MODELING THE EFFECTS OF DEEP CHISELING WITH DRAINMOD FOR ALLUVIAL SOILS

D. N. Moriasi, J. L. Fouss, R. L. Bengtson

ABSTRACT. DRAINMOD is a drainage model that has been widely used in the shallow water table regions of the U.S., including the southeastern U.S. Therefore, it is important that DRAINMOD realistically simulate the water balance components for alluvial soils that are prone to surface seal formation, which are the predominant soils in much of the southeastern U.S. In this study, DRAINMOD 5.1 was modified to address the problems associated with the assumption of constant vertical saturated hydraulic conductivity ($K_s$) and constant maximum surface depressional storage (STMAX) for these alluvial soils. The first objective was to modify DRAINMOD 5.1 to incorporate the effects of deep chiseling ($K_s$ and STMAX vary) in order to improve its prediction of infiltration and surface runoff. The second objective was to evaluate the modified DRAINMOD models with dynamic $K_s$ and STMAX subroutines (DRAINMOD-$K_s$, DRAINMOD-STMAX, and the combined DRAINMOD-$K_s$-STMAX), using two years (Sept. 1995 to Nov. 1996 and Nov. 1996 to Nov. 1997 when deep chiseling was carried out) of measured surface runoff data from the USDA-ARS Ben Hur research site. Simulations by DRAINMOD 5.1 were compared with those by DRAINMOD-$K_s$, DRAINMOD-STMAX, and DRAINMOD-$K_s$-STMAX to further determine the effect of the modifications on surface runoff and infiltration predictions. In general, DRAINMOD-STMAX, DRAINMOD-$K_s$, and DRAINMOD-$K_s$-STMAX improved surface runoff prediction by 57%, 73%, and 82%, respectively, in the 1995-1996 season and by 27%, 45%, and 62%, respectively, in the 1996-1997 season.

Keywords. Drainage, Infiltration, Maximum surface depressional storage, Modeling, Surface runoff, Vertical saturated hydraulic conductivity.

The short-duration, high-intensity rainfall (Bengtson and Carter, 2004; Keim and Faiers, 1996; Fouss et al., 1987) that occurs on alluvial soils in the southeastern U.S. leads to soil surface seal formation (Martinez-Gamino, 1994). This phenomenon happens especially during seedbed preparation and planting periods when the soil is bare. Machine traffic and compaction tend to accelerate the sealing/crusting problem (Hillel, 1982) while promoting the formation of a hard pan in the lower subsoil layers. The formed surface seal leads to low infiltration and high surface runoff, both of which are undesirable.

DRAINMOD (Skaggs, 1978) is a computer model that was developed for the design and evaluation of agricultural drainage and water table management systems. The model conducts a water balance on the soil surface and in the soil profile midway between parallel drains. DRAINMOD predicts surface runoff, water table depth, drainage outflow, soil water content, evapotranspiration (ET), and infiltration on an hourly, daily, monthly, or annual basis in response to given soil properties, crop variables, climatological data, and site parameter inputs. This model was developed for soils with natural or induced shallow water tables, which contain a network of parallel drainage ditches or subsurface drains. DRAINMOD has been tested, verified, applied, and modified on the USDA-ARS Ben Hur research site near Baton Rouge, Louisiana (Fouss, 1985; Fouss et al., 1987; Fouss et al., 1989).

This research focuses on the water balance on the surface (where rain water is distributed as infiltration), surface depressional storage (which eventually infiltrates into the soil or evaporates), and runoff. The surface seal formation may lead to inaccurate prediction of infiltration rates and hence predictions of infiltration and runoff. The Green-Ampt equation (Green and Ampt, 1911), used in DRAINMOD to predict infiltration rates, gives good results for soils with uniform soil profiles, soil profiles that become denser with depth, and soils with partially sealed surfaces (Skaggs, 1978). In other words, the Green-Ampt equation gives good results for soil profiles that have the same hydraulic properties throughout the profile, for soil profiles in which the hydraulic properties decrease with depth, and for soils that have limited surface sealing effects. This is not the case with alluvial soils. For instance, for the Commerce silt loam soil (fine silty, mixed, non-acid, thermic Aeric Flivaquent), a southern Louisiana alluvial soil, the top (surface) soil layer is the least conductive (Rogers et al., 1991) due to the formation of soil surface seal (Martinez-Gamino, 1994). Saturated lateral hydraulic conductivity ($K$) for the Commerce silt loam soil increases with depth, from 1.46 cm h$^{-1}$ at 0.6 m to 4.39 cm h$^{-1}$...
at 1.5 m, and then decreases with additional depth to 2.88 cm h\(^{-1}\) at 2.4 m (Rogers et al., 1991).

Tillage operations increase infiltration and reduce surface runoff (Barisas et al., 1978; Ankey et al., 1995; van Es et al., 1999; Kincaid, 2002) by increasing the vertical saturated hydraulic conductivity (\(K_s\)) of the top and adjacent layers of soil (Kincaid, 2002) and increasing the maximum surface depressional storage (STMAX). Soil saturated hydraulic conductivity is a measure of the soil’s ability to transmit water under saturated conditions. Maximum surface depressional storage is related to the depth of the soil surface depressions and the ability of the soil surface to hold (or pond) water. Roughly tilled fields hold considerable amounts of water in their surface depressions, thus reducing surface runoff, as opposed to smooth-surface fields, which lead to high surface runoff when a surface seal has formed. Some of the ponded water held in the surface depressional storage infiltrates into the subsoil, while some can evaporate into the atmosphere.

Unfortunately, the benefits of tillage operations in increasing \(K_s\) and hence infiltration and reducing surface runoff are only temporary because of the soil surface seal reformation (Martinez-Gamino, 1994; Slattery and Bryan, 1994; Assouline and Mualem, 2002) in addition to soil compaction increasing gradually to the previous condition. Surface seal gradually reforms as the fine particles fill the soil pore spaces after subsequent rainfall events (Allen and Musick, 2001; Rao et al., 1998; Kim and Chung, 1994).

