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Modification and Evaluation of the WEPP Hillslope Model for Subsurface Drained Cropland

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Abstract. *Runoff, drain flow, and water table depth predictions from the WEPP hillslope model were evaluated against eight years measured runoff and drain flows from North Central Ohio and water table depths predicted using DRAINMOD. WEPP produced large average deviations between daily predicted and measured runoff depths, overpredicted daily drain flow for all storm events, and may not be truly simulating water table depth.Therefore, the WEPP was modified to improve the water balance, runoff, drain flow, and water table depth prediction capabilities for subsurface drained cropland. The modified model is WEPP-Water Table Management (WTM). Most of the new algorithms and modeling approaches and procedures were adapted from DRAINMOD. WEPP-WTM predicts hourly runoff, drain flow, subirrigation flow, controlled drainage and subirrigation excess flows, water table depth, and daily sediment yields from fields that contain any combination of water table management practices. Runoff, drain flow, and water table depth predictions from WEPP-WTM were evaluated against the measured runoff and drain flows from Ohio, and field water table depths from North Carolina. Overall, WEPP-WTM produced drain flow and runoff results similar to those from DRAINMOD and better than all of those obtained with WEPP.*

Keywords. WEPP-WTM, subsurface drainage, subirrigation, controlled drainage, runoff, model.

Introduction

The Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995; Nearing et al., 1989) is a continuous simulation erosion model with hillslope and watershed applications. The accuracy of predictions by WEPP's hydrology component has been evaluated by Liu et al. (1997), Savabi (1993), Savabi and Williams (1995), and Zhang et al. (1996) using field measured data. However the drain flow and water table depth predictions of WEPP were not tested against field measured data.

Water table management is the management, control, and/or regulation of soil-water conditions in the profile of agricultural soils. Water table management practices include subsurface drainage, controlled drainage, and subirrigation.

Analyses of the relationships between precipitation, runoff, water table depth, drain flow, upflux, nutrient and pesticide losses, and sediment yield are important in understanding and simulating the effects of water table management practices. In addition to runoff, drain flow, and upflux determination, water table depth is important for determining soil water distribution in the root zone. Soil water content affects rainfall/runoff events, plant growth, and residue decomposition. For these kinds of analyses, a number of approximate models have been developed. The WEPP model has the potential to model hydrologic and erosional processes, in particular to estimate sediment yield and runoff by interrill and rill erosion, and erosion by concentrated flow in field-sized areas.

Oztekin (2000) evaluated the hydrology component of the WEPP hillslope model for subsurface drained cropland, and found the following limitations: i) the water table depth prediction capability of WEPP is poor compared to DRAINMOD (Skaggs, 1978); ii) WEPP runoff, infiltration, soil water content distribution, and upflux are not calculated in relation to water table depth; iii) WEPP's time step to calculate drain flow and water table depth is 24 hours, too large for accurate water table predictions; iv) WEPP uses only the Hooghoudt equation to predict subsurface drainage flow; v) WEPP's predicted water table depth and drain flow are not provided as an output; vi) WEPP can not be used to simulate runoff, water table depth, sediment yield, and drainage flow from a field on which controlled drainage or subirrigation is planned or present; vii) WEPP may overestimate water loss by deep seepage, especially for poorly drained soils in humid regions; and viii) WEPP does not contain any option for the user to use field or lab measured saturated hydraulic conductivity values which might be used to predict drain flows. Except for the work conducted by Oztekin (2000), no research has appropriately evaluated the current water table depth and drain flow prediction capabilities of WEPP for subsurface drained cropland.

The WEPP-Water Table Management (WEPP-WTM) model was developed to address all of the above limitations of WEPP.

Model Modifications

WEPP (Version 97.3) was modified to develop WEPP-WTM. The main modifications were made in two subroutine files of the WEPP. In the input file, WEPP and WEPP-WTM input data are entered and, if needed, additional calculations are made to prepare the parameters to be used in the algorithms of WEPP-WTM. These calculations include upflux, soil water content, unsaturated hydraulic conductivity, and drained volume if water table depth relationships for these parameters are entered. The flowchart showing these calculations is presented in Figure 1 (the letter A in this figure was used to show connection between this figure and Fig. 2). In the water balance file of WEPP, all calculations for the water balance simulation were modified to accommodate hourly time step. The flowchart showing the water balance calculations of WEPP-WTM is given in Figure 2 (the letter C in this figure represents the connection to the rest of the original WEPP simulations). Since hourly time step was incorporated into the water balance simulations, WEPP-WTM was developed to use the WEPP weather input file in breakpoint form, where rainfall is entered hourly. This hourly time step should allow WEPP-WTM to better predict hourly runoff, drain flow, and water table depth. In WEPP-WTM, melted snow water (predicted by the original WEPP) and rainfall are used in place of precipitation data in the water balance routines. Furthermore, the user input saturated hydraulic values are adjusted for frozen soil conditions using with the original WEPP equations given by Alberts et al. (1995). These last two modifications should allow WEPP-WTM to be more applicable for the winter months of cold humid regions.

Runoff

Runoff in WEPP-WTM is calculated by subtracting the infiltration capacity of the soil from the rainfall rate. When hourly rainfall is greater than the infiltration capacity of the soil, a 5-minute time step is used in the infiltration routine of the model to calculate runoff. For this condition, the infiltration capacity (cm/hr) of the soil is calculated using the following form of the Green and Ampt (1911) infiltration equation:

$$f = K_s + K_s M S_{av} / F \qquad (1)$$

where K_s is the core method based vertical saturated hydraulic conductivity (cm/hr) of the surface layer; M is the initial soil water deficit (%), and F is the cumulative infiltration (cm). The parameter S_{av} in Eq. 1 is the effective suction at the wetting front (cm), which is calculated in DRAINMOD (Skaggs, 1980) as:

$$S_{av} = \int_0^h K_r \, dh \qquad (2)$$

where h is the water table depth (cm); K_r is the relative hydraulic conductivity ($K(h)/K_s$); and K(h) is unsaturated hydraulic conductivity (cm/hr). When the water table is on the surface, the infiltration capacity of the soil is assumed to be equal to the drain flow plus evapotranspiration. At the soil surface, runoff depth in WEPP-WTM is calculated using the following equation (Skaggs, 1978):

$$RO = P - (\Delta S + F) \qquad (3)$$

where RO is runoff depth (cm); P is the rainfall and/or melted snow (cm); and ΔS is the change in the depth of water in the depressional storage at the soil surface. The predicted runoff is checked with the DRAINMOD water balance equation for soil profile as given below:

$$\Delta V_a = D + ET + DS - F \qquad (4)$$

where ΔV_a is the change in the drained volume of the soil profile (cm); D is the drain flow (or subirrigation flow) (cm); ET is the evapotranspiration (cm); and DS is the deep seepage (cm). If the value of ΔV_a in Eq. 4 becomes negative, the absolute value of ΔV_a is then assumed to be runoff. The final runoff predicted in WEPP-WTM is the absolute value of ΔV_a, if it is larger than the runoff calculated by using Eq. 3. Otherwise, the final predicted runoff is equal to the runoff value calculated by Eq. 4. The calculated runoff depth was corrected for depressional storage on the soil surface. There is an option for the user to either use the field measured constant

