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ASSESSING THE FEASIBILITY OF DRAINMOD APPLICATION USING SOIL HYDRAULIC PROPERTIES ESTIMATED BY PEDOTRANSFER FUNCTIONS

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ABSTRACT DRAINMOD is one of the widely used computer simulation models for drainage water management. Direct and indirect methods are available to feed DRAINMOD with the required inputs. Direct measurements of soil parameters are time consuming and costly compared with indirect methods such as the use of pedotransfer functions (PTFs). The goal of this study is to assess the feasibility of running DRAINMOD using saturated hydraulic conductivity (Ksat) and soil water characteristics (SWC) data estimated by PTFs. In previous research, we have identified the best performing PTFs for estimating the Ksat and SWC data for US soils of different textural classes. Data from Four U.S. agricultural drained sites, having different soils, crops, drainage systems, and climatological conditions, were used in the analysis. For each of the four sites Ksat and SWC data have been estimated using the best performing PTFs according to the soil textural class. The model was run using both calibrated and PTF-estimated Ksat and SWC data. Measured annual drainage was compared to predicted drainage using estimated and calibrated soil hydraulic properties. The Normalized Root Mean Square Error and Modeling Efficiency were used to assess the model performance. As expected, predicted annual drainage using the calibrated soil parameters (NRMSE=9-24%, EF=0.62-0.91) was more accurate than predicted drainage using PTF-estimated soil parameters (NRMSE=21-33%, EF=0.29-0.70). The errors in DRAINMOD predictions induced by using PTF-estimated soil parameters appear to have a small impact on DRAINMOD predictions of the system's response (annual drainage rate) to different management scenarios (e.g. conventional and controlled drainage). This finding has important implications regarding the large scale application of DRAINMOD to quantify the hydrologic and water quality impacts of controlled drainage across the U.S. Midwest.

Keywords: DRAINMOD, Pedotransfer functions, Hydraulic conductivity, Soil water characteristics data.

INTRODUCTION DRAINMOD (Skaggs, 1980) is a field-scale hydrologic model that was developed in early 1980s to simulate the hydrology of poorly drained high water table soils. DRAINMOD and the companion carbon and nitrogen model, DRAINMOD-N II (Youssef et al., 2005), are used to design sustainable crop production systems on artificially drained lands. Compared with many hydrologic models, DRAINMOD is easy to use, requires relatively few inputs, and yet provides quite accurate predictions. In the last two decades, many researchers have extensively tested the model for different climatic conditions, soil types, and farming practices (e.g. Skaggs et al., 1981; Fouss et al., 1987; Sabbagh et al., 1993.). In these evaluations, the model is calibrated and validated against field measured water table and subsurface drain flow data. During the calibration process, model inputs of soil hydraulic properties, which are usually based on field/lab measurements, are often adjusted within "acceptable range" to minimize the errors between measured and predicted water tables and drain flows. The calibrated model consistently showed high performance in predicting water table fluctuation and drain flow during the validation periods of these model evaluations. However, any large scale application of the model will be without calibration and will also be based on estimated rather than measured soil hydraulic properties.

DRAINMOD predictions are most sensitive to lateral saturated hydraulic conductivity (K_{sat}) of the soil profile followed by the unsaturated hydraulic properties estimated from the soil water characteristic (SWC) relationship (volumetric water content vs. Pressure head). For large scale applications of DRAINMOD, the direct measurement of K_{sat} and SWC data will be costly and time consuming. Alternatively these inputs can be estimated from readily available soil data (e.g. particle size distribution, bulk density, and organic matter) using pedotransfer functions (PTFs).