The impact of high-energy raindrops breaks up the surface soil clumps into fine aggregates, which fill the soil pores and form a surface seal (Haan et al., 1994). The soil surface seal is compacted by further raindrops. Upon drying, the cementing agents in clays bind the soil particles together, forming a continuous sheet (crust) on the soil surface (Martinez-Gamino, 1994). Therefore, there is a gradual decrease in saturated hydraulic conductivity as the surface seal reforms to its previous condition. The main cementing agents in soils are silica, sesquioxides, and organic matter (Martinez-Gamino, 1994). Other cementing agents include amorphous silicate (\(\text{SiO}_2\)) and Si-Fe complexes (Chartres et al., 1990).

Several field studies support soil surface sealing theory. Kim and Chung (1994) found that average saturated hydraulic conductivity on a tilled sandy loam gradually decreased exponentially as a function of cumulative rainfall energy after tillage. According to Rao et al. (1998), the decline in infiltration rate since tillage on an Alfisol was found to have an exponential relationship with cumulative rainfall since tillage. Allen and Musick (2001) found that deep ripping increased infiltration on a clay loam soil (Torrertic Paleustoll) by 26% to 29% immediately after primary tillage, but the benefit of ripping was lost because of the subsequent furrow traffic and soil consolidation from irrigation and rainfall.

In addition to the gradual decrease of \(K_s\), surface depressions are also smoothed out after subsequent rainfall events. STMAX is difficult to measure; it is usually estimated from the surface roughness index (Onstad, 1984; Huang and Bradford, 1990; Kamphorst et al., 2000; Guzha, 2004). Models that have been used to calculate STMAX include those by Moore and Larson (1979), Onstad (1984), and Guzha (2004). Moore and Larson (1979) developed a distributed model for estimating surface storage and runoff amounts for a plot from grid elevations. However, this model does not show trends depending on either the amount of rainfall over time or over the tillage and farming operations. Onstad (1984) developed a depressional storage model based on the random roughness and slope of the depressions. Generally, depressional storage decreases with decreasing random roughness and increasing slope steepness (Onstad, 1984).

Deep chiseling is a tillage practice that has been used in Louisiana to break the soil surface crust and the hard pan in order to increase infiltration and reduce surface runoff (Bengtson et al., 1995) by increasing \(K_s\) and STMAX. To deep chisel a field, a farmer attaches short, angled subsoil shanks to a tractor tool bar and pulls them through the soil, breaking the soil to at least 30 cm below the ground surface (Grigg and Fouss, 2002). However, surface seal reformation and soil compaction gradually decrease \(K_s\) and STMAX to the original values. Although \(K_s\) and STMAX decrease gradually depending on total rainfall (Freebairn et al., 1991) over time (cumulative rainfall since deep chiseling), DRAINMOD 5.1, the current version of the model, assumes that both \(K_s\) and STMAX remain constant irrespective of any tillage practice (Skaggs, 1978). Therefore, DRAINMOD 5.1 is likely to give less accurate predictions of both infiltration and runoff depending on the stage of surface seal reformation. In addition, DRAINMOD 5.1 cannot be used to quantify how long the benefit of a deep chiseling operation, based on \(K_s\) and STMAX parameters, may last and how frequently to deep chisel a farm field.

In this study, DRAINMOD 5.1 was modified to address the problems associated with the assumption of constant \(K_s\) and STMAX for the alluvial soils in the southeastern U.S. The first objective was to modify DRAINMOD 5.1 by allowing \(K_s\) and STMAX to vary in response to deep chiseling and subsequent rainfall events, which should improve model predictions of infiltration and surface runoff. The second objective was to evaluate the modified DRAINMOD models with dynamic \(K_s\) and STMAX subroutines (DRAINMOD-\(K_s\), DRAINMOD-STMAX, and the combined DRAINMOD-\(K_s\)-STMAX) using measured data from the USDA-ARS Ben Hur research site and to compare the performance of both the original and modified DRAINMOD models.

**Model Modifications**

**Modeling the Effect of Deep Chiseling on Vertical Saturated Hydraulic Conductivity**

The modifications made in DRAINMOD 5.1 to incorporate the effects of deep chiseling are shown in figure 1. For a given soil with given initial water content, the infiltration rate in DRAINMOD 5.1 is computed by the Green-Ampt equation as:

\[
f = \frac{A}{F} + B
\]

where \(f\) is the infiltration rate (cm h\(^{-1}\)) at any time \(t\) (h), \(F\) is the cumulative infiltration in time \(t\) (cm), and \(A = K_sMS_{sat}\), cm\(^2\) h\(^{-1}\) and \(B = K_s\), cm h\(^{-1}\) are the Green-Ampt parameters. The Green-Ampt parameters (\(A\) and \(B\)) are affected by the soil properties (such as \(K_s\)), fillable porosity defined as water content at saturation minus water content at desired water table depth (\(M\), dimensionless), suction at the wetting
Figure 1. A general flowchart of modifications made to incorporate the deep chiseling effects in the calculation of infiltration: solid line = original flowchart, dotted line = modifications, $R_c$ = cumulative rainfall since deep chiseling (cm), $DCHI$ = number of days since deep chiseling, and Green-Ampt WTD = Green-Ampt water table depth parameters.

...
parameters ($A$ and $B$) for all soil layers within the profile and is the limiting $K_v$ for the computation of infiltration (table 7). The third condition occurs when $K_{so}$ is equal to or less than the relatively steady $K_{sf}$. In this case, $K_{sf}$ is the limiting $K_v$ and is used to determine Green-Ampt parameters $A$ and $B$ for all soil layers (table 8).

**MODELING THE EFFECT OF DEEP CHISELING ON MAXIMUM SURFACE DEPRESSIONAL STORAGE**

This research used surface depressional measurements for clay loam soil conducted by Gayle and Skaggs (1978) and explained by Moriasi (2004) because this soil is similar to the top layer of the Commerce silt loam soil at the research location (Kornecki and Fouss, 2001). In addition, the farm practices reported by Gayle and Skaggs (1978) are approximately representative of the practices at the research study location. Usually, deep chiseling on the alluvial soils of Louisiana is carried out in the fall, followed in the spring by disking, seed preparation, and planting. Cultivation is done to reduce competition from weeds after the corn or other crop has grown, followed finally by harvesting. Figure 2 shows the annual variation of micro-storage for clay loam soil, and includes representative farming practices throughout the year.

