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Modeling Trench Sidewall and Bottom Flow in On-Site Wastewater Systems

S. D. Finch¹; D. E. Radcliffe²; and L. T. West³

Abstract: Little is known about how much wastewater infiltrates the soil via the trench sidewall versus the trench bottom in onsite wastewater systems. Our objectives were to develop a method of simulating trench bottom and sidewall flow using a two-dimensional numerical computer model that would include the trench within the model space and determine how much sidewall flow would occur under steady-state conditions. We used HYDRUS-2D to simulate water flow in a two-dimensional cross section of a conventional gravel-filled trench and the surrounding drainfield. Hydraulic properties of the gravel were assumed (saturated hydraulic conductivity $K_s=1,000 \text{ cm d}^{-1}$) and simulations were run for drainfield soils consisting of a clay loam ($K_s=3.2 \text{ cm d}^{-1}$) and a sand ($K_s=41 \text{ cm d}^{-1}$). Biomats were simulated at the bottom of the trench and part way up the trench sidewall ($K_s=0.2$ to 2.8 cm d^{-1} depending on the simulation). Typical wastewater loading rates for Georgia of 2 and 4 cm d^{-1} for the clay loam and sand, respectively, were simulated in three daily doses of 1.4 min in length. Simulations were run until the water level in the trench reached a dynamic equilibrium, as indicated by a repeating pattern of water level daily changes. The method we developed predicted the water level in the trench instead of specifying it as a boundary condition, as has been done in previous modeling studies. In the clay loam soil, we found that the water level in the trench at steady conditions averaged a depth of 9.5–10.9 cm and that 29–31% of the total flow occurred through the sidewall. In the sand soil, we found that water did not pond in the trench and there was no sidewall flow. Much of the sidewall flow in the clay loam soil appeared to be in the “lip” area just above the maximum height of the sidewall biomat. Our results show that sidewall flow is important, but not as high as others have estimated.

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Introduction

Drainfield trenches in on-site wastewater systems (OWSs) are used to distribute septic tank effluent over an area of soil and allow it to infiltrate into the soil. Thus, hydraulic properties of the soil, which are relatively easy to measure or estimate, are used to size the drainfield. Numerous studies have shown, however, that the wastewater infiltration rate in drainfield trenches declines during the first few years after installation. This decline is attributed to the formation of a low conductivity “biomat” at the soil-trench interface, which impedes infiltration but is a zone of intense microbial activity and important in purifying wastewater (van Cuyk et al. 2001, 2004). The final steady wastewater infiltration rate is often referred to as the long-term acceptance rate (LTAR) (units

of volume per area of trench infiltration surface per time) and an estimate of this value is used to evaluate the suitability of soils for installing OWS, and determine the drainfield size needed to accommodate design wastewater flow.

Although regulations vary among states, only the basal area of the drainfield trenches typically is used in determinations of drainfield size. The sidewall infiltrative area is commonly reserved as a safety factor, since wastewater would only move through the sidewalls if it was ponded in the trench. Wastewater ponding in the trenches of functioning OWSs has been reported, however (Bouma 1975; Keys et al. 1998).

Little is known about how much wastewater infiltrates the soil via the trench sidewall versus the trench bottom. Bouma (1975) investigated the trenches of 13 mature OWSs in Wisconsin. He found that biomats extended only part of the way up the sidewall. He estimated sidewall and bottom flux by measuring the depth of ponding in each trench (all systems had wastewater ponded to some depth) and the soil matric potential head just below the trench and to the side of the trench using tensiometers. The equation for vertical flow was given in Bouma (1975)

$$Q_b = Q_s$$

$$-K_b \frac{dH}{dz} = -K(h) \frac{dH}{dz}$$

$$K_b \frac{h_0 - h_s + Z_b}{Z_b} = K(h_s) \left(\frac{dh}{dz} + 1 \right)$$

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$$K_b \frac{h_0 - h_s + Z_b}{Z_b} = K(h_s) \quad (1)$$

This equation assumes that under steady flow conditions, the vertical flux through the bottom biomat (Q_b in cm d^{-1}) is equal to the vertical flux through the soil (Q_s in cm d^{-1}) immediately beneath the biomat. The total water potential head is H in cm; z is distance in cm; K_b =hydraulic conductivity of the biomat (unsaturated or saturated depending on the pressure head within the biomat) in cm d^{-1} ; and $K(h)$ =unsaturated hydraulic conductivity of the soil in cm d^{-1} . The gradient in the biomat flux term includes the height of water ponded in the trench (h_0 in cm), the matric potential head in the soil just beneath the biomat (h_s in cm), and the thickness of the biomat (Z_b in cm). The gradient in the soil flux term includes a term for change in matric potential head with depth (dh/dz) and a unit gradient term for the effect of gravity. Bouma (1975) assumed that matric potential head would be constant with depth for at least a short interval beneath the biomat ($dh/dz=0$), based on his measurements of soil matric potential within cores where a crust was applied. Hence, the flux through the biomat and soil is equal to the unsaturated hydraulic conductivity of the soil at the matric potential head just beneath the biomat (h_s), as shown in Eq. (1).

