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Hydraulic Conductivity Evaluation for a Drainage Simulation Model (DRAINMOD)

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Abstract: The objective of this study was to determine the most suitable saturated hydraulic conductivity (K) values as input into DRAINMOD among a range of K data sets developed for the drainage experiment site in North Central Ohio using seven different K estimation methods. The K methods evaluated were monolith, core, auger-hole, MUUF soil database, and using the Hooghoudt, Kirkham, and van Schilfgaarde equations with water table drawdown and drainage discharge data. Simulations using DRAINMOD (Version 4.6) were conducted for the years 1962-1964 and 1967-1971, and runoff and drain discharge predictions were compared with measured discharges. The analyses showed that none of the K estimation methods provided the smallest deviation in discharges when individual years were considered, except for drain discharge in 1967-1971. For 1967-1971, the simulation results with the van Schilfgaarde equation produced the smallest average deviation. The simulations with the van Schilfgaarde equation also produced the smallest deviation in runoff in three of the five years that also had the smallest drain discharge deviation. Overall, the simulation results with the van Schilfgaarde equation produced the smallest total deviation for both drain discharge and runoff over all eight test-years. The rank order (smallest to largest total deviation) of the K methods for drain discharge was van Schilfgaarde, Hooghoudt, and Kirkham equations, followed by auger-hole, monolith, core methods, and then the MUUF soil database. The rank order of the K methods for runoff was van Schilfgaarde, Hooghoudt, Kirkham, auger-hole, MUUF soil database, core, and monolith. Where drain discharge and water table depth measurements are available or practical to obtain, using the hydraulic conductivity values estimated with the van Schilfgaarde equation in DRAINMOD may provide more reliable modeling results.

Key Words: Hydraulic conductivity, DRAINMOD, runoff, drain discharge

Drenaj Simulasyon Modeli (DRAINMOD) için Hidrolik İletkenlik Değerlendirmesi

Özet: Bu çalışmanın amacı, Orta Kuzey Ohio'daki bir drenaj deneme alanı için yedi farklı doymuş koşullar için hidrolik iletkenlik (K) belirleme yöntemi kullanarak geliştirilmiş bir dizi K veri seti arasından, DRAINMOD modeli için en uygun olanını belirlemektir. Değerlendirilen K yöntemleri; monolit, silindir permeametre, burgu deliği, MUUF toprak veri tabanı ve arazide ölçülen su tablası derinliği ile dren debilerini Hooghoudt, Kirkham, van Schilfgaarde eşitliklerinde kullanma yöntemleridir. DRAINMOD, 1962-1964 ve 1967-1971 yılları için kullanılarak model dren debileri ve yüzey akış tahminleri arazide ölçülen debi ve akış değerleriyle karşılaştırılmıştır. Yıllar tek başına ele alındığında, 1967-1971 yıllarındaki dren debileri dışında, hiçbir hidrolik iletkenlik belirleme yöntemi debi ve akışlar için en küçük sapmayı vermemiştir. Anılan yıllarda, van Schilfgaarde eşitliği ile belirlenen K değerlerinin modelde kullanılması, en küçük ortalama sapmayı vermiştir. Ek olarak, van Schilfgaarde eşitliği ile belirlenen K değerleriyle, dren debilerinde en küçük sapmayı veren beş yılın üçünde yüzey akışlarda en küçük sapmayı vermiştir. Sekiz yıllık test süresi bir bütün olarak dikkate alındığında, van Schilfgaarde eşitliği kullanılarak elde edilen K değerleriyle elde edilen model dren debileri ve yüzey akışları, arazide ölçülen dren debi ve yüzey akış değerlerinden en az toplam sapmayı vermiştir. Dren debileri için, en küçükten en büyüğe doğru toplam sapmayı veren K yöntemleri sırasıyla; van Schilfgaarde, Hooghoudt ve Kirkham eşitlikleriyle K belirleme yöntemleri; bunları burgu deliği, monolit, silindir permeametre yöntemleri ve son olarak ta MUUF toprak veri tabanı izlemiştir. Yüzey akışları için, en küçükten en büyüğe doğru toplam sapmayı veren K yöntemleri ise sırasıyla; van Schilfgaarde, Hooghoudt, Kirkham, burgu deliği, MUUF toprak veri tabanı, silindir permeametre, ve monolith yöntemleri olmuştur. Dren debisi ve su tablası derinliği ölçümlerinin mevcut ve/veya elde edilmelerinin kolay olduğu yerlerde van Schilfgaarde eşitliği kullanılarak tahmin edilen hidrolik iletkenlik ölçümlerinin DRAINMOD modelinde kullanılması, modelden daha güvenilir sonuçların alınmasını sağlayabilir.

Anahtar Sözcükler: Hidrolik iletkenlik, DRAINMOD, yüzey akış, dren debisi

Introduction

DRAINMOD (Skaggs, 1978), which is a popular model used in the USA and around the world, has the capability of simulating on a day-to-day, hour-by-hour basis, the water table position, soil water content, drainage, evapotranspiration and runoff in terms of climatological data, soil properties, crop parameters, and the water management system design.

