

# Evaluation of the Hooghoudt and Kirkham Tile Drain Equations in the Soil and Water Assessment Tool to Simulate Tile Flow and Nitrate-Nitrogen

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Subsurface tile drains in agricultural systems of the midwestern United States are a major contributor of nitrate-N ( $\text{NO}_3\text{-N}$ ) loadings to hypoxic conditions in the Gulf of Mexico. Hydrologic and water quality models, such as the Soil and Water Assessment Tool, are widely used to simulate tile drainage systems. The Hooghoudt and Kirkham tile drain equations in the Soil and Water Assessment Tool have not been rigorously tested for predicting tile flow and the corresponding  $\text{NO}_3\text{-N}$  losses. In this study, long-term (1983–1996) monitoring plot data from southern Minnesota were used to evaluate the SWAT version 2009 revision 531 (hereafter referred to as SWAT) model for accurately estimating subsurface tile drain flows and associated  $\text{NO}_3\text{-N}$  losses. A retention parameter adjustment factor was incorporated to account for the effects of tile drainage and slope changes on the computation of surface runoff using the curve number method (hereafter referred to as Revised SWAT). The SWAT and Revised SWAT models were calibrated and validated for tile flow and associated  $\text{NO}_3\text{-N}$  losses. Results indicated that, on average, Revised SWAT predicted monthly tile flow and associated  $\text{NO}_3\text{-N}$  losses better than SWAT by 48 and 28%, respectively. For the calibration period, the Revised SWAT model simulated tile flow and  $\text{NO}_3\text{-N}$  losses within 4 and 1% of the observed data, respectively. For the validation period, it simulated tile flow and  $\text{NO}_3\text{-N}$  losses within 8 and 2%, respectively, of the observed values. Therefore, the Revised SWAT model is expected to provide more accurate simulation of the effectiveness of tile drainage and  $\text{NO}_3\text{-N}$  management practices.

**S**UBSURFACE TILE DRAINAGE is a commonly used agricultural practice to enhance crop yield in poorly drained but highly productive soils in the midwestern United States and many other similar regions of the world. It improves soil aeration, increases availability of plant nutrients (Lal and Taylor, 1970), and enhances crop productivity (Cannell, 1979) by facilitating timely implementation of farm operations. It reduces crop diseases, soil erosion, and surface runoff (Fausey et al., 1986). Long-term studies on clay soils in northern Ohio have demonstrated that subsurface drainage substantially improved average corn and soybean yields and helped to reduce year-to-year variability in yields (Brown et al., 1998). However, the presence of subsurface tile drainage systems also expedites the transport of nitrate-nitrogen ( $\text{NO}_3\text{-N}$ ) and pesticides such as herbicides, insecticides, and fungicides to surface waters (Thomas et al., 1992; Zucker and Brown, 1998; Dinnes et al., 2002; Randall and Vetsch, 2005).

Hydrologic and water quality models such as DRAINMOD (Skaggs, 1982), ADAPT (Ward et al., 1993), the Root Zone Water Quality Model (Ahuja et al., 2000; Ma et al., 2000), and the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) are widely used to simulate tile drainage systems at various spatial scales. SWAT is a widely used watershed model that contains a subsurface tile drainage component (Green et al., 2006; Moriasi et al., 2012). The amount of water available for drainage is affected by surface runoff and evapotranspiration because they affect infiltration (Fig. 1). Therefore, to properly reflect the area hydrology, partitioning of the surface runoff and infiltration must be maintained.

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**Abbreviations:** CN, curve number; HRU, hydrological response unit; ICN, daily curve number calculation method; NSE, Nash-Sutcliffe efficiency; PET, plant evapotranspiration; PBIAS, percent bias; wtd, water table depth; RMSE, root mean square error.

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# The Hydrologic System

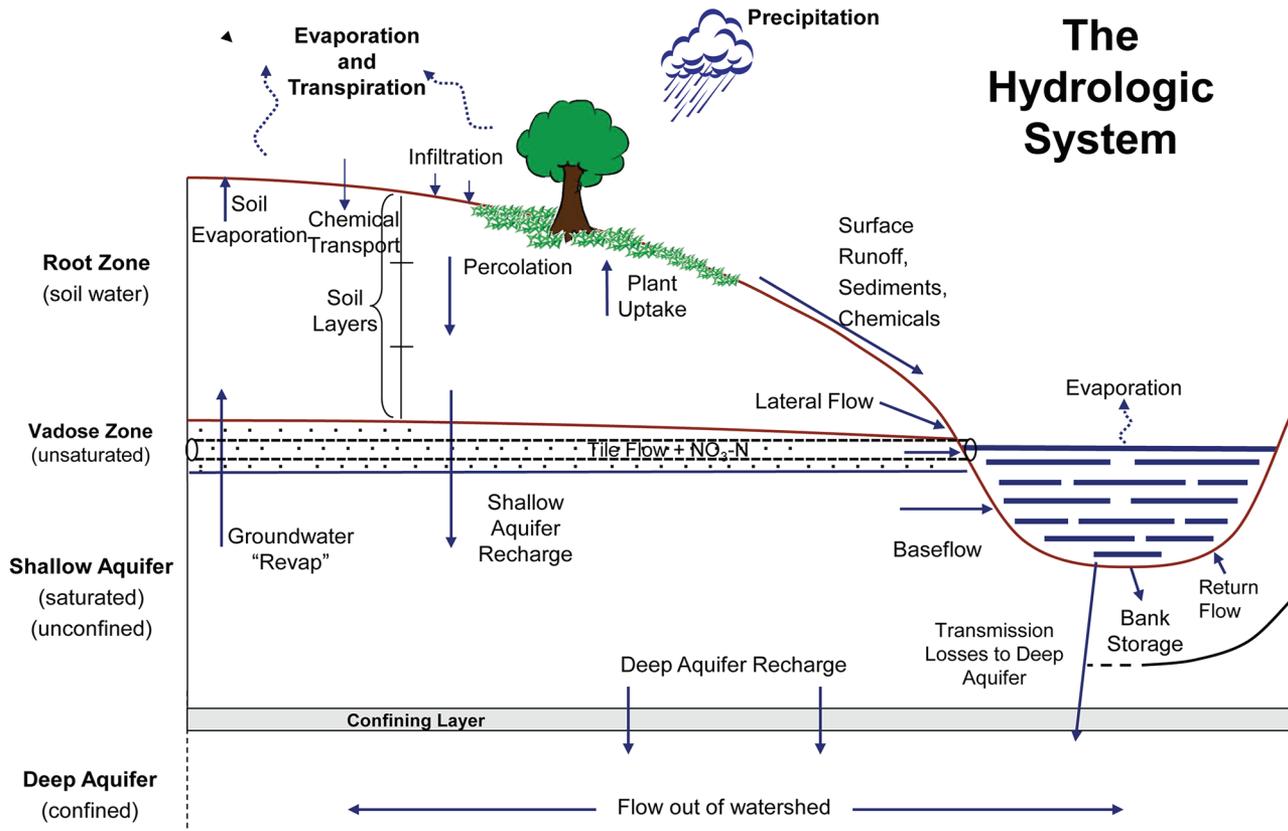


Fig. 1. Schematic of the hydrologic cycle and the sediment and chemical transport pathways.

