APPLICATION OF DRAINMOD-K_S-STMAX TO PREDICT DEEP CHISELING EFFECTS ON A DRAINED SOUTHERN ALLUVIAL SOIL

D. N. Moriasi, J. L. Fouss, S. G. Hall, T. S. Kornecki

ABSTRACT. *Deep chiseling in heavy drained soils can help increase infiltration and hence reduce erosion, potentially enhancing growth by reducing excess water in the root zone and reducing nutrient losses through the reduction of runoff to surface waters. The goals of this study were to apply DRAINMOD-K_S-STMAX, a modified form of the water management model, DRAINMOD 1) to predict the effects of deep chiseling on hydrology for a subsurface drained plot and 2) to determine the frequency and timing of deep chiseling. Data from a subsurface drained plot at Ben Hur Research site near Baton Rouge, Louisiana, were used. Simulation results indicated that deep chiseling a Commerce silt loam, a southern alluvial soil, increased cumulative infiltration (CI) by 16% and reduced cumulative sub-surface drainage (CSD) and cumulative surface runoff (CRO) by 26% and 37%, respectively, between 28 September 1995 and 21 November 1996. Between 22 November 1996 and 22 November 1997, it increased CI and CSD by 9% and 17%, respectively, and reduced CRO by 22%. Vertical saturated hydraulic conductivity (K_S) had decreased by 99%, from a maximum initial value immediately after deep chiseling, by the time 150 cm of rain had fallen (approximately 12 months) since deep chiseling. For high rainfall states like Louisiana, with average annual rainfall often exceeding 150 cm, this translates to deep chiseling once every year whereas in drier states deep chiseling can be done once every two to three years depending on the amount of rainfall. Depending on the cumulative amount of rainfall at planting, producers can lose 85% or more of the maximum deep chiseling benefits due to reduced K_S. Because of great rainfall variability in Louisiana and other southern states, it is advisable for farmers to deep chisel their fields just prior to the planting season. Results of this model simulation study indicate that DRAINMOD-K_S-STMAX can be used as a cost-effective (saving time and money) tool to predict the effects of deep chiseling in poorly drained soils with subsurface drainage and potentially open ditch drainage, and to advise farmers on the frequency and timing of deep chiseling based on science. However, the model needs to be tested for longer time periods and under different climatic conditions and soil types before it can be recommended for general application for the purposes listed above.*

Keywords. *Drainage, Infiltration, Modeling, Surface runoff, Cumulative rainfall, Tillage operations.*

Agricultural drainage is a common water management practice in agricultural regions with seasonal high water tables such as the Midwest United States, the Great Lakes states, and southeastern United States. Agricultural drainage is the removal of excess water from the soil surface and/or soil profile of cropland, by either gravity (surface drainage) or artificial means such as tiles or drain tubes (subsurface drainage). Surface drainage includes land leveling and smoothing; and the construction of shallow ditches and grass waterways, which empty into open ditches and streams. Agricultural drainage systems are mainly installed (1) to allow timely seedbed preparation, planting, harvesting, and other field operations; and (2) to protect field crops from extended periods of flooded soil conditions especially within the root zone. Subsurface drainage is common in the Midwestern and Great Lakes states and open ditch drainage is common in the southeastern United States. In Louisiana, 60% of cropland is drained with only 1% of this total accomplished through subsurface drainage systems (USDA-ERS, 1987) and the rest through open ditch drainage.

While the benefit of increased crop production is evident (Bengtson et al., 1984; Carter, 1987) subsurface drainage has been reported to expedite the transport of nitrate nitrogen and some soluble pesticides to surface waters (Thomas et al., 1992; Randall et al., 1997; Zucker and Brown, 1998; Dinnes et al., 2002). An approach used to minimize nitrate loss from subsurface drained fields is controlled drainage in order to enhance the denitrification process and decrease drainage volumes (Dinnes et al., 2002). Controlled drainage has been shown to reduce drainage volumes and subsequent nitrate loads to surface waters (Kalita and Kanwar, 1993; Evans et al., 1995; Drury et al., 1993; Fausey, 2004). Currently, Appelboom and Fouss (2006) are studying the impact of drainage water management in open ditch drainage systems, similar to controlled subsurface drainage, on reduction of

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nitrate losses in the Mississippi Alluvial Valley. For open ditch, this is achieved by installation of a water control structure at a drainage outlet either in a field ditch to control drainage from a single field or placed in a collector canal to control drainage from several fields (Appelboom and Fouss, 2006). Although subsurface drainage often leads to accelerated transport of soluble nitrates, in some cases it leads to decreased sediments and sediment-borne nutrients and pesticides by reducing surface runoff (Bengtson et al., 1995; Bengtson and Carter, 2004).

