

COMPARISON OF SIMULATED (DRAINMOD) AND MEASURED TILE OUTFLOW AND WATER TABLE ELEVATIONS FROM TWO FIELD SITES IN IOWA

J. Sanoja, R. S. Kanwar, S. W. Melvin

MEMBER
ASAE

MEMBER
ASAE

ABSTRACT

Four years of field data on subsurface drain flows and water table elevations from two experimental sites in Iowa were used to compare the predicted values by DRAINMOD, a water management model. DRAINMOD simulations conducted for Nicollet silt loam and Kenyon loam soils of Iowa predicted water table elevations within an average deviation of 15 cm and 19 cm, respectively. The subsurface drain outflows predicted by DRAINMOD were within an average deviation of 0.065 cm/day.

INTRODUCTION

Artificial drainage is a necessity for farming some of the most productive soils of Iowa and the Midwest. Without artificial drainage planting and harvesting operations will most likely be delayed, but in wet years poor growing conditions may lead to reduced yields or total crop failure (Kanwar et al., 1983b; 1984a; and 1988a). There is a need for better water management systems if the production capacity of agricultural soils is to be optimized. Therefore, design of water management systems such as subsurface drainage in humid regions is important in determining the most efficient means of agricultural water management.

A promising approach to the design of water management systems is the development and use of computer simulation models. Skaggs (1978) developed a computer simulation model, called DRAINMOD, that simulates the movement of soil water as affected by the various subsurface water management systems. DRAINMOD can evaluate surface and subsurface drainage systems, sub-irrigation or control drainage systems, and irrigation of waste water onto land. DRAINMOD has been used successfully in many parts of the U.S.A. for solving drainage/sub-irrigation related problems (Chang et al., 1983; Evans and Skaggs, 1984; Fouss et al., 1987, 1989; Hardjoamidjojo and Skaggs, 1982; McMohan et al., 1987; Skaggs et al., 1981). This model has also been adopted by the U.S. Soil Conservation Service for design and evaluation of water management systems. Therefore, the objective of this study was to evaluate the applicability of DRAINMOD for artificially drained soils of central, and

northeastern Iowa by using data from two long-term field experiments.

MODEL DESCRIPTION

DRAINMOD (Skaggs, 1978) is a computer model that simulates the response of soil water regime to various combinations of surface and subsurface water management systems. It can be used to predict the water table depth, subsurface drainage, evapotranspiration and surface runoff as affected by the various drainage, weather and soil properties data. DRAINMOD is a water management model based on a water balance at midpoint between parallel drains for soils having an impeding layer at a known depth from the soil surface. The water balance equation used in DRAINMOD for a unit time increment is expressed as:

$$\Delta V_a = D + ET + DS - I$$

where ΔV_a is the change in air volume (cm), D is the water removed by artificial drainage (cm), ET is the evapotranspiration (cm), DS is deep seepage (cm) and I is the infiltration (cm) (equal to rainfall minus runoff and depression storage).

The subsurface drainage flow into the tile lines (D) is calculated by the Hooghoudt's steady-state equation, as used by Bouwer and van Schilfgaarde (1963). The daily ET is calculated by first calculating the potential ET, and the potential evapotranspiration (PET) is calculated with Thornthwaite (1948) equation. Each ET calculation involves a check to determine if soil water conditions are limiting. When the water table is near the surface, or when the upper layers of the soil profile have a high water content, ET will be equal to PET. However, for deep water tables and under drier conditions, ET may be limited by the rate of water uptake by plant roots. To account for water depletion, the vertical profile is divided into two zones. The zone of soil that is directly above the water table is called the wet zone. This wet zone extends from the water table up to a dry zone or the soil surface. The dry zone extends from the soil surface down to the maximum root depth. The dry zone develops when water is removed from the root zone to satisfy ET demand. A detailed description of DRAINMOD is given by Skaggs (1978).

DESCRIPTION OF FIELD EXPERIMENTS

Experimental data used in this article to evaluate DRAINMOD were collected from two long-term field drainage experiments at Iowa State University's Agronomy and Agricultural Engineering Research Center near Ames

Article was submitted for publication in July 1989; reviewed and approved for publication by the Soil and Water Div. of ASAE in March 1990. Presented as ASAE Paper No. 88-2057.

Journal Paper No. J-13592 of the Iowa Agriculture and Home Economics Experiment Station, Ames, IA, Project No. 2792.

