APPENDIX G

FIELD TESTS OF DRAINMOD

The model predicts water table depth, drain outflow, surface runoff, dry zone depth and other soil water variables on a continuous basis. Therefore the validity of the model can be tested directly by measuring these variables in the field and comparing model predictions with measured values. It is important that field tests of the model be conducted and especially that final predictions of the model be compared to measured data.

The basis of DRAINMOD is an expression for a water balance in the soil profile. Individual components of the water balance are evaluated from approximate methods. While most of these methods have been tested individually, to varying degrees, and their limitations documented in the literature, accumulation of errors from the various components could cause large inaccuracies in the composite model. The most direct and meaningful way of testing the reliability of DRAINMOD is to compare model predictions with results measured in field situations. Such experiments not only provide a good test of the reliability of the model but also documents the required model inputs for the sites and soils considered. They also provide a measure of the difficulty and expense of obtaining input values for the model.

Most of the uses contemplated for the model are related in some way to water table depth and its variation over time. Therefore, when possible the model has been tested by comparing measured and predicted water table depths. In the case of the Ohio experiments discussed later in this section, water table measurements were not made but excellent data for subsurface drainage rates and surface runoff were available for several years of record. In this case comparison between measured and predicted drainage and runoff rates were used as a basis for judging the validity of the model for Ohio conditions.

Data from four states representing widely different soils and climatological conditions are being used to test the validity of the model. Extensive field experiments were conducted to test DRAINMOD during its development in North Carolina and the results presented in a technical report (Skaggs, 1978). Additional data have been obtained from researchers in Ohio, Florida, and California. The results of the tests of the model for each location are discussed in the following sections.

NORTH CAROLINA

Field experiments were installed in four locations to determine soil property and climatological inputs and to test the reliability of the model. Experiments were conducted over a five year period and comparisons of predicted and measured daily water table depths were made for a total of 21 site-years. The results of the experiments have been reported by the author (Skaggs, 1978) and are reproduced in the following sections for the convenience of the user.

Experimental Procedure

Field Sites

Experimental sites were located near Aurora, Plymouth, Laurinburg and Kinston, N.C. so field data representing a good geographical distribution of the Coastal Plains and Tidewater Regions in North Carolina were obtained. The water management systems on all sites have facilities for subsurface drainage and water table control as well as varying degrees of surface drainage. A brief description of each site is given below. Drainage system parameters for each site are given in Table 10-1 and a list of crops grown on the research sites is given in Table 10-2.

Table 10-1. Drainage system parameters for the experimental sites.

Parameter	Aurora - Austin Farm 7.5 m	Aurora - Austin Farm 15 m	Aurora - Austin Farm 30 m	Plymouth	Laurinburg	Kinston Rains	Kinston Goldsboro
Soil type	Lumbee s.l.*	(some Myatt)*		Cape Fear l.	Ogeechee l.*	Rains s.l.	Goldsboro s.l.
Type Drain	clay tile - 4 in.			open ditch	tubing	tubing	clay tile
Drain spacing	7.5 m	15 m	30 m	85 m	48 m	30 m	30 m
Drain depth	0.8 m	0.9 m	1.0 m	0.8 m	1.1 m	1 m	1 m
Drain diameter	102 mm	102 mm	102 mm	open	125 mm	152 mm	102 mm
Effective drain radius	2.5 mm	2.5 mm	2.5 mm	-	7 mm	7 mm	5.1 mm
Depth from drain to restrictive layer	0.5 m	0.5 m	0.7 m	2.2 m	1.4 m	0.4 m	0.4 m
Facilities for water table control							
a. controlled outlet	yes	yes	yes	yes	yes	yes	yes
b. pump-in capability	yes	yes	yes	yes	limited	no	no

*A recent examination of the soil profile descriptions by SCS soil scientists indicate that the following changes should be made in soil names used in this report.

1. The soils referred to as Lumbee s.l. and Myatt s.l. should have been classified as Tomotly s.l.

2. The soil referred to herein as Ogeechee l. should be classified as a Coxville l.

Detailed descriptions of the soil profiles are given in Appendix B. The soil properties and other inputs used in DRAINMOD were determined from on-site measurements and from soil samples analyzed in the lab and not inferred from published descriptions or properties of the soil series. The soil series names are used herein for identification purposes only and the Lumbee and Ogeechee names remain unchanged in the text, tables and figures of this report.

Table 10-2. Crops grown on research sites; planting and harvesting dates.

	Aurora			Plymouth			Laurinburg		
Year	Crop	Plant date	Harvest date	Crop	Plant date	Harvest date	Crop	Plant date	Harvest date
1973	potato	3-10*	6-20	corn	4-15*	9-12	-	-	-
	soybean	7-17	11-14						
1974	potato	3-10*	6-17	corn	4-15*	10-4	cotton	4-1*	10-15*
	soybean	7-10	11-27						
1975	corn	4-21	9-10	corn	4-21	9-23	cotton	4-1*	10-15*
	wheat	11-12	-						
1976	wheat	-	6-16	corn	4-15	9-1	cotton	4-4*	11-10*
	soybean	6-17	11-17	wheat	12-1	-			
1977	corn	4-25	9-1*	wheat	-	6-18*	cotton	4-5*	10-25*
				soybean	6-20*	11-20*			

*Approximate dates for planting or harvest.

