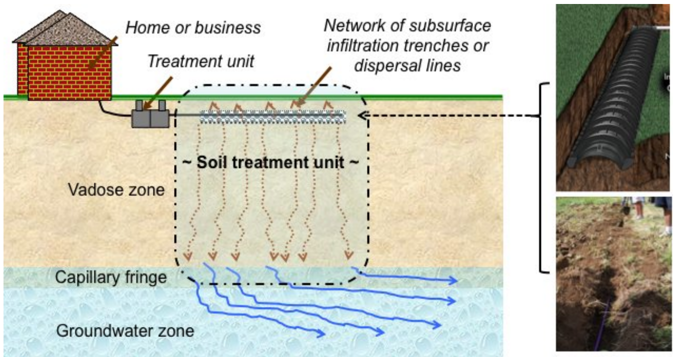


Fig. 1. Illustration of a modern soil treatment unit, which uses infiltration chambers placed in trenches or drip dispersal tubing inserted in the rhizosphere within an *in situ* soil profile for infiltration and purification of primary or secondary treated effluents.

To develop a fundamental understanding of the principles and processes important to the design and performance of soil treatment units used within onsite and decentralized wastewater systems, research has been ongoing for more than a decade within the Small Flows Program at the Colorado School of Mines in Golden, Colorado, USA. Recent and ongoing research has been focused on soil treatment of different quality effluents using two onsite system approaches: 1) effluent dispersal into a soil profile using shallow trenches outfitted with infiltration chambers and 2) effluent dispersal into the rhizosphere using drip tubing with pressure-compensating emitters (Figure 2).

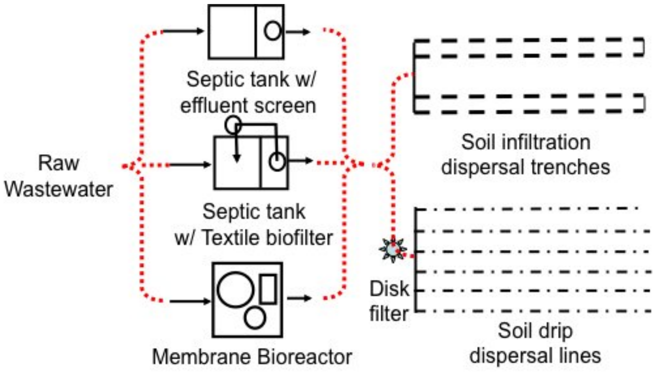


Fig. 2. Schematic of the onsite wastewater system components involved in soil treatment unit research within the Small Flows Program at the Colorado School of Mines.

Within the Small Flows Program, soil treatment unit research has included laboratory experiments, controlled field experiments with pilot-scale units, field monitoring of full-scale systems, and analytical and numerical modeling. The program of research has been conceived to develop a quantitative understanding of soil treatment unit design and performance including flow and transport and the removal of pollutants and pathogens as affected by soil properties, system features, effluent quality and loading, and other design factors and environmental conditions. The research has also developed models and decision-support tools for soil treatment unit applications. This paper provides highlights of the research carried out. Additional details on a given topic may be found in the literature cited. Due to space limitations, this paper is focused on soil treatment using subsurface infiltration trenches. While many of the principles and processes are also applicable to soil treatment using drip dispersal of effluent into the rhizosphere, this soil treatment approach is not explicitly covered in this paper.

Soil Treatment Units and Key Processes

Flow and Transport Processes. When a partially treated effluent (e.g., STE) is applied to soil, effluent infiltration and percolation with eventual ground water recharge involves a complex set of hydraulic and purification processes. The major processes can categorized to include:

- 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, evolving as the soil treatment unit matures from startup through the first year(s) of operation.