The authors are J. Sanoja, Research Assistant, R. S. Kanwar, Associate Professor, and S. W. Melvin, Professor, Dept. of Agricultural Engineering, Iowa State University, Ames, IA.

in central Iowa and at Iowa State University's Northeast Research Center near Nashua in northeastern Iowa. The first set of data was obtained from a drainage experiment conducted at the central Iowa experimental site. This experimental site is located on Nicollet silt-loam soil from the Nicollet series. The Nicollet series consists of somewhat poorly to moderately drained soils with slopes less than 2%. The drainage system at the experimental site consists of 102 mm diameter clay tiles spaced 36.6 m apart. These subsurface tile lines were installed at a depth of 1.22 m in 1960. Observations made from one plot, having an area of about 0.42 ha, were used in testing and evaluating the model (Kanwar et al., 1988b).

To provide access to the subsurface tile line, a sump 1.52 m deep was installed to intercept the tile outflow. A float-activated recorder was installed in conjunction with an H-flume to provide a record of tile flow rates as a function of time. Daily tile flow rates were collected from 1984 through 1987.

Observation wells (1.8 m long and 38 mm diameter) were installed 30 m apart in the plot, midway between subsurface drains to measure water table depths. Observation wells were read three times a week during 1984 through 1987.

The second set of data was obtained from a drainage experiment conducted at the Iowa State University's Northeast Research Center at Nashua in northeastern Iowa. The soils at the experimental site are predominantly Kenyon loam in the Kenyon-Clyde-Floyd Soil Association. Kenyon soils are gently sloping on ridge slope and moderately sloping on side slopes. These soils are moderately well drained, with a thick dark loamy surface layer and a high available water capacity (Kanwar et al., 1984b). At the experimental site, plastic pipe drains were installed at a depth of 1.20 m. All lines are spaced 24.6 m apart and arranged in groups of three lines installed with a trencher, alternated with three lines installed with a plow (Kanwar et al., 1986). The middle lines of each installation method were monitored for water table depths during the crop growing season (April through November) for 4 years (1981 to 1984). Water table depths were monitored from observation wells 1.20 m long installed midway between lines. Water table depths were read once a week during the 1981 through 1984 growing season.

Because of frozen conditions, drains did not flow during January, February, and most of March. Model evaluations were based on data collected from 1 April to 31 October.

MODEL INPUT DATA

The input data required for DRAINMOD include soil properties, crop parameters, drainage system parameters and climatological data. Drainage system input parameters include drain depth and spacing, depth to the impermeable layer, depth of surface depression storage, drainage coefficient as limited by the hydraulics of the system, geometric parameters used in computing the drainage rate ponded surface conditions, and depth of the water in the outlet as a function of time.

CLIMATOLOGICAL DATA

Hourly precipitation data were obtained from a rain gaging station located about 200 m from the experimental

site near Ames. Data on daily maximum and minimum temperatures used to estimate PET by the Thornthwaite method were also collected at the local gaging station.

At the northeastern experimental site near Nashua, daily precipitation and temperatures data were obtained from the nearby weather station at Charles City, which is about 11 miles from Nashua, Iowa. For model testing, the daily precipitation was distributed uniformly during the day, and entered into the model as hourly precipitation.

SOIL PROPERTIES DATA

Soil-moisture retention tests for each 250 mm depth increments down to the drain depth were obtained on small undisturbed soil samples from different locations in the plot at each site. The soil-moisture retention tests were performed by using a tension-table and pressure-plate apparatus as explained by Kanwar et al. (1989). Soil-moisture retention curves for the Nicollet silt loam and Kenyon loam soil are tabulated in Tables 1 and 2, respectively. Drainage volume-water table depth relationships calculated from those data are plotted in figure 1.

Saturated hydraulic conductivity (K) measurements were made for the experimental site in central Iowa by using a constant head permeameter in the laboratory as described by Klute (1965). Five undisturbed soil cores (75 mm in diameter and 75 mm long) were collected from each depth in 150 mm increments to a depth of 900 mm for conductivity determinations. These soil cores were saturated by soaking from bottom to top in 0.01N CaSO₄ solution. Then CaSO₄ solution was ponded overnight on the surface of the cores to establish steady flow. Once steady flow was reached in the soil cores, saturated hydraulic conductivity was determined (Kanwar et al., 1989). An average value of K equal to 0.87 cm/hr was used for the entire soil profile for the central Iowa location.

At the experimental site in northeastern Iowa, saturated hydraulic conductivity of the soil was also measured by using the laboratory constant head permeameter. The measured data for K values for this site are given in table 3.