Aurora. The site near Aurora is located on the H. Carroll Austin farm and is the same site that was used in a previous study to investigate the feasibility of water table control and subirrigation in the Coastal Plains (Skaggs and Kriz, 1972). The water management system consists of tile drains spaced 7.5, 15, and 30 m apart and buried approximately 1 m deep. The soil is primarily Lumbee* sandy loam with some Myatt sandy loam and Torhunta sandy loam in the areas of the 7.5 and 15 m spacings. A schematic of the experimental setup is shown in Figure 10-1. The four drains for each spacing empty into an outlet ditch where a water level control structure is used to raise or lower the water level for subirrigation or drainage. Subirrigation was implemented by pumping additional water into the ditch from a well located near the five acre field. In some years this system was used to control the water table during April - July for growing potatoes and corn; however, it was used as a conventional drainage system during most of the experimental period.

Plymouth. The experimental site near Plymouth is located on the Tidewater Research Station and was also used in the previous water table control study. The soil is a Cape Fear loam and the water management system consists of open lateral ditches spaced 85 m apart. The field was land-formed in about 1969 and has excellent surface drainage. A water level control structure in the outlet ditch permitted the water level in the ditches to be controlled by either collecting field runoff and drainage waters or by pumping into the ditch from an irrigation well. A weir was installed in the outlet structure to raise the water table during the months of May, June, and July in 1974 and 1975 to supply water to the crop. Water was pumped into the outlet and the ditch water maintained for subirrigation purposes for short periods in both years. However the system was operated in a controlled drainage mode without pumping for most of the growing season. Figure 10-2 shows the weir and the raised water level in the outlet. This field was also used as one treatment in another Water Resources Research Institute sponsored study reported by Gilliam et al. (1978) on controlling the movement of fertilizer nitrates in drainage waters. As a part of this investigation the weir level was raised almost to the surface during the winter months of

* See footnote, Table 10-1.

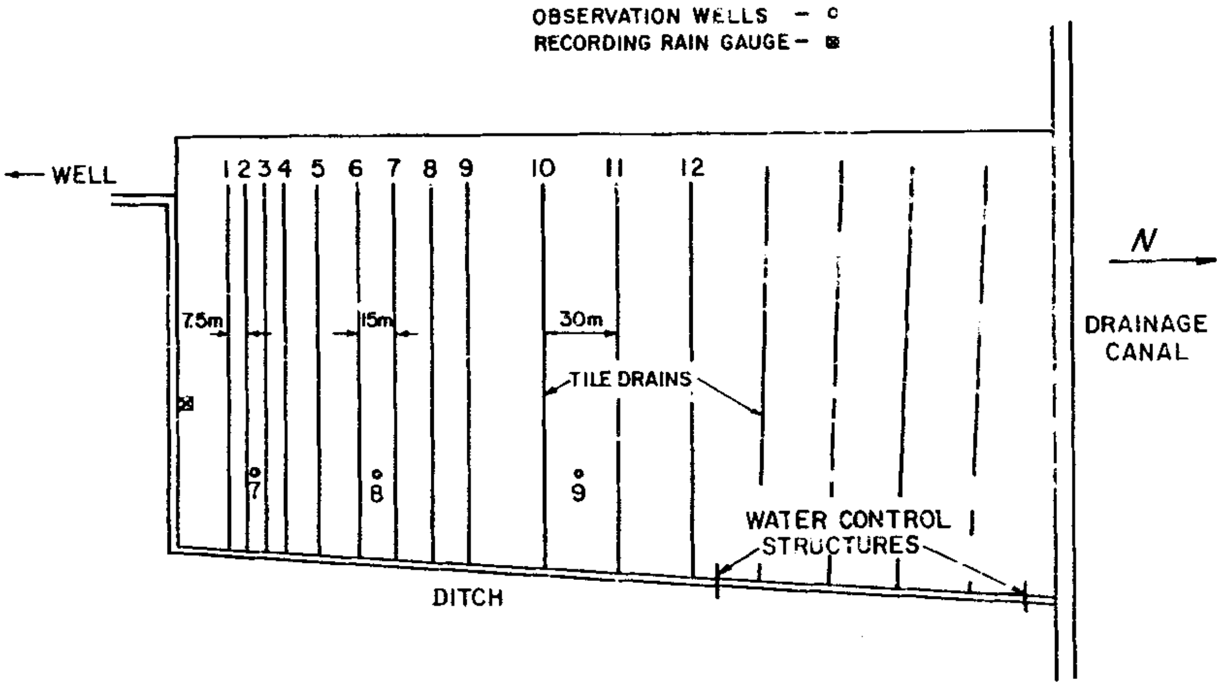


Figure 10-1. Schematic of experimental setup on the H. Carroll Austin Farm, Aurora, N.C.

