Incorporation of a New Shallow Water Table Depth Algorithm into SWAT2005

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Abstract. *The fluctuation of the shallow water table depth (wtd) is important for planning drainage systems at the plot-, field-, and watershed-scale because its proximity to the ground surface impacts farm machine trafficability, crop development, agricultural chemical transport, soil salinity, and drainage. Therefore, it is important for hydrologic models to accurately simulate wtd. The goals of this study were to: (1) develop and incorporate a new wtd algorithm into the Soil and Water Assessment Tool model (SWAT Release 2005), a continuous-time, physically based, watershed-scale hydrologic model, in order to improve the prediction of the wtd; and (2) evaluate the wtd prediction improvement using measured wtd data for three observation wells located within the Muscatatuck River basin in southeast Indiana. The Modified DRAINMOD wtd simulation approach, based on the DRAINMOD wtd prediction approach, was developed and incorporated into SWAT2005. SWAT2005 was calibrated and validated for wtd for the three observation wells, and the wtd prediction performance of the Modified DRAINMOD approach was compared to those of three other wtd routines used in SWAT. Based on the simulation results, the Modified DRAINMOD approach yielded the best wtd prediction performance, as indicated by the highest average daily calibration and validation Nash-Sutcliffe efficiency (NSE) values of 0.64 and 0.41, respectively, and correlation coefficient (R) values of 0.81 and 0.65, respectively, and the lowest percent bias (PBIAS) values of -13% and -3%, respectively, and root mean square error (RMSE) values of 0.41 m and 0.59 m, respectively, for the three observation wells. This implies that the Modified DRAINMOD approach within SWAT2005 improved the prediction of wtd. Enhanced wtd prediction is anticipated to increase the simulation accuracy of watershed hydrologic processes and water management components such as tile drainage.*

Keywords. *DRAINMOD, Simulation, SWAT, Watershed, Water table depth.*

The proximity of the shallow water table depth (*wtd*) to the soil surface can negatively impact farm machine trafficability (Paul and De Vries, 1979), crop development (Stone and Ekwue, 1993; Brisson et al., 2002), agricultural chemical transport, soil salinity (Northey et al., 2005), and drainage (Skaggs, 1980). In light of these significant impacts of *wtd* fluctuations on the various aspects of agricultural production, it is important for hydrologic models to accurately simulate *wtd* fluctuations. Some of the methods used to simulate *wtd* include TOPMODEL (Beven and Kirkby, 1979), kinematic wave formulation, diffusion theory, and DRAINMOD approaches.

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TOPMODEL (Beven and Kirkby, 1979), a hillslope hydrology model, considers gravity as the main force driving water within the soil, where subsurface flow is represented as a water sheet running locally parallel to the topographic surface. The flow is expressed using Darcy's law while making three main assumptions: (1) the local hydraulic gradient is constant in time and equal to the local topographic slope, (2) the discharge per unit area is steady in space, and (3) the transmissivity and the hydraulic conductivity decrease exponentially with depth. Combined with the mass conservation law, these assumptions lead to a relation between the local water table and the mean catchment water table. According to Molénat et al. (2005), the TOPMODEL concept can reasonably simulate *wtd* for areas in or around the stream where there is low groundwater surface fluctuations (e.g., within 40 cm of the top soil layer). However, the assumptions used are far from reality in some regions of the catchment where the hydraulic gradients are variable in time and do not equal the topographic slope (Molénat et al., 2005). In addition, these assumptions are not realistic where the groundwater shape appears to change with time, especially in the upslope area (Molénat et al., 2005).

For the kinematic wave formulation approach, water is routed from one grid cell to another, which relaxes TOPMODEL's steady-state assumption. This concept is used by the TNT2 (topography-based nitrogen transfer and transformation) model (Beaujouan et al., 2002), which was developed to study nitrogen fluxes in small catchments. In this case, water mass balance is computed locally for each cell and at each time step by considering the vertical recharge, total flow from the upslope cell, and total flow to the downslope cell. At the end of each time step, the new *wtd* is computed as the sum of the previous water table depth and the mass balance divided by the drainable porosity. In the case of an occurrence of return flow, the return flow is immediately routed towards the downslope cell and the water table is set to zero. Relaxing the steady-state assumption improves water table depth simulation in the mid-slope and to a small extent the summit areas (Molénat et al., 2005).

Molénat et al. (2005) describe another *wtd* concept based on diffusion theory. In the diffusive approach, the water is routed cell by cell similar to the kinematic model but based only on the assumption that the transmissivity still decreases exponentially with depth and that the local hydraulic gradient varies with time. Therefore, the diffusive model relaxes both the steady-state and constant hydraulic gradient assumptions made by TOPMODEL. Thus, in a given cell, the local hydraulic gradient is estimated at each time step from the *wtd* values and the elevations of this cell and its neighboring downslope cell. The relaxation of the hydraulic gradient assumption further improves the simulation of the water table in summit areas, while still providing realistic water table depths in the bottom lands (Molénat et al., 2005). Although the diffusive approach gives the best results for distributed water table depth simulation, the simulated *wtd* values obtained with the diffusive model are still far removed from the actual observed values, especially in places where the bedrock surface is irregular.

DRAINMOD (Skaggs et al., 1978) is a field-scale computer model developed to aid in the design and evaluation of agricultural drainage and water table management systems for poorly drained, high water table soils. DRAINMOD computes *wtd* based on the drainage volume versus *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. This relationship is used to determine how far the water table falls or rises when a given amount of water is removed or added. When the drainage volume is zero, it means that all the pore spaces in the profile are filled with water and hence the *wtd* is set to zero. The drained water volume at various water table depths (also known as water yield) can be measured directly from large undisturbed soil cores, estimated from the soil water characteristics, or estimated from drainable porosities of each layer (Skaggs, 1980). One of the advantages of using the DRAINMOD approach to simulate *wtd* is that it requires easily measurable soil properties mentioned at a plot or field scale. However, it is difficult to determine the drainage volume versus *wtd* relationships using the more accurate direct measurement from large undisturbed soil cores or estimation from soil water characteristics for soils at a watershed scale.

Vazquez-Amábile and Engel (2005) used water balance outputs from the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Arnold and Fohrer, 2005) as inputs for the DRAINMOD approach to compute perched *wtd* in order to expand the capabilities of SWAT to estimate *wtd*. Drainage volume was estimated from drainable porosities of each soil layer because this approach is suitable for watershed-scale studies where soil water characteristics are hard to obtain and because of its compatibility with the SWAT soil input data (Vazquez-Amábile and Engel, 2005). According to Vazquez-Amábile and Engel (2005), SWAT *wtd* predictions for three soils at sites located within the Muscatatuck River basin in southeast Indiana resembled the seasonal variation of the measured *wtd* (with correlation coefficients of 0.68, 0.67, and 0.45 for the three wells during validation). As a result, Vazquez-Amábile and Engel (2005) concluded that including the DRAINMOD *wtd* prediction approach in SWAT would increase its capabilities. One of the major limitations of this approach is that the slope of the drainage volume versus *wtd* relationship is depicted by the drainage porosity, assuming that the soil is completely drained immediately above the water table (Vazquez-Amábile and Engel, 2005). However, there is a transition zone, or capillary fringe, above the water table, which is at saturation near its base while its upper extent is near field capacity (Charbeneau, 2000). This transition zone above the water table is more evidenced in fine soils than in coarse soils, which leads to underestimation of water table depth (Vazquez-Amábile and Engel, 2005). In addition, this procedure becomes cumbersome when there is a large amount of data.

The goals of this study were to: (1) develop and incorporate a new water table depth algorithm, the Modified DRAINMOD approach based on the DRAINMOD approach, into SWAT in order to improve the prediction of *wtd*; and (2) evaluate the *wtd* prediction improvement using measured *wtd* data for three observation wells located within the Muscatatuck River basin in southeast Indiana. SWAT was calibrated and validated for *wtd* for the three observation wells and the *wtd* prediction performance of the Modified DRAINMOD approach method was compared to those of three other *wtd* routines used in SWAT (described below). The DRAINMOD *wtd* simulation approach was selected as a starting point in this study because it requires easily measurable soil properties, is compatible with the SWAT soil input data, and has been tested with SWAT (Vazquez-Amábile and Engel, 2005) with reasonable results.