A few studies have been conducted to evaluate the feasibility of applying DRAINMOD with K_{sat} and SWC data predicted using PTF models such as ROSETTA (Salazar et al., 2008). In Italy, Borin et al. (2000) compared measured water table depths and drain flows to values predicted by DRAINMOD using three levels of details of soil inputs: 1) soil texture and porosity of top layer are the only available data; 2) soil texture and porosity are known for the entire soil profile; 3) K_{sat} and SWC data are measured for the entire soil profile. For scenarios 1 and 2, K_{sat} and SWC data were estimated using PTFs developed by Rawls et al. (1993) and Rawls and Brakensiek (1982), respectively. Borin et al. concluded that DRAINMOD was able to describe water table fluctuation and drain discharge under limited input of soil hydraulic properties. Two similar studies have recently been conducted in Iowa, USA (Qi et al.,2006) and Sweden (Salazar et al., 2008) to investigate the impact of using soil hydraulic properties predicted by the PTF model ROSETTA on the accuracy of DRAINMOD predictions of drainage volumes. Results of both studies showed the potential for using PTFs to estimate soil hydraulic properties that are required for DRAINMOD application.

Several studies have been conducted to evaluate the performance of different PTFs in predicting K_{sat} and SWC data (Tietje and Hennings, 1996; Minasny and McBratney, 2000; Wagner et al., 2001; Cornelis et al., 2001). In previous research, we have identified the best performing PTFs for predicting K_{sat} and SWC data for US soils (Abdel Baki et al., 2009a; 2009b). The goal of this study was to extensively assess the feasibility of running DRAINMOD with PTFs-predicted soil hydraulic parameters.

MATERIALS AND METHODS DRAINMOD has recently been tested against field measured data collected from four U.S. agricultural drained sites; three sites are located in the U.S. Midwest (Wang et al., 2006; Ale et al., 2009; Thorp et al., 2009) and one site is located in south eastern U.S. (Youssef et al., 2006). These sites have different soils, crops, drainage systems, and climatological conditions. In these evaluations, the model was calibrated and validated against field measured subsurface drain flow (and water table) data. During the calibration process, measured soil hydraulic properties have been adjusted to minimize the errors between measured and predicted drain flow (and water

Table1. Main features of study sites

Site	No of years	Soil textural class	Drainage system			Crop rotation
			Depth (cm)	Spacing (m)	Conv./Ctrl.	
SEPAC	6	Silt loam	75	5,10,20	Conv.	Continuous Corn
WQFS	16	Silty clay loam	90	10	Conv.	Continuous Corn
STORY CITY	10	Silty clay loam	145	27.4	Conv.	Corn-Soybean
TES	6	Sandy loam	116	22.72	both	Corn-Wheat-

table) data. The results of these four evaluations have indicated that the calibrated model accurately predicted drain flows (and water table fluctuation). In order to assess the feasibility of using DRAINMOD with PTFs-predicted soil properties, drain flows predicted by the calibrated model for the four sites were compared to drain flows predicted by DRAINMOD with soil hydraulic properties estimated by PTFs.

In this study, the soil hydraulic properties for the four sites have been estimated using the best performing PTFs for each site. Then, DRAINMOD model with PTFs-estimated soil parameters was used to simulate the hydrology of the four sites and predict subsurface drainage volumes. These predicted drainage rates have been compared to measured values and previously predicted values by the calibrated model for each site.

Description of Study Sites. Four U.S. sites have been used in this study: 1) the Southeast Purdue Agricultural Center (SEPAC) site, south eastern Indiana; 2) the Purdue University's Water Quality Field Station (WQFS) site, west central Indiana; 3) the Story City site, central Iowa; and 4) the Tidewater Experiment Station (TES) site, eastern North Carolina. Table 1 summarizes the main features of the four sites including soil types, drainage systems, and crop rotations. For more detailed description of the sites, readers are referred to Wang et al., 2006 for SEPAC site, Ale et al., 2009 for WQFS site, Thorp et al., 2009 for Story City site, and Youssef et al., 2006 for TES site.

Pedotransfer Functions for Predicting Soil Hydraulic Properties: Unlike previous studies (Qi et al., 2006; Salazar et al., 2008), which used the PTF model ROSETTA (Schaap et al., 2001) for predicting DRAINMOD soil inputs, we have used the best performing PTFs to predict K_{sat} and SWC data for each of the four sites.

