# Modeling of Subsurface Tile Drainage using MIKE SHE

X. Zhou, M. Helmers, Z. Qi

**Abstract.** *Accurate estimation of subsurface drainage flow is essential for effectively evaluating the performance of management strategies in tile-drained landscapes. The objectives of this study were to calibrate and validate MIKE SHE for simulating subsurface tile drainage flow in central Iowa and to evaluate the simulated impact of two specific management strategies on tile flow. The model was calibrated and validated using the measured daily drainage in a 15.2 × 38 m row-cropped plot during 2006-2009 with a split-sample method. Drainage time constant and macropore flow were found to be important in predicting drainage flow. The calibrated drainage time constant of 5.6 h was outside the recommended range, which might be attributed to the shorter response time of subsurface flow at the plot scale used in this study. The calibrated model showed a satisfactory performance in simulating daily tile drainage flow with Nash-Sutcliffe model coefficient values of 0.78 and 0.73 for the calibration and validation periods, respectively. The measured and predicted total drainage from 2006-2009 were 865 and 958 mm, respectively. The results suggest that MIKE SHE has potential for predicting tile drainage flows; guiding management decisions and for assessment of drainage design of water flow to downstream water bodies.*

**Keywords.** *Water management, Drainage time constant, Macropore flow.*

Artificial subsurface drainage systems, primarily tile drains, have been widely used in Iowa and the Midwest United States to remove excess water from agricultural fields for improving the productivity of poorly drained soils. In Iowa, approximately 3.6 million ha of cropland are artificially drained, accounting for more than 25% of the state's agricultural land (Baker et al., 2004). Subsurface drainage allows for greater soil aeration, possibly earlier planting, and better field conditions for crop growth and field operations.

The overall environmental impact of artificial subsurface drainage systems continues to generate significant discussion. Subsurface drainage has the potential to reduce surface runoff and associated loss of surface runoff pollutants including sediment and chemicals (Bengtson et al., 1995; Skaggs et al., 1995). In comparison with undrained soils in the United States, Skaggs et al. (1994) estimated that subsurface drainage reduced surface runoff by 34% to 55%, by altering hydrology through changes in infiltration rate (Shipitalo et al., 2004), water storage capacity (Irwin and Whitely, 1983), soil structure (Gardner et al., 1994), and subsurface water pathways (Gardenas et al., 2006). Tile drained soils can also act as a buffer for rainfall and thus significantly reduce peak flow volumes (Skaggs and Broadhead, 1982). On the other hand, during the last decade there has been increased concern on the role of artificial subsurface drainage in flood generation and pollutant transport. There has been an increased frequency of severe river floods in the Midwest and other states in the United States during the past decades (Karl et al., 2009). A number of factors, such as climate change, aggressive tillage operations, and changes in land use and cropping systems, could be responsible for the changes in flood behavior. However, it is widely recognized that a better understanding of the role of subsurface drainage in flood behavior is critical (Wiskow and van der Ploeg, 2003), particularly in the tile-drained Corn Belt area. Furthermore, subsurface drainage provides a major transport pathway for soluble agricultural chemicals such as nitrate, which has been identified as a major contributor to the hypoxic zone in the Gulf of Mexico (Rabalais et al., 2001). Generally, nitrate loss increases as subsurface drainage flow volume increases (Cambardella et al., 1999; Kanwar et al., 2005). Therefore, characterizing the response of subsurface drainage flow to precipitation is essential for understanding the hydrologic footprint of land management practices in the Midwest United States.

Field monitoring of subsurface drainage flow is generally expensive and hence many subsurface drainage systems are ungaged. Alternatively, hydrologic models have been developed to simulate underlying hydrological processes and provide a quantitative estimation of drainage discharge. Examples of these models are DRAINMOD, ADAPT, and MIKE SHE. The European Hydrological System model or MIKE SHE was developed by three

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European Organizations (Danish Hydraulic Institute, British Institute of Hydrology, and the French consulting company SOGREAH) and has been successfully applied in various hydrologic studies, including irrigation planning and management of water resources (Singh et al., 1997), groundwater management (Demetriou and Punthakey, 1999), floodplain studies (Jaber and Shukla, 2005), and land planning and management (Thompson et al., 2004; Helmers et al., 2005).

Application of MIKE SHE to subsurface drainage is limited compared to its application in surface hydrology. The impact of subsurface drainage on pumped discharge and soil moisture storage was simulated at a small agricultural catchment in the United Kingdom using the MIKE SHE model (Al-Khudhairy et al., 1999). They found that theoretically removing subsurface drainage increased the magnitude of flood peaks during the spring recession but reduced annual discharges. These findings are consistent with DRAINMOD studies which have generally found that increased subsurface drainage intensity increases annual discharge from drained catchments (Konyha et al., 1992). Feyen et al. (2000) calibrated and validated MIKE SHE using daily discharge of a 600 km$^2$ catchment in Belgium. They found that the drainage time constant, a key parameter for subsurface drainage, influenced the peaks of the hydrograph, while the drainage depth had a less pronounced effect on streamflow discharge. This was in agreement with the findings of another study in a tropical mountainous watershed (Sahoo et al., 2006). In all of those studies, however, the MIKE SHE model was calibrated and validated against stream discharge at watershed outlets, and the component of subsurface drainage was incorporated in the model mainly for the purpose of better correlation between the observed and predicted discharges. Consequently, subsurface drainage discharge was not directly measured and could not be compared to model predictions during calibration and validation. Thus, little is known about the accuracy of subsurface drainage predictions of MIKE SHE. Iowa soils are extensively tile drained; there is a clear need to assess the performance of MIKE SHE for simulating subsurface drainage flow. The objectives of this study are: (1) to calibrate and validate MIKE SHE for predicting subsurface drainage flow within a row-cropped setting in central Iowa, and (2) to evaluate the impact of management strategies, including converting row-crops to pasture or adopting shallow drainage, on subsurface drainage flow using MIKE SHE.

# METHODS

## SITE DESCRIPTION

The study location is at the Agricultural Drainage Water Quality - Research and Demonstration Site (ADWQ-RDS) in Pocahontas County, north central Iowa. It is within the Des Moines Lobe region (MLRA 103), which is a nearly level to gently rolling till plain. Subsurface drainage tiles have been widely installed to lower the water table during the spring in this region. Corn and soybeans are the major crops, with some cropland used for hay. The glacial till soils of the ADWQ-RDS are naturally poorly to somewhat poorly drained.

