Design Hydraulic Loading Rates for Onsite Wastewater Systems

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Design hydraulic loading rates (HLR_D) are used in specifying the area of the bottom of drainfield trenches required for onsite wastewater systems (OWSs). Our objective was to develop a method for estimating the HLR_D based on soil and biomat hydraulic properties. We used a two-dimensional computer model to determine the steady flux through the trench bottom for the 12 USDA soil textural classes with 5 cm of wastewater ponded in the trench as an estimate of the performance under normal operating conditions. We used two sets of boundary conditions at the bottom of the soil profile: a deep water table and a shallow water table. We also tested how well the simple Bouma equation estimated the bottom flux. To estimate the HLR_D, we took 50% of the steady trench bottom flux as a safety factor. Despite the wide range in saturated hydraulic conductivities of the soil textural classes (8.18–642.98 cm d⁻¹), the steady flow through the bottom of the trench in these soils fell in a narrow range of 2.92 to 10.43 cm d⁻¹. With a modification to account for unsaturated flow within the biomat, the Bouma equation produced remarkably accurate estimates of trench bottom flux for all soil textural classes. Based on our estimates of HLR_D, we divided the soil textural classes into four groups. Our results show that medium-textured soils should have higher HLR_D than has been assumed in some systems for estimating HLR_D due to the importance of unsaturated flow in OWS hydraulic performance.

ABBREVIATIONS: HLR_D, design hydraulic loading rate; LTAR, long-term acceptance rate; OWS, onsite wastewater system; STU, soil treatment unit.

Rainfield Trenches in OWSs are used to distribute septic tank effluent and allow it to infiltrate into the soil. Studies have shown that the wastewater infiltration rate in drainfield trenches declines with time due to the formation of a low-conductivity “biomat” at the soil–trench interface that impedes infiltration and causes ponding in the trench. The formation of a mature biomat may take as little as 20 wk (van Cuyk et al., 2001, 2004) or as much as 4 yr (Jenssen and Siegrist, 1991). Onsite wastewater systems can operate effectively in a ponded condition indefinitely but the designed service life of a system should be 20 yr or more (Siegrist, 2007). The biomat is also a zone of intense microbial activity and plays an important role in purifying wastewater. An estimate of the final steady wastewater infiltration rate is needed to evaluate the suitability of soils for installing an OWS and to determine the HLR_D. Here, we use this term as one aspect of the long-term acceptance rate (LTAR) for an OWS. The LTAR must also consider the limiting organic loading rate that will result in adequate biological and chemical treatment of pollutants. In this study, we have only addressed hydraulic loading.

Siegrist (2007) noted that HLR_D values vary widely among states in the United States and are often based on limited empirical evidence. He called for a more rational and uniform approach based on properties of the “soil treatment unit” (STU) and suggested using computer models as an aid for designing these systems. Siegrist (2007) recommended using the trench bottom infiltration rate to determine the HLR_D and reserving the trench sidewall areas for handling peak flows. How the peak flow capacity compares with the HLR_D is generally not known. Amoozegar et al. (2007) stressed that soil heterogeneity must be taken into account in estimated HLR_D and LTAR values.

Computer models of two-dimensional water flow in soils can improve our understanding of OWSs and STUs in a number of ways. They can quantify processes that we know occur but can’t measure easily (an example is how much flow occurs through trench sidewalls). They can also validate or debunk simple approaches, surprise us with new concepts, identify research gaps, and serve as aides for teaching students and professionals.

One such model is HYDRUS-2D, developed by Šimůnek et al. (2006), and it has been used in a number of studies to analyze OWSs (Beach and McCray, 2003; Beal et al., 2008; Bumgarner and McCray, 2007; Finch et al., 2008; Radcliffe et al., 2005; Radcliffe and West, 2007). Heatwole and McCray (2007) used HYDRUS-2D to model infiltration in trenches with simulated, fully developed (mature) biomats in four common soil types and two different OWS architectures (gravel and chamber). They found that the unsaturated flow properties of the soil played...
an important role in determining the hydraulic performance of the systems.

Bouma (1975) developed a simple equation for estimating steady downward flow through the bottom of an OWS trench:

\[ K_{bs} \frac{h_b - h_i + Z_{bs}}{Z_{bs}} = K(b_i) \]  

where \( K_{bs} \) is the saturated hydraulic conductivity of the biomat \([L T^{-1}]\), \( h_b \) is the height of water ponded in the trench \([L]\), \( h_i \) is the pressure head in the trench \([L]\) just beneath the biomat \([L]\), \( Z_{bs} \) is the thickness of the biomat \([L]\), and \( K(b_i) \) is the unsaturated hydraulic conductivity of the soil \([L T^{-1}]\) at a pressure head of \( b_i \). Under the conditions present in OWS trenches, the flux through the biomat is equal to the flux through the underlying soil. The term on the left-hand side of Eq. [1] represents flux through the biomat and the term on the right-hand side represents flux through the underlying soil. Bouma (1975) used a unit hydraulic gradient below the trench bottom by assuming that the pressure head would be constant with depth for at least a short interval beneath the biomat \((db/dz = 0)\), and hence flux would be equal to the unsaturated hydraulic conductivity of the soil at the soil water pressure head just beneath the biomat \((b_i)\) as shown in Eq. [1]. To solve Eq. [1] under these conditions, an iterative approach or a root solver must be used to find the value of \( b_i \) that will make the fluxes on both sides of the equation equal.

Beal et al. (2004a,b) used Eq. [1] to estimate steady fluxes through trench bottoms. They showed that for six Australian soils with saturated hydraulic conductivity \( (K_s) \) spanning four orders of magnitude, the trench bottom fluxes collapsed to within one order of magnitude due to the limiting effect of the biomat. They developed a spreadsheet called FLUX (Flux for Septic Trenches) to solve Eq. [1].