Saturated hydraulic conductivity (K) is a parameter to which many water table management models are very sensitive. In sensitivity analyses of DRAINMOD reported by Workman et al. (1986), K ranked second behind potential evapotranspiration adjustment factors in having the greatest effect on model results.

There are many field and laboratory methods to estimate K (Amoozegar and Warrick, 1986; Klute and Dirksen, 1986). One widely used laboratory method for determining K is the core method (Klute and Dirksen, 1986). Skaggs (1980) states that K values determined from cores tend to be smaller than field values because the cores usually do not contain cracks, worm-holes, etc. Skaggs (1980) also mentioned that these values usually represent vertical K while drainage discharges depend more on horizontal K.

The auger-hole method (Bouwer and Jackson, 1974) is an easy, fast, and widely used field method to determine horizontal K. To evaluate DRAINMOD for a Commerce clay loam soil in the Lower Mississippi Valley, Fouss et al. (1987) used the auger-hole method to determine effective horizontal hydraulic conductivity (Ke) values. In addition, Workman et al. (1986) recommended the auger-hole and well permeameter methods to obtain field hydraulic conductivity values for DRAINMOD.

Another method to determine hydraulic conductivity is based on the use of steady state drainage equations with measured water table depths and corresponding drain discharges. Hoffman (1963) used the equations of Glover (as reported by Dumm, 1959), van Schilfgaarde (van Schilfgaarde, 1963), Hooghoudt (Hooghoudt, 1940), and Kirkham (Kirkham, 1957) to calculate equivalent hydraulic conductivity (K_e) values from drain discharge and water table drawdown data from a drainage experiment (Schwab et al., 1963; 1975; and 1985) in North Central Ohio. The major advantages of determining K from these equations are as follows: the effects of soil profile heterogeneities and anisotropy tend to be lumped, errors made in estimating the effects of soil layering and determining the depth to the impermeable layer are incorporated in the K values (Skaggs, 1980), they take into account the effect of tile-crack spacing and deep percolation, and soil variability is also reduced because of the large sample size (Hoffman and Schwab, 1964).

Since drainage and subirrigation usually involve horizontal flow to and from drains, the horizontal K values are preferable for use in DRAINMOD. Skaggs (1980) states that horizontal and vertical K may differ by a factor of 10. Since horizontal K values are not always available, vertical K values are used in place of horizontal K, with the assumption that they are equal. In addition, if there are no measured K values, some soil database programs such as the MUUF (Map Unit Use File) soil database (Baumer, 1989) can be used to obtain an estimate of K. So far in no study have the effects of different K values on the DRAINMOD prediction results been evaluated. The purpose of this study was to determine the most suitable hydraulic conductivity (K) values as input into DRAINMOD.

Materials and Methods

Runoff and drain discharge data measured by Schwab et al. (1963, 1975, and 1985) for eight years (1962-64 and 1967-71) from North Central Ohio were used in this research because the same crop (corn) was grown during these years. The predominant soil type (about 80% of areal coverage) at the site was Toledo silty clay. Because of the starting inconsistency of discharge measurements made in March as stated by Skaggs et al. (1981), this evaluation is based on the data from April 1 to September 30 each year. Hourly rainfall, and daily maximum and minimum temperatures were recorded at the site. Irrigation water was applied twice each year in May, June or July to provide a repeatable 10-year return period storm.

In this study, to calculate average deviations between the predicted and measured drain discharges and runoff, runoff and drain discharges predicted by DRAINMOD were used with the measured runoff and drain discharges. The agreement between predicted and measured values was quantified on the basis of daily and daily cumulative values for the test years by computing average deviation (cm/day) within each year as

$$\text{average deviation} = \sum_{i=1}^{n} |x_i - y_i|/n \qquad \text{[Eq. 1]}$$

where, x_i is the predicted daily drain discharge or runoff depth, y_i is the measured daily drain discharge or runoff depth on day i and n=183, the number of days in the simulation period (April 1 to September 30). Equation 1 was also used to calculate the agreement between cumulative predicted and measured discharges.

For the current study, the same general subsurface drainage system parameters and values used by Skaggs et al. (1981) were used except K values and equivalent depth from the drain to the impermeable layer (d_e). The input values of subsurface drainage system parameters used in this study are listed in Table 1 and illustrated in Figure 1. A 75 cm value for d_e was used by Skaggs et al. (1981). DRAINMOD (Version 4.6) now estimates this value. A value of 47.52 cm for de was predicted by DRAINMOD and used in this study in place of the 75 cm. The soil water retention data were obtained from field experiment notes of Schwab et al. (1963; 1975; and 1985) and data presented by Skaggs et al. (1981). The relationships between water table depths versus drained volumes, upward fluxes, and Green-Ampt equation parameters were taken from data developed by Skaggs et al. (1981).

Table 1. Summary of drainage system input parameters used in DRAINMOD for Toledo silty clay in North Central Ohio.

