Spreadsheet for Converting Saturated Hydraulic Conductivity to Long-Term Acceptance Rate for On-Site Wastewater Systems

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abstract

Long-term acceptance rates (LTAR) are used in specifying the area of the bottom of drainfield trenches required for onsite wastewater systems (OWSs). Our objective is to present a simple method for converting soil saturated hydraulic conductivity (K_s) to LTAR, given a number of assumptions about soil and biomat hydraulic properties. In this paper, we describe an Excel spreadsheet that uses a modified equation from Bouma (1975) to calculate the steady trench bottom flux in an OWS based on an input of soil K_s. The soil water retention parameters are also required, but they can be taken from a table in the spreadsheet that provides parameters for the 12 USDA soil textural classes on the basis of the Rosetta database. Biomat thickness and saturated hydraulic conductivity are also required, and values are suggested in the spreadsheet. Bottom flux as a percentage of K_s varied widely from 52% in the silt loam class to 2% in the sand class. To convert steady bottom flux to LTAR, a safety factor should be used, and we suggest that LTAR should be one-half of the steady bottom flux. Using these assumptions we calculated LTAR for 12 USDA soil textural classes. The LTAR ranged from 1.48 cm d^{-1} (0.36 gal d^{-1} ft^{-2}) for the sandy clay class to 5.40 cm d^{-1} (1.32 gal d^{-1} ft^{-2}) for the silt class.

Drainfield trenches in on-site wastewater systems (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 drain-field–trench interface that impedes infiltration and causes ponding in the trench. An estimate of the final steady wastewater infiltration rate is needed to specifying the area of the trench bottom required for onsite wastewater systems (OWSs). This rate is commonly referred to as the *Long Term Acceptance Rate* (LTAR). Although the rate is more properly called the *Design Hydraulic Loading Rate* (HLR_D), which only considers hydraulic loading and does not consider biological and chemical treatment of pollutants, we will use the more common term of LTAR.

Estimates of the LTAR are often made based on identification of the soil series or texture, structure, and/or mineralogy of the soil horizons. In some cases, measurements of soil K_s are made, especially if the soil is a borderline case for suitability. In this case, a method is needed for converting K_s to an estimate of LTAR.

Radcliffe and West (2008) used the HYDRUS (Šimůnek et al., 2006) 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 also tested how well a simple equation developed by Bouma (1975) estimated the bottom flux. To estimate the LTAR, we took 50% of the steady trench bottom flux as a safety factor. Despite the wide range in K_s of the soil textural classes (8.18–642.98 cm d^{-1}), the steady flux through the bottom of the trench in these soils fell in a narrow range of 2.64 to 16.54 cm d^{-1}. With a modification to account for unsaturated flow within the biomat, the Bouma equation produced very similar estimates of trench bottom flux for all soil textural classes to those found using HYDRUS. Our objective here is to describe an Excel spreadsheet we developed based on the modified Bouma equation that can be used to convert soil K_s to an estimate of LTAR, given a number of assumptions about soil and biomat hydraulic properties.

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Methods

In the approach developed by Bouma (1975), it is assumed that the flux at the trench bottom through the biomat will be equal to the flux through the soil just beneath the biomat at steady state:

$$Q_b = Q_s$$
$$K_{bs}\frac{h_0 - h_s + Z_b}{Z_b} = K(h_s) \qquad [1]$$

where Q_b is the flux through the biomat (cm d^{-1}) and Q_s is the flux through the soil just beneath the biomat.

The flux through the biomat (Q_b) is described using a form of the Darcy equation (left-hand side of Eq. [2]:

$$Q_b = Q_s$$

$$K_{bs} \frac{h_0 - h_s + Z_b}{Z_b} = K(h_s) \quad [2]$$

that includes the saturated hydraulic conductivity of the biomat (K_{bs}) (cm d^{-1}), h_0 is the height of water ponded in the trench (cm), h_s is the negative pressure head in the soil just beneath the biomat (cm), and Z_b is the thickness of the biomat (cm). The flux through the soil (right-hand side of Eq. [1]) is equal to the unsaturated hydraulic conductivity of the soil [$K(h_s)$] (cm d^{-1}) (right-hand side of Eq. [2]) because the approach assumes that there will be a unit gradient in pressure heads beneath the biomat. To solve Eq. [2], the value of h_s that makes both sides of the equation equal has to be found. Since h_s appears in two places and the equation cannot be solved explicitly for h_s, an iterative procedure has to be used.