Relationship between the upward flux and water table depth was also determined for each soil type. It determined how much water can be supplied from the water table to satisfy the daily ET need. Upward flux was calculated by solving the Darcy-Buckingham equation:

$$q = -k(h)(dh/dz) + k(h) \quad (1)$$

TABLE 1. Soil-water characteristics of Nicollet loam soils at the experimental site of Central Iowa

Depth	Volumetric soil-moisture contents								
	Tensions, cm								
	0.00	10	30	50	80	100	325	1000	15000
cm	-----%-----								
0-25	0.49	0.39	0.37	0.35	0.33	0.32	0.30	0.25	0.17
25-45	0.51	0.38	0.36	0.33	0.31	0.31	0.28	0.24	0.17
45-75	0.49	0.36	0.33	0.31	0.29	0.29	0.27	0.24	0.17
75-120	0.46	0.35	0.31	0.29	0.28	0.27	0.25	0.22	0.13

TABLE 2. Soil-water characteristics of Kenyon loam soils at the experimental site in Northeast Iowa

Depth cm	Volumetric soil-moisture contents							
	Tensions, cm							
	0.00	40	60	122	204	340	1000	15000
	-----%							
0-30	0.47	0.42	0.41	0.38	0.37	0.36	0.22	0.14
30-60	0.47	0.42	0.41	0.39	0.38	0.37	0.24	0.13
60-75	0.45	0.41	0.41	0.39	0.39	0.37	0.23	0.12
75-90	0.46	0.42	0.41	0.38	0.38	0.36	0.22	0.15

where

- q = the flux,
 z = the vertical position from the water table,
 h = the pressure head, and
 $k(h)$ = the unsaturated hydraulic conductivity.

The soil-water characteristic data were used to determine $k(h)$ based on a method by Millington and Quirk (1960). These relationships are shown in figure 2.

The amount of water entering the soil, is a function of the infiltration capacity (f), which is calculated in the model by the Green-Ampt equation (Green and Ampt, 1911; Skaggs, 1978):

$$f = A / \ln F + B \quad (2)$$

where

- $\ln F$ = cumulative infiltration,
 A = $K_s * M * S_{av}$, and
 B = K_s (where K_s = the saturated hydraulic conductivity, M = the drainable porosity, and S_{av} = the effective suction at the wetting front.)

Values for the A and B coefficients were derived mathematically from the hydraulic conductivity and the soil water characteristics.

A double-ring infiltrometer apparatus was used to measure the infiltration rate of soils as a function of time. For the double ring apparatus, the inner ring, also called the measuring ring, was 37 cm in diameter and 20 cm in height. The rings were forced into the soil to a depth of 5 cm. A water stage recorder was used to record the

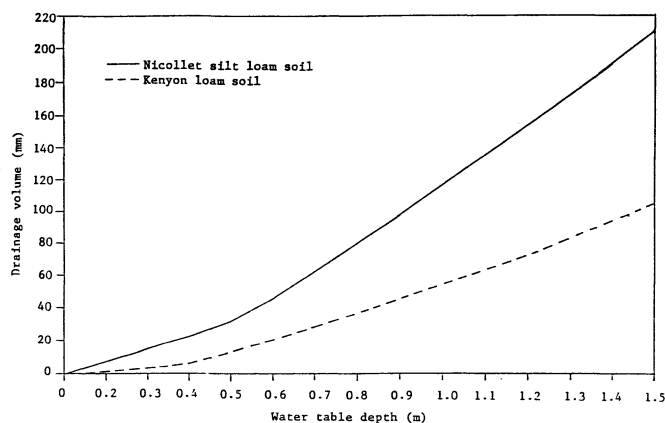


Figure 1—Drainage volume as a function of water table depth for two different soils considered in this study.

TABLE 3. Parameters for the Green-Ampt equation for various water table depths at the start of rainfall for the experimental site ($A=K_s * M * S_{av}$, cm^2/hr , $B=K_s, \text{cm/hr}$)

Water table depth, (cm)	Central Iowa		Northeastern Iowa	
	A	B	A	B
0.00	0.00	0.87	0.00	0.35
10.00	3.23	0.87	1.23	0.35
50.00	4.63	0.87	2.66	0.50
100.00	5.26	0.87	2.59	0.43
150.00	5.50	0.87	2.72	0.43
190.00	5.73	0.87	2.83	0.43
325.00	5.84	0.87	2.89	0.43

recession of water in the inner ring as a function of time (Mukhtar et al., 1985). The parameters A and B were determined by plotting the infiltration rate vs time in each of the four runs at both sites, and the constant rate of infiltration, B , was considered equal to the saturated hydraulic conductivity of the soil (figs. 3 and 4). The average effective suction (S_{av}) was assumed equal to 35 cm as suggested by Brakensiek (1980). After B and S_{av} have been determined, they are kept constant so that different values of A can be estimated by obtaining the appropriate value of M at each water table depth. A and B parameters vs. water table depth are tabulated in Table 3 for both experimental sites.