Whereas the benefits of agricultural drainage can be achieved without manipulation of the soil profiles in the Midwestern and the Great Lakes states, it is not possible to achieve the same benefits on alluvial soil profiles without manipulation of these profiles. Unlike the soil profiles in the Midwest where the surface soil layer is the most conductive followed by less conductive layers underneath, alluvial soil profiles begin with the least conductive surface layer followed by more conductive layers beneath (Grigg and Fouss, 2002). For instance, for the Commerce silt loam soil [fine silty, mixed, non-acid, thermic Aeric Flivaquent], a southern alluvial soil, the top (surface) soil layer is the least conductive (Rogers et al., 1991). According to Rogers et al. (1991), saturated hydraulic conductivity 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 depth to 2.88 cm h^{-1} at 2.4 m. Alluvial soils deposited by floodwaters over thousands of years, are the predominant soils in much of the southeastern United States. Although alluvial soils are moderately to poorly drained (Grigg et al., 2003), they are very productive with high crop yields when fertilized and properly farmed.

One of the challenges to farmers in the southeastern United States is excess rainfall and its subsequent impacts. The southeastern U.S. region is characterized by intense rainfall events and up to 160 cm of annual rainfall (Bengtson and Carter, 2004). High intensity rainfall leads to surface seal formation in fine textured soils such as alluvial soils, especially during seedbed preparation when the soil is bare (Haan et al., 1994; Martinez-Gamino, 1994). High intensity rainfall on alluvial soils is less utilizable by the crops than low intensity rainfall because a greater proportion runs off and does not infiltrate into the root zone for crop use. High runoff can lead to lower crop yields because of the loss of crop nutrients such as nitrogen, phosphorus, and potassium. Without manipulation of the soil profiles, these climate and soil factors in this region in combination with frequent shallow water tables present serious challenges to utilizing drainage to improve crop production and they result in a high potential of transport of crop nutrients (Bengtson et al., 1998; Willis et al, 1998) and pesticides (Bengtson et al., 1989; Southwick et al., 2003) in surface runoff to receiving surface waters.

Deep chiseling is used to break the soil surface seal and the hard pan in alluvial soils in order to increase infiltration and reduce surface runoff, sediments, and sediment-borne nutrients (Bengtson et al, 1995; Bengtson and Carter, 2004) by increasing vertical saturated hydraulic conductivity (K_s) (Kincaid, 2002) and surface depressional storage (STMAX) (Kamphorst et al., 2000; Kincaid, 2002; Guzha, 2004). 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) (fig. 1). The percent of residue remaining on the soil surface after deep chiseling for the non-fragile and fragile residue are 50% to 70% and 40% to 50%, respectively (CTSM, 2000). Deep chiseling used to be a common practice in southeastern United States. In more recent years farmers have not used it because they did not see any economic benefits of increased crop yields and because minimum tillage was adopted which required less energy for the equipment (Grigg and Fouss, 2002).

Figure 1. Deep chiseling operation on the USDA-ARS Research Fields in Ben Hur.

In the southeastern United States, deep chiseling is usually carried out during the fall while fields are prepared for planting and seeding in the spring. In previous research on Commerce silt loam soil (Bengtson et al., 1995), when deep chiseling was carried out every one year to two years and data collection beginning right after deep chiseling, subsurface drainage systems decreased surface runoff, sediments, and total nitrogen by 35%, 31%, and 17%, respectively. However, research by Grigg et al. (2003) from 1995 to 1996 on fields also fitted with subsurface drainage but whose measurements were taken 3 to 5 months after deep chiseling showed no significant reduction in surface runoff due to subsurface drainage.

Deep chiseling on Grigg et al.'s (2003) fields was done in the late fall, the usual time deep chiseling is carried out, and measurements were taken beginning after planting corn and applying crop nutrients and pesticides in late March 1996 and in late April 1997. Because of the large amount of rainfall in Louisiana (Bengtson and Carter, 2004), the top clay loam soil aggregates could have been broken into fine particles which may have caused surface sealing (Martinez-Gamino, 1994) thus diminishing the benefits of deep chiseling by the time measurements were taken (Grigg et al., 2003). This may explain the difference between Bengtson et al.'s (1995) and Grigg et al.'s (2003) contradicting results and why the farmers may have abandoned the practice for economic reasons.

Grigg et al.'s (2003) results suggested that subsurface drainage systems should be coupled with deep chiseling, just before the growing season, in order to reduce nutrient loss through surface runoff from the Commerce silt loam soil, an alluvial soil. The same recommendation may be necessary for farmers who drain their fields through open ditches, if they should expect to gain economic benefits due to increased crop yields that will more than offset the cost of deep chiseling. However, it is very important to note that the level of benefits from deep chiseling depends to a large extent on the prevailing weather conditions especially precipitation, which vary from year to year. Therefore, there is a need for a cost-effective tool that can be used to predict the benefits of deep chiseling depending on the prevailing weather conditions and to offer farmers guidance on how frequently to deep chisel.

