Wastewater Infiltration into Soil and the Effects of Infiltrative Surface Architecture

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ABSTRACT: Wastewater facilities serving individual residences, commercial establishments, and small communities commonly rely on wastewater soil absorption systems (WSAS) where treatment and disposal is accomplished by infiltration of wastewater effluents into subsurface soils and recharge to local groundwater under the site. In these systems, understanding the infiltration rate (IR) behavior during operation and its progression to a long-term acceptance rate (LTAR) is critical to effective system design. During design, choices can be made regarding many features of a WSAS, including the daily hydraulic loading rate for a given infiltrative surface architecture (ISA). ISA includes physical attributes, such as infiltrative surface geometry and depth, as well as interface character. Interface character embodies the physical characteristics of the space effluent moves through once it is released from the piping network and infiltrates the pore network of the natural soil. The IR behavior experienced during treatment of wastewater effluents in soils and the LTARs to be used for design that account for the effects of different ISA are extremely complex and often poorly understood. This paper highlights key experimental and modeling studies completed by researchers at the Colorado School of Mines to understand the dynamics of infiltration rate behavior during treatment of wastewater effluents in soil, including the effects of ISA and other features of WSAS design. Regarding the question of IR behavior as affected by gravel or other solid objects on and within the soil infiltrative surface zone, the results of theoretical and experimental studies designed to elucidate this question are consistent in revealing that the soil's ability to infiltrate wastewater effluent is lower for a gravel-laden infiltrative surface compared to an open infiltrative surface, with the magnitude of the reduction in capacity (e.g., LTAR) correlated with the volume of the infiltrative surface zone that is obstructed by the gravel or other solid media.

The majority of onsite and decentralized wastewater facilities rely on the infiltration of wastewater effluents into subsurface soils where percolation results in the recharge of local groundwater (Siegrist et al., 2001). In these systems, a critical design element involves estimating the design infiltration rate for a particular type of wastewater effluent into a specific soil and environmental setting.

The infiltration of wastewater effluents into soils and estimation of design application rates for a given system design and environmental setting are extremely complex and often poorly understood and oversimplified.

Below is a short overview of infiltration rate (IR) theory as applicable to wastewater effluents, followed by a synopsis of recent and ongoing research at the Colorado School of Mines (CSM). The goal at CSM has been to advance the quantitative understanding of the dynamics of infiltration rate behavior during treatment of wastewater effluents in soil and account for the effects of infiltrative surface architecture (ISA) and other elements during wastewater soil absorption system (WSAS) design.

Wastewater Infiltration into Soil

Wastewater systems that involve in-ground dispersal of wastewater effluent commonly consist of a network of buried trenches. Effluent in the trenches infiltrates the soil and moves vertically downward through an unsaturated zone (often 2 to 4 ft. [60 to 120 cm] or more in thickness) before recharge to groundwater under the site. An unsaturated flow regime is typically a design objective for a soil-based wastewater treatment system, since it can yield higher treatment efficiencies due to an increased hydraulic retention time, more extensive contact between percolating effluent and porous media surfaces, and more rapid reactions within an aerobic environment.

Unsaturated flow conditions can be achieved by limiting design application rates to a small fraction of the soil's saturated hydraulic conductivity (K_{sat}) (e.g., 1 to 5 cm/day loading rates which are 1 percent or less of the soil K_{sat}). In addition, at the infiltrative surface, a clogging zone (also called a biomat) can evolve in response to effluent infiltration and yield more uniform infiltration (both spatially and temporally), thereby contributing to unsaturated flow conditions.

Critical to the design and performance of a soil-based wastewater system is an understanding of the infiltration rate behavior that evolves during wastewater application to soil. Onsite wastewater systems that rely on soil-based treatment of septic tank effluent have been characterized to have three major operational stages regarding the soil's hydraulic behavior (e.g., Thomas et al., 1966; Tyler and Converse, 1989; Siegrist et al., 2001; Siegrist et al., 2002).

Stage 1 may be characterized as the startup and early maturation period when the daily hydraulic loading rate (HLR) infiltrates the soil but in a nonuniform manner due to imperfect distribution networks and the fact that the clean soil infiltration rate is typically 10 to 100 times higher than the design HLR. With continued effluent infiltration, the soil permeability decreases at the infiltrative surface due to the accumulation of pore-filling agents

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(e.g., biomass, mineral matter), and effluent infiltration becomes more uniform across the available infiltrative surface and the rate of infiltration declines substantially. Stage 1 may last for a few months to a year or more, and during this period, localized overloading can become attenuated, an unsaturated flow regime begins to dominate, and biochemical purification processes (e.g., nitrification and bacterial removal) become well established, all of which contribute to a very high treatment efficiency that approaches a pseudo-steady state.

Stage 1 transitions to Stage 2 as soil clogging develops to the point where the horizontal infiltrative surface area in the trench system is fully utilized and the IR has declined to a small fraction of the soil's initial K_{sat}. Stage 2 then continues, normally for several years or more during which time the IR may continue to decline and ponding may ensue and increase in height such that the daily HLR continues to be processed. During this period, treatment efficiency continues at a pseudo-steady state although capacity-limited processes may become exhausted, and treatment may decline (e.g., available P sorption capacity may be exhausted, and P breakthrough may occur).

Stage 3 involves the period of operation when the IR has declined substantially but the system may function hydraulically at a long-term acceptance rate (LTAR) for another 10 to 20 years of continuous operation. It is likely that a pseudo-steady-state LTAR will not continue indefinitely when the system is continuously used and in the absence of permeability restoring processes (e.g., soil biota penetration, freeze-thaw effects). Rather, most systems that are operated under continuous use (e.g., with septic tank effluent [STE] applied at a design rate of 0.24 to 1.23 gpd/ft^2 [1 to 5 cm/day]) will eventually reach an operational state where hydraulic failure can occur; i.e., the daily application rate exceeds the infiltration rate at time, t (IR_t), and maintenance is required. Long-term resting can help restore infiltration capacity but the rate of recovery can be very slow particularly in colder climates.

Effluent Infiltration is Conceptually Simple but Quantitatively Complex

While conceptually simple as just described, quantifying the IR behavior within soil-based wastewater systems is extremely complex (Siegrist et al., 2001). While there is qualitative and empirical understanding regarding some facets of the relationships between long-term IR behavior and design parameters (e.g., effluent composition and loading rate, method of application, and infiltrative surface geometry) and environmental conditions (e.g., soil texture and structure, hydrologic regime, and temperature), complete quantitative understanding is now being achieved and predictive mathematical models are being developed and/or validated.

Due to its conceptual simplicity, wastewater effluent infiltration can be oversimplified and inappropriately quantified. For example, the analysis and interpretation presented by White and West (2003) describes in-ground dispersal of wastewater effluent within a WSAS trench as conceptualized as a stack of uniform homogeneous layers. In the paper, the authors present a well-documented modification of Darcy's Law developed to simulate flow of clean water through a saturated soil column with uniform horizontal layers and attempt to account for unsaturated flow by uniformly reducing the hydraulic conductivity of some of the layers by a certain factor. A primary conclusion the authors reach is that a gravel-laden soil infiltrative surface does not cause a significant reduction in wastewater infiltration capacity compared to an aggregate-free surface, other than that due to the impact of fines associated with the gravel. In other words, if clean stones (or other solid objects) were placed upon a soil infiltrative surface, no reduction in hydraulic capacity of the system for wastewater effluent would result.