Based on the annual variation of surface depressional storage in figure 2 and assuming that approximately same farm operations are carried out annually, a decreasing exponential STMAX model, depending only on the number of days (which incorporates the weathering effects, e.g., between February and mid-March and the farm operations) after deep chiseling a Commerce silt loam in fall or spring, was hypothesized and is expressed by equation 3:

$$\maxst = \maxstf + (\maxsti - \maxstf) \times \exp(-A \maxx \times \DCHI) \quad (3)$$

where $\maxst$ is the current maximum depressional storage (cm) $\DCHI$ days after deep chiseling a Commerce silt loam soil, $\maxstf$ is the final maximum depressional storage (cm), $\maxsti$ is the initial maximum depressional storage (cm), and $A\maxx$ is the model exponent, which depends on farm operations and the type of soil (day$^{-1}$).

Although the weathering effects (such as cumulative rainfall since deep chiseling) were not considered in this model because there were no data to support its inclusion, cumulative rainfall can be used in combination with number of days (that covers the farming operations throughout the year) since deep chiseling or any other initial tillage operation such as first disk.

The values for the parameters in equation 3 can be obtained using one of the maximum depressional storage models (Moore and Larson, 1979; Onstad, 1984; Huang and Bradford, 1990; Kamphorst et al., 2000; Guzha, 2004). After selecting a suitable model for the application, nonlinear regression analysis is carried out using site-specific measured data or data from published literature for similar soils. As mentioned earlier, in cases where long-term measured data are not available, the values of these parameters can be evaluated by calibrating the modified DRAINMOD model (DRAINMOD-STMAX) in which simulated runoff and drainage are compared with the measured runoff and drainage data for a particular tillage operation period as the parameters in question are varied within a reasonable range. Finally, $\maxst$ is computed using equation 3 depending on $\DCHI$.

**MODEL EVALUATION**

Research Site Description

This study was conducted on a Commerce silt loam soil at the USDA-ARS Ben Hur research site located 5 km south of Baton Rouge, Louisiana. The soil texture properties of Commerce silt loam are given in table 1. The site is composed of 16 (0.2 ha) bordered field plots (fig. 3) equipped with shallow and deep subsurface drains, surface ditches, sumps, and instrumentation for automated water table management and sampling of surface and subsurface drain effluent (Fouss and Willis, 1990). The ground surface of all plots was precision leveled to a compound slope of 0.2% slope perpendicular to and 0.2% slope parallel to the direction of the subsurface drainage flow (Fouss and Willis, 1990). A detailed description of the initial site and water management treatments was given by Fouss and Willis (1990). Willis et al. (1991) gave a detailed description of the initial experimental design and field instrumentation. The construction was completed in 1993, and full data collection began in 1995.

Later, Grigg and Fouss (2002) modified the water management treatments. At the time of this study, there were four treatments each with four replications (Grigg and Fouss, 2002). The four treatments were: (I) surface drainage only with deep chiseling, (II) shallow installed (0.6 m deep) drainage with deep chiseling, (III) deep installed (1.0 m deep) and controlled drainage with deep chiseling, and (IV) deep installed (1.0 m deep) and controlled drainage without deep

| Table 1. Soil texture properties for Commerce silt loam at the Ben Hur research site (from Kornecki and Fouss, 2001). |
|---|---|---|---|---|---|
| Depth (cm) | Sand (%) | Silt (%) | Clay (%) | Soil Type Classification |
| 0-28 | 36.0 | 37.0 | 27.0 | Clay loam |
| 28-74 | 50.0 | 36.5 | 13.5 | Silt loam |
| 74-153 | 50.0 | 39.5 | 10.5 | Loam |

Figure 2. Schematic of annual variation in micro-storage for a Cape Fear clay loam soil, North Carolina (recreated from actual graph; Gayle and Skaggs, 1978).
chiseling. Treatment IV was set as a control to test how deep chisel plowing affects surface runoff and nutrient movement in the Lower Mississippi River Valley (Grigg and Fouss, 2002). The construction of the modified water management treatments was completed in 2003.

During this study, an experiment was conducted on two plots, one with treatment III and the other with treatment IV (control), to determine the $K_s$ parameters for equation 2. Drainage was not being controlled during this experiment for the two treatments. Therefore, at the time of this study, there were 6.5 years of data from the initial water management treatments and limited data after treatment modifications.

**MODEL COMPUTATION OF DYNAMIC GREEN-AMPT PARAMETERS FOR COMMERCE Silt Loam**

The values associated with input parameters for equation 2 ($K_{ai} = 2 \text{ cm h}^{-1}, K_e = 0.50 \text{ cm h}^{-1}, \text{ and } a = 0.03 \text{ cm}^{-1}$) were determined using the $K_e$ data measured by Moriasi (2004) at the USDA-ARS Ben Hur research site using the double-ring infiltrometer method (Bouwer, 1986). Moriasi’s (2004) study sought to determine the variation of $K_e$ for the top layer of the Commerce silt loam depending on cumulative rainfall after deep chiseling. Except where restrictive layers result in perched water tables, true saturated conditions rarely occur in the vadose zone because of entrapped air (Bouwer, 1966). The entrapped air prevents water from moving into air-filled pores, which consequently may reduce in-situ hydraulic conductivity by as much as 50% (Reynolds and Elrick, 1986). Therefore, the values of $K_e$ used in this study were assumed to be 1/3 of the measured $K_e$. Finally, a nonlinear regression procedure (SAS, 1999) was used to determine the values for the three variables.

Unlike the soils in the Midwest, where the top soil layer is the most conductive followed by less conductive layers underneath, the top layer of the Commerce silt loam soil is the least conductive layer because of the high surface clay content, about 27% (Kornecki and Fouss, 2001). According to Rogers et al. (1991), the saturated hydraulic conductivity of the Commerce silt loam soil increases with depth down to 1.5 m and then decreases with depth to the deeper soil layers. Therefore, the surface soil layer is the limiting layer for water infiltration for the Commerce silt loam. In other words, it does not matter how conductive the lower layers are; if the surface layer allows water into the soil at a certain rate, then that rate is the limiting water infiltration rate.