CROP INPUT DATA

An effective rooting depth as a function of time is used in DRAINMOD to define the zone from which water can be removed to meet the ET demand. The effective root depth for corn was estimated from the data of Shaw (1963). Table 4 gives the effective root depths as a function of time. It was assumed that water could be removed from the top 5 cm of soil by evaporation so that the minimum effective root depth was assumed to be 5 cm.

DRAINAGE SYSTEM PARAMETER

The method used in DRAINMOD to estimate subsurface drain flow rates is based on the assumption that, in the saturated region, the water movement occurs mainly laterally. Therefore, input data describing the drainage system are needed to compute drainage flux. Table 5 gives a summary of the data on the field drainage systems (Kanwar et al., 1983a, 1984b).

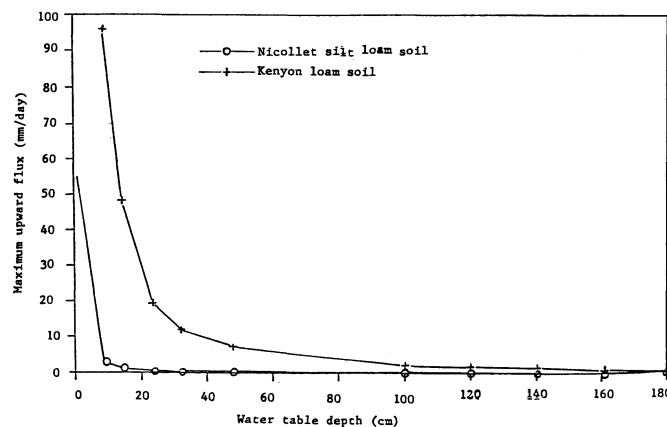


Figure 2—Effect of water table depth on steady upward flux from the water table.

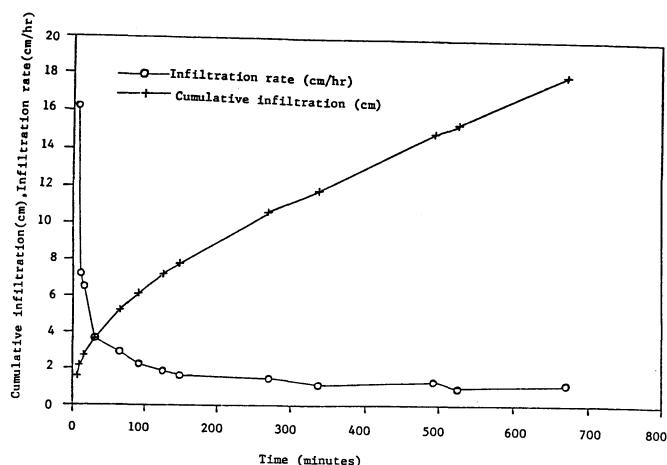


Figure 3—Cumulative infiltration and infiltration rate at the experimental site in central Iowa.

METHODS FOR DRAINMOD SIMULATIONS

Field data on tile flow rates and water table depths were used to test the performance of DRAINMOD. The model was used to predict the water table depth and subsurface drain flows during the growing season. Model simulations required data on surface storage, depth of impermeable layer, and estimates on deep and lateral seepage. Some of these data were taken from Kanwar et al. (1983a, 1984b), but data on surface storage was estimated by using some of the data from the literature (Skaggs et al., 1981). Model simulations were conducted from 1 April to 31 October for 1981 to 1984 at the experimental site in northeastern Iowa, and for 1984 to 1987 at the experimental site in central Iowa. Measured and predicted water table depths and subsurface drain flows were compared to evaluate the reliability of the model. The standard error (SE) and average deviation (AD) between the observed and simulated data were calculated by using the equations:

$$SE = \left[\frac{\sum_{i=1}^n (x_{i,m} - x_{i,p})^2}{n} \right]^{1/2}$$

$$AD = \left\{ \frac{\sum_{i=1}^n \text{ABS} [X_{i,m} - X_{i,p}]}{n} \right\}$$

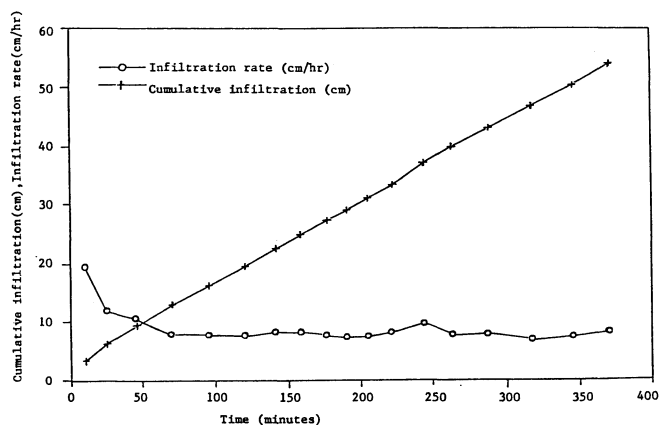


Figure 4—Cumulative infiltration and infiltration rate at the experimental site in northeastern Iowa.