SWAT Overview and Water Table Depth Approaches

SWAT Overview

SWAT is a continuous-time, physically based, watershed-scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in watersheds with varying soils, land use, and management conditions over time. SWAT has been successfully used to evaluate nonpoint-source water resource problems for a large variety of water quality applications nationally and internationally, and as a result it is under continuous development to meet the needs of its many users, while maintaining a user-friendly framework (Gassman et al., 2007). SWAT requires specific information about weather, soil properties, topography, vegetation, ponds or reservoirs (if present), groundwater, the main channel, and land management practices to simulate water quality and quantity (Neitsch et al., 2002a, 2002b). The model simulates a watershed by dividing it into sub-basins, which are further subdivided into hydrologic response units (HRUs). These HRUs are the product of overlaying soils and land use. Components of SWAT include: hydrology, weather, sedimentation/erosion, soil temperature, plant growth, nutrients, pesticides, and agricultural management (Neitsch et al., 2002a, 2002b). The hydrologic components include surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, percolation/deep seepage, consumptive use through pumping (if any), shallow aquifer contribution to streamflow for a nearby stream (baseflow), recharge by seepage from surface water bodies (Neitsch et al., 2002a, 2002b), and water table depth (although not an output of interest currently).

SWAT uses two methods to estimate surface runoff and infiltration: the SCS curve number procedure (SCS, 1972), and the Green and Ampt infiltration method (Green and Ampt, 1911). The SCS curve number approach was used in this study to evaluate the Modified DRAINMOD approach incorporated into SWAT. Percolation is calculated for each soil layer in the profile in SWAT (Neitsch et al., 2002a). Water is allowed to percolate if the water content exceeds the field capacity water content for that layer and the layer below is not saturated. There are two approaches used to compute tile drainage in SWAT. In the first approach, tile drainage in an HRU is simulated when the user specifies the depth from the soil surface to the drains, the amount of time required to drain the soil to field capacity, and the amount of lag between the time water enters the tile until it exits the tile and enters the main channel (Arnold et al., 1999). A more recent approach incorporated by Moriasi et al. (2007) utilizes the Hooghoudt (1940) steady-state and Kirkham (1957) tile equations, which have been successfully used in DRAINMOD (Skaggs et al., 1978). A detailed description of how these and the rest of the hydrologic components are computed in SWAT is given by Arnold et al. (1998) and/or in the SWAT theoretical documentation (Neitsch et al., 2002a). The *wtd* simulation approaches that are available in or have been associated with SWAT are the SWAT-M approach, the SWAT2005 approach, and the DRAINMOD approach using the SWAT soil data outputs (Vazquez-Amábile and Engel, 2005).

SWAT-M Approach

In the SWAT-M approach (Du et al., 2005), a restrictive layer, which simulates a confining layer and is used as the maximum *wtd*, is set at the bottom of the soil profile. Beginning with the bottom soil layer, the soil profile above the confining layer is allowed to fill with water to field capacity. When the bottom soil layer reaches field capacity, additional water is allowed to fill the profile from the bottom of the soil layer upward, from which the height of the water table above the restrictive layer and hence the *wtd* from the ground surface is computed. The SWAT-M approach does not require calibration. A detailed description and an example calculation of this *wtd* algorithm are given by Du et al. (2005).

SWAT2005 Approach

The SWAT2005 approach, which is based on antecedent climate, serves as the master soil percolation component. This routine computes *wtd* using 30-day moving summations of precipitation, surface runoff, and ET as follows:

$$wtab(j) = wtab(j) - w1 * \left(wtab(j) - wt1\right) \qquad (1)$$

where *wtab(j)* is the *wtd* or the day in hydrologic response unit (HRU) *j* (m); $w1$ is a factor computed as the minimum value of either 0.1 or the absolute value of $w2$, which is the ratio of the 30-day moving sum of (precipitation - surface runoff - ET) to the 30-day moving sum of ET; $wt1$ (m) is assigned *wtab_mn(j)* if $w1 > 0.0$ and *wtab_mx(j)* if $w1 \leq 0.0$, where *wtab_mn(j)* is the minimum *wtd* for the day for HRU *j* set at 0.0 m, and *wtab_mx(j)* is the maximum water table depth for the day for HRU *j* set at 2.6 m below the ground surface. The value of *wtab(j)* at the beginning of simulation is set at 0.80 m. Like the SWAT-M approach, this approach does not require calibration.

Another *wtd* approach that has been used in connection with SWAT is the DRAINMOD approach used in SWAT (Vazquez-Amábile and Engel, 2005). The DRAINMOD approach determines the *wtd* outside of SWAT using soil water balance outputs, as briefly described in the introduction of this article. For a detailed description of how this approach computes the *wtd*, refer to Vazquez-Amábile and Engel (2005).

The SWAT-M and SWAT2005 *wtd* approaches used in SWAT are appropriate for simulation of streamflow, sediment, and nutrients, as indicated by the many applications described by Gassman et al. (2007). According to Molénat et al. (2005), most *wtd* simulation approaches appear appropriate to simulate streamflow discharge because of low water table fluctuations. However, water management systems such as tile drainage used in agricultural regions with seasonal high water tables, such as the Midwest U.S., require accurate *wtd* simulations. While incorporating the Hooghoudt (1940) steady-state and Kirkham (1957) tile equations into SWAT2005 to allow for multiple scenario simulations, such as varying tile spacing, depth, and size, Moriasi et al. (2007) noted that the SWAT-M and SWAT2005 approaches exhibited some weaknesses in simulating *wtd*. Closer inspection of the simulated *wtd* time series revealed that the *wtd* profile was intuitively reasonable during relatively long wet periods. However, during relatively short dry periods followed by short wet periods, the *wtd* profile was somewhat erratic in terms of its fluctuations within the soil profile. Although *wtd* predictions using the DRAINMOD approach based on the soil moisture output data from SWAT resembled the seasonal variation of the measured groundwater table, the DRAINMOD approach was tested outside of SWAT, its *wtd* predictions would need improvement if it is to be used for simulating tile drainage on a daily time step, and finally this approach is difficult to implement for watershed-scale hydrologic modeling without major modifications. Therefore, an improved *wtd* simulation approach is needed within SWAT in order to increase the accuracy of simulating water management systems such as tile drainage and other watershed hydrologic processes.

Modified DRAINMOD Approach

In general, the Modified DRAINMOD approach in SWAT is based on the DRAINMOD water table depth determination concept of relating the drainage volume to the *wtd* (Skaggs, 1980). However, this modified approach differs from the DRAINMOD approach (Vazquez-Amábile and Engel, 2005) in how the drainage volume is determined and how the drainage volume is related to the water table depth.

The drainage volume, *vol*, is determined by carrying out water balance within the soil profile between the ground surface and the restrictive layer using the soil water balance components computed by SWAT. In this approach, the restrictive layer is set at the bottom of the deepest layer within the soil profile. Water is removed from the soil profile by drainage, ET, lateral flow, consumptive use through pumping (if any), deep seepage, and shallow aquifer contribution to streamflow for a nearby stream (baseflow). Water enters the soil profile by infiltration, although some recharge by seepage from surface water bodies within the watershed may occur. In SWAT, the shallow unconfined aquifer recharge by seepage from surface water bodies within the watershed is not computed because it is assumed that it rarely occurs and that its contribution is insignificant; hence, it is not considered in the computation of *vol*. Therefore, the *vol* in each HRU is computed as follows:

$$vol = vol_i - \inf lpcp + sepbtm + qtile + latq$$

$$+ etday + gw\_q + wushall \text{ if } vol \geq 0.0 \quad (2)$$

$$vol = 0.0 \text{ if } vol < 0.0 \quad (3)$$

where vol_i is the HRU drainage volume at the beginning of the simulation, which, if unknown, may be taken as 0 mm when the model has a warm-up period before the simulation time period; *inflpcp* is the daily amount of water or precipitation that infiltrates into the soil in the HRU (mm); *sepbtm* is the daily percolation from the bottom of the soil profile or deep seepage in the HRU (mm); *qtile* is the daily drainage tile flow in the soil profile in the HRU (mm); *latq* is the total daily lateral flow in soil profile in the HRU (mm); *etday* is the daily actual amount of ET in the HRU (mm); *gw_q* is the daily shallow aquifer contribution to streamflow (baseflow) from the HRU (mm); and *wushall* is the average daily water removal from the shallow aquifer on a given month for the HRU within the sub-basin (mm). All the soil profile water balance components used in equation 2 are computed by SWAT, and a detailed theoretical description for each component is given in the SWAT theoretical documentation (Neitsch et al., 2002a).