Abdelbaki et al. (2009 a, b) evaluated PTFs for predicting K_{sat} and SWC data for U.S. soils and identified the best performing functions for different soil textural classes. The K_{sat} can be estimated by three groups of PTFs that require different soil inputs. Two groups were included in this study; group1 requires only the effective porosity and group 2 requires the particle size distribution and bulk density as inputs. The three best

Table 2. PTFs for predicting saturated hydraulic conductivity for the four test sites.

		STORY CITY	SEPAC	WQFS	STORY CITY	TES (NC)
Layers		1,2	1,2,3	1,2,3	3,4,5	1,2,3,4
Textural class		Fine	Medium	Medium	Medium	Coarse
Group 1 PTFs	K1	Suleiman et al. (2001)				
	K2	Minasny and McBratney (2000)				
	K3	Forrest et al. (1985)				
Group 2 PTFs	KK1	Rosetta SSC (Schaap et al.,2001)	Cosby et al. (1984)			Puckett et al. (1985)
	KK2	Cosby et al. (1984)	Dane & Puckett (1994)			Julia et al. (2004)
	KK3	Rosetta SSC-BD (Schaap et al.,2001)	Jabro et al. (1992)			Cosby et al. (1984)

Table 3. PTFs for predicting soil water characteristics data for the four test sites.

	STORY CITY	SEPAC	WQFS	STORY CITY	TES (NC)
Layers	1,2	1,2,3	1,2,3	3,4,5	1,2,3,4
Texture class	Fine	Medium	Medium	Medium	Coarse
θ1	Adhikary et al. (2008)	Zacharias et al. (2007)			Zacharias et al. (2007)
θ2	Cosby et al. (1984)	Cosby et al. (1984)			Rosetta SSC-BD
θ3	Homaee et al. (2008)	Rosetta SSC-BD			Cosby et al. (1984)

performing PTFs of these two groups were identified for each site (Table 2). The PTFs that predict SWC data require the particle size distribution and bulk density as inputs. Table 3 lists the three best performing PTFs for predicting SWC data for the four sites.

Model Evaluation: Thirteen DRAINMOD simulations (Table 4) were conducted for each site to assess the feasibility of applying DRAINMOD with indirectly estimated soil hydraulic data. The first simulation involved the calibrated model for the site, which used both calibrated/measured K_{sat} and SWC data. Then, six simulations were conducted using calibrated/measured SWC data and K_{sat} values estimated by the three best performing PTFs of groups 1 and 2 for each site. Another three simulations were conducted using calibrated/measured K_{sat} and SWC estimated by the three best performing PTFs for the each site. Lastly, three simulations were conducted using K_{sat} and SWC that are both estimated using the three best performing functions.

Table 4. DRAINMOD simulations with different K_{sat} and SWC inputs

Dataset	Description
D_O	Observed values
D_C	DRAINMOD simulation using calibrated/measured K_{sat} and SWC parameters
D_{K1}, D_{K2}, D_{K3}	DRAINMOD simulations using K_{sat} predicted by the first, second, and third ranked PTFs requiring effective porosity.
D_{KK1}, D_{KK2}, D_{KK3}	DRAINMOD simulations using K_{sat} predicted by the first, second, and third ranked PTFs requiring particle size distribution and bulk density.
$D_{\theta1}$, $D_{\theta2}$, $D_{\theta3}$	DRAINMOD simulation using θ(h) predicted by the first, second, and third ranked PTFs requiring particle size distribution and bulk density.
$D_{K\theta1}$, $D_{K\theta2}$, $D_{K\theta3}$	DRAINMOD simulations using K_{sat} and θ(h) predicted by the three best performing PTFs for each site.

Drainage rates predicted by the model using calibrated/measured and PTF-estimated K_{sat} and SWC data were compared to measured values for each site. Statistical performances measures used for comparing predicted and measured subsurface drainage are the Normalized Root Mean Square Error (NRMSE),

$$NRMSE = 100 * \left[\sqrt{\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2} \Big/ \overline{O} \right] \quad (1)$$

and Nash-Sutcliffe modeling efficiency (EF),

$$EF = \frac{\sum_{i=1}^{N} (O_i - \overline{O})^2 - \sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (O_i - \overline{O})^2} \quad (2)$$

where N is the number of data points, P_i and O_i are predicted and observed drainage in year *i*, respectively, and $\overline{O}$ is observed yearly drainage.