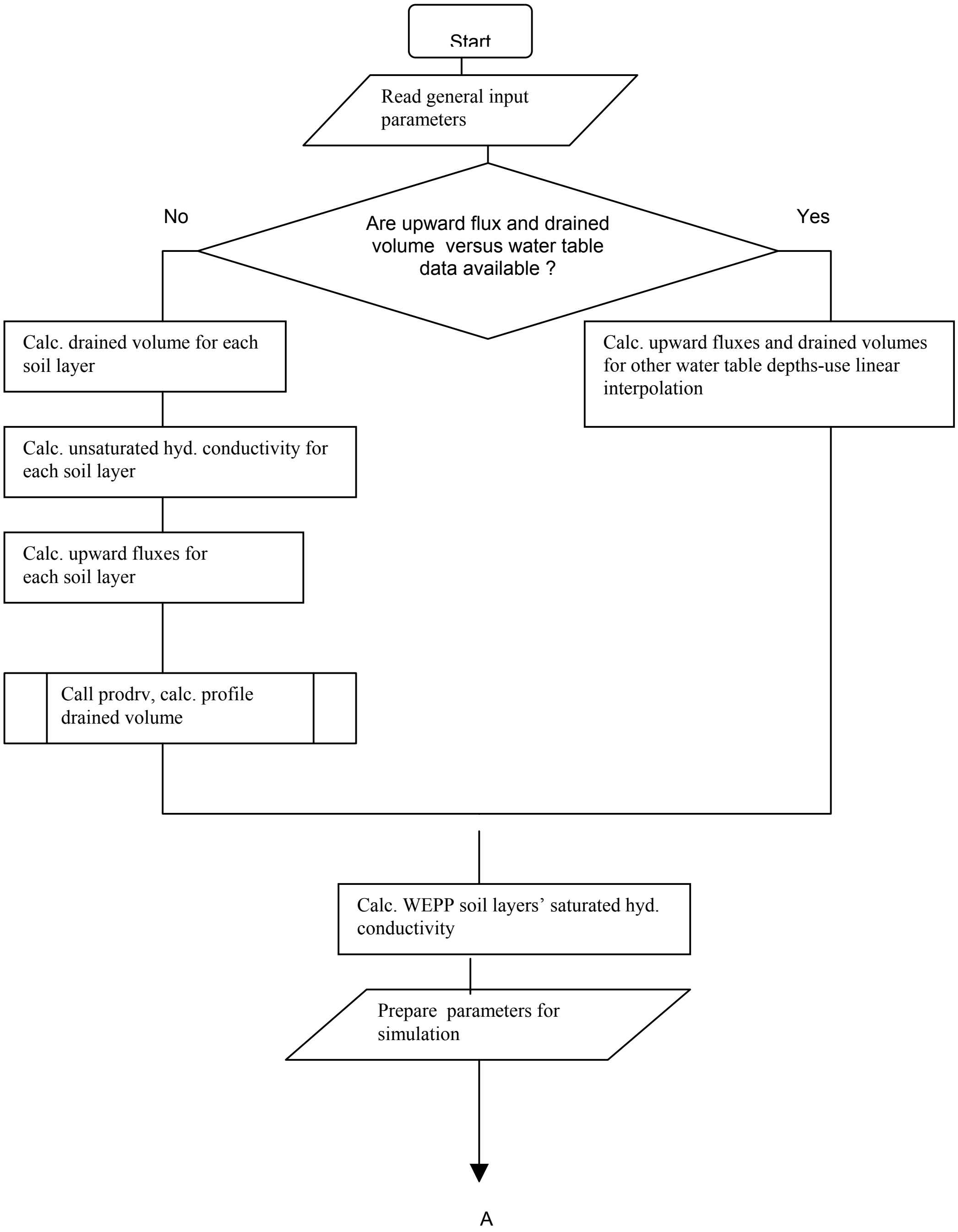

Figure 1. Flowchart for the water table depth corresponding upward flux and drained volume calculations

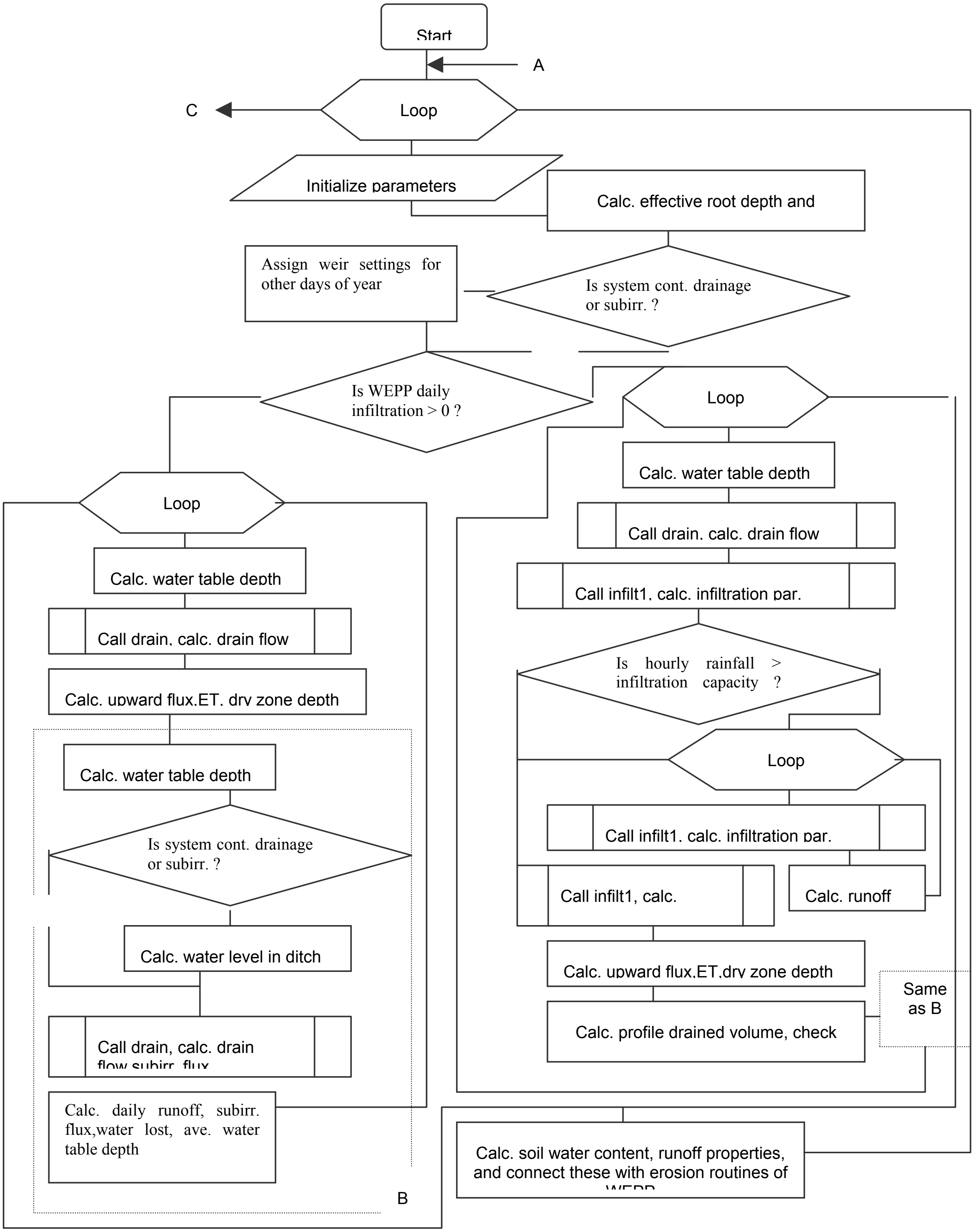

Figure 2. Flowchart for the water balance calculations of WEPP-WTM

depressional storage depth value or let WEPP-WTM use the original WEPP predicted value. This value is also used to represent surface drainage. The considered components for water balance are shown in Figure 3.

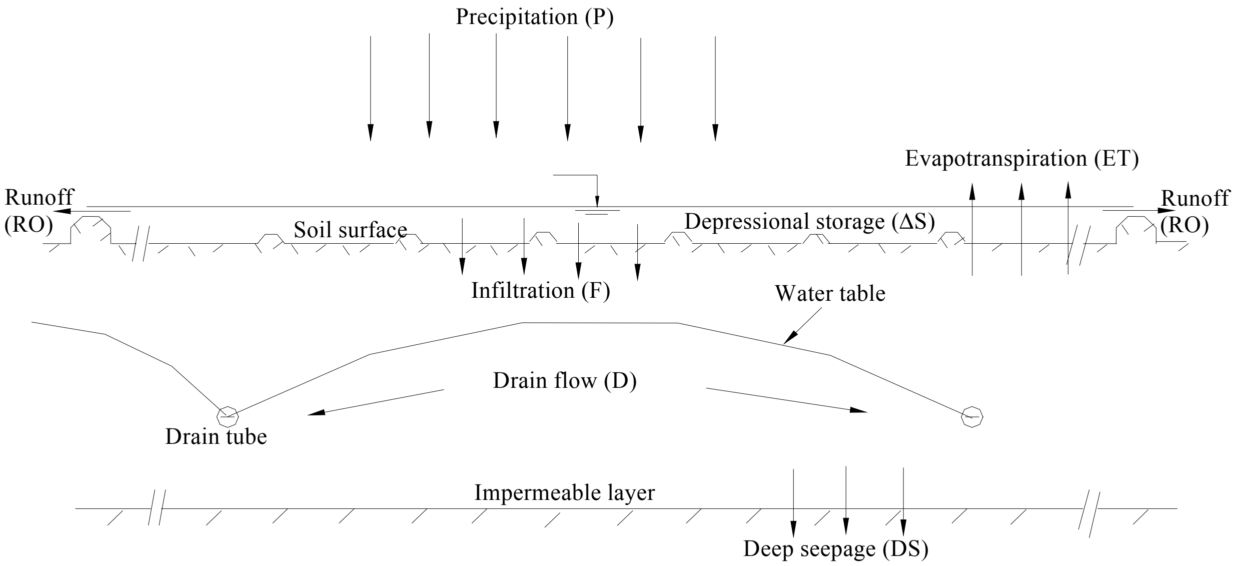

Figure 3. The components considered in the water balance of WEPP-WTM model

Subsurface Drainage, Controlled Drainage, and Subirrigation

To predict the drain flow removed from the soil profile by drain tubes or ditches, the WEPP model uses only the Hooghoudt equation (Savabi et al., 1995) as given below:

$$Q = \frac{8K_e d_e H + 4K_e H^2}{L^2} \qquad (5)$$

where Q is the drain flow depth (cm/hr); H is the midspace water table elevation above drain (cm); K_e is the equivalent saturated hydraulic conductivity (cm/hr); L is the drain spacing (cm); and d_e is the equivalent depth (cm). In WEPP-WTM, the Hooghoudt equation is used when the water table is at least 0.5 cm below the soil surface (drawdown condition). When the water table is at the soil surface (ponded condition), the form of the Kirkham equation given by Skaggs (1980) is used, given as:

$$Q = 4\pi K_e (t + b - r)/gL \qquad (6)$$

where

$$g = 2\ln(\frac{\tan(\pi(2d - r)/4h)}{\tan(\pi r/4h)} \qquad (7)$$

h is the depth of soil profile (cm); r is the radius of the drain tube (cm); t is the depth of water on the surface (cm); and b is the depth from the surface to the drains (cm). The equivalent saturated hydraulic conductivity (K_e) in both the Kirkham and Hooghoudt equations is calculated for the saturated section of the soil profile using the depth weighted average of horizontal saturated hydraulic conductivity values of layers.

When controlled drainage or subirrigation is used, the water table level is controlled by a weir. The weir is set at a given elevation at the drainage outlet or ditch. In WEPP-WTM, weir settings (elevations), along with their respective dates and subirrigation or controlled drainage flag code, are entered as input in the drainage section of the plant/management input file. After considering the chosen water table management option, WEPP-WTM checks for the weir setting for the day. If the weir setting is lower than the drain depth of the water table management system, the system is simulated as being in a free drainage mode (conventional subsurface drainage) without regard to the chosen option.

In some subirrigation and controlled drainage systems, drainage flow and runoff from these systems may not go to the same outlet ditch or stream. In WEPP-WTM, the user can choose this option. Ditch side slopes and bottom depths are entered in the drainage section of the plant/management input file. If the side slope is entered as zero, the model assumes that the shape of the ditch is rectangular, otherwise it is trapezoidal. The amount of water lost from the system and that remaining in the ditch is calculated.

When subirrigation is used, the water level in the ditch is raised by pumping water into the ditch. The following equation is used to predict the needed subirrigation flux (Skaggs, 1980):

$$Q = \frac{4K_e m(2h_0 + \frac{h_0}{D_0} m}{L^2} \qquad (8)$$

where D_o is the pressure head at a point on the impermeable layer just below the drain calculated as y_o +d; h_o is the equivalent pressure head at a point on the impermeable layer just below the drain calculated as y_o +d_e; y_0 is water table elevation above the drain (cm); and m is midspace water table elevation minus the water table elevation at the drain (cm).

Water Table Depth

Drain flow and ET calculations in WEPP-WTM depend on the predicted midspace water table depths. In the water balance routines, the water table depth is calculated at the end of every hour. The water table depth based on the soil water content distribution in the soil profile is calculated hourly. The soil water content below the water table is assumed to be saturated. Above the water table, the soil water is assumed to be equilibrium with the water table depth. For deep water table depths, a dry zone starting from the soil surface can develop, but this depends on the ET rate, root depth, and the unsaturated hydraulic conductivity of the soil. The drained volume-water table depth relationship is used to simulate fluctuations of the water table, and therefore allows WEPP-WTM to determine how far the water table falls or rises when a given amount of water is removed or added. The following equation was used to develop this relationship (Skaggs, 1980):

$$V_d = \int_0^{y_i} (Q_0(y) - Q(y))dy \qquad (9)$$

where V_d is the volume drained (cm^3/cm^3); y_1 is the water table depth (cm); $Q_0(y)$ is the saturated soil water content (cm^3/cm^3); Q(y) is the soil water content for a water table depth of y (cm^3/cm^3); and y is any water table depth between zero and y_1 (cm). In the model, the parameter V_d is calculated for a maximum of 10 soil layers. The parameters Q_0 and Q for each soil layer are calculated from the soil water content versus pressure data that may be entered into the soil input file of WEPP-WTM. As an alternative to this calculation, the user may substitute another drained volume-water table depth relationship.

Upward Flux

The upflux or capillary rise from a water table is important to transmit the water from water table to the plant roots, therefore upflux is an important phenomenon in each of the three components of water table management systems. In particular, subirrigation systems allow water to be introduced to the subsurface drains via water table control structures. As the water table is raised, water can be transmitted by capillary rise to the root zone to satisfy the ET demand by the crops. Upward flux affects the water table draw down since soil profile water is lost by upward flux. The upward flux rate also affects the ET. For these reasons, it is desirable to determine the steady upward flux from a water table over the range of possible water table depths. For a particular soil, this relationship can be developed and then provided as input to the model.

WEPP-WTM has two options for obtaining the upflux versus water table depth relationship. The user can input a known relationship into the soil input file. If the user does not have this relationship, WEPP-WTM can develop this relationship using a method developed by Memon et al. (1986). They used the concept of matrix flux potential (MFLP) as discussed by Shaykewich and Stroosnijder (1977), and defined the MFLP function as follows:

$$MFLP(h) = \int_{h_0}^{h_{\max}} K(h)dh \tag{10}$$

where MFLP(h) is the matrix flux potential (cm^2/hr) at the water table depth h; hmax is the maximum allowable pressure head (cm) at the center of the effective root zone; and ho is the pressure head at the water table (cm). Memon et al. noted that Taylor and Ashcroft (1972) presented values of hmax for various crops. For example, a hmax value of 12000 is used for corn. The procedure to use the matrix flux potential approach is as follows. A matrix of MFLP values and unsaturated hydraulic conductivity values are determined for the anticipated range of water table depths. Then, for each of a range of assumed constant upflux (q) values, the water table depth (z) which corresponds to each constant value of q is calculated as follows (Memon et al., 1986):

$$Z = \sum_{i=1}^{i=h_{\max}} \frac{MFLP_{i+1} - MFLP_i}{q + [K(h_{i+1}) + K(h_i)]/2} \tag{11}$$

where Z is the water table depth (cm) corresponding to the assumed constant upflux, q (cm/hr); K(h) is unsaturated hydraulic conductivity of surface soil when water table depth is h (cm); and i = 1 to hmax (cm) with increments of 1. An adjustment was made to get an upward flux value equal to the vertical saturated hydraulic conductivity of the first soil layer when the water table is on the soil surface. Upward flux values for other water table depths that are between those calculated with Eq. 11 can be determined using linear interpolation.

Root Depth and Evapotranspiration

In WEPP-WTM, the effective root depth is used to calculate the zone from which water can be removed as necessary to supply the ET demand of the crops. The root depth for annual crops in WEPP is simulated using an equation by Arnold et al. (1995). In WEPP-WTM, 20% of the root depth is used as the effective root depth. When the predicted root depth is less than 3 cm or when plants do not exist in the field during a particular simulation time, a 3-cm root depth is then used to reflect the soil depth from which water may be evaporated. In WEPP-WTM, the calculated reference potential ET (PET) algorithms from WEPP are used or the user can enter daily measured PET data.