The DRAINMOD model (Skaggs, 1978) has been widely used to simulate water management systems such as surface and sub-surface irrigation and drainage (Gayle et al., 1985; Skaggs and Nassehzadeh-Tabrizi, 1986; Fouss et al., 1987; McMahon et al., 1988; McCarthey and Skaggs, 1989; Cox et al., 1994). DRAINMOD version 5.1 (DRAINMOD 5.1) (Skaggs and Fernandez, 1998), which was modified to incorporate deep chiseling routines, has additional extensions to predict the fate of salt (Kandil et al., 1995) and nitrogen (Breve et al., 1997) in shallow water table soils. Although DRAINMOD has been widely used to evaluate the effect of drain tube size and spacing (among other factors) on field hydrology, it has not been used to determine the effect of tillage operations such as deep chiseling on field hydrology in areas with shallow water tables and alluvial soils. This is due to its lack of tillage operation algorithms. Results of such algorithms could be used to predict the effects and hence the benefits of deep chiseling and to provide guidelines to farmers on how often deep chiseling is needed to obtain maximum benefits. Potential deep chiseling benefits include 1) increased crop yields due to increased water infiltration and reduced runoff, 2) reduced crop input costs because of reduced surface runoff, and 3) a clean environment for a healthy population and increased aquaculture and fish production.

DRAINMOD 5.1 was therefore modified to include deep chiseling algorithms (DRAINMOD-K_S-STMAX) for the alluvial soils (Moriasi et al., 2007). The details of the new algorithms and the associated modifications are presented by Moriasi et al. (2007). In brief, Moriasi et al. (2007) modified DRAINMOD 5.1 to incorporate deep chiseling algorithms [K_S and maximum depressional storage (STMAX)] in order to improve DRAINMOD prediction accuracy for infiltration and hence surface runoff and sub-surface drainage for the predominant alluvial soils in the southeastern United States. The new decreasing exponential K_s algorithm, based on the theory of soil surface seal formation (Martinez-Gamino, 1994; Slattery and Bryan, 1994; Assouline and Mualem, 2002) and past field research findings (Allen and Musick, 2001; Rao et al., 1998; Kim and Chung, 1994), allows K_s to decrease from a maximum value at the time of deep chiseling to a final steady state value depending on cumulative rainfall since deep chiseling (Moriasi et al., 2007). The current K_S value is then used to generate a current Green-Ampt parameters table (table 1), which is used to compute infiltration and hence surface runoff and sub-surface drainage. The decreasing exponential K_S algorithm is applicable to soils that are prone to sealing due to high clay content in the surface (top) soil layer. However, the parameter values may vary depending on the type of crops grown or the amount of residue.

The new exponential STMAX algorithm, which is based on past research (Gayle and Skaggs, 1978; Onstad, 1984; Kincaid, 2002) findings, allows STMAX to decrease from a maximum value at the time of deep chiseling to a final steady state value based on the number of days since deep chiseling (Moriasi et al., 2007). The current STMAX value is then used in the calculation of infiltration, surface runoff, and subsurface drainage. The modifications allow the user to keep a record [if needed] of the changes in K_S, Green and Ampt parameters, and STMAX (table 1) since deep chiseling. For instance, with a cumulative rainfall of 0.00 cm since deep chiseling, the values of K_S and the Green and Ampt parameters A and B at a water table depth of 111 cm, were 2.00 cm h^{-1}, 3.56 cm h^{-2}, and 1.33 cm h^{-1}, respectively whereas the values of K_S and the Green and Ampt parameters A and B at a water table depth of 0 cm after cumulative rainfall of 28.88 cm since deep chiseling were 1.13 cm h^{-1}, 0.00 cm h^{-2}, and 0.00 cm h^{-1}, respectively (table 1). Similarly, the value of STMAX 145 days after deep chiseling is 0.30 cm (table 1).

DRAINMOD-K_S-STMAX also contains flags (table 2) that allow the user to switch on and off the deep chiseling algorithms. The purpose of these flags is two-fold. First, the flags allow the modelers to run simulations on fields with and without deep chiseling. In this case if no deep chiseling is carried out, the flags are switched off or set to zero (0) whereas if deep chiseling operation is carried out, the flags are switched on or set to one (1) so as to include the effects of deep chiseling in model simulation and thereby increase model prediction accuracy. According to Moriasi et al. (2007), incorporation of the deep chiseling algorithms improved surface runoff prediction by between 62% and 82%. The second purpose for these flags is to aid modelers run simulations to quantify/predict the benefits of deep chiseling an alluvial soil, specifically increasing infiltration and sub-surface drainage and reducing surface runoff. In this case, model simulation scenario outputs with flags switched off form the baseline/benchmark whereas model simulation scenario outputs with the flags switched on include the effect of deep chiseling on the outputs. Hence the difference between the two model simulation scenario outputs is an indication of the impact/effect of deep chiseling on model output components such as infiltration, subsurface drainage, and surface runoff.

The objectives of this study were to apply DRAINMOD-K_S-STMAX model 1) to predict the effects/benefits of deep chiseling (increasing infiltration and decreasing surface runoff) at plot scale and 2) to use the simulation results to determine how frequently to deep chisel in order to maximize the benefits of deep chiseling.