Saturated hydraulic conductivity ($K$) values determined by the auger-hole method at different water table depths for the Commerce silt loam soil are given in Table 2 (Fouss et al., 1987). Using the water table depths for the Green-Ampt equation parameters and assuming vertical saturated hydraulic conductivity ($K_s$) equal to 1/3 of the in-situ $K$ (Fouss et al., 1987), the values of $K_s$ were computed (Table 3).

![Figure 3. Schematic layout of the Ben Hur research site located 5 km south of Baton Rouge, Louisiana. Construction site was completed in 1993, and data collection began in 1995 (modified from Grigg et al., 2003).](image-url)
However, because the \( K_s \) for the top soil layer (layer 1) was the limiting \( K_s \) for soil water infiltration, Fouss et al. (1987) generated the parameters for the Green-Ampt infiltration equation for different water table depths based only on the \( K_s \) for layer 1 (table 4). The Green-Ampt parameters in table 4 used in DRAINMOD 5.1 for the Commerce silt loam soil are assumed constant irrespective of farm management operations such as tillage. Given the values of \( A \) and \( B \) in table 4 (Fouss et al., 1987) and assuming that \( M \) and \( S_{av} \) at each water table depth remain constant for this soil profile, the values of the product of \( M \) and \( S_{av} \) for each water table depth were evaluated (table 5).

As discussed earlier in this article, tillage operations tend to increase \( K_s \), which attains its maximum value immediately following tillage and gradually decreases to the value just before the tillage operation (Kim and Chung, 1994). Therefore, three possible Green-Ampt WTD parameter conditions were considered after \( K_s \) was allowed to vary exponentially depending on cumulative rainfall after deep chiseling a Commerce silt loam (eq. 2). Table 6 shows computation of the Green-Ampt parameters in condition 1, which occurs when \( K_{st} \) (for layer 1, i.e., 0-30 cm) is greater than or equal to \( K_s \) for layer 2 (1.33 cm h\(^{-1}\)). The second condition occurs when \( K_{st} \) is less than \( K_s \) for layer 2 (1.33 cm h\(^{-1}\)) but greater than \( K_{gf} \) (0.40 cm h\(^{-1}\)) (table 7). The third condition occurs when \( K_{st} \) is equal to or less than \( K_{gf} \) (0.40 cm h\(^{-1}\)) (table 8). This modification allows the user to keep a record (if needed) of the changes in the Green-Ampt parameters (\( A \) and \( B \)) since the deep chiseling operation. An output file with the project name and an extension (CHK) for the current Green-Ampt parameters is automatically generated.

### Model Computation of Dynamic STMAX for Commerce Silt Loam

The values of the parameters in equation 3 (\( MAXSTI = 1.25 \text{ cm, } MAXSTF = 0.10 \text{ cm, and } A_{max} = 0.012 \text{ day}^{-1} \)) were determined as follows: MAXSTI was determined using a maximum depressional storage model developed by Onstad (1984). This model is written as:

\[
S_d = 0.112R_c + 0.031R_r^2 - 0.012R_rS \tag{4}
\]

where \( S_d \) is the maximum depressional storage (cm) and the same as \( MAXSTI \) in equation 3, \( R_c \) is the random roughness (cm), and \( S \) is the slope steepness (%). According to the USDA (1997), \( R_c \) for chisel with twisted shovel, disk with heavy plowing, and moldboard plow is 4.826 cm. The slope steepness at the USDA-ARS Ben Hur research site is 0.2% (Fouss and Willis, 1990). Substituting the values for these parameters into equation 4 resulted in a \( MAXSTI \) value of 1.25 cm. The STMAX value of 0.10 cm, used in DRAINMOD 5.1 for the USDA-ARS Ben Hur research site, was used as \( MAXSTF \). The value of the parameter \( A_{max} \) was determined by running a nonlinear regression (SAS, 1999) using data collected by Gayle and Skaggs (1978) and modified by the authors for the deep chiseling tillage operation on Commerce silt loam soil. The STMAX values are computed depending on the number of days since deep chiseling (DCHI). This modification allows the user to keep a record of the changes in STMAX since the deep chiseling operation. An output file with the project name and an extension (CHS) for the current STMAX is automatically generated.

### Sensitivity Analysis

The sensitivity of model predictions to the two parameters (\( K_{gf} \) and \( MAXSTI \)) related to the \( K_s \) and STMAX subroutines of DRAINMOD were analyzed. These parameters were chosen because their values vary depending on the type of tillage operation. The values of \( K_{gf} \) and \( MAXSTF \) for a given soil type were assumed constant and hence were not considered in this analysis.

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Table 4. Parameters for the Green-Ampt infiltration equation for various water table depths at the start of rainfall on Commerce silt loam (from Fouss et al., 1987).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>( A ) ( (= K_s M_{S_{av}} \text{ cm}^2 \text{ h}^{-1}) )</th>
<th>( B ) ( (= K_s \text{ cm} \text{ h}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.4</td>
</tr>
<tr>
<td>30</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>60</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>120</td>
<td>1.12</td>
<td>0.4</td>
</tr>
<tr>
<td>150</td>
<td>1.76</td>
<td>0.4</td>
</tr>
<tr>
<td>500</td>
<td>1.76</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 5. Product of \( M \) and \( S_{av} \) for various water table depths for a Commerce silt loam calculated from data in table 4.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>( M_{S_{av}} ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>30</td>
<td>1.00</td>
</tr>
<tr>
<td>60</td>
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<td>120</td>
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</tr>
<tr>
<td>150</td>
<td>4.40</td>
</tr>
<tr>
<td>500</td>
<td>4.40</td>
</tr>
</tbody>
</table>

Table 6. Green-Ampt infiltration equation parameters when \( K_{gf} \) is greater than 1.33 cm h\(^{-1}\) (condition 1).

<table>
<thead>
<tr>
<th>WTD (cm)</th>
<th>( A ) ( (\text{cm}^2 \text{ h}^{-1}) )</th>
<th>( B ) ( (\text{cm} \text{ h}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
<tr>
<td>30</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
<tr>
<td>60</td>
<td>( 1.33 \times 2.00 )</td>
<td>1.33</td>
</tr>
<tr>
<td>120</td>
<td>( 1.33 \times 2.80 )</td>
<td>1.33</td>
</tr>
<tr>
<td>150</td>
<td>0.03 \times 4.40</td>
<td>0.03</td>
</tr>
<tr>
<td>500</td>
<td>0.03 \times 4.40</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 7. Green-Ampt infiltration equation parameters when \( K_{gf} \) is equal or less than 1.33 cm h\(^{-1}\) but greater than or less than 0.4 cm h\(^{-1}\) (condition 2).