Our overall objective in this study was to develop a method for estimating the HLRD for OWSs that was firmly based on soil and biomat hydraulic properties. We first used the HYDRUS simulation model to determine the steady flux through the trench bottom for a wide range of soils with shallow ponding in the trench. We estimated the steady fluxes under two sets of boundary conditions at the bottom of the soil profile: a deep water table and a shallow water table. We also tested the effect of including soil heterogeneity. Then, we tested how well Eq. [1] might estimate the bottom flux. If it were accurate, this method could serve as a simple alternative to two-dimensional computer models in estimating the bottom flux. We also used HYDRUS to determine the peak flow capacity by modeling a trench nearly full of water and compared the total flow out of this system with the total flow under shallow ponding in the trench. Finally, we developed a method to translate the steady bottom flux into a HLRD and compared it with rates that have been proposed.

**Materials and Methods**

**HYDRUS Simulations**

We used HYDRUS (beta version 7) to model two-dimensional water flow in variably saturated soil. This new version of the model is capable of modeling two- and three-dimensional flow, but we used only a two-dimensional analysis. The HYDRUS model 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. We used the van Genuchten (1980) equation for the water retention curve:

\[ \theta(b) = \left( \frac{\theta_s - \theta_i}{1 + \alpha b^n} \right)^m + \theta_r \]  

where \( \alpha \) \([L^{-1}]\), \( m \) (dimensionless), and \( n \) (dimensionless) are fitted parameters, \( \theta(b) \) is the volumetric water content \([L^3 L^{-3}]\), \( \theta_s \) is the saturated volumetric water content \([L^3 L^{-3}]\), and \( \theta_r \) is the residual volumetric water content \([L^3 L^{-3}]\). We also used the unsaturated hydraulic conductivity function \( K(b) \) \([L T^{-1}]\) from van Genuchten (1980):

\[ K(b) = K_s \left[ \frac{\theta(b) - \theta_i}{\theta_s - \theta_i} \right]^{0.5} \left( 1 - \left[ \frac{\theta(b) - \theta_i}{\theta_s - \theta_i} \right] \right)^m \]  

where \( K_s \) is the saturated hydraulic conductivity \([L T^{-1}]\), \( m \) is the fitted parameter from Eq. [2], and it is assumed that \( m = 1 - 1/n \).

Finch et al. (2007) reported the measured soil and biomat hydraulic properties of seven OWSs in Georgia. They were able to calculate a biomat saturated conductivity at six of these sites with soil textures of clay, clay loam, loam, sandy clay loam, sandy clay, and clay. In our simulations, we used a geometric mean \( K_{bs} \) of 0.23 cm d\(^{-1}\) (the experimental range was 0.03–1.29 cm d\(^{-1}\)) and an average biomat thickness of 0.5 cm. To test the effect of the \( K_{bs} \), we ran one soil textural class (loam) with a \( K_{bs} \) 10 times the experimental geometric mean \( (2.30 \text{ cm d}^{-1}) \). We did not test the effect of varying the biomat thickness because this would have required a new finite element mesh.

Water retention and unsaturated hydraulic conductivity parameters for Eq. [2–3] were predicted using the HYDRUS implementation of the Rosetta database developed by Schaap et al. (2001). This module uses a neural network to determine soil hydraulic properties from a large database of retention and conductivity parameters using different levels of inputs. The simplest level uses only the textural class as an input (higher levels of inputs include bulk density and water contents at field capacity and the wilting point). We used the simplest level to obtain retention and conductivity parameters for the 12 USDA soil textural classes shown in Table 1. The Rosetta database includes records from >2000 soils for water retention and >1000 soils for \( K_s \) (Schaap et al., 2001).

For the biomat water retention parameters \( (\theta_i, \theta_s, \alpha, n) \), we assumed that they were the same as those of the loam textural class. This was a somewhat arbitrary assumption, but we thought biomat retention properties did not vary as much as soil retention parameters and chose the retention parameters of a medium-textured soil. Beal et al. (2004a) assumed that the biomat in their simulations had a silty clay texture, but noted the lack of information in the literature on biomat retention properties. To test the effect of the biomat water retention properties, we also ran all of the soil textural classes with biomat water retention parameters that were the same as the simulated soil.

The drainfield and trench were modeled in cross-section with one axis vertical and the other horizontal (Fig. 1). In using a two-dimensional analysis, we were assuming that most of the horizontal forces driving water flow occurred in a plane perpendicular to the trench longitudinal axis. This was certainly a
simplification, but full three-dimensional analyses are limited by computer run times and our lack of information on how soil and biomat properties vary along the longitudinal axis of trench lines. One half of the 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 300 cm in the horizontal dimension. This placed the right boundary at a sufficiently large distance from the trench that the contours of total potential near the trench had ceased changing before the wetting front reached the right boundary. The model space was 200 cm in the vertical dimension with the trench bottom placed 100 cm below the soil surface. The soil surface formed the top of the model space and was treated as a no-flux boundary. The simulated trench bottom was 45 cm in width (half that of a full trench) and 100 cm in depth, with 70 cm of backfill (forming a 30-cm-tall cavity). These are typical dimensions for conventional OWSs. The boundary condition at the bottom of the model space for a deep water table was a vertical gradient in pressure head equal to zero \((\partial h/\partial z = 0)\), which required that only gravity cause vertical flow. According to Rassam et al. (2003), this boundary condition is appropriate for a deep water table. For a shallow water table, the bottom boundary condition was a constant pressure head of 39 cm, which placed the water table 61 cm below the trench bottom. This is the minimum distance allowed between trench bottoms and the seasonal high water table in Georgia. The surrounding soil was modeled as one of the 12 textural classes shown in Table 1.