SWAT provides two methods for estimating surface runoff and infiltration: the SCS curve number (CN) method (SCS, 1972) and the Green & Ampt infiltration method (Green and Ampt, 1911). With a few exceptions (e.g., King et al., 1999; Kannan et al., 2007), most SWAT studies use the SCS-CN method to compute surface runoff and infiltration (Gassman et al., 2007) due to the availability of input data at the watershed scale. Accumulated surface runoff is a function of the rainfall for the day, initial abstractions including surface storage, interception, infiltration before runoff, and the retention parameter.

The retention parameter is used to calculate the daily CN and is computed in SWAT using two methods (Neitsch et al., 2005). The daily curve number calculation method is indicated by the daily curve number calculation method (ICN). When the ICN value is 0 (default), the daily CN is calculated as a function of antecedent soil moisture; when the ICN value is 1, the daily CN is computed as a function of plant evapotranspiration (PET). In the first traditional method, the retention parameter is allowed to vary with the soil profile water content; however, it overpredicts runoff in shallow, poorly drained soils (Neitsch et al., 2005). These soils are usually tile drained for agricultural production. A second method in which the retention parameter varies with accumulated PET added to SWAT deals with the issue of overprediction of surface runoff in shallow, poorly drained soils.

The retention parameter ( $S$ ) is estimated as a function of CN, which in turn is a function of the soil's permeability, land use, and antecedent soil moisture conditions (Williams et al., 2008; Neitsch et al., 2005). However, it does not account for the effects of subsurface tile drainage. In addition, the CN values provided in the tables for soil moisture condition II are assumed

to be appropriate for 5% slopes (Neitsch et al., 2005). Although Williams (1995) developed an equation to adjust the CN to a different slope, SWAT does not use that equation. If the user wishes to adjust the CN values for slope effects, the adjustment must be done to CN values (staying within 10% of the default CN2 input value) (Green et al. (2006) before entering them in the management input file (Neitsch et al., 2005). As a result, the traditional daily CN method, which computes the daily CN in SWAT as a function of soil profile water content, generally overpredicts runoff in shallow, poorly drained, and mildly sloped soils (Neitsch et al., 2005). These soils are usually equipped with subsurface tile drains to facilitate agricultural production in the midwestern United States. In general, tile drainage increases soil moisture storage capacity due to the continuous removal of excess water from the profile (Skaggs and Broadhead, 1982) and by improving soil structure and increasing soil porosity (Gardner et al., 1994). Increased soil storage capacity leads to greater infiltration and, hence, lower surface runoff (Hill, 1976; Thomas et al., 1992; Skaggs et al., 1994; Bengtson et al., 1995; Davis et al., 2000; Bengtson and Carter, 2004). Soils with lower slopes generate lower surface runoff during a rainfall event (Williams, 1995); therefore, it is important that modifications be made to the soil moisture retention parameter computation method in SWAT to improve the accuracy for tile drained and mildly sloped agricultural system hydrology.

There are two tile drainage algorithms in SWAT version 2009 (hereafter referred to as SWAT). The first tile drainage algorithm calculates tile flow as a function of water table depth (wtd), tile depth, and the time required to drain the soil to field capacity (Green et al., 2006) assuming that the tile systems

have equidistant tile spacing and size. The second tile drainage algorithm computes tile flow using Hooghoudt's (1940) steady state and Kirkham (1957) tile drain equations that are a function of water table depth, tile drain depth, size, and spacing (Moriassi et al., 2007a, 2012).

There are three methods used to calculate wtd in SWAT (Moriassi et al., 2011). In the first method, known as the SWAT-M approach, the soil profile above the confining layer is allowed to fill with water to field capacity beginning with the bottom soil layer. In the second method (SWAT2005), wtd is computed using 30-d moving summations of precipitation, surface runoff, and evapotranspiration (ET). The third modified DRAINMOD approach uses the drainage volume-wtd relationship, where drainage volume is the effective air volume above the water table defined as the void space that holds water between field capacity and saturation.

An important aspect in hydrologic modeling is ensuring that the algorithms used are thoroughly tested with physical input data so that they best represent the processes being simulated. To build user confidence in models' capabilities to accurately simulate hydrology, the algorithms need to be calibrated and validated for all of the major hydrologic processes, including new algorithms/modules, such as subsurface tile drainage. The first tile drainage algorithm in SWAT has been tested for tile flow and NO<sub>3</sub>-N in tile flow (Du et al., 2005; Du et al., 2006; Green et al., 2006; David et al., 2009; Beeson et al., 2011). However, the second tile drainage algorithm, which uses Hooghoudt's steady state and Kirkham tile drain equations in SWAT (Moriassi et al., 2007a), has not been tested with as many datasets. Rahman et al. (2011) calibrated and validated the Hooghoudt's and Kirkham tile drain equations in SWAT and used the validated model to analyze the impact of subsurface drainage on streamflow in the Upper Red River watershed in North Dakota. More recently, Moriassi et al. (2012) used streamflow data from the South Fork watershed in Iowa to evaluate the capability of the Hooghoudt's steady state and Kirkham tile drain equations to simulate water balance components for this Iowa tile drained watershed (Green et al., 2006). In both of these studies, measured data were limited to streamflow to test the capability of the added tile drain equations. Therefore, the Hooghoudt's and Kirkham's equations in the SWAT model can be more rigorously tested based on measured tile flow and NO<sub>3</sub>-N in tile flow data. The 14-yr tile flow and NO<sub>3</sub>-N Minnesota observed data, one of the best datasets on subsurface tile drainage in the Upper Midwest (Davis et al., 2000), is a good dataset to test these new equations.

The main objective of this work was to test the Hooghoudt's steady state and Kirkham tile drain equations to ensure that they properly simulate tile flow and associated NO<sub>3</sub>-N leaching within the SWAT model. Where necessary, modifications were made to the SWAT model to ensure that tile flow and associated NO<sub>3</sub>-N leaching were correctly simulated (within the limits of SWAT and its N processes). This is a critical step before recommending the use of these equations within SWAT for applications that determine the impact of tile drainage on tile flow quantification and water quality. Therefore, this paper presents (i) modifications made to the soil moisture retention parameter algorithm (dailycn.f) in SWAT to account for the effects of subsurface tile drainage in the computation of surface runoff (Fig. 1) (the version of this study's modified model is

hereafter referred to as Revised SWAT) and (ii) calibration and validation of the SWAT and Revised SWAT for prediction of subsurface tile flow and NO<sub>3</sub>-N losses using long-term (1983–1996) tile flow and the corresponding NO<sub>3</sub>-N losses monitoring data from three southern Minnesota plots. In this study area, tile drain flows and the related NO<sub>3</sub>-N losses were measured during the April–August growing season (Davis et al., 2000). Only these data were used to evaluate the SWAT and Revised SWAT models. The Hooghoudt's steady state and Kirkham tile drain equations were used to compute tile flow in this study because tile spacing and size data were available.

## Materials and Methods

### Modification to the Soil Moisture Retention Parameter Calculation Method

In the traditional soil moisture estimation method (ICN = 0), the retention parameter is computed following Eq. [1] (Williams et al., 2008):

$$S = S_{\max} \left( 1 - \frac{SW}{[SW + \exp(w_1 - w_2 \cdot SW)]} \right) \quad [1]$$

where  $S$  is the retention parameter for a given day (mm),  $S_{\max}$  is the maximum value the retention parameter can achieve on any given day (mm),  $SW$  is the soil water content of the entire profile excluding the amount of water held in the profile at wilting point (mm H<sub>2</sub>O), and  $w_1$  and  $w_2$  are shape coefficients.