Infiltration Rate Behavior. During normal continuous use of a soil treatment unit over months to years of operation, the application of effluent solids, as measured by total solids (TS) and total suspended solids (TSS), and the total biochemical oxygen demand (BOD) (ultimate carbonaceous BOD (cBOD) plus nitrogenous BOD (nBOD)) can contribute to pore filling at the infiltrative surface and loss of infiltration capacity (Bouma 1975, SSWMP 1978, Siegrist *et al.* 2001, Beach *et al.* 2005, Beal *et al.* 2005, Van Cuyk *et al.* 2005, Lowe and Siegrist 2008). With continued operation, the native soil's capacity to infiltrate wastewater effluent will decline substantially from the capacity for clean water infiltration that was present prior to initiating effluent application to the soil infiltrative surface. The decline in infiltration capacity during operation is often characterized as a 3-phase process (Figure 3), which is caused by biomat formation and pore-filling at and near the location where effluent enters the soil pore network (effects II and III in Figure 4).

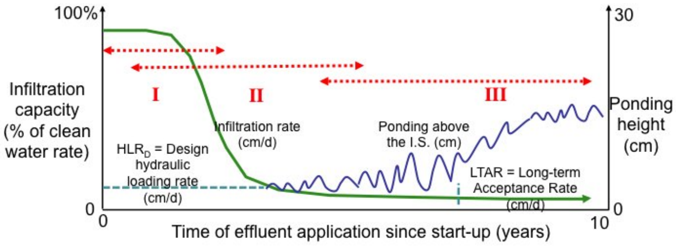


Fig. 3. Illustration of the soil infiltration rate behavior during longer-term effluent application following a 3-phase process with an asymptotic approach to a long-term acceptance rate (LTAR).

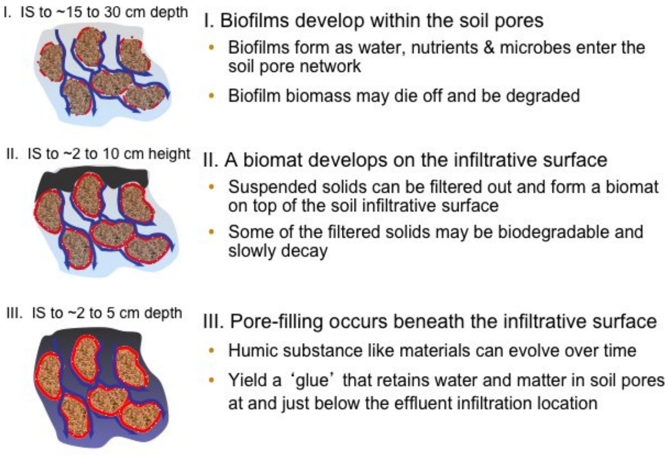


Fig. 4. Key changes at and near the soil infiltrative surface in response to effluent application in a soil treatment unit (after McKinley and Siegrist 2010).

After a period of operation, a soil treatment unit can experience a sufficient decline in infiltration capacity such that intermittent or continuous ponding of the infiltrative surface ensues (Figure 3). However, the time to development or sustained occurrence of ponding does not necessarily correlate with long-term hydraulic or treatment performance. A soil treatment unit can operate effectively in an intermittent or continuously ponded condition for an indefinite period of time. The depth of ponding above the infiltrative surface can fluctuate dramatically on a daily or seasonal basis due to system operation and environmental conditions (Siegrist and Boyle 1987).

Under some conditions, such as when higher strength wastewater or higher daily loading rates occur compared to design assumptions, or after an extended period of continuous use (e.g., 20 years or more), excessive soil clogging can occur. This can lead to hydraulic dysfunction where the infiltrative surface becomes so impermeable that that the daily wastewater loading can no longer be fully infiltrated (Siegrist and Boyle 1987, Siegrist *et al.* 2001).

Purification Behavior. Wastewaters treated by onsite systems can contain a variety of pollutants and pathogens at low to very high levels. The nature of the source and the water-use and waste-generation characteristics within it determine the composition of the wastewater stream that must be handled by an onsite system (Lowe *et al.* 2009). Traditional constituents of potential concern include oxygen consuming compounds, particulate solids, nitrogen, phosphorus, heavy metals, bacteria and virus (Table 1). Emerging constituents of concern include an array of organic compounds (e.g., caffeine, nonylphenols, Tricosan) which can be referred to as trace organics (due to their relatively low concentrations). Consumer product chemicals can routinely occur at varied levels depending on the source (e.g., residential dwellings vs. commercial establishments) (Conn *et al.* 2006, Conn *et al.* 2010a). Pharmaceuticals, pesticides and flame retardants can also occur, but much less pervasively and typically at much lower levels (Conn *et al.* 2010a).