RESULTS AND DISCUSSION

Assessing DRAINMOD application with K_{sat} estimated by Group 1 PTFs: The results of DRAINMOD simulations using K_{sat} values predicted by group 1 PTFs, which require only the effective porosity as input, are presented in Figure 1 and Table 5. The model poorly predicted yearly subsurface drainage for all sites except for the North Carolina site (TES). DRAINMOD predictions of drainage volumes were closely correlated with the transmisivity of the soil profile (defined as the sum of the product of Ksat and thickness of each layer in the soil profile above the impervious layer), which is a direct function of estimated Ksat. Group 1 PTFs considerably under-estimated Ksat values for the three U.S. Midwest sites (SEPAC, WQFS, Story City) and as a result DRAINMOD drastically under-predicted drainage volumes for these sites (Figure 1). According to the statistical performance measures listed in Table 5, all DRAINMOD predictions of yearly drainage volumes for the Midwest sites, which are based on Ksat values estimated by group 1 PTFs, are considered unsatisfactory. Using Ksat estimated by third ranked function of group 1 gave relatively better predictions of yearly drainage for the three sites, compared with DRAINMOD predictions based on Ksat estimated by first and second ranked functions. The NRMSE in predicting yearly drainage by the calibrated model was in the range of 15-24% for the three U.S. Midwest sites. The corresponding modeling efficiencies ranged from 0.62 to 0.91. The use of Ksat values estimated by the best performing function of group 1 PTFs resulted in a substantial increase in the NRMSEs in DRAINMOD predictions of yearly drainage (28 to 63%) and a substantial decrease in the corresponding EF values (-1.60 to 0.47). For the TES site, the use of Ksat estimated by the first ranked function gave the closest predictions to measured drainage (NRMSE=15% and EF=0.63) and DRAINMOD performance was relatively comparable to the calibrated model for the site (NRMSE=9% and EF=0.88). The relatively better predictions of yearly drainage for the TES site are attributed to the relatively smaller difference between the profile transmissivities determined based on calibrated and group 1 PTFs-predicted Ksat values.

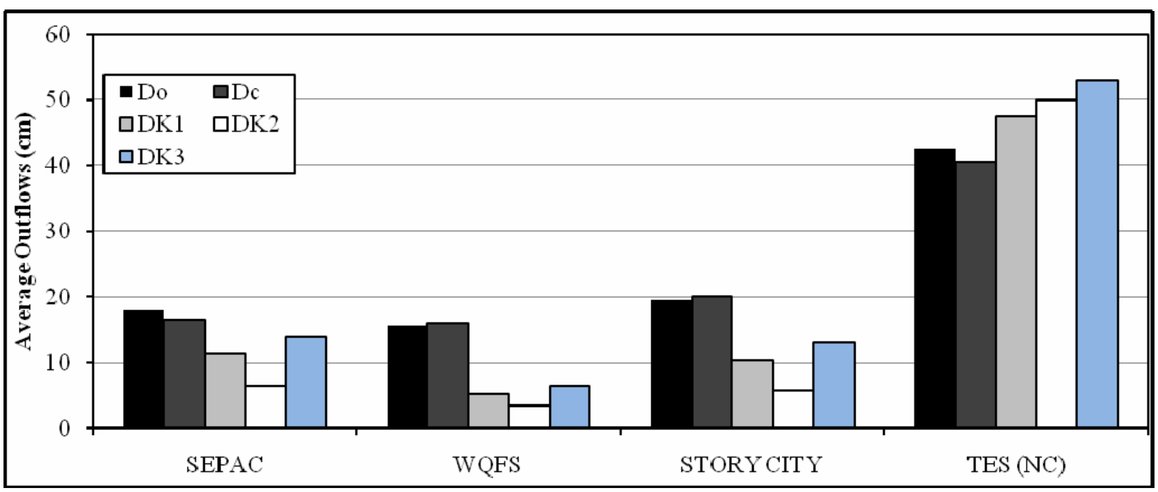

Figure 1. Observed and DRAINMOD-predicted yearly drainage volumes using K_{sat} values estimated by group 1 PTFs.