Tile drainage increases water storage capacity in the soil profile due to continuous removal of excess water from the soil profile (Skaggs and Broadhead, 1982). The amount of water that can be drained from the soil depends on the "drainable porosity" of a soil. Drainable porosity, also known as "specific water yield" (Logsdon et al., 2010), is the quantity of water drained for a given drop in the water table (Sands, 2009) for a given soil. Logsdon et al. (2010) found that specific or drainable porosity varied with ET demands, soil-water dynamics, and water table depth. This could be due to the presence of soil layers within the profile that have different physical properties, including drainable porosity.

For example, take two soils with the same drainable porosity of 4% (Table 1), one surface drained (undrained) and another subsurface tile drained (drained) at 1000 mm below the surface. If the water table depth for the undrained soil is 100 mm below surface and the drained soil is 1000 mm below surface on any given day, the undrained soil has  $(4 \times 100 \text{ mm}/100) = 4$  mm of pore space available between the surface and the water table depth, whereas the drained soil has  $(4 \times 1000/100) = 40$  mm of pore space available. This equates to 10 times more available (empty) pore space. If low-intensity rainfall of 50 mm occurs,

**Table 1. The variability of drainable porosity with soil texture and structure.†**

Soil texture	Field capacity	Wilting point	Drainable porosity
	% by vol.		
Clays, clay loams, silty clays	30–50	15–24	3–11
Well-structured loams	20–30	8–17	10–15
Sandy	10–30	3–10	18–35

† Data from Sands (2009).

one would expect 46 mm of surface runoff from the undrained soil and 10 mm from the drained soil (“sponge effect”). This has immense implications on the prediction of soil erosion and phosphorus losses while greatly affecting the partitioning of NO<sub>3</sub>-N losses between surface runoff and subsurface tile drainage. This also has major implications on the time to peak flow and the magnitude of peak flow, which are important in channel processes. The smaller the drainable porosity, the more drastic the impact of drainage, infiltration, and ET on water table (Asbjornsen et al., 2007).

The increased soil water storage capacity increases soil water retention and therefore reduces surface runoff. Therefore, we modified the traditional soil moisture estimation method for shallow, poorly drained soils, which may be surface or subsurface tile drained. This was accomplished by introducing a factor,  $SA_{fctr}$  (Eq. [2]), to adjust for slope and account for tile flow, which is one of the predominant components of the water budget in tile drained watersheds.

$$S = SA_{fctr} * S_{max} \left( 1 - \frac{SW}{[SW + \exp(w_1 - w_2 \cdot SW)]} \right) \quad [2]$$

where  $SA_{fctr}$  is the retention parameter adjustment factor ( $\geq 1$ ) for a given hydrological response unit (HRU), which is a function of the effective soil profile drainable porosity (Sands, 2009), slope, drainage system design, and target average annual surface runoff component of the water budget. The optimal  $SA_{fctr}$  for the study area was 8. The study area consisted of three Minnesota 14-yr study plots with an effective soil drainable porosity of 7% (estimated from soil input data), an average slope of 0.1%, tile drain depth of 1.2 m, and a minimal average annual surface runoff (Randall and Iragavarapu, 1995). We recommend that model users determine an optimal  $SA_{fctr}$  for their study area during the calibration process and based on user knowledge of the system because suitable boundary values have not been determined for this parameter. In general, the presence of tile drainage systems leads to a larger  $SA_{fctr}$ . In addition,  $SA_{fctr}$  will be larger if the effective soil profile drainable porosity is larger and if the slope and target annual average surface runoff for the study area are smaller. For a given soil type and slope, the degree of reduction in surface runoff is dependent on antecedent soil moisture and on the intensity and amount of rainfall (Sands, 2009). This modification was incorporated into SWAT as a third alternative method (ICN = 2, Revised SWAT model) for computing the retention parameters.

### Other SWAT Variables Pertinent to This Study

The shallow water table depth was computed using the drainage volume–wtd relationship method (Moriasi et al., 2011), as presented in Eq. [3], varying water table between the soil surface and depth to impervious layer.

$$wtd_j = wtd_{pj} + wt\_del_{cj} \quad [3]$$

where  $wt\_del_{cj}$  is the change in water table depth on the current day (mm) in HRU  $j$ , and  $wtd_j$  and  $wtd_{pj}$  are the current and previous day water table depth measured from the ground surface to the water table (mm), respectively, for HRU  $j$ . In this approach, drainage volume is computed as the change in the soil

water for the whole soil profile ( $sw\_del_{cj}$ ) for HRU  $j$ . The  $sw\_del_{cj}$  is converted to  $wt\_del_{cj}$  using a variable water table factor ( $wt\_fctr$ ), which is automatically computed as a function of soil layer drainable porosity as presented in Eq. [4]. Factor  $wt\_fctr_j$  on the current day in HRU  $j$  is determined based on the soil layer in which the water table was located on the previous day. The  $wt\_del_{cj}$  is computed as:

$$wt\_del_{cj} = wt\_fctr * sw\_del_{cj} \quad [4]$$

However, it was observed in this study that computing  $wt\_del_{cj}$  based on change in the soil water for the whole soil profile tends to overestimate wtd when long-term (>20 yr) simulations are performed, more commonly in the cases where days without rainfall dominate. In other words, for long-term wtd simulations, the computed wtd gradually drops deeper as profile soil water decreases due to ET, which makes it harder for the water table to rise closer to the surface after rain events. Therefore, Eq. [4] was modified to enable stability in wtd fluctuations especially for long-term scenario simulations:

$$wt\_del_{cj} = \sum_{k=1}^{nn} wt\_fctr_{k,j} * sw\_del_{k,j} \quad [5]$$

where  $wt\_fctr_{k,j}$  is the conversion factor for soil layer  $k$  in HRU  $j$  computed as a function of drainable or effective porosity for soil layer  $k$  (Moriasi et al., 2011),  $sw\_del_{k,j}$  is the current change in soil water for soil layer  $k$  in HRU  $j$ , and  $nn$  is the total number of soil layers in HRU  $j$ .

When the water table is below the surface and ponded surface depressional depths are below a threshold (i.e., when surface water cannot move freely toward the drains), the Hooghoudt steady state equation is used to compute drainage flux:

$$q = \frac{8K_c d_c m + 4K_c m^2}{L^2} \quad [6]$$

where  $q$  is the drainage flux in mm h<sup>-1</sup>,  $m$  is the midpoint water table height above the drain (mm),  $K_c$  is the effective lateral saturated hydraulic conductivity (mm h<sup>-1</sup>),  $L$  is the distance between drains (mm), and  $d_c$  is the equivalent depth of the impermeable layer below the tile drains (as affected by drain depth and midpoint water table height; mm). For ponded depths, when the water table rises to completely fill the surface and the ponded water remains at the surface for relatively long periods of time, drainage flux is computed using the Kirkham (Eq. [7]):

$$q = \frac{4\pi K_c (t + b - r)}{gL} \quad [7]$$

where  $t$  is the average depressional storage depth (mm);  $b$  is the depth of the tile drain from the soil surface (mm);  $r$  is the radius of the tile drain (mm); and  $g$  is a dimensionless factor, which is determined using an equation developed by Kirkham (1957). Finally, when the drainage flux predicted by the appropriate equation is greater than the drainage coefficient (DC, mm d<sup>-1</sup>), then the flux is set equal to the DC as:

$$q = DC \quad [8]$$

Nitrate-nitrogen may be transported with surface runoff, lateral flow, tile flow, or percolation (Neitsch et al., 2005). To calculate