TABLE 4. Effective root depth as a function of time

Month	Days	Root depth, (cm)
1	1	5.00
5	1	6.00
6	1	15.00
6	21	30.00
7	2	45.00
7	17	60.00
9	15	60.00
10	15	60.00
12	31	4.00

where $X_{i,m}$ is the measured water table depth or drain flow on day i , $X_{i,p}$ is the predicted water table depth or drain flow on day i , and n is the number of observations during the growing season.

ANALYSIS OF THE RESULTS

EXPERIMENTAL SITE AT CENTRAL IOWA

Measured and predicted tile flows and water table elevations for 1984, 1985, 1986, and 1987 are plotted in figures 5 through 10. In general, the model predictions followed the trend of the observed values. Except for few exceptions, the predicted water table depths were in agreement with the measured water table depths for 1985 and 1986. Figures 5 through 10 seem to indicate that DRAINMOD has the capability to simulate tile flow and water table depths for the central Iowa soils.

Values of average deviation and standard error for water table depths and tile flow data are given in Table 6. Water table data were not collected in 1984 and tiles did not flow for most of 1985, therefore, Table 6 does not show these two data sets. The average deviation and standard error for the comparison of predicted and measured water table depths ranged from 8.40 to 18.56 cm and 10.14 to 21.65 cm, respectively. Statistically, the average deviation to the range of 18.56 cm and standard error to the range of 21.65 cm are indicators of quantitative dispersion between the measured and predicted water table depths.

TABLE 5. Drainage system parameters for the experimental sites

Parameters	Variables	Values			
		Name	Central Iowa	Northeast Iowa	
Initial water table	DTWT	1984	120 cm	1981	120 cm
		1985	120 cm	1982	120 cm
		1986	75 cm	1983	120 cm
		1987	90 cm	1984	120 cm
Tile diameter	TD		10.16 cm	10.16 cm	
Drain spacing	SDRAIN		3600.00 cm	2456.00 cm	
Equivalent depth from impermeable layer	HDRAIN		139.00 cm	113.00 cm	
Drain depth	DRAIN		120.00 cm	120.00 cm	
Wilting point	WP		0.17	0.14	
Maximum depth of surfact pounding	STMAX		1.25 cm	1.25 cm	
Depth to the impermeable layer	ADEPTH		390.00 cm	390.00 cm	

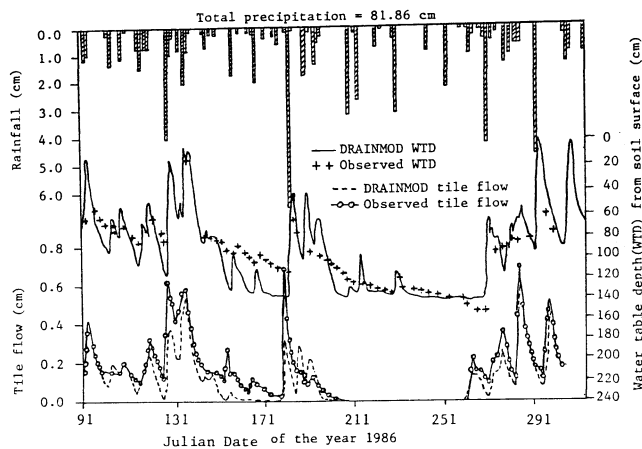


Figure 5—Rainfall, tile flow (measured and predicted), and water table depth (measured and predicted) for central Iowa site in 1986.

The water table elevations fluctuated from the soil surface to a depth of more than 160 cm. Comparisons shown in figures 6 through 8, indicated that the model predicted shallower water table depths than the measured water table depths during very wet periods and reverse was true during dry periods. This might be because of some of the assumptions made between the relationships for the drainage volume versus water table depth, and water table depth versus Green and Ampt infiltration parameters.

A summary of the monthly average values of the predicted and measured subsurface drain flows for the central Iowa site are given in Table 7. The agreement between the overall monthly predicted and observed subsurface drain flows for 1984 was excellent with standard errors of estimates of the daily tile flows. On the average, DRAINMOD predicted larger monthly subsurface drain flows by only 0.33 cm for 1984. However, DRAINMOD predictions on the drain flows were less than the measured values for 1986 and 1987. The worst fit for subsurface drainage, as determined by the average deviation (AD = 0.061 cm) and standard error (SE = 0.13 cm), was obtained for 1987 data (figure 6). Errors of prediction would be expected to be higher if ET had not been limited by the upward flux and if deep seepage had been considered.