The authors attempt to validate their layered model analysis using results from one-dimensional columns packed with layers of porous media having different hydraulic conductivity properties and operated with clean water under saturated conditions. The authors of this paper respectfully disagree with their modeling approach and contend that it is not appropriate for describing in-ground dispersal of wastewater effluent from a buried trench. In the following paragraphs we present the reasoning and rationale underpinning our critical assessment of the approach used by White and West (2003), and in so doing, provide insight into the quantitative complexities of wastewater effluent infiltration into soil.

The conceptual model and analysis presented by White and West (2003) is based on a model trench composed of a series of layers with dramatically different K_{sat} and the calculation of an effective saturated hydraulic conductivity (K_{EFF}) for the entire profile of layers (e.g., as shown in their Figure 7, there are five layers: gravel, gravel/biomat, gravel/biomat/fines, soil biomat, and soil). Then a portion of the total hydraulic resistance in the layered profile is assigned to each of the five layers.

After analyzing saturated flow conditions, they attempt to account for unsaturated flow by assuming a reduction in the previously used K_{sat} to yield an unsaturated K for three of the layers (i.e., the fines, soil/biomat, and unsaturated soil layer). Their analysis results reveal that the presence of clean gravel (i.e., with zero fines) has no impact on hydraulic resistance of the layered system to clean water movement due to the very low K of the gravel fines and soil/biomat layers.

We do not disagree with the conclusion that the K_{sat} of fine-grained layers (i.e., the fines from gravel accumulating at the soil infiltrative surface, or a soil/biomat layer) can be orders of magnitude lower than that of very coarse-grained layers (i.e., the gravel within the trench). However, conditions within a wastewater infiltration trench invalidate the use of the multi-layer form of Darcy's Law for modeling the in-ground dispersal of wastewater effluents from trenches installed in the unsaturated zone.

The computation of a K_{EFF} is technically incorrect for a system comprising variably saturated layers of porous media with widely varying properties. For example, consider the situation where the K_{EFF} is calculated to be 3.41 gpd/ft^2 (13.9 cm/day) for a four-layer trench system with the following thicknesses and K_{sats}: gravel with no fines (0.3 ft. thick, 1,000 gpd/ft^2), fines (0.03 ft., 0.5 gpd/ft^2), soil/biomat (0.04 ft., 0.5 gpd/ft^2), and effluent saturated soil (0.25 ft., 6 gpd/ft^2), as presented in Table 4 of White and West (2003). This implies that under a unit vertical hydraulic gradient, the flow rate through the layered system should be 3.41 gpd/ft^2 (13.9 cm/day).

However, even if the gravel layer were fully saturated, putting a hydraulic head of 0.3 ft. (9.2 cm) on the fines and biomat/fines layers (i.e., the soil infiltrative surface is ponded to a 0.3-ft.-[9.2-cm] depth), and assuming that all the head is lost during flow through these two layers, the flow rate through the fines and the soil/biomat layers would be only 2.6 gpd/ft^2 (10.6 cm/day), less than the 3.41 gpd/ft^2 (13.9 cm/day) result produced by the K_{EFF} calculation. Thus, the K_{EFF} calculation does not produce a physically realistic result.

One problem with the K_{EFF} approach is the assumption of a unit hydraulic gradient throughout the layered system. A unit hydraulic gradient means that the pressure-head gradient is zero, which is likely to occur in the coarser soil layer below the soil/biomat layer. However, the hydraulic gradient is considerably larger than unity in the top low-permeability layer (i.e., the soil/biomat layer), because the pressure head above the layer is positive (e.g., in the preceding example, 0.3 ft [9.2 cm] due to ponding) and the pressure head below the fine soil/biomat layers is negative. The existence of negative pressure heads in an underlying coarser layer in layered systems of this type is well documented (e.g., Warrick and Yeh, 1990, and Beach and McCray, 2003). In the above example, the hydraulic-head gradient is at least five across the soil/biomat layer, and probably higher.

In a layered system where the K of the layers varies by nearly five orders of magnitude (as can be the case in a WSAS), use of a K_{EFF} approach has serious limitations, particularly during unsaturated flow conditions. Accounting for unsaturated flow simply by assuming that the unsaturated hydraulic conductivity is a fraction of K_{sat} may be appropriate if the water content in each layer were constant and known. However, in a layered system, there are major discontinuities in water content at the layer interfaces, and water content can change drastically with depth within a particular layer during vertical infiltration (Lopez-Bakovic and Nieber, 1989, and Warrick and Yeh, 1990).

Warrick and Yeh (1990) present numerical simulations of vertical unsaturated flow in three layered soil profiles, each with a 0.32-ft. (10-cm) ponding height at the infiltrative surface and a water table 19.7 ft. (600 cm) below the surface. The first case (A) is a loam over sand. This might be similar to the case of wastewater infiltration into a sandy soil with a biomat. The next case (B) is loam-sand-loam-sand system, and the final case (C) is sand over a loam (coarse over fine, analogous to clean gravel over sand). For this discussion, we will consider cases A and C. The unsaturated hydraulic conductivity function for both cases is presented as a function of pressure head (h), with h expressed in cm and K in cm/day (Equation 1):

$$K(h)=\frac{a}{b+|h|^n} \qquad h<0 \qquad (1)$$

where coefficients for the sand are
a = 1.7x10^8,
b = 2.5x10^6, and
n=4.
For the loam,
a = 700,
b = 1,450, and
n = 2.

If each system were fully saturated, then the above equation yields K_{sat} values of 16.7 gpd/ft^2 (68 cm/day) for the sand and 0.12 gpd/ft^2 (0.48 cm/day) for the loam. Resulting infiltration rates for these two cases were 0.26 gpd/ft^2 (1.05 cm/day) for case A and 0.13 gpd/ft^2 (0.52 cm/day) for case C. The pressure head profile for case A shows a nonlinear pressure-head gradient in both layers. The overall hydraulic gradient is about 4 in the overlying loam layer. In the underlying sand layer, the hydraulic gradient is slightly greater than unity in the upper part of the layer, but rapidly declines to near 0.1 in the bottom part of the profile.

The K_{EFF} approach would yield values of 1.6 gpd/ft^2 (6.6 cm/day) for case A and 0.13 gpd/ft^2 (0.52 cm/day) for case C. For the hydraulic gradient of 1.017 (610 cm/600 cm) across the soil column in both cases, an infiltration rate of 1.64 gpd/ft^2 (6.7 cm/day) would be predicted for case A, and a rate of 0.13 gpd/ft^2 (0.53 cm/day) would be predicted for case C. For case C, the model reproduced the K_{EFF} approach predicted result exactly. This occurred because the column remained saturated ($h\geq0$) throughout the column. The K(h) values throughout each layer were the same as the K_{sat} values, and thus the Darcy approach would be appropriate for this clean-water system with uniform layers.

However, in Case A, the modeled infiltration rate was 0.26 gpd/ft^2 (1.05 cm/day), more than six times smaller than that predicted with the K_{EFF} approach. This occurs because of unsaturated-flow dynamics. Now, if a factor of 6 were fortuitously applied with the K_{EFF} approach to reduce the K value, then an approximately correct infiltration rate would be deduced. However, this factor could not, in practice, be predetermined because, in case A, the unsaturated K value in both layers varies considerably with depth. In the overlying loam, K(h) varies *nonlinearly* between values of 16.7 gpd/ft^2 (68 cm/day) of at the top of the layer and 0.28 gpd/ft^2 (1.14 cm/day) at the interface between the two layers (Equation 1). In the subsoil sand, K(h) varies between 0.01 gpd/ft^2 (0.05 cm/day) at the layer interface and 0.12 gpd/ft^2 (0.48 cm/day) at the bottom of the column. Because the variation is nonlinear, a representative depth-averaged value of K(h) to use in the K_{EFF} approach is not easily obtained.