MATERIALS AND METHODS

MODEL DESCRIPTION

The DRAINMOD-K_S-STMAX model, validated using data from artificially drained USDA-ARS Ben Hur Research plots (Moriasi et al., 2007), was used to run model simulation scenarios. To predict the benefits of deep chiseling, two model simulation scenarios were run for a plot under conventional drainage treatment described in the next sub-section. The first scenario consisted of running DRAINMOD-K_S-STMAX model simulations with deep chiseling algorithms switched off (ICHIS = ICHK = 0, table 2), which is equivalent to running DRAINMOD 5.1 without the modifications. The second scenario, involved running DRAINMOD-K_S-STMAX model simulations with deep chiseling algorithms switched on (ICHIS = ICHK = 1, table 2). The differences between the predicted infiltration,

Table 1. Excerpt of DRAINMOD-Ks and DRAINMOD-STMAX model output files – Test8.CHK and Test8.CHS

```
*            DRAINMOD-Ks                  *               *             DRAINMOD-STMAX                     *
-----------------------------------------------------------------------------------------------------------------
   * Copyright 1980-99 North Carolina State University *     * Copyright 1980-99 North Carolina State University *
   BENHUR - CONVENTIONAL DRAINAGE (05-05-2003)               BENHUR - CONVENTIONAL DRAINAGE (05-05-2003)
            1994-2000 DRAINMOD-Ks                                     1994-2000 DRAINMOD-STMAX
   ********************************************              ********************************************
      Cum rainfall on chiseling day (cm)=   .00              -----------RUN STATISTICS --------    time:  8/6/2004  @  3:59
         TODAYS RAIN       CURRENT Ks                                     input file:   Test8.prj
            (cm)              (cm/h)                          ********************************************
             .00               2.00                          No. of Days Since Chiseling       STMAXC (cm)
 CURRENT GREEN AMPT INFILTRATION PARAMETERS TABLE             ************************       **************
              W.T.D.       A         B                                  0                       1.25
               (cm)   (cm^2/h)   (cm/h)                                 1                       1.24
               .000      .000      2.000                                2                       1.22
             30.000     2.000      2.000                                3                       1.21
             60.000     2.660     1.330                                 4                       1.20
            120.000     3.720     1.330                                 .                        .
            150.000      .130      .030                                 .                        .
            500.000      .130      .030                                 .                        .
           1000.000      .130      .030                                141                       .31
      Current WTD    Interpol A    Interpol B                          142                       .31
          (cm)       (cm^2/h)      (cm/h)                              143                       31
          111          3.56          1.33                              144                       .30
      Cum rainfall since chiseling (cm)=    .00                        145                       .30
     Cum rainfall since chiseling (cm)=   28.88                         .                        .
         TODAYS RAIN       CURRENT Ks                                   .                        .
             (cm)             (cm/h)                                    .                        .
             1.02              1.13                                    281                       .14
 CURRENT GREEN AMPT INFILTRATION PARAMETERS TABLE                      282                       .14
              W.T.D.        A        B                                 283                       .14
             (cm)     (cm^2/h)    (cm/h)                               284                       .14
             .000        .000       1.130                              285                       .14
             30.000      1.130      1.130                               .                        .
             60.000     2.260      1.130                                .                        .
            120.000      3.170      1.130                               .                        .
            150.000      4.980      1.130                              416                       .11
            500.000      4.980      1.130                              417                       .11
           1000.000     4.980      1.130                               418                       .11
      Current WTD    Interpol A    Interpol B                          419                       .11
          (cm)       (cm^2/h)      (cm/h)                              420                       .11
            0           .00           .00                               .                        .
      Cum rainfall since chiseling (cm) = 29.90                         .                        .
     Cum rainfall since chiseling (cm) = 175.29                         .                        .
         TODAYS RAIN        CURRENT Ks                                  .                        .
               (cm)         (cm/h)                                      .                        .
               7.90           .51                                       .                        .
 CURRENT GREEN AMPT INFILTRATION PARAMETERS TABLE                       .                        .
              W.T.D.        A        B                                  .                        .
             (cm)      (cm^2/h)  (cm/h)                                 .                        .
              .000        .000      .400                                .                        .
             30.000      .400      .400                                 .                        .
             60.000      .800      .400                                 .                        .
            120.000     1.120      .400                                 .                        .
            150.000     1.760      .400                                 .                        .
            500.000     1.760      .400                                 .                        .
           1000.000     1.760      .400                                 .                        .
      Current WTD     Interpol A    Interpol B                          .                        .
          (cm)        (cm^2/h)      (cm/h)                              .                        .
           12           .16           .40                               .                        .
     Cum rainfall since chiseling (cm)=  183.18                        454                       .10
```

Table 2. DRAINMOD input parameters for hydrologic predictions at Ben Hur Research site, Louisiana.

DRAINMOD Variable Name	Parameter Description	Input Value
SDRAIN	Distance between drains (cm)	1500.0
DDRAIN	Depth to drain (cm)	120.0
EFFRAD	Effect radius of drain (cm)	0.50
DC	Drainage coefficient (cm day^{-1})	
STMAX	Maximum depressional storage or maximum depth of surface ponding (cm)	0.10
HDRAIN	Effective depth from drain to impermeable layer (cm)	26.4
	Additional inputs for DRAINMOD-K_s-STMAX	
ICHIS	STMAX algorithm flag	0 = no deep chiseling, 1 = deep chiseling
ICHIK	K_s algorithm flag	0 = no deep chiseling, 1 = deep chiseling
IYDARCS	Year when deep chiseling was done	1995 and 1996
JCHIS	Julian date when deep chiseling was done	271 for 1995 and 327 for 1996
IYDARCE	Year when deep chiseling was ended, just before the next deep chiseling	1996 and 1997
JCHIE	Julian date when deep chiseling was ended	326 for both 1996 and 1997
Amaxs	STMAX equation exponent (day^{-1})	0.012
MAXSTI	Initial (starting) STMAX (cm)	1.25
MAXSTF	Final (starting) STMAX (cm)	0.10
aKs	K_s equation exponent (cm^{-1})	0.03
Ksi	Initial (just after deep chiseling) K_s (cm h^{-1})	2.00
Ksf	Final (just before deep chiseling) K_s (cm h^{-1})	0.50