The water table depth is computed as a function of *vol* using the following simple linear water table depth prediction equations that closely matched the measured water table depth values:

$$wtd = c * vol \text{ if } wtd \leq dep\_imp \quad (4)$$

$$wtd = dep\_imp \text{ if } wtd > dep\_imp \quad (5)$$

where *wtd* is the water table depth (mm); *vol* is the drainage volume (mm); $c > 0.0$ is the equation coefficient, which is a calibration parameter that is a function of the soil type; and *dep_imp* is depth from the ground surface to the impervious layer (mm). This relationship was determined by relating the *vol* values, computed using the calibrated SWAT model parameter values for the Muscatatuck River basin (MRB) in southeast Indiana (Vazquez-Amábile and Engel, 2005) to the measured *wtd* for three wells within MRB. Several *wtd* prediction equations (exponential, logarithmic, power, linear, and combinations) that relate the computed *vol* to the measured *wtd* and the equations whose values closely matched the measured *wtd* values were selected.

In this approach, the water table falls or rises when a given amount of water is removed from or added into the soil profile fluctuating between the ground surface and the impervious layer (*dep_imp*). When *vol* is zero, this means that all the pore spaces within the soil profile are filled with water (saturated), and hence *wtd* is set to zero. If the computed *vol* is less than zero, it is set to zero (eq. 3). There is no upper bound for the computed value of *vol*, and hence the simulated *wtd* value can be as high as possible depending on the computed *vol*. When the simulated *wtd* is greater than the depth to impervious layer, the *wtd* is set equal to *dep_imp* (eq. 5).

This Modified DRAINMOD *wtd* prediction approach was incorporated into SWAT2005 in this study. In addition to the basic model inputs such as the digital elevation model (DEM), soils, land use, and weather, the depth to the impervious layer (*dep_imp*) and the equation coefficient *c* for each HRU are required in order to simulate *wtd* using this new approach.

Materials and Evaluation Methods

Watershed Description

Evaluation of the four *wtd* simulation approaches used in SWAT discussed in this study used the data and information from a study by Vazquez-Amábile and Engel (2005) at the Muscatatuck River basin (MRB). As a result, only a brief description is given here, while complete details are given by Vazquez-Amábile and Engel (2005). The MRB is located in Decatur, Jennings, Ripley, Jefferson, Scott, and Jackson counties in southeast Indiana (fig. 1). There are three USGS stream gauges within the watershed located at Vernon, Deputy, and Harberts creeks, where daily streamflow discharge data is recorded. The *wtd* recorded by Jenkinson (1998) at three observation wells located in the Storm Creek lower watershed was used in this study to calibrate and validate the Modified DRAINMOD approach.

Input Data

Weather, streamflow, groundwater table, soil, land use, elevation, and hydrologic data and water table inputs used by Vazquez-Amábile and Engel (2005) to investigate the performance of SWAT to compute *wtd* and streamflow in the MRB were converted into the SWAT2005 model format and used in this study. A brief description of some of these data is given below, while a detailed description of each of the data used in this study is given by Vazquez-Amábile and Engel (2005).

Daily weather data were obtained from the records of the Greensburg 2E, Greensburg, and North Vernon 2 ESE weather stations (fig. 1) measured between 1976 and 2002. Daily streamflow data obtained from USGS gauges located in Vernon, Deputy, and Harberts Creek near Madison (fig. 1) for the years 1976-2002 were used by Vazquez-Amábile and Engel (2005) to calibrate and validate SWAT for streamflow. Groundwater table data measured by Jenkinson (1998) between 1992 and 1996 at three observation wells located in the Avonburg, Rossmoyne, and Cobbsfork soil series at the Muscatatuck Wildlife Refuge in the Storm Creek lower watershed (MWR) (fig. 1) were used to evaluate the *wtd* routines in SWAT2005. The observation wells were made from a 3.0 m length of schedule 40 PVC pipe that had an inside diameter of 7.62 cm. Two slots 0.32 cm wide with a chord length of 6.50 cm were located on opposite sides at 5.00 cm intervals along the length of the pipe for a distance of 2.5 m. The pipes were installed in the soil by digging a hole using an 8.90 cm diameter auger bit to a depth 2.5 m (Jenkinson, 1998).

The State Soil Geographic Database (STATSGO; approximate scale 1:250,000) was used to calibrate and validate streamflow because detailed soils data from the Soil Survey Geographic database (SSURGO) were not available for all the six counties covering MWR when SWAT2000 projects were built (Vazquez-Amábile and Engel, 2005). Although

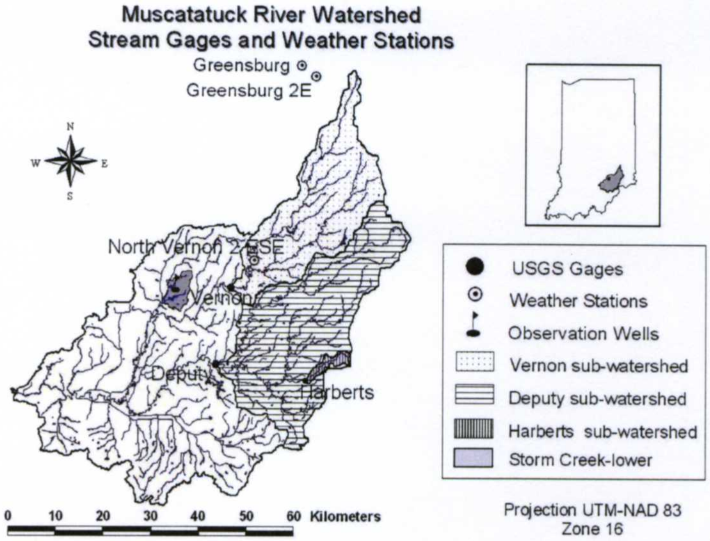

Figure 1. Weather stations and USGS gauges for the MRW (Vazquez-Amábile and Engel, 2005).

the SSURGO database was available during this study, the STATSGO soils database was used in order to maintain uniformity with the previous study (Vazquez-Amábile and Engel, 2005). In addition, the SSURGO soils database does not always significantly improve model performance compared to the STATSGO database (Wang and Melesse, 2006; Ghidey et al., 2007), although the SSURGO database requires more resources such as computer storage space and time to build and run the model project due to a greater number of HRUs. However, available SSURGO data for Jennings and Jackson counties, in which the three wells reside, were checked and updated by Vazquez-Amábile and Engel (2005) for use in evaluating the *wtd* routines in SWAT2005. The soil input data for the three soils are presented in table 1. The land use at each of these soil series was forest.

Measures of Model Performance

In addition to percent bias (PBIAS), the same model performance measures used by Vazquez-Amábile and Engel (2005) were adopted and used to compare the performance of each of the *wtd* prediction approaches. These performance measures include the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970), root mean square error (RMSE), correlation coefficient (R), and the single-factor analysis of variance (ANOVA) on the correlation. NSE indicates how well the plot of observed versus simulated data fits the 1:1 line, and it is determined as follows:

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} (Y^{obs}{}_i - Y^{sim}{}_i)^2}{\sum_{i=1}^{n} (Y^{obs}{}_i - Y^{mean})^2} \right] \quad (6)$$

where Y^{obs}_i is the *i*th observation for the constituent being evaluated, Y^{sim}_i is the *i*th simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and *n* is the total number of ob-

Table 1. Soil input data by layer for the three soil series (Vazquez-Amábile and Engel, 2005).

Soil Series	Layer	Cumulative Depth (mm)	Clay (%)	Silt (%)	Sand (%)	Available Water Content (mm mm^{-1})	Wilting Point (mm mm^{-1})	Bulk Density (g cm^{-3})	Porosity (mm mm^{-1})	Drainage Porosity (mm mm^{-1})
Avonburg	1	450	16.1	67.8	16.1	0.22	0.09	1.38	0.48	0.17
	2	1070	28.7	62.0	9.3	0.14	0.18	1.55	0.42	0.10
	3	1420	22.8	61.1	16.1	0.14	0.15	1.69	0.36	0.07
	4	2000	19.0	55.3	25.7	0.18	0.13	1.70	0.36	0.05
	5	2440	26.7	46.4	26.9	0.13	0.18	1.73	0.35	0.03
	6	2870	35.2	30.7	34.1	0.14	0.23	1.61	0.39	0.03
Cobbsfork	1	280	16.5	65.9	17.6	0.20	0.10	1.45	0.45	0.16
	2	560	18.0	65.0	17.0	0.19	0.11	1.56	0.41	0.11
	3	1070	25.2	59.0	15.8	0.17	0.16	1.63	0.39	0.05
	4	1930	23.9	54.7	21.4	0.15	0.16	1.72	0.35	0.04
	5	2590	29.3	48.7	22.0	0.09	0.21	1.75	0.34	0.05
Rossmoyne	1	320	11.5	71.0	17.5	0.23	0.06	1.32	0.50	0.21
	2	570	12.0	72.2	15.8	0.25	0.07	1.55	0.42	0.09
	3	940	26.6	63.5	9.9	0.11	0.16	1.52	0.43	0.16
	4	1200	24.5	63.5	12.0	0.14	0.16	1.62	0.39	0.09
	5	2400	20.4	51.1	28.5	0.16	0.14	1.75	0.34	0.04

servations. NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values greater than 0.75 are generally considered good, 0.36 to 0.75 are adequate, and values less than 0.36 indicate poor levels of performance (Motovilov et al., 1999). Values ≤ 0.0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance.