Recent numerical simulations were completed by Beach and McCray (2003) that include rigorous unsaturated-zone flow physics for wastewater infiltration through basal and sidewall biomats into two different subsoil types (sand and silt). The numerical model HYDRUS-2D was used to simulate unsaturated flow within an onsite wastewater system to study the effects of a biomat on unsaturated flow behavior and hydraulic retention times in sandy and silty soils. The study demonstrated some very important unsaturated-flow influences that could not be explained by the simple K_{EFF} approach.

First, the study showed that infiltration through a sidewall can be a critical component in maintaining long-term infiltration in a wastewater trench. Second, the simulations showed that the biomat resulted in different effects on the infiltration rate into a trench installed in silt versus sandy because of the layer effects imparted by discontinuities in water content during unsaturated-flow conditions.

While we recognize the usefulness of simple-to-use equations for WSAS

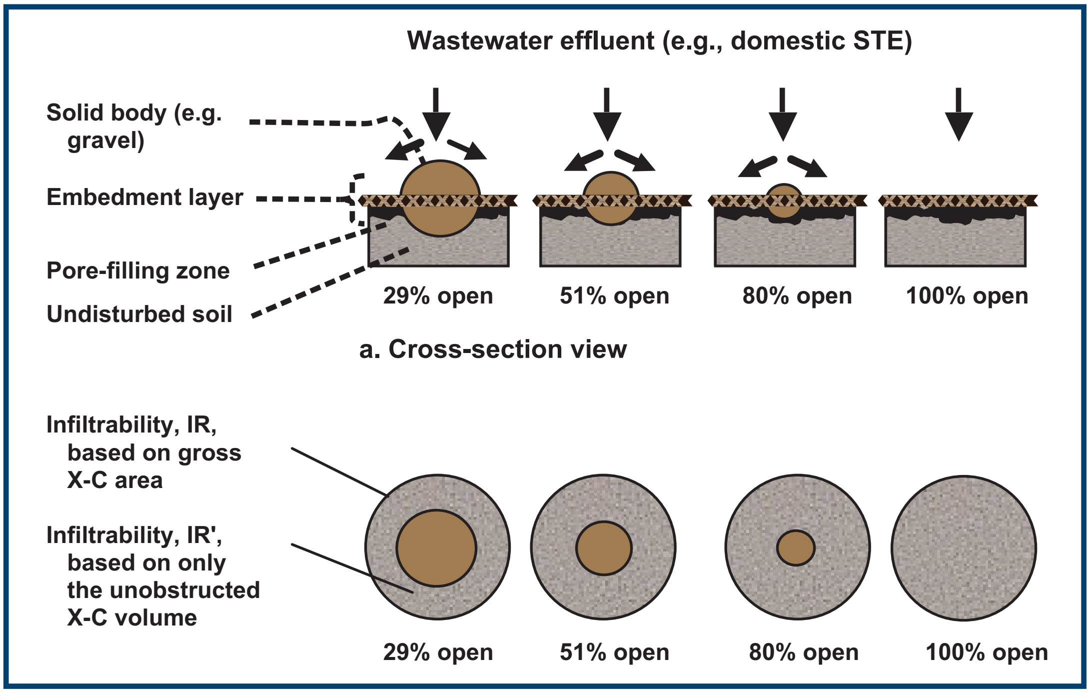

Figure 1 Conceptual model illustrating the effects of solid objects such as gravel or synthetic stones on the architecture of the infiltrative surface zone and the infiltration rate behavior.

design purposes, we contend that the complexities of wastewater infiltration preclude the simple K_{EFF} approach, such as that used by West and White (2003), because it gives a false sense that the proper flow physics are being quantified. The above discussion focuses on the deficiencies of a K_{EFF} approach for a wastewater infiltration trench based on the issues associated with unsaturated flow. However, the impact of gravel on the infiltrative surface architecture, and thus on hydraulic properties, in realistic WSAS is an equally complex and important issue. If this effect is considered rigorously, then additional problems arise with use of the K_{EFF} approach.

Below, we describe additional theoretical and experimental research completed by Siegrist, McCray, and co-workers that provides an alternative and thorough analysis and description of the in-ground dispersal of wastewater effluents and the science of getting wastewater effluent into the ground. The following discussion focuses on the effect that the presence of clean gravel or other solid objects can have on the hydraulic behavior and LTAR's during wastewater effluent infiltration into soil.

Infiltration and LTARs as Affected by Infiltrative Surface Architecture

Conceptual Analysis

More than 15 years ago, Siegrist (1987) published a paper describing a controlled field experiment designed to elucidate soil clogging during subsurface wastewater infiltration as affected by effluent composition and hydraulic loading rate. Pilot-scale soil absorption units were installed in a structured silty clay loam subsoil in Wisconsin, and over a 70-month period, domestic STE, graywater STE, and tapwater were intermittently applied in an average of 5.2 doses/day to yield daily HLRs of 0.32, 0.64, or 1.3 gpd/ft^2 (1.3, 2.6, or 5.2 cm/day). Hydraulic properties were monitored over time, and after 62 and 70 months of operation, soil properties were examined at the infiltrative surface and with depth below it.

A regression model fit to the experimental data confirmed that soil clogging development was highly correlated with the cumulative mass density loadings of total biochemical oxygen demand (tBOD) (carbonaceous plus nitrogenous demand) and suspended solids (SS). Clogged infiltrative surface zones exhibited significant accumulations of organic materials at the infiltrative surface and within the first few mm of the natural soil. Siegrist (1987) also reported the following: “A feature observed in the clogged soil cells, both in the field and in thin section, was the distinct lack of either zone or organic matter accumulation (within or atop the soil matrix) in locations where the cell aggregate was in direct contact with the soil infiltrative surface. The infiltrative surface area actually available for wastewater infiltration may have been substantially reduced by this gravel masking phenomenon.”

The observations reported by Siegrist (1987) can be explained by a conceptual model for a soil infiltrative surface with solid objects located on top of and within it as presented in Figure 1. As illustrated in this figure, in a typical WSAS where gravel or other solid objects are buried within a trench, there is pore entry blockage and an embedment layer composed of solid objects (e.g., stones) impressed into and/or intermingled with soil media at the infiltrative surface. This embedment layer occurs in most solid object-laden WSAS, although the degree of embedment is dependent on various factors such as soil texture and structure, trench depth and geometry, and construction equipment and methods.

The concept of an embedment layer is relatively simple to understand and should be easy to accept. Embedment has been observed during probing of operating systems in the field with the embedment layer ranging in thickness from 0.4 to 4.0 in. (1 to 10 cm) or more. This embedment can result from several causes including (1) the dumping of loads of gravel (or similar material) onto a disrupted soil infiltrative surface created by backhoe excavation using a bucket with teeth on it, (2) the overburden pressures that occur during trench installation and backfilling, and (3) the wetting/drainage cycles that occur during intermittent wastewater effluent application.