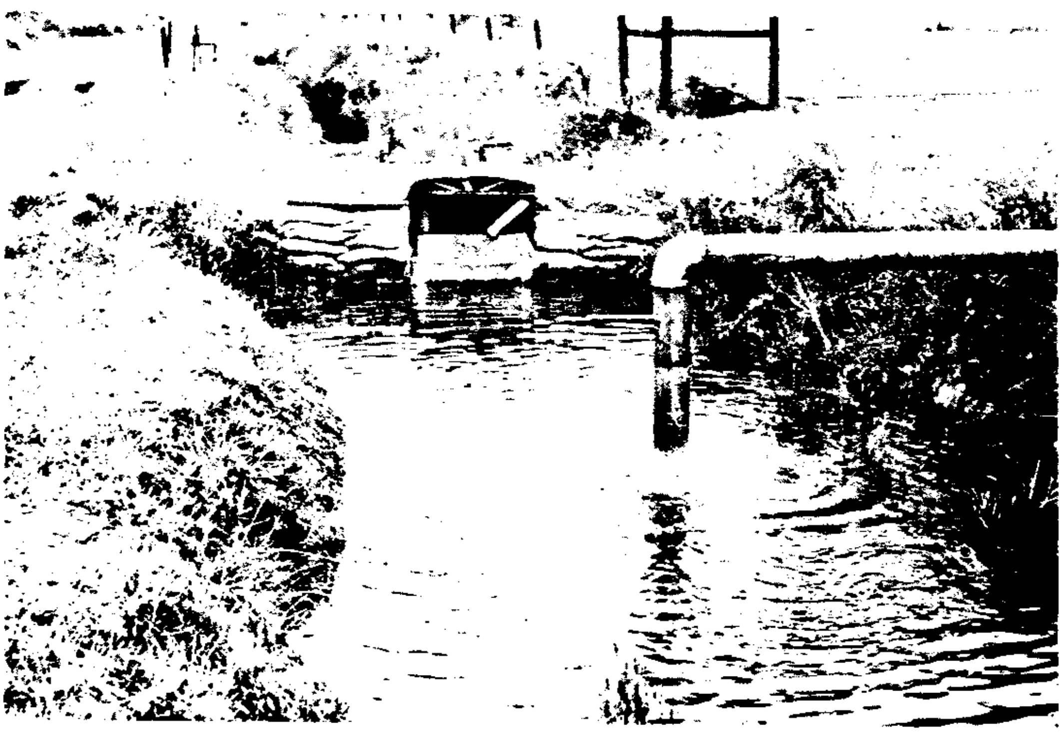


Figure 10-2. A water level control structure in the outlet ditch at the Tidewater Research Station permitted controlled drainage and subirrigation on the Cape Fear soil.

1973-74 and 1974-75 and the system operated in the controlled drainage mode for purposes of studying the effect of high water tables on the movement and denitrification of fertilizer nitrates.

Laurinburg. Experiments were conducted on a water management system located on the McArne Bay farm of McNair Seed Company near Laurinburg, N.C. The soil was formerly classified as a Portsmouth loam but more detailed analysis indicated primarily Ogeechee* with small areas of Coxville in the experimental area. The loam and sandy clay surface layers are underlain at about 1 m by a coarse sand layer which varies in thickness from 0.50 to 1.2 m. Drain tubes are spaced 48 m apart and outlet into a large drainage ditch. The water level in the ditch is controlled by raising or lowering the weir on a water level control structure and holding drainage and runoff water in the ditch. During dry periods water may be pumped from a drainage canal to raise the water in the outlet ditch. This water management system is an integral part of the drainage and irrigation system for an entire Carolina Bay consisting of about 1200 acres.

Kinston. Water management systems on a Rains sandy loam and a Goldsboro sandy loam on the Tobacco Experiment Station at Kinston were studied. Both systems have good surface drainage and have tile drains spaced 30 m apart and buried 1 to 1.2 m deep. Water level control structures were installed on the main tile lines in each system to control the drainage rate and were used in the fertilizer nitrate study by Gilliam et al. (1978) referenced above. Although water table records of sufficient length to test the model were not collected on these sites, short term experiments were conducted and input properties were measured for each soil and may be used for long term simulations.

Field Measurements.

Although the design and management of the water table control systems vary in some respects among the sites discussed above, most of the field measurement procedures were the same for each site. The water table elevation midway between drains was measured in 10 cm diameter observation wells, drilled to the depth of the impermeable layer, and fitted with Leupold and Stevens type F water level recorders

* See footnote, Table 10-1.

to give a continuous record of the water table position. The same instrument was used to record the water level in the drainage ditches, or, in the case of drain tubes, the water level in the outlet ditch. The unsaturated soil water pressure head distribution was measured with tensiometers for intervals of a few weeks duration during the growing season at the Plymouth and Aurora sites. Tensiometers were placed at 15, 30, 45, 60, 75, and 120 cm depths midway between subsurface drains.

Tests of short duration were conducted on the Aurora and Plymouth sites to make intensive measurements of soil water conditions during drainage and subirrigation. The water table was raised to near the soil surface by raising the weir levels in the water level control structures and pumping water into the outlet ditches. Piezometers were installed at the tensiometer depths given above at the midpoint and quarter points between drains and used to determine the existence of vertical gradients in the saturated zone of the profile. Then the weir level was lowered and the tensiometers and piezometers read several times daily during the drainage period to test the validity of the linear pressure head distributions assumed in DRAINMOD for the drainage period.

Rainfall was measured on each site with a WeatherMeasure Model P501-1 tipping bucket recording rain gauge with a P521 event recorder. Although this instrument accurately measured the variation of rainfall intensity with time, hourly values were used as inputs to test DRAINMOD. Use of rainfall data on a more frequent basis, say 10 to 15 minutes, was possible and would have probably allowed a better estimation of infiltration and runoff. However, data available from weather station records have a maximum frequency of one hour in most cases. Since these are the data that will be used in simulation, the model was tested using measured rainfall accumulated over one-hour intervals.

Daily maximum and minimum temperatures were obtained from weather stations near each site and the potential ET calculated by the Thornthwaite method. U.S. Weather Bureau standard evaporation pans were installed at each location and modified to record evaporation continuously (Figure 10-3). Details of the design and operation of the recording pan as well as comparisons between pan measurements and Thornthwaite predictions are given by Mohammad (1978). However, the Thornthwaite method is used to compute PET in the present version of DRAINMOD, so it was also used in testing the validity of the model predictions.