The biomat properties were assumed to be the same on the bottom and sidewall and the biomat extended all the way to the top of the sidewall in our simulations. We chose these conditions to represent a mature or fully developed biomat appropriate for estimating HLRD. In their model simulations, Beal et al. (2004a) assumed that the upper section of the sidewall did not have a biomat and found that for three Australian soils suitable for OWSs, 82 to 96% of the flow out of the trench occurred in this area. Since there is little information in the literature on sidewall biomat properties, we chose a more conservative approach.

We assumed that 5 cm of water was ponded in the trench. This too was an arbitrary choice, but we wanted to simulate the shallow ponding one might expect under normal loading of the OWS, saving most of the sidewall and trench volume for peak flows under abnormal loading, as suggested by Siegrist (2007).

As such, the boundary condition on the trench bottom was a constant pressure of 5 cm (Fig. 1). We also ran simulations in one soil textural class with a ponding height of 1 and 10 cm to test the sensitivity of the steady trench bottom flux to the ponding height. On the trench sidewall, a graduated pressure from 0 to 5 cm was assumed in the bottom 5 cm. Above this height, a zero-flux boundary condition was used for the trench sidewall. A zero-flux condition was also used for the top of the trench. In the new version of HYDRUS, up to five constant-pressure boundary conditions can be set and the model will output the fluxes across each boundary. As such, in the shallow water table simulations, we could distinguish the flux across the trench bottom (a constant-pressure boundary) from the flux across the soil profile bottom (also a constant-pressure boundary). The flux across the trench sidewall was also available as an output as a third constant-pressure boundary condition. To simulate peak flow capacity, we changed the ponding depth in the trench from 5 to 27 cm (90% of the height of the trench).

The initial conditions were a relatively wet soil profile at equilibrium. We started with a wet profile because we wanted to minimize the time it would take to reach steady state. For the deep water table simulations, the initial conditions were a distribution of pressure heads such that the soil profile was at equilibrium with a pressure head of −100 cm at the bottom boundary. For the shallow water table simulations, the initial conditions were a distribution of pressure heads such that the soil profile was at equilibrium with a water table 39 cm above the bottom boundary.

A total of 25,296 nodes were used in the model space, with the densest network of nodes in the biomats and near the trench. The number and distribution of nodes was chosen through a process of trial and error to find the combination that would result in a numerical solution that converged and maintained a water balance error of <1% at all time steps. The tolerances for iteration convergence were set at a water content of 0.001 m$^3$ m$^{-3}$ and a pressure head of 1 cm. Distances between nodes were as small as 0.05 cm within the biomat and as large as 8 cm at the right boundary. The key to getting the model to run was providing a sufficient number of nodes within the biomat. We used a constant spacing within the biomat so that there were 11 nodes across the

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**Table 1. Water retention and hydraulic conductivity parameters† for the model simulations of 12 USDA soil textural classes taken from the HYDRUS Rosetta database and listed in order of decreasing saturated hydraulic conductivity \((K_s)\).**

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>(K_s) cm d$^{-1}$</th>
<th>(n)</th>
<th>(\alpha)</th>
<th>(\theta_s)</th>
<th>(\theta_f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>642.98</td>
<td>3.18</td>
<td>0.0353</td>
<td>0.053</td>
<td>0.375</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>105.12</td>
<td>1.75</td>
<td>0.0347</td>
<td>0.049</td>
<td>0.390</td>
</tr>
<tr>
<td>Silt</td>
<td>43.74</td>
<td>1.68</td>
<td>0.0056</td>
<td>0.050</td>
<td>0.489</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>38.25</td>
<td>1.45</td>
<td>0.0267</td>
<td>0.039</td>
<td>0.387</td>
</tr>
<tr>
<td>Silt loam</td>
<td>18.26</td>
<td>1.66</td>
<td>0.0051</td>
<td>0.065</td>
<td>0.439</td>
</tr>
<tr>
<td>Clay</td>
<td>14.75</td>
<td>1.25</td>
<td>0.0150</td>
<td>0.098</td>
<td>0.459</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>13.19</td>
<td>1.33</td>
<td>0.0211</td>
<td>0.063</td>
<td>0.384</td>
</tr>
<tr>
<td>Loam</td>
<td>12.04</td>
<td>1.47</td>
<td>0.0111</td>
<td>0.061</td>
<td>0.399</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>11.35</td>
<td>1.21</td>
<td>0.0334</td>
<td>0.117</td>
<td>0.385</td>
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<tr>
<td>Silty clay loam</td>
<td>11.11</td>
<td>1.52</td>
<td>0.0084</td>
<td>0.090</td>
<td>0.482</td>
</tr>
<tr>
<td>Silty clay</td>
<td>9.61</td>
<td>1.32</td>
<td>0.0162</td>
<td>0.111</td>
<td>0.481</td>
</tr>
<tr>
<td>Clay loam</td>
<td>8.18</td>
<td>1.41</td>
<td>0.0158</td>
<td>0.079</td>
<td>0.442</td>
</tr>
</tbody>
</table>

† \(\theta_s\), residual water content; \(\theta_f\), saturated water content; \(n\) and \(\alpha\), fitted parameters.
0.5-cm-thick biomat. The same finite element mesh was used for all simulations. With a sufficiently high density of nodes within the biomat, it was not necessary to use the option of an air-entry value of −2 cm with the \( K(h) \) function for clayey soils, unlike our simulations in Radcliffe and West (2007).

We also ran a series of simulations where the model space consisted of only the region below the trench. This was designed to simulate purely vertical flow below the trench. Boundary and initial conditions were the same as the deep water table simulations described above. By comparing the simulations using the region below the trench with the full simulations, the effect of two-dimensional flow below the trench on the steady-state flux through the trench bottom could be isolated.