To calculate sidewall flow, Bouma et al. (1972) also assumed a unit gradient for horizontal flow, which is not a common assumption. The equation for sidewall flux was not given, but using the same assumptions of steady flow through the sidewall biomat and soil immediately adjacent to the biomat, the equation is

$$\begin{aligned} Q_b &= Q_s \\ -K_b \frac{dH}{dx} &= -K(h_s) \frac{dH}{dx} \\ K_b \frac{h_0 - h_s}{Z_b} &= K(h_s) \frac{dh}{dx} \\ K_b \frac{h_0 - h_s}{Z_b} &= K(h_s) \end{aligned} \quad (2)$$

where x =horizontal distance in cm; h_0 =height of ponding in the trench in cm *above the point where the sidewall flux is estimated*; and h_s =matric potential head in cm in the soil immediately adjacent to the sidewall biomat (Fig. 1). Unlike Eq. (1), the gradient in the biomat flux does not include the thickness of the biomat (Z_b) in the numerator. Instead of assuming that the matric potential head does not change with distance, Bouma assumed it would change at a rate of 1 cm per cm ($|dh/dx|=1$), based on his measurements with tensiometers near the sidewall of several of the trenches in his study (although there were only 2–3 tensiometers adjacent to the sidewalls at each site where measurements were made). Since there is no effect of gravity on horizontal flow, the net effect is again that steady flux through the biomat and soil is equal to the unsaturated hydraulic conductivity of the soil at the matric potential head immediately adjacent to the biomat (h_s), as shown in Eq. (2) and Fig. 1.

With these assumptions, Bouma (1975) estimated that bottom and sidewall fluxes were similar in magnitude and that approximately 48% of the total flow out of the trench occurred through the sidewall. Despite the high percentage, Bouma (1975) recommended that sidewall flow not be considered in estimating LTAR except in low conductivity clays where he estimated about one-third of the flow would be through the sidewall. The reason for

Fig. 1. Cross section of a trench showing the components of lateral flow in Eq. (2): Q_b is flux through the sidewall biomat; Q_s is flux through the soil; h_0 =height of ponding in the trench above the point where the sidewall flux is estimated; and h_s =matric potential in the soil immediately adjacent to the sidewall biomat

excluding coarse textured soils may have been to ensure that water was adequately treated in these soils before reaching groundwater.

Bouma (1975) also used Eq. (1) to estimate the LTAR of a mature system. Assuming values for the thickness (Z_b) and hydraulic conductivity (K_b) of the biomat and knowing the soil unsaturated hydraulic conductivity function [$K(h)$], Eq. (1) can be solved iteratively to find the value of h_s that makes the flux through the biomat and soil equal (or it can be done graphically by plotting the two fluxes as a function of h_s and finding the value of h_s where the curves cross each other). Once this value is known, the LTAR is equal to $K(h_s)$. The Bouma (1975) approach only considered flow through the bottom to determine the LTAR. Ignoring sidewall flow in determining the LTAR may be a way to build in a “safety factor,” but the size of the safety factor is unknown. Alternatively, the sidewall flow component of the LTAR might be calculated (if a method was available) and a known safety factor applied.

Keys et al. (1998) proposed that sidewall biomats only extend to the average height of ponding in the trench. They also proposed that as the trench ages, the bottom and sidewall biomats become less conductive, the ponding height increases, and a significant portion of wastewater flows into the soil through the sidewall. They divided the sidewall into three regions: the lower section contains a fully developed biomat, above this is a short section with a poorly developed biomat (the “lip” area), and above the lip to the top of the sidewall is a section with no biomat. As ponding depth increases over time, the height of the sidewall biomat increases and failure occurs once the biomat extends all the way to the top of the sidewall. Keys et al. (1998) measured infiltration rates in two mature trenches in a sand under a falling head. From these infiltration rates, they estimated fluxes through the bottom, sidewall biomat, sidewall lip, and the area above the sidewall lip. It is not clear from the paper how they divided the total infiltration rate into these different components. Presumably, they calculated infiltration rates at different heights of ponding, starting with the lowest ponding height where flow could be considered through the bottom only and estimating the sidewall components from the additional flow that occurred at greater ponding heights [and perhaps adjusting for the effect of ponding height on flow through the bottom using Eq. (1)]. They concluded that flow through the sidewall biomat and lip area could account for 60 to 90% of the total flow out of the trench. If the ponding level in the trench rose high enough, flow through the sidewall

Table 1. Water Retention and Hydraulic Conductivity Parameters for the Model Simulations

Porous media	K_s (cm d ⁻¹)	n	α (cm ⁻¹)	θ_r (cm ³ cm ⁻³)	θ_s (cm ³ cm ⁻³)
Clay loam	3.2	1.52	0.01	0.08	0.46
Bottom biomat for clay loam	0.2	1.52	0.01	0.08	0.46
Sidewall biomat for clay loam	0.2 or 0.4 ^a	1.52	0.01	0.08	0.46
Sand	41	2.22	0.03	0.05	0.32
Bottom biomat for sand	1.4	2.22	0.03	0.05	0.32
Sidewall biomat for sand	1.4 or 2.8 ^a	2.22	0.03	0.05	0.32
Trench gravel for clay loam and sand	1,000	2.80	1.75	0.05	0.50

^aSidewall biomat K_s was assumed to have the same value or twice the value of the bottom biomat in simulations.

above the lip area increased total sidewall flow to 97–99% of the total flow.

Beach and McCray (2003), Beal et al. (2008), and Bumgarner and McCray (2007) have used HYDRUS-2D, a two-dimensional numerical model developed by Šimúnek et al. (1998), to study water flow in OWSs. Radcliffe et al. (2005) also used HYDRUS-2D to compare infiltration in conventional gravel-filled trenches with chamber systems that do not use gravel. Simulations were conducted with and without sidewall flow. In the simulations that considered sidewall flow, the trench bottom and sidewall formed part of the boundary of the model space and an arbitrary, constant level of wastewater in the trench was chosen (5 cm of ponded water). A better way to simulate sidewall flow would be to include the trench as part of the model space and let the simulation determine what the level of wastewater would be. The level would depend on the amount of water entering the trench through the drain line and the amount infiltrating the soil through the trench bottom and sidewall.