Parameter	Value (cm)
Drain spacing	1220
Drain depth	90
Equivalent depth from drain to impermeable layer	47.52
Estimated profile depth	165
Depth of surface storage	0.25
Kirkham's depth (STORRO)	0.1
Drain diameter	10

DRAINMOD (Version 4.6) now uses a Kirkham's depth (STORRO) and drainage coefficient (DC) compared with the version described by Skaggs (1980) and used by Skaggs et al. (1981). The STORRO is used to determine whether the model uses Hooghoudt's or Kirkham's equation when water table depth is less than 0.5 cm from the soil surface. In this study, a value of 0.1 cm was used for STORRO based upon the fact that the field data were collected on plots that were surface drained at 0.2% slope. The parameter DC is used as the hydraulic capacity or design discharge capacity of the drain. In DRAINMOD, the drain discharge predicted by the Kirkham and Hooghoudt equations is limited to the value of DC. A DC value of 5.3 cm/day was determined using the empirical equation developed by Hoffman (1963). The metric unit form of this equation is

$$\text{Log}Q = \frac{H^2}{1935.42} - \frac{H}{56.44} - 1.865 \qquad \text{[Eq. 2]}$$

where Q is drain discharge depth (cm/day) and H is midspace water table elevation (cm) above the drain. Assuming that the midspace water table elevation was a maximum at 90 cm, the DC would correspond to the discharge calculated at the maximum elevation using Equation 2. The English unit form of Equation 2 was found as the best empirical solution by Hoffman (1963) using data from the North Central Ohio site.

In this research, the average deviations between the predicted and measured discharges were used to determine the most suitable K values as input into DRAINMOD. DRAINMOD was run for seven different K data sets, based on seven different methods of estimating K values. The K methods evaluated were monolith (Taylor et al., 1970), core (Klute and Dirksen, 1986), MUUF soil database (Baumer, 1989), auger-hole (Bouwer and Jackson, 1974), and using the Hooghoudt, Kirkham, and van Schilfgaarde equations with water table drawdown and drainage discharge data. The vertical hydraulic conductivity values from the monolith and core methods were used as horizontal K values.

Equation 2 was used to calculate drain discharges for different midspace water table elevations above the drain. These midspace water table elevations were derived from the soil horizon data given by Schwab et al. (1963). The drain discharges were then used to estimate the equivalent hydraulic conductivity (K_e) values using the van Schilfgaarde and Hooghoudt equations, and Kirkham's

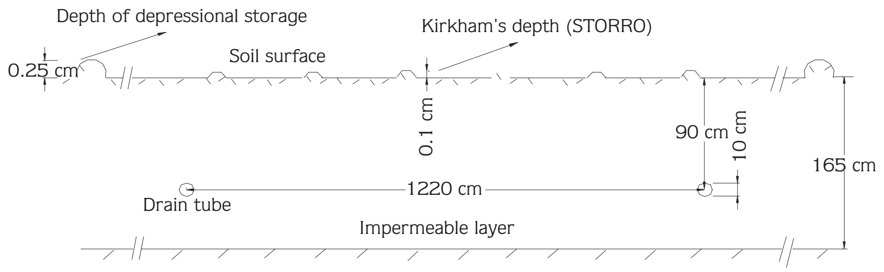

Figure 1. Subsurface drainage system input parameters (from Table 1) used in DRAINMOD for the North Central Ohio site.

approach. To estimate equivalent K_e values using Kirkham's approach, graphs for the Kirkham equation developed by Toksoz and Kirkham (1971) were used in place of the Kirkham equation.

Other estimates of hydraulic conductivity at this site were obtained by the Ohio Soil Survey personnel (Ohio Soil Survey, 1960), Schwab et al. (1963), and Taylor et al. (1970). To use any of the hydraulic conductivity data sets mentioned above as input to DRAINMOD, horizontal K values of each soil layer must be entered with each layer's specific bottom depth. For this reason, the K_e values were converted to layer specific horizontal K_i values using the following form of Equation 2.16 given by Skaggs (1980):

$$K_i = \frac{K_e \sum D_i - \sum K_{i-1} D_{i-1}}{D_i} \qquad \text{[Eq. 3]}$$

where D_i is the thickness of soil layer i; the other parameters were already described. The assumption that the lowest layer's K_e value was equal to the lowest layer's horizontal K value was used in this conversion and the conversion operation was started from the lowest layer and continued to the next lower layer, and so forth to the top soil layer. The horizontal K values from all the considered methods are given in Table 2.

Results and Discussion

The results of the hydraulic conductivity analyses shown in Tables 3 and 4 are the average daily and cumulative deviations, respectively, between measured and predicted drain discharge and runoff for the eight years 1962-1964 and 1967-1971, with totals over the eight years.