To test the effect of soil heterogeneity, we used the stochastic scaling factors feature in HYDRUS. This implements a scaling procedure that assigns hydraulic parameter values to nodes in a random manner such that the overall mean coincides with the desired value but the distribution has a standard deviation set by the user. We used the data from Schoenberger and Amoozegar (1990) to decide on what standard deviation to use for the soil hydraulic conductivity. These researchers reported on a study where \( K_s \) was measured by horizon in soils of the Piedmont region of North Carolina. We used the averaged data from two horizons: a clay Bt and a clay loam B/C horizon. Pooling the values for different orientations and geomorphic positions, the mean \( K_s \) for the clay horizon (based on a lognormal distribution) was 12.03 cm d\(^{-1} \) with a CV of 0.66. This mean \( K_s \) was quite close to the clay textural class value from the HYDRUS database (14.75 cm d\(^{-1} \) in Table 1). The mean \( K_s \) for the clay loam horizon was 0.333 cm d\(^{-1} \) with a CV of 3.17. This mean \( K_s \) was considerably lower than the value for the clay loam textural class in the HYDRUS database (8.18 cm d\(^{-1} \) in Table 1). The HYDRUS model assumes a lognormal distribution of scaling factors. To convert the data CV to a lognormal distribution standard deviation (\( \sigma \)), we used the relationship given in Jury and Horton (2004):

\[
CV = \sqrt{\exp(\sigma^2) - 1}
\]

This produced a scaling factor \( \sigma \) of 0.60 for the clay and 1.55 for the clay loam. Since the largest value that can be used for \( \sigma \) is 1.00 in HYDRUS, we used that value for the clay loam. We ran simulations for the clay and clay loam textural classes using the soil parameter values in Table 1, but specified these values of \( \sigma \) for \( K_s \). We ran five “realizations” by recalculating the value for \( K_s \) at each node based on the same \( \sigma \) each time before running the simulation. We compared the trench bottom fluxes in the simulations including soil heterogeneity to simulations that did not include soil heterogeneity. Scaling factors can be used for water content and pressure head as well as for hydraulic conductivity in HYDRUS. We did not use scaling factors for these other two hydraulic parameters because these parameters are much less variable than hydraulic conductivity (Jury and Horton, 2004).

**Bouma Equations**

Equation [1] (Bouma, 1975) was used to estimate steady flux through the bottom of the trench for each soil textural class with a deep water table is shown in Fig. 2. The finite element mesh can be seen in the background showing the dense distribution of nodes near the trench. The wettest

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**Results and Discussion**

**HYDRUS Simulations of Steady Trench Bottom Flux**

HYDRUS automatically adjusts the time steps (within user-specified limits) to maintain an accurate water balance within the model space so that run times for simulations vary, depending on the difficulty of the numerical problem. Run times to reach 30 d for the HYDRUS deep water table simulations with 5 cm of ponded water in the trench varied substantially with soil textural class. Using a Pentium 4 computer, the shortest run time was for the silt class (665 s) and the longest run time was for the sandy clay class (7879 s). Run times for the shallow water table simulations were much shorter and in a narrow range from 230 to 321 s for all the soils except the sandy clay, which required the longest time of any of the shallow ponding simulations, 12,307 s. The longest run times were for the estimation of peak capacity when water in the trench was ponded to a depth of 27 cm. Many of these simulations ran >48 h and we stopped the runs before they reached 30 d as long as the fluxes out of the trench bottom and sidewall had reached steady rates.

The distribution of pressure heads after 30 d of simulation for the silt textural class with a deep water table is shown in Fig. 2. The finite element mesh can be seen in the background showing the dense distribution of nodes near the trench. The wettest
The distribution of pressure heads after 30 d of simulation for the sandy clay textural class with a deep water table is shown in Fig. 3. This soil class had the lowest steady-state infiltration rate through the trench bottom in the deep water table simulations (Table 2). Fluxes through the trench bottom reached a steady state within 3 d and the fluxes through the trench sidewall reached a steady state within 10 d. The wet area below the trench in the sandy clay (Fig. 3) was much larger than in the silt (Fig. 2) due to the lower permeability of the sandy clay class. Within the wettest contour below the trench, pressure heads varied from about −23 cm, which was considerably wetter than the silt but still not saturated.

The distribution of pressure heads for the remaining soil textural classes in the deep water table simulations showed a pattern that was intermediate between the two extremes represented by the silt and sandy clay classes.

Overall, the trench bottom steady fluxes simulated with HYDRUS for the deep water table were in a fairly narrow range between 2.92 and 10.43 cm d\(^{-1}\), compared with the range of \(K_s\) for these soils of 8.18 to 642.98 cm d\(^{-1}\) (Tables 1 and 2). This shows the dominant effect that a low \(K_{bs}\) had on the flow out of the trench, despite the thinness of this layer. Other studies have shown the same effect of a biomat for soils with a wide range in \(K_s\) (Beach and McCray, 2003; Beal et al., 2004b; Bouma, 1975). It’s also interesting to note that the soil with the highest \(K_s\) (the sand in Table 1) was not the soil with the highest bottom flux (the silt in Table 2). The bottom flux as a percentage of the \(K_s\) varied widely from 1% in the sand to 57% in the silty clay loam (Table 2). This shows that \(K_s\) alone is not a good predictor of the hydraulic performance of a STU.

A shallow water table had very little effect on the HYDRUS simulations of steady flux through the trench bottom for most soil textural classes (Table 2). Only the soils with the highest fluxes (silt and silt loam) showed a substantial reduction in infiltration rate with a shallow water table. The water table was about 56 cm below the trench, indicating that 6 cm of groundwater mounding had occurred (the initial and bottom boundary conditions placed a water table at 61 cm below the trench bottom). The area below the trench in the silt was wetter with the shallow water table than with the deep water table in that the lowest pressure head between the bottom of the trench and the water table was about −38 cm (it varied between −85 and −95 cm with the deep water table).