Soil treatment units are often expected to achieve tertiary treatment and natural disinfection. For this to occur, highly unsaturated flow under aerobic conditions is normally critical. This flow regime facilitates contact between wastewater constituents and the soil grain surfaces and their associated biofilms and provides for a relatively long period for treatment processes to occur (Emerick *et al.* 1997, Schwager and Boller 1997, Van Cuyk *et al.* 2001, Siegrist *et al.* 2001, Van Cuyk *et al.* 2004, Van Cuyk and Siegrist 2007). Unsaturated flow conditions can be achieved by hydraulic design if the design hydraulic loading rate (HLR_D) is limited to a small fraction of the soil's saturated hydraulic conductivity (Ksat) (e.g., HLR_D = 1 to 5 cm/d vs. Ksat = 100 to 1000 cm/d) and application is achieved by intermittent dosing through pressurized piping networks. Also, over time, effluent infiltration can lead to soil clogging and unsaturated flow conditions irrespective of hydraulic design attributes (Siegrist 1986, Siegrist and Boyle 1987).

Pollutants and pathogens can be removed in a soil treatment unit by many physical-chemical and biological processes. BOD removal can occur by biodegradation in biofilms that grow on soil grains and within soil organic matter. Suspended solids can be removed by physical filtration and absorption followed by biodegradation. Reduced forms of nitrogen (e.g., NH_4^+) can be biologically oxidized completely and some total N can be removed by biodenitrification. Phosphorus removal varies widely depending on soil mineralogy and its P-sorption properties. Pathogens such as parasites and bacteria can be filtered out and die-off while virus can attach to grain surfaces and be inactivated. Effluent infiltration can also lead to the establishment of a biozone (Figure 4) that can provide more rapid and extensive treatment of the constituents in the applied effluent (e.g., by enhanced sorption, nitrification, and biological decay at and near the soil infiltrative surface) (Siegrist 1987, Van Cuyk *et al.* 2001, Siegrist *et al.* 2005, Van Cuyk *et al.* 2005, Van Cuyk and Siegrist 2007, Tomaras *et al.* 2009).

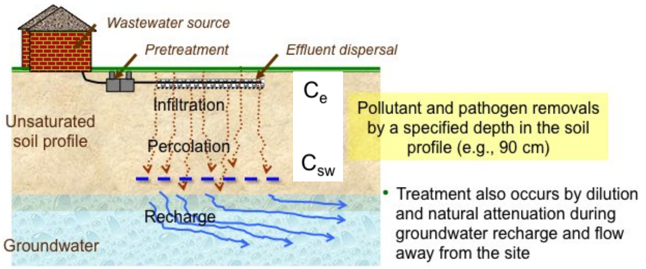
Purification of trace organic compounds (e.g., caffeine, nonylphenols, Tricosan) in a soil treatment unit principally occurs by sorption and biodegradation. Achieving high removal efficiency for a particular organic compound depends on the properties of the compound as well as the conditions present in the soil treatment unit (Conn *et al.* 2010b).

Soil Treatment Unit Performance

A soil treatment unit can be designed and implemented to reliably achieve tertiary treatment with natural disinfection over a service life of 20 years or more. Key conditions that are required to achieve this performance level include: 1) the hydraulic conductivity of the infiltrative surface zone is not dramatically reduced by compaction, smearing, or solids deposition during installation and startup; 2) the HLR_D and/or concentrations of pollutants that cause soil clogging are not excessive compared to design assumptions; 3) there is an adequate soil profile depth for treatment - depending on effluent loading rate and quality, a certain depth of unsaturated aerobic soil is needed for treatment to occur; 4) there is unsaturated flow in the soil profile with long travel times so kinetic processes can achieve pollutant removals (e.g., removal of BOD, NH_4^+, Fecal coliforms); 5) there is an adequate volume of soil profile to provide soil grain surface area for sorption processes (e.g., P removal); and 6) subsurface conditions are conducive to treatment (e.g., circumneutral pH, high Eh, moderate temperatures, no biotoxins).