This research site was established in the late 1980s for a long-term drainage and nutrient management study. The total research area is 4.5 ha with slopes varying between 0.5% and 1.5%. There are a total of 73 individually drained plots at the site. The size of each plot is 38 m in length and 15.2 m in width. At each plot, corrugated plastic drain tiles were installed in 1988 at the center and plot borders parallel to the long dimension (7.6 m spacing) at a depth of 1.06 m. Lateral subsurface flow from adjacent plots was minimized by installing two border drains, which have an outlet to the surface at a remote location. Drainage flow was monitored in the center drainage line of each plot using an automatic pumping and volume monitoring system. The tile flow was generally monitored from April to November to avoid damage during freezing conditions in the winter. More details of the tile drainage design can be found in Lawlor et al. (2008).

Plot No. 7-1 was selected for modeling subsurface tile drainage to minimize the lateral effect from neighboring plots, due to its relatively higher elevation and being separated from the upper land by an open ditch. The predominant soil in this plot is Canisteo clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls). The slope of the plot is about 1% in the north-south direction (parallel to tile lines) and nearly flat in the east-west direction. A 2-m digital elevation model (DEM) was created from the LiDAR data of the study area using ArcGIS (ESRI, Redlands, Calif.) to represent the topography of the plot.

## THE MIKE SHE MODEL

The MIKE SHE model is a deterministic, fully distributed and physically-based model that allows for simulation of the major processes occurring in the land phase of the hydrologic cycle (Refsgaard and Storm, 1995; DHI, 2004). It is a computationally intensive model simulating surface, subsurface, and stream flow separately for distributed grid-points using numerical solutions of partial differential equations. The model's distributed nature allows for spatially varying climate variables, vegetation, soil properties, and land uses. MIKE SHE has a module structure consisting of several modules such as the Water Movement (WM) module, Advection/Dispersion of Solutes (AD) module, and Soil Erosion (SE) module, and other modules.

The WM module used in this study consists of several components to represent the major physical processes of the hydrological cycle. These include interception/evapotranspiration, overland and channel flow, unsaturated zone, saturated zone, and snowmelt. The interception/evapotranspiration processes are calculated using meteorological and vegetative data based on the Kristensen-Jensen method (1975). The potential evaporation rate is required as input data to calculate actual evapotranspiration. The 1-D channel flow and 2-D overland flow are modeled using a finite difference approximation of the Saint Venant equations. MIKE SHE uses the 1-D Richards' equation for unsaturated zone flow and the 3-D

Boussinesq equation for saturated zone flow. In MIKE SHE, snowmelt is calculated using the empirical degree-day approach.

## MODEL CONSTRUCTION

### *Meteorological Data*

Rainfall intensity and reference evapotranspiration ($ET_0$) were required by MIKE SHE as climate input data. The 5-min meteorological data including rainfall, air temperature, solar radiation, relative humidity, and wind speed were collected from an automatic meteorological weather station at the study site. An additional tipping-bucket rain gauge (Campbell Scientific, Inc., Logan, Utah) was installed at the site as a backup system. The FAO Penman-Monteith method was used to estimate $ET_0$ (FAO, 1998). Snow data was also obtained from the National Climate Data Center (NCDC) station. In MIKE SHE, the degree-day coefficient and threshold melting temperature were set to 2 mm/day/°C and 0°C, respectively. The 30-year (1971-2000) normal precipitation for Pocahontas County was calculated based on the records from the NCDC station at Humboldt, Iowa, located 15 km to the east of the site.

### *Land Use*

A corn-soybean rotation system was implemented at the modeling plot, with corn planted in odd years (2005, 2007, and 2009) and soybean in even years (2006 and 2008). Since 2004, rye (*Secale cereale*) was planted each year as a winter cover crop to reduce soil and nutrient loss, and was killed in the spring of the following year. Glyphosate resistant corn (*Zea maize*) and soybean (*Glycine max*) were planted after the growth of rye was terminated by glyphosate in early spring. The plot was fall disked and field cultivated before drill-seeding rye.

Evapotranspiration parameters are required for each crop to estimate the actual evapotranspiration (table 1). The leaf area index (LAI) was measured by an AccuPAR/LAI ceptometer (Decagon Devices, Inc., Pullman, Wash.). The reported values from literature were adopted for the root depth (RD) (Oogathoo, 2006) and crop coefficient (Kc) (Al-Kaisi, 2000). The MIKE SHE recommended values were used for the evapotranspiration parameters for the Kristensen and Jensen model.

### *Overland Flow*

The overland flow was found to be sensitive to the Manning's number (M), which is the reciprocal of Manning's roughness coefficient (n). A higher value of M leads to faster overland flow and thus lower subsurface drainage flow. A value of 0.16 was recommended for Manning's n on cropland with a disk tillage system (Engman, 1986), which is equivalent to 6.0 for Manning's M. The Manning's M was subjected to calibration in this study. Considering the small and flat study area, the impact of depression storage depth on surface runoff and drainage flow was relatively small and was set to 0.

### *Unsaturated Zone*

Undisturbed soil cores at various depths (0-10, 10-20, 20-30, 30-40, 40-60, 60-80, and 80-100 cm) were collected at the modeling plot to determine soil properties, including bulk density, particle size distribution, and saturated hydraulic conductivity (table 2). Other model-required van Genuchten parameters were estimated by the neural network program in the Rosetta model for each soil layer using the measured soil texture and bulk density of each depth (Schaap et al., 2001).

Flow through macropores in unsaturated soil is important for water and solute transport, occurring primarily in wet conditions. Macropore flow was simulated in MIKE SHE using the simple bypass flow method (DHI, 2004). In this method, the actual bypass flow is a function of a user-specified maximum fraction, the minimum water content allowing for bypass flow, and the actual water content of the unsaturated zone. The bypass flow parameters were subjected to calibration.

### *Saturated Zone*

Vertical and horizontal saturated hydraulic conductivities in the saturated zone substantially influence the characteristics of streamflow and base flow. In the absence of field-measured data, the sensitivity of tile drainage flow to saturated hydraulic conductivities in the saturated zone was investigated (table 3). The depth to the impermeable layer was set to 3.9 m for the study site (Singh et al., 2006).