It is a little counterintuitive that the soils with the lowest trench bottom fluxes, such as the sandy clay and clay, were least affected by a shallow water table (Table 2). This seemed to indicate that in low-permeability soils, the trench infiltration rate was determined by soil conditions very close to the trench. It appears that greater separation between the trench bottom and seasonal water table should be required for soils with high trench infiltration rates for hydraulic purposes as well as for treatment purposes (the common practice is to require a greater separation

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>Deep water table</th>
<th>Shallow water table</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bottom flux</td>
<td>Bottom flux/K(_s^)</td>
</tr>
<tr>
<td>Sand</td>
<td>8.74</td>
<td>1</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>7.53</td>
<td>7</td>
</tr>
<tr>
<td>Silt</td>
<td>10.43</td>
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<td>Sandy loam</td>
<td>6.06</td>
<td>16</td>
</tr>
<tr>
<td>Silt loam</td>
<td>9.68</td>
<td>53</td>
</tr>
<tr>
<td>Clay</td>
<td>4.00</td>
<td>27</td>
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<tr>
<td>Sandy clay loam</td>
<td>4.07</td>
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<tr>
<td>Loam</td>
<td>5.68</td>
<td>47</td>
</tr>
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<td>Sandy clay</td>
<td>2.92</td>
<td>26</td>
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<tr>
<td>Silty clay loam</td>
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<td>57</td>
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<td>Silty clay</td>
<td>3.76</td>
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<tr>
<td>Clay loam</td>
<td>4.04</td>
<td>49</td>
</tr>
</tbody>
</table>

† \(K_s\) saturated hydraulic conductivity.

Fig. 3. Distribution of pressure heads after 30 d of simulation for a sandy clay soil with a deep water table. Lengths (L) of the x axis in the horizontal direction and the z axis in the vertical direction are given. Dimensions are in centimeters.
Bouma Equation Estimate of Steady Trench Bottom Flux

The estimated steady bottom fluxes for the various soils using the Bouma (1975) Eq. [1] are shown in Table 2 and plotted against the HYDRUS simulated fluxes for the deep water table simulations in Fig. 4. Bouma’s equation accurately estimated trench bottom fluxes in the soil textural classes with low fluxes but considerably overestimated the flux in the five textural classes with high fluxes: sand, silt, loamy sand, silt loam, and sandy loam.

There are three simplifying assumptions in the Bouma (1975) equation that are potential sources of error in estimating steady bottom flux. These assumptions are: a unit gradient \( \frac{dh}{dz} = 0 \) in the soil immediately below the biomat, saturated conditions in the biomat, and one-dimensional vertical flow within the biomat and the soil beneath the biomat. Since the HYDRUS simulations do not make these assumptions, we could investigate their validity by examining the simulation results. Pressure heads within the biomat and immediately below the biomat midway between the trench centerline and the trench sidewall in the HYDRUS simulation of the sand textural class with a deep water table after 30 d are shown in Fig. 5. Below the biomat, the pressure heads are constant at a value of about −44 cm. The constant values satisfy the assumption that \( \frac{dh}{dz} = 0 \). Because of the large number of nodes within the biomat cross-section, we were able to see clearly the distribution of pressure heads within the biomat (the top 0.5 cm of the transect). They were negative for most of the biomat and reached the minimum pressure of −44 cm at the bottom of the biomat. This indicated that the assumption of a saturated biomat hydraulic conductivity \( K_b \) in Eq. [1] was not valid and could lead to an overestimation of the bottom flux. We modified Eq. [1] to account for unsaturated flow within the biomat by substituting an effective biomat hydraulic conductivity \( K_{beff} \) appropriate for hydraulic resistances in series (Jury and Horton, 2004) in Eq. [1] for \( K_b \):

\[
K_{beff} = \frac{1}{\sum_{i=1}^{k} \frac{1}{kK_b(h_i)}}
\]

where \( K_b(h_i) \) is the unsaturated hydraulic conductivity for the biomat in layer \( i \) and \( k \) is the number of subdivisions (of uniform thickness) in the biomat. This function was based on the van Genuchten (1980) equation we used for soil \( K(h) \) (Eq. [3]) with \( K_b \) for the saturated hydraulic conductivity of the biomat and the retention parameters \( \theta_r, \theta_s, \alpha, \) and \( n \) for the loam textural class. Based on Fig. 5 (and similar plots for the other soil textural classes), we assumed that the distribution of \( h \) within the biomat could be described by a parabolic equation that has a value of \( h_0 \) at the top of the biomat and a value of \( h_k \) at the bottom of the biomat:

\[
h_i = h_0 - h_k \left( \frac{Z_b}{k} (i-1) \right)^2 + h_0
\]

This distribution is shown in Fig. 5 for comparison with the distribution obtained in the HYDRUS simulations. Substituting Eq. [5] and [6] into Eq. [1], we obtained

\[
\sum_{i=1}^{k} \frac{1}{kK_b \left( h_0 - h_k \left( \frac{Z_b}{k} (i-1) \right)^2 + h_0 \right)} \frac{h_b - h_i + Z_b}{Z_b} = K(h_k)
\]

We subdivided the biomat into five even layers \( k = 5 \) for all our calculations.

The estimated steady fluxes for the various soils using the modified Bouma Eq. [7] for bottom flux are shown in Table 2 and plotted against the HYDRUS simulated fluxes for the deep water table simulations in Fig. 6. The modified equation improved the agreement with the HYDRUS estimates, as indicated by the improved \( r^2 \), the regression line intercept near zero, and the slope
As a result, the Bouma equation for flux through the biomat was plotted with the HYDRUS-simulated flux for 12 soil textural classes. The dashed line is the 1:1 line. The solid line is the least squares regression line for which the equation and $r^2$ are shown.

Fig. 6. Bouma Eq. [7] estimate of steady trench bottom flux vs. HYDRUS-simulated flux for 12 soil textural classes. The dashed line is the 1:1 line. The solid line is the least squares regression line for which the equation and $r^2$ are shown.

near one as shown in Fig. 6. The modification reduced fluxes in the soil textural classes with high fluxes but had little effect on the classes with low fluxes. This was because, in the soil classes with low fluxes, there was less of a difference between $K_{bs}$ and $K_s$. As a result, $h_b$ was closer to zero and there was less desaturation in the biomat and less of a reduction in the effective hydraulic conductivity of the biomat.