the amount of  $\text{NO}_3\text{-N}$  that moved with the water in various flow paths, the concentration of  $\text{NO}_3\text{-N}$  in the mobile water is calculated. The  $\text{NO}_3\text{-N}$  concentration in the surface runoff fraction is multiplied by the  $\text{NO}_3\text{-N}$  reduction coefficient (NPERCO). Nitrate-N in the tile flow from a soil layer was also multiplied by NPERCO. This  $\text{NO}_3\text{-N}$  concentration is multiplied by the volume of water moving in each pathway to obtain the mass of  $\text{NO}_3\text{-N}$  lost from a soil layer (Neitsch et al., 2005). Therefore, in this study the  $\text{NO}_3\text{-N}$  leached via tile drains was determined by multiplying tile flow ( $\text{m}^3 \text{d}^{-1}$ ) by  $\text{NO}_3\text{-N}$  concentration in solution in the layer containing the tile drain and NPERCO. Neitsch et al. (2005) provide details of how N is modeled by SWAT in the soil profile and in the shallow aquifer. SWAT determines the amount of N lost to denitrification using Eq. [9] and [10] (Neitsch et al., 2005):

$$N_{\text{denit},ly} = \text{NO}_{3ly} \cdot [1 - (\exp(-\beta_{\text{denit}} \cdot \gamma_{\text{tmp},ly} \cdot \text{orgC}_{ly}))] \text{ if } \gamma_{\text{sw},ly} \geq \gamma_{\text{sw},\text{thr}} \quad [9]$$

$$N_{\text{denit},ly} = 0.0 \text{ if } \gamma_{\text{sw},ly} < \gamma_{\text{sw},\text{thr}} \quad [10]$$

where  $N_{\text{denit},ly}$  is the amount of N lost to denitrification ( $\text{kg N ha}^{-1}$ ),  $\text{NO}_{3ly}$  is the amount of  $\text{NO}_3\text{-N}$  in layer  $ly$  ( $\text{kg N ha}^{-1}$ ),  $\beta_{\text{denit}}$  is the rate coefficient for denitrification,  $\gamma_{\text{tmp},ly}$  is the nutrient cycling temperature factor for layer  $ly$ ,  $\text{orgC}_{ly}$  is the amount of organic carbon in the layer (%), and  $\gamma_{\text{sw},\text{thr}}$  is the threshold value of nutrient cycling water factor for denitrification to occur.

## SWAT Model Set-Up

The ArcSWAT2009 interphase was used to delineate the watershed, with two subbasins consisting of the three study area plots and a pseudo-subbasin for flux-routing purposes. Although all the three plots consisted of the same soil and land cover (corn), they were manually designed as three different HRUs to represent replication. In this study, the initial soil water storage, which is expressed as a fraction of field capacity water content, was set equal to field capacity (1.0).

## Model Evaluation Methods

In addition to graphical methods, model performance measures such as the percent bias (PBIAS) (Gupta et al., 1999), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), and the root mean square error (RMSE) were used to assess the performance of the models.

## Study Area and Input Data

Long-term (1983–1996) monitoring data on subsurface tile drainage and associated  $\text{NO}_3\text{-N}$  losses from an experimental field at the University of Minnesota's Agricultural Experiment Station near Waseca, southern Minnesota (Fig. 2) were used to evaluate and compare the performances of SWAT and Revised SWAT models. Measured tile drainage was collected from three 13.5- by 15.0-m continuous corn plots designed to represent tile drain spacing (SDRAIN) of 27 m by installing the tile drain at the end of the plot. Tile drains (100 mm diameter) were installed at a depth (DDRAIN) of 1.2 m with a gradient of 0.1% (Table 2). Since 1982, the plots were planted with continuous corn under moldboard plow tillage. Tile drain flows were measured

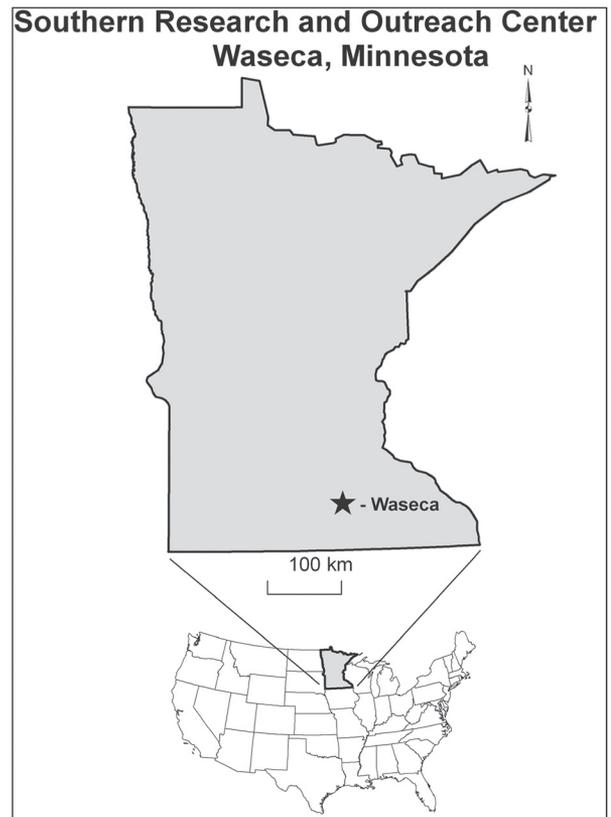


Fig. 2. University of Minnesota's Agricultural Experiment Station near Waseca, southern Minnesota.

daily during the April–August growing season and summed to calculate monthly values (Davis et al., 2000). Water, crop, and nutrient management practices on these plots were typical of the upper midwestern United States, and field measurements of soil (Table 3) and crop properties were made as a part of a tile drainage study (Buhler et al., 1993; Randall and Iragavarapu, 1995; Randall et al., 1997).

Weather data, including daily values of precipitation, minimum and maximum air temperatures, solar radiation, wind speed, and average relative humidity recorded at a weather station located at about 0.5 km from the experimental plots, were used in the simulation. The Priestley-Taylor method (Priestley and Taylor, 1972) was used for calculating PET. The subsurface tile drainage system parameter values and soil input data for the study location (Tables 2 and 3) were held constant for all simulations unless otherwise stated. Soil properties such as depth of each horizon, particle size distribution, and organic matter content were taken from Culley (1986); hydraulic conductivity was obtained from Davis et al. (2000); and initial N content of the soil was obtained from Randall (1983). A depth to impervious layer of 2 m was used. The SCS runoff curve number for soil moisture condition II (CN2) of 78 was

Table 2. Values used for subsurface drainage systems in the study plot.†

Parameter	Description	Value
DDRAIN	depth to subsurface tile (mm)	12,00
RE	effective radius of tile drain (mm)	50
SDRAIN	distance between two drain or tile tubes (mm)	27,000

† Data from Davis et al. (2000).

**Table 3. Soil input data.†**

Layer	Thickness	Clay	Silt	Sand	Organic C	Wilting point	Hydraulic conductivity	Porosity	Initial soil N
	mm	%				mm mm <sup>-1</sup>	mm h <sup>-1</sup>	mm mm <sup>-1</sup>	mg kg <sup>-1</sup>
1	310	33	38	29	6.10	0.23	48	0.45	6.70
2	310	31	33	36	2.10	0.21	48	0.41	6.40
3	310	30	31	39	1.00	0.19	48	0.39	5.50
4	870	29	32	39	1.00	0.19	48	0.39	4.60

† Data from Davis et al. (2000).

estimated for the hydrologic group of the Webster soil (B/good hydrologic condition) under a straight row cropping system at 5% slope (SCS, 1972). The CN2 was held constant (78) for the Revised SWAT model but was used as a calibration parameter for the SWAT model, in addition to other calibration parameters described in the next section. For the SWAT model (Table 4), we had two scenarios, one in which CN2 was unchanged (CN2 = 78) and one in which the CN2 was significantly reduced through calibration (CN2 = 30) to obtain realistic surface runoff.