<table>
<thead>
<tr>
<th>WTD (cm)</th>
<th>( A ) ( (\text{cm}^2 \text{ h}^{-1}) )</th>
<th>( B ) ( (\text{cm} \text{ h}^{-1}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
<tr>
<td>30</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
<tr>
<td>60</td>
<td>( [K_{gf} + (K_{gf} - K_s)\exp(-aR_c)]^2 \times 0.90 )</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
<tr>
<td>120</td>
<td>( [K_{gf} + (K_{gf} - K_s)\exp(-aR_c)]^2 \times 0.80 )</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
<tr>
<td>150</td>
<td>( [K_{gf} + (K_{gf} - K_s)\exp(-aR_c)]^4 \times 0.40 )</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
<tr>
<td>500</td>
<td>( [K_{gf} + (K_{gf} - K_s)\exp(-aR_c)]^4 \times 0.40 )</td>
<td>( K_{gf} + (K_{gf} - K_s)\exp(-aR_c) )</td>
</tr>
</tbody>
</table>

Table 8. Green-Ampt infiltration equation parameters when the topsoil \( K_s \) is equal or less than 0.4 cm h\(^{-1}\) (condition 3).

<table>
<thead>
<tr>
<th>WTD (cm)</th>
<th>( A ) ( (\text{cm}^2 \text{ h}^{-1}) )</th>
<th>( B ) ( (\text{cm} \text{ h}^{-1}) )</th>
</tr>
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<tbody>
<tr>
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<td>0.4</td>
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<tr>
<td>60</td>
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<tr>
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</tbody>
</table>
Sensitivity analysis, for a particular parameter, was carried out by varying the parameter value over a reasonable range (explained below) and observing the relative change in model response while holding the other parameters at their typical values. The impacts of $K_{s}$ and MAXSTI on daily surface runoff were investigated using the Nash-Sutcliffe efficiency (NSE) values (Nash and Sutcliffe, 1970) and the percent bias (PBIAS).

The highest $K_{s}$ value was taken as 6.0 cm h$^{-1}$ (Rao et al., 1998), and the minimum $K_{s}$ was taken as 1.0 cm h$^{-1}$ (2.5 times the base value). The mid-range value of 2.0 cm h$^{-1}$ was determined from the field experiment conducted by Moriasi (2004). The maximum MAXSTI was 1.25 cm, with a minimum of 0.65 (half the base value) and mid-range value of 0.95 cm.

**DATA MEASUREMENT**

Measured surface runoff data from the USDA-ARS Ben Hur research site were used to evaluate the DRAINMOD 5.1, DRAINMOD-$K_{s}$, DRAINMOD-STMAX, and DRAINMOD-$K_{s}$-STMAX models. Previously, surface runoff was collected in a shallow ditch on the downslope side of the plots, which routes the flow through an H-flume for measurement (Fouss and Willis, 1990). Currently, surface runoff is collected in quarter drains across the plot at the sump end and routed through a 20 cm diameter PVC pipe collection unit fixed below the soil surface for measurement. The collection unit allows water flow in only one direction to prevent water backup during heavy storm events.

Measurement was accomplished using a refrigerated sampler (StreamLog 800SL, American Sigma, Inc., Loveland, Colo.). Using a pressure transducer, which correlates flow with height of flow in the collection unit using Manning’s formula, a sample of 200 mL was collected for every 2,000 L of flow. This fraction (1/10,000) of flow was automatically collected and preserved by refrigeration for nutrient and pesticide analysis. The data were downloaded from the 800SL sampler using an external modem into a desktop PC.

There were few rainfall events significant enough to cause surface runoff during the field research period, as described by Moriasi (2004). During the few events that had a significant amount of rainfall, the storms were so intense that backup of runoff caused the system to overestimate surface runoff, which made the data invalid. Therefore, event runoff data collected at the research site between 28 September 1995 and 21 November 1996 and between 22 November 1996 and 22 November 1997 (when deep chiseling was carried out) were used. It was observed that on some days, surface runoff measurements were higher than rainfall data, and no runoff was recorded with 13 cm or more rainfall. A possible reason for measured runoff being higher than rainfall would be water backup during heavy rainfall events, and a possible explanation for no runoff during heavy rainfall events would be data-logger problems. Data collected during such days were discarded and not used in the model evaluation. Therefore, there were 24 days of data available for analysis for the 1995-96 period and 35 days for the 1996-1997 period.

**MODEL EVALUATION METHODS**

The Nash-Sutcliffe model efficiency (NSE), percent bias (PBIAS), coefficient of determination ($R^2$) and its test of significance (paired t-test statistic at 5% significance level), and graphical methods were used to compare simulated surface runoff values with the measured values. The NSE is computed as:

$$\text{NSE} = 1 - \left[ \frac{\sum_{i=1}^{n}(Y_{obs_i} - Y_{sim_i})^2}{\sum_{i=1}^{n}(Y_{obs_i} - Y_{mean})^2} \right]$$

where $Y_{obs_i}$ and $Y_{sim_i}$ are the $i$th observed and simulated values of the component being evaluated, $Y_{mean}$ is the mean of observed data for the component being evaluated, $n$ is the total number of observations, and the component can be surface runoff, infiltration, or drainage volume. The NSE measures the relative magnitude of the residual variance (“noise”) to the variance of the component being evaluated (“information”). It varies from a large negative value to one; a value of 1.0 indicates a perfect match between model prediction and measured data, whereas a negative NSE indicates that the mean of the measured data is a better predictor than the model.

The PBIAS was found to be a model performance evaluation criterion with power to clearly indicate poor model performance (Gupta et al., 1999). It measures the average tendency of the simulated component to be larger or smaller than their observed counterparts; the optimal value is zero; positive values indicate a model bias toward underestimation, whereas negative values indicate a bias toward overestimation (Gupta et al., 1999). The PBIAS is expressed as:

$$\text{PBIAS} = \left[ \frac{n}{\sum_{i=1}^{n}(Y_{obs_i} - Y_{sim_i})100} \right]$$

According to Gupta et al. (1999), PBIAS values tend to vary more during dry years than during wet years. This fact should be considered when attempting to do a split-sample performance evaluation, one for calibration and the other for validation of the model.