Evaluations of Models

Experimental Sites

In this study, data from two subsurface drained cropland field sites were used to test and evaluate the runoff, drain flow and water table depth prediction accuracy of WEPP and WEPP-WTM models. Eight years of measured drain flow and runoff data obtained from Schwab et al. (1963; 1975; 1985) for a site in North Central Ohio were used for testing and evaluating the drain flow and runoff predictions of WEPP and WEPP-WTM models. Sprinkler irrigation water was applied to the plots twice each year in May, June, or July to provide a repeatable ten-year return period storm. There were no continuous water table depth measurements at this site. For this reason, water table depth predictions of WEPP-WTM were tested and evaluated against a five-year field data set from Aurora, North Carolina. This experiment sometimes used subirrigation. Since WEPP can not be used to simulate subirrigation, water table depth predictions of WEPP were compared to those using DRAINMOD for the Ohio site. Experimental details for the Ohio and North Carolina sites can be found in Schwab et al. (1963; 1975; 1985) and Skaggs (1978), respectively.

Models Input Data

The weather input file for both sites were prepared in hourly breakpoint form of the WEPP weather input file. For the Ohio site, hourly precipitation, and daily maximum and minimum temperatures were recorded at the site. Daily solar radiation, wind direction and speed, and dew point temperatures were obtained from the Midwestern Climate Data Center for Toledo, Ohio, which is approximately 65 km from the site. For the North Carolina site, the rainfall was recorded at the site, and daily maximum and minimum temperatures were measured at the Aurora weather station. The same evaporation pan data as used by Skaggs (1978) were used in place of daily potential evapotranspiration calculations in WEPP-WTM.

The predominant soil type at the Ohio site was Toledo silty clay. The soil water retention data were obtained from Skaggs et al. (1981), Schwab et al. (1963), and field experiment notes. To determine the water table depth versus upward flux relationships and infiltration parameters in WEPP-WTM, the vertical saturated hydraulic conductivity values for Toledo silty clay obtained from Schwab et al. (1963) were used as input data for WEPP-WTM. The four soil layers were used as input to the models. Horizontal saturated hydraulic conductivity values for these soil layers were estimated using the van Schilfgaarde equation (van Schilfgaarde, 1963) with field measured water table drawdown and drainage flow data. Sand and clay contents of the soil layers were obtained from Schwab et al. (1963). At the North Carolina site, the dominant soil type was Tomotly sandy loam with some Myatt sandy loam and Torhunta sandy loam. Based on the horizontal saturated hydraulic conductivity values given by Skaggs (1978), the soil profile was divided into two layers. Skaggs (1978) stated that the corresponding conductivity values for these layers were obtained using the drawdown and auger hole methods. The upward fluxes with the corresponding water table depths for the Tomotly sandy clay are given by Skaggs (1978). In WEPP-WTM, these upward flux values with their corresponding water table depths were also used as input data. The soil water retention data for a 60 cm depth of soil profile of Tomotly sandy clay as given by Skaggs (1978) were used for both of the soil layers. Soil input values for albedo, baseline interrill and rill erodibility, and critical shear were obtained using default equations given in the WEPP User Summary (Flanagan and Livingston, 1995). Organic matter (OM) and cation exchange capacity (CEC) values were obtained using the MUUF (Map Unit Use File) soil database (Baumer, 1989). Table 1 lists these soil input data.

Table 1. Soil input data used in the WEPP hillslope and WEPP-WTM models for Toledo silty clay and Tomotly sandy loam at the Ohio and North Carolina sites, respectively.

	Ohio site				North Carolina site	
Albedo*:	0.1				0.1	
Initial saturation level (%)*:	0.81				0.30	
Baseline inter-rill erodibility (kgs/m^{4})*:	3.24x10^{6}				3.9x10^{6}	
Baseline rill erodibility (s/m)*:	0.0069				0.0070	
Baseline critical shear (N/m^2)*:	3.1				3.5	
Baseline effective conductivity (mm/hr)*:	0.79				2.96	
	Soil Layers					
	1	2	3	4	1	2
Depth from soil surface (cm)$^{\#}$:	20	50	102	165	100	158
Horizontal sat. hyd. con.(cm/hr):	42.50	1.92	0.05	0.01	1.0	3.0
Vertical sat. hyd. con. (cm/hr):	2.54	0.20	0.14	0.27	0.5	0.5
Sand (%)$^{+}$:	3	3	4	3	19	19
Clay (%)$^{+}$:	51	53	55.7	57.3	39	39
OM (%)$^{+}$:	4.5	1.5	1.5	1.5	4.4	1.0
CEC (meq/100 g of soil)*:	35	31	29	28	15	15

*: These values were calculated using default equations given in the WEPP User Summary (Flanagan and Livingston, 1995)

#: Taken from Skaggs et al. (1981) and Skaggs (1978)

+: Taken from Schwab et al. (1963) and MUUF soil database.

The plots at the Ohio site were surface drained at a 0.2% slope, and therefore a constant 0.2% slope value was used for these simulations. The profile width and length of the overland flow elements were chosen as equal to the plot width (37 m) and length (61 m), respectively. A constant 0.5% slope value was used for the simulations at the North Carolina site. This value was obtained from one of the input file used in the ADAPT evaluation for this site by Desmond et al. (1995). At this site, the widths of the plots having drain spacings of 7.5, 15, and 30 m, are 30, 60, and 120 m, respectively. These values were obtained by multiplying the drain spacings by four (four laterals per plot). The length of the overland flow element was calculated as 60 m from the schematic given by Skaggs (1978).

In addition to the drainage system parameters used in WEPP, WEPP-WTM includes a water table management option, drain pipe effective radius, Kirkham’s equation depth and initial water table depth. The drainage system parameters are given in Table 2. To simulate surface drainage for the Ohio site in WEPP-WTM, a constant 0.25 cm depressional storage depth as used by Skaggs et al. (1981) was used. All model inputs for both sites are described in detail by Oztekin (2000).

Table 2. Drainage system parameters for the test sites. The Ohio site data were obtained from Skaggs et al. (1981). The North Carolina site data were obtained from Skaggs (1978) and Desmond et al. (1995). The ditch parameters were suggested by Workman (1999).

Parameter	North Central Ohio	Aurora, North Carolina		
Drain type	concrete tile	clay tile		
Drain spacing (m)	12.20	7.50	15.00	30.00
Drain depth (m)	0.90	0.80	0.90	1.00
Drain diameter (cm)	10.00	10.00	10.00	10.00
Drainage coefficient (cm/day)	5.30	1.00	1.00	1.00
Effective drain radius (cm)	0.48	0.25	0.25	0.25
Kirkham's depth (cm)	0.11	0.40	0.40	0.40
Ditch bottom width (cm)	-	2.00	2.00	2.00
Ditch side slope (cm/cm)	-	0.10	0.10	0.10

Corn was grown at the Ohio site during the eight test years. Field operations, dates, and additional input data were obtained from field notes. The crops grown at the Aurora, and their planting and harvesting dates were obtained from Skaggs (1978). Plant input parameters for the models were obtained from the WEPP validation input data set files and from the WEPP User Summary (Flanagan and Livingston, 1995).

Evaluation Procedures

Agreements between predicted and measured drain flows, runoff, and water table depths were quantified on the basis of daily and cumulative average deviations (cm) using the following equation:

$$\text{average deviation} = \sum_{i=1}^{n} \left| x_i - y_i / n \right| \qquad (12)$$

where x_i is the predicted daily drain flow, runoff volume or water table depth; y_i is the measured daily drain flow, runoff volume or water table depth on day i; and n is the number of days in the evaluation period (year). Equation 12 was also used to calculate the agreement between cumulative predicted and measured outflows. Standard errors between predicted and observed daily water table depths were calculated using the following equation:

$$s = \sqrt{\sum_{i=1}^{n} (x_i - y_i) / n} \qquad (13)$$

where the symbols are same as defined for Eq. 12.

RESULTS AND DISCUSSION

The means of the average deviations for daily and cumulative drain flows and runoff for Ohio site are given in Table 3. Again these values are the mean values of the average deviations

Table 3. Average deviations (cm) between daily and cumulative observed and WEPP-WTM and WEPP predicted outflows for the Ohio site.