The modified Bouma equation developed in Radcliffe and West (2008) differs in the way the hydraulic conductivity term for the biomat is described:

$$\frac{1}{\sum_{i=1}^{5} 1/[5K_b(h_i)]} \times \frac{h_0 - h_s + Z_b}{Z_b} = K(h_s) \quad [3]$$

To accurately represent the biomat hydraulic conductivity, the biomat is divided into five layers. The $K_b(h_i)$ is the unsaturated hydraulic conductivity of the biomat in each of these layers at pressure heads h_i, with $i = 1$ to 5. The values for h_i are calculated using a parabolic equation with a value of h_0 at the top of the biomat and a value of h_s at the bottom of the biomat:

$$h_i = \frac{h_s - h_0}{Z_b^{\,2}} \cdot \left(\frac{Z_b}{k} \cdot (i-1) \right)^2 + h_0 \quad [4]$$

The unsaturated hydraulic conductivity functions in Eq. [3] [$K(h_s)$ and $K_b(h_i)$] are described by the van Genuchten (1980) equation:

$$K(h) = K_s \left[\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \right]^{0.5} \left\{ 1 - \left[1 - \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \right)^{\frac{1}{m}} \right]^m \right\} \quad [5]$$

where K_s is the saturated hydraulic conductivity (of the soil or biomat) (cm d^{-1}). The other variables in Eq. [5] come from the van Genuchten (1980) equation for water retention:

$$\theta(h) = \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} + \theta_r \quad [6]$$

where α (cm^{-1}) and n (unitless) are fitted parameters, $\theta(h)$ is the volumetric water content (cm^3 cm^{-3}), θ_s is the saturated volumetric water content (cm^3 cm^{-3}), θ_r is the residual volumetric water content (cm^3 cm^{-3}), and $m = 1 - 1/n$.

Equations [3–6] were implemented in an Excel spreadsheet so that the steady flux through a trench bottom could be calculated. The primary input variable required is the soil K_s in centimeters per day. Secondary input variables are the water retention parameters for the soil and biomat: α, n, θ_s, and θ_r. A table with these parameters for the 12 USDA soil textural classes, taken from the Rosetta database (Schaap et al., 2001) is provided in the spreadsheet. We assumed that the biomat water retention parameters (α, n, θ_s, and θ_r) were that of the loam textural class in the Rosetta database for all calculations. However, they can be easily changed in the spreadsheet (e.g., to have the same values as the soil).

The other secondary input variables are the biomat thickness (Z_b in cm), biomat saturated hydraulic conductivity (K_{bs} in cm d^{-1}), and height of water ponded in the trench (h_0 in cm). Estimates of biomat Z_b and K_s are provided in the spreadsheet based on a study by Finch et al. (2007) of seven OWSs in Georgia (K_{bs} = 0.23 cm d^{-1} and Z_b = 0.5 cm). The spreadsheet assumes the depth of ponding in the trench to be 5 cm. This value was chosen to simulate the shallow ponding one might expect under normal loading of the OWS, reserving most of the sidewall and trench volume for peak flows under abnormal loading as suggested by Siegrist (2007).

To convert the trench bottom flux to an estimate of LTAR, a safety factor must be chosen. The suggested value for the safety factor in the spreadsheet is that estimated LTAR should be one-half of the steady trench bottom flow. As such, a user can specify the input soil K_s, take the water retention parameters from the table for the appropriate textural class, and calculate LTAR if they are willing to accept the suggested values for biomat properties, safety factor, and depth of ponding. Otherwise, users can specify their own values for water retention parameters, biomat properties, safety factor, and depth of ponding.