In a gravel-filled trench, the embedment layer is essentially gravel (e.g., 0.75 to 2.0 in. [1.9 to 5 cm] diameter) mixed with soil, which results in a poorly-sorted stony-soil layer. It is well known that poorly-sorted layers exhibit smaller porosity and hydraulic conductivity due to smaller effective pore sizes and increased tortuousity. This also results in a smaller unsaturated hydraulic conductivity, K(θ), based on the well-established and accepted theory by Mualem (1976). Jaynes and Rice (1983) present a theoretical discussion and then an experimental study focused on equations for describing hydraulic conductivity and water content in stony-soil layers. The theory and results show that the hydraulic properties of a stony-soil layer can be calculated directly from the properties of the soil matrix alone and the stone volume ratio. A relationship between K(θ) of a stony-soil layer and K(θ) of the soil matrix alone is given by Equation 2:

$$K_b\ (\theta_b) = (e_b/e_m)\ K_m\ (\theta_m) \qquad (2)$$

where,

$K_b\ (\theta_b)$ = hydraulic conductivity of the bulk stony soil (cm/sec) at the bulk volumetric water content of the stony soil, θ_b;

$K_m\ (\theta_m)$ = hydraulic conductivity of the soil matrix without stones (cm/sec) at the bulk volumetric water content of the matrix soil, (θ_m);

e_b= bulk void ratio for the entire stony soil (volume of voids/volume solids) (cm^3/cm^3), and

e_m= mean void ratio for the matrix soil alone (cm^3/cm^3).

The LTAR (gpd/ft^2 or cm/day) for a gravel-filled trench with an embedment layer (without or with fines) should be lower than the LTAR for a chamber-design trench without an embedment layer (i.e., a trench outfitted with a chamber enables an open, gravel-free infiltrative surface). During effluent infiltration through a gravel-laden soil surface, the effective HLR and mass loading of pore-clogging pollutants like tBOD and SS will be higher through the available soil matrix since the effluent applied has to move through the pores within the soil matrix within the stony-soil layer.

As noted above, it is the soil matrix within a stony-soil layer that controls effluent movement through an embedment layer. Consequently, the pore filling and clogging of the soil matrix will be accelerated and more pronounced, yielding a correspondingly lower LTAR for the gross cross-sectional area of a gravel-laden soil surface. Moreover, the adverse effects of an embedment layer on reducing the system's LTAR can be further exacerbated by the accumulation of fines that wash off of gravel and accumulate at the infiltrative surface and yield an even lower permeability within the gravel/biomat/fines layer.

Clement et al. (1996) developed a model to predict the change in permeability and water movement in porous media due to microbial biomass accumulation and filling of soil pores (Equation 3):

$$k_b = k_o(1\text{-}n_f/n_o)^{19/6} \qquad (3)$$

where,

k_b (L^2) and k_o (L^2) are the clogging-affected and initial soil permeabilities, respectively;

n_f (V/V) is the fraction of pores filled; and

n_o (V/V) is the initial porosity of the porous media.

Soil permeability can be converted to K using Equation 4:

$$K = k\rho g/\mu \qquad (4)$$

where,

K = hydraulic conductivity (L/T),
k = permeability (L^2),
ρ = fluid density (M/L^3),
g = gravitational constant (L/T^2), and
μ = viscosity (L*M/T).

Using the conceptual model presented in Figure 1, one can calculate that the porosity and K_{sat} of a 0.2-in. (0.5-cm) thick section of an infiltrative zone with different degrees of solid-object volumes varies by more than a factor of 3 as shown in Figure 2.

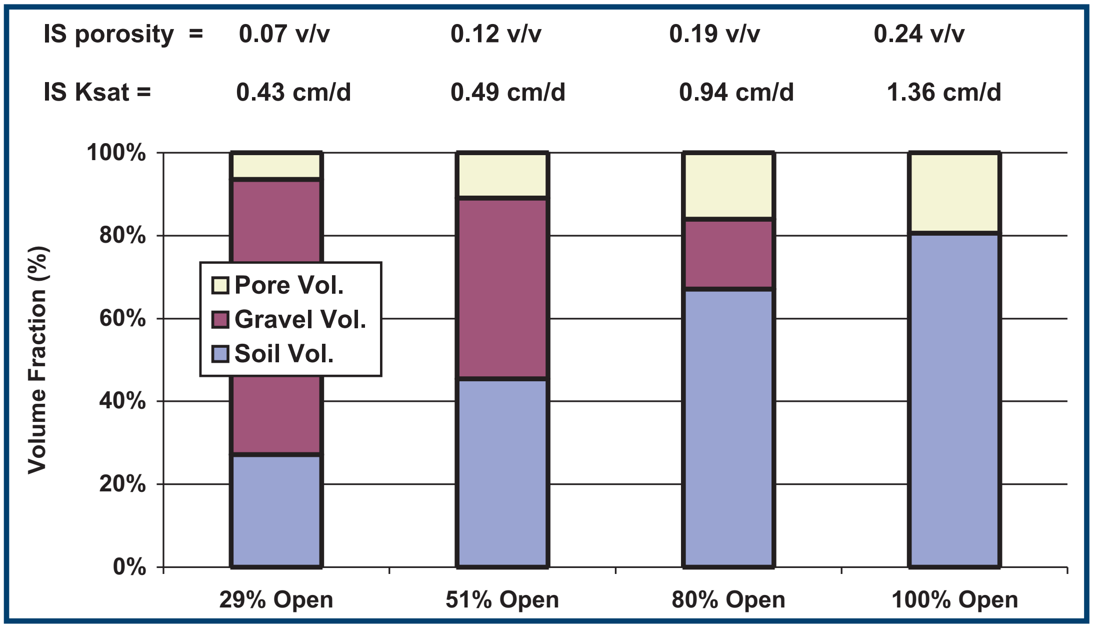

Figure 2 Calculated physical characteristics of a 0.2-in. (0.5-cm) section of an infiltrative surface zone with varying degrees of solid objects (e.g., gravel) present within the zone (after Diaz 2003 and Clement et al. 1996). (Note: See conceptual model in Figure 1; IS porosity is the volumetric pore space of the 0.2-in. (0.5-cm) thick section of the infiltrative surface zone before wastewater effluent infiltration while the IS Ksat is the saturated hydraulic conductivity for that zone after 90% volumetric pore-filling has occurred due to soil clogging.)