### Model Calibration and Validation

According to Davis et al. (2000), the most sensitive water budget components for the study plots were ET, surface runoff, and subsurface tile flow. Davis et al. (2000) determined these parameters while applying the ADAPT model on the same plots. Based on this information, the following parameters were varied for tile flow during manual calibration: the plant uptake compensation factor (EPCO) was adjusted for ET, and drainage coefficient (DRAIN-CO, mm d<sup>-1</sup>); multiplication factor to determine lateral saturated hydraulic conductivity from the vertical hydraulic conductivity input values for each HRU (LATKSATF); snow melt parameters, such as snow pack temperature lag factor (TIMP); minimum snow water content, which corresponds to 100% snow cover (SNOCOV MX, mm); and fraction of snow volume represented by SNOCOV MX, which corresponds to 50% snow cover (SNO50COV). The soil moisture condition II curve number (CN2) was varied for the SWAT model only. It was unchanged for the Revised SWAT model because the Revised SWAT model simulated an average annual surface runoff value close to the measured average annual surface runoff for the study plot (Davis et al., 2000).

The N parameters included in the calibration process were the N reduction coefficient (NPERCO), rate coefficient for mineralization of the humus active organic nutrients (CNM), denitrification exponential rate coefficient (CDN), and denitrification threshold water content (SDNCO). The parameter values and their acceptable ranges are presented in Table 4. All other parameters (Neitsch et al., 2005) were kept at the SWAT default values. The SWAT and Revised SWAT models were manually calibrated and validated for tile flow and NO<sub>3</sub>-N losses in tile flow by varying the calibration parameters one at a time while holding the other parameters constant.

Calibration and validation of the SWAT and Revised SWAT models consisted of comparing predicted monthly tile flow with measured data between the months of April and August per year. Although the model run was continuous, measured data for the odd numbered years (1983, 1985, ....., 1995) were used for calibration, and the measured data for the remaining (even) years were used for validation. The selection of odd years for calibration and even years for validation was made to evaluate model performance across a wide range of climatic conditions. Years 1989 and 1993 were the driest and wettest years, respectively, in the last 40 yr; therefore, the simulations included representative climatic conditions.

Water and N budgets simulated by the SWAT and the Revised SWAT models were compared with measured data to evaluate their ability to predict individual components of the water and N budget. In addition, the calibrated Revised SWAT model was tested to determine if it simulated the effect of tile drains on surface runoff reasonably. This was accomplished by running both models with (DDRAIN = 1.20 m) and without (DDRAIN = 0.0 m) tile drainage and comparing the simulated

**Table 4. Calibrated values of adjusted parameters for tile flow and nitrate-N calibration of the Revised SWAT model for the Waseca watershed.**

Parameter	Description	Range	Calibrated
EPCO	plant uptake compensation factor	0.001–1.00	0.001
TIMP	snow melt parameters snow pack temperature lag factor	0.01–1.00	0.60
SNOCOV MX	minimum snow water content that corresponds to 100% snow cover (mm)	–†	20.0
SNO50COV	fraction of snow volume represented by SNOCOV MX that corresponds to 50% snow cover	0.01–1.0	0.528
CN2 (for SWAT model only)	soil moisture condition II curve number	30–100	30
ICN	CN method flag: 0 use traditional SWAT method, which bases CN on soil moisture, 1 use alternative method which bases CN on plant ET, 2 use traditional SWAT method, which bases CN on soil moisture but retention is adjusted for shallow poorly drained soils and mildly sloped cropped areas (Revised SWAT)	0 or 1	0
DRAIN-CO	drainage coefficient (mm d <sup>-1</sup> )	10–51	51
LATKSATF	multiplication factor to determine lateral ksat from SWAT ksat input value for HRU	0.01–4.00	3.80
NPERCO	nitrogen concentration reduction coefficient	0.01–1.00	0.14
CMN	rate factor for mineralization of the humus active organic nutrients (N)	0.001–0.003	0.001
CDN	denitrification exponential rate coefficient	0.00–3.00	0.06
SDNCO	denitrification threshold water content	–	1.00

† Unknown parameter range.

surface runoff. Also, simulated crop yields were compared with the available measured data. The water and N budget, time series of tile flow and the associated  $\text{NO}_3\text{-N}$  losses, and simulation performance statistics for the calibration and validation time periods were presented for the SWAT (CN2 = 78) model uncalibrated for CN2 (to indicate the current overprediction problem) and for the SWAT (CN2 = 30) model calibrated for CN2 (to obtain correct surface runoff) for comparison with the Revised SWAT model using CN2 = 78. The SWAT (CN2 = 78) and Revised SWAT models used the calibrated ET, tile flow, and  $\text{NO}_3\text{-N}$  parameter values while maintaining CN2 at 78, whereas the SWAT (CN2 = 30) model was calibrated for CN2 in addition to ET, snowmelt, tile flow, and  $\text{NO}_3\text{-N}$  parameters (Table 4).

## Results and Discussion

### Calibrated Parameter Values and Water and Nitrogen Budgets

The range of parameter values and the calibrated values used in this study are presented in Table 4. Tables 5 and 6 present results of the comparison between the water and N budgets predicted by the SWAT (CN = 78 and CN = 30) and Revised SWAT models relative to the measured average for the combined calibration and validation period of 1983–1996 during the April–August growing season.

The average April–August ET, surface runoff, and tile flow predicted by the SWAT (CN2 = 78) model were 72, 23, and 18% of the growing season precipitation, respectively (Table 5). Although not measured for the study area, the average ET predicted by SWAT (CN2 = 78) was comparable to measured values of 64 to 70% in 1994 on a fine-textured, tile-drained soil cropped with corn located in central Iowa (Moorman et al., 1999), a border state to Minnesota. However, the surface runoff predicted by SWAT (CN2 = 78) was highly overpredicted compared with Randall and Iragavarapu (1995), who considered surface runoff to be minimal, and Davis et al. (2000), who

obtained similar results using the ADAPT model on the same plots. In addition, Nangia et al. (2010) simulated an average annual surface runoff value, which was 5.4% of average annual precipitation, on a nearby commercial field equipped with tile drains. As a result of overprediction of surface runoff, the SWAT (CN2 = 78) underpredicted tile flow by 54% (Table 5). Nitrogen plant uptake,  $\text{NO}_3\text{-N}$  losses through tile drains, and denitrification simulated by SWAT (CN2 = 78) were 148.8, 23.7, and 19.9  $\text{kg ha}^{-1}$ , respectively (Table 6). The simulated plant uptake was within 4% of the measured annual average value of 143  $\text{kg N ha}^{-1}$  (Table 6). The average corn yield simulated by the SWAT (CN2 = 78) model for the period from 1983 to 1996 was 9.1 metric tons  $\text{ha}^{-1}$ . This value was 6% greater than the observed annual average corn yield of 8.6 metric tons  $\text{ha}^{-1}$  for the years 1983 to 1992. This overprediction of yield corresponds to the overpredicted plant N uptake. Nitrogen losses by denitrification simulated by the SWAT (CN2 = 78) model during the growing months were within the annual average value of 10 to 25% of the applied N, as reported by Meisinger and Randall (1991). However, the SWAT (CN2 = 78) model underpredicted the  $\text{NO}_3\text{-N}$  in tile flow by 29% compared with the measured annual losses by tile drainage value of 33.5  $\text{kg ha}^{-1}$  (Table 6). This result corresponds to the fact that the SWAT (CN2 = 78) model underpredicted tile flow amount by 54% due to overprediction of surface runoff (Table 5).