The subsurface tile drainage system was included as a component of the saturated zone at a depth of 1.06 m below

**Table 2. Soil properties of the study site.**

| Depth (cm) | BD[a] (g cm$^{-3}$) | Sand (%) | Silt (%) | $K_{sat}$ (cm h$^{-1}$) | $\theta_r$ (cm$^{-3}$ cm$^{-3}$) | $\theta_s$ (cm$^{-3}$ cm$^{-3}$) |
|---|---|---|---|---|---|---|
| 0-10 | 1.37 | 32 | 36 | 4.8 | 0.071 | 0.482 |
| 10-20 | 1.38 | 32 | 36 | 3.3 | 0.072 | 0.476 |
| 20-30 | 1.39 | 33 | 53 | 5.1 | 0.079 | 0.473 |
| 30-40 | 1.39 | 40 | 30 | 4.1 | 0.072 | 0.474 |
| 40-60 | 1.39 | 46 | 30 | 4.1 | 0.065 | 0.474 |
| 60-90 | 1.45 | 44 | 34 | 2.6 | 0.034 | 0.450 |
| >90 | 1.46 | 44 | 34 | 2.6 | 0.033 | 0.450 |

[a] BD – bulk density, $K_{sat}$ – saturated hydraulic conductivity, $\theta_r$ – residue water content, $\theta_r$ – saturated water content

**Table 1. Evapotranspiration parameters for the simulated crops.**

| Corn | | | | Soybean | | | | Pasture | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Growth Day | LAI[a] | RD (mm) | Kc | Growth Day | LAI | RD (mm) | Kc | Growth Day | LAI | RD (mm) | Kc |
| 1 | 0 | 0 | 0.30 | 1 | 0 | 0 | 0.2 | 0 | 1.0 | 300 | 0.1 |
| 34 | 0.72 | 100 | 0.45 | 20 | 1.00 | 100 | 0.4 | 90 | 1.0 | 300 | 0.3 |
| 78 | 3.45 | 900 | 0.83 | 55 | 6.22 | 800 | 0.9 | 100 | 1.0 | 450 | 0.6 |
| 132 | 3.45 | 900 | 0.55 | 115 | 6.22 | 800 | 1.0 | 120 | 2.5 | 600 | 0.7 |
| 176 | 2.5 | 900 | 0.55 | 143 | 4.22 | 800 | 0.3 | 150 | 4.0 | 700 | 0.9 |
| | | | | | | | | 270 | 4.0 | 700 | 0.9 |
| | | | | | | | | 330 | 2.0 | 300 | 0.7 |
| | | | | | | | | 365 | 1.0 | 300 | 0.1 |

[a] LAI – leaf area index, RD – root depth, Kc – crop coefficient.

**Table 3. Parameters calibration for tile drainage flow.**

| | Calibration Range | Final Value |
|---|---|---|
| Manning's number ($m^{1/3}$ $s^{-1}$) | 4.0 – 12.0 | 6.0 |
| Horizontal hydraulic conductivity (m $s^{-1}$) | $1 \times 10^{-6} - 1 \times 10^{-3}$ | $7.3 \times 10^{-6}$ |
| Vertical hydraulic conductivity (m $s^{-1}$) | $1 \times 10^{-6} - 1 \times 10^{-3}$ | $7.3 \times 10^{-6}$ |
| Drainage time constant (h) | 0.56 - 2784 | 5.6 |
| Macropore flow | | |
| Maximum bypass fraction | 0.30 – 0.80 | 0.50 |
| Water content for reduced bypass flow ($cm^3$ $cm^{-3}$) | 0.25 – 0.45 | 0.30 |
| Minimal water content for bypass flow ($cm^3$ $cm^{-3}$) | 0.15 – 0.35 | 0.20 |

the ground surface. In this model, drain line was set in the center of the plot and a grid code map was created to link the drain flow producing cells to the drain line. So, in the model constructed for these plots the actual drain spacing was used although the center grid that was drained is 2 m wide so wider than the drain. In MIKE SHE, subsurface drainage flow occurs when the water table rises above the elevation of tile drains (fig. 1). The drainage flow rate is computed as a linear reservoir and is proportional to the height of the water table above the drainage depth and the specific drainage time constant:

$$Q = \frac{(h - Z_{dr})}{C_{dr}} \quad (1)$$

where Q (m $s^{-1}$) is the drainage flow rate, h (m) and $Z_{dr}$ (m) are the levels of water table and tile drain, respectively, and $C_{dr}$ (s) is the drainage time constant.

The drainage time constant characterizes the density of the drainage system and the permeability conditions around the drains, and therefore determines the velocity of the drainage. The typical value of the time constant is believed to be between 10 and 120 days (DHI, 2004). However, MIKE SHE is often applied to a much larger watershed size than in this study and no previous calibration has been conducted against observed drainage discharges. Thus, the drainage time constant was subject to calibration for the study plot.

### MODEL CALIBRATION

The years 2004 and 2005 were used as a "warm up period" to establish initial conditions for MIKE SHE. The split-sample calibration-validation method was employed for model calibration and validation. The MIKE SHE model was calibrated against the observed daily tile drainage flow from the monitored plot in 2006 and 2007. Model validation occurred during the following two years (2008 and 2009). To avoid over-parameterization, the number of parameters subjected to adjustment for a distributed model like MIKE SHE should be as small as possible (Regsgaard and Storm, 1995). Therefore, the parameters with measured values such as soil properties and climate data were not calibrated in this study, although subsurface flow may be very sensitive to some of these parameters.

The model performance in simulating subsurface drainage flow was evaluated by both visual comparison of the predicted versus observed hydrographs and some quantitative measures. Two statistical measures were used for quantitative assessment: the Nash-Sutcliffe (NS) model efficiency coefficient (Nash and Sutcliffe, 1970) and coefficient of determination ($r^2$).

$$NS = \frac{\sum(O_i - \overline{O})^2 - \sum(P_i - O_i)^2}{\sum(O_i - \overline{O})^2} \quad (2)$$

$$r^2 = \frac{\left[\sum(O_i - \overline{O})(P_i - \overline{P})\right]^2}{\sum(O_i - \overline{O})^2 \sum(P_i - \overline{P})^2} \quad (3)$$

where $O_i$ and $P_i$ are the observed and predicted values, respectively, and $\overline{O}$ and $\overline{P}$ are the mean observed and predicted values, respectively. It should be noted that the days with zero drainage (observed and predicted) were not included in determining the values of NS and $r^2$.