Surface runoff plots were installed to measure surface runoff during rainfall events and to be used in determining the infiltration characteristics of the soils. Sheet metal barriers were installed around the 3 m x 4 m plots and the runoff was diverted to buried reservoirs (Figure 10-4). Runoff rates were measured and recorded using a tipping bucket apparatus in conjunction with an event recorder. Infiltration tests were conducted by sprinkling water on the surface of the plot at a rate of approximately 120 mm/hr and measuring the runoff rate.

Surface depression storage was characterized by making elevation surveys on a fine meshed grid and by using a surface sealing procedure to determine the storage in small pockets or depressions caused by micro-relief. These measurements were made as a part of a detailed study of surface storage and are described in detail by Gayle and Skaggs (1978).

One of the functions of DRAINMOD is to determine, on a day to day basis, whether conditions are suitable for conducting field operations, as discussed in Chapter 3. This determination is based on soil and weather conditions and requires input data specifying the drained, or air, volume below which conditions are not suitable for field operations. The amount of rainfall necessary to postpone field operations and the length of time after rainfall occurs before operations can continue are also needed inputs to the model. These parameters were approximated for the soils considered in this study by field observations in the spring months of 1975 and 1976. Field conditions on all research sites were monitored by experienced technicians in coordination with the farmer or experiment station personnel. When the soil reached a condition that was just dry enough to plow and prepare seedbed, soil samples were taken from 10 and 20 cm depths at several locations within the field

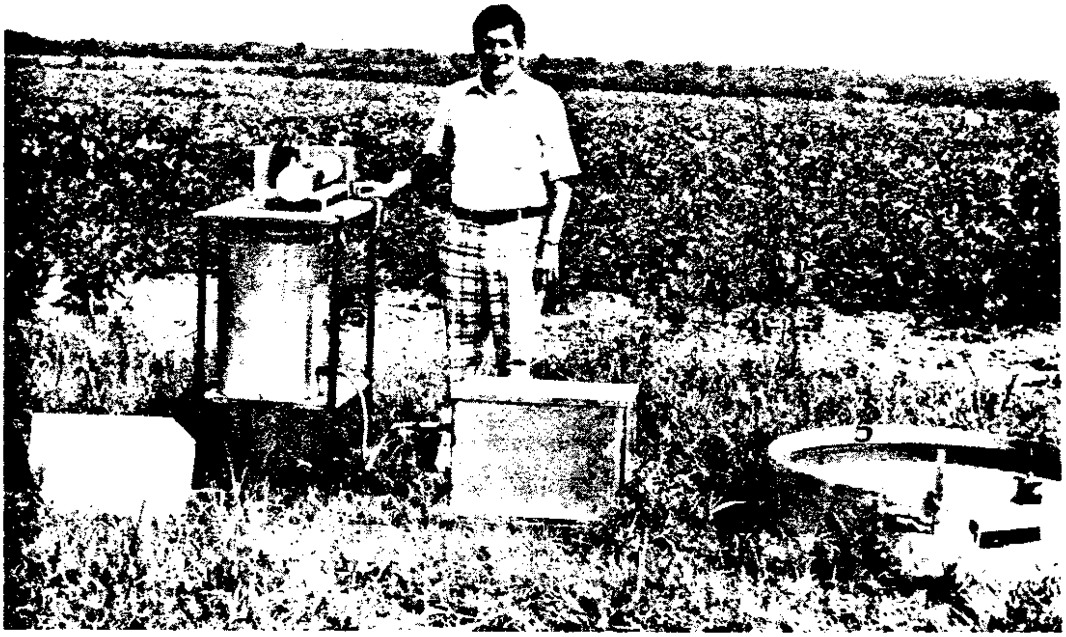


Figure 10-3. A standard evaporation pan was modified to record pan evaporation directly. A reservoir was set up to supply water to the pan through a float valve as evaporation took place. By recording the water level in the reservoir, evaporation could be determined as a function of time.

Figure 10-4. Runoff from 3 m X 4 m plots was recorded with a tipping bucket apparatus and an event recorder.

and the volumetric water content determined. Drainage or air volumes corresponding to the measured water contents were determined from the soil water characteristics and the drainage volume - water table depth relationships. The amount of rain necessary to postpone field operations and the minimum time required after that amount of rainfall before operations can proceed were also approximated based on the soil type and experience of the farmer or station manager.

Soil Property Measurements.

The saturated hydraulic conductivity was measured in the field using the auger hole method (Boast and Kirkham, 1971) and a method based on water table drawdown (Skaggs, 1976). The unsaturated hydraulic conductivity function K(h) was estimated using the method of Millington and Quirk (1960) with a matching factor at saturation. The K(h) function for the Wagram and top 60 cm of the Lumbee soils were measured experimentally (Wells and Skaggs, 1976).

Soil water characteristics for each soil horizon down to the drain depth were determined on small undisturbed core samples using a standard pressure plate method (Richards, 1965). The relationship between drainage volume and water table depth was measured directly on large undisturbed soil cores (0.50 m in diameter and approximately 1 m long). The procedures for extracting the cores and making the measurements are described by Skaggs et al. (1978). The cores were attached to gravel filled bases in the lab and wetted from the bottom by raising a water reservoir connected to the outlet. After the water table rose to the surface and remained for at least one day the outlet reservoir was lowered in small increments and the drainage volume measured at each water table depth.