The objectives of this study were threefold: (1) to develop a method of simulating OWS bottom and sidewall flow that would include the trench within the model space; (2) to determine how much sidewall flow would occur in a coarse- and fine-textured soil under steady-state conditions (representative of the LTAR); and (3) to compare the numerical estimates of sidewall flow to the Bouma (1975) simple method of estimating sidewall flow. In this paper, we use the term “sidewall” to include all areas of the vertical trench face so it includes the lower sidewall where a biomat is present, the “lip” area immediately above the biomat where much of the flow is thought to occur, and the area above the lip extending to the top of the sidewall. This is consistent with the terminology used by Bouma (1975) but in contrast to the terminology used by Keys et al. (1998) who used sidewall to refer to the biomat area only.

Materials and Methods

We used HYDRUS-2D to model two-dimensional water flow in variably saturated soil (Šimúnek et al. 1998). HYDRUS-2D is a finite-element model that uses a numerical solution to the Richards (1931) equation. Various equations are available in the model for describing the soil water retention and unsaturated hydraulic conductivity functions of each soil layer. We used the van Genuchten (1980) equation for the water retention curve

$$\Theta = (1 + |\alpha h|^n)^{-m} \quad (3)$$

where α , m , and n =fitted parameters and it is assumed that $m=1-1/n$. Relative water content (Θ) is defined as

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

where θ =volumetric water content (cm³ cm⁻³); θ_s =saturated volumetric water content (cm³ cm⁻³); and θ_r =residual volumetric water content (cm³ cm⁻³). We used the unsaturated hydraulic conductivity function $K(h)$ from van Genuchten (1980) as well

$$K(h) = K_s \Theta^{0.5} [1 - 1 - (\Theta^{1/m})^m]^2 \quad (5)$$

where m =fitted parameter from Eq. (3); and K_s =saturated hydraulic conductivity in cm d⁻¹.

Finch (2006) measured soil and biomat properties of seven OWSs in Georgia. The soil properties were measured on the horizon in which the drainfield trench was installed. We selected two sites from this study for soil and biomat properties in our simulation. One site was in the Georgia piedmont where the trench bottom was in a clay loam textured BC2 horizon. The other site was in the coastal plain where the trench bottom was in a sand textured Bh horizon. The piedmont system was 7 years old and the coastal plain system was 10 years old. Both OWSs used a chamber system. Measurements of particle size distribution, bulk density, and K_s of the natural soil and biomat were made at each site (Finch 2006).

Water retention and unsaturated hydraulic conductivity parameters for Eqs. (3)–(5) were predicted using HYDRUS-2D's neural network and Rosetta database (Schaap 2001). Particle size distribution, bulk density, and K_s measured for the sites were input and the parameters n , α , θ_s , and θ_r were derived from the database (Table 1). Finch (2006) sampled sidewalls to a height of about 12 cm above the trench bottom. Biomats were present on the sidewall to this height and she did not find any significant difference in K_s of sidewall and bottom biomats. In our simulations, we tested two scenarios for each soil: one in which the sidewall and bottom biomat had the same K_s and one in which the sidewall biomat had twice the K_s of the bottom biomat (Table 1). For the gravel in the trench, we used water characteristic curve parameters that would result in a steep moisture release curve, high K_s (1,000 cm d⁻¹), low residual water content ($\theta_r=0.05$ cm³ cm⁻³), and a saturated water content based on half the pore space being filled with gravel ($\theta_s=0.50$ cm³ cm⁻³). Accurate modeling of water flow through gravel in our case was difficult for several reasons: (1) the steep moisture release curve caused numerical instabilities, (2) the large difference in hydraulic properties (such as K_s) between the gravel and soil/biomats also caused numerical instabilities, and (3) turbulent flow is more likely in gravel and the Richards equation does not account for turbulent flow.

The drainfield and trench were modeled in a cross section with one axis vertical and the other horizontal (Fig. 2). One-half of the

Fig. 2. Model space and boundary conditions for simulations

drainfield was used for the model space, assuming the middle of the trench would be an axis of symmetry and form a no-flux boundary on the left side of the model space. The model space was 180 cm in the horizontal dimension. This placed the right boundary sufficiently distant from the trench that a wetting front never reached this boundary (a no-flux boundary condition was imposed). The model space was 190 cm in the vertical dimension with the trench bottom placed 130 cm below the soil surface, which would be a typical installation in Georgia. The soil surface formed the top of the model space and was treated as a no-flux boundary. The trench was 45 cm in width (half that of a full trench) and 30 cm in depth. Georgia regulations require that drainfield trenches be at least 61 cm above the seasonal water table so we placed the trench bottom 63 cm below the trench and imposed a boundary condition of a constant head of zero to simulate a water table at the bottom of the model space. The surrounding soil was modeled as either a clay loam or sand with the soil hydraulic properties shown in Table 1.