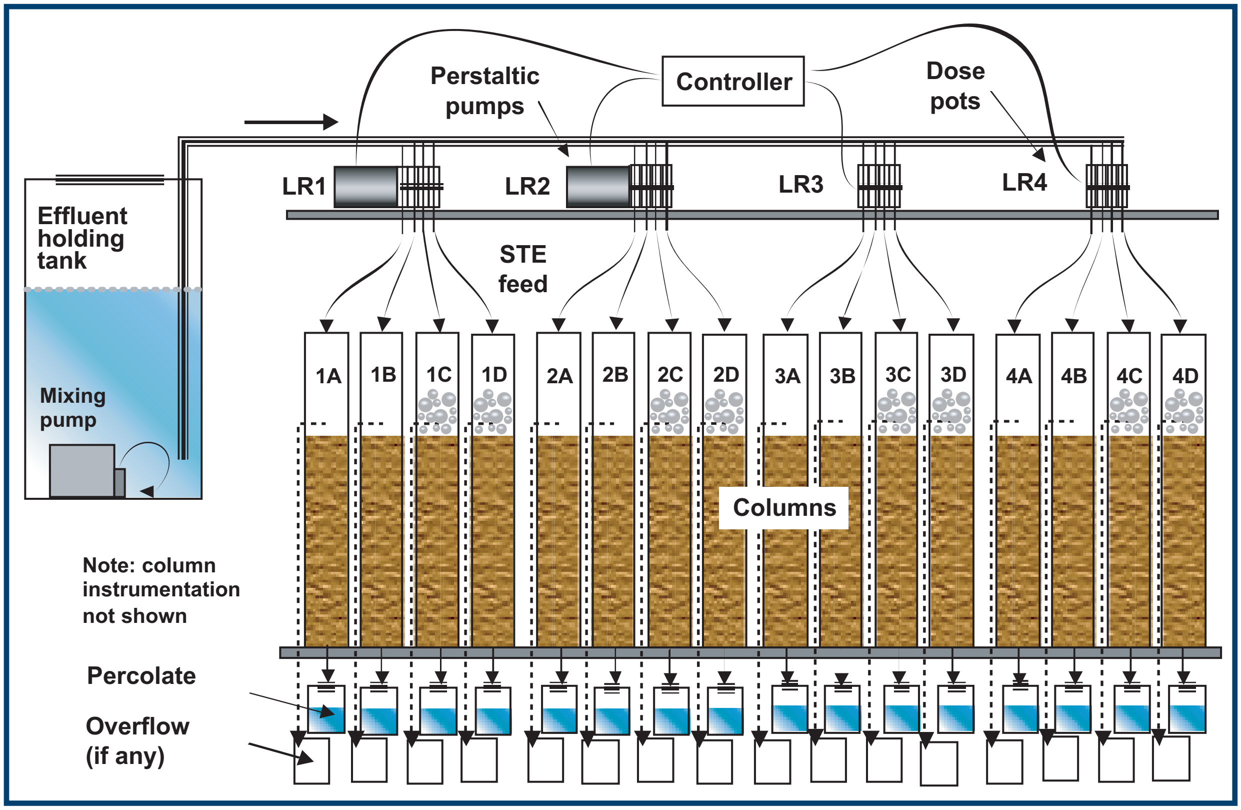

Figure 3 Experimental apparatus used for a laboratory study examining the hydraulic and purification performance effects of infiltrative surface architecture (clean gravel-laden vs. gravel-free infiltrative surfaces) and hydraulic loading regime (Siegrist et al., 2002, and Beach et al. 2004).

Controlled Experimentation

Controlled laboratory and field research has been designed and carried out at CSM to understand in-ground dispersal of wastewater effluent as affected by different design parameters and environmental conditions. Considerable research has been conducted to determine how ISA, due to the presence of gravel or other solid objects on an infiltrative surface, can affect wastewater infiltration and reduce the magnitude of a LTAR. It is important to note that research to elucidate the effects of ISA on wastewater effluent infiltration and LTARs requires an integrated set of studies carried out under laboratory and field conditions with substantial replication and extensive and detailed monitoring and measurement. This is illustrated through several key research efforts at CSM, highlights of which are given below.

Beach et al. (2004) conducted experiments wherein 16 one-dimensional sand columns (6-in. [15-cm] diameter by 2.0-ft. [60-cm] length) with gravel-free and gravel-laden infiltrative surfaces were loaded with STE (Figure 3). The goal of the research was to quantify the temporal evolution of the biomat and its effective hydraulic conductivity (K_e). The sand media (d_{10}=0.22 mm, d_{60}=0.60 mm, TOC=0.017 dry wt%) was the same as used in previous 3-D lysimeter experiments at CSM (e.g., Van Cuyk et al. 2001).

During preparation of the gravel-laden columns, after column packing, a 0.5-in. (1-cm) layer of sand was removed from the top of the column. The sand surface was scarified and a layer of washed gravel (nominal 0.8-in. [2-cm] diameter) was placed on the scarified surface and then the same sand was used to fill in the gravel void spaces. This gravel-sand lift was then compacted and gravel was added to a height of 4 in. (10 cm) above it. This procedure was not completed to simulate the washing of fines from gravel onto a soil infiltrative surface, but rather to mimic what happens when gravel is dumped onto a sandy soil as well as the operational embedment of aggregate that results from effluent loading.

The K_{sat} of two of the columns was measured before and after gravel placement using clean water, and, as expected, there was no significant difference in K_{sat} (95 percent confidence level). The K_{sat} of all 16 columns averaged 220 gpd/ft^2 (901 cm/day) (standard error of the mean [S.E.] = 5.0 gpd/ft^2 [20.3 cm/day]). Each column was equipped with measurement devices to monitor both soil moisture tension (soil moisture tensiometers) at two locations and water content (time domain reflectometry) at three locations.

After the columns were fully assembled and baseline K_{sat} measurements were completed, they were cloaked with black plastic and maintained at 18 to 20°C. STE was applied using four loading regimes, each representative of possible field conditions during startup and maturation (i.e., Stage 1 as described earlier) (Siegrist et al. 2002). Duplicate columns were loaded at initial HLR's of approximately 3.9 to 39 gpd/ft^2 (~16 to 160 cm/day) and operated for 20 weeks, which actually reflected up to approximately 2.5 years of field operation (assuming a typical design HLR of 1.3 gpd/ft^2 [5 cm/day]). The K_e of the biomat for each column was determined from analyses of bromide-tracer tests, falling-head permeability tests, and volumetric water content measurements.

For all columns, the final K_e values were approximately three orders of magnitude smaller than the original

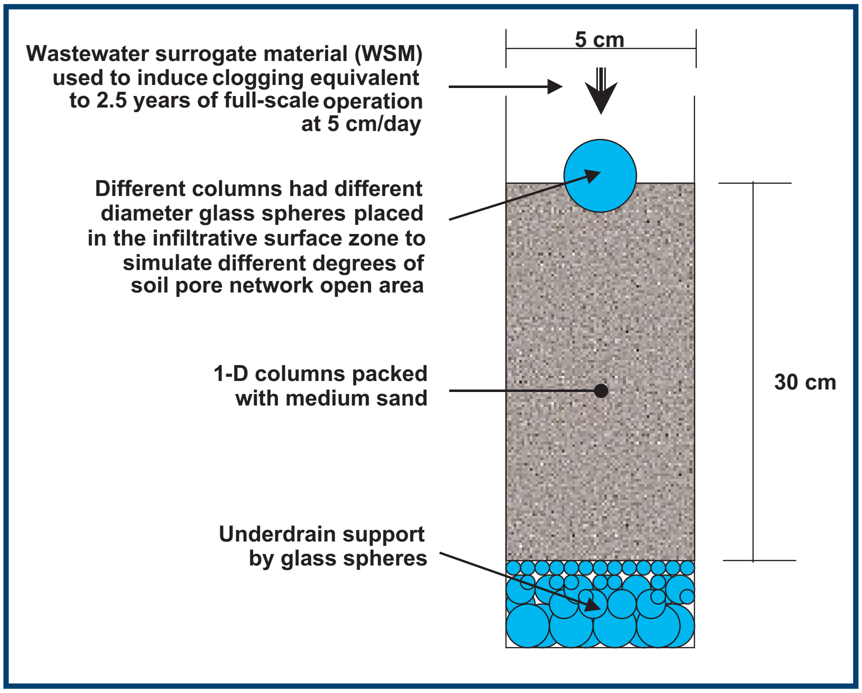

Figure 4 Experimental approach used during a controlled laboratory study to quantify the infiltration rate effects of solid objects within an infiltrative surface zone (after Diaz 2003).

value. A similar K_e is reached regardless of wastewater HLR, although a gravel-free surface has a relatively higher K_e. K_e declined exponentially as the volume of wastewater applied to the column increased.