These results indicated that changes were needed to SWAT to ensure that surface runoff, tile flow, and  $\text{NO}_3\text{-N}$  losses through tile flow were properly simulated. Therefore, we calibrated SWAT by changing CN2 from 78 to 30 and obtained the SWAT (CN2 = 30) model. The average April to August ET, surface runoff, and tile flow predicted by the SWAT (CN2 = 30) model were 74, 0, and 38% of the growing season precipitation, respectively (Table 5). The ET predicted by the SWAT (CN = 30) model was in the same order of magnitude of the reported values (Moorman et al., 1999). The surface runoff and tile flow predicted by the SWAT (CN2 = 30) model, calibrated for CN2, were much closer to the reported (Randall and Iragavarapu, 1995; Davis et al.,

**Table 5. Observed/reported and simulated average (April–August) water budget for the SWAT and Revised SWAT models.**

Component	Observed/reported		SWAT (CN2 = 78)		SWAT (CN2 = 30)		Revised SWAT (CN2 = 78)	
	Depth	Percent of precipitation	Depth	Percent of precipitation	Depth	Percent of precipitation	Depth	Percent of precipitation
	cm		cm		cm		cm	
Precipitation	52.8	100	52.8	100	52.8	100	52.8	100
Evapotranspiration		64–70†	37.9	72	38.8	74	38.8	74
Tile flow	20.7	39	9.5	18	19.8	38	19.4	37
Runoff		5‡	12.3	23	0.1	0	0.4	1

† Data from Moorman et al. (1999).

‡ Data from Nangia et al. (2010).

**Table 6. Observed/reported and simulated average April–August nitrogen budget for the SWAT and Revised SWAT models.**

	Annual average obs./literature		SWAT (CN2 = 78)		SWAT (CN2 = 30)		Revised SWAT (CN2 = 78)	
	N	Applied N	N	Applied N	N	Applied N	N	Applied N
	$\text{kg ha}^{-1}$	%	$\text{kg ha}^{-1}$	%	$\text{kg ha}^{-1}$	%	$\text{kg ha}^{-1}$	%
Applied fertilizer	200.0	100	200.0	100	200.0	100	200.0	100
Total N crop uptake	143	73	148.8	74	152.3	76	152.3	76
$\text{NO}_3\text{-N}$ losses in tile flow	33.5	17	23.7	12	32.7	16	33.4	17
Denitrification		10–25†	19.9	10.0	14.9	7.5	14.9	7.5

† Data from Meisinger and Randall (1991).

2000; Nangia et al., 2010) and measured values than the values predicted by the SWAT (CN2 = 78) model uncalibrated for CN2. The plant N uptake simulated by the SWAT (CN2 = 30) model was 7% greater than the measured annual average value of 143 kg ha<sup>-1</sup> N (Table 6). The corresponding average corn yield simulated by the SWAT (CN2 = 30) model was 9.4 metric tons ha<sup>-1</sup>, which was higher than that simulated by the SWAT (CN2 = 78) due to higher simulated plant N uptake (Table 6). The average annual NO<sub>3</sub>-N losses by denitrification simulated by the SWAT (CN2 = 30) model were less than the annual average denitrification losses reported by Meisinger and Randall (1991). The SWAT (CN2 = 30) model predicted NO<sub>3</sub>-N in tile flow was within 2% of the measured annual losses by tile drainage (Table 6) due to a better simulation of the predicted tile flow (Table 5).

Although the SWAT (CN2 = 30) model simulated the water and N budgets well, setting CN2 = 30 represents meadow (continuous grass, protected from grazing, and generally mowed for hay) on soil hydrologic group A (good hydrologic condition) or brush (brush-weed-grass mixture with brush the major element) on soil hydrologic group A or woods on soil hydrologic group A (SCS, 1972). None of these three cases represents corn on a hydrologic group B soil (in good condition). This scenario was included in this study to demonstrate that, although it is possible to obtain proper water and N budgets and statistics by changing CN2, such a drastic adjustment of CN2 during the calibration process is unrealistic and not recommended. This scenario also made the case for the modifications to the retention parameter in the SWAT model and the development of the Revised SWAT model.

The Revised SWAT model adjusts the estimated daily curve numbers and thereby decreases the predicted surface runoff to a reasonable amount without changing the CN2 input parameter beyond the NRCS recommended ranges (SCS, 1972). The average ET, surface runoff, and tile flow predicted by the Revised SWAT models were 74, 1, and 37% of growing season precipitation, respectively (Table 5). Just as with the SWAT (CN2 = 30) model, the ET predicted by the Revised SWAT model was within the reported values (Moorman et al., 1999). The surface runoff predicted by the Revised SWAT model was close to the reported value (Randall and Iragavarapu, 1995; Davis et al., 2000; Nangia et al., 2010). The predicted tile flow was also close to the measured value (Table 5). According to Moriasi et al. (2007b), a model is considered satisfactorily calibrated for stream flow, sediments, and nutrients if monthly NSE ≥ 0.65 and if PBIAS ≤ ±10%, PBIAS ≤ ±15%, and PBIAS ≤ ±25% for streamflow, sediments, and nutrients, respectively. These results

imply that the Revised SWAT model simulated surface runoff and tile flow amounts properly and indicate that it partitioned water much closer to the measured and reported values than the SWAT (CN2 = 78) model (Table 5).

With additional testing, the surface runoff simulated by the Revised SWAT with and without tile drainage was found to be 1 and 28% of total annual rainfall, respectively. Although we did not have observed surface runoff data from paired plots (with and without tile drainage) near the study area, these simulated surface runoff values were in the same order of magnitude as the values reported in literature (Istok and Kling, 1983; Bengtson et al., 1995; Bengtson and Carter, 2004) of the impacts of tile drainage on water budgets for field studies. The surface runoff reduction due to the presence of tile drains simulated by the Revised SWAT model is in the same order of magnitude as the 35% reduction reported by Bengtson et al. (1995) and the 29% reduction reported by Bengtson and Carter (2004) for plot-scale studies in Louisiana. In western Oregon, Istok and Kling (1983) observed that when tile drainage was installed in a 1.4-ha silt loam watershed with slopes ranging from 0 to 15%, watershed runoff yield was reduced by 65%. The reduction in surface runoff due to the implementation of tile drainage was greatest with low-intensity rainfall and least for high-intensity rainfall (Irwin and Whitely, 1983; Sands, 2009).

For N, the average annual plant N uptake simulated by the Revised SWAT model for the growing season months of April to August was 7% greater than the measured annual average value (Table 6). The average corn yield simulated by the Revised SWAT model for the period from 1983 to 1996 was 9.4 t ha<sup>-1</sup> similar to the value simulated by the SWAT (CN2 = 30) but was about 6% higher than the average (1983–1992) observed yield. As with the SWAT (CN2 = 30) model, the N losses by denitrification simulated by the Revised SWAT model were less than the annual average value reported by Meisinger and Randall (1991). The Revised SWAT model predicted the same average annual NO<sub>3</sub>-N losses in tile flow as the measured average annual losses (Table 6) and corresponded well to correct partitioning of the surface runoff and tile flow components (Table 5).