sub-surface drainage, and surface drainage with and without deep chiseling algorithms, respectively, were expressed as a percent of the predicted simulation results without deep chiseling algorithms.

The effects/benefits of deep chiseling were considered finished when the current K_s had decreased to a value equal to K_s just before deep chiseling the plots or its final steady state value. The decrease in STMAX was not used to determine when the benefits of deep chiseling were completed because STMAX is a function of number of days (Moriasi et al., 2007) and not a function of cumulative rainfall amount and intensity since deep chiseling as well. The percentage by which K_s had decreased since deep chiseling was computed in this study as follows:

$$PDK_s = \left(\frac{K_{si} - K_{st}}{K_{si} - K_{sf}} \right) * 100 \tag{1}$$

where PDK_s is the percent decrease in K_s as a function of cumulative rainfall since deep chiseling (%), K_{st} is the current K_s (cm h^{-1}) for top soil layer (layer 1), K_{si} is layer 1 K_s immediately following deep chiseling or initial K_s (cm h^{-1}), K_{sf} is an asymptotical final K_s for layer 1 (cm h^{-1}). The value of K_{st} at planting time was used to calculate the percent decrease in K_s at corn planting and hence determine the remaining deep chiseling benefits. The planting dates were 29 March 1996 and 22 April 1997.

RESEARCH SITE DESCRIPTION

This simulation study was conducted using information from a Commerce silt loam [Aeric Fluvaquent, fine-silty, mixed, nonacid, thermic] soil at the USDA-ARS Ben Hur Research Site located on the LSU Ag Center Central Station, 5 km south of Baton Rouge, Louisiana. The soil texture properties of Commerce silt loam are given in table 3. The site is composed of 16 (0.2 ha) 0.15-mm polyethylene subsurface barrier bordered field plots (fig. 2) 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 0.2% slope perpendicular to and 0.2% slope parallel to the direction of the subsurface drainage flow (Fouss and Willis, 1990). The water management treatments evaluated in these plots were: (1) surface drainage only, (2) conventional sub-surface drainage at a depth of 120 cm, (3) controlled water table at 45 ± 5 cm depth, and (4) controlled water table at 75 ± 5 cm depth (Fouss and Willis, 1990).

This study was conducted on a plot with conventional sub-surface drainage treatment. Conventional sub-surface drainage treatment refers to a treatment in which water is drained only when the water table rises above the pipe/drain/tile depth. In this case, water continues to be drained from the soil profile until the water table falls to the bottom of the drain/tile depth when drainage stops. Although there were 6.5 years of data at the time of this study, only weather data for the periods 28 September 1995 to 21 November 1996 and 22 November 1996 to 22 November 1997, when deep chiseling was done in Ben Hur Research site, were used for simulations. Moriasi et al. (2007) observed that on some days, instrumented surface runoff measurements were higher than recorded rainfall, 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 backup of drainage water at the outlet thus not allowing discharge, or datalogger problems. Data collected during such days were discarded and not used in the simulation scenarios. Therefore, there were 24 days of data available for analysis for the 1995-1996 period and 35 days for the 1996-1997 period (Moriasi et al., 2007) and these were the only data sets used in this study.

Table 3. Soil texture properties for Commerce silt loam at Ben Hur Field Site (from Kornecki and Fouss, 2001).

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil Type Classification
0-28	36	37	27	Clay loam
28-74	50	37	13	Silt loam
74-153	50	40	9	Loam

MODEL INPUTS

Based on the soil, weather, and cropping information for Ben Hur Research site, the DRAINMOD-K_S-STMAX model was used to simulate surface runoff, infiltration, and subsurface drainage. In addition to inputs for the DRAINMOD model, which include soil properties, drainage design parameters, weather data, and crop yield parameters, the DRAINMOD-K_S-STMAX model requires several new inputs. These include initial layer 1 K_s (K_{si}) measured immediately following deep chiseling, layer 1 final steady state K_s (K_{sf}) measured just before the next deep chiseling operation, a model exponent which is a function of soil texture, deep chiseling dates (beginning and ending year and date), initial and final steady state STMAX, and STMAX model exponent which is a function of soil type and tillage operation. The saturated hydraulic conductivity values for the Commerce silt loam soil at Ben Hur Research site are presented in table 4. Other model input parameters for this research site are listed in table 2. The values listed in table 2 were chosen from the initial calibration of DRAINMOD by Fouss et al. (1987), the STMAX values determined by Moriasi et al. (2007), and the K_S values determined by Moriasi et al. (2007) using the K_S data measured by Moriasi (2004) at the USDA-ARS Ben Hur research site using the double-ring infiltrometer method (Bouwer, 1986). Both K_S and STMAX parameter values are a function of soil and tillage operation type. Since parameter values were determined for the Commerce silt loam soil and deep chiseling, Moriasi et al. (2007) validated DRAINMOD-K_S-STMAX using these parameter values and those of the previously calibrated DRAINMOD (Fouss et al., 1987). The validated DRAINMOD-K_S-STMAX model for Ben Hur site was used in this simulation study to predict the benefits of deep chiseling.