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999). PBIAS is computed as:

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n} (Y^{obs}{}_i - Y^{sim}{}_i) \times 100}{\sum_{i=1}^{n} (Y^{obs}{}_i)} \right] \quad (7)$$

where PBIAS equals the deviation of the data being evaluated, expressed as a percent, and the rest of the parameters are as defined above. According to Donigian et al. (1983), absolute PBIAS < 10% are considered very good, 10% < PBIAS < 15% are good, 15% < PBIAS < 25% are satisfactory, and PBIAS > 25% are unsatisfactory.

RMSE is an error index, in units of the constituent of interest, used to measure model performance. RMSE is computed as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2}{n}} \quad (8)$$

where n is the number of observations used to compute RMSE. It varies between 0 and $+\infty$, with RMSE = 0 as the optimal and the smaller the RMSE, the better the model performance.

Pearson's correlation coefficient (R) describes the degree of collinearity between simulated and measured data. The correlation coefficient, which ranges from -1 to 1, is an index of the degree of linear relationship between observed and simulated data. If R = 0, no linear relationship exists. If R = 1 or -1, a perfect positive or negative linear relationship exists. The single-factor analysis of variance (ANOVA) provides a test of the hypothesis that each sample is drawn from the same underlying probability distribution against the alternative hypothesis that underlying probability distribu-tions are not the same for all samples.

Evaluation Method

The sensitivity of the model calibration coefficient c in the Modified DRAINMOD approach in SWAT2005 was analyzed in order to understand its impact on the water table depth predictions. Sensitivity analysis was carried out by varying the value of parameter c starting with $c = 0$ and incrementing by 2, and then observing the relative change in the *wtd* prediction performance of SWAT2005, as enhanced with the Modified DRAINMOD approach, while holding the rest of the parameters at the calibrated and validated SWAT values (Vazquez-Amábile and Engel, 2005). The upper limit of c for the sensitivity analysis was determined as the value of c that resulted in an NSE value of zero or less during the recession phase of the variation of NSE as c was incremented by 2 for all three soil series. The impacts of c on predicted water table depth were investigated using the NSE and PBIAS values. Once a reasonable range was determined from the graphical display, a more refined calibration (using smaller increments) was carried out.

Vazquez-Amábile and Engel (2005) obtained monthly NSE values of 0.59, 0.73, and 0.80 for the Harberts, Deputy, and Vernon watersheds, respectively, during the calibration period (1976-1994) and 0.49, 0.61, and 0.81 for the Harberts, Deputy, and Vernon watersheds, respectively, for the validation period (1995-2002). Using the same SWAT2000 streamflow calibration parameter values in SWAT2005 resulted in monthly NSE values of 0.43, 0.55, and 0.78 for the Harberts, Deputy, and Vernon watersheds, respectively, during the validation period. According to Santhi et al. (2001) a monthly streamflow NSE > 0.5 is considered a satisfactory model performance rating. Model performance may have been unsatisfactory for the Harberts watershed because it was the most remote watershed from the weather station (fig. 1). Since the NSE values obtained by SWAT2005 were not significantly different (p-value = 0.79 at 5% significance level, using two-sample t-test assuming equal variance) from those obtained by SWAT2000, the calibration streamflow parameter values obtained by Vazquez-Amábile and Engel (2005) were adopted and used in this study, and hence SWAT2005 was not recalibrated for streamflow. The streamflow calibrated SWAT2005 was then calibrated for *wtd* using the *wtd* measured between 1992 and 1996 at the three wells located in MWR in the Storm Creek lower watershed near Madison (Jenkinson, 1998). The *wtd* calibration was accomplished by varying the *wtd* equation coefficient c until an optimum model performance, based on NSE and PBIAS, was obtained. The calibrated and validated *wtd* prediction results using the Modified DRAINMOD approach were compared with those of the calibrated and validated DRAINMOD approach (Vazquez-Amábile and Engel, 2005), and the predictions by the uncalibrated SWAT-M approach and SWAT2005 approach. In addition, as part of the comparison of the performance of these four approaches, continuous five-year *wtd* fluctuation profiles simulated by each approach are presented.

Results and Discussion

Sensitivity of the Modified DRAINMOD Approach Coefficient (c)

Figure 2 shows the sensitivity of c on the predicted daily *wtd*. The upper limit of parameter c for the three soils series was determined as 14 based on the procedure described in the preceding section. The NSE and PBIAS values for the three *wtd* wells, located on the Avonburg, Cobbsfork, and Rossmoyne soil series, varied greatly, indicating that daily *wtd* is quite sensitive to c. Values of NSE increased to a maximum and then started decreasing, whereas the values of PBIAS decreased from large positive (underprediction) values to an optimum (0%) and continued to decrease to large negative (overprediction) values. The optimum range of c values, which maximize the daily *wtd* NSE and minimize the daily *wtd* PBIAS, was from 3 to 5, 4 to 7, and 5 to 8 for the Avonburg, Cobbsfork, and Rossmoyne soil series, respectively.

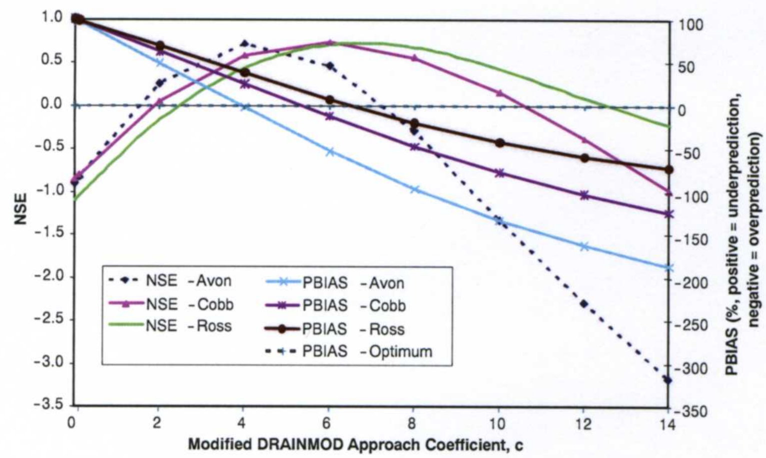

Figure 2. Effects (NSE and PBIAS values) of the Modified DRAINMOD approach equation coefficient (*c*) on daily *wtd* at three soil series located within MRW.

Based on the sensitivity result, the approximate optimum values of *c* for the Avonburg, Cobbsfork, and Rossmoyne soil series were 4, 6, and 6.5 for respectively. Using these *c* parameter values, Pearson's correlation coefficient (R) values for *c* against weighted average soil porosity and average soil profile clay content, obtained from the limited data in table 1, were computed to determine if there was any correlation between *c* and these soil properties. The results indicated a negative correlation with weighted average soil profile porosity (R = -0.55) and with average soil profile clay content (R = -0.95). However, the single-factor ANOVA test results for these correlations were not significant at 5% significance level, with p-values of 0.64 and 0.20 (table 1) for the weighted average soil profile porosity and average soil profile clay content, respectively.