To illustrate the use of the spreadsheet, we used an example in which K_s and the textural class were known and the spreadsheet was used to estimate LTAR. We also calculated steady trench bottom flux and LTAR for the 12 USDA soil textural classes in the Rosetta database. This database includes records from more than 2000 soils for water retention and more than 1000 soils for K_s. The values taken from the Rosetta database are shown in Table 1. We performed a sensitivity analysis where we varied the biomat properties and the height of ponding to see the effect on trench bottom flux.

Results and Discussion

Sand Textural Class Example

For the sand textural class, the flux through the biomat and flux through the underlying soil as predicted by Eq. [3] are shown in Fig. 1.

Table 1. Water retention and hydraulic conductivity (K_s) parameters for the model simulations of 12 USDA soil textural classes taken from the HYDRUS Rosetta database listed in order of decreasing K_s. Parameters are from van Genuchten (1980) as follows: α (cm^{-1}) and n (unitless) are fitted parameters, θ_s is the saturated volumetric water content (cm^3 cm^{-3}), and θ_r is the residual volumetric water content (cm^3 cm^{-3})

Soil textural class	K_s	n	α	θ_r	θ_s
	cm d^{-1}		cm^{-1}	cm^3 cm^{-3}	
Sand	642.98	3.18	0.0353	0.053	0.375
Loamy sand	105.12	1.75	0.0347	0.049	0.390
Silt	43.74	1.68	0.0066	0.050	0.489
Sandy loam	38.25	1.45	0.0267	0.039	0.387
Silt loam	18.26	1.66	0.0051	0.065	0.439
Clay	14.75	1.25	0.0150	0.098	0.459
Sandy clay loam	13.19	1.33	0.0211	0.063	0.384
Loam	12.04	1.47	0.0111	0.061	0.399
Sandy clay	11.35	1.21	0.0334	0.117	0.385
Silty clay loam	11.11	1.52	0.0084	0.090	0.482
Silty clay	9.61	1.32	0.0162	0.111	0.481
Clay loam	8.18	1.41	0.0158	0.079	0.442

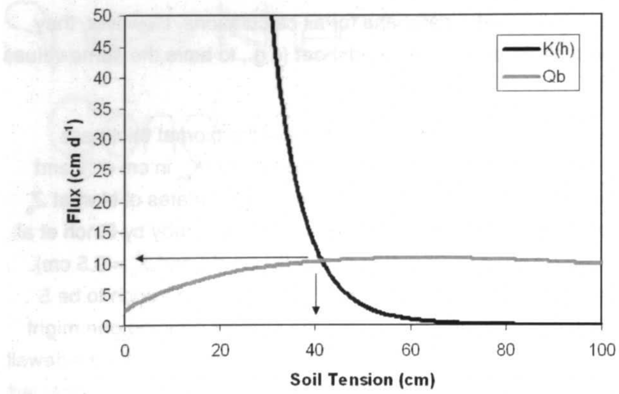

Fig. 1. For the sand textural class, flux through the biomat (the black curve) and flux through the underlying soil (the gray curve) as predicted by Eq. [3]. The point of intersection gives the value of soil tension (absolute value of h_s) on the x axis and the value of the steady-state flux on the y axis.

Table 2. Steady trench bottom fluxes calculated using the Bouma Calculator spreadsheet for 12 soil textural classes. Also shown is the estimated LTAR assuming a safety factor of 1/2.

Soil textural class	Bottom flux			LTAR†	
	cm d^{-1}	g d^{-1} ft^{-2}	% of K_s	cm d^{-1}	g d^{-1} ft^{-2}
Sand	10.31	2.53	2	5.16	1.26
Loamy sand	8.88	2.18	8	4.44	1.09
Silt	10.80	2.65	25	5.40	1.32
Sandy loam	6.62	1.62	17	3.31	0.81
Silt loam	9.41	2.31	52	4.71	1.15
Clay	4.04	0.99	27	2.02	0.49
Sandy clay loam	4.16	1.02	32	2.08	0.51
Loam	5.59	1.37	46	2.79	0.68
Sandy clay	2.97	0.73	26	1.48	0.36
Silty clay loam	5.93	1.45	53	2.97	0.73
Silty clay	3.82	0.93	40	1.91	0.47
Clay loam	4.00	0.98	49	2.00	0.49

† Using a safety factor of 1/2.