The vertical saturated hydraulic conductivity (K_S) can be measured using the double ring infiltrometer method proposed by Bouwer (1986) or any other suitable method. In this method, two concentric double rings are driven several centimeters into the soil. Water is first ponded within the outer ring above the soil surface and then within the inner ring. The outer ring is included to ensure that one-dimensional downward flow exists within the tested horizon of the inner ring. For the constant head measurements, the volumetric rate of water added to the ring to maintain a constant head within the ring is measured. On the hand, for a falling head test, the flow rate is measured by measuring the rate of decline of the water level within the ring. Infiltration is stopped after the flow rate has approximately attained a steady state. Field K_S measurement should be carried out after every significant rain event since deep chiseling and should continue until K_{si} decreases to K_{sf} and the data used to determine the equation exponent (aKs). In cases where long-term measured K_S data are not available, the values of these parameters can be evaluated by calibrating DRAINMOD-K_S-STMAX model, in which simulated

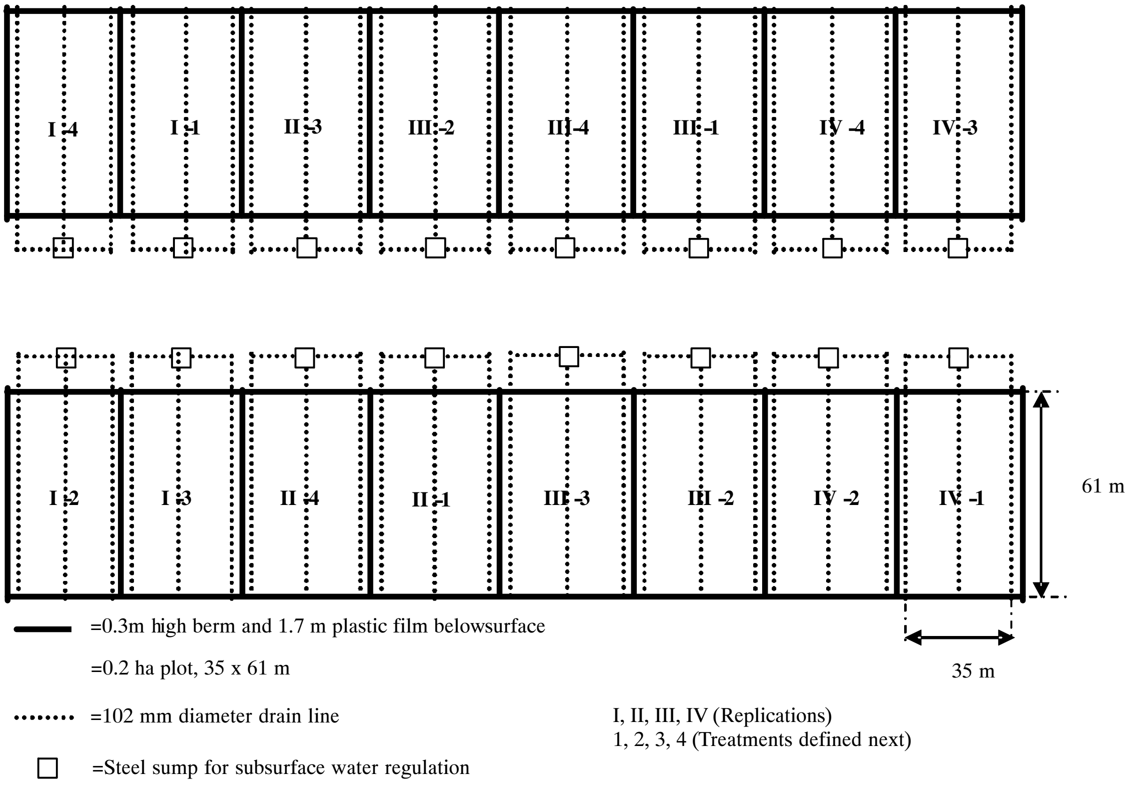

Figure 2. Schematic layout of the Ben Hur Field Site located 5 km south of Baton Rouge, Louisiana. Construction site was completed in 1993 and data collection began in 1995 (from Fouss and Willis, 1990).

Table 4. Measured saturated hydraulic conductivity for Ben Hur (K_{sat}) (from Fouss et al., 1987).

Layer	Depth (cm)	K_{sat} (cm h^{-1})
1	0 to 50	1.00
2	50 to 80	4.00
3	80 to 120	4.00
4	120 to 146	1.00

runoff and drainage are compared with the measured runoff and drainage data for a particular tillage operation period.