The trench was simulated to be filled with gravel and an 8 cm diam distribution pipe was installed 19 cm above the trench bottom (Fig. 2). We assumed the sidewall biomat extended to a height of 12 cm above the trench bottom because this was the height to which Finch (2006) sampled sidewalls and found biomats present (they may have extended higher than this height but probably not to the top of the sidewall). Although measurements by Finch (2006) indicated the biomat thickness in these soils was less than 0.8 cm thick, a biomat thickness of 3 cm was used for model simulations in order to increase the number of nodes within the biomat and improve the accuracy in predicting wastewater flow. The biomat hydraulic conductivity was increased from that measured at the sites such that the biomat hydraulic resistance ($R_b = Z_b/K_b$) remained the same as that measured for the sites (R_b of 15.6 and 2.2 d and a K_b of 0.2 and 1.4 cm d⁻¹ for the clay loam and sand sites, respectively).

A total of 4,700 nodes were used in the model space with the densest network of nodes in the trench and biomat areas. The number and distribution of nodes were chosen through a process of trial and error to find the combination that would result in a numerical solution that converged and a water balance error of less than 1% at all time steps.

The wastewater loading rate was 2 cm d⁻¹ for the clay loam and 4 cm d⁻¹ for the sand, applied in three equal doses during the day at 8 am, 2 pm, and 8 pm. The loading rates are typical loading

Fig. 3. Water level in the trench of the clay loam and sand simulations as a function of time for two scenarios: sidewall and bottom biomat K_s the same, and sidewall K_s twice that of bottom biomat

rates used for soils with properties similar to these in Georgia. The doses were simulated by applying a time-varying flux boundary condition along the nodes that formed the distribution pipe boundary (Fig. 2). Dosing times were chosen from the frequency pattern of a single-family residence (USEPA 2002). Each dose lasted 0.001 day (1.44 min) and the instantaneous fluxes during the pulse were 2,000 cm d⁻¹ for the clay loam and 4,000 cm d⁻¹ for the sand. During the period between doses, the nodes along the drain pipe boundary were treated as a no-flux boundary.

The initial conditions were a distribution of matric potential heads such that all nodes were at equilibrium with the water table at the bottom of the model space (so there was no driving force for water flow other than wastewater entering through the distribution pipe). In HYDRUS-2D, observation nodes can be identified so that pressures at that node during simulations can be an output. We placed an observation node in the trench at the top of the bottom biomat midway between the left boundary and the trench sidewall. We used this observation node to measure pressure at the bottom of the trench, which (when it was positive), indicated the level of wastewater ponded in the trench.

HYDRUS-2D calculates the flux across all external boundaries and will calculate the flux across internal lines if they are specified. We specified lines that represented the boundaries of the trench bottom and sidewall. Since the calculations were done in a two-dimensional space, the flux is reported as the volume of water that flowed across a width of trench bottom or sidewall per unit time and per unit longitudinal length of trench (units of cm³ cm⁻¹ d⁻¹ = cm² d⁻¹).

There were four model simulations. One simulation for each site (clay loam and sand) used the same K_s for the trench bottom and sidewall biomats. The other two simulations assumed that the sidewall biomat K_s was twice that of the trench bottom (Table 1). Model simulations were run until total water levels in the trench reached a quasi-steady state.

Results and Discussion

Clay Loam Simulations

The water level in the trench of the clay loam simulations is shown in Fig. 3 for two scenarios: one for the sidewall and bot-

Table 2. Calculated Volume of Wastewater Flowing into and out of the Trench Averaged over a 24-h Period during the Time from 15.3 to 16.3 Days from Four Model Simulations; Calculations Are for Half the Trench Width and a Longitudinal Length of Trench of 1 cm

Model run	Sidewall biomat K_s	Drain pipe inflow (cm ³)	Sidewall outflow (cm ³)	Bottom outflow (cm ³)	Total outflow	
					(cm ³)	(%)
Clay loam	Equal to bottom biomat K_s	90.0	26.2	64.3	90.5	101
	Twice bottom biomat K_s	90.0	27.3	61.2	88.5	98
Sand	Equal to bottom biomat K_s	180.0	0.0	179.2	179.7	100
	Twice bottom biomat K_s	180.0	0.0	179.2	179.2	100

tom biomat K_s the same, and one for the sidewall biomat K_s twice that of the bottom biomat. Water levels were about 2 cm higher in the scenario where the sidewall and bottom biomat K_s were the same. The level fluctuated three times each day in response to the doses, but the overall trend was a rise in levels until about day 12. After that time, the water level reached a quasi-steady state, rising in response to the doses, and reaching a peak after the third dose, then returning to the original minimum level just before the first dose of the following day.

Volumes of flow (per unit length of trench) in and out of the trench were calculated for a one-day period from 15.3 to 16.3 days to get daily flow at quasi-steady state (Table 2). Calculations are for half the trench width and a longitudinal length of trench of 1 cm. For the clay loam soil with the same K_s for bottom and sidewall biomats, the total inflow to the trench through the drain pipe was 90 cm³ (dividing by the bottom area for the half-trench, 45 cm², gave the intended daily waste application load of 2 cm). Summing the volumes of flow out of the trench bottom, entire sidewall, and trench ceiling, the total outflow from the trench for this simulation was 90.5 cm³, which was 101% of the input volume (Table 2). For the clay loam soil with the sidewall biomat K_s twice that of the bottom biomat, the total outflow from the trench was 88.5 cm³, which was 98% of the input volume. The close agreement between inflows and outflows confirmed that a steady-state condition had been reached in these simulations.