## Model Calibration and Validation Performance for Monthly Tile Flow and Nitrate-Nitrogen Losses

The calibration and validation performance results for predicting monthly tile flow and associated NO<sub>3</sub>-N losses are presented in Table 7. Supporting time series graphical plots for the calibration and validation periods of monthly tile flow and NO<sub>3</sub>-N are illustrated in Fig. 3 and 4, respectively. Because of

**Table 7. Tile flow and NO<sub>3</sub>-N simulation performances: monthly tile flow and associated NO<sub>3</sub>-N losses calibration and validation statistics for the SWAT and the Revised SWAT models.**

Component	Method	Calibration†			Validation		
		NSE	PBIAS	RMSE	NSE	PBIAS	RMSE
Tile flow	SWAT (CN2 = 78)	0.46	53	4.4 mm	0.27	55	3.6 mm
	SWAT (CN2 = 30)	0.85	2	2.3 mm	0.70	7	2.3 mm
	Revised SWAT	0.84	4	2.4 mm	0.76	8	2.1 mm
NO <sub>3</sub> -N losses in tile flow	SWAT (CN2 = 78)	0.64	24	6.6 kg ha <sup>-1</sup>	0.46	35	6.9 kg ha <sup>-1</sup>
	SWAT (CN2 = 30)	0.77	0	5.3 kg ha <sup>-1</sup>	0.64	5	5.6 kg ha <sup>-1</sup>
	Revised SWAT	0.78	-1	5.2 kg ha <sup>-1</sup>	0.65	2	5.6 kg ha <sup>-1</sup>

† NSE, Nash-Sutcliffe efficiency; PBIAS, percent bias; RMSE, root mean square error.

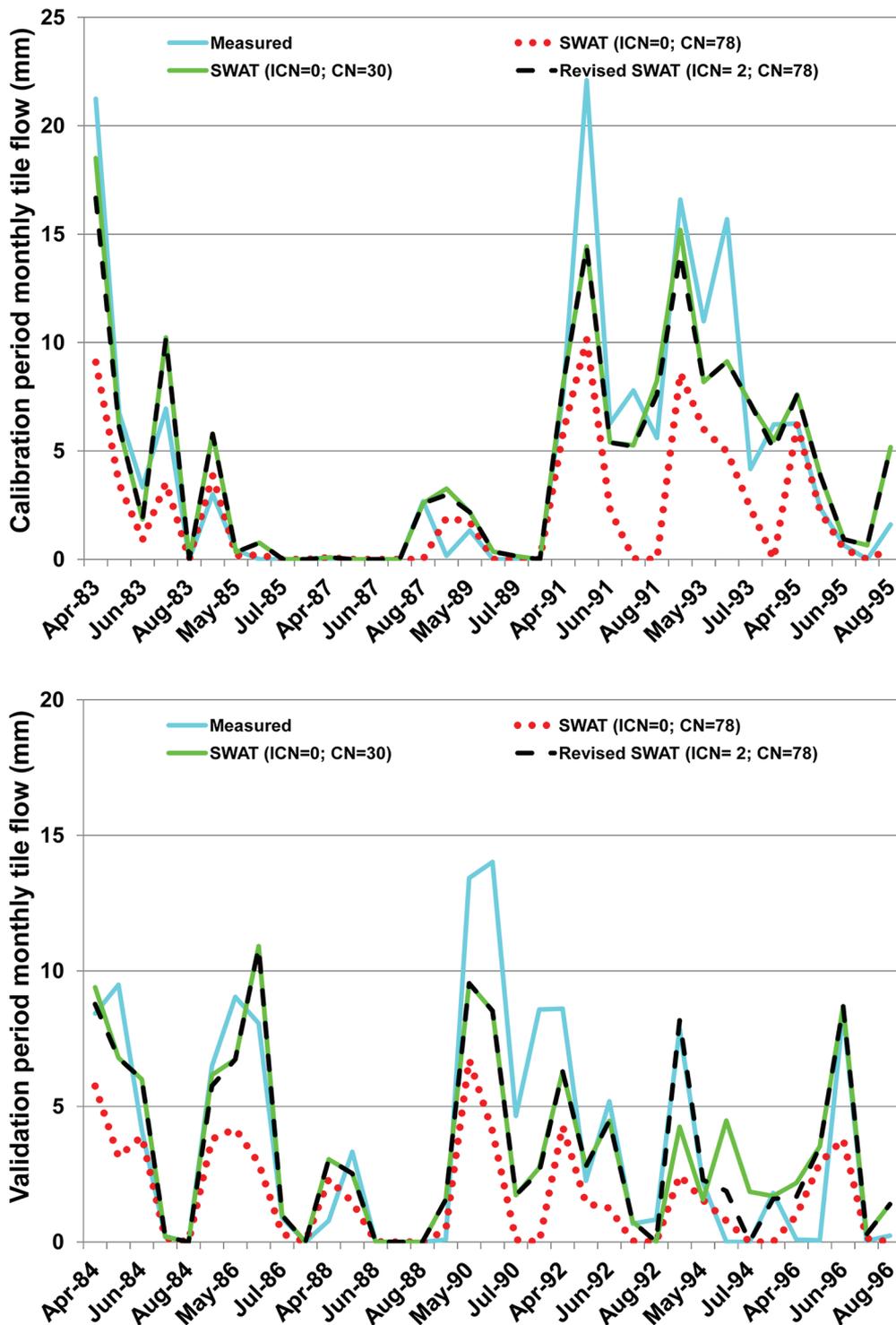


Fig. 3. Time series of monthly tile flow for the calibration and validation periods. CN, curve number; ICN, daily curve number calculation method.

the failure to correctly partition surface runoff and tile flow and the corresponding  $\text{NO}_3\text{-N}$  losses through tile drains, the SWAT (CN2 = 78) model did not perform well (Table 7; supported by the monthly hydrographs in Fig. 3 and 4). During the calibration period, the monthly tile flow NSE and PBIAS for SWAT (CN2 = 78) were 0.46 and 53%, respectively, whereas for the  $\text{NO}_3\text{-N}$  losses they were 0.64 and 24%, respectively (Table 7). During the validation period, the monthly tile flow NSE and PBIAS for SWAT (CN2 = 78) were 0.27 and 55%, respectively, whereas for

the  $\text{NO}_3\text{-N}$  losses they were 0.46 and 35%, respectively (Table 7). Based on Moriasi et al. (2007b) criterion, the SWAT (CN2 = 78) calibration was unsatisfactory for tile flow and for the corresponding  $\text{NO}_3\text{-N}$  losses.