Using the correlation result (table 2), it was inferred that the value of *c* varied inversely with the average weighted soil profile porosity. Soil porosity is a function of soil bulk density (ρ_b), and the value of ρ_b depends on soil texture. For example, in sandy soils, ρ_b can be as high as 1.6 g cm^{-3}, whereas in aggregated loams and in clay soils, it can be as low as 1.1 g cm^{-3} (Hillel, 1982). According to Hillel (1982), ρ_b is affected by the soil structure, i.e., the soil's degree of compaction, as well as by its swelling and shrinkage characteristics. In general, soil porosity ranges from 0.25 to 0.40 for gravel, 0.25 to 0.50 for sand, 0.35 to 0.50 for silt, and 0.40 to 0.70 for clay textured soils (Davis, 1969). Based on the correlation of *c* with the average weighted soil profile porosity (table 2) and the porosity ranges for the various soil textures (Davis, 1969), the general rule of thumb is that the value of *c* will tend to be largest with gravel and sand structured soils and smallest for clay textured soils. This is in agreement with the strong negative correlation (R = -0.95) found between *c* and the average soil profile clay content, which implies that the larger the percent average soil profile clay content, the smaller the value of *c*. However, a detailed study of the impact of soil texture and soil groups on *c* is recommended in order to determine reasonable range values for the different soil texture and hence soil groups. Such a study will provide database of default *c* values for each soil group.

Calibration and Validation of the Modified DRAINMOD Approach

The calibration and validation model performance results for the daily and monthly time steps are presented in table 3, while the time-series graphical plots of daily *wtd* fluctuations for the Avonburg, Cobbsfork, and Rossmoyne soil series are illustrated in figures 3, 4, and 5, respectively. In general, the Modified DRAINMOD approach simulated *wtd* fluctuation patterns better during the calibration period (0.59 ≤ NSE ≤ 0.66 daily; 0.72 ≤ NSE ≤ 0.73 monthly) than during the validation period (0.30 ≤ NSE ≤ 0.57 daily; 0.29 ≤ NSE ≤ 0.60 monthly) for the wells located at the three soil series, as indicated by lower NSE values and supported by figures 3, 4, and 5. Since we had limited *wtd* data, we split the data into the two periods whose conditions were different, as shown in figure 6. Although the average annual precipitation for the five-year period was 1198 mm, the annual precipitation data during the calibration period varied greatly, from 1029 mm in 1994 to 1390 mm in 1993. During the two-year validation period, the annual precipitation did not deviate much from the annual average value, with the values ranging between 1160 mm in 1996 and 1268 mm in 1995. The differences in

Table 2. Correlation (R) between *c* and total soil porosity and average soil profile clay content.

Soil Series	*c*	Avg. Weighted Soil Profile Porosity (mm mm^{-1})	Average Soil Profile Clay Content (%)
Avonburg	4.0	0.393	26.48
Cobbsfork	6.0	0.372	22.58
Rossmoyne	6.5	0.388	19.00
R		-0.55	-0.95
Single-factor ANOVA p-value		0.64	0.20

Table 3. NSE and PBIAS for water table depth during the calibration and validation periods.

		Daily		Monthly	
	Soil Series	NSE	PBIAS (%)	NSE	PBIAS (%)
Calibration (1992 -1994)	Avonburg	0.66	-12	0.72	-7
	Cobbsfork	0.66	-18	0.73	-12
	Rossmoyne	0.59	-9	0.73	-2
Validation (1995 -1996)	Avonburg	0.30	-16	0.29	-9
	Cobbsfork	0.36	5	0.30	6
	Rossmoyne	0.57	1	0.60	1

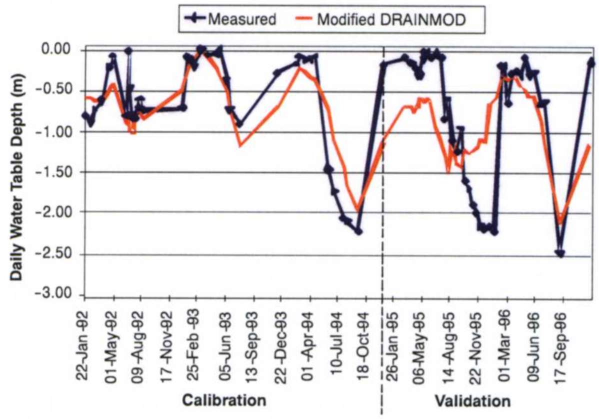

Figure 3. Daily observed and simulated water table depth fluctuation for the calibration and validation periods for the observation well located on the Avonburg soil.

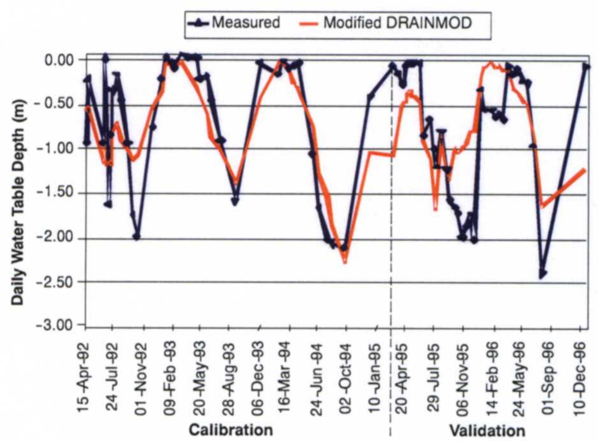

Figure 4. Daily observed and simulated water table depth fluctuations for the calibration and validation periods for the observation well located on the Cobbsfork soil.

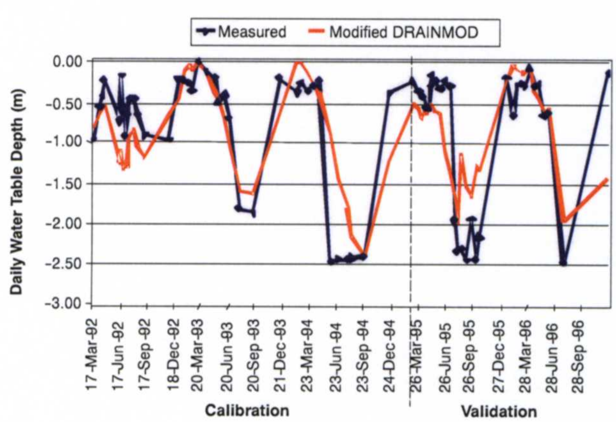

Figure 5. Daily observed and simulated water table depth fluctuation for the calibration and validation periods for the observation well located on the Rossmoyne soil.

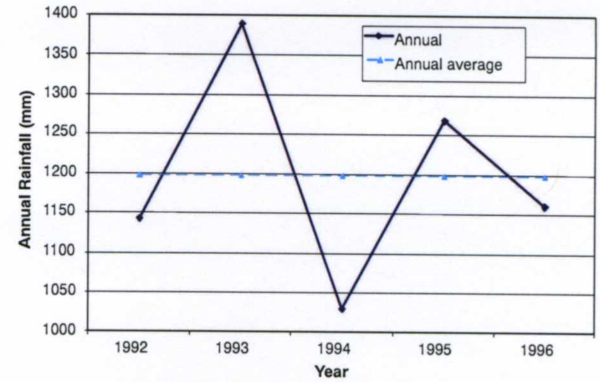

Figure 6. Annual precipitation during the calibration (1992-1994) and validation (1995-1996) periods for the North Vernon 2 ESE weather station.

the climatic conditions between the two periods could have led to the calibration parameter values that were not representative of the climatic conditions prevalent during the validation period. Ideally, a good calibration should cover a long time period to ensure that dry, average, and wet conditions are used to determine robust parameter values, which reduces the chances of huge differences in the simulation of *wtd* or any other hydrologic component of interest during the validation period.

Although the NSE values (table 3) were not high, the Modified DRAINMOD approach simulated *wtd* fluctuation patterns adequately (Motovilov et al., 1999) during the calibration and validation period on both the daily and monthly time steps, except during validation on both the daily (NSE = 0.30) and monthly (NSE = 0.29) time steps for the Avonburg soil series and the Cobbsfork series on a monthly (NSE = 0.30) time step. This could be due to inaccurate soils data and, according to Vazquez-Amábile and Engel (2005), *wtd* was sensitive to soil properties such as texture, bulk density, and available water content. According to Amatya et al. (2003), DRAINMOD poorly simulated *wtd* when the model was not calibrated using *in situ* soil measurements. Although the Avonburg, Cobbsfork, and Rossmoyne soils were listed as *in situ*, the soils data were obtained from USDA Natural Resources Conservation Service reports because *in situ* soil measurements were not available (Vazquez-Amábile and Engel, 2005). A closer look at the properties of the three soil series (table 1) reveals that both the Avonburg and Cobbsfork soil series have a greater average soil profile and top soil layer clay content values than the Rossmoyne soil series. As a result, the Avonburg and Cobbsfork soil series belong to soil hydrologic group D, while the Rossmoyne soil series belongs to soil hydrologic group C (NRCS, 1996). According to NRCS (1996), hydrologic group C soils have a slow infiltration rate when thoroughly wetted and consist of a layer that impedes downward movement of water or have moderately fine to fine texture. Meanwhile, hydrologic group D soils have a very slow infiltration rate when thoroughly wetted and consist of clay soils that have a high swelling potential, soils that have a permanent water table, soils that have a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material (NRCS, 1996). Therefore, the Avonburg and Cobbsfork soil series have lower infiltration than the Rossmoyne soil series for a given rain event, and hence they lead to deeper *wtd*. Therefore, if the Avonburg and Cobbsfork soil series data used do not accurately represent the actual soil properties at the observation wells, then this could lead to deeper simulated water tables depending on the prevailing weather and antecedent soil moisture conditions, thereby resulting in low NSE (table 3) values during the validation period. It is also possible that the Modified DRAINMOD model does not perform well in simulating the *wtd* for poorly drained (group D) soils.