Results - Soil Properties

Hydraulic Conductivity

The results of the saturated conductivity measurements are summarized in Table 10-3. Values obtained from both drawdown and auger hole measurements varied with initial water table depth and from point to point in the fields so average values are tabulated. The soils on the Aurora, Plymouth and Laurinburg sites have sandy layers at depths below about 1 m (Appendix B) which have higher K values than the surface layers. The con-

Table 10-3. Summary of average hydraulic conductivity values from auger hole and drawdown measurements.

Site	Method	No. measurement	Average K value
Aurora			
7.5 m	drawdown	17	1.01 cm/hr
	auger hole	9	1.84
15 m	drawdown	19	1.84
	auger hole	9	1.73
30 m	drawdown	19	
	auger hole	10	3.16
Plymouth	drawdown	7	37.2
	auger hole	6	15.3
Laurinburg	drawdown	8	6.3
	auger hole	3	7.8
Kinston			
Goldsboro	auger hole	3	6.5
	large core ((vertical K)	2	1.7
Rains	auger hole	6	4.3
	large core (vertical K)	1	1.8

ductivities of the various profile layers are difficult to determine from drawdown measurements as the drawdown depends on the conductivities in all layers below the water table. Likewise measurements from auger holes that penetrate or closely approach the sandy layer may be expected to give an intermediate value between the K's of the upper and lower layers.

The soils on the Aurora site are particularly difficult to characterize because of sandy layers in the surface horizons which are of varying thickness and sometimes discontinuous. For example, in previous studies (Wells and Skaggs, 1976), we found the vertical K in 3 large cores of the surface 60 cm of Lumbee to be greater than 10 cm/hr yet only 1.2 cm/hr in a 4th core from the same general area of the field. Measurements from other cores greater than 1 m deep and analysis of the K determinations from auger hole and drawdown measurements according to initial water table depth indicates that the surface 0.75 to 1 m of the Aurora soils have an effective lateral K of about 1 cm/hr. In some field locations the effective K of the surface zone is higher, and there are high K layers within this zone in nearly all locations. However draw-down and auger hole measurements indicate that the effective K falls within the range of 0.75 to 1.5 cm/hr for the surface layer. Values tend to be near the higher end of the range for the Lumbee soils where the spacing is 30 m and somewhat lower for the soils in the 7.5 and 15 m spacing. The K value of the deeper sandy layer is about 3 cm/hr.

Analysis of the K values with respect to initial water table depth and soil profile layering resulted in the values given in Table 10-4 for conductivities at each site. The effective lateral K of the profile when the water table is near the surface was calculated from the conductivities of the two layers and may be compared to the values in Table 10-3.

Table 10-4. Summary of K values of profile layers used as input to DRAINMOD.

Site	Layer Depth (m)	K (cm/hr)	Equivalent K* for profile (cm/hr)
Aurora			
7.5 m	0 - 1.0 **	1.0 cm/hr	
	1.0 - 1.08	3.0	1.14 cm/hr
15 m	0 - 1.0 **	1.0	
	1.0 - 1.23	3.0	1.37
30 m	0 - 1.0 **	1.0	
	1.0 - 1.58	3.0	1.73
Plymouth	0 - 1.1 **	15.0	
	1.1 - 2.82	45.0	34.0
Laurinburg	0 - 1.20	0.75	3.5
	1.20- 2.40	6.3	
Kinston			
Goldsboro	0 - 1.4	6.5	6.5
Rains	0 - 1.1	4.3	3.6
	1.1 - 1.4	1.0	3.6

*This value is calculated for lateral flow (parallel to the layers) with the water table at the surface.

**Effective depths of the profiles when corrected for convergence near the drain.

The conductivity inputs to DRAINMOD are the values given for individual layers in Table 10-4. It should be noted that the values given for the drawdown method in Table 10 are averages obtained for a range of initial water table depths. Generally the values for Aurora and Plymouth increased with initial water table depth. Likewise the equivalent conductivities obtained from the layer values given in Table 10-4 will increase with depth because of the higher conductivity of the bottom layer.

Soil Water Characteristic and Drainage Volume - Water Table Depth Relationships

Soil water characteristic data (drainage branch) are tabulated in Table 10-5 for the soils considered in this study. Data are also presented for two additional soils, a Wagram loamy sand, and a Portsmouth sandy loam; the latter soil is located on the Tidewater Experiment Station at Plymouth. Wilting point water contents are also included in the soil water characteristic data. The main use of the soil water characteristic in DRAINMOD is to calculate the relationship between drainage volume and water table depth. However these relationships were measured directly from large field cores for all soils on the experimental sites except for the Ogeechee soil on the Laurinburg site. The measured drainage volume - water table depth relationships are plotted in Figure 10-5. Relationships for water table depths greater than the core depth were calculated from the soil water characteristics. The entire relationship was calculated for the soil on the Laurinburg site as large cores were not collected from this location.

Infiltration Parameters

Coefficients of the Green-Ampt infiltration equation were determined from infiltration measurements on the surface runoff plots and on large undisturbed field cores. Some runoff plot infiltration measurements were made by sprinkling water at a known rate on the plot and subtracting the measured runoff rate from the application rate. Other infiltration measurements were determined from runoff caused by natural rainfall events. Measurements on field cores were made by ponding water on the surface of the same large cores used to determine the drainage volume -

Table 10-5. Drainage branch of the soil water characteristics for the soils considered in this study. Values given in table are volumetric water contents.