A generalized equation was offered for estimating K_e (cm/day) as a function of total wastewater volume applied. Beach et al. (2004) also found that for a gravel-free infiltrative surface, the mean falling head infiltration rate was 1.16 gpd/ft^2 (4.75 cm/day) (S.E. = 0.13 gpd/ft^2 [0.54 cm/day]), compared to that for a gravel-laden infiltrative surface, which had a mean falling head infiltration rate of 0.70 gpd/ft^2 (2.84 cm/day) (S.E. = 0.11 gpd/ft^2 [0.44 cm/day]).

Diaz (2003) completed a controlled experiment at the CSM to explore the effective mass-loading rate of wastewater pollutants and infiltration rate behavior as affected by the presence of solid objects on the infiltrative surface. The conceptual model Diaz (2003) examined experimentally is presented in Figure 1, which illustrates different degrees of solid-object obstruction and embedment at the infiltrative surface.

It was hypothesized that effluent infiltration and LTARs can be described using quantitative expressions for features such as the degree of solid object obstruction, in a fashion similar to that of Jaynes and Rice (1983). To enable controlled and reproducible experimentation, the materials and methods included the use of 1-D columns packed with soil media and different degrees of solid-object embedment (Figure 4). Aliquots of a wastewater surrogate material (WSM) were applied to enable addition of soil clogging pollutants equivalent to those experienced under normal periods of operation of months to more than one year. IR measurements were made prior to WSM addition and after each of three fractions were added (10, 30, and 60 wt.% fractional addition), with the total designed to be equivalent to 3.3 or 17 years of operation at a normal HLR of 1.23 or 0.24 gpd/ft^2 (5 or 1 cm/day), respectively.

In this research, 2-in. (5-cm) diameter by 12-in. (30-cm) long columns were used with different degrees of open soil surface equivalent to 29, 51, 80, and 100 percent of the total cross-sectional area of the column (see Figure 1). Diaz (2003) found that there was a clear correlation between IR decline after WSM addition and the cross-sectional area that was obstructed by solid objects. In the sand columns, the greatest final IR was observed in those columns with the greatest open soil area (Figure 5). Moreover, when normalized to the unobstructed open soil surface area, the following relationship (Equations 5 and 6) was revealed for the IR based on the entire column cross-sectional area:

$$\text{IR} = 0.43 \times (\%\ \text{Open Area}) \quad \text{or}$$
$$\text{IR}' = \text{IR}/((\%\ \text{Open Area})/100) \qquad (5)\ \text{and}\ (6)$$

where

IR′ is the IR based on only the unobstructed infiltration area.

Results with another soil media were supportive of this observation with medium sand, but further research is necessary with finer-grained ▶

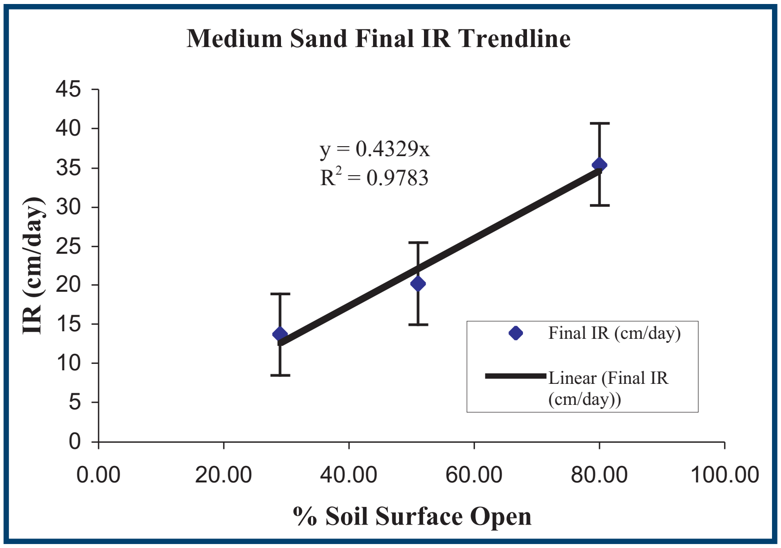

Figure 5 The direct correlation between the fraction of obstructed soil infiltrative surface in sandy porous media and the infiltration rate after the addition of pore-filling materials equivalent to approximately 5 years of effluent application (Diaz 2003). (Note: refer to Figure 1 for the conceptual model illustrating what is meant by "% Soil Surface Open").