For the clay loam soil with equal sidewall and bottom biomat, 64.3 cm³ (71% of the total outflow) flowed through the bottom of the trench and 26.2 cm³ (29% of the total outflow) passed through the trench sidewall (Table 2). The total, bottom, and sidewall flows out of the trench as a function of time for this scenario are shown in Fig. 4 for a two-day cycle from 14.3 to 16.3 days. The

Fig. 4. Total flow out of the trench, flow out of the trench bottom, and flow out of the trench sidewall in the clay loam soil with equal trench bottom and sidewall K_s during a two-day cycle from 14.3 to 16.3 days. Flow is given in volume per unit longitudinal length of trench per day. Water level in the trench is also shown.

units for flow are volume of outflow per unit longitudinal length of trench per unit time, hence, cm² d⁻¹. Flow through the bottom was relatively constant at approximately 62 cm² d⁻¹. Flow through the sidewall varied substantially from 17 to 36 cm² d⁻¹ and caused total outflow to vary between 79 and 101 cm² d⁻¹. Increased flow through the sidewall coincided with increases in water levels in the trench (also shown in Fig. 4), which varied between 9.9 and 11.7 cm (mean of 10.9 cm). The increase in sidewall flow was due in large part to flux of water just above the sidewall biomat when the water level rose to near or above the level where the biomat ended [the region referred to as the sidewall biomat “lip” by Keys et al. (1998)]. This can be seen in Fig. 5 where velocity vectors in the trench area are shown for the clay loam with equal sidewall and bottom biomat K_s at a time of 15.85 days (8:24 pm).

For the clay loam soil with sidewall biomat K_s twice that of the bottom biomat, 61.2 cm³ (69% of the total outflow) flowed through the bottom of the trench and 27.3 cm³ (31% of the total outflow) passed through the trench sidewall (Table 2). The slight increase in sidewall flow was expected because the sidewall biomat had a higher K_s in this scenario compared to the earlier scenario with equal sidewall and bottom biomat K_s . The total, bottom, and sidewall flows out of the trench as a function of time for this scenario are shown in Fig. 6. Flow through the sidewall varied from 22 to 34 cm² d⁻¹ and caused total outflow to vary between 81 and 97 cm² d⁻¹. This is a slightly narrower range than for the simulation with the same K_s for bottom and sidewall biomats (Fig. 4), but the pattern was quite similar between these scenarios. Increased flow through the sidewall again coincided

Fig. 5. Velocity vectors showing direction and magnitude (indicated by length) of flow in the trench area at a time of 15.85 days for the clay loam with equal sidewall and bottom biomat K_s . Flow enters the trench via the drain pipe on the left and flows out of the trench through the bottom and sidewall. Much of the sidewall flow occurs in the area just above the sidewall biomat on the right.

Fig. 6. Total flow out of the trench, flow out of the trench bottom, and flow out of the trench sidewall in the clay loam sidewall biomat K_s twice that of bottom biomat during a two-day cycle from 14.3 to 16.3 days. Flow is given in volume per unit longitudinal length of trench per day. Water level in the trench is also shown.

with increases in water levels in the trench, which varied between 8.9 and 10.7 cm (mean of 9.5 cm). In this case, more flow through the sidewall occurred as the water level rose because more sidewall area was exposed and the sidewall biomat was more conductive than the bottom biomat. More flow also occurred because of flow above the sidewall biomat, in spite of the fact that the water level in the trench never exceeded the height of the sidewall biomat (11 cm above the bottom of the trench). This flow may be an artifact of the water characteristic curve parameters of the simulated gravel filling the trench (Table 1). The curve for the gravel at the very wet end (matric potential head between 0 and -6 cm) is shown in the top graph in Fig. 7. The curves for the biomat and clay loam are the same since they had the same water characteristic curve parameters (Table 1) and they are approximately equal to the saturated water content ($\theta_s = 0.46 \text{ cm}^3 \text{ cm}^{-3}$) in this range of matric potential. Ideally, the curve for gravel should be flat and equal to the small value for residual water content ($\theta_r = 0.05 \text{ cm}^3 \text{ cm}^{-3}$) for all negative matric potentials and rise to saturation abruptly at positive pressures. This would require α and n to be very large. We used the largest value of α and n that resulted in convergent numerical solutions ($\alpha = 1.75 \text{ cm}^{-1}$ and $n = 2.80$; Table 1). As a result, the unsaturated hydraulic conductivity function for the gravel exceeded that of the clay loam once matric potential rose above about -2 cm (bottom graph in Fig. 7). The effect of this was that a capillary fringe was present in the gravel layer that allowed water to flow above the biomat whenever the water level in the trench rose to within about 1.5 cm of the top of the sidewall biomat. As such, our simulations may have overestimated sidewall flow.

Sand Simulations

A consistent pattern of water levels in the trench was reached after only three days in the sand simulation (compared to 13 days in the clay loam simulations) due to the higher hydraulic conductivity of the sand (Fig. 3). Water ponded at the observation point (midway between the trench center line and the sidewall) for short periods of time after each dose but the water level dropped to zero before the next dose. There was no difference in height between the simulation with equal sidewall and bottom biomat K_s and the simulation with the sidewall biomat K_s twice that of the bottom biomat.