The flux through the biomat is described by the left-hand side of Eq. [3]. Soil water tension in the underlying soil (the absolute value of h_s) is plotted on the x axis, and flux is plotted on the y axis. As soil water tension increases, the flux through the biomat increases because the gradient becomes larger. The flux through the underlying soil is described by the right-hand side of Eq. [3]. As soil water tension increases, the flux through the underlying soil decreases because the soil becomes drier. To determine the steady-state flux through the biomat and the underlying soil, the point of intersection of these two curves must be found by an iterative process. The point of intersection gives the value of soil tension on the x axis and the value of the steady-state flux on the y axis as shown by the arrows in Fig. 1. For the sand, the point of intersection occurs at a soil tension of 41.5 cm, and the steady-state flux has a value of 10.31 cm d^{-1} (see sand textural class in Table 2). Converted to gallons per day per square foot, the flux is 2.53. Using a safety factor of one-half, the LTAR is 5.16 cm d^{-1}, or 1.26 gal d^{-1} ft^{-2}.

Using the Excel Spreadsheet

The Excel spreadsheet (which we refer to as the Bouma Calculator) and a guidance document are posted on our website at http://mulch.cropsoil.uga.edu/soilphysics/research.html. The calculator worksheet is shown in Fig. 2. The yellow shaded areas show the user input values that must be provided for the soil of interest. These consist of the van Genuchten (1980) hydraulic parameters for the soil: residual water content (θ_r in cm^3 cm^{-3}), saturated water content (θ_s in cm^3 cm^{-3}), two fitting parameters (α in cm^{-1} and n which is unitless), and the saturated hydraulic conductivity (K_s in cm d^{-1}). The user has the option of specifying the depth of ponding in the trench (h_0 in cm), the saturated hydraulic conductivity of the biomat (K_{bs} in cm d^{-1}), and the thickness of the biomat (Z_b in cm). The default values for the biomat parameters are shown in Fig. 2. The van Genuchten (1980) parameters can be obtained from the mean values for textural classes shown in the Soil Textural Classes worksheet (see the tab in the lower left corner of Fig. 2).

For example, to find the flux through a soil with a sand texture and a measured K_s = 600 cm d^{-1}, a user would copy the values for θ_r, θ_s, α, and n for the sand class from the Soil Textural Classes worksheet into the Calculator worksheet. Then enter the measured value of K_s (Fig. 3). The soil tension that results in an equal flow through the biomat and soil beneath the biomat must be found through a trial and error process. In the graph in Fig. 3, the flux through the biomat is shown as the gray curve and the unsaturated hydraulic conductivity function for the