The annual values in these tables are the means of the average deviations for each of the seven K estimation methods for each replicate plot. The minimum average daily deviation for each year is underlined in Tables 3 and 4. The results in Table 3 suggest that no one method provided the smallest deviation in discharges when we consider the individual years, except for drain discharge in 1967-1971. For each of these five years, the simulation results with the van Schilfgaarde equation produced the smallest average deviation. When we consider the total deviation over all eight years, the simulation results with the van Schilfgaarde equation produced the smallest total average deviations for both drain discharge and runoff. The rank order of the K methods, which produced smallest to largest total deviations in drain discharge, is van Schilfgaarde, Hooghoudt, and Kirkham equations, auger-hole, monolith, core, and MUUF soil database. The rank order of the K methods, which produced smallest to largest total deviations in runoff, is van Schilfgaarde, Hooghoudt, and Kirkham equations, auger-hole, MUUF soil database, core, and monolith. It should be noted that the simulations with the van Schilfgaarde equation also produced the smallest deviation in runoff in three of the five years with the smallest drain discharge deviation. Therefore, the simulations using the van Schilfgaarde equation produced the smallest deviation in both drain discharge and runoff for three of the eight years (37.5%).

Figures 2 through 5 illustrate daily drain discharge and runoff predictions for 1971 using the van

Table 2. Estimated horizontal saturated hydraulic conductivity (K) values (cm/h) for Toledo silty clay soil layers.

Layer Depth (cm)	Hydraulic Conductivity Calculated from Drain Discharge			Monolith Method*	Core Method$^{\#}$	Auger-Hole Method^{+}	MUUF Soil Database
	van Schilfgaarde	Hooghoudt	Kirkham				
0-20	42.477	47.166	80.260	1.397	2.540	25.500	0.879
20-50	1.920	2.461	3.859	1.016	0.204	9.160	0.336
50-102	0.052	0.125	0.156	0.102	0.142	0.200	0.279
102-165	0.010	0.010	0.010	0.051	0.267	0.010	0.279

*From Table 4 by Taylor et al. (1970)

$^{\#}$From Table A1 by Schwab et al. (1963)

$^{+}$From Ohio Soil Survey (1960)

Table 3. Means of average deviation (cm/day) between daily observed and predicted drain discharge and runoff.

	Analytical Methods Using Drain Discharge Data						Monolith		Core		Auger-Hole		MUUF Soil	
	van Schilfgaarde		Hooghoudt		Kirkham		Method		Method		Method		Database	
Year	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain. Disch.	Runoff
1962	0.048	0.012	0.048	0.012	0.056	0.010	0.045	0.017	0.046	0.016	0.052	0.011	0.045	0.016
1963	0.044	0.007	0.044	0.006	0.044	0.007	0.055	0.013	0.054	0.012	0.042	0.005	0.055	0.012
1964	0.069	0.010	0.067	0.010	0.075	0.009	0.078	0.029	0.077	0.026	0.078	0.012	0.080	0.027
1967	0.039	0.027	0.041	0.028	0.045	0.029	0.047	0.028	0.049	0.027	0.053	0.029	0.055	0.027
1968	0.034	0.030	0.035	0.031	0.035	0.029	0.045	0.025	0.045	0.025	0.038	0.029	0.050	0.027
1969	0.043	0.032	0.045	0.032	0.049	0.032	0.094	0.075	0.094	0.070	0.058	0.034	0.103	0.068
1970	0.055	0.047	0.057	0.048	0.067	0.054	0.085	0.055	0.087	0.053	0.062	0.050	0.096	0.047
1971	0.024	0.020	0.026	0.020	0.027	0.020	0.036	0.018	0.036	0.018	0.028	0.020	0.039	0.019
Total	0.356	0.185	0.363	0.187	0.398	0.190	0.485	0.260	0.488	0.247	0.411	0.190	0.523	0.243

Table 4. Means of average deviation (cm/day) between daily cumulative observed and predicted drain discharge and runoff.

	Analytical Methods Using Drain Discharge Data						Monolith		Core		Auger-Hole		MUUF Soil	
	van Schilfgaarde		Hooghoudt		Kirkham		Method		Method		Method		Database	
Year	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain Disch.	Runoff	Drain. Disch.	Runoff
1962	2.013	0.846	1.841	0.841	2.456	0.701	3.665	1.029	3.202	0.969	1.614	0.777	3.249	0.883
1963	5.073	0.282	4.977	0.315	4.761	0.361	5.969	0.851	5.689	0.570	4.401	0.405	5.721	0.555
1964	3.725	0.626	3.614	0.730	3.500	0.405	5.581	2.041	5.152	1.679	3.078	0.832	5.123	1.617
1967	3.817	1.822	4.075	2.075	4.485	2.424	1.396	2.043	1.329	1.719	4.699	2.440	1.451	1.507
1968	0.765	2.557	0.765	2.697	0.836	2.841	2.359	1.182	2.135	1.242	1.046	3.086	2.023	1.323
1969	3.388	2.068	3.735	1.908	4.311	1.908	4.518	8.009	3.808	7.247	4.532	1.899	3.685	7.030
1970	2.650	5.087	2.833	5.275	3.293	5.512	2.339	2.229	2.044	2.292	3.670	5.648	1.957	2.458
1971	0.813	1.616	0.826	1.739	0.907	1.902	1.837	0.990	2.008	0.955	1.063	2.049	1.948	1.005
Total	22.24	14.90	22.66	15.58	24.55	16.05	27.66	18.37	25.37	16.67	24.10	17.14	25.16	16.38

Schilfgaarde equation (Figures 2 and 3) and MUUF soil database (Figures 4 and 5). The predicted values are compared with the mean of the two individual replicates. These predictions are typical for each of these two methods. While neither of these two methods were perfect, the MUUF based K simulations underpredicted drain discharge and overpredicted runoff, sometimes by as much as 80% and 50%, respectively. For runoff, both methods produced simulation results that overpredicted runoff for at least two of the 1971 runoff events (simulation days 90 and 143), and neither predicted runoff for simulation days 54 and 55.

