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

D. E. Radcliffe and L. T. West

abstract

Long-term acceptance rates (LTAR) are used in specifying the area of the bottom of drain-field 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.

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:

$$ Q_b = Q_s $$

$$ K_{bs} \frac{h_0 - h_s + Z_d}{Z_d} = K(h_s) $$

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]):

$$ \frac{Q_b}{Z_d} = K(h_s) $$

D. Radcliffe, Professor, Crop and Soil Sciences Dep., University of Georgia, Athens, GA (dradclif@uga.edu); L. T. West, National Program Leader—Soil Survey Investigations, USDA-NRCS, National Soil Survey Center, Lincoln, NE. Published in Soil Surv. Horiz. 50:20-24 (2009).
that includes the saturated hydraulic conductivity of the biomat \( (K_{bb}) \) (cm d\(^{-1}\)), \( h_s \) 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:

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

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 \( h_i \) at the top of the biomat and a value of \( h_s \) at the bottom of the biomat:

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

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

\[
K(h) = K_s \left[ \left( \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \right)^{1.5} \right]^{0.5} \left[ 1 - \left( \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \right)^{1.5} \right]^{-1}
\]

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:

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

where \( \alpha \) (cm\(^{-1}\)) and \( n \) (unitless) are fitted parameters, \( \theta(h) \) is the volumetric water content (cm\(^3\) cm\(^{-3}\)), \( \theta_s \) is the saturated volumetric water content (cm\(^3\) cm\(^{-3}\)), \( \theta_r \) 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: \( \alpha, n, \theta_s, \) and \( \theta_r \). 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 \( (\alpha, n, \theta_s, \text{and } \theta_r) \) 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 \( (Z_b \text{ in cm}) \), biomat saturated hydraulic conductivity \( (K_{bs} \text{ in cm d}^{-1}) \), and height of water ponded in the trench \( (h_s \text{ in cm}) \). Estimates of biomat \( Z_b \) and \( K_b \) are provided in the spreadsheet based on a study by Finch et al. (2007) of seven OWSs in Georgia \( (K_{bs} = 0.23 \text{ cm d}^{-1} \text{ and } Z_b = 0.5 \text{ cm}) \). 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) parameters for the model simulations of 12 USDA soil textural classes taken from the HYDRUS Rosetta database listed in order of decreasing K. Parameters are from van Genuchten (1980) as follows:** \( \alpha \) (cm\(^{-1}\)) and \( n \) (unitless) are fitted parameters, \( \theta_s \) is the saturated volumetric water content (cm\(^3\) cm\(^{-3}\)), and \( \theta_r \) is the residual volumetric water content (cm\(^3\) cm\(^{-3}\)).

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>( K_s ) (cm d(^{-1}))</th>
<th>( n )</th>
<th>( \alpha ) (cm(^{-1}))</th>
<th>( \theta_r ) (cm(^3) cm(^{-3}))</th>
<th>( \theta_s ) (cm(^3) cm(^{-3}))</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>0.0066</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>
</tr>
<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>
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 $h_5$) 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 gpd/ft$^2$. 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 ($\theta_r$ in cm$^3$ cm$^{-3}$), saturated water content ($\theta_s$ in cm$^3$ cm$^{-3}$), two fitting parameters ($\alpha$ 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 ($h_4$ 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 $\theta_r$, $\theta_s$, $\alpha$, 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

---

**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.**

<table>
<thead>
<tr>
<th>Soil textural class</th>
<th>Bottom flux</th>
<th>LTAR*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>cm d$^{-1}$</td>
<td>g d$^{-1}$ ft$^{-2}$</td>
</tr>
<tr>
<td>Sand</td>
<td>10.31</td>
<td>2.53</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>8.88</td>
<td>2.18</td>
</tr>
<tr>
<td>Silt</td>
<td>10.80</td>
<td>2.65</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>6.62</td>
<td>1.62</td>
</tr>
<tr>
<td>Silt loam</td>
<td>9.41</td>
<td>2.31</td>
</tr>
<tr>
<td>Clay</td>
<td>4.04</td>
<td>0.99</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>4.16</td>
<td>1.02</td>
</tr>
<tr>
<td>Clay loam</td>
<td>5.59</td>
<td>1.37</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>2.97</td>
<td>0.73</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>5.93</td>
<td>1.46</td>
</tr>
<tr>
<td>Silty clay</td>
<td>3.82</td>
<td>0.93</td>
</tr>
<tr>
<td>Clay loam</td>
<td>4.00</td>
<td>0.98</td>
</tr>
</tbody>
</table>

* Using a safety factor of 1/2.
underlying 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 \(K_v\) will have on flow out of the trench, despite the thickness 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 \(K_v\) 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 \(K_v\). The sandy clay had the lowest estimated flux due to a low \(K_v\) 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 \(K_v\), ranging from 1 to 52% (Table 2). In the soils with a high \(K_v\) (the coarse-textured soils),
bottom flux was a small percentage of $K_b$ 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 $K_b$ 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 $K_b$ 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 $K_b$ (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 $K_b$ 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 silty clay 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 $K_{bb}$ 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 $K_{bb}$ 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 $K_b$, then $K_b$ 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 $K_b$ 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 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 ($\theta_s$, $\theta_f$, $\alpha$, 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.

References