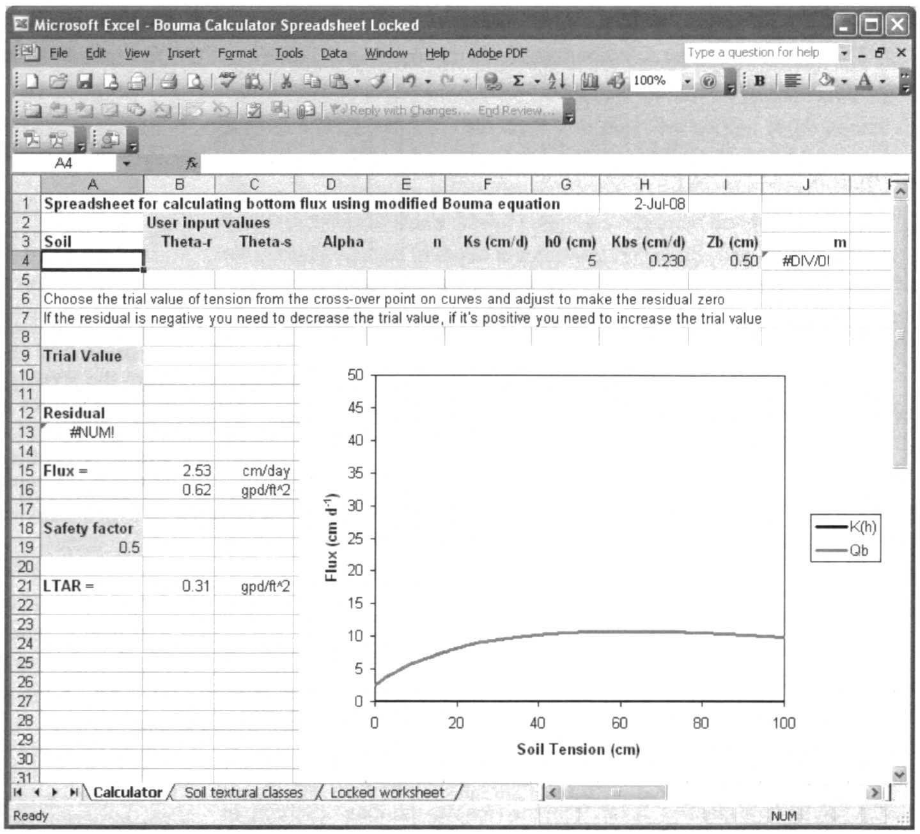

Fig. 2. Bouma Calculator Excel spreadsheet.

underling soil [$K(h)$], as the black curve. Both are plotted as a function of the soil tension beneath the biomat on the x axis. Where the curves cross, flow through the biomat and underlying soil are the same. From the graph it can be seen that the soil tension value where the curves cross is about 40 cm.

The difference between Q_b and $K(h)$ is shown in the Residual cell A13. If the residual is positive, the trial value needs to be increased. If the residual is negative, it has to be decreased. By trial and error, one can find that the exact tension that produces a residual of 0.00 is 41.055 cm (Fig. 4). Once the residual is zero, the flux shown in cell B15 is an accurate estimate of the steady flux through the trench bottom. For this example, it is 10.29 cm d^{-1}. The flux in gal d^{-1} ft^2 is shown in cell B16. To convert this to an estimate of LTAR, one must choose a value for the safety factor (cell A19). Using a safety factor of 0.50, the LTAR is 5.15 cm d^{-1} or 1.26 gal d^{-1} ft^2 for the sand textural class (cell B21).

As an alternative to the trial and error approach, one can use the Goal Seek tool in Excel. This procedure is described in the guidance document on our website.

Results for 12 USDA Soil Textural Classes

The estimated steady trench bottom fluxes for the 12 soil textural classes using the spreadsheet are shown in Table 2. Overall, the fluxes were in a fairly narrow range between 2.97 and 10.80 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 biomat K_{bs} will have on 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., 2004; Bouma, 1975).

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 reason why the silt textural class had the highest flux is 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.

Bottom flux was not a fixed percentage of soil K_s, ranging from 1 to 52% (Table 2). In the soils with a high K_s (the coarse-textured soils),