Table 4 shows the average deviation (cm) between daily cumulative observed and predicted drain discharge and runoff averaged over the four replications, for each of the eight years for each of the seven K methods, along with the total average deviation over all eight years. The smallest deviation in cumulative discharges for each year is underlined. Similar to the daily deviation results (Table 3), there is no one method that provides the smallest deviation in cumulative drain discharge and runoff in each year. However, when we consider the total cumulative deviation over all eight years, the simulations with the van Schilfgaarde equation again produced the smallest total deviation in both drain discharge and runoff.

Table 5 provides a summary of the annual total of rainfall and irrigation, and average total cumulative drain discharge and runoff for the eight simulation years for April 1-September 31 (183 days). Also included in Table 5 are the measured and predicted (using with van Schilfgaarde equation) average total cumulative values and the differences. For the drain discharge data, the simulations underpredicted about half the time, with a net difference over the eight years (total of rainfall and irrigation was 480.77 cm) of 6.86 cm. The runoff was also underpredicted in five of the eight years, with a net

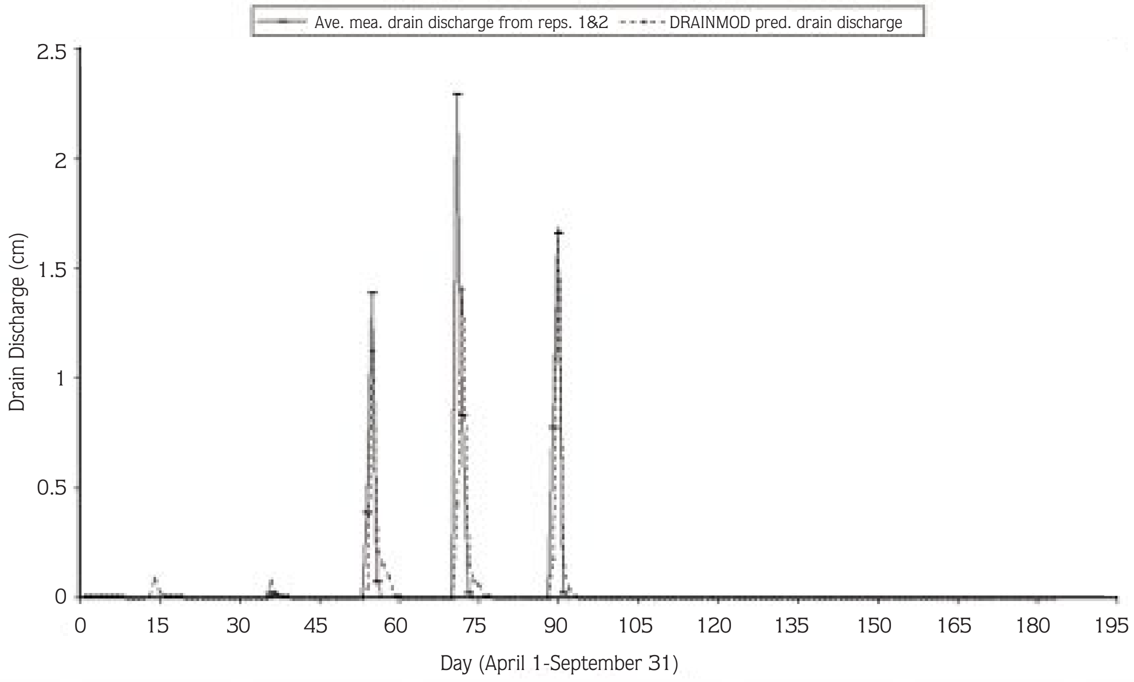

Figure 2. Daily predicted (using K values estimated with the van Schilfgaarde equation) and average measured drain flows from replications of 1 and 2 during 1971 at the North Central Ohio site.