Table 5. Statistical comparison between observed and DRAINMOD-predicted yearly drainage volumes using K_{sat} values predicted by group 1 PTFs.

	SEPAC		WQFS		STORY CITY		TES (NC)	
	NRMSE	EF	NRMSE	EF	NRMSE	EF	NRMSE	EF
D_C	20.9	0.70	24.1	0.62	14.8	0.91	8.6	0.88
D_{K1}	40.3	-0.11	72.2	-2.37	55.9	-0.35	15.0	0.63
D_{K2}	67.3	-2.10	83.4	-3.51	80.1	-1.78	18.1	0.47
D_{K3}	27.9	0.47	63.4	-1.60	42.5	0.22	27.7	-0.24

The soil textural class appears to be an important factor affecting the performance of group 1 PTFs and consequently DRAINMOD predictions which are based on Ksat estimated using these PTFs. Group 1 PTFs performed poorly for the three Midwest sites, which have fine to medium texture soils. These PTFs performed relatively better for the TES site, which has coarse texture soil.

Assessing DRAINMOD application with K_{sat} estimated by group 2 PTFs: Figure 2 and Table 6 summarize the results of the DRAINMOD simulations using K_{sat} values estimated by group 2 PTFs, which require the particle size distribution and bulk density as inputs. Generally, the use of Ksat values estimated by group 2 PTFs has greatly improved DRAINMOD predictions of yearly drainage volumes. The accuracy of DRAINMOD predictions using K_{sat} estimated by the first ranked function of group 2 PTFs were comparable to the accuracy of the calibrated model for the three US Midwest sites. For these three sites, the NRMSEs in yearly drainage predicted by the calibrated model were in the range of 15 to 24% with corresponding modeling efficiencies ranging from 0.62 to 0.91. The use of Ksat estimated by the first ranked PTF of group 2 slightly increased the NRMSE (19-30%)and slightly decreased the EF (0.43-0.85). The second ranked PTF out performed the first ranked function for the WQFS site. For this site, the yearly drainage volumes predicted using the K_{sat} estimated by the second ranked PTF were considerably closer to measured and predicted by the calibrated model than the drainage volumes predicted using the first ranked PTF. However, the use of Ksat estimated by group 2 PTFs resulted in poor predictions of drain flow for the TES site. For this site, the NRMSE and EF for the calibrated model were 9% and 0.88, respectively. The corresponding NRMSE and EF for yearly drainage predicted by DRAINMOD using the best performing PTF among group 2 were 22% and 0.22. For this site, yearly drainage predicted using group 1 PTFs were more accurate than those based on group 2 PTFs.