We tested for the third source of error in the Bouma (1975) equation (i.e., assuming no lateral flow below the trench bottom) by comparing the simulations described so far with simulations using the model space confined to the area below the trench, which restricted flow to the vertical dimension. The ratio of steady bottom fluxes (two-dimensional/one-dimensional) ranged from 1.0 in the sand textural class to 1.17 in the silt loam. We would expect lateral flow to be least in a sand where capillarity is at a minimum. Thus, lateral flow was only a very minor source of error in using the original or the modified Bouma equations. For narrower trenches, however, we would expect a greater lateral flow effect.

The modified Bouma equation provided a simple method for estimating the steady flux through the trench bottom and also provided insight into the HYDRUS simulations. The reason why the silt textural class had the highest flux (despite the fact that it did not have the highest $K_s$) was apparent when the modified Bouma equation for flux through the biomat was plotted with the unsaturated hydraulic conductivity curves of the different soils as a function of pressure head (Fig. 7). The unsaturated hydraulic conductivity curves are based on the parameters in Table 1. The modified Bouma estimates of flux are the values of $K(h)$ where the biomat flux curve intersects the $K(h)$ curves. It is clear that the silt textural class had the highest bottom flux because it had a relatively high $K_s$ and a $K(h)$ curve that dropped off slowly, typical of a medium-textured soil. This also applied to the silt loam textural class. The sand and loamy sand soils had high estimated fluxes in spite of relatively steep $K(h)$ curves due to their high $K_s$. The sandy clay had the lowest estimated flux due to a low $K_s$ and a steep $K(h)$ curve. The other soil textural classes had intermediate $K(h)$ curves and estimated fluxes.

With Fig. 7 in mind, it’s easier to think about what effect a higher or lower flux through the biomat might have on steady trench bottom fluxes and the order of the soil textural classes. If the biomat is more conductive or thinner, or more water is ponded in the trench, the biomat flux curve will move higher in Fig. 7. This will push the point of intersection with the $K(h)$ curves closer to the $y$ axis and the order of the soil textural classes in terms of trench bottom fluxes will more closely resemble the order of $K_s$ (it will be a better predictor of trench hydraulic performance). Conversely, anything that reduces the flux through the biomat will lower the biomat flux curve and $K_s$ will be a poorer predictor of hydraulic performance.

The modified Bouma equation (Eq. [7]) underpredicted steady trench bottom flux in the silt and silt loam textural classes for a shallow water table, but accurately predicted the flux for all the other textural classes (Table 2). This was due to the assumption (in the original as well as the modified equations) that $\frac{db}{dz} = 0$ just below the trench. For these two soils with the highest trench bottom fluxes, a shallow water table reduced the pressure head gradient slightly ($\frac{db}{dz} < 0$) just below the biomat and consequently Eq. [7] overestimated the bottom flux.

Biomat and Ponding Height Sensitivity Analysis

Increasing the $K_{bs}$ 10-fold to 2.30 cm d$^{-1}$ in the loam soil textural class HYDRUS simulation with a deep water table increased the steady trench bottom flux from 4.68 to 14.30 cm
d−1. Assuming that the biomat water retention parameters were the same as the soil simulated (but keeping $K_{bs}$ at 0.23 cm d−1) resulted in a slightly wider range of steady trench bottom fluxes for all of the soil textural class simulations with a deep water table (2.64–16.54 cm d−1) compared with the simulations with a uniform loam-textured biomat (2.92–10.43 cm d−1, Table 2). These results showed that $K_{bs}$ was more important than the biomat water retention parameters. Changing the ponding height in the trench to 1 and 10 cm produced steady trench bottom fluxes of 4.70 and 7.01 cm d−1 in the loam soil with a deep water table, which were relatively close to the flux with 5 cm of ponded water (5.68 cm d−1, Table 2), indicating that ponding height was not a sensitive input variable.

Soil Heterogeneity

The effect of including soil heterogeneity on the distribution of pressure heads after 2 d is shown in Fig. 8 for the clay textural class with a deep water table after 2 d. The contour lines of pressure head are much more variable than in the simulations where heterogeneity in $K_s$ was not included (Fig. 2–3). The mean trench bottom flux for five simulations with separate realizations of the random values of $K_s$ assigned to each node was 5.01 cm d−1, compared with the flux for the simulations with uniform $K_s$ of 4.00 cm d−1 (see clay textural class in Table 2). The standard deviation for the trench bottom flux in the five realizations was relatively small, 0.05 cm d−1. For the clay loam textural class, the mean trench bottom flux for five realizations was 6.17 cm d−1, compared with 4.04 cm d−1 for simulations that did not include heterogeneity (see clay loam textural class in Table 2), also with a standard deviation of 0.05 cm d−1. Thus, including soil heterogeneity increased the steady trench bottom flux by 25 to 53%. Basing HLRD on estimates of fluxes in homogeneous soils is therefore likely to underestimate the hydraulic performance of soils with a high degree of heterogeneity, such as structured clays. In this sense, assuming homogeneous soils results in a conservative estimate of the hydraulic performance but it probably overestimates the capacity of the soil to treat wastewater (the organic loading component of the LTAR).

Peak Flow Capacity

Our HYDRUS simulations of a trench nearly full of effluent (ponded to 27 cm) for the sand class showed that the total flow out of the trench (including bottom and sidewalls) reached a steady state of 1182 cm3 d−1 cm−1 of trench length in the longitudinal (z axis) direction. This was 2.71 times the total flow out of the trench for the same soil class with 5 cm of ponded effluent. The largest ratio for peak flow occurred in the sandy clay textural class, where peak flow was 4.78 times the flow out of the trench with 5 cm of water ponded. The lowest ratio (1.81) occurred in the silt loam textural class. These results indicate that peak capacity is two to five times that of normal operating conditions (shallow ponding). Our simulations assumed that sidewall biomat properties are identical to bottom biomat properties. That is probably not the case in that biomats on the upper sidewall are probably more permeable, thinner, or both (Keys et al., 1998). Under these conditions, peak capacity would be greater than what we estimated.