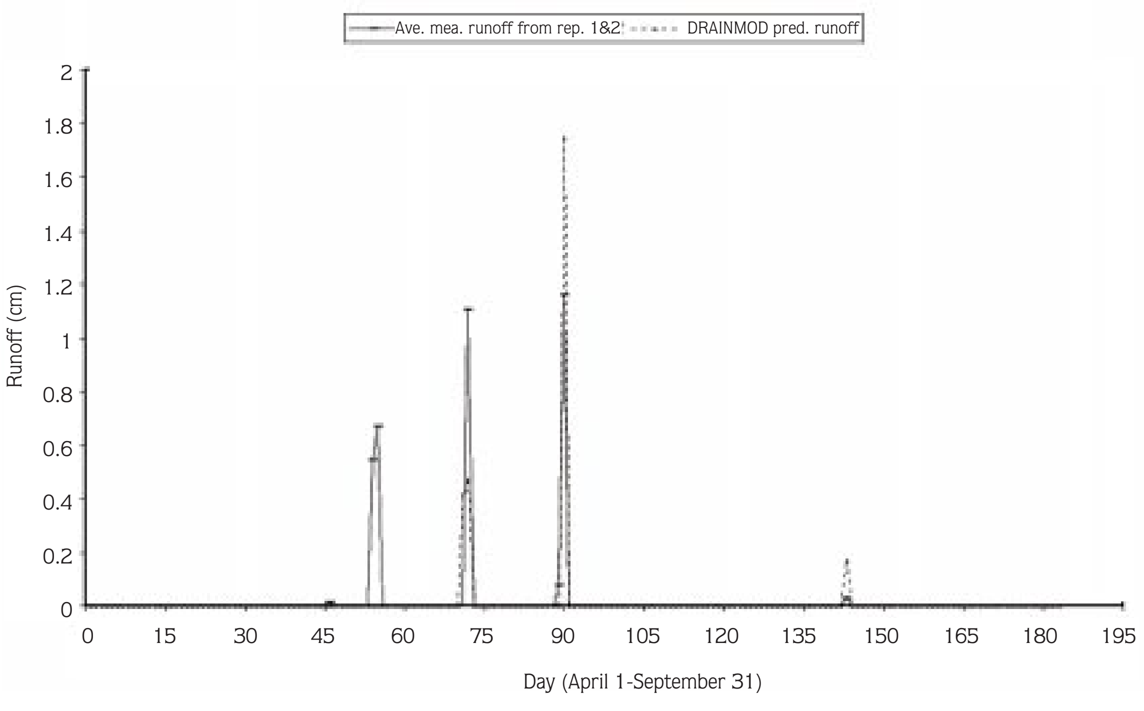

Figure 3. Daily predicted (using K values estimated with the van Schilfgaarde equation) and average measured runoff from replications of 1 and 2 during 1971 at the North Central Ohio site.

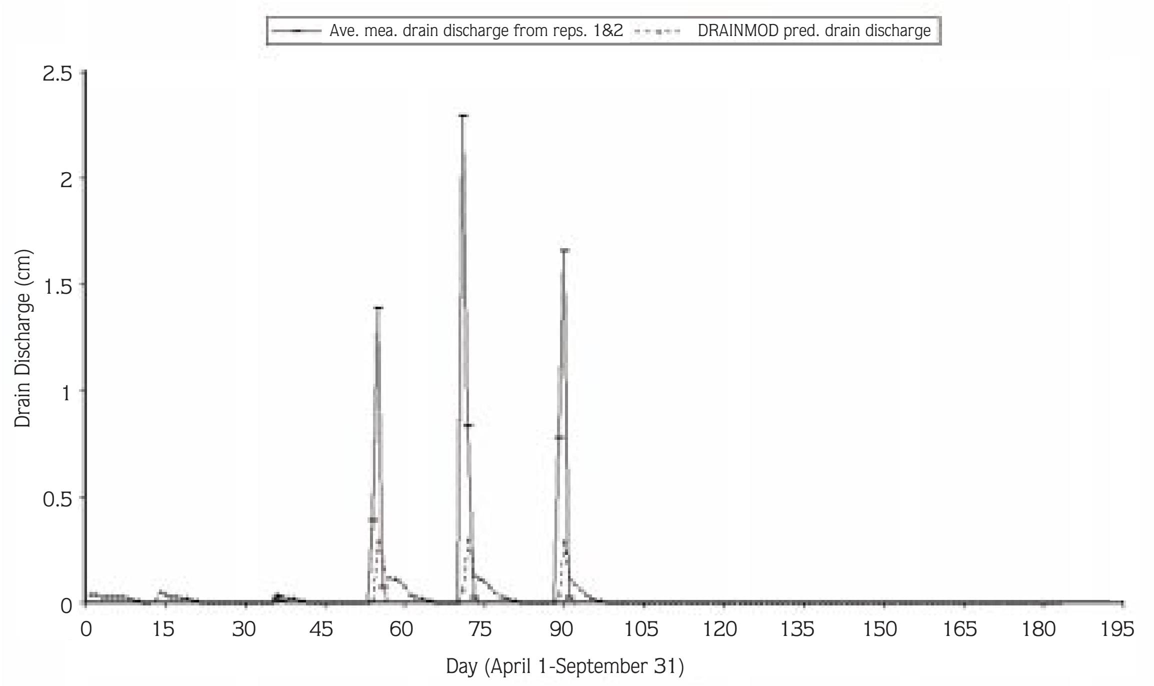

Figure 4. Daily predicted (using K values estimated with the MUUF Soil Database) and average measured drain flows from the replications of 1 and 2 during 1971 at the North Central Ohio site.