The differences between the daily observed and simulated *wtd* fluctuations are more likely a result of improper soil-water relationship characterization and drained volume relationships (He et al., 2002) for the STATSGO and SSURGO soils data sets used to generate the soils input parameters. Water table depth was sometimes overpredicted and sometimes underpredicted during both the calibration and validation periods, as illustrated in figures 3, 4, and 5. The differences in the observed and simulated *wtd* values at different times may also be due to uncertainty in the soils data (as explained above) and precipitation records used, in addition to the general uncertainty of the equations used by the new Modified DRAINMOD method to estimate *wtd*. A closer look at the *wtd* time series did not show observable trends in seasonal disagreements between the simulated *wtd* and the measured *wtd* for the observation wells located in the Avonburg and Cobbsfork soil series. However, on average, the model underpredicted the *wtd* during the summer season and overpredicted during the winter season for the observation well located in the Rossmoyne soil series.

Precipitation is perhaps the most critical input that determines how accurately watershed hydrology and sediment and nutrient transport are simulated because it activates flow and mass transport processes in hydrologic systems. Although the three observation wells are located in the Storm Creek lower watershed, the daily weather data for precipitation and maximum and minimum temperature were obtained from the records of the weather stations located in the Vernon subwatershed (fig. 1). These weather data were assumed to be representative of the weather conditions at the observation wells. However, there can be great spatial precipitation variability. For example, Chaubey et al. (1999) found that precipitation measured at 17 weather stations distributed within and close to the Cement watershed located in the Little Washita basin (610 km^2) in southwest Oklahoma varied between 57 and 95 mm, 31 and 137 mm, and 0 and 45 mm for rain events that occurred on 31 May, 9 July, and 27 October 1996, respectively. Vazquez-Amábile and Engel (2005) reported monthly streamflow NSE values of 0.81, 0.61, and 0.49 for the Vernon, Deputy, and Harberts watersheds, respectively, all located within MRB. The Vernon watershed streamflow gauging station, being closest to the weather station, exhibited the highest NSE value (0.81), while the Harberts watershed streamflow gauging station, being farthest from the weather station, exhibited the lowest NSE value (0.49).

The possible great spatial precipitation variability could explain the differences between the measured *wtd* and the simulated *wtd* for the well located on the Avonburg soil for a few selected days shown in table 4. For example, on 4 August 1995, the measured *wtd* value was 0.58 m while the simulated *wtd* was 1.50 m. Between 4 and 19 August 1995, there was a total of about 289 mm of rainfall (CumRain), yet the measured *wtd* on 19 August 1995 was 1.11 m, indicating that there was a large net water removal from the profile that lowered the *wtd* by 0.53 m, which could imply that the well did not respond to the huge amount of rainfall (289 mm). On the other hand, the Modified DRAINMOD approach raised *wtd* by 0.41 m, from 1.50 m to 1.09 m, which indicates that the Modified DRAINMOD *wtd* prediction method responded to the precipitation data input.

Finally, there is uncertainty with the equations used to estimate the drainage volume (eqs. 2 and 3) and *wtd* (eqs. 4 and 5). Each of the components used in equation 2 is estimated with verified, tested, and widely used equations discussed in detail in the SWAT theoretical documentation (Neitsch et al., 2002a), although each is based on some assumptions. Cumulative uncertainty resulting from these equations in addition to uncertainty of input data lead to the resulting differences between the measured and simulated *wtd*. Although the uncertainty of the observed *wtd* data used in this study was not known, it is important to state that measured data are not 100% accurate (Harmel et al., 2006); hence, models should not be forced to fit every measured value exactly.

The average magnitude of simulated daily and monthly *wtd* values were within the good ($\pm 10\% <$ PBIAS $< \pm 15\%$) and very good (PBIAS $< \pm 10\%$) ranges for the three soil series, except the daily *wtd* values for the Cobbsfork soil during the calibration period and the Avonburg soil during validation period when the values were within the satisfactory range ($\pm 15\% <$ PBIAS $< \pm 25\%$) (Donigian et al., 1983). As explained before with regards to low NSE values, the possibility that the Avonburg and Cobbsfork soil series data used do not accurately represent the actual soil properties at the observation wells could explain the larger *wtd* underprediction. On average, the Modified DRAINMOD approach within SWAT2005 adequately predicted *wtd* fluctuations patterns (NSE $\geq$ 0.40) within 15% of the measured *wtd* for the three soil series (PBIAS $\leq \pm 13\%$, table 10). The Modified DRAINMOD approach best predicted the *wtd* for the Rossmoyne soil series during the validation period both at the daily (NSE = 0.57, PBIAS = 1%, table 5) and monthly (NSE = 0.60, PBIAS = 1%) time steps.

Vazquez-Amábile and Engel (2005) reported that SWAT predicted *wtd* with monthly NSE values of 0.61, 0.36, and 0.40 for Avonburg, Cobbsfork, and Rossmoyne, respectively, during the calibration period, and 0.10, -0.51, and 0.38 for Avonburg, Cobbsfork, and Rossmoyne, respectively, during the validation period. Vazquez-Amábile and Engel (2005)

Table 4. Excerpt of measured rainfall and water table depth and simulated infiltration, ET and water table depth for the observation well located on the Avonburg soil. CumET, CumInfil, and CumRain are measured cumulative rainfall, simulated infiltration, and simulated ET, respectively, from the last measurement date to the measurement data for the current date; ET = evapotranspiration, Infil = Infiltration, Meas = Measured, and Sim = Simulated.

Date	Rain (mm)	CumRain (mm)	Infil (mm)	CumInfil (mm)	ET (mm)	CumET (mm)	Meas *wtd* (m)	Sim *wtd* (m)
23 July 1995	29.50	--	25.96	--	2.59	--	0.84	1.29
4 Aug. 1995	**0.00**	**17.80**	**0.00**	**17.80**	**5.72**	**66.89**	**0.58**	**1.50**
19 Aug. 1995	**0.00**	**289.10**	**0.00**	**168.54**	**5.99**	**72.07**	**1.11**	**1.09**
5 Sept. 1995	0.00	17.70	0.00	17.29	4.28	79.72	1.23	1.36
19 Sept. 1995	0.00	18.30	0.00	18.30	0.93	34.58	0.95	1.43

also reported that SWAT predicted *wtd* with an average monthly RMSE of 55 cm for the calibration period and 76 cm for the validation period. For the same soil series, the Modified DRAINMOD routine predicted *wtd* with average RMSE values of 41 cm and 39 cm for daily and monthly time steps, respectively, during the calibration period (table 10). The Modified DRAINMOD approach also predicted the *wtd* with average RMSE values of 59 cm and 60 cm for the daily and monthly time steps, respectively, during the validation period (table 10). Therefore, the Modified DRAINMOD routine simulated the *wtd* fairly well, considering that SWAT is a watershed-scale model that generally uses average input data sets, as compared to more detailed field-scale models, such as DRAINMOD, that compute *wtd* on an hourly time-step using mainly *in situ* data inputs. DRAINMOD *wtd* simulation using field data from Aurora, North Carolina, resulted in a standard error (RMSE) of 19 cm (Desmond et al., 1996). In addition, Madramootoo et al. (1999) reported that DRAINMOD-N predicted *wtd* with a standard error 16 to 21 cm in eastern Canada.