Soil	Soil water pressure head (cm of water)													Wilting point (15 bars)
	0	-10	-20	-30	-40	-50	-60	-70	-80	-100	-150	-200	-500	
Lumbee s.l. - Aurora														
(0 - 0.6 m)	0.342	0.335	0.322	0.305	0.290	0.280	0.270	0.265	0.256	0.250	0.210	0.190		0.12
Cape Fear l. - Plymouth														
(0.15 m)	0.482	0.444	0.429	0.418	0.410	0.402	0.396	0.392	0.388	0.381	0.372	0.368		0.22
(0.5 m)	0.462	0.444	0.329	0.422	0.417	0.412	0.409	0.405	0.401	0.394	0.378	0.367		
Ogeechee l. - Laurinburg														
(0.3 m)	0.450	0.433	0.420	0.410	0.405	0.402	0.398	0.397	0.391	0.385	0.372	0.365	0.340	0.24
(0.75 m)	0.425	0.398	0.383	0.368	0.358	0.347	0.335	0.331	0.326	0.320	0.312	0.307	0.293	
Goldsboro s.l. - Kinston														
(0.15 m)	0.364	0.354	0.340	0.322	0.300	0.272	0.253	0.242	0.234	0.224	0.192	0.186		0.06
(0.40 m)	0.370	0.360	0.350	0.340	0.326	0.312	0.303	0.297	0.294	0.288	0.282	0.280		
Rains s.l. - Kinston														
(0.15 m)	0.370	0.300	0.282	0.272	0.266	0.258	0.254	0.248	0.244	0.238	0.228	0.224		0.09
(0.40 m)	0.368	0.326	0.302	0.286	0.275	0.267	0.261	0.256	0.251	0.244	0.231	0.222		
Wagram l.s.														
(0-0.9 m)	0.302	0.299	0.285	0.254	0.218	0.184	0.154	0.132	0.117	0.103	0.087	0.072	0.051	0.03
Portsmouth s.l. - Plymouth														
(0.15 m)	0.390	0.363	0.354	0.346	0.340	0.334	0.328	0.324	0.319	0.312	0.304	0.296		0.13
(0.40 m)	0.400	0.382	0.370	0.361	0.354	0.348	0.342	0.338	0.336	0.334	0.331	0.328		

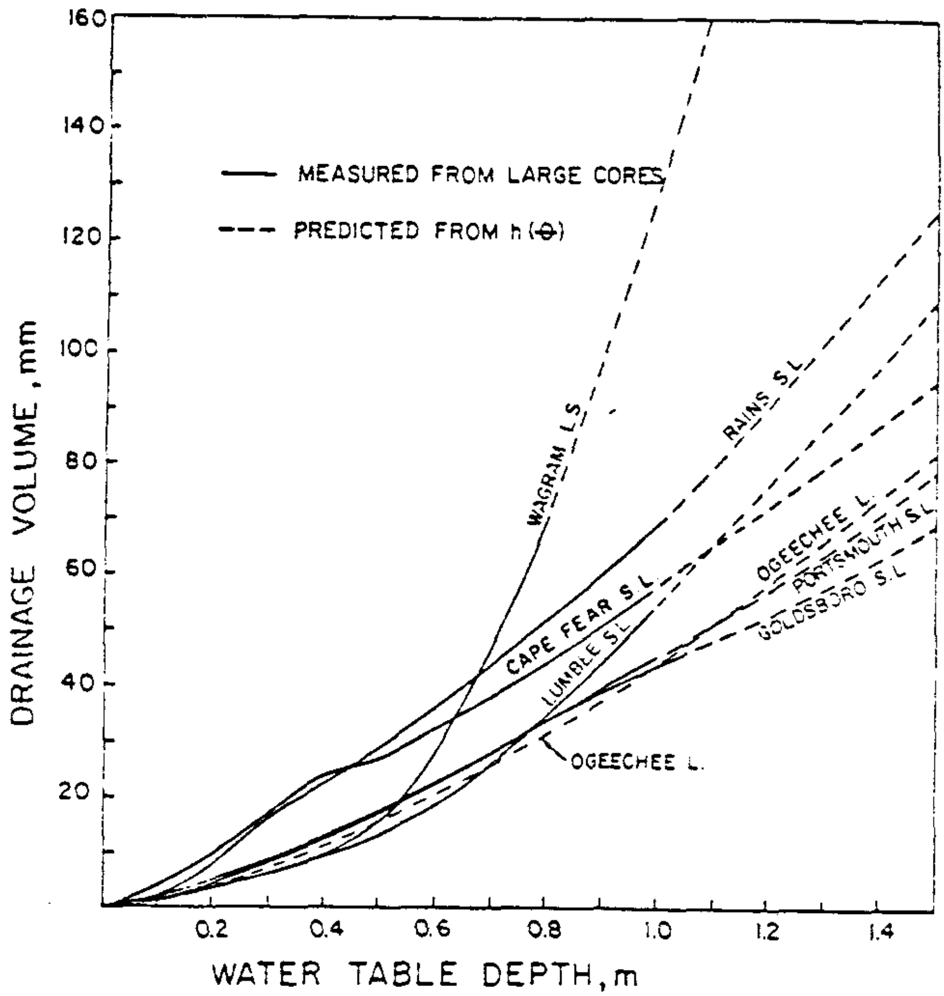


Figure 10-5. Drainage volume or air volume (cm^3/cm^2) as a function of water table depth for soils considered in this study. (Same as Figure 5-4).