During the calibration period, the monthly tile flow NSE and PBIAS for SWAT (CN2 = 30) model were 0.85 and  $\pm 2\%$ , respectively, whereas for the Revised SWAT they were 0.84 and  $\pm 4\%$ , respectively (Table 7). Based on the Moriasi et al. (2007b) criterion, the SWAT (CN2 = 30) and Revised SWAT models

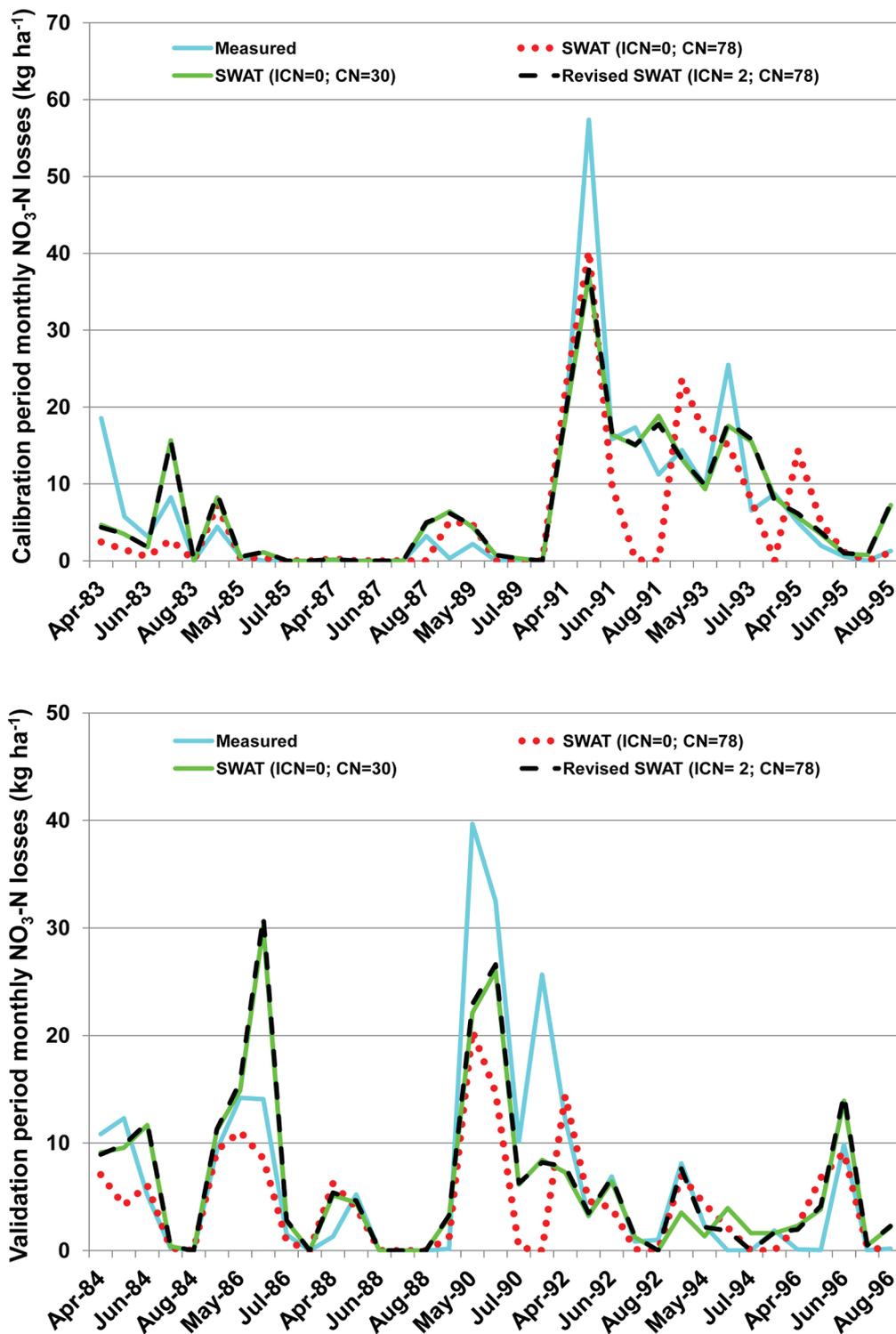


Fig. 4. Time series of monthly  $\text{NO}_3\text{-N}$  losses in tile flow for the calibration and validation periods. CN, curve number; ICN, daily curve number calculation method.

were satisfactorily calibrated for tile flow as presented in Table 7 and supported by the monthly hydrograph (Fig. 3). The statistical results during the validation period were good but not as good as those during the calibration period for the SWAT (CN2 = 30) and Revised SWAT models, although the Revised SWAT model simulated the trends better (NSE = 0.76) than the SWAT (CN2 = 30) model (NSE = 0.70) (Table 7; Fig. 3). The tile flow RMSE values simulated by the SWAT (CN2 = 30) and Revised SWAT

models during the calibration and validation periods were much lower than the those simulated by the SWAT (CN2 = 78) model, although the Revised SWAT model simulated approximately 9% lower tile flow RMSE during the validation period (Table 7).

Figure 4 illustrates the monthly  $\text{NO}_3\text{-N}$  losses through tile drainage during the calibration and validation periods. In general, the  $\text{NO}_3\text{-N}$  losses simulated by the SWAT (CN = 30) and Revised SWAT models compared fairly well with the

observed data. As with tile flow, the SWAT (CN2 = 30) and Revised SWAT models simulated tile drain NO<sub>3</sub>-N losses fairly well during the calibration and validation periods, as indicated by NSE and PBIAS (Table 7). As with tile flow, the RMSE values for tile drainage NO<sub>3</sub>-N losses simulated by the SWAT (CN2 = 30) and Revised SWAT models during the calibration and validation periods were less than those simulated by the SWAT (CN2 = 78) model (Table 7). However, calibration of CN2 by drastically changing it from 78 to 30 is unrealistic, as explained earlier, and the Revised SWAT, completed in this study, is the most realistic and is the recommended model as proven by good model simulation performance for the recommended CN2 value of 78 for corn. Due to improvements in simulating water budgets for the poorly drained and mildly sloped agricultural areas that dominate the midwestern United States, the retention parameter adjustment factor introduced in this study has already been incorporated in ArcSWAT2012 (Arnold et al., 2013).

## Conclusions

Subsurface tile drainage is a commonly used agricultural practice to enhance crop yield in poorly drained but highly productive soils in many regions of the world. However, the presence of subsurface tile drainage systems expedites the transport of NO<sub>3</sub>-N and other chemicals to surface waters. Hydrologic and water quality models such as SWAT are widely used to simulate tile drainage systems at various spatial scales. However, the soil profile moisture accounting method used by SWAT to compute the daily CN does not correctly partition surface runoff and tile flow for poorly drained soils and mildly sloped agricultural areas. This deficiency has detrimental implications on the prediction of soil erosion and greatly affects the partitioning of NO<sub>3</sub>-N losses between surface runoff and subsurface tile drainage. This has major implications on time to peak flow and on the magnitude of peak flow, which are important in channel processes. In this study, modifications were made to correct the stated problem by revising the soil profile method to introduce a retention parameter adjustment factor ( $SA_{fctr}$ ) to account for variable tile drainage systems, mild slopes, and drainable properties of shallow, poorly drained soils. Long-term monitoring data (14 yr) on subsurface tile flow and NO<sub>3</sub>-N losses in tile flow from Minnesota were used to evaluate the Revised SWAT model. Based on the results, the Revised SWAT model simulated the water and N budgets more accurately compared with the SWAT model. The calibration and validation results indicated that the Revised SWAT model simulated tile flow and its associated NO<sub>3</sub>-N losses reasonably well on a monthly time step compared with the nonrevised SWAT model. The retention parameter adjustment factor has already been incorporated into ArcSWAT2012. The accurate simulation of tile flow and NO<sub>3</sub>-N losses will lead to reliable simulation of the effectiveness of drainage water and NO<sub>3</sub>-N management and winter cover crops on reducing its losses to surface water bodies. Additional studies are underway to determine how well the Revised SWAT model simulates water and N budgets during the winter and growing seasons. Further studies are needed to determine suitable lower and upper bounds of the  $SA_{fctr}$ . Accurate simulations of the impacts of management practices, such as drainage water management and winter

cover crops, on drainage and associated NO<sub>3</sub>-N losses will help farmers, water managers, policy and decision makers, and researchers in the midwestern United States and in similar areas globally.

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