Comparison of the Performance of Water Table Depth Routines Used in SWAT

Figure 7 is a daily time-series graphical illustration of the *wtd* prediction performance of the four above-mentioned *wtd* routines used in SWAT for the observation well located on the Avonburg soil. To avoid redundancy, the time-series graphical illustrations of the *wtd* prediction for the Cobbsfork and Rossmoyne soil series are not presented herein. Based on figure 6, the *wtd* fluctuations predicted using both the Modified DRAINMOD and DRAINMOD approaches were closer to the measured *wtd* fluctuations during both the calibration and validation periods compared to the *wtd* fluctuations predicted by the SWAT-M and SWAT2005 methods. However, the *wtd* fluctuation profile predicted by the DRAINMOD approach seemed closest to the measured *wtd* fluctuation profile (fig. 7). Although not shown herein, similar graphical results were obtained for the Cobbsfork and Rossmoyne soil series. Tables 5, 6, and 7 summarize the results of the *wtd* fluctuation prediction performance by the four *wtd* simulation approaches for the observation well located on the Avonburg, Cobbsfork, and Rossmoyne soil series, respectively. Results in tables 5, 6, and 7 indicate that the Modified DRAINMOD approach yielded the best *wtd* prediction performance overall, based on NSE, PBIAS, RMSE, and R, during both the calibration period and the validation period for the Avonburg, Cobbsfork, and Rossmoyne soil series.

Predicted Continuous Five-Year Water Table Depth Fluctuation Profiles

Figure 8 illustrates the complete five-year (1992-1996) daily and monthly simulated *wtd* fluctuation profiles by SWAT2005 and SWAT-M, Modified DRAINMOD, and DRAINMOD approaches for the well located in the Avonburg soil series. Similar *wtd* fluctuation profiles by all approaches were observed for the observation wells located in the Cobbsfork and Rossmoyne soil series. Based on figure 8, it was observed that the *wtd* oscillations predicted by the

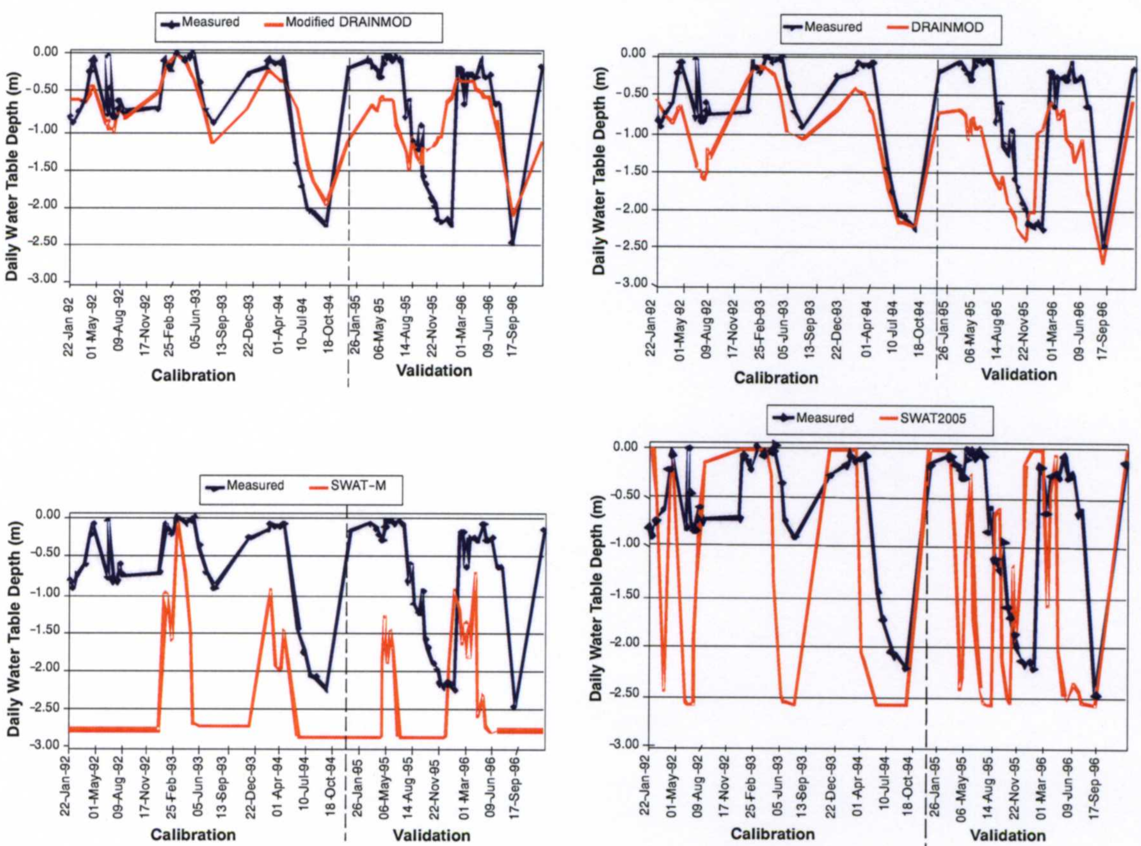

Figure 7. Daily measured and simulated water table depth using the four water table depth routines for the calibration and validation periods for the observation well located on the Avonburg soil.

Table 5. Values of NSE, PBIAS, RMSE, and R for daily and monthly water table depth for calibration and validation period for the observation well located on the Avonburg soil.

		Daily Water Table Depth				Monthly Water Table Depth			
	Approach	NSE	PBIAS (%)	RMSE (m)	R	NSE	PBIAS	RMSE (m)	R
Calibration (1992-1994)	Modified DRAINMOD	0.66	-12	0.35	0.83	0.72	-7	0.36	0.86
	DRAINMOD	0.28	-62	0.51	0.82	0.61	-43	0.42	0.88
	SWAT-M	-8.81	-298	1.88	0.52	-5.90	-253	1.77	0.57
	SWAT2005	-2.71	-105	1.15	0.55	-1.38	-79	1.04	0.63
Validation (1995-1996)	Modified DRAINMOD	0.30	-16	0.65	0.57	0.29	-9	0.69	0.54
	DRAINMOD	-0.05	-78	0.80	0.71	0.10	-61	0.79	0.68
	SWAT-M	-4.39	-215	1.82	0.27	-3.44	-173	1.73	0.22
	SWAT2005	-2.67	-101	1.50	0.06	-2.01	-76	1.43	0.01

Table 6. Values of NSE, PBIAS, RMSE, and R for daily and monthly *wtd* for the calibration and validation periods for the observation well located on the Cobbsfork soil.

		Daily Water Table Depth				Monthly Water Table Depth			
	Approach	NSE	PBIAS (%)	RMSE (m)	R	NSE	PBIAS	RMSE (m)	R
Calibration (1992-1994)	Modified DRAINMOD	0.66	-18	0.41	0.83	0.73	-12	0.38	0.87
	DRAINMOD	-0.12	-44	0.74	0.60	0.36	-25	0.59	0.71
	SWAT-M	-3.88	-223	1.54	0.56	-0.15	-42	0.87	0.66
	SWAT2005	-1.85	-103	1.18	0.54	-1.04	-74	1.06	0.60
Validation (1995-1996)	Modified DRAINMOD	0.36	5	0.56	0.61	0.30	6	0.57	0.56
	DRAINMOD	-0.74	-86	0.92	0.41	-0.51	-71	0.84	0.45
	SWAT-M	-3.21	-175	1.43	0.32	0.36	-8	0.69	0.76
	SWAT2005	-2.68	-91	1.34	0.17	-2.00	-65	1.17	0.32

Table 7. Values of NSE, PBIAS, RMSE, and R for daily and monthly *wtd* for calibration and validation period for the observation well located on the Rossmoyne soil.

		Daily Water Table Depth				Monthly Water Table Depth			
	Approach	NSE	PBIAS (%)	RMSE (m)	R	NSE	PBIAS	RMSE (m)	R
Calibration (1992-1994)	Modified DRAINMOD	0.59	-9	0.48	0.77	0.73	-2	0.43	0.85
	DRAINMOD	0.15	-17	0.69	0.46	0.40	0	0.65	0.64
	SWAT-M	-0.96	-67	1.04	0.54	-0.15	-42	0.87	0.66
	SWAT2005	-1.63	-73	1.20	0.48	-0.75	-48	1.08	0.56
Validation (1995-1996)	Modified DRAINMOD	0.57	1	0.55	0.77	0.60	1	0.55	0.78
	DRAINMOD	0.33	-16	0.69	0.63	0.38	-10	0.65	0.67
	SWAT-M	0.33	0	0.69	0.75	0.36	-8	0.69	0.76
	SWAT2005	-2.32	-121	1.54	0.15	-1.41	-91	1.34	0.32

Table 8. Average daily and monthly statistics for the simulated *wtd* during the calibration and validation periods for observation wells located on the Avonburg, Cobbsfork, and Rossmoyne soil.