	Daily Outflows				Cumulative Outflows			
	Drain Flow		Runoff		Drain Flow		Runoff	
Year	WEPP-WTM	WEPP	WEPP-WTM	WEPP	WEPP-WTM	WEPP	WEPP-WTM	WEPP
1962	0.051	0.194	0.021	0.035	1.59	18.59	1.56	3.14
1963	0.052	0.102	0.030	0.040	2.89	6.11	2.98	3.67
1964	0.077	0.291	0.024	0.035	3.65	27.30	1.33	2.71
1967	0.028	0.251	0.023	0.021	1.67	28.45	1.67	1.81
1968	0.020	0.223	0.022	0.029	1.25	23.41	0.66	0.98
1969	0.057	0.294	0.069	0.092	1.75	32.31	4.85	7.94
1970	0.044	0.202	0.048	0.050	1.23	21.39	2.64	2.49
1971	0.025	0.126	0.027	0.053	1.05	14.17	1.13	2.05

from four replications. The minimum average daily and cumulative deviation for each year is underlined. The WEPP-WTM produced the smallest mean of daily drain flow deviations for the eight test years compared to WEPP. For the daily drain flow for each year, WEPP results were 3.8, 2.0, 3.8, 9.0, 11.2, 5.2, 4.6, and 5.0 times larger than those obtained with WEPP-WTM for the test years of 1962-1964 and 1967-1971, respectively. For seven of the eight test years (88%), the WEPP-WTM model produced smaller daily runoff deviations than those obtained with WEPP model. Only for the test year of 1967, the WEPP model produced smaller deviation than those obtained with WEPP-WTM. For the cumulative drain flows, WEPP-WTM again produced the smallest cumulative deviations for all the eight test years compared to WEPP. The WEPP results were 11.7, 2.1, 7.5, 17.0, 18.7, 18.5, 17.4, and 13.5 times larger than those obtained with WEPP-WTM for the test years of 1962-1964 and 1967-1971, respectively. Similar to daily runoff deviations, WEPP-WTM again produced smaller cumulative runoff deviations for seven of the eight test years (88%). At this time, WEPP produced smaller deviation for the test year of 1970. Overall, WEPP-WTM drain flow predictions were better than those obtained with WEPP for eight test-year comparisons. For runoff, however, predictions by WEPP-WTM are better than those obtained from WEPP in 88% of the comparisons.

Figure 4 illustrates daily drain flows predicted by WEPP-WTM for the test year of 1969, compared to the measured drain flows. Similar figures were obtained for the other replications of other testing years. In these figures, the model simulation results were compared to the mean of the two replications where the same rainfall and irrigation data were valid for both replications. The predicted and measured drain flow depths and storm event times matched each other closely. These results show that WEPP-WTM did not consistently under or overpredict drain flow. Within the same year on some storm events, the model underpredicted and on other storm events the model overpredicted. However, the overall differences are not large. Figure 5 illustrates daily drain flows predicted by WEPP for the test year of 1969, compared to the measured drain flows. Again similar figures were obtained for other replications of other testing years. From these figures, daily drain flows were overpredicted for almost all

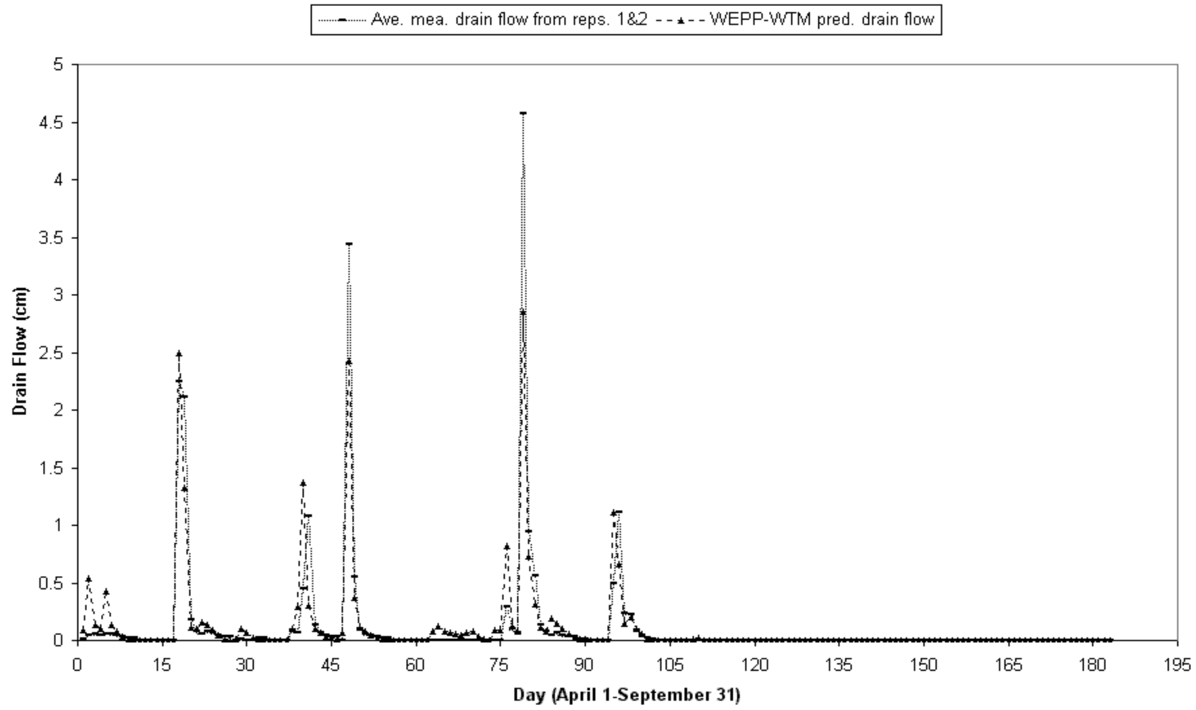

Figure 4. WEPP-WTM model predicted and average measured daily drain flows for the replications 1 and 2 at the Ohio site during 1969.

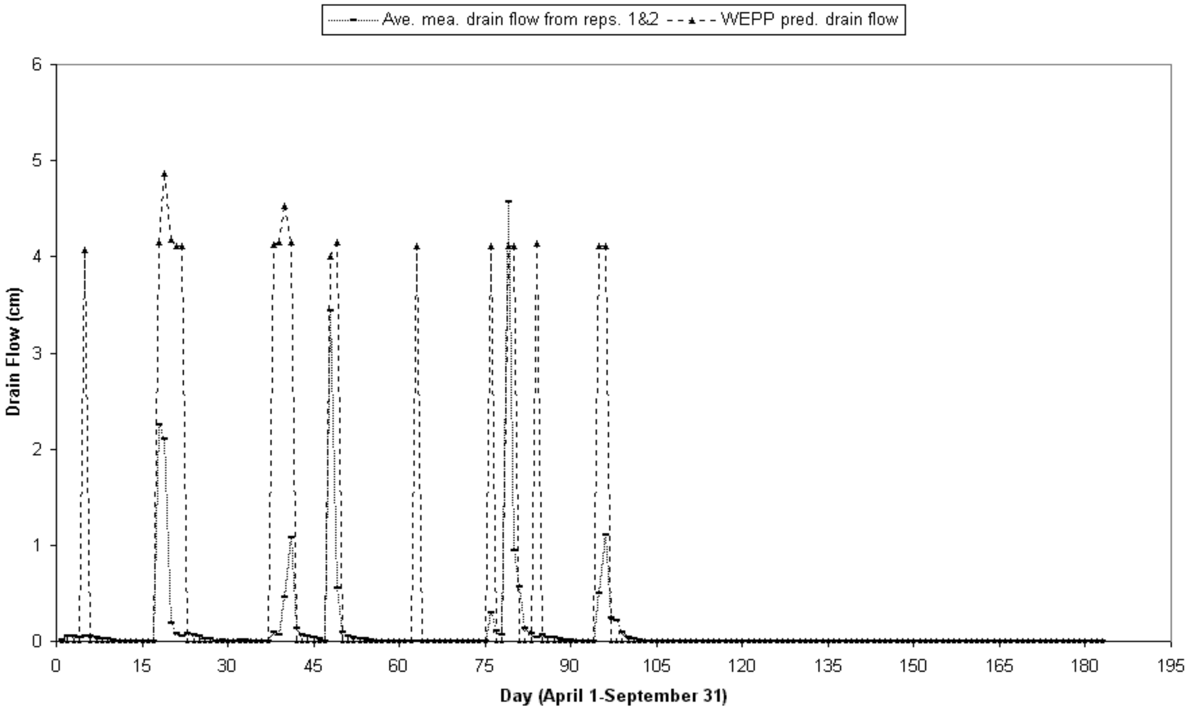

Figure 5. WEPP model predicted and average measured daily drain flows for the replications 1 and 2 at the Ohio site during 1969.