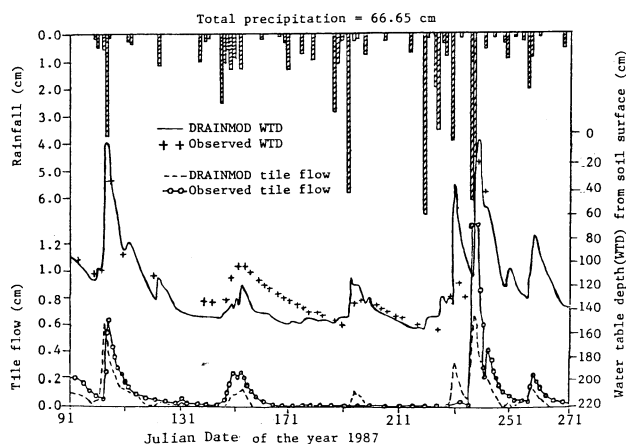


Figure 6—Rainfall, tile flow (measured and predicted), and water table depth (measured and predicted) for central Iowa site in 1987.

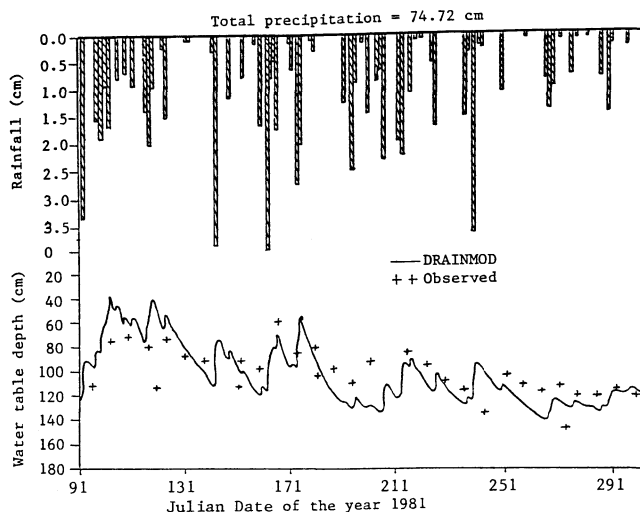


Figure 7—Rainfall and measured and predicted water table depth from soil surface for northeastern Iowa site for 1981.

EXPERIMENTAL SITE AT NORTHEAST IOWA

Results of model predictions using northeastern Iowa data are summarized in figures 11 through 14. These figures show that the predicted water table depths agreed well with the observed data. The predicted water table drawdown rate was usually lower than the observed rate when water table was above the tile line. This could have been due to the K value used, which may be too low or because of an erroneous relationship for the drainage volume versus water table depth. The results given in figures 11 through 14 indicate that agreement between predicted and observed results can be improved considerably by using a larger K value for the Nashua site. This indicates that the measured K values in the laboratory might have been bit lower than *in-situ* values.

Table 6 gives values of two statistical parameters (namely, average deviation and standard error) that were used for the comparison of observed and predicted water table depths. The average deviation varied from 13.71 to 18.75 cm, and the standard error varied from 16.11 to 22.65 cm. These results show that the model has the capability of simulating different soil systems satisfactorily.

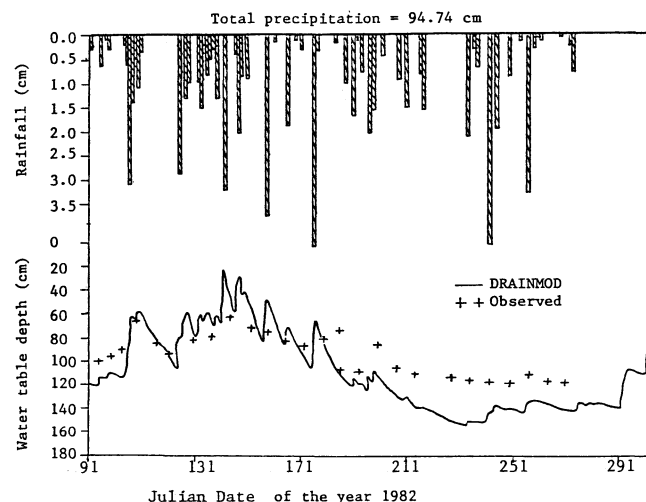


Figure 8—Rainfall and measured and predicted water table depth from soil surface for northeastern Iowa site for 1982.