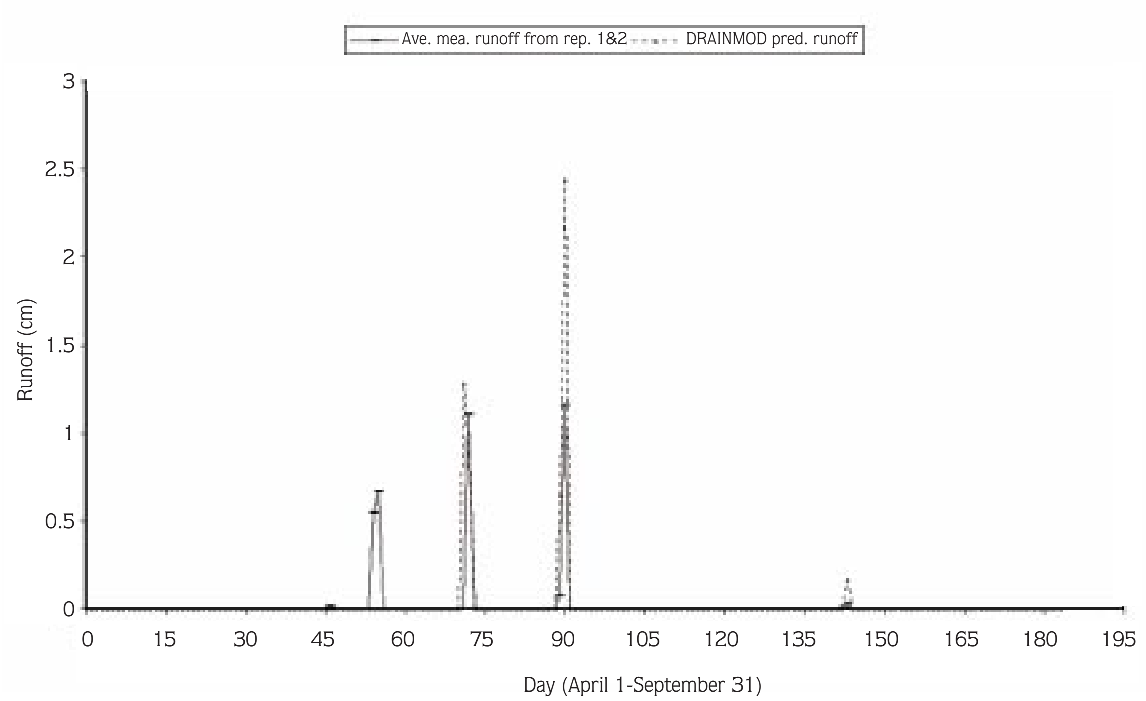

Figure 5. Daily predicted (using K values estimated with the MUUF Soil Database) and average measured runoff from the replications of 1 and 2 during 1971 at the North Central Ohio site.

Table 5. Average predicted (using K estimated with van Schilfgaarde equation) and measured (from the drainage experiment at the North Central Ohio site) discharges.

Year	Rainfall*	Drain Discharge (cm)			Runoff (cm)		
		Measured	Predicted	Difference	Measured	Predicted	Difference
1962	57.01	8.89	6.06	-2.83	2.25	3.07	+0.82
1963	40.24	12.28	4.41	-7.87	1.64	1.68	+0.04
1964	59.71	20.21	14.79	-5.42	3.28	2.36	-0.92
1967	56.90	9.76	14.12	+4.36	6.57	3.72	-2.85
1968	57.47	9.65	9.00	-0.65	7.92	3.97	-3.95
1969	86.62	19.30	22.83	+3.53	25.64	26.36	+0.72
1970	67.62	12.50	14.56	+2.06	13.46	5.41	-8.05
1971	55.20	6.35	6.31	-0.04	5.25	2.88	-2.37
Total	480.77	98.94	92.08	-6.86	66.01	49.45	-16.56

* Includes both total rainfall and irrigation (cm) for the months of April through September of each year.

+ Predicted minus measured.

difference of 16.56 cm. The results of a similar analysis for the other five K methods were also obtained.

While the goal of this modeling work was to identify the K estimation method that produced the smallest daily and cumulative deviations, accurate prediction of total discharge is also important. When the average total difference between predicted and measured drain discharges is considered, the minimum absolute difference value for drain discharge was obtained from the Kirkham equation. The rank order (smallest to largest total absolute difference) of the K methods for drain discharge was the Kirkham equation, followed by the auger-hole, Hooghoudt, van Schilfgaarde, MUUF, core, and monolith. When the average total absolute difference for runoff is considered, the minimum absolute difference value for runoff was obtained from the MUUF soil database. The subsequent rank order (smallest to largest total absolute difference) of the remaining six K methods for runoff was core, monolith, van Schilfgaarde, Hooghoudt, auger-hole, and the Kirkham equation.

Summary and Conclusions

The objective of this study was to determine the most suitable hydraulic conductivity (K) values as input into DRAINMOD among a range of K data sets developed for the drainage experiment site in North Central Ohio using seven different K estimation methods. Simulations using DRAINMOD (Version 4.6) were conducted for the years 1962-1964 and 1967-1971, and predictions were compared with measured discharges from Schwab et al. (1963; 1975; and 1985). Overall, the simulation results with the van Schilfgaarde equation produced the smallest total deviation for both drain discharge and runoff over all eight test years. The rank order (smallest to largest total deviation) of the K methods for drain discharge were van Schilfgaarde, Hooghoudt, and Kirkham equations, followed by auger-hole, monolith, core, and then the MUUF soil database. The rank order of the K methods for runoff was van Schilfgaarde, Hooghoudt, Kirkham, auger-hole, MUUF soil database, core, and monolith.