The $R^2$ value represents the percentage of the variance in the measured data that is explained by the predicted data; $R^2$ varies between 0 and 1, and the larger the value, the better. The NSE and PBIAS were used to compare the pattern and magnitude of the simulated runoff values to the measured runoff values. For the simulation results, $R^2$ values $\geq 0.60$ were considered satisfactory (Santhi et al., 2001). NSE values $\geq 0.65$ were considered “very good,” and NSE values between 0.65 and 0.54 were considered adequate (Saleh et al., 2000). PBIAS values $\pm 10\%$ were considered very good, values between $\pm 10\%$ and $\pm 15\%$ were considered good, values between $\pm 15\%$ and $\pm 25\%$ were considered satisfactory, and values $>\pm 25\%$ were considered unsatisfactory (Van Liew et al., 2006).

The DRAINMOD 5.1 model and the modified DRAINMOD models were evaluated for the periods between 28 September 1995 and 21 November 1996 and between 22 November 1996 and 22 November 1997 (when deep chiseling was carried out). The calibration of DRAINMOD 5.1 performed by Fouss et al. (1987) for all water balance components was considered the best DRAINMOD 5.1 calibration. It was therefore used as a baseline for comparing the modified DRAINMOD models.
RESULTS AND DISCUSSION

SENSITIVITY OF INITIAL MAXSTI MAXSTIMAX AND Ks (MAXSTI AND Ks)

Figures 4a and 4b illustrate the sensitivity of predicting surface runoff to MAXSTI during rainfall events between September 1995 and November 1996 and between November 1996 and November 1997, respectively, when deep chiseling was performed on the plots at the USDA-ARS Ben Hur research site. The variable MAXSTI was varied from 0.65 to 1.25 cm. Although model performance was better between 1995 and 1996 (0.90 ≤ NSE ≤ 0.91 and -33.0% ≤ PBIAS ≤ -19.6%) than between 1996 and 1997 (0.26 ≤ NSE ≤ 0.27 and -44.4% ≤ PBIAS ≤ -39.3%), both NSE and PBIAS did not vary greatly over different values of MAXSTI. However, PBIAS (-33.0% to -19.6%) varied more than NSE (0.90 to 0.91) between 1995 and 1996. Based on these results, event surface runoff is not very sensitive to changes in MAXSTI; therefore, one can use any value within a reasonable range (0.65 and 1.25 cm) if one does not have an actual measured value.

Figures 5a and 5b illustrate the sensitivity of predicting surface runoff to Ks during rainfall events between September 1995 and November 1996 and between November 1996 and November 1997, respectively. The variable Ks was varied from 1 to 6 cm h⁻¹. As with MAXSTI, model performance, as Ks was varied, was better between 1995 and 1996 (0.93 ≤ NSE ≤ 0.94 and -22.7% ≤ PBIAS ≤ -2.8%) than between 1996 and 1997 (0.13 ≤ NSE ≤ 0.18 and -41.0% ≤ PBIAS ≤ -19.5%).

Overall, there is less variation in NSE than in PBIAS in either year as Ks changes. This implies that changes in Ks affect the average tendency of the simulated components to be larger or smaller than their observed counterparts more than the relative magnitude of the residual variance (“noise”) to the variance of the component being evaluated (“information”). The rate of variation of PBIAS as Ks changes is greater between 1 and 2 cm h⁻¹ than between 2 and 6 cm h⁻¹ (figs. 5a and 5b).

Based on PBIAS, Ks has a greater effect on surface runoff (-22.7% ≤ PBIAS ≤ -2.8% and -41.0% ≤ PBIAS ≤ -19.5%) than MAXSTI (-33.0% ≤ PBIAS ≤ -19.6% and -44.4% ≤ PBIAS ≤ -39.3%). Therefore, care needs to be taken when deciding the value of Ks to be used, and it is recommended that this value be determined for a given soil and tillage operation.

Figure 4. Effects (NSE and PBIAS values) of initial maximum surface depressional storage (MAXSTI) on surface runoff at the USDA-ARS Ben Hur research site during (a) 1995-1996 and (b) 1996-1997.

Figure 5. Effects (NSE and PBIAS values) of initial saturated hydraulic conductivity (Ks) on surface runoff at the USDA-ARS Ben Hur research site during (a) 1995-1996 and (b) 1996-1997.
**EVALUATION OF THE DRAINMOD MODELS**

The first objective in the model evaluation process was to determine whether the model-predicted values were significantly different from the measured values. The null hypothesis tested to evaluate all the DRAINMOD models was that the event mean measured surface runoff was equal to the mean predicted surface runoff for days when surface runoff occurred. Only the surface runoff (RUNOFF) component predicted by DRAINMOD and its modified forms was used for comparison with the measured data.

Between September 1995 and November 1996, the runoff predicted by DRAINMOD 5.1 was significantly different from the measured runoff (p-value = 0.03), whereas the runoff values predicted by the modified DRAINMOD-STMAX, DRAINMOD-Ks, and the combined DRAINMOD-Ks-STMAX models were not significantly different (p-values = 0.35, 0.47, and 0.65, respectively), as shown in table 9. The mean event and total runoff values predicted by DRAINMOD-Ks-STMAX (0.69 and 16.50 cm, respectively) were closest to the mean event and total measured runoff (0.75 and 18.01 cm, respectively), followed by the mean event and total runoff predicted by DRAINMOD-Ks (0.84 and 20.26 cm) and by DRAINMOD-STMAX (0.90 and 21.54 cm), respectively (table 9).

Between November 1996 and November 1997, the predicted runoff by the DRAINMOD 5.1 model and the modified DRAINMOD models were not significantly different from the measured runoff (p-value = 0.12; table 9). However, mean event and total runoff predicted by the modified DRAINMOD models were closer to the mean and total measured runoff than the mean and total runoff predicted by the DRAINMOD 5.1 model (0.97 cm, 33.86 cm). The mean and total runoff values predicted by the DRAINMOD-Ks-STMAX model (0.76 cm, 26.55 cm) were closest to the mean and total measured runoff (0.63 cm, 21.98 cm), followed by the DRAINMOD-Ks values (0.81 cm, 28.49 cm) and the DRAINMOD-STMAX model values (0.87 cm, 30.61 cm) (table 9).