The NS value varies from -∞ to 1, measuring the goodness-of-fit between the predicted and observed values. The greater the NS value, the better the model's performance. A negative NS value indicates that even simply using the observation mean would be better than the predicted values by the model. The value of $r^2$ was used to validate the best-fit line between the predicted and observed values.

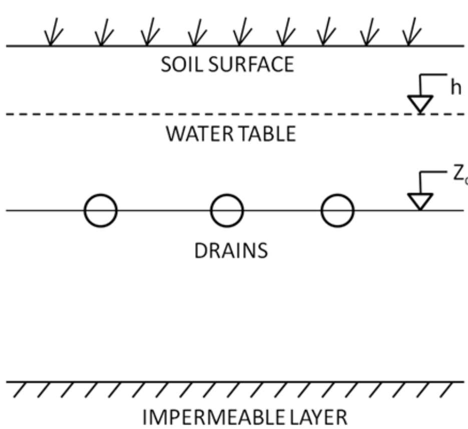


**Figure 1. Schematic representation of the drainage flow computations (Modified from DHI, 2004).**

### MANAGEMENT SCENARIO SIMULATION

Strategic integration of land management practices to conventional row-crop agriculture can enhance long-term soil and water quality. Converting row-crops to perennial vegetation has many beneficial effects including reducing soil erosion and water pollution, while minimizing soil disturbance and chemical use. For extensively tile-drained areas, placing tile drains at shallower depths could minimize subsurface drainage and associated pollutant loss while still maximizing crop production (Sands et al., 2003). These two management scenarios were simulated using the calibrated MIKE SHE model: (1) converting row-crops to pasture, and (2) adopting shallow drainage with a higher drain level of 0.75 m. The crop parameters for pasture including LAI and Kc were adopted from FAO (Allen et al., 1998).

# Results and Discussion

The climate of central Iowa showed a large variability during the study years. The total precipitation at the study site in 2006 was 626 mm representing a “dry” year well below the 30-year (1971-2000) normal annual precipitation of 821 mm in this area. In 2007 and 2008 the total precipitation was 1050 and 926 mm, respectively (table 4; fig. 2), representing “wet” years. The total precipitation in 2009 was 776 mm, which is closer to the long-term normal.

The long-term (1990-2009) average annual drainage during the drainage season (March-November) is 282 mm for this site. Because of the excessive precipitation, the total observed drainage in 2007 and 2008 was 394 and 310 mm, respectively, accounting for about 81% of the total drainage for the entire study period (2006-2009). Most of the drainage occurred in the spring and early summer (April-June) and the fall (September-November) (fig. 2). The wet conditions in the fall of 2007 and the intense precipitation in 2008 led to significant drainage in the spring and early summer of 2008 (table 4). Much less drainage was observed in 2006 and 2009, with only 30 and 134 mm during the monitored period in 2006 and 2009, respectively.

## Model Calibration

Model calibration showed that the subsurface tile drainage discharge simulated by MIKE SHE was insensitive to the Manning’s number and thereby the recommended value (M = 6.0) for a disked crop system was adopted (table 3). This is not surprising considering the small size and low slope of the plot. In such field conditions, overland flow plays a small role compared to subsurface flow and other hydrologic processes; the predicted surface runoff was only 1.2 and 2.3 mm in 2006 and 2007, respectively. Nevertheless, the finding that subsurface drainage was insensitive to the Manning’s number is consistent with the findings of Sahoo et al. (2006); they found that the Manning’s number had more influence on the predicted surface flow than base flow. Changes in horizontal and vertical hydraulic conductivities in the saturated zone also showed little impact on the simulated subsurface drainage. The insensitivity of flow simulation to the hydraulic conductivity could be due to the small plot scale of this study. The effect of soil hydraulic properties has been lumped into the drainage time constant at this scale. Therefore, the value of measured saturated hydraulic conductivity ($7.3 \times 10^{-6}$ m $s^{-1}$) of the soil profile from 80-100 cm was used for both the horizontal and vertical hydraulic conductivities in the saturated zone (table 3).

**Table 4. Annual precipitation and tile drainage flow during April-November in 2006-2009 for study plot.**

| Year | Precipitation (mm) | Measured Flow (mm) | Predicted Flow (mm) |
|---|---|---|---|
| 2006 | 626 | 30 | 37 |
| 2007 | 1050 | 394 | 388 |
| 2008 | 926 | 305 | 328 |
| 2009 | 776 | 136 | 205 |
| Total | 3378 | 865 | 956 |

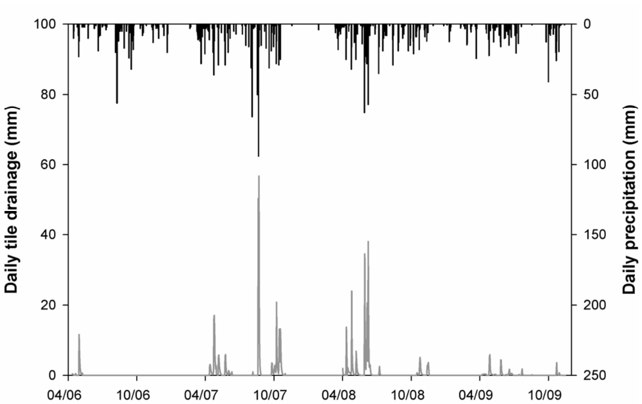


**Figure 2. Precipitation and observed daily tile drainage from April to October during 2006-2009.**

The predicted total drainage discharge during the calibration period was very sensitive to the drainage time constant, while inclusion of macropore flows had greater influence on flow peaks than the total drainage. The impacts of these parameters are described in detail below.

### *Drainage Time Constant*

The drainage time constant ($C_{dr}$) was found to be the most critical parameter when simulating subsurface drainage flow. MIKE SHE lumps the effects of drainage intensity and soil hydraulic properties in drainage time constant, which reflects how fast subsurface water enters into the subsurface drainage system. The influence of the time constant was investigated for values between 0.56 h and 116 days (table 3). As expected, the predicted tile drainage was very sensitive to this parameter, decreasing as the value of $C_{dr}$ increased until it was greater than 56 h (fig. 3). When $C_{dr}$ < 56 h, the predicted total drainage in 2006-2007 kept nearly the same; however, the model had a better performance for predicting individual storm events for a lower value of $C_{dr}$. Generally, the daily tile drainage hydrographs had lower peaks but longer tails for larger values of $C_{dr}$. During the calibration period, both the visual inspection of the drainage hydrographs and the statistical measures suggested that the model had the best performance with a value of $C_{dr}$ equal to 5.6 h.