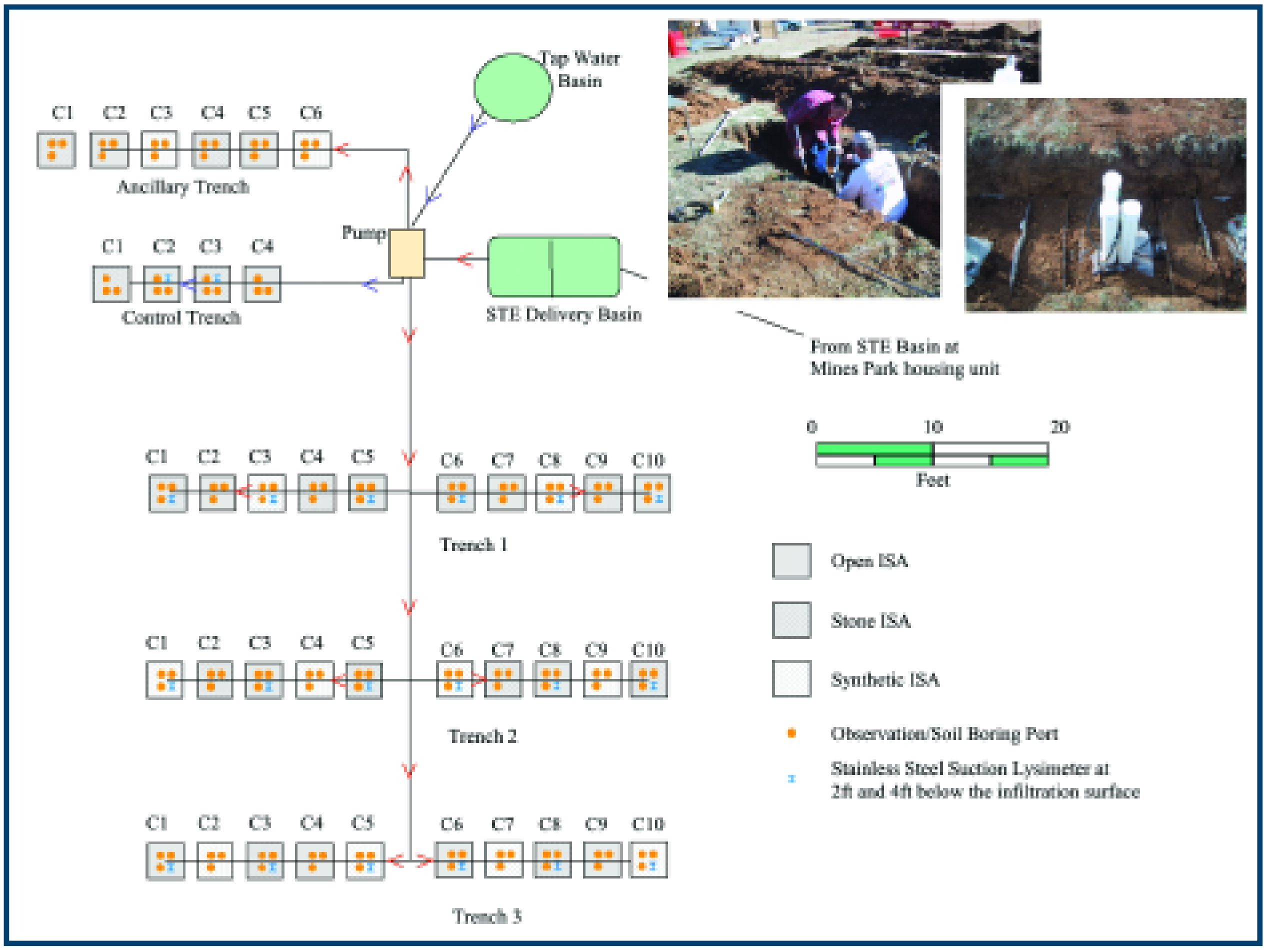

Figure 6 Schematic of the CSM Mines Park Test Site used for a replicated field experiment to study hydraulic and purification processes as a function of soil infiltrative surface architecture and hydraulic loading rate (Tackett et al. 2004).

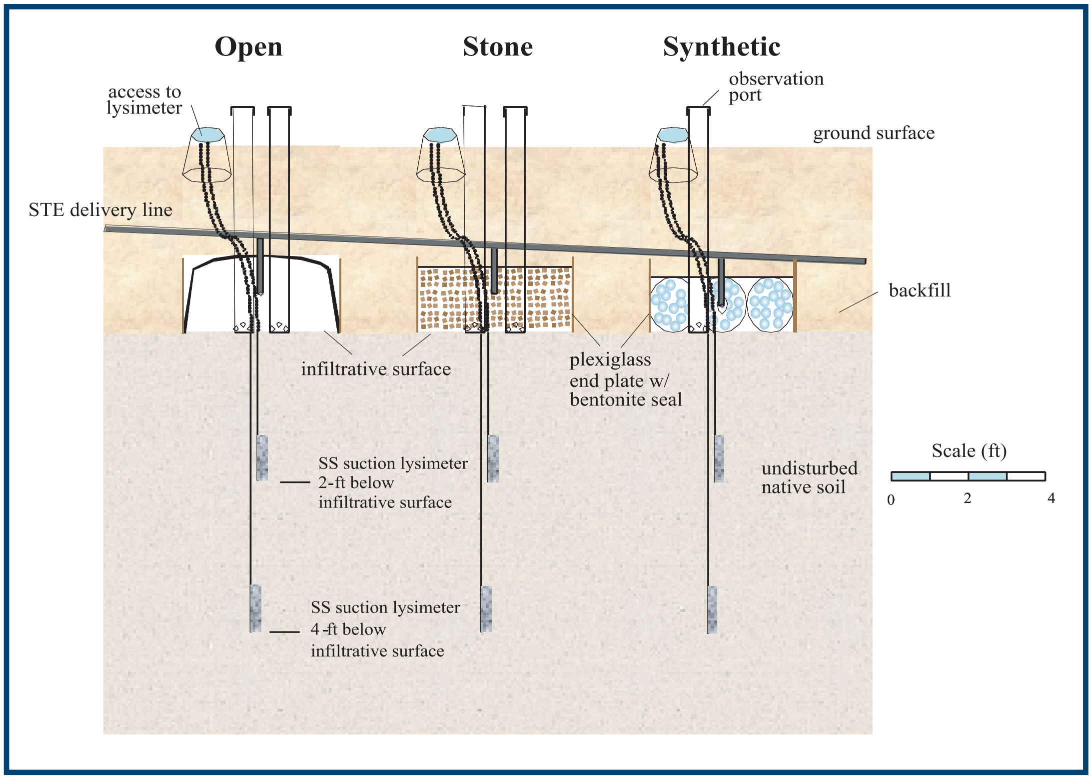

Figure 7 Profile schematic of the pilot-scale WSAS test cells installed at the CSM Mines Park Test Site for a replicated field experiment to study hydraulic and purification processes as a function of soil infiltrative surface architecture and hydraulic loading rate.

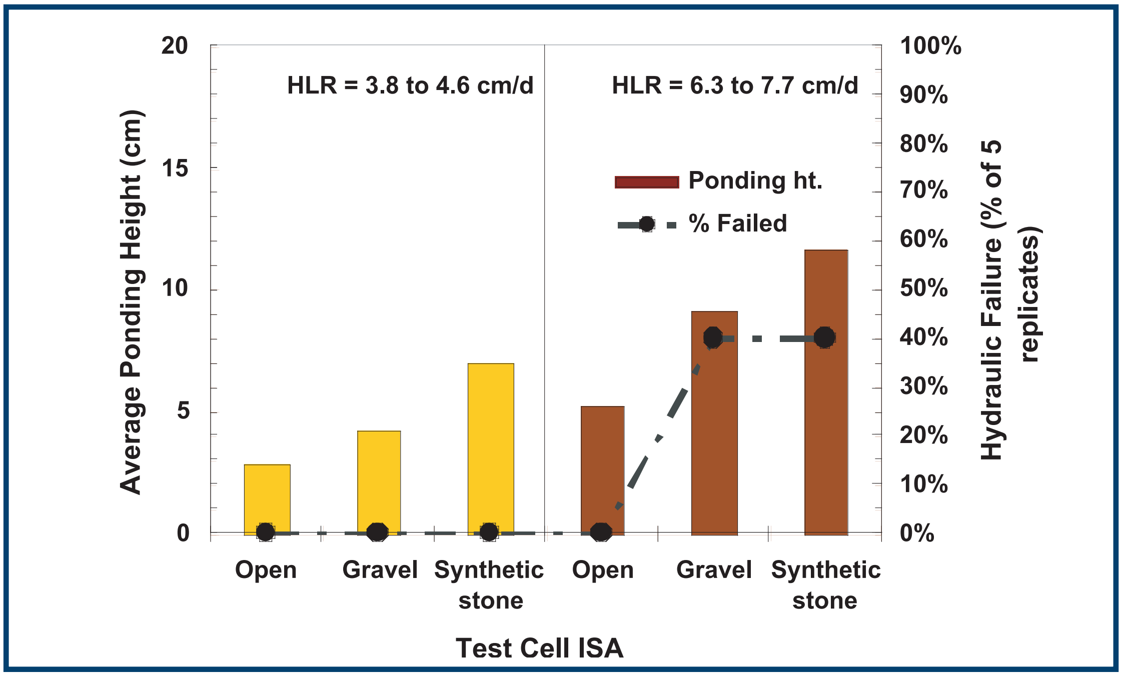

Figure 8 Summary of hydraulic performance observations from ongoing field testing at Mines Park with replicate test cells installed in sandy loam soil and receiving domestic septic tank effluent. (Note: average ponding height after 8 months of STE loading at the design/application rate excluding gravel and synthetic stone test cells that have failed hydraulically as defined by continuous ponding to a height of >7.9 in. (20 cm) for three consecutive weeks).

media and structured soils.

To further explore the effect of infiltrative surface architecture on LTARs, a field experiment was initiated by Tackett et al., at CSM in early 2003 (Tackett et al., 2004). In this project, 34 pilot-scale WSAS test cells were established in a sandy loam soil (Ascalon sandy loam) at the Mines Park Water Reclamation Test Site located on the CSM campus. The experimental design includes five replicates of each of three infiltrative surface architectures (i.e., chamber, gravel-laden, synthetic-stone laden) and two hydraulic loading rates (1.0 and 2.0 gpd/ft^2 [4 and 8 cm/day], equivalent to 2x and 4x the regulatory prescribed LTAR of 0.5 gpd/ft^2 [2 cm/day]) for domestic STE, plus several cells for control purposes (Figures 6 and 7).