Fig. 7. Hydraulic properties of the clay loam, biomat, and gravel for the simulations of the clay loam with the same K_s for bottom and sidewall biomats: (a) volumetric water content as a function of matric potential head; (b) hydraulic conductivity as a function of matric potential head

Steady-state measurements of flow in and out of the trench were made during the interval 15.3 to 16.3 d to be consistent with the clay loam simulation. Of the 180 cm^3 applied (per cm of longitudinal trench length) to the sand each day, 179.2 cm^3 (99.6%) infiltrated the trench bottom (Table 2). There was no sidewall flow. The high acceptance by the trench bottom was due to the high $K(h)$ of the sand and biomat and the large gradient across the biomat [due to the differences in $K(h)$ between these layers]. The matric potential just below the biomat in the sand during the interval 15.3 to 16.3 d was about -27 cm. At this matric potential, $K(h)$ for the sand was a relatively high 5.97 cm d^{-1} [in spite of the steep $K(h)$ curve typical of sand].

The water level in the trench varied in time and in location across the trench. The soil closest to the drain pipe had the highest water level (varying between zero and a maximum ponding depth of 3.7 cm at the end of a dose) and the level decreased steadily to unsaturated conditions before reaching the sidewall. At the sidewall, water never ponded in the trench and consequently, there was no sidewall flow. Ideally, the water levels should have been uniform across the trench except at the instance when the dose was applied. However, our model resulted in rather “sluggish” flow in the trench that delayed movement of water through the gravel. We do not think this had a substantial effect on any of our results. Increasing the saturated hydraulic conductivity of

the gravel might have helped with this problem but if we used values larger than $1,000 \text{ cm d}^{-1}$, the model became unstable with the grid and time settings we used. Modeling unsaturated flow in porous media with very different hydraulic properties ($K_s > 1,000 \text{ cm d}^{-1}$ for gravel and $< 1 \text{ cm d}^{-1}$ for clay loam biomats) is particularly difficult (Smith 1985).

Comparisons with Earlier Studies

Our results differ somewhat from those of Bouma (1975) who used Eqs. (1) and (2) to calculate bottom and sidewall flow, respectively. He found that about 50% of the total flow occurred through the sidewall, whereas we found that 29–31% of the total flow was through the sidewall in the clay loam and none in the sand. We converted the trench bottom flows in our study to fluxes for comparison with the Bouma 1975 study by dividing the bottom outflows in Table 2 by the cross-sectional area of a half trench (45 cm^2). The resulting bottom fluxes for our clay loam were $1.36\text{--}1.43 \text{ cm d}^{-1}$, which were considerably higher than the range in the Bouma (1975) study for clay soils (their conductivity class IV) of $0.17\text{--}0.75 \text{ cm d}^{-1}$. For the sand in our study, the bottom flux was 3.98 cm d^{-1} , which was a little lower than the range in the Bouma (1975) study for sands (their conductivity class I) of $5.8\text{--}7.5 \text{ cm d}^{-1}$. To convert sidewall flows for the clay loam simulation in Table 2 to fluxes, we divided by the average height of ponding ($9.5\text{--}10.9 \text{ cm}$ depending on the sidewall biomat K_s) and the longitudinal length of trench in our simulations (1 cm). The resulting sidewall fluxes were $2.40\text{--}2.87 \text{ cm d}^{-1}$, which were higher than the range in the Bouma (1975) study for clay soils of $0.17\text{--}0.62 \text{ cm d}^{-1}$. So our simulations predicted higher flow through the biomats in the clay loam, especially at the bottom of the trench. We do not think the difference was due to the use of Bouma's Eq. (1) (below we show that it accurately predicts bottom flow, using our values for biomat hydraulic resistances R_b). Rather, the difference was likely due to the lower R_b used in our study. We used $R_b = 15.6 \text{ d}$ for the clay loam and 2.2 d for the sand bottom and sidewall biomats [based on field measurements in our soils by Finch (2006)]. By comparison, Bouma (1975) estimated bottom biomat $R_b = 54.3 \text{ d}$ for trenches in clays and 6.3 d for trenches in sands.

Our results are also contrary to those of Keys et al. (1998) who estimated that over 60–90% of the flow out of a trench in sand would be through the sidewall biomat and lip area. The authors reported a range of hydraulic conductivities for the bottom biomat area of $0.02\text{--}0.05 \text{ cm d}^{-1}$. Presumably, these are unsaturated hydraulic conductivities of the soil (and not the biomat hydraulic conductivities) based on the assumptions in Eq. (1) that a unit gradient will apply and steady flux out of the trench through the bottom and sidewall will be equal to $K(h_s)$. The steady flux through the bottom biomat in our simulations for the sand was 3.98 cm d^{-1} . This is nearly two orders of magnitude greater than the bottom area conductivity in Keys et al. (1998). They reported that K_s of their sands were in the range of 144 cm d^{-1} . Since we used a K_s for our sand of 41 cm d^{-1} (Table 1), the higher flow through the bottom was unlikely to have been due to the hydraulic conductivity of the underlying soil. Instead, it was probably due to a less negative matric potential in the soil beneath the biomat in our study. This was due to a lower biomat R_b in our study than that in the trenches of Keys et al. (1998). If we had used a higher R_b in our sand simulation, that might have caused more ponding and sidewall flow.