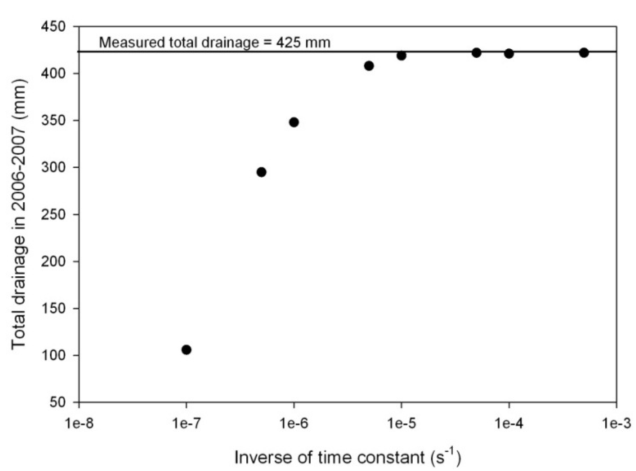


**Figure 3. Impact of the inverse of drainage time constant on drainage flow. The measured total drainage from April to October during 2006-2007 was 425 mm.**

The time constant value determined from this study was well outside the normal range of 10 to 120 days (DHI, 2004). Several causes may account for the smaller time constant in this study. First, the time constant is usually calibrated against surface discharge at the watershed/basin outlet. Subsurface flow after rain storms could move into the groundwater system as baseflow before it recharges to surface flow, and therefore the influence of the drainage time constant on subsurface drainage or interflow may take a longer time to be detected from monitoring surface discharge. Second, model calibrations were usually performed at a watershed or basin-scale rather than the field-scale employed in this study. For example, a time constant of 33 days was obtained for the 440 $km^2$ Karup catchment (Refsgaard, 1997), which is about $10^6$ times greater than the plot size of this study. As a result, a longer travel time of subsurface drainage flowing out of a watershed would be expected for larger watersheds than smaller watersheds. It should be pointed out that in a large watershed usually only a portion of the entire watershed is artificially drained. This may also contribute to a greater time constant in large watersheds than the one obtained in this study.

### *Macropore Flow*

When excluding the macropore flow component from the simulation, the total drainage flow in 2006-2007 was estimated by MIKE SHE to be 422 mm, very close to the measured total flow of 425 mm. However, the peak flows after the large storms were generally underestimated, as illustrated in the daily hydrograph of 2007 (fig. 4). Preferential flows through soil macropores and other preferential pathways facilitate subsurface flow when soils are wet. While the addition of macropore flow in the model did not significantly increase the total predicted drainage (424 mm), it improved the prediction on peak flows by providing shortcut pathways for the movement of surface water to the water table. Al-Khudhairy et al. (1999) also observed an improved fit between measured and simulated discharge during wet conditions after including macropore flow in MIKE SHE. The simulated flow peaks were also sensitive to macropore flow parameters, and optimal values shown in table 3 were determined by a combination of visual inspection and quantitative measures. The maximum bypass fraction, water content for reduced bypass flow, and minimal water content for bypass flow were set to 0.6, 0.3, and 0.2, respectively. A larger bypass fraction or a lower water content threshold value enhanced the contribution of macropore flow to the flow peaks. The less successful prediction of peak flow could also be related to the negligence of non-linearities, which execute more impacts when water tables are high, in the subsurface drainage model of MIKE SHE.

### *Model Evaluation*

Overall, the MIKE SHE model showed a good performance in predicting subsurface tile drainage for the study site, particularly the total drainage and monthly drainage flow (fig. 5). This is especially encouraging considering only two parameters (drainage time constant and macropore flow) were adjusted. The values of NS and $r^2$ for the monthly drainage prediction were 0.97 and 0.98, respectively. Generally, predictions with model efficiency greater than 0.5 indicate a good model performance (Henriksen et al., 2003). The predicted daily drainage flow also matched the measured flow reasonably well. Overall, the MIKE SHE model showed a good performance during the dry periods and small storm events, but underestimated peak discharges during the large storm events (fig. 5). Despite this, the values of NS and $r^2$ were 0.78 and 0.80 for

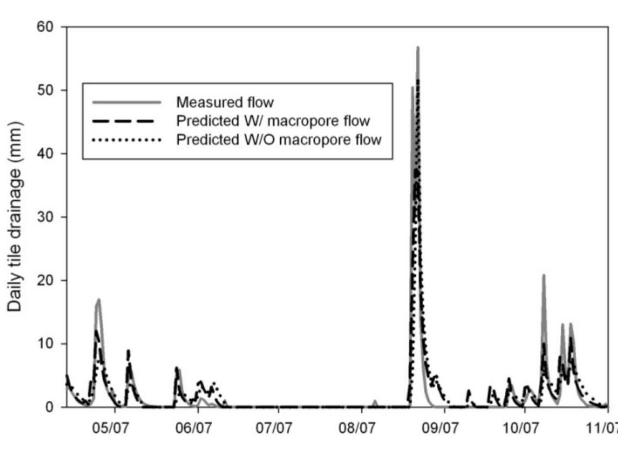


**Figure 4. Impact of macropore flow on daily drainage hydrograph in 2007.**

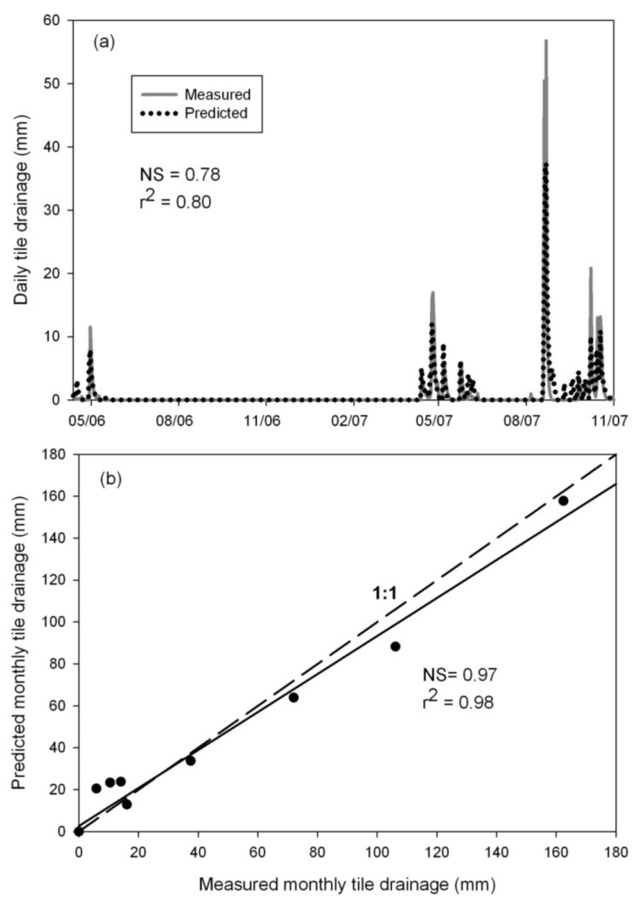


**Figure 5. Measured and predicted (a) daily tile drainage and (b) monthly tile drainage during 2006-2007 for model calibration.**

the prediction of the daily drainage in 2006-2007, respectively.