water table depth relationships. Finally, additional measurements were made using guarded ring infiltrometers. Coefficients A and B of the Green-Ampt equation were determined from each measured relationship and plotted versus the initial water table depth (e.g. Figure 10-6 for Lumbee sandy loam). When a dry zone existed at the soil surface an equivalent initial water table depth was defined such that the air volume corresponding to the equivalent depth is equal to the total air volume in the profile including the dry zone. Values of the coefficients A and B corresponding to selected initial water table depths were obtained from

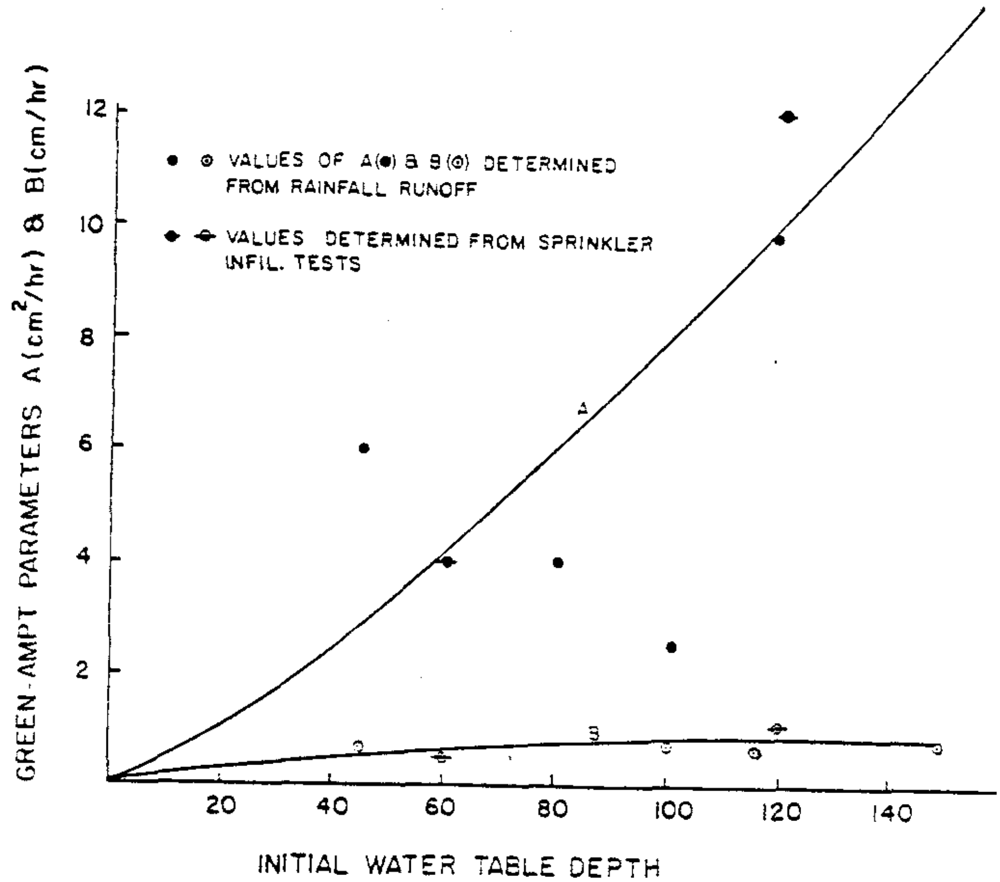


Figure 24. Green-Ampt parameters A and B versus water table depth for the Lumbee sandy loam soil on the Aurora site.

the plots and used as inputs to the computer program. These values are tabulated in Table 13 for the experimental sites. In the simulation process, DRAINMOD selects coefficients by interpolation from the table based on the initial equivalent water table depth.

Upward Water Movement

Relationships between maximum rate of upward water movement and water table depth were defined for each soil by numerically solving equation 18 for vertical unsaturated water movement due to ET at the surface. The surface boundary condition was assumed to be h = -1000 cm. The relationships are plotted in Figure 25.

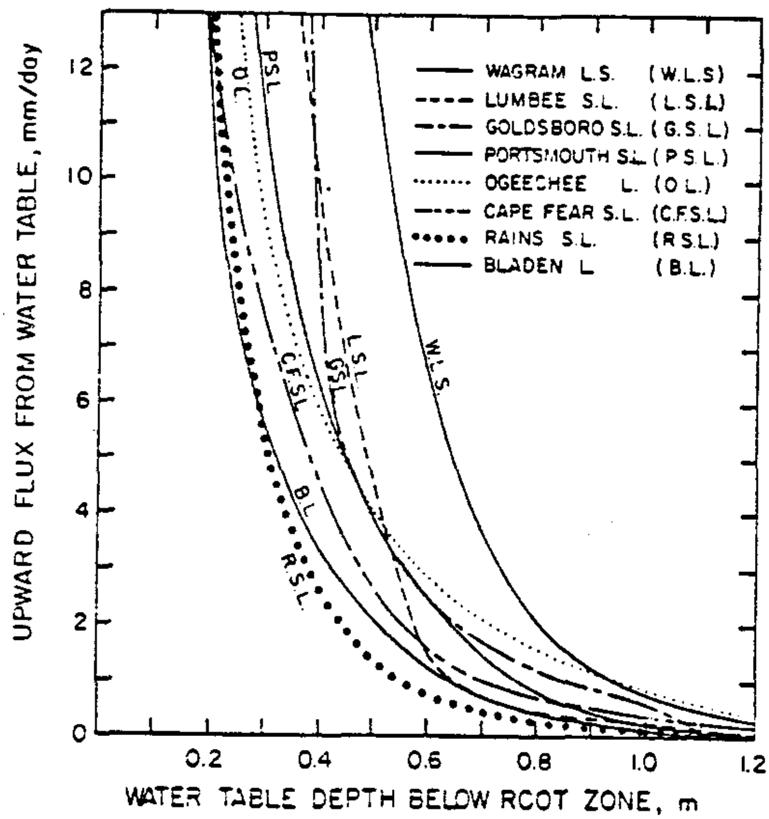


Figure 10-7. Effect of water table depth on steady upward flux from the water table. (Same as Figure 5-6).