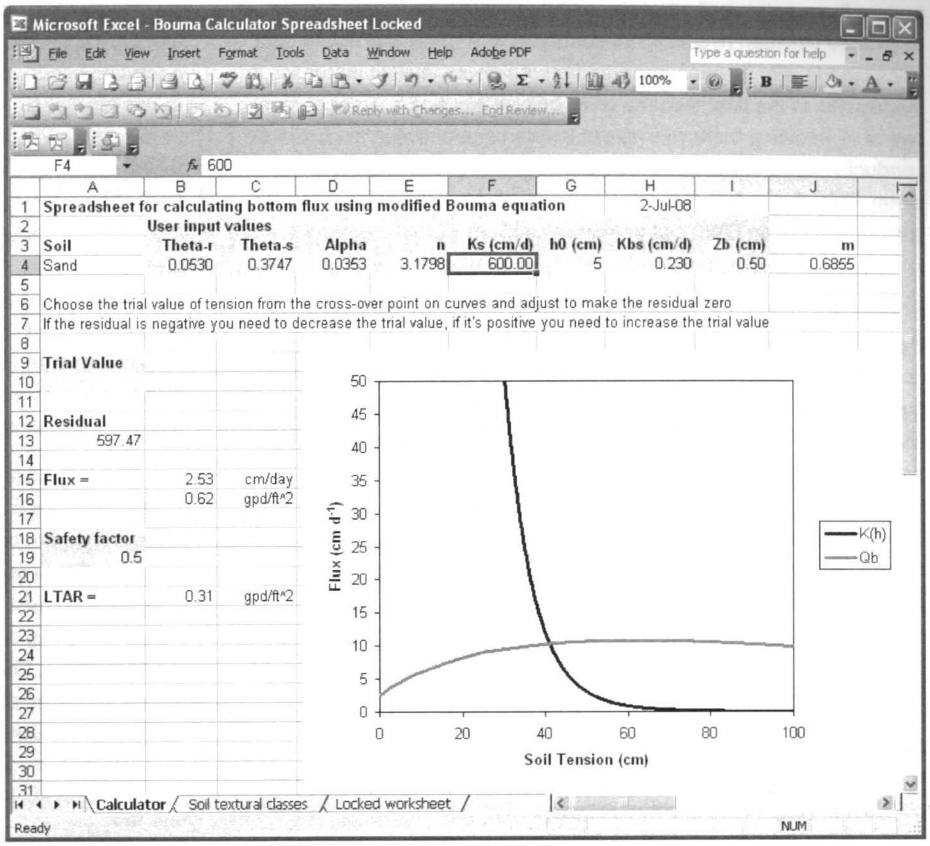

Fig. 3. The parameter values for the sand from the Soil Textural Classes worksheet have been copied into cells B4-F4 in the Calculator worksheet.

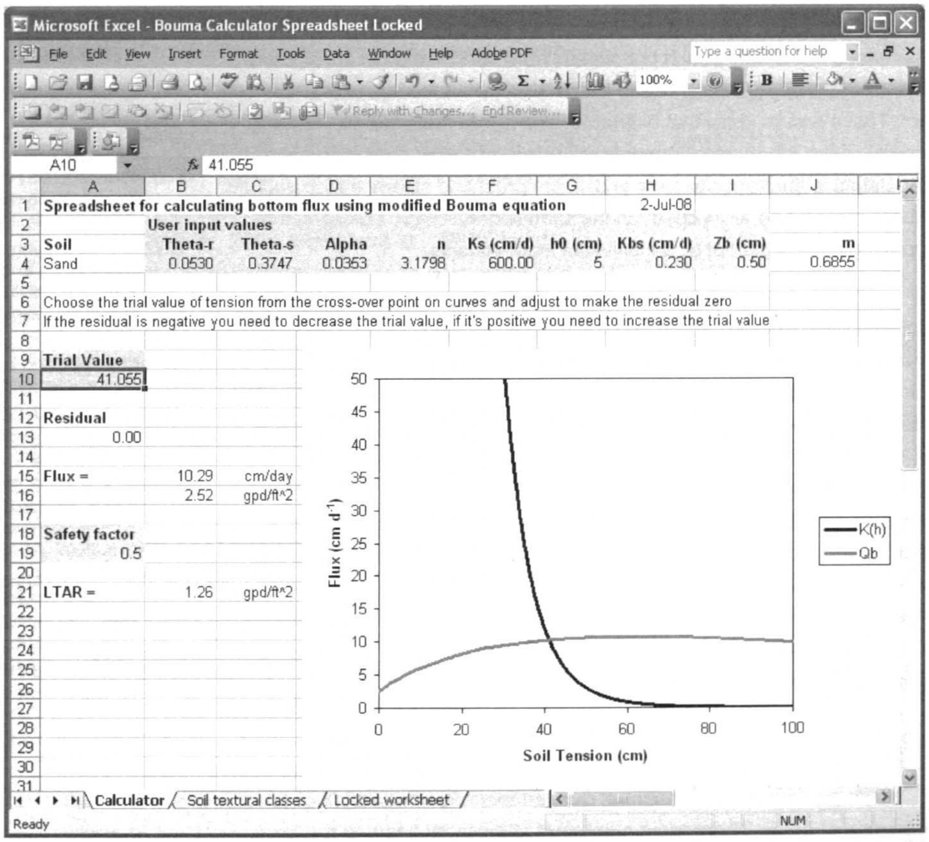

Fig. 4. By trial and error, the soil tension in cell A10 that results in a residual of 0.00 is found to be 41.52 cm. The steady-state bottom flux is 10.31 cm d^{-1} or 2.53 gal d^{-1} ft^2. Using a safety factor of 0.5, the estimated LTAR is 5.15 cm d^{-1} or 1.26 gal d^{-1} ft^2.