### Model Validation

The calibrated MIKE SHE model was validated using the daily tile drainage in 2008-2009. Similar to the calibration period, the peaks of large storms in 2008 were somewhat underestimated (fig. 6). However, the model generally overestimated the drainage in 2009, especially for the early summer. In addition, an unobserved peak was also predicted in early April 2008 by the model (fig. 6), possibly because the effect of the winter cover crop on removing excess water during the early spring was underestimated in the model. Nevertheless, the calibrated model had a NS value of 0.73 and $r^2$ of 0.74 for daily drainage prediction and a NS value of 0.76 and $r^2$ of 0.79 for monthly drainage prediction, showing a good performance during the validation period. As in the calibration period, the predicted surface runoff was only 0.5 and 0.2 mm in 2008 and 2009, respectively, due to the flat and rough ground surface of the study site.

### Management Scenarios Simulation

#### *Row-Crops vs. Pasture*

Land use change from row-crops with cover crops to pasture generally reduced subsurface drainage during the simulation period. The increased evapotranspiration predicted by the model may at least partly account for the subsurface drainage reduction (fig. 7). The effect of land use change on drainage was most evident in 2007, which was a wet year, where tile drainage was reduced by 330 mm (table 5). The simulated drainage reduction in 2008 was only 47 mm despite the fact that 2008 was also a wet year with a total drainage of 310 mm during April-November. This might be attributed to the different pattern of rainfall distribution and field conditions between 2007 and 2008. In 2008, most of the high-intensity storms occurred in the spring and early summer, during which the pasture grasses may be using less water. In addition, due to the wet fall and winter of 2007 and the continuous large storms in the spring of 2008, the lasting wet and cold field conditions may minimize the effect of grasses in removing excess precipitation through transpiration. Consequently, the difference of the simulated ET between row-crops and pasture was only 58 mm in 2008, much smaller than the difference in other years (fig. 7b). The reduced tile drainage by land use change was estimated to be 24 mm in the dry year of 2006. In a 6-year study, Randall et al. (1997) found that total tile flow was 1.6 times higher with row crop systems compared to perennial systems.

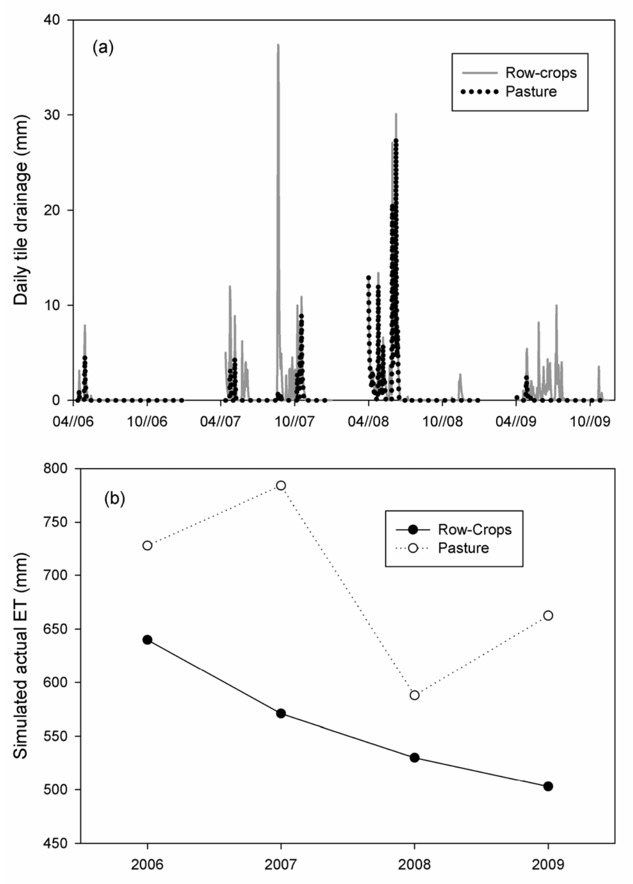


**Figure 7. Simulated (a) daily tile drainage and (b) annual actual ET under row-crops vs. pasture.**

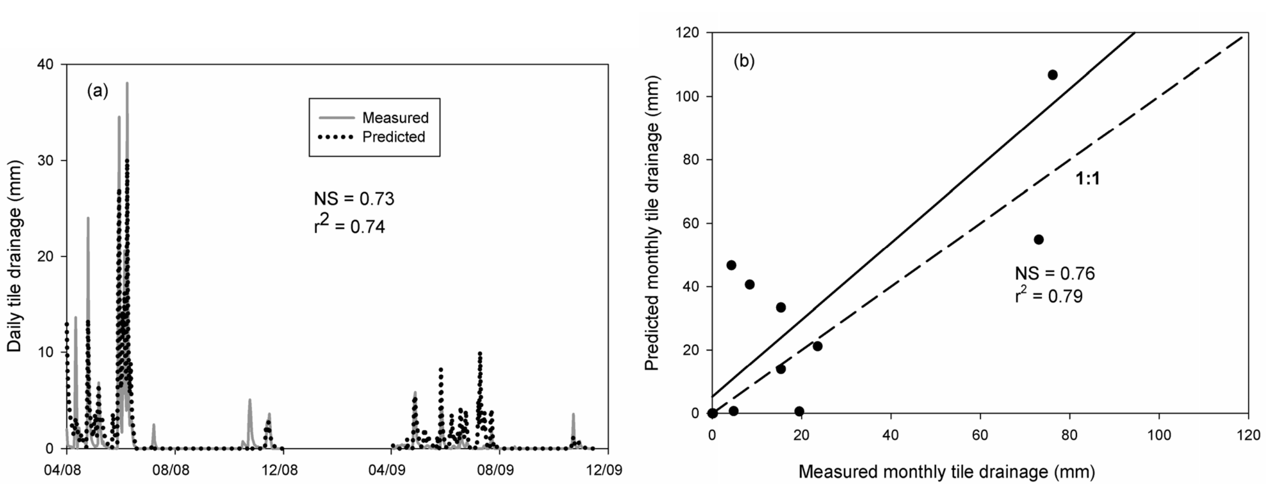


**Figure 6. Measured and predicted (a) daily tile drainage and (b) monthly tile drainage during 2008-2009 for model validation.**