RESULTS AND DISCUSSION

QUANTIFYING THE BENEFITS OF DEEP CHISELING

Comparing simulated infiltration, subsurface drainage, and surface runoff, using the calibrated and validated DRAINMOD-K_s-STMAX model with and without the deep chiseling algorithms, respectively, it was determined that deep chiseling increased the predicted cumulative infiltration (CI) by 16% and reduced the predicted cumulative runoff (CRO) and cumulative subsurface drainage (CSD) by 37% and 26%, respectively, between September 1995 and November 1996 (table 5). Between November 1996 and November 1997 deep chiseling operation increased the predicted CI and CSD by 9% and 17%, respectively, and reduced the predicted CRO by 22% (table 5).

A closer look at the surface drainage results indicates a decrease in CSD between September 1995 and November 1996 (-26%) compared to an increase between November 1996 and November 1997 (17%).The cumulative rainfall for 1995-96 and 1996-97 periods were 1880 and 1840 mm, respectively, both of which were greater than long-term annual average of 1500 mm (Fouss et al., 1987). However, Moriasi et al. (2007) found that DRAINMOD-K_s-STMAX under-predicted cumulative surface runoff between September 1995 and November 1996 period. According to Moriasi et al. (2007), leveling/grading operations carried out on the research plots between mid and end of February 1996, could have reduced both STMAX and K_s of the top soil layer. Therefore, the decreasing exponential DRAINMOD-K_s-STMAX model computed and used higher K_s and STMAX values than the actual values after the plots had been graded, which could lead to underprediction of the overall cumulative surface runoff by DRAINMOD-K_s-STMAX between September 1995 and November 1996.

This underprediction of surface runoff could explain the unrealistic reduction in CSD (-26%) between September 1995 and November 1996 compared to the expected increase in CSD (17%) between November 1996 and November 1997 as a result of higher STMAX and K_s values due to deep chiseling. The same underprediction could explain the much higher percent surface runoff reduction (-37%) between September 1995 and November 1996 compared to the period between November 1996 and November 1997 (-22%) and the modest differences in the predicted increase in CI between September 1995 and November 1996 (16%) and between November 1996 and November 1997(9%).

Although there were no field measurements to compare with the predicted results from this study, the predicted surface runoff during the two time periods were modest compared to the measured runoff reported by other studies on the same soil in the same area (Bengtson et al., 1995; Grigg et al., 2003). Grigg et al.'s (2003) research results for the year 1995-1996 showed that subsurface drainage, measured 3 to 5 months after deep chiseling a southern alluvial soil, did not significantly reduce surface runoff. These results were in contrast to the results by Bengtson et al. (1995) who reported that subsurface drainage reduced surface runoff on the same alluvial soil, with the only difference being that Bengtson et al. (1995) deep chiseled their fields and began collecting data immediately after deep chiseling, which could explain the difference. If we take Grigg et al.'s (2003) result to represent modeling results with the flag set to zero (0) when deep chiseling was not carried out and Bengtson et al.'s (1995) to represent model output when flag is set to one (1) and when deep chiseling was carried out, the difference signifies the benefits of deep chiseling with regards to surface runoff reduction. In 1995 surface runoff reduction was 35% (Bengtson et al., 1995) and further research by Bengtson and Carter (2004) showed a reduction of 29% in surface runoff on subsurface drained fields. These reported results show that the surface runoff reductions predicted by the model (37% and 22%) and the model predictions for CI and CSD are modest.

FREQUENCY AND TIMING OF DEEP CHISELING

All deep chiseling effects/benefits, predicted by DRAINMOD-K_s-STMAX (Moriasi et al., 2007), were considered complete when K_s decreased to K_{sf}, in this case 0.5 cm h^{-1}. The K_s value decreased from K_{si} to within 1% of K_{sf} after about 150 cm of cumulative rainfall since deep chiseling. Between September 1995 and November 1996 deep chiseling benefits were hardly evident in the simulated

Table 5. Predicted benefits of deep chiseling. [a]

September 1995 to November 1996						
Deep chiseling flag (ICHIS and ICHIK)	CI (cm)	CRO (cm)	CSD (cm)	% IC	% ROC	%SDC
0 (without deep chiseling algorithms - equivalent to DRAINMOD 5.1)	54.65	26.28	17.10	16	-37	-26
1 (with deep chiseling algorithms -- DRAINMOD-K_s-STMAX)	63.23	16.50	12.69			
November 1996 to November 1997						
Deep chiseling flag (ICHIS and ICHIK)	CI (cm)	CRO (cm)	CSD (cm)	% IC	% ROC	%SDC
0 (without deep chiseling algorithms - equivalent to DRAINMOD 5.1)	83.22	33.86	18.80	9	-22	17
1 (with deep chiseling algorithms -- DRAINMOD-K_s-STMAX)	90.53	26.55	21.95			

[a] CI is cumulative infiltration, CRO is cumulative runoff, CSD is cumulative subsurface drainage, % IC, % ROC, and % SDC are differences between the predicted infiltration, runoff, and subsurface drainage using DRAINMOD-K_s-STMAX with and without deep chiseling algorithms, respectively, expressed as a percent of predicted results without deep chiseling algorithms.