The treatment efficiencies normally expected of a well designed and properly operated soil treatment unit are given in Table 1. The effects of several key design factors and environmental conditions and their relative contributions to overall performance are highlighted in Table 2.

The inherent nature of a soil treatment unit can complicate the use of quantitative treatment expectations (e.g., Table 1) and the ability to verify their achievement through monitoring. This is because, unlike a tank-based unit such as a sand filter, there is no outlet pipe and "effluent" per se from a soil treatment unit. Rather, the "end-of-pipe equivalent" is the soil solution at some depth (e.g., 0.6 m below the infiltrative surface which may be where shallow groundwater exists) (Figure 5).



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

Fig. 5. Assessing treatment efficiency by comparing concentrations in soil pore water at a specified depth (C_{sw}) to the effluent applied (C_e).

Depending on the environmental setting, further purification of this "end-of-pipe" effluent equivalent can occur as reclaimed water moves through the subsurface (deeper vadose zone or ground water zone) and exits the ground water into surface water. This assimilation of effluent from a soil treatment unit and attenuation of residual constituents of potential concern can be critically important to achieving public health and water quality protection goals (e.g., attenuation of nitrate-nitrogen, virus, trace organics).

Use of a mass discharge approach for evaluating treatment effectiveness and impacts incorporates this attenuation within the vadose zone and groundwater system. Figure 6 illustrates the concept of mass discharge as applied to a soil treatment unit.

Modeling Operation and Performance

Analytical and numerical models of varying scope and complexity are available to aid design of an isolated system or clusters of soil treatment units as well as for assessment of onsite system impacts at the local, development, and watershed scale (e.g., Beach and McCray 2003, McCray *et al.* 2005, Poeter *et al.* 2005, Siegrist *et al.* 2005, Heatwole and McCray 2007, McCray *et al.* 2009, 2010, Geza *et al.* 2009, 2010, 2012). Modeling tools are also available to evaluate the relative environmental effects of onsite and decentralized systems vs. centralized wastewater facilities within a particular planning area (e.g., Kellogg *et al.* 1997, Siegrist *et al.* 2005, Lemonds and McCray 2007, Geza *et al.* 2010).

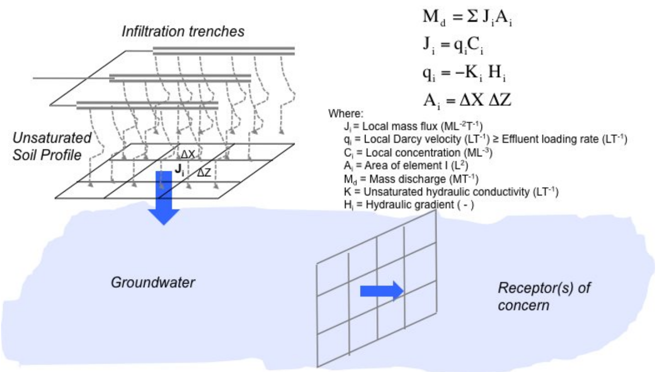
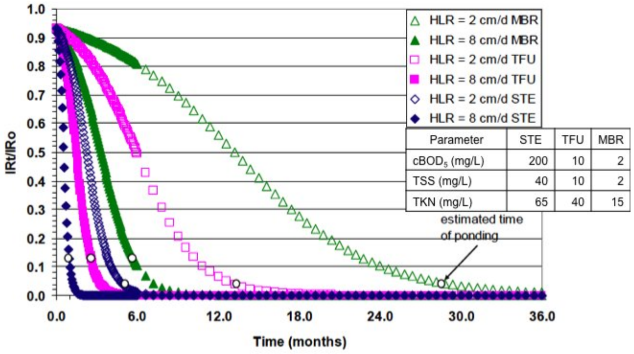


Fig. 6. Assessing treatment effectiveness of a soil treatment unit using a pollutant mass discharge (M_d) approach.