Table 5. Predicted tile drainage flow under different management scenarios.

| Year | Row-crops with Conventional Drainage (mm) | Row-crops with Shallow Drainage (mm) | Pasture (mm) |
|---|---|---|---|
| 2006 | 37 | 31 | 13 |
| 2007 | 388 | 356 | 58 |
| 2008 | 365 | 330 | 218 |
| 2009 | 205 | 194 | 9 |

### *Conventional vs. Shallow Drainage*

The simulated tile drainage flow was less sensitive to drainage depth than the drainage time constant (fig. 8), consistent with the findings of other studies (Feyen et al., 2000; Sahoo et al., 2006). As expected, the shallow drainage system at a drain depth of 0.75 m drained less water as compared to the conventional drain depth of 1.05 m. The total subsurface drainage during 2006-2009 was estimated to be 911 mm for shallow drainage, an 8.4% reduction from the conventional drainage system (table 5). The limited reduction may be attributed to the narrow drain spacing of the study site, which is narrower than would be expected in most field conditions. From DRAINMOD simulations at the same location, Singh et al. (2006) found that the subsurface drainage could be reduced by 15% with a shallow drainage system while maintaining the same drainage intensity. Seepage to and from the groundwater is simulated in the MIKE SHE model. Other research showed that the amount of decrease in subsurface drainage by raising water table was impacted by seepage (Skaggs et al., 2010).

## SUMMARY AND CONCLUSIONS

This study attempted to apply the spatially-distributed, physically-based MIKE SHE model for a subsurface tile drainage study in the Midwestern United States. The model was calibrated and validated to subsurface tile drainage flow in a 15.2 × 38 m row-cropped plot in north central Iowa. Among the tested parameters, the drainage time constant and macropore flow had the most notable effect on the predicted drainage. The calibrated drainage time constant was about 5.6 h, which is much smaller than the reported values for large watersheds. The shorter response time of subsurface flow at the study scale could be responsible for the small drainage time constant in this study. The simulation results suggest that incorporation of macropore flow in hydrological modeling is important for characterizing peak discharges in subsurface drainage systems.

Both the visual comparison of hydrographs and statistical measures (Nash-Sutcliffe model efficiency coefficient and coefficient of determination) indicated that MIKE SHE showed a satisfactory performance in simulating tile drainage flow of the study site during the calibration and validation periods. This is encouraging since only two parameters were adjusted for the calibrated model. The results of modeling changes in land management indicated the potential to reduce subsurface drainage by converting from row-crop to pasture or by shallow drain placement. The role of tile drainage in flood generation and pollutant transport remains under controversy and is difficult to monitor on watershed scales. This study suggests that MIKE SHE has the potential for accurately predicting subsurface flows and ultimately being used in management decisions. The application of MIKE SHE in simulating tile drainage flow from agricultural lands in the Midwestern United States is being investigated at larger scales (e.g., catchment/watershed scales).

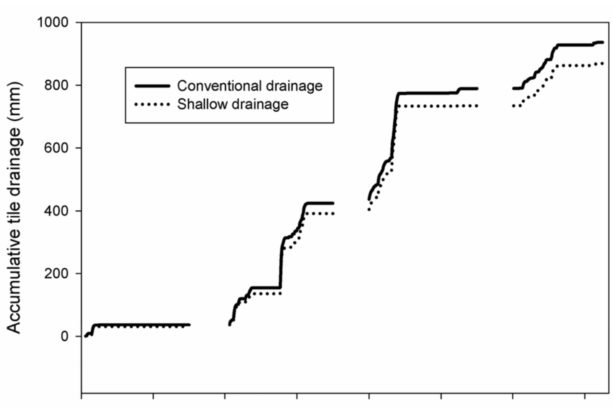


**Figure 8. Impact of tile level on tile drainage flow. For shallow drainage, tile drains were at 0.75 m below ground surface.**

## REFERENCES


Al-Kaisi, M. 2000. Crop water use or evapotranspiration. *Integrated Crop Management* 484, 85-86. Ames, Iowa: Iowa State University-University Extension.

Al-Khudhairy, D. H. A., J. R. Thompson, H. Gavin, and N. A. S. Hamm. 1999. Hydrological modeling of a drained grazing marsh under agricultural land use and the simulation of restoration management scenario. *Hydrological Science J.* 44(6): 943-971.

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: guidelines for computing crop water requirements. Rome: FAO-Irrigation and Drainage.

Baker, J. L., S. W. Melvin, D. W. Lemke, P. A. Lawlor, W. G. Crumpton, and M. J. Helmers. 2004. Subsurface drainage in Iowa and the water quality benefits and problem. *Drainage VIII Proceedings of the Eighth International Symposium.* St. Joseph, Mich.: ASAE.

Bengtson, R. L., C. E. Carter, J. L. Fouss, L. M. Southwick, and G. H. Willis. 1995. Agricultural drainage and water quality in Mississippi Delta. *J. of Irrigation and Drainage Engineering* 121(4): 292-295.

Cambardella, C. A., T. B. Moorman, D. B. Jaynes, T. B. Parkin, and D. L. Karlen. 1999. Water quality in Walnut Creek watershed: $NO_3$-N nitrogen in soils, subsurface drainage water and shallow groundwater. *J. of Environmental Quality* 28(.1): 25-34.

Demetriou, C., and J. F. Punthakey. 1999. Evaluating sustainable groundwater management options using the MIKE SHE integrated hydrogeological modelling package. *Environmental Modelling and Software* 14(2-3): 129-140.

DHI. 2004. *MIKE SHE User Manual.* Hørsholm, Denmark: Danish Hydraulic Institute.

Engman, E. T. 1986. Roughness coefficients for routing surface runoff. *J. of Irrigation and Drainage Engineering* 112(1): 39-53.