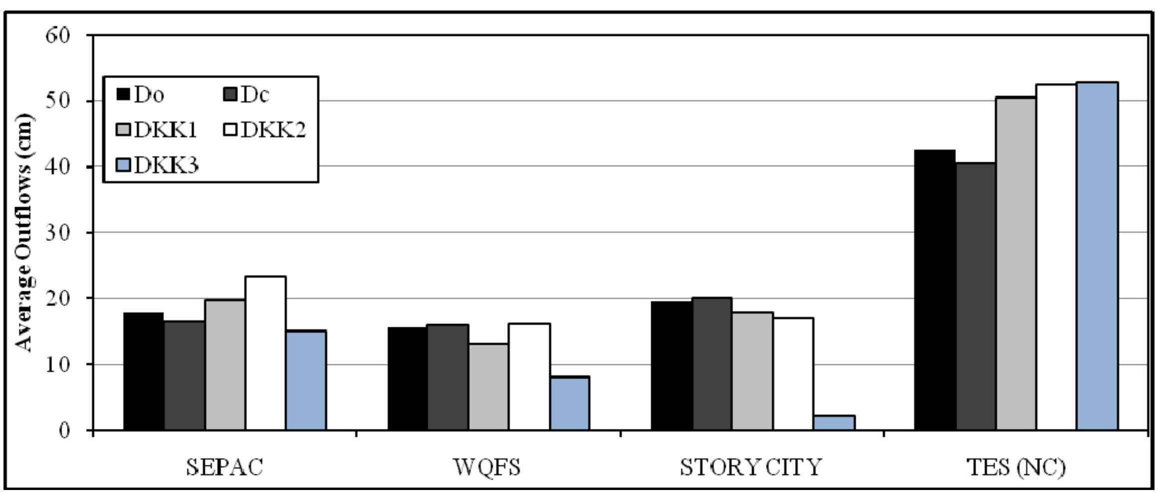

Figure 2. Observed and DRAINMOD-predicted yearly drainage volumes using K_{sat} values estimated by group 2 PTFs.

Table 6. Statistical comparison between observed and DRAINMOD-predicted yearly drainage volumes using K_{sat} values estimated by group 2 PTFs.

	SEPAC		WQFS		STORY CITY		TES (NC)	
	NRMSE	EF	NRMSE	EF	NRMSE	EF	NRMSE	EF
D_C	20.9	0.70	24.1	0.62	14.8	0.91	8.6	0.88
D_{KK1}	22.6	0.65	29.7	0.43	18.7	0.85	21.9	0.22
D_{KK2}	45.1	-0.39	24.7	0.61	24.7	0.74	26.1	-0.11
D_{KK3}	24.6	0.58	53.7	-0.86	96.7	-3.06	27.2	-0.20

Assessing DRAINMOD application with SWC Data estimated by PTFs: Results of DRAINMOD simulations using PTFs-predicted SWC data are presented in Figure 3 and Table 7. The results showed that the SWC data has a relatively smaller effect on DRAINMOD predictions of yearly drainage than Ksat. The use of the SWC data predicted by the first ranked PTF resulted in good agreement between the simulated and observed yearly drainage for the four study sites. The statistical performance measures showed that the performance of DRAINMOD was comparable to the calibrated model, especially for the SEPAC and Story City sites (Table 7). DRAINMOD performance in predicting yearly drainage was directly related to the performance of different PTFs in predicting SWC. The most accurate predictions of yearly drainage for all sites are those based on SWC data estimated by the first ranked PTF. The use of SWC data estimated by the second ranked PTF resulted in the second accurate predicted drainage. The least accurate predictions of drainage volumes resulted from using SWC data estimated by the third ranked PTF.

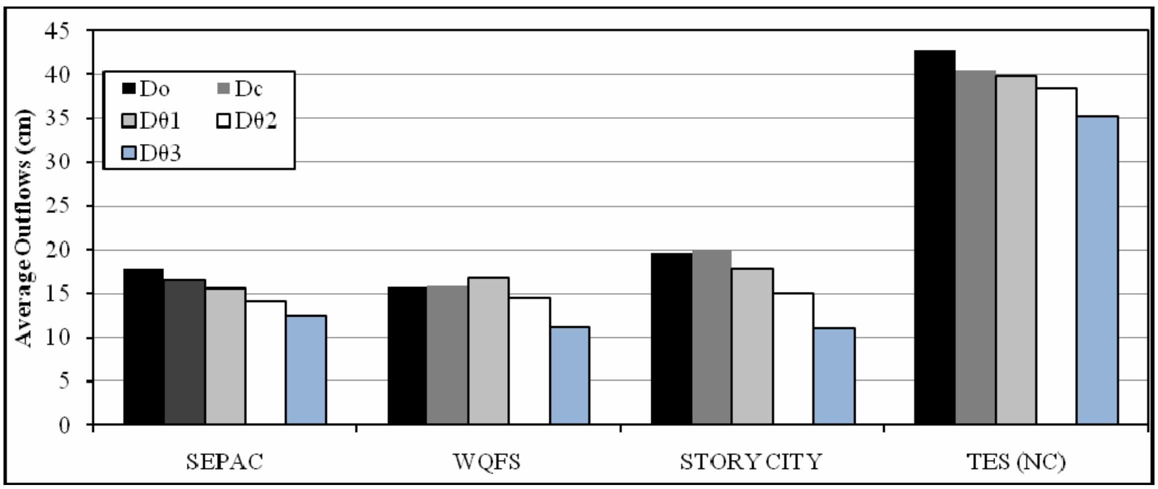

Figure 3. Observed and DRAINMOD-predicted yearly drainage volumes using SWC data estimated by PTFs.