An example of a model which can be used to predict the hydraulic performance of a soil treatment unit is the infiltration rate (IR) model developed by Siegrist and Boyle (1987). This model predicts the IR response during long-term application of a particular effluent quality at a certain hydraulic loading rate (see Figure 7). The model consists of a regression equation that was developed based on long-term field experiments in a silt loam soil. Subsequent to its development, the model has been applied to soil treatment units in other soil systems and it has been found to be reasonably predictive (e.g., sandy loam soils as shown in Figure 7).

A prime example of a model which can be used to predict purification performance is STUMOD (Soil Treatment Unit Model) (Geza *et* *al.* 2009). STUMOD was developed to predict the fate and transport of nitrogen in a soil treatment unit. STUMOD calculates nitrogen species concentrations with depth in the soil profile (Figure 8a) and the fraction of nitrogen remaining with depth (Figure 8b). By repeatedly running STUMOD using randomly selected values from ranges of potential values, the probability that a certain fraction of the total nitrogen in the effluent infiltrated will reach a specified soil depth can be estimated (Figure 8c).



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

Fig. 7. Model simulation of the infiltration rate (IRt) decline as a ratio of the initial infiltration rate (IRo) for a sandy loam soil as affected by three effluent qualities and two loading rate (Siegrist and Boyle (1987) model as reported in Van Cuyk *et al.* 2005).

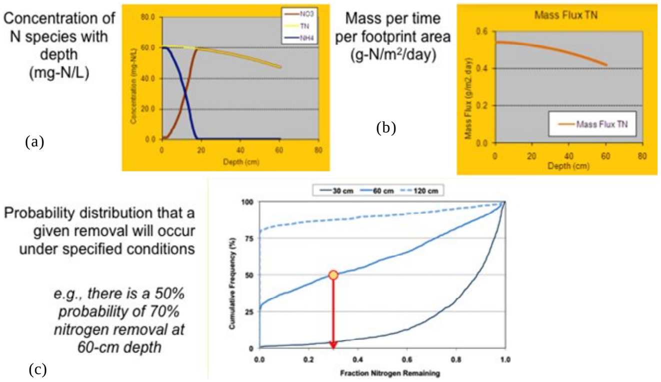


Fig. 8. STUMOD simulation of nitrogen transformation and fate when 2 cm/d of STE is applied to a soil treatment unit installed in a sandy loam soil (Geza *et al.* (2009, 2010, 2012) as reported in McCray *et al*. 2010).

STUMOD involves a number of complex equations, which are implemented in a spreadsheet. It is relatively simple to use but can account for important processes such as ammonium sorption, nitrification and denitrification. STUMOD is being modified to account for: 1) evapotranspiration and plant uptake on nitrogen removal; 2) fate and transport during lateral movement in an aquifer (by linkage with a groundwater model); and 3) transport of organic nitrogen and trace organics in the vadose zone.

While these types of relatively simple models provide insight into the operation of soil treatment units and quantitative estimates of performance as affected by a range of conditions, many complex processes and less-common operating conditions can be better addressed by numerical models such as HYDRUS (Šimůnek *et al.* 1999). HYDRUS has been used for a variety of modeling studies exploring soil treatment unit design and performance (e.g., Beach and McCray 2003; Radcliffe *et al.* 2005; Pang *et al.* 2006; Bumgarner and McCray 2007; Heatwole and McCray 2007; Radcliffe and West 2007; Beal *et al.* 2008; Finch *et al.* 2008).

Summary

Within the Small Flows Program, one of several research thrusts has focused on soil treatment units. Over the past decade, research has encompassed laboratory experiments, controlled field experiments with pilot-scale systems, field monitoring of full-scale systems, and analytical and numerical modeling. The results of this research have enhanced the understanding of fundamental principles and processes important to system design and performance. There is now a more quantitative understanding of key flow and transport processes and the removal of pollutants and pathogens as affected by soil properties, system features, effluent quality and loading, and other design factors and environmental conditions.

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Table 1. Wastewater constituents of concern and treatment expectations from a well-designed and properly operated soil treatment unit treating 1 to 5 cm/d of domestic septic tank effluent.