Feyen, L., R. Vazquez, K. Christiaens, O. Sels, and J. Feyen. 2000. Application of a distributed physically-based hydrological model to a medium size catchment. *Hydrology and Earth System Sciences* 4(1): 47-63.

Gardenas, A. I., J. Simunek, N. Jarvis, and M.T. van Genuchten. 2006. Two-dimensional modeling of preferential water flow and pesticide transport from a tile-drained field. *J. of Hydrology* 329(3-4): 647-660.

Gardner, W. K., M. F. Drendel, and G. K. McDonald. 1994. Effects of subsurface drainage, cultivation and stubble retention on soil porosity and crop growth in a high rainfall area. *Australian J. of Experimental Agriculture* 34(3): 411-418.

Helmers, M. J., D. E. Eisenhauer, T. G. Franti, and M. G. Dosskey. 2005. Modeling sediment trapping in a vegetative filter accounting for converging overland flow. *Trans. ASAE* 48(2): 541-555.

Henriksen, H. J., L. Troldborg, P. Nyegaard, T. O. Sonnenborg, J. C. Refsgaard, and B.Madsen. 2003. Methodology for construction, calibration and validation of a national hydrological model for Denmark. *J. of Hydrology* 280(1-4): 52-71.

Irwin, R. W., and H. R. Whiteley.1983. Effects of land drainage on stream flow. *Canadian Water Resources J.* 8(2): 88-103.

Jaber, F. H., and S.Shukla. 2005. Hydrodynamic modeling approaches for agricultural storm water impoundments. *J. of Irrigation and Drainage Eng.* 131(4): 307-315.

Kanwar, R. S., R. M. Cruse, M. Ghaffarzadeh, A. Bakhsh, D. L. Karlen, and T. B. Bailey. 2005. Corn soybean and alternative cropping systems effected on $NO_3$-N leaching losses in subsurface drainage water. *Applied Eng. in Agric.* 21(2):181-188.

Karl, T. R., J. M. Melillo, and T. C. Peterson. 2009. Global climate change impacts in the United States. New York, N.Y.: Cambridge University Press.

Konyha, K. D., R. W. Skaggs, and J. W. Gilliam. 1992. Effects of drainage and water management practices on hydrology. *J. of Irrigation and Drainage Eng.* 118(5): 807-819.

Kristensen, K. J., and S. E. Jensen. 1975. A model for estimating actual evapotranspiration from potential evapotranspiration. *Nordic Hydrology* 6(3): 170-188.

Lawlor, P. A., M. J. Helmers, J. L. Baker, S. W. Melvin, and D. W. Lemke. 2008. Nitrogen application rate effect on NO3-N-nitrogen concentration and loss in subsurface drainage for a corn-soybean rotation. *Trans. ASAE* 51(1): 83-94.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models. Part I. A discussion of principles. *J. of Hydrology* 10(3): 282-290.

Oogathoo, S. 2006. Runoff simulation in the Canagagigue creek watershed watershed using the MIKE SHE Model. M.S. thesis. Sainte Anne-de-Bellevue, QC: McGill University, Department of Agricultural and Biosystems Engineering.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman, Jr. 2001. Hypoxia in the Gulf of Mexico. *J. of Environmental Quality* 30(2): 320-329.

Randall, G. W., D. R. Huggins, D. J. Fuchs, W. W. Nelson., and J. L. Anderson. 1997. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa, and row crop systems. *J. of Environmental Quality* 26(5): 1240-1247.

Refsgaard, J. C. 1997. Parameterisation, calibration and validation of distributed hydrological models. *J. of Hydrology* 198(1-4): 69-97.

Refsgaard, J. C., and B. Storm. 1995. MIKE SHE. In *Computer Models of Watershed Hydrology*, 809-846. V. Singh, ed. Highlands Ranch, Colo.: Water Resources Publications.

Sahoo, G. B., C. Ray, and E. H. De Carlo. 2006. Calibration and validation of a physically distributed hydrological model, MIKE SHE, to predict streamflow at high frequency in a flashy mountainous Hawaii Stream. *J. of Hydrology* 327(1-2): 94-109.

Sands, G. R., L. M. Busman, W. E. Ruger, and B. Hansen. 2003. The impact of drain depth on water quality in a cold climate. ASAE Paper No. 032365. St. Joseph, Mich.: ASAE.

Schaap, M. G., F. J. Leij, and M. Th. van Genuchten. 2001. Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedo-transfer functions. *J. of Hydrology* 251(3): 163-176.

Shipitalo, M. J., V. Nuutinen, and K. R. Butt. 2004. Interaction of earthworm burrows and cracks in a clayey, subsurface drained, soil. *Applied Soil Ecology* 26(3): 209-217.

Singh, R., J. C. Refsgaard, L. Yde, G. H. Jorgensen, and M. Thorsen. 1997. Hydraulic-hydrological simulations of canal-command for irrigation water management. *Irrigation and Drainage Systems* 11(3?): 185-213.

Singh, R., M. J. Helmers, and Z. Qi. 2006. Calibration and validation of DRAINMOD to design subsurface drainage systems for Iowa's tile landscape. *Agricultural Water Management* 85(3): 221-232.

Skaggs, R. W., and R. G. Broadhead. 1982. Drainage strategies and peak flood flows. ASAE Paper No. 822054. St. Joseph, Mich.: ASAE.

Skaggs, R. W., M. A. Breve, and J. W. Gilliam. 1994. Hydrologic and water quality impact of agricultural drainage. *Critical Reviews in Environmental Science and Technology* 24(1): 1-32.

Skaggs, R. W., M. A. Breve, and J. W. Gilliam. 1995. Simulation of drainage water quality with DRAINMOD. *Irrigation and Drainage Systems* 9(3): 259-277.

Skaggs, R. W., M. A. Youself, J. W. Gilliam, and R. O. Evans. 2010. Effect of controlled drainage on water and nutrient balances in drained lands. *Trans. ASABE* 53(6): 1843-1850.

Thompson, J. R., H. R. Sorenson, H. Gavin, and A. Refsgaard. 2004. Application of the coupled MIKE SHE/MIKE 11 modelling system to a lowland wet grassland in southeast England. *J. of Hydrology* 293(1-4): 151-179.

Wiskow, W. and R. R. van der Ploeg. 2003. Calculation of drain spacings for optimal rainstorm flood control. *J. of Hydrology* 272(1-4): 163-174.