Table 6. Determination of frequency and timing of deep chiseling for Commerce silt loam - September 1995 to November 1996 and November 1996 to November 1997.

September 1995 to November 1996				November 1996 to November 1997			
Date	Cum. Rainfall (cm)	K_S (cm/h)	% K_S Decrease	Date	Cum. Rainfall (cm)	K_S (cm/h)	% K_S Decrease
09/28/95	0.00	2.00	0	11/22/96	0	2.00	0
10/14/95	12.10	1.54	30	12/18/96	10.24	1.60	26
11/02/95	28.88	1.13	58	01/22/97	23.07	1.25	50
12/06/95	36.31	1.00	66	02/12/97	37.00	0.99	67
12/08/95	51.98	0.81	79	02/25/97	47.26	0.86	76
01/24/96	58.06	0.76	82	04/04/97	55.97	0.78	81
02/28/96	71.58	0.67	88	**04/22/97**	**63.90**	**0.72**	**85**
03/29/96	**75.13**	**0.65**	**90**	04/26/97	69.54	0.68	88
04/13/96	80.29	0.63	91	05/15/97	80.96	0.63	91
04/24/96	92.71	0.59	94	05/24/97	92.41	0.59	94
05/30/96	104.55	0.56	96	06/16/97	102.77	0.56	95
06/25/96	114.82	0.54	97	06/17/97	114.96	0.54	97

data approximately nine months after deep chiseling (table 6). Similarly, between November 1996 and November 1997, there were virtually no deep chiseling benefits after seven months (table 6). This implies that farmers would need to deep chisel once every year for wet areas such as Louisiana where average annual rainfall is about 150 cm.

These results revealed that the length of time when one can benefit from deep chiseling a field depends on the prevailing weather conditions. During wet years (>100 cm) this translates to deep chiseling once every year whereas in dry years (<100 cm), deep chiseling carried out once every two or more years. This recommendation compares well with the deep chiseling frequency of once every one to two years practiced by Bengtson et al. (1995) based on experience. Therefore, this modeling tool provides a scientific basis for making deep chiseling frequency decisions based on optimum benefits depending on the prevailing weather.

The data indicated in bold in table 6 illustrate the predicted deep chiseling benefits at the time of planting. Based on the decrease in the K_S, 90% of the predicted deep chiseling benefits had been lost by planting date during the period beginning September 1995 to November 1996. For the period beginning November 1996 to November 1997, 85% of the predicted deep chiseling benefits had been lost by planting date. These loses are due to surface seal formation caused by high intensity rainfall on Commerce silt loam soil and hardpan formation due to both traffic compaction and natural consolidation of this soil.

The difference in the percent decrease of K_S between the two periods could have been due to the differences in cumulative rainfall at planting time and also due to the differences in planting dates. Generally, the closer the deep chiseling date is to planting date, the smaller the loss of the deep chiseling benefits. Therefore, it is very important for producers to deep chisel their fields as close to planting time as possible in order to obtain maximum benefits of deep chiseling.

SUMMARY AND CONCLUSIONS

Deep chiseling a subsurface drained Commerce silt loam soil increased the predicted cumulative infiltration by 16% and reduced predicted cumulative runoff and cumulative subsurface drainage by 37% and 26%, respectively, between 28 September 1995 and 21 November 1996. Between 22 November 1996 and 22 November 1997, deep chiseling increased predicted cumulative infiltration and cumulative subsurface runoff by 9% and 17%, respectively, and reduced cumulative runoff by 22%. Ninety-nine percent of the benefits, resulting from deep chiseling due to increased K_S, are lost after 150 cm of rainfall since deep chiseling. For high rainfall states like Louisiana with annual rainfall often exceeding 150 cm (Fouss et al., 1987) this translates to deep chiseling once every year whereas in dry states (<100 cm of rainfall per year) deep chiseling can be done once every two to three years depending on the amount of rainfall.

Depending on the amount of rainfall after deep chiseling and the time elapsed from deep chiseling to the planting season, farmers could lose up to 85% or more of the maximum deep chiseling benefits. Because of great rainfall variability in Louisiana and other southern states (Keim and Faiers, 1996; Bengtson and Carter, 2004), it is advisable for farmers to deep chisel their fields just before the planting period of the season.

Results of this modeling study indicate that the DRAINMOD-K_S-STMAX model has potential to be used as cost-effective (saving time and money) tool 1) to predict the effects/benefits of deep chiseling in poorly drained soils with artificial drainage and 2) to determine the frequency and timing of deep chiseling based on science. However, the model needs to be tested on a field-scale, for longer time periods, and under different climatic conditions and soil types before it can be recommended for general application to predict the benefits of deep chiseling and determine the frequency and timing of deep chiseling. In addition, the STMAX algorithm needs modifications to allow STMAX to change as a function of cumulative rainfall amount and intensity since deep chiseling. Finally, a simple cost-benefit-analysis algorithm could be added to DRAINMOD-K_S-STMAX to determine the benefits of deep chiseling in monetary terms to encourage farmers to adopt or accept the results of the deep chiseling recommendations.

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