Our simulations provided the opportunity to test Bouma's

method for calculating the LTAR using Eq. (1). Using Bouma's method for the clay loam simulation, we set $Z_b = 3 \text{ cm}$, $K_b = 0.2 \text{ cm d}^{-1}$, $h_0 = 10.5$ (the average ponding height on day 15.3–16.3) in Eq. (1). Using the $K(h)$ function described by Eq. (5) with the parameters from Table 1, the value of h_s that resulted in an equal flux through the biomat and underlying soil [satisfying Eq. (1)] was -11.1 cm . The associated unsaturated hydraulic conductivity at this matric potential head [$K(h_s)$] was 1.49 cm d^{-1} . Our simulated flux for the scenario with the same K_s for bottom and sidewall biomats was 1.43 cm d^{-1} , so Bouma's method did an excellent job of estimating steady flux through the bottom in our clay loam soil. The reason this worked is the assumption of a unit gradient was valid for vertical flow. This is shown in Fig. 8, where the pressure head as a function of depth is plotted for a vertical transect through the trench, bottom biomat, and underlying soil at time of 15.85 days in the clay loam simulation with the same K_s for bottom and sidewall biomats. Depths are measured from the bottom of the biomat. Pressures are positive in the trench above the biomat and reach a maximum at the top of the biomat indicating that approximately 12 cm of water was ponded in the trench at this time (during the third daily dose). Pressures dropped sharply within the biomat and became negative (indicating matric potential heads). A minimum value of about -14 cm occurred just below the biomat at a depth of approximately 3 cm and this value remained constant within a zone from about 3 to 10 cm below the top of the biomat. Clearly, $dh/dz = 0$ in this zone and flow was due entirely to gravity ($dH/dz = 1$ or a unit gradient).

We were also able to check Bouma's assumption of a unit gradient for horizontal flow [Eq. (2)]. A horizontal transect of pressure head as a function of distance from the trench (to the left) through the sidewall biomat and soil adjacent to the biomat (to the right) in the clay loam simulation with equal sidewall and bottom biomat K_s is shown in Fig. 9. The time of simulation was 15.85 days and distance was measured from the trench wall. The transect was taken at a height near the middle of the sidewall biomat (6 cm above the bottom of the trench). The pressure at the zero distance was positive and indicated the depth of ponding in the trench above the particular elevation of the transect. As the transect passed through the sidewall biomat, the pressure dropped sharply to about -25 cm at the biomat-soil interface (a horizontal distance of 3 cm in Fig. 9). At the interface, there was a sharp change in slope and the curve was nearly linear out to a distance of 60 cm from the trench. The pressure head gradient (slope of the pressure head curve) is also plotted in Fig. 9. The gradient is very negative within the biomat, but reaches a value of -1 one just beyond the interface between the biomat and soil (distance of 4 cm) indicating that at this point $|dh/dx| \approx 1$, as suggested by Bouma et al. (1972) and shown in Eq. (2).

Since Bouma's assumption regarding a unit gradient for horizontal flow appeared to be valid, we thought it might be possible to use Eq. (2) as a relatively simple way to find the sidewall flow component of LTAR. For the clay loam simulation with equal sidewall and bottom K_s , we chose a point approximately midway up the wetted sidewall (5 cm above the bottom of the trench) to calculate the horizontal flux. With an average depth of ponding for day 15.3–16.3 of 10.9 cm, this meant the depth of ponding above this point (h_0) was on average 5.9 cm. Biomat and soil properties were the same as before [$Z_b = 3 \text{ cm}$ and $K_b = 0.2 \text{ cm d}^{-1}$, and the $K(h)$ function described by Eq. (5) with the parameters from Table 1]. The value of h_s in Eq. (2) that caused equal flow through the sidewall biomat and adjacent soil was about -17 cm and the associated unsaturated hydraulic con-

Fig. 8. Vertical transect of pressure head as a function of depth through the trench, bottom biomat, and soil beneath the biomat in the clay loam simulation with the same K_s for bottom and sidewall biomats. Time of simulation is 15.85 d. Depth is measured from the bottom of the biomat.

ductivity at this matric potential head [$K(h_s)$] was 1.18 cm d^{-1} . Our sidewall flux was 2.40 cm d^{-1} . Eq. (2), therefore, predicted a sidewall flow that was about half that observed in our simulations, so it appeared that using this equation would underestimate the sidewall component of LTAR for a trench with shallow ponding (such as our simulations). The reason for the underestimation is probably the assumption that only a horizontal gradient is present. This is equivalent to assuming that all of the flow vectors near the sidewall are horizontal. As can be seen in Fig. 5, flow vectors near the middle of the wetted sidewall region are horizontal, but at the bottom of the sidewall (in the trench corner) and especially at the top of the wetted sidewall area, the vectors are not. In the trench corner, there is a strong downward gradient pulling water into the deeper soil. Similarly, at the top of the wetted area, capillarity pulls water up into the dryer soil above. This is similar to the two-dimensional gradients that occur beneath gravel particles that mask the trench surface and cause accelerated flow (Radcliffe et al. 2005). Lateral gradients in the trench corner area should also cause the Bouma (1975) method for calculating vertical flow through the bottom to underpredict the actual flow, but this was not the case as we have shown. The reason may be that the effect of the corner area is less important when flow occurs across the entire trench bottom (45 cm) instead of just a small section of the wetted sidewall (10.9 cm). The Bouma (1975) approach may not work for estimating the sidewall component of the LTAR in a trench with shallow ponding, but it might work for a trench that was nearly full (a worst-case scenario). In this case, flow would be through nearly the entire sidewall area and the capillary effect of the soil above and below the sidewall area might be minimal.