storm events. Furthermore, large amounts of daily drain flows were predicted while there were little or no drain flows from the field, such as day 4, 63, and 84 in Figure 5. Figure 6 illustrates daily runoff predictions with WEPP-WTM model for the year of 1969. The predicted values are again compared to the mean of the measured runoff depths from the two individual replicates. For 1969 (Fig. 6), WEPP-WTM predicted runoff on the same days on which runoff was measured, however, the model overpredicted by 100% runoff for day 79 (small event), and by 14% on day 95 (large event). Figure 7 illustrates daily runoff predictions with WEPP for the same year. For this year, WEPP predicted runoff on the same days on which runoff was measured, however, WEPP overpredicted runoff for these days, especially for days 48 and 79 (almost three times larger). The cumulative drain flows were also illustrated in figures for the testing years. The figures such as Figure 8 showed how well the WEPP-WTM predicted cumulative drain flows match the measured cumulative drain flows. Except for the test years of 1963 and 1964, WEPP-WTM predicted cumulative drain flows are between the measured flows from the replications. The figures such as Figure 9 illustrate again the differences between WEPP predicted and measured cumulative drain flows. From these figures, it is apparent that there are large differences between measured and WEPP predicted cumulative drain flows. The predicted cumulative drain flows at the end of evaluation season are 4.4, 1.8, 2.9, 5.3, 4.5, 3.4, 3.6, and 4.7 times larger than the measured cumulative drain flows for the testing years of 1962-1964 and 1967-1971, respectively.

The models predicted and measured cumulative runoff depths were also illustrated in figures for the testing years. In general, both models overpredicted the cumulative runoff depths. The cumulative runoff depths with WEPP-WTM were eleven times overpredicted (2.4, 1.8, 3.8, 4.3, 1.5, 2.0, 1.6, 1.2, 1.5, 1.2, and 1.9 times larger than those measured runoff depths), two times underpredicted and three times the predictions were fall between the measured cumulative depths from the replication couples. With WEPP model, runoff depths were fourteen times (4.3, 3.0, 4.7, 5.0, 2.3, 3.1, 1.7, 1.2, 1.4, 1.7, 1.4, 1.5, 2.4, and 1.7 times larger than those measured runoff depths) overpredicted and two times the predictions were fall between the measured cumulative runoff depths from the replication couples.

Water table depths predicted by WEPP and DRAINMOD for the Ohio site were compared and illustrated in figures such as Figure 10. The calculated standard errors and average deviations between WEPP and DRAINMOD predicted midspace water table depths are given in Table 4. It is almost impossible to conclude that WEPP was actually simulating a water table. WEPP does not continuously model water table depth. The water table moves to the surface from the bottom of the soil profile very quickly with only a small amount of rainfall. On a few simulation days, the water table stayed at the surface, then quickly returned to the bottom of the soil profile. In another word, the soil profile transitions between saturated and unsaturated conditions very quickly, which is unusual for a silty clay soil. Furthermore, the calculated standard errors and average deviations between WEPP and DRAINMOD predicted water table depths are very large, in the range of 56 to 75 and 45 to 61 cm, respectively.

There are a number of possible reasons that the WEPP drain flow, runoff, and water table depth predictions may be so poor for the conditions of this study. First, the 24 hour time step used to calculate these values in WEPP is large, and water table depths can change quickly during a 24 hour period. Secondly, WEPP predicts a large amount of deep seepage at the bottom of the soil profile. Because of the assumptions and concepts modeled with most drainage models, deep seepage in large amounts is rare for soils that have a so-called impermeable layer. Next, the WEPP model predicts baseline effective conductivity based upon an empirical relationship with clay content, and at least for this study, grossly underpredicted conductivity values. In addition, WEPP appears to actually be predicting a perched water table, not a water table produced with

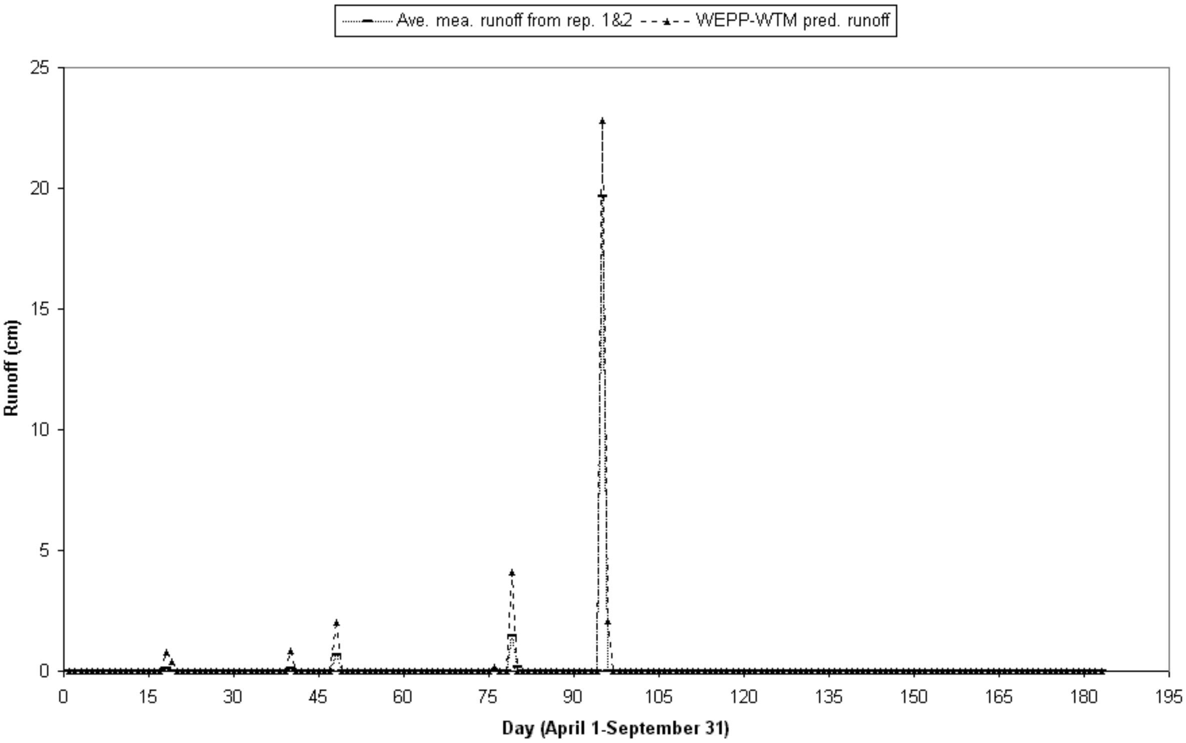

Figure 6. WEPP-WTM model predicted and average measured daily runoff depths for the replications 1 and 2 at the Ohio site during 1969.

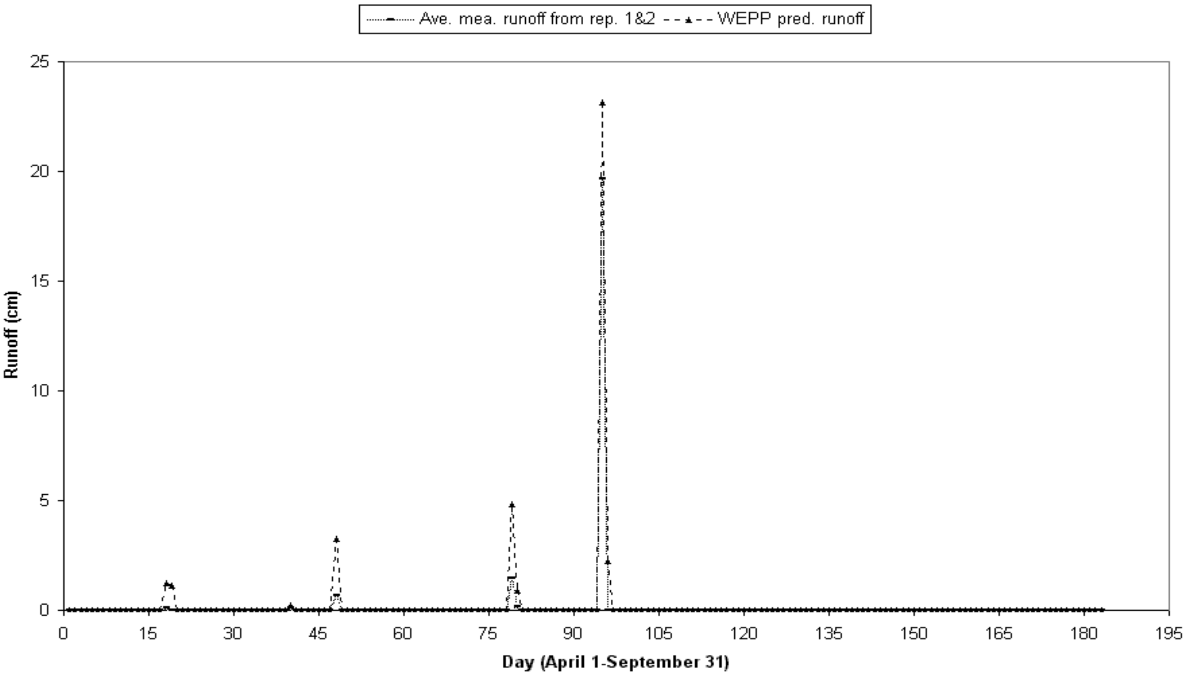

Figure 7. WEPP model predicted and average measured daily runoff depths for the replications 1 and 2 at the Ohio site during 1969.