Table 3. Design hydraulic loading rates (HLR_D) for 12 soil textural classes based on the trench bottom flux estimated in the HYDRUS simulations for a shallow water table and the modified Bouma Eq. [7]. The values were calculated as 50% of the fluxes shown in Table 2. Based on the HLR_D, soil textural classes were divided into Class I, II, III, or IV.

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>HLR_D based on HYDRUS simulations, shallow water table</th>
<th>HLR_D based on modified Bouma Eq. [7]</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>4.36 (1.07)</td>
<td>5.16 (1.26)</td>
<td>I</td>
</tr>
<tr>
<td>Silt</td>
<td>4.28 (1.05)</td>
<td>5.40 (1.32)</td>
<td>I</td>
</tr>
<tr>
<td>Silt loam</td>
<td>3.77 (0.92)</td>
<td>4.71 (1.15)</td>
<td>I</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>3.73 (0.91)</td>
<td>4.44 (1.09)</td>
<td>I</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>3.00 (0.74)</td>
<td>3.31 (0.81)</td>
<td>II</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>2.83 (0.69)</td>
<td>2.97 (0.73)</td>
<td>II</td>
</tr>
<tr>
<td>Loam</td>
<td>2.68 (0.66)</td>
<td>2.79 (0.68)</td>
<td>II</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>2.03 (0.50)</td>
<td>2.08 (0.51)</td>
<td>III</td>
</tr>
<tr>
<td>Clay loam</td>
<td>1.99 (0.49)</td>
<td>2.00 (0.49)</td>
<td>III</td>
</tr>
<tr>
<td>Clay</td>
<td>1.99 (0.49)</td>
<td>2.02 (0.49)</td>
<td>III</td>
</tr>
<tr>
<td>Silty clay</td>
<td>1.87 (0.46)</td>
<td>1.91 (0.47)</td>
<td>III</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>1.46 (0.36)</td>
<td>1.48 (0.36)</td>
<td>IV</td>
</tr>
</tbody>
</table>

As a safety factor, we have taken 50% of the HYDRUS-simulated trench bottom flux with a shallow water table (Table 2) and used that as a proposed HLR_D in Table 3. The soil textural classes are shown in order based on the HLR_D in centimeters per day as well as gallons per square foot per day (gal ft−2 d−1), which are the common units used in regulations (state and local) for HLR_D. We have grouped the soils into four classes based on HLR_D (Table 3). In Class I are the four soils with HLR_D values near 4 cm d−1. In Class II are three soils with HLR_D values in a narrow range near 3 cm d−1. In Class III are four soils with HLR_D values in a narrow range near 2 cm d−1. Class IV consists of only one soil textural class, but we believe that there are other soil classes that would fall in this category in the southern Piedmont region of the United States. An example is the clay loam horizon.
in the study by Schoeneberger and Amoozegar (1990) with a $K_s$ of 0.333 cm d$^{-1}$ as we mentioned above. The Rosetta database from which we drew our soil parameters has relatively few records for soils from the clayey region of the soil textural triangle (clay, silty clay, and sandy clay) (Schaap et al., 2001), and the flux through these soils may be overestimated in our analysis.

We also used the modified Bouma Eq. [7] to determine the HLRD$_D$ by taking 50% of the estimated trench bottom fluxes shown in Table 2. The resulting values are shown in Table 3. The order of the soils in terms of HLRD$_D$ was exactly the same as that based on the HYDRUS simulations except that the clay and silt textural classes reversed order, as did the clay loam and clay textural classes. The only substantial difference in estimated HLRD$_D$ occurred with the silt and silt loam soils, where a shallow water table reduced flux (as we discussed above). The soil classes (I–IV) were the same whether we used the HYDRUS simulations or the modified Bouma Eq. [7]. In our opinion, taking 50% of the trench bottom flux estimated by the modified Bouma Eq. [7] serves quite well as a basis for estimating HLRD$_D$ and grouping soils.

Siegrist (2007) proposed that HLRD$_D$ should vary with the type of OWS: a conventional system (Type I), a system with an aerobic treatment unit or constructed wetland (Type II), and a system with a packed bed filter or membrane bioreactor (Type III), with the lowest rates for Type I systems. Since we simulated a conventional OWS, we compared our values to the HLRD$_D$ values for Type I systems. Siegrist (2007) grouped soils into three classes in terms of their HLRD$_D$ (Table 4). The HLRD$_D$ values ranged from 4 cm d$^{-1}$ (1.0 gal ft$^{-2}$ d$^{-1}$) for Class I to 1.0 cm d$^{-1}$ (0.25 gal ft$^{-2}$ d$^{-1}$) for Class IV. These values are also quite close to the range we propose and we have adopted midpoint values for our four classes very similar to those in the North Carolina system (Table 4). Our results suggest, however, that the silt and silt loam soils should be moved from Class III to Class I, the silty clay loam soil should be moved from Class III to Class II, and the silty clay and clay should be moved from Class IV to Class III. This would more accurately reflect the high infiltration capacities of these soils.