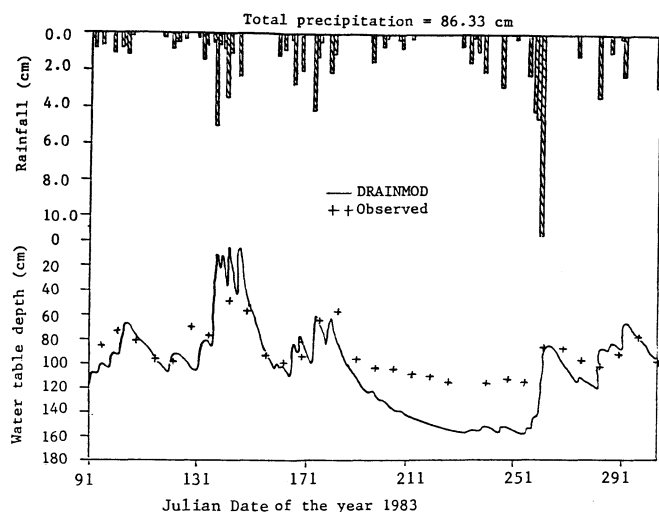


Figure 9—Rainfall and measured and predicted water table depth from soil surface for northeastern Iowa site for 1983.

SUMMARY AND CONCLUSIONS

1. DRAINMOD, a water management simulation model, was used to predict the daily tile flows and water table elevations for two Iowa soils. A comparison was made by comparing predicted and measured water table depths and tile flow rates for the Nicollet silt-loam soil in central Iowa and water table depths for the Kenyon loam soil in northeastern Iowa using four years of observed data. Predicted water table depths and tile flow rates were in agreement (figs. 5-10) with the measured values for all four years.
2. The average deviation and standard error for the comparison of predicted and measured water table depths ranged from 8.40 to 18.61 cm and 10.14 to 21.65 cm, respectively. This shows that the hydrology component of the model has the capability of simulating the water balance for two Iowa soils.
3. The overall performance of the model suggests that the model can be used successfully for other soil systems if data on site characteristics and soil-water properties are available.

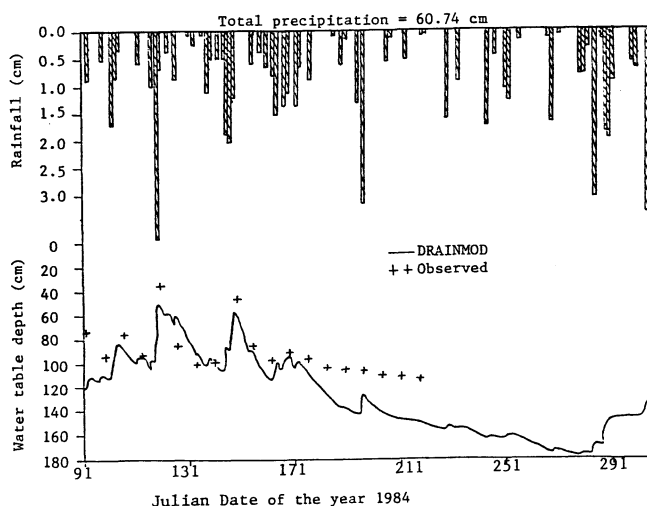


Figure 10—Rainfall and measured and predicted water table depth from soil surface for northeastern Iowa site for 1984.

TABLE 6. Average deviations and standard errors for years of observed and predicted water table depth and tile flow

Year	Central Iowa				Northeast Iowa	
	Water Table Depth, cm		Tile Flow Rate, cm		Water Table Depth, cm	
	SE	AD	SE	AD	SE	AD
1984			0.096	0.065	1981	16.11 13.71
1985	10.14	8.40			1982	18.75 15.22
1986	17.96	13.98	0.083	0.057	1983	21.30 18.61
1987	19.28	14.97	0.130	0.061	1984	21.65 18.56

TABLE 7. Summary of the predicted and measured tile flow rates for Central Iowa Experimental site

Month	1984		1986		1987	
	DRAINMOD cm	Observed cm	DRAINMOD cm	Observed cm	DRAINMOD cm	Observed cm
4	7.71	6.28	5.06	5.44	3.79	4.89
5	5.44	6.39	6.14	9.53	0.31	1.24
6	5.46	5.58	0.45	3.07	0.51	1.44
7	0.00	0.03	2.37	2.58	0.43	0.04
8	0.00	0.00	0.00	0.00	3.98	6.21
9	0.00	0.00	0.98	1.59	1.15	2.95
10	0.00	0.00	7.22	8.60	0.00	0.00
Total	18.61	18.28	22.22	30.81	10.17	16.77