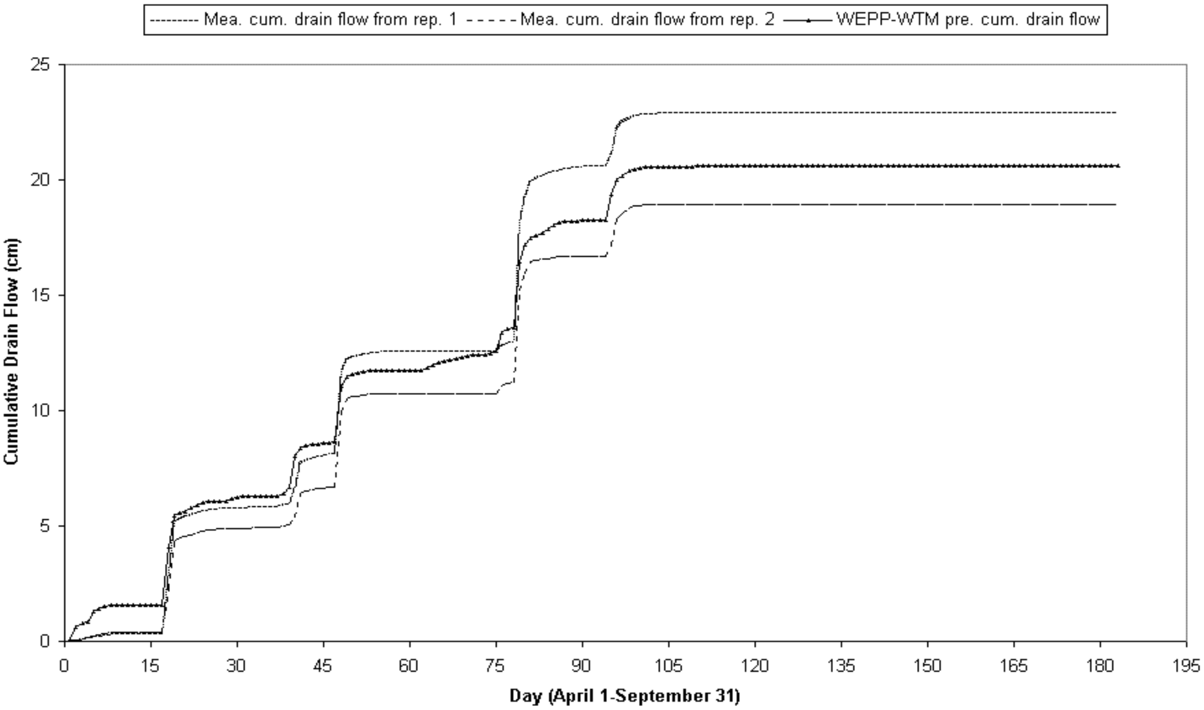

Figure 8. WEPP-WTM model predicted and measured cumulative drain flows for the replications 1 and 2 at the Ohio site during 1969.

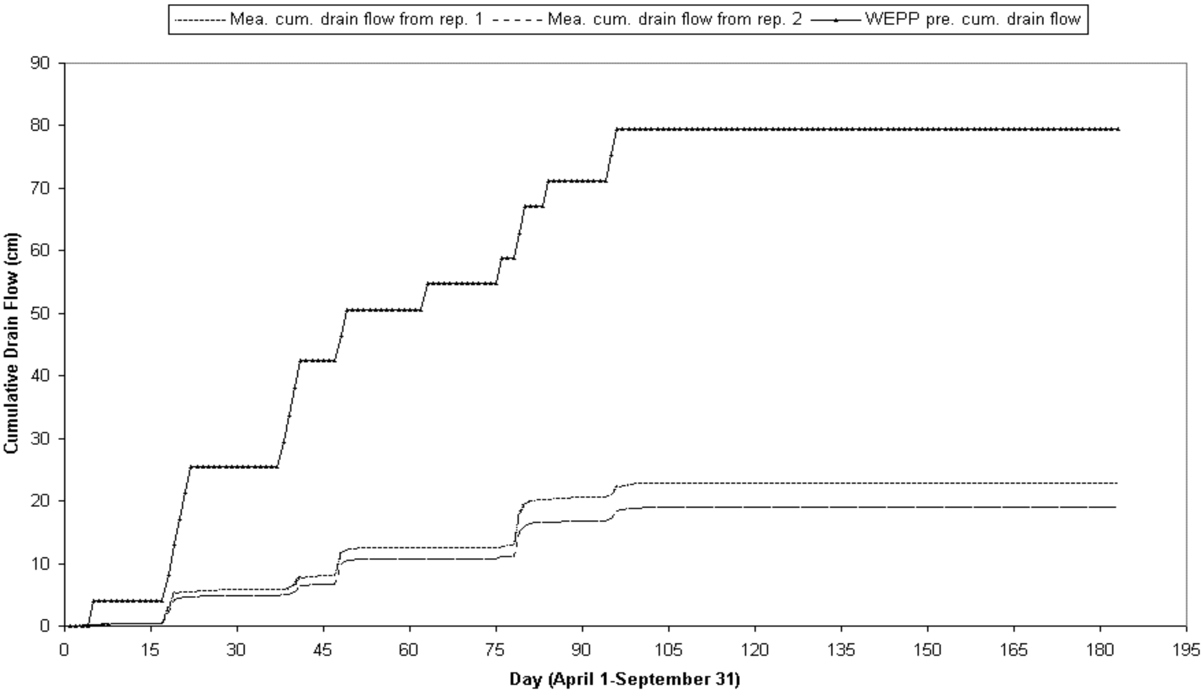

Figure 9. WEPP model predicted and measured cumulative drain flows for the replications 1 and 2 at the Ohio site during 1969.

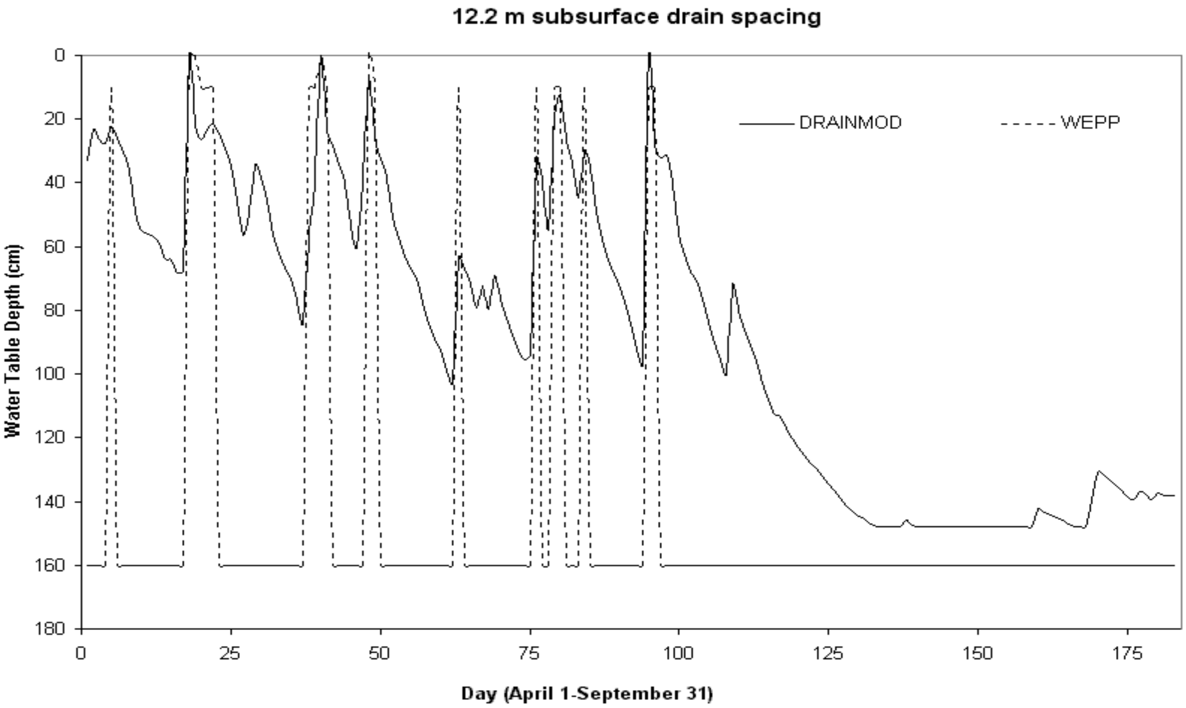

Figure 10. WEPP and DRAINMOD predicted midspace water table depths for the replications 1 and 2 during 1969 at the Ohio site.