By loading the test cells at daily HLRs of 1.0 and 2.0 gpd/ft^2 (4 or 8 cm/day), 6 months of daily operation are anticipated to reflect periods of operation equivalent to 1 and 2 years, based on a 0.5 gpd/ft^2 (2 cm/day) regulatory prescribed design rate for the Ascalon sandy loam soil. Baseline IRs were measured within each test cell using a constant head permeameter (1 in. [2.5-cm] head at the soil infiltrative surface). A minimum of three IR tests were completed for each test cell with a total of more than 800 measurements made across the site. Based on these tests, the soil IRs within the test cells were relatively uniform with an average IR of 10.2 gpd/ft^2 (41.8 cm/day) (standard deviation = 5.1 gpd/ft^2 [20.8 cm/day]).

The time dependent changes in hydraulic capacity associated with biomat formation at the infiltrative surface are being examined by measuring the IRs of each cell over time during STE application and observing the occurrence and magnitude of STE ponding. Purification of chemicals and pathogens achieved by undisturbed sandy loam soil is also being assessed by sampling and analysis of the effluent applied and the soil solution at 2.0 and 4.0 ft. (60 and 120 cm) beneath the infiltrative surface.

Application of STE was initiated in May 2003 and is ongoing. Incipient to continuous ponding of STE on the infiltrative surface was observed within approximately one to two months of STE loading, consistent with predictions made using the model of Siegrist (1987).

Comparison of infiltration rates measured using a constant head permeameter prior to STE application and after 1month of operation revealed a 60 to 85 percent reduction in IRs. Constant head IRs are also being measured at the point when an individual test cell has reached the hydraulic failure condition, which for the purposes of this field testing, is defined as STE ponding of ≥ 7.9 in. (20 cm) for three consecutive weeks.

Figure 8 presents a summary of the hydraulic performance data observed during eight months of continuous operation, while Figure 9 on page 38 shows the reduction in IR for the four test cells (two gravel and two synthetic stone) that have reached the defined hydraulic failure condition. Results after about eight months of continuous operation revealed that solid objects on an infiltrative surface do reduce the WSAS's capacity to infiltrate wastewater effluent.

Conclusions and Implications

Infiltration of wastewater effluents in soils and the estimation of design infiltration rates for a given system design and environmental setting is extremely complex and often poorly understood and oversimplified. Simplified conceptual models and associated analysis (e.g., White and West [2003]) can be technically flawed and inappropriate for formal design of wastewater infiltration systems or as a tool to guide regulatory decisions for two primary reasons.

First, wastewater infiltration systems are unsaturated flow systems, and while numerical models can simulate flow in these situations, the simple K_{EFF} approach cannot. Second, the impact of gravel embedded in the infiltrative surface is not considered. Gravel (or other solid objects) embedded at and within an infiltrative surface zone reduces the volume of the unobstructed soil pore network that is accessible for effluent infiltration and movement. As a result, a gravel-laden WSAS that receives the same HLR of wastewater effluent as a gravel-free WSAS, must process it through a smaller volume of open soil pore network and this results in more rapid and extensive pore-filling with a concommitant loss in hydraulic conductivity of the gravel-laden infiltrative zone.

To advance the understanding of wastewater infiltration dynamics, including the role of ISA in determining design infiltration rates for WSAS, integrated experimental and modeling research has been ongoing at CSM for five years. Models and decision support tools are being developed and validated to facilitate proper WSAS design and regulatory decision-making. Highlights of some of this research are presented herein, while further details are provided in existing and forthcoming publications.

Considerable research has been conducted to understand how design IRs (e.g., LTARs) for wastewater effluent application to soil are affected by ISA associated with gravel or other solid objects on and within the soil infiltrative surface zone. The results of research designed to elucidate this question are consistent in revealing that the soil's ability to infiltrate STE (e.g., LTAR) is lower for a solid-object-laden (e.g., clean gravel) infiltrative surface compared to that of an open infiltrative surface, with the magnitude of the reduction in capacity correlated with the cross-sectional pore volume obstructed by the gravel or other solid media.

Conceptual analysis and experimental research completed to date with sand and sandy loam soils demonstrate that the LTAR for wastewater through an open infiltrative surface (e.g., chamber) is substantially higher (e.g., 1.5 to 2.0 times higher) than that for a solid-object laden infiltrative surface (e.g., gravel or synthetic stone). While further analysis and research is in progress with finer-textured and structured soils, similar results are anticipated. The implications of these results are that a WSAS employing a chamber outfitted trench design can be sized with a smaller soil infiltration surface area compared to that required for a gravel-filled trench design (or similar solid-object laden infiltrative surface design). It is noted that in soil systems with extremely low K_{sats} due to low permeability of the natural soil profile (e.g., bulk deposits of dense clays or silty clay layers underneath but near the infiltrative surface), the soil profile rather than the infiltrative surface architecture and biomat development may control wastewater infiltration and the effluent application rate appropriate for WSAS design.

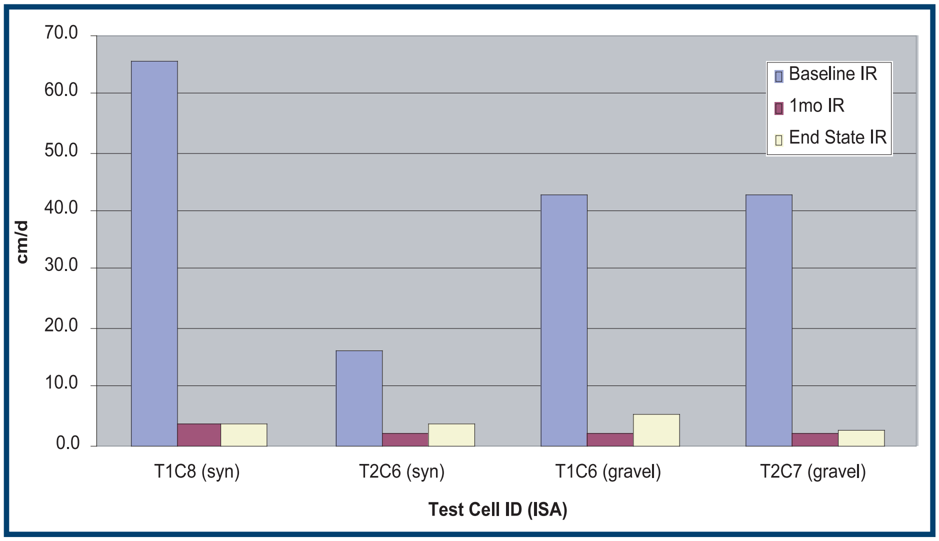

Figure 9 Comparison of constant head infiltration rates after 6 months of STE application for four hydraulically failed pilot-scale WSAS cells installed in sandy loam soil. (Note: hydraulic failure is defined as >20 cm of STE ponding above the infiltrative surface for three consecutive weeks).

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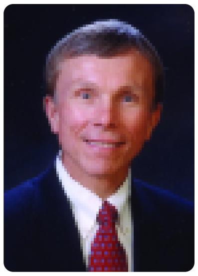

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