Statistical analysis was carried out between the predicted and measured event and cumulative runoff to determine how well the models performed in predicting surface runoff. The results of the model performance for surface runoff are summarized in table 10. The event surface runoff R^2 values of 0.93, 0.94, 0.94, and 0.98 for DRAINMOD 5.1, DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX, respectively, and the cumulative runoff R^2 values of 0.97, 0.97, 0.99, and 0.99 for the respective models indicate that 93% or more of the variance in the measured event and cumulative surface runoff data was explained by the simulated data between 1995 and 1996. Event NSE values of 0.90, 0.91, 0.94, and 0.93 for DRAINMOD 5.1, DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX, respectively, for 1995-1996 indicate that the patterns of the predicted runoff values matched those of the measured runoff values well for all DRAINMOD models for most of the events. However, for cumulative runoff, NSE values of 0.50, 0.94, 0.96, and 0.92 for DRAINMOD 5.1, DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX, respectively, for the same time period, indicate that only the modified DRAINMOD models’ patterns of the predicted runoff values matched those of the measured runoff values well. With the exception of DRAINMOD 5.1 (PBIAS values of −45.9% and −37.3% for event and cumulative runoff, respectively), all DRAINMOD models (PBIAS values of −19.6%, −12.5%, and 8.4% for event runoff and −7.3%, −9.6%, and 14.8% for cumulative runoff for DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX, respectively) predicted surface runoff within ±25% of the measured event and cumulative runoff, a satisfactory model performance level (Van Liew et al., 2006).

Figure 6 illustrates that, with the exception of low runoff events in early and late 1996, patterns of event surface runoff between 1995 and 1996 were predicted well by all DRAINMOD models. Figure 7, on the other hand, shows that the patterns of cumulative runoff between 1995 and 1996 were predicted well by all DRAINMOD models except for 1996. The modified DRAINMOD models predicted cumulative runoff better than the original models.

Table 10. Event and cumulative surface runoff model evaluation results.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>Surface Runoff (cm)[a]</td>
<td>Surface Runoff (cm)[a]</td>
</tr>
<tr>
<td></td>
<td>TM</td>
<td>MM</td>
</tr>
<tr>
<td>DRAINMOD 5.1</td>
<td>18.01</td>
<td>0.75</td>
</tr>
<tr>
<td>DRAINMOD-STMAX</td>
<td>21.54</td>
<td>0.90</td>
</tr>
<tr>
<td>DRAINMOD-Ks</td>
<td>20.26</td>
<td>0.84</td>
</tr>
<tr>
<td>DRAINMOD-Ks-STMAX</td>
<td>16.50</td>
<td>0.69</td>
</tr>
</tbody>
</table>

[a] TM is total measured runoff, MM is average event measured runoff, TP is total predicted runoff, and MP is average event predicted runoff.
A possible reason for the overall underprediction by DRAINMOD-Ks-STMAX between September 1995 and November 1996 could be the leveling/grading operation on the research plots that occurred from the middle to the end of February 1996, which could have reduced both STMAX and Ks of the top soil layer. Therefore, the decreasing exponential DRAINMOD-Ks-STMAX model computed and used higher Ks and STMAX values than the actual values after the plots had been graded. The leveling/grading could have also affected the runoff simulation results of DRAINMOD-STMAX and DRAINMOD-Ks due to possible use of higher STMAX and Ks values, respectively. However, the individual effect of STMAX and Ks on runoff, within DRAINMOD-STMAX and DRAINMOD-Ks, was not as pronounced as the combined effect of both Ks and STMAX within DRAINMOD-Ks-STMAX.

Between November 1996 and November 1997, event runoff R² values of 0.38, 0.39, 0.31, and 0.31 for DRAINMOD 5.1, DRAINMOD-STMAX, DRAINMOD-Ks and DRAINMOD-Ks-STMAX, respectively, indicate that a maximum of

![Figure 6. Measured and predicted event runoff: September 1995 to November 1996.](image)

![Figure 7. Measured and model predicted cumulative runoff: September 1995 to November 1996.](image)
39% of the variance in the measured event and cumulative surface runoff data could be explained by the simulated data. For the same time period, cumulative runoff R² value of 0.98 for all DRAINMOD models indicates that a maximum of 98% of the variance in the measured cumulative surface runoff data could be explained by the simulated data. A possible reason for the cumulative R² values being much better than the event R² values could be the fact that R² is overly sensitive to extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Willmott, 1981; Legates and McCabe, 1999).

Event NSE values of 0.24, 0.27, 0.17, and 0.20 for DRAINMOD 5.1, DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX, respectively, between 1996 and 1997 indicate that the patterns of the predicted runoff values did not adequately match those of the measured runoff values for all DRAINMOD models. For cumulative runoff, NSE values of 0.13, 0.61, 0.70, and 0.86 for DRAINMOD 5.1, DRAINMOD-STMAX, DRAINMOD-Ks, and DRAIN-

![Figure 8. Measured and predicted event runoff: November 1996 to November 1997.](image1)

![Figure 9. Measured and model predicted cumulative runoff: November 1996 to November 1997.](image2)
MOD-Ks-STMAX, respectively, for the same time period, indicate that only the modified DRAINMOD models’ patterns of predicted runoff values adequately matched those of the measured runoff values.

With the exception of the predicted DRAINMOD-Ks-STMAX model values (PBIAS value of ~20.8%) that was within the satisfactory level (between ±15% and ±25%), all predicted DRAINMOD model values (PBIAS values of -54.06%, -39.3%, and -29.6% for DRAINMOD 5.1, DRAINMOD-STMAX, and DRAINMOD-Ks, respectively) were >±25% of the measured values for 1996-1997, which is unsatisfactory according to Van Liew et al. (2006). For the same time period, none of the models (PBIAS values of -79.4%, -50.2%, -45.6%, and -29.8% for DRAINMOD 5.1, DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX, respectively) predicted cumulative runoff within the satisfactory level of <±25% of the measured values, although predicted cumulative values by DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX were closer to the measured cumulative runoff values than the cumulative runoff values predicted by DRAINMOD 5.1. Figure 8 shows that between 1996 and 1997, the patterns of the predicted event surface runoff values were not adequately matched to those of the measured event runoff values by all DRAINMOD models. Figure 9, on the other hand, shows that although the patterns of predicted cumulative runoff values did not match the measured cumulative runoff patterns as well between 1996 and 1997 as between 1995 and 1996, the predicted cumulative runoff patterns for the modified DRAINMOD models were closer to the measured cumulative runoff patterns than the cumulative runoff patterns predicted by DRAINMOD 5.1.