Where drain discharge and water table depth measurements are available or practical to obtain, K estimates made with the van Schilfgaarde equation may provide more reliable modeling results since they take into account the overall effect of backfill, drain spacing and depth, deep percolation, drain pipe parameters, etc.

References

Amoozegar, A. and A.W. Warrick. 1986. Hydraulic conductivity of saturated soils: Field Methods. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods (Ed. A. Klute). SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin, USA, pp. 735-768.

Baumer, Otto W. 1989. Predicting unsaturated hydraulic parameters. In: Proceedings of the international workshop on indirect methods for estimating the hydraulic properties of unsaturated soils (Eds., M. Th. van Genuchten and F.J. Leij, and L.J. Lund), Riverside, California, U.S. Dept. of Agriculture: Dept. of Soil and Environmental Sciences, University of California, USA, pp. 341-354.

Bouwer, H. and R.D. Jackson. 1974. Determining soil properties, section X. p. 611-666. In J. van Schilfgaarde (Ed.). Drainage for Agriculture. Agronomy No. 17. American Society of Agronomy. Madison, Wisconsin. 700 p.

Dumm, L.D. 1959. Drain spacing formula. Agricultural Engineering. 35: 726-730.

Fouss, J.L., R.L. Bengtson and C.E. Carter. 1987. Simulating Subsurface Drainage in the Lower Mississippi Valley with DRAINMOD. Transactions of the ASAE 30: 1679-1688.

Hoffman, G.J. 1963. Tile flow from a stratified anisotropic soil with a falling water table. Master of Science Thesis, Ohio State University. Columbus, Ohio, USA, p. 83.

Hoffman, G.J. and G.O. Schwab. 1964. Tile spacing prediction based on drain outflow. Transactions of the ASAE 7: 444-447.

Hooghoudt, S.B. 1940. Algemene beschouwing van het probleem van de detailontwatering en de infiltratie door middel van parallel lopende drains, greppels, sloten, en kanalen. Versl. Landbouwk. Onderz. 46: 515-707.

Kirkham, D. 1957. II. Theory of land drainage, III. The ponded water case. In: Drainage of Agricultural Lands (Ed. J.N. Luthin), Agronomy Monograph No. 7, American Society of Agronomy, Madison, Wisconsin, USA, pp: 139-181.

Klute, A. and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods (Ed. A. Klute). SSSA Book Series: 5 (formerly Agronomy Monograph 9). Madison, Wisconsin, USA, pp: 687-732.

Ohio Soil Survey. 1960. Auger-hole percolation tests conducted by Jim Evans and Ken Donaldson from the field experiment notes of the drainage experiment at the Ohio Agricultural Research and Development Center, North Central Branch, near Sandusky, Ohio, USA.

Schwab, G.O., T.J. Thiel, G.S. Taylor and J.L. Fouss. 1963. Tile and surface drainage of clay soils. Research Bulletin 935, Departments of Agricultural Engineering and Agronomy, Ohio Agricultural Experiment Station Wooster, Ohio, USA, p. 47.

Schwab, G.O., N.R. Fausey and C.R. Weaver. 1975. Tile and surface drainage of clay soils. Research Bulletin 1081, Ohio Agricultural Research and Development Center, Wooster, Ohio, USA, p. 37.

Schwab, G.O., N.R. Fausey, E.D. Desmond and J.R. Holman. 1985. Tile and surface drainage of clay soils. Research Bulletin 1166, Ohio Agricultural Research and Development Center, Wooster, Ohio, USA, p. 29.

Skaggs, R.W. 1978. A water management model for shallow water table soils. Report No. 134, Raleigh, North Carolina. Water Resources Research Institute, Univ. of North Carolina, USA, p. 175.

Skaggs, R.W. 1980. DRAINMOD Reference Report. Methods for design and evaluation of drainage-water management systems for soils with high water tables. North Carolina State University, Raleigh, North Carolina, USA, p. 177.

Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. Transactions of the ASAE 24: 922-928.

Taylor, G.S., E. Stibbe, T.J. Thiel and J.H. Jones. 1970. Hydraulic conductivity profiles of Toledo and Miami Soils as measured by field monoliths. Research Bulletin. 1025, Ohio Agricultural Research and Development Center, Wooster, Ohio, USA, p. 17.

Toksoz, S. and D. Kirkham. 1971. Steady drainage of layered soils: II, Nomographs. J. Irrigation and Drainage Engineering, ASCE 97: 19-37.

Van Schilfgaarde, J. 1963. Design of tile drainage for falling water tables. J. Irrigation and Drainage Engineering ASCE 89: 1-11.

Workman, S.R., R.W. Skaggs, J.E. Parsons and J. Rice (Eds). 1986. DRAINMOD User's Manual. Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, North Carolina, USA, p. 90.