REFERENCES

- Bouwer, H. and J. van Schilfhaarde. 1963. Simplified method of predicting the fall of water table in drained land. *Transactions of the ASAE* 6(4): 288-291,296.
- Brakensiek, D.L., R.L. Engleman and W.J. Rawls. 1980. Variation within texture classes of soil water parameters. ASAE Paper No. 80-2006. St. Joseph, MI: ASAE.
- Chang, A.C., R.W. Skaggs, L.F. Hermsmeier and W.R. Johnson. 1983. Evaluation of a water management model for irrigated agriculture. *Transactions of the ASAE* 26(2): 412-418.
- Evans, R.O. and R.W. Skaggs. 1984. Operating controlled drainage and subirrigation systems. North Carolina Agric. Ext. Service, North Carolina State University, Raleigh.
- 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(6): 1679-1688.
- Fouss, J.L., J.S. Rogers and C.E. Carter. 1989. Sump - controlled water table management predicted with DRAINMOD. *Transactions of the ASAE* 32(4): 1303-1308.
- Green, W.H. and G. Ampt. 1911. Studies of soil physics, Part 1- The flow of air and water through soils. *J. Agr. Sci.* 4: 1-24.
- Hardjoamidjojo, S. and R.W. Skaggs. 1982. Corn yield response to excessive soil water conditions. *Transactions of the ASAE* 25(4): 922-927, 934.
- Kanwar, R.S., H.A. Rizvi, M. Ahmed, R. Horton and S.J. Marley. 1989. Measurement of field saturated hydraulic conductivity by using Guelph and Velocity permeameters. *Transactions of the ASAE* 32(6): 1885-1890.

- Kanwar, R.S., J.L. Baker and S. Mukhtar. 1988a. Growth and yield of corn as affected by excess soil water at various stages of development. *Transactions of the ASAE* 31(1): 133-141.
- Kanwar, R.S., J.L. Baker and D.G. Baker. 1988b. Tillage and split-fertilization effects on subsurface drainage water quality and crop yields. *Transactions of the ASAE* 31(2): 453-460.
- Kanwar, R.S., T.S. Colvin and S.W. Melvin. 1986. Comparison of trenchless drain plow and trench methods of drain installations. *Transactions of the ASAE* 29(2): 456-461.
- Kanwar, R.S., H.P. Johnson and T.E. Fenton. 1984a. Determination of crop production loss due to inadequate drainage in a large watershed. *Water Resources Bulletin* 20(4): 589-597.
- Kanwar, R.S., T.S. Colvin and H.P. Johnson. 1984b. Field evaluation of a drainage simulation model. In *Proc. of the Specialty Conference on Water: Today and Tomorrow*, 351-361. Sponsored by Irrigation and Drainage Division of the American Society of Civil Engineers.
- Kanwar, R.S., H.P. Johnson and J.L. Baker. 1983a. Comparison of simulated and measured nitrate losses in the tile effluent. *Transactions of the ASAE* 26(5): 1951-1957.
- Kanwar, R.S., H.P. Johnson, D. Schult, T.E. Fenton and R.D. Hickman. 1983b. Drainage needs and returns in north central Iowa. *Transactions of the ASAE* 26(2): 457-464.
- Klute, A. 1965. Laboratory measurements of hydraulic conductivity of saturated soil. In *Methods of Soil Analysis*, 253-261. Monograph No. 9, Am. Society of Agronomy, Madison, WI.
- Millington, R.J. and J.P. Quirk. 1960. Permeability of porous media. In 7th Int. Cong. Soil Sci. Trans. (Madison, WI) 1.3:97-106.
- McMohan, P.C., S. Mostaghimi and F.S. Wright. 1987. Simulation of corn yield by a water management model for a costal plain soil in Virginia. ASAE Paper No. 87-2047. St. Joseph, MI: ASAE.
- Mukhtar, S., J.L. Baker, R. Horton and D.C. Erbach. 1985. Soil water infiltration as affected by use of the paraplow. *Transactions of the ASAE* 28(6): 1811-1816.
- Shaw, R.H. 1963. Estimation of soil moisture under corn. Iowa Agric. Home Econ. Exp. Stn. Research Bulletin 520.
- Skaggs, R.W. 1978. A water management model for shallow water table soil. Report No. 134, Water Resour. Res. Inst., North Carolina State University, Raleigh.
- Skaggs, R.W., N.R. Fausey and B.H. Nolte. 1981. Water management model evaluation for North Central Ohio. *Transactions of the ASAE* 24(4): 922-928.
- Thorntwaite, C.W. 1948. An approach toward a rational classification of climate. *Geog. Rev.* 38:55-94.