Conclusions

We developed a new method for modeling water flow from OWS trenches that includes the trench within the model space. That allowed us to predict the level of water in the trench under

Fig. 9. Horizontal transect of pressure head and pressure head gradient (slope of the pressure head curve, unitless) as a function of distance from the trench wall (to the left) through the sidewall biomat and soil adjacent to the biomat (to the right) in the clay loam simulation with equal sidewall and bottom biomat K_s . Time of simulation is 15.85 d. Transects were taken at the middle of the sidewall biomat 6 cm above the bottom of the trench.

equilibrium conditions in a system that received three doses per day. This is an alternative to previous modeling approaches that specified the level of water in the trench as a boundary condition (Beach and McCray 2003; Radcliffe et al. 2005). With the new method, the water level is dynamic and integrates the effect of input to the trench from the drain pipe and flow out of the trench, as it is affected by soil and biomat properties (bottom and sidewall). It allowed us to determine the water level that would result once equilibrium conditions were reached and how pulsing might affect flow over the lip of the sidewall biomat. The water level in the trench is also something that is easily measured and may provide a simple way of comparing model results with field measurements.

Our estimates of sidewall flow in gravel systems installed in two contrasting soil textures indicated that soil texture is important. In simulations of the clay loam soil, we found that the water level in the trench at steady conditions averaged a depth of 9.5–10.9 cm and that 29–31% of the total flow occurred through the sidewall, depending on what assumptions were made about the sidewall biomat K_s (either equal to or twice the bottom biomat K_s). In the sand soil, we found that water did not pond in the trench next to the sidewall and there was no sidewall flow. Much of the sidewall flow in the clay loam soil appeared to be in the “lip” area just above the maximum height of the sidewall biomat. With our new method of simulation, which included the trench within the model space, we were unable to avoid a capillary rise effect in gravel that may have caused exaggerated flow just above the depth of ponding in the trench and through the lip area. Our estimates of sidewall flow were less than the estimates of Bouma (1975) and Keys et al. (1998), apparently because we assumed more permeable biomats.

Our simulations show that Bouma’s (1975) method of predicting steady flow through the trench bottom using a simple equation worked quite well in the clay loam soil. To use this method, an estimate of the biomat K_s and thickness are required as well as the depth of ponding in the trench and the unsaturated hydraulic conductivity function of the underlying soil. This method offers a promising approach for estimating LTAR in our opinion. Our simulations also show that Bouma’s observation that a unit gra-

dient may apply for lateral flow is true in the middle of the wetted zone where sidewall flow occurs, but not in the area just above and below the wetted area.

References

- Beal, C. D., Rassam, D. W., Gardner, E. A., Kirchhof, G., and Menzies, N. W. (2008). "Influence of hydraulic loading and effluent flux on hydraulic failure of soil absorption systems." *J. Hydrol. Eng.*, 134(8), 681–692.
- Bumgarner, J., and McCray, J. E. (2007). "Estimating biozone hydraulic conductivity in wastewater soil-infiltration systems using inverse numerical modeling." *Water Res.*, 41, 2349–2360.
- Beach, D. N. H., and McCray, J. E. (2003). "Numerical modeling of unsaturated flow in wastewater soil absorption systems." *Ground Water Monit. Rem.*, 23, 64–72.
- Bouma, J. (1975). "Unsaturated flow during soil treatment of septic tank effluent." *J. Envir. Engrg. Div.*, 101, 967–983.
- Bouma, J., Ziebell, W. A., Walker, W. G., Olcott, P. G., McCoy, E., and Hole, F. D. (1972). "Soil absorption of septic tank effluent: A field study of major soils in Wisconsin." *Information circular No. 20*, Univ. of Wisconsin Extension, Madison, Wis.
- Finch, S. D. (2006). "Biomat effects on wastewater infiltration from onsite system dispersal trenches." MS thesis, Univ. of Georgia, Athens, Ga.
- Keys, J. R., Tyler, E. J., and Converse, J. C. (1998). "Predicting life for wastewater absorption systems." *Proc., Eighth National Symp. on Individual and Small Community Sewage Systems*, ASAE, St. Joseph, Mich., 167–176.
- Radcliffe, D. E., West, L. T., and Singer, J. (2005). "Gravel effect on wastewater infiltration from septic system trenches." *Soil Sci. Soc. Am. J.*, 69, 1217–1224.
- Richards, L. A. (1931). "Capillary conduction of liquids in porous mediums." *Physics (N.Y.)*, 1, 318–333.
- Schaap, M. G. (2001). "ROSETTA." Version 1.2, U.S. Salinity Laboratory ARS-USDA, Riverside, Calif.
- Šimunek, J., Huang, K., and van Genuchten, M. T. (1998). "The Hydrus code for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media." Version 6.0 Res. Rep. 144, U.S. Salinity Laboratory, USDA-ARS, Riverside, Calif.
- Smith, G. D. (1985). *Numerical solution of partial differential equations. Finite-difference methods*, Clarendon, Oxford, U.K.
- USEPA. (2002). *On-site wastewater treatment systems manual*, EPA/625/R-00/008, Office of Water, Office of Research and Development (available online at <http://www.epa.gov/ORD/NRMRL/Pubs/625R00008/625R00008.pdf>) (Aug. 13, 2002).
- van Cuyk, S., Siegrist, R., Logan, A., Masson, S., Fischer, E., and Figueroa, L. (2001). "Hydraulic and purification behaviors and their interactions during wastewater treatment in soil infiltration systems." *Water Res.*, 35, 953–964.
- van Cuyk, S., Siegrist, R. L., Lowe, K., and Harvey, R. W. (2004). "Evaluating microbial purification during soil treatment of wastewater with multicomponent tracer and surrogate tests." *J. Environ. Qual.*, 33, 316–329.
- van Genuchten, M. T. (1980). "A closed form equation for predicting the hydraulic conductivity of unsaturated soils." *Soil Sci. Soc. Am. J.*, 44, 892–898.