Table 7. Statistical comparison between observed and DRAINMOD-predicted yearly drainage volumes using SWC data estimated by PTFs

	SEPAC		WQFS		STORY CITY		TES (NC)	
	NRMSE	EF	NRMSE	EF	NRMSE	EF	NRMSE	EF
D_C	20.9	0.70	24.1	0.62	14.8	0.91	8.6	0.88
$D_{\theta 1}$	24.0	0.60	31.8	0.35	15.9	0.89	17.5	0.50
$D_{\theta 2}$	29.8	0.39	31.8	0.34	28.4	0.65	20.6	0.31
$D_{\theta 3}$	36.0	0.11	34.5	0.23	50.4	-0.10	25.6	-0.06

Assessing DRAINMOD Application with K_{sat} and SWC Data Predicted from PTFs: These simulations were conducted to assess the overall effect of using both Ksat and SWC data estimated by PTFs on the accuracy of DRAINMOD predictions of yearly drainage. This scenario represents the most likely case when DRAINMOD is to be applied at large scale. Three simulations were conducted using the best three performing PTFs for predicting Ksat and SWC data for each of the four sites. The functions theta 1, theta 2, and theta three (Table 3) are consistently ranked from the best to the least performing functions for predicting SWC data for all sites. The thee best performing PTFs for predicting Ksat varied depending on the site. For example, K1, K2, and KK1 are the best performing functions for the TES site. Likewise, KK1 is the best performing function for the SEPAC site, followed by KK3 and K3. The results of these simulations are presented in Figure 4 and Table 8.

As expected, the use of both PTF-estimated Ksat and SWC data as inputs to DRAINMOD resulted in less accurate model predictions of yearly drainage, compared with predicted drainage based on using only PTF-estimated Ksat or PTF-estimated SWC. For example, the NRMSE in predicting yearly drainage for the Story City was 19% (Table 6) when only Ksat estimated by the best performing function (KK1) was used, 16% (Table 7) when only SWC data estimated by the best performing function ($D_{\theta 1}$) was used, and 26% (Table 8) when both same PTF-estimated Ksat and SWC data were used. The corresponding EF values for the three simulations were 0.85, 0.89, and 0.7, respectively. The same trend can be observed for the WQFS and TES sites. For the SEPAC site, the use of both Ksat and SWC data estimated by PTFs resulted in slightly better predictions of yearly drainage, compared with predicted drainage based on PTF-estimated SWC data only. Another important observation is that best performing PTF for eastimating Ksat and the best performing PTF for estimating SWC is the only combination that resulted in reasonable DRAINMOD predictions of yearly drainage.