Constituents of potential concern	Basis for concern over wastewater constituent	Example unit of measure (units)	Domestic septic tank effluent [1]	Treatment efficiency after 90 cm of unsaturated aerobic soil
Oxygen demanding substances	Can create anoxic or anaerobic conditions and can contribute to soil clogging	BOD_5 (mg/L)	140 to 200	>90%
Particulate solids	Contributes to soil pore filling and accelerated soil clogging	TSS (mg/L)	50 to 100	>90%
Nitrogen	Can contribute to oxygen demand, can be toxic via drinking water ingestion, can upset ecosystems	Total N (mg-N/L)	40 to 100	10 to 20%
Phosphorus	Can cause increased productivity in sensitive surface waters	Total P (mg-P/L)	5 to 15	100 to 0% [2]
Bacteria	Infectious disease transmission via drinking water, contact with seepage, or recreational water activities	Fecal coliforms (org./100 mL)	10^6 to 10^8	>99.99%
Virus	Infectious disease transmission via drinking water, contact with seepage, or recreational water activities	Specific virus (pfu/mL)	0 to 10^5 *(episodically high levels)*	>99.9%
Heavy metals	Potential toxicants to humans by ingestion in drinking water or to ecosystem biota	Individual metals (ug/L)	0 to low levels	>99%
Trace organic compounds	Potential health effects to humans by ingestion of drinking water or vapor inhalation during showering or environmental effects to ecosystem biota	Specific organics associated with consumer products, pharmaceuticals, pesticides, and flame retardants (ng/L or ug/L)	0 to trace levels	Low to >99% [3]

[1] Note: STE concentrations given are representative of those for residential dwelling units. However, commercial sources such as restaurants can produce STE that is markedly higher in some pollutants (e.g., BOD_5, COD, TSS, trace organics) while other sources can produce STE that is markedly lower in some pollutants (e.g., laundry can have lower total nitrogen and pathogen levels).

[2] P-removal is highly dependent on media sorption capacity and P loading rates and time of operation.

[3] Removal of trace organic compounds (e.g., nonylphenol, Triclosan, EDTA, caffeine,…) is highly dependent on the properties of the organic compound and conditions within the soil treatment unit (e.g., conditions conducive to sorption and biotransformation during adequately long hydraulic retention times).

Table 2. Key design factors and environmental conditions and their relative importance in determining the performance of a soil treatment unit.

Design factors and environmental conditions	Effects on performance of a soil treatment unit (*relative importance*)[1]
Initial Ksat of the soil profile	For well-drained soil profiles with Ksats of ~5 to 2500 cm/d, the long-term acceptance rates (LTAR) for infiltration of domestic STE under continuous routine use will normally approach ~2 cm/d (*minor to moderate*) [2]
Soil profile conditions during operation	Higher temperatures, lower soil water contents, and higher aeration levels tend to enable relatively higher LTAR's and treatment efficiencies (*moderate*)
Geometry and infiltrative surface architecture	Horizontal infiltrative surfaces that are aggregate-free in low-height, narrow trenches characterized by sidewall-to-bottom area ratios of 0.5 to 1.0 and placed shallow in the subsurface enhance infiltrability and higher LTAR's and improved treatment (*moderate*)
Actual operating HLR (HLR_A)	For a given effluent quality, the actual HLR_A exerts a major effect by 1) determining the mass loadings of total BOD and TSS, which control wastewater-induced soil clogging behavior, and 2) the loadings of other pollutants of concern that need to be treated to acceptable levels (*major*)
Quality of effluent being treated in the soil treatment unit	At a given HLR_A, effluent quality exerts a major effect on the treatment requirements for pollutants and pathogens of concern (*major*)
Method of effluent application to the soil treatment unit	For systems in continuous daily use, major effects may be exerted on the volume processed per unit area and time but the LTAR and pollutant removal may be unaffected or enhanced (*minor to major*)
Continuity of use	Infrequent or intermittent use with long periods of resting can sustain higher soil infiltration capacity and LTAR's as well as enhanced treatment capability (*major*)

[1] This table is presented for illustrative purposes and the attributes and effects given are not intended to provide comprehensive coverage of this subject.

[2] The descriptors used have the following meanings: "minor" indicates a relative effect of ~+/-20% or less, "moderate" indicates an effect on the order of +/-50%, and "major" indicates an effect on the order of +/- 100% or more.