Table 4. Standard errors (cm) and average deviations (cm) between WEPP and DRAINMOD predicted water table depths for the Ohio site.

Year	standard error	average deviation
1962	63.90	52.78
1963	56.19	45.07
1964	64.18	49.41
1967	70.39	52.45
1968	59.88	45.21
1969	74.47	60.57
1970	69.77	56.17
1971	61.87	49.35

saturated conditions from the bottom of the soil profile. It appears that the water routing calculation times between layers may produce somewhat artificial saturated conditions in an upper layer while a lower layer may not be saturated. Therefore, the first layer may became saturated very quickly while lower layers do not become saturated with the water table at the bottom of soil profile. When the first layer becomes saturated, WEPP assumes that a water table was built starting from the bottom of the soil profile and then arriving at the soil surface. In this situation, the lower layers may still be in an unsaturated condition, or their soil water content is far from the saturation. Therefore, with the soil profile saturation assumption of WEPP, the profile is transitioning between unsaturated and saturated conditions very quickly. Lastly, it seems that the water balance predictions of WEPP throughout the soil profile may not be accurate for subsurface drained cropland. The main purpose of WEPP is to predict runoff induced erosion. If it is assumed that WEPP's runoff predictions are valid for the study conditions evaluated previously (Liu et al., 1997; Savabi, 1993; Savabi et al.; 1995; Zhang et al., 1996), then it may not be important to properly model the full soil profile water balance for most soils, especially those where subsurface drainage is not an appropriate management strategy. However, Savabi et al. (1995) stated that the root zone soil water distribution is an important part of the WEPP model hydrology because the soil water content affects subsequent rainfall/runoff events, the root zone soil water content is used in the interaction between soil water and plant growth, and the soil water content is used in the residue decomposition routines.

Measured and WEPP-WTM predicted daily water table depths with weir depths for the three drain spacings and the five years of observations at the North Carolina site were evaluated and illustrated in figures such as Figure 11. The weir depths indicate periods of free drainage and where subirrigation were employed. For free drainage, the weir was set at 80, 90, and 100 cm for the drain spacings of 7.5, 15, and 30 m, respectively. Most of the time, the changes in water table depths predicted with WEPP-WTM matched the changes in weir depths, and in most cases the predicted water table depth responses are similar to those observed. The calculated standard errors and average deviations between measured and WEPP-WTM predicted daily water table depths are given in Table 5. The overall best predictions were obtained in 1977. If the standard errors are considered alone, the poorest predictions were obtained in 1976, 1973, and 1975 within the drain spacings of 7.5, 15, and 30 m, respectively. When average deviations are considered alone, WEPP-WTM simulations produced the poorest water table depths in 1976, 1974, and 1975 within the drain spacings of 7.5, 15, and 30 m, respectively.

Table 5. Standard errors (cm) and average deviations (a.d.) (cm) between observed and WEPP-WTM predicted water table depths for North Carolina site.

	Drain Spacing (m)					
	7.5		15		30	
Year	s	a.d.	s	a.d.	s	a.d.
1973	16.55	12.39	25.18	18.92	20.07	15.04
1974	13.76	11.78	23.05	19.78	18.84	15.15
1975	13.45	10.45	20.56	17.60	21.98	15.94
1976	20.71	16.24	24.08	18.96	19.56	13.98
1977	8.96	6.89	9.73	7.12	11.27	8.89

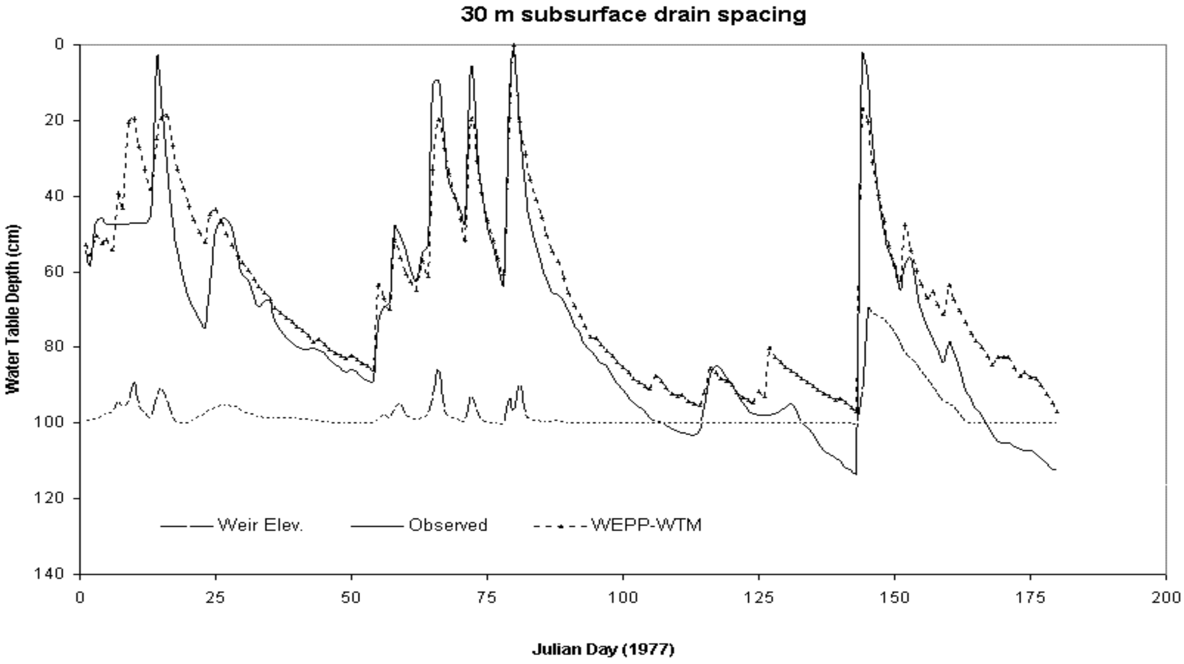

Figure 11. Observed and WEPP-WTM predicted daily water table depths at the midspace of drains spaced 30 m apart on the North Carolina site during 1977.

SUMMARY AND CONCLUSIONS

The WEPP-Water Table Management (WTM) model was developed to improve the water balance, runoff, drain flow, and water table depth prediction capabilities for subsurface drained cropland. WEPP-WTM is linked with the WEPP erosion prediction algorithms to calculate the erosion parameters from landscapes where subsurface drainage, controlled drainage, and/or subirrigation are planned or present.

The objective of this study was to evaluate runoff, drain flow and daily water table depth prediction accuracy of the WEPP hillslope and WEPP-WTM models for subsurface drained cropland conditions. Eight years of measured drain flow and runoff data from the drainage experiment at the North Central Ohio were used. Since there were no continuous water table depth measurements at this site, the water table depths predicted with WEPP model were compared with those predicted with DRAINMOD model. Water table depth prediction accuracy of WEPP-WTM model was evaluated against a five year field data set from Aurora, North Carolina.

Overall agreements between measured and predicted drain flows, runoff, and water table depths with WEPP-WTM model are good. Although there are some deviations in the magnitude of predicted and measured outflows, they are usually small and, in most cases, are about the same magnitude as the differences between replications. Most of the time, the changes in water table depths predicted with WEPP-WTM matched the changes in weir depths, and in most cases the predicted water table depth responses are similar to those observed.

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