		Daily Water Table Depth				Monthly Water Table Depth			
	Approach	NSE	PBIAS (%)	RMSE (m)	R	NSE	PBIAS (%)	RMSE (m)	R
Calibration (1992-1994)	Modified DRAINMOD	0.64	-13	0.41	0.81	0.73	-7	0.39	0.86
	DRAINMOD	0.10	-41	0.65	0.63	0.46	-23	0.55	0.74
	SWAT-M	-4.55	-196	1.49	0.54	-2.07	-112	1.17	0.63
	SWAT2005	-2.06	-94	1.18	0.52	-1.06	-67	1.06	0.60
Validation (1995-1996)	Modified DRAINMOD	0.41	-3	0.59	0.65	0.40	-1	0.60	0.63
	DRAINMOD	-0.15	-60	0.80	0.58	-0.01	-47	0.76	0.60
	SWAT-M	-2.42	-130	1.31	0.45	-0.91	-63	1.04	0.58
	SWAT2005	-2.56	-104	1.46	0.13	-1.81	-77	1.31	0.22

Modified DRAINMOD and DRAINMOD methods were more gradual and more likely representative of actual conditions compared to the *wtd* fluctuations predicted by the SWAT2005 and SWAT-M methods, whose oscillations tended to be more rapid. This may explain why the SWAT2005 and SWAT-M methods performed more poorly than the Modified DRAINMOD and DRAINMOD methods in simulating the *wtd*. The general similarity in the predicted *wtd* profiles using the Modified DRAINMOD and DRAINMOD methods may be due to the fact that both originate from the water table depth versus drainage volume relationship theory used in DRAINMOD (Skaggs et al., 1978).

Finally, table 8 summarizes the statistics of the *wtd* fluctuation simulation performance by the four *wtd* simulation approaches used in SWAT for the three observation wells located on the Avonburg, Cobbsfork, and Rossmoyne soil series. Based on these statistics and the simulated continuous five-year fluctuation profiles, the Modified DRAINMOD approach consistently predicted the *wtd* fluctuations best for the three observation wells located on the Avonburg, Cobbsfork,

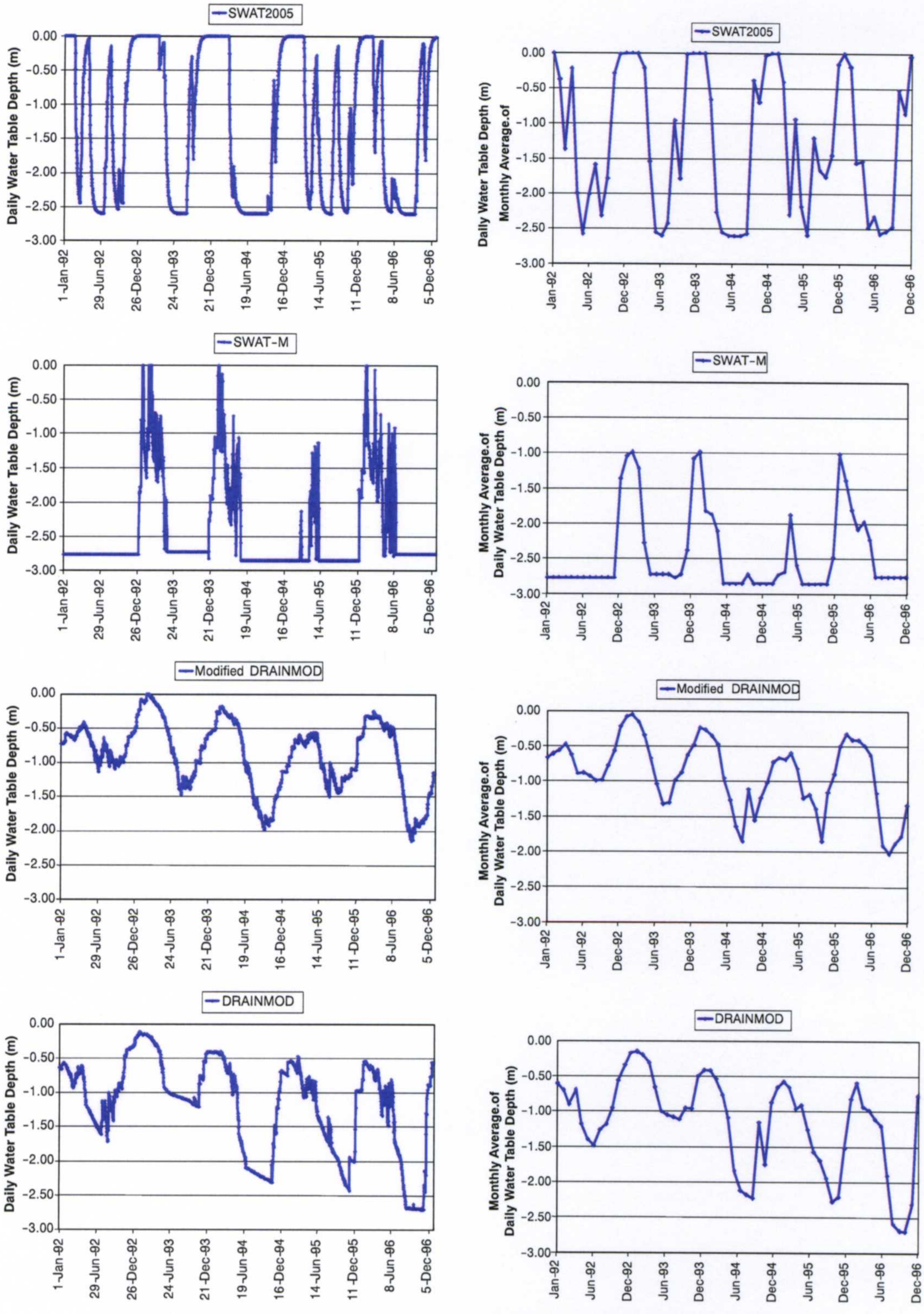

Figure 8. Complete predicted water table depth oscillation profiles on the Avonburg soil.

and Rossmoyne soils compared with the DRAINMOD, SWAT-M, and SWAT2005 approaches. Its incorporation into SWAT is anticipated to improve the water balance budget for the hydrologic components, especially the computation of the tile drainage volume component.

Summary and Conclusions

The proximity of the shallow *wtd* to the soil surface can negatively impact farm machine trafficability, crop development, agricultural chemical transport, soil salinity, and drainage. In light of these significant impacts of *wtd* fluctuations on the various aspects of agricultural production, it is important for hydrologic models to accurately simulate *wtd* fluctuations. The *wtd* simulation approaches used in SWAT do not accurately simulate *wtd* fluctuation profiles, especially during relatively short dry periods followed by short wet periods. In this study, a new *wtd* prediction approach (Modified DRAINMOD), based on the drainage volume versus water table depth relationship theory used by DRAINMOD, was developed and included in SWAT2005 to improve the simulation of *wtd* dynamics. In the Modified DRAINMOD approach, the drainage volume (*vol*) is computed using the soil water balance components computed by SWAT. SWAT was calibrated and validated for *wtd* using the *wtd* data measured at three observation wells located in the Storm Creek lower watershed within the Muscatatuck River basin in southeast Indiana. The optimum range of *c* values was 3 to 5, 4 to 7, and 5 to 8 for the Avonburg, Cobbsfork, and Rossmoyne soil series, respectively.

The *wtd* prediction performance of the Modified DRAINMOD approach was compared to those of the DRAINMOD, SWAT-M, and SWAT2005 approaches also used in SWAT. Based on the simulation results, the Modified DRAINMOD approach yielded the best *wtd* prediction performance, as indicated by the highest average daily calibration and validation NSE values of 0.64 and 0.41, respectively, and R values of 0.81 and 0.65, respectively, and the lowest PBIAS values of -13% and -3%, respectively, and RMSE values of 0.41 m and 0.59 m, respectively, for the three observation wells. This implies that the Modified DRAINMOD approach incorporated into SWAT2005 enhanced the prediction of *wtd*. Enhanced *wtd* prediction in SWAT2005 is anticipated to improve the simulation accuracy of watershed hydrologic processes and water management components, such as tile drainage. However, further studies, using complete long-term *wtd* data along with *in situ* precipitation and soil measurements, are needed to better analyze the performance of the Modified DRAINMOD approach within SWAT2005 in predicting *wtd*. In addition, a detailed study of the impact of soil texture and soil groups on *c* is recommended in order to determine reasonable values for the different soil textures and hence soil groups. Such a study will provide a database of default *c* values for each soil group.

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