bottom flux was a small percentage of K_s because there was a large difference between hydraulic conductivities of the soil and biomat and because the $K(h)$ function tends to drop rapidly as tension increases in these soils. In the finer textured soils, bottom flux was a larger percentage of K_s because there was less of a difference between the hydraulic conductivities of the soil and biomat and the $K(h)$ functions were not as steep. This shows that K_s alone is not a good predictor of the hydraulic performance of an OWS soil treatment unit.

With Fig. 1 in mind, it's possible 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, thinner or more water is ponded in the trench, the biomat flux curve will move higher in Fig. 1. 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 estimated LTAR using a safety factor of one-half is shown in Table 2. These values ranged from 1.48 cm d^{-1} (0.36 gal d^{-1} ft^2) in the sandy clay textural class to 5.40 cm d^{-1} (1.32 gal d^{-1} ft^2) in the silt textural class. Our range of values for LTAR are close to the range that have been suggested in other publications. Siegrist (2007) suggested that soils could be grouped into three classes with LTARs ranging from 0.5 to 4.1 cm d^{-1} (0.12–1.0 gal d^{-1} ft^2). In North Carolina, soils are grouped into four classes with LTARs ranging from 1.0 to 4.1 cm d^{-1} (0.25–1.0 gal d^{-1} ft^2) (Lindbo et al., 2007).

Doubling the biomat K_{bs} to 0.46 cm d^{-1} in the sand soil textural class increased the steady trench bottom flux from 10.31 cm d^{-1} to 20.07 cm d^{-1}. Doubling the biomat thickness to 1.0 cm decreased the flux to 5.31 cm d^{-1}. These results show that biomat K_{bs} and Z_b are sensitive parameters, and we need more measurements of these properties. Changing ponding height in the trench to 1 cm and 10 cm produced steady trench bottom fluxes of 8.56 and 12.74 cm d^{-1} in the sand textural class, indicating that ponding height was not as sensitive an input variable.

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 soil structure and clay mineralogy will certainly affect fluxes in these soils. The database provides an average for each textural class that could include a wide range in these characteristics, especially in the clayey soils. If the spreadsheet is used to predict LTAR with a measured K_s, then K_s will account for these effects to an extent. We have suggested that soils be placed into four categories in terms of LTAR. One way to account for mineralogy or structure might be to move a soil textural class up or down in these categories depending on whether a soil is well structured or poorly structured, swelling or nonswelling. In North Carolina, Lindbo et al. (2007) use a decision tree approach to make similar adjustments.

Conclusions

We presented a spreadsheet method for converting soil K_s to an estimate of LTAR. There are a number of choices that can be made so that the method can be tailored to the needs of different users. A user can decide on what level of ponding to assume in the trench 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 system and architecture could be incorporated by assuming different biomat properties for these systems. In converting the estimated trench bottom flux to a LTAR, one can choose the value for a safety factor. The important feature of the process we propose is that the method for determining LTAR 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). The spreadsheet along with a guidance document is posted on our website at http://mulch.cropsoil.uga.edu/soilphysics/publications.html.

Our results show the importance of the unsaturated hydraulic properties of soils and biomats. To use the method we present, an estimate of the retention properties of a soil (θ_r, θ_s, α, and *n* in our case) are required. These values can be obtained from soil databases such as Rosetta using just textural class, or using additional information about the soil, such as bulk density, field capacity, and permanent wilting point water contents. Our work also shows the need for more information on biomat hydraulic properties, such as thickness, saturated hydraulic conductivity, retention properties, uniformity, and rate of development.

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