### Conclusions

We found that the HYDRUS model or a modified form of the Bouma (1975) equation could be used to develop HLRD$_D$ values for OWSs based on soil hydraulic properties. The HYDRUS simulations with 12 soil textural classes showed that steady trench bottom fluxes were in a fairly narrow range of 2.92 to 10.43 cm d$^{-1}$ with a deep water table, despite the wide range in $K_s$ for these soils of 8.18 to 642.98 cm d$^{-1}$. This indicated the importance of a biomat in restricting flow in OWSs. Saturated hydraulic conductivity was not a good predictor of trench bottom flux in that flux as a percentage of $K_s$ varied from 1 to 57%. A shallow water table did not reduce the steady trench bottom flux except for the two soil textural classes with the highest fluxes: the silt and silt loam textural classes. The Bouma (1975) equation, modified to account for unsaturated conditions in the biomat, accurately predicted trench bottom fluxes in all cases except the shallow water table simulations with the silt and silt loam textural classes. Including soil heterogeneity increased trench bottom fluxes by 25 to 53%, depending on the assumed degree of heterogeneity. Therefore, analyses such as ours that are based on assumptions of homogeneous soils are a conservative estimate of hydraulic performance. Peak capacity with a nearly full trench was estimated to be two to five times the total infiltration rate (trench bottom flow plus sidewall flow) with 5 cm of water ponded in the trench. This is a conservative estimate of peak capacity in that biomat properties near the top of the sidewall are unlikely to be as fully developed as those at the bottom of the trench.

To convert the steady trench bottom flux to a HLRD$_D$, we took 50% of the flux simulated with HYDRUS or estimated with the modified Bouma (1975) equation. We then grouped the 12 soil textural classes into four classes based on HLRD$_D$. Our HLRD$_D$ values ranged from 1.46 to 4.36 cm d$^{-1}$ (0.36–1.07 gal ft$^{-2}$ d$^{-1}$), which was very close to the systems proposed by Siegrist (2007) and Lindbo et al. (2007). Our results differ from these

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**Table 4.** Soil classes and design hydraulic loading rates (HLRD) for systems that are in use by states or have been proposed compared with our analysis.

<table>
<thead>
<tr>
<th>System</th>
<th>Class I</th>
<th>Class II</th>
<th>Class III</th>
<th>Class IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siegrist (2007)</td>
<td>HLRD$_D$, cm d$^{-1}$ (gal ft$^{-2}$ d$^{-1}$)</td>
<td>sand, loamy sand</td>
<td>sandy loam, loam, silt loam</td>
<td>0.5 (0.12) silty clay loam, clay loam</td>
</tr>
<tr>
<td>Soil classes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lindbo et al. (2007)</td>
<td>HLRD$_D$, cm d$^{-1}$ (gal ft$^{-2}$ d$^{-1}$)</td>
<td>sand, loamy sand</td>
<td>sandy loam, loam, silt loam</td>
<td>1.8 (0.45) silt loam, clay loam, sandy clay loam, clay loam</td>
</tr>
<tr>
<td>Soil classes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Our analysis</td>
<td>HLRD$_D$, cm d$^{-1}$ (gal ft$^{-2}$ d$^{-1}$)</td>
<td>Sand, silt, silt loam, loamy sand</td>
<td>sandy loam, silty clay loam, loam</td>
<td>2 (0.50) sandy clay loam, clay loam, clay, silty clay</td>
</tr>
<tr>
<td>Soil classes</td>
<td></td>
<td></td>
<td></td>
<td>1 (0.25) sandy clay</td>
</tr>
</tbody>
</table>

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other systems primarily in that we show that medium-textured soils with intermediate $K_s$ should be in the higher categories for $HLOD$ due to their unsaturated hydraulic properties.

In this study, we are recommending a system for determining $HLOD$ rather than a particular set of values. There are a number of choices that can be made so that the method can be tailored to the needs of different jurisdictions. The system can be based on HYDRUS simulations or the modified Bouma (1975) equation. In either case, one can decide on what level of ponding to assume in the trench (we chose 5 cm) for normal operating conditions. One can also choose the properties of the biomat to use (thickness, saturated hydraulic conductivity, and water retention parameters). The effect of different OWS pretreatment systems and architectures could be incorporated by assuming different biomat properties for these systems. In converting the estimated trench bottom flux to a $HLOD$, one can choose the percentage of the flux to use as a safety factor (we used 50%), how many groups to use (we used four), and where to make the cuts between groups. The important feature of the process we propose is that the method for determining the $HLOD$ is based on quantifiable soil hydraulic properties and the assumptions are evident (and can be changed as more information becomes available, using an adaptive management approach). To facilitate the use of the modified Bouma (1975) equation, we have developed a spreadsheet that uses an iterative process to solve Eq. [7]. This spreadsheet, along with a guidance document, is posted on our website at mulch.cropsoil.uga.edu/soilphysics/research.html (verified 21 Nov. 2008).

One of the findings of this study and that of Heatwole and McCray (2007) is the importance of the unsaturated hydraulic properties of soils and biomats. To use the method we propose, one needs to estimate the retention properties of a soil ($\theta$, $\alpha$, and $n$ in our case) are required as well as the saturated hydraulic conductivity. These values can be obtained from soil databases such as Rosetta using just textural class, or a more accurate estimate can be obtained using additional information about the soil such as bulk density and the field capacity and permanent wilting point water contents. The literature on pedotransfer functions provides a rich source of information on the unsaturated hydraulic properties of soils (Wösten et al., 2001) as well. Our work also shows the need for more information on biomat hydraulic properties (thickness, saturated hydraulic conductivity, retention properties, uniformity, and rate of development).

Like all model studies, our findings are based on a number of assumptions that may not hold true under various field conditions. Our HYDRUS simulation model, with the use of soil data from Rosetta, needs to be verified against field data. Also, we could not separate out the effect of soil structure or clay mineralogy (which some state and local regulations consider) in that the textural class hydraulic parameters in the Rosetta database are an average of all the soils within that textural class, which may include varying degrees of structure and different clay mineralogy. The methods we present here (the model and the modified form of the Bouma equation), however, provide an approach for developing $HLOD$ values for OWSs based on soil hydraulic properties as an alternative to the conventional empirical approach used by most states and local jurisdictions.

References