There was no clear explanation for the poor results for the event runoff predictions between November 1996 and November 1997 compared with those between September 1995 and November 1996. The annual rainfall values for 1995-1996 and 1996-1997 were 1880 and 1840 mm, respectively, both of which are greater than the long-term annual average of 1500 mm (Fouss et al., 1987). Perhaps differences in the rainfall patterns (distribution and intensity) for different years in this region (Keim and Fairai, 1996; Bengston and Carter, 2004) could explain the conflicting model prediction results. The effect of rainfall patterns in the research area was beyond the scope of this study. Therefore, further validation work is needed to determine the reliability of the modified DRAINMOD models under different weather conditions.

QUANTIFYING DRAINMOD PREDICTION IMPROVEMENT DUE TO THE MODIFICATIONS

DRAINMOD model improvement due to deep chiseling modifications was evaluated using absolute PBIAS values for the event runoff between 1995 and 1996 and between 1996 and 1997, with the PBIAS values for DRAINMOD 5.1 as the benchmark (tables 11 and 12). The modified DRAINMOD models’ surface runoff prediction improvements varied from a minimum of 27% for DRAINMOD-STMAX between November 1996 to November 1997 (table 12) to a maximum of 82% for DRAINMOD-Ks-STMAX between September 1995 and November 1996 (table 11). The DRAINMOD-Ks-STMAX model, which combines Ks and STMAX modifications, improved on DRAINMOD 5.1 the most for the two time periods: by 82% between September 1995 and November 1996, and by 62% between November 1996 and November 1997.

Table 11. Runoff prediction improvement by the three modified DRAINMOD models, September 1995 to November 1996 (PBIAS Diff. is the difference between DRAINMOD 5.1 absolute PBIAS and modified DRAINMOD model PBIAS).

<table>
<thead>
<tr>
<th>Model</th>
<th>Absolute PBIAS (%)</th>
<th>PBIAS Diff. (%)</th>
<th>Prediction Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAINMOD 5.1</td>
<td>45.6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>DRAINMOD-STMAX</td>
<td>19.6</td>
<td>26.1</td>
<td>57.1</td>
</tr>
<tr>
<td>DRAINMOD-Ks</td>
<td>12.5</td>
<td>33.1</td>
<td>72.6</td>
</tr>
<tr>
<td>DRAINMOD-Ks-STMAX</td>
<td>8.4</td>
<td>37.2</td>
<td>81.6</td>
</tr>
</tbody>
</table>

Table 12. Runoff prediction improvement by the three modified DRAINMOD models, November 1995 to November 1997 (PBIAS Diff. is the difference between DRAINMOD 5.1 absolute PBIAS and modified DRAINMOD model PBIAS).

<table>
<thead>
<tr>
<th>Model</th>
<th>Absolute PBIAS (%)</th>
<th>PBIAS Diff. (%)</th>
<th>Prediction Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAINMOD 5.1</td>
<td>54.1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>DRAINMOD-STMAX</td>
<td>39.3</td>
<td>14.8</td>
<td>27.4</td>
</tr>
<tr>
<td>DRAINMOD-Ks</td>
<td>29.6</td>
<td>24.5</td>
<td>45.3</td>
</tr>
<tr>
<td>DRAINMOD-Ks-STMAX</td>
<td>20.8</td>
<td>33.3</td>
<td>61.5</td>
</tr>
</tbody>
</table>

SUMMARY AND CONCLUSION

In this study, the DRAINMOD 5.1 model was modified to simulate deep chiseling effects (Ks and STMAX) on the alluvial soils in the southeastern U.S. in order to improve DRAINMOD’s prediction accuracy for infiltration and hence surface runoff for the alluvial soils. The new decreasing exponential Ks equation, based on the theory of soil surface seal formation and past work, uses the initial and final Ks, a model exponent, and the deep chiseling dates (beginning and ending) to evaluate current Ks as a function of cumulative rainfall since deep chiseling. Current Ks is used to generate a current Green-Ampt parameters table, which is used to compute infiltration and hence surface runoff. The new exponential STMAX equation, based on past research (Gayle and Skaggs, 1978; Onstad, 1984; Kincaid, 2002), uses initial and final STMAX, a model exponent, and deep chiseling dates (starting and ending) to calculate current STMAX, which is used in the calculation of infiltration and surface runoff.

The modifications allow the user to keep a record (if needed) of the changes in Ks, Green-Ampt parameters (A and B), and STMAX since a deep chiseling operation. The new subroutines show that surface runoff decreases as both the initial and final saturated hydraulic conductivity (Kst) and the initial maximum surface depressional storage depth (MAXSTI) increase, although runoff was more sensitive to changes in Kst.

The DRAINMOD 5.1 model and the modified DRAINMOD models were evaluated at field scale using the two years of measured runoff data (1995-1996 and 1996-1997) from the USDA-ARS Ben Hur research site. Using event absolute percent bias (PBIAS, %) value of DRAINMOD 5.1 as a reference, event runoff prediction improvements due to the deep chiseling modifications within DRAINMOD were computed. The DRAINMOD-STMAX, DRAINMOD-Ks, and DRAINMOD-Ks-STMAX models improved surface runoff prediction by 57%, 73%, and 82%, respectively, between September 1995 and November 1996, and by 27%,
45%, and 62%, respectively, between November 1996 and November 1997.

The DRAINMOD-Ks-STMAX model, after further validation, could be used to quantify the benefits of deep chiseling under various weather conditions to determine how frequently to deep chisel and how close to planting time farmers should perform deep chiseling to draw the maximum benefits. The findings of such research would need to be relayed to engineers, scientists, and farmers.

ACKNOWLEDGEMENTS
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