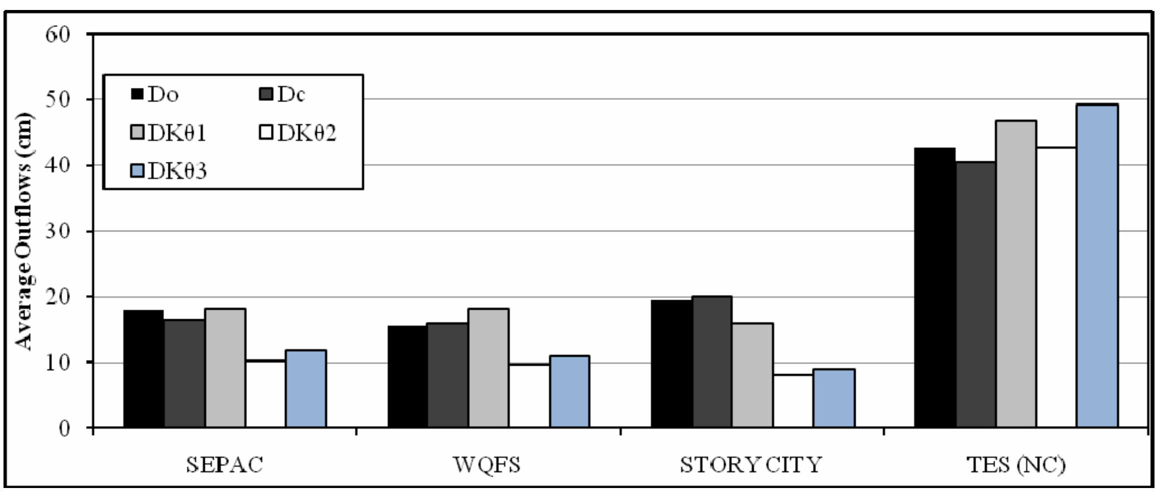

Figure 4. Observed and predicted outflows using K_{sat} and SWC data predicted by PTFs

Table 8. Statistical comparison between observed and simulated drainage using K_{sat} and SWC data predicted by PTFs

	SEPAC		WQFS		STORY CITY		TES (NC)	
	NRMSE	EF	NRMSE	EF	NRMSE	EF	NRMSE	EF
D_C	20.9	0.70	24.1	0.62	14.8	0.91	8.6	0.88
$D_{K\theta 1}$	23.2	0.63	33.1	0.29	26.1	0.70	20.5	0.32
$D_{K\theta 2}$	45.8	-0.44	49.8	-0.61	64.2	-0.79	22.8	0.16
$D_{K\theta 3}$	38.6	-0.02	45.3	-0.33	60.5	-0.59	27.8	-0.26

A Predictive analysis using DRAINMOD with PTF-estimated K_{sat} and SWC Data: In the previous analysis, both measured drainage and drainage predicted by the calibrated model for the four sites were compared to drainage predicted by the model using PTF-estimated Ksat and SWC data. The results of the analysis quantified the errors in DRAINMOD predictions of yearly drainage induced by using PTF-estimated Ksat and SWC rather than the calibrated/measured values. The use of PTF-estimated Ksat and SWC data resulted in a substantial increase in the NRMSEs by 11% for SEPAC, 37% for WQFS, 76% for Story City, and 138% for TES sites. This demonstrates the importance of the calibration and validation of DRAINMOD using field measured data. The previous analysis, however, does not assess the use of DRAINMOD with PTF-estimated Ksat and SWC in a predictive mode, in which the model simulates different scenarios of land use and water management practices.

In this analysis, the effect of controlled drainage on reduction of yearly drainage volumes was assessed for the four sites using both the calibrated model for and the model that uses PTF-estimated Ksat and SWC data. The results of the simulations reveal an important finding. The use of PTF-estimated Ksat and SWC resulted in an over-prediction/under-prediction of yearly average drainage by 15 to 21% for conventional drainage and by 7 to 23% for controlled drainage. Despite this relatively large difference in the predicted yearly average drainage for each drainage management scenario, the predicted annual reduction in drain flow, on a percentage basis, because of implementing controlled drainage at the four sites was very similar (0.8 to 6.2% difference in the percent reduction). Thus the errors in DRAIMOD predictions induced by the use of PTF-estimated soil hydraulic properties does not have a large impact on the accuracy of the model prediction of the system's response (e.g. annual drainage rate) to different management scenarios (e.g. conventional and controlled drainage).These results have an important implications regarding the large scale application of DRAINMOD model using the PTF-estimated soil hydraulic properties.

Table 9. DRAINMOD-Predicted yearly average drainage for four US sites under conventional and controlled drainage using calibrated and PTF-estimated Ksat and SWC data.

		Dc			D-θ-K(1)	
	Conv.	Ctrl.	(Δ (%))	Conv.	Ctrl.	(Δ (%))
SEPAC	15.6	12.0	23.1	18.1	12.8	29.3
WQFS	15.9	10.5	34.0	18.2	11.8	35.2
Story City	20.0	18.5	7.5	15.9	14.3	10.1
TES (NC)	43.9	38.5	12.3	52.0	46.0	11.5

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