Trafficability parameters

Trafficability parameters for the soils considered in this study are listed in Table 10-7. These data are not used to test the model but are important inputs for long term simulations for the given soils. The parameters given were determined for plowing and seedbed preparation in the spring. No attempt was made to determine the parameter values for the harvest season. Generally the maximum allowable soil water content for field operations would be higher and the required drained (air) volume lower during the harvest season than for seedbed preparation.

Root Depths

The crop root depths were estimated from the planting and harvesting dates given in Table 10-2. The plots given in Figure 2-22 were used as a guide to determine the rooting depth for corn. The maximum effective

Table 10-6. Estimates of coefficients for the Green-Ampt infiltration equation as a function of initial equivalent water table depths.

Soil	*Equivalent water table depth (m)											
	0		0.50		1.0		1.5		2.0		5.0	
	A	B	A	B	A	B	A	B	A	B	A	B
Cape Fear	0	0	0.8	0.5	6.6	0.8	9.5	1.0	11.0	1.0	13.0	1.0
Lumbee**	0	0	3.3	0.3	8.0	0.8	15	1.0	20	1.0	20	1.0
Ogeeche**	0	0	2.0	0.75	4.0	1.0	6.0	2.0	8.6	2.6	30	2.6
Goldsboro	0	0	1.2	0.75	2.7	1.25	4.4	2.0	5.3	2.0	26.0	2.0
Rains	0	0	1.2	0.50	3.0	0.75	6.0	1.0	9.2	1.0	25.0	1.0
Wagram	0	0	3.0	1.0	5.5	2.0	8.7	3.0	11.5	3.0	25	3.0
Portsmouth	0	0	1.2	0.75	6.5	1.2	10.0	1.5	12.0	1.5	15.0	1.5
Bladen	0	0	0.82	0.15	1.3	0.15	1.5	0.15	1.8	0.15	2.1	0.15

*Equivalent water table depth is the drained to equilibrium water table depth corresponding to a given amount of air volume in the profile. For example if the water table depth was 1.0 m but a dry zone exists so that the profile contains 10 cm^3 of air per cm^2 of surface area, the equivalent water table depth is the drained to equilibrium depth that would have 10 cm of air.

**See footnote, Table 10-1.

Table 10-7. Trafficability parameters for plowing and seedbed preparation.

Soil	Maximum water content-plow layer (cm^3/cm^3)	AMIN* (mm)	ROUTA** (mm)	ROUTT*** (days)
Cape Fear l.	0.395	33	12	2
Lumbee s.l.	0.265	28	15	1
Ogeechee l.	0.39	34	12	2
Goldsboro s.l.	0.23	32	15	1
Rains s.l.	0.25	39	12	2
Wagram l.s.	0.15	35	15	1
Bladen s.l.	0.40	30	10	2
Portsmouth s.l.	0.32	30	12	2

*AMIN = the minimum air volume (or drained volume) for plowing and seedbed preparation. That is, it would be too wet to prepare seedbeds if the drained volume is less than AMIN.

**ROUTA = the amount of rain necessary to postpone field work.

***ROUTT = the time necessary for soil water redistribution before field work can be restarted after it has been postponed by rainfall in excess of ROUTT.

rooting depth for corn was assumed to be 30 cm while 25 cm was assumed for potatoes, soybeans and wheat. The rooting depths for each site are tabulated as a function of Julian date for each year in Appendix C.

Climatological Data

Hourly precipitation data measured on each experimental site are given by Skaggs (1978) for the duration of the study. Daily maximum and minimum temperatures were obtained from published U.S. Weather Bureau records for stations at Aurora, Plymouth and Laurinburg. The Plymouth weather records were collected on the Tidewater Experiment Station while the weather stations at Aurora and Laurinburg were within a few km of the experimental sites.

Water Level in Drainage Outlet

The drainage outlets in the field experiments at Aurora, Plymouth and Laurinburg all received water from large areas outside of the experimental areas. As a result it was not possible to predict the water level in the drainage outlet. The water level in the outlet was measured continuously and the average daily value was used as an input to test DRAINMOD. That is, the measured water level in the ditch was read in rather than predicted from subroutine YDITCH in the model. The outlet water levels are plotted for the Aurora site in Figures 10-23 to 10-26.

Measured Versus Predicted Water Table Elevations

Water table elevations predicted by DRAINMOD are compared to measured values in the plots given on the following pages. The measured and predicted water table elevations at the end of each day were plotted automatically by the computer for a series of one-year test periods. The agreement between predicted and measured values was quantified by calculating a standard error for each test period defined as follows,

$$s = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - Y_i')^2}{n}} \qquad (10\text{-}1)$$

where s is the standard error, n is the number of days in the test period (year), Y_i is the measured water table elevation above a datum at the end of each day and Y_i' is the predicted water table elevation. The average deviation (a.d.) was also computed for each test period as,

$$a.d. = \sum_{i=1}^{n}|Y_i - Y_i'|/n \qquad (10\text{-}2)$$

where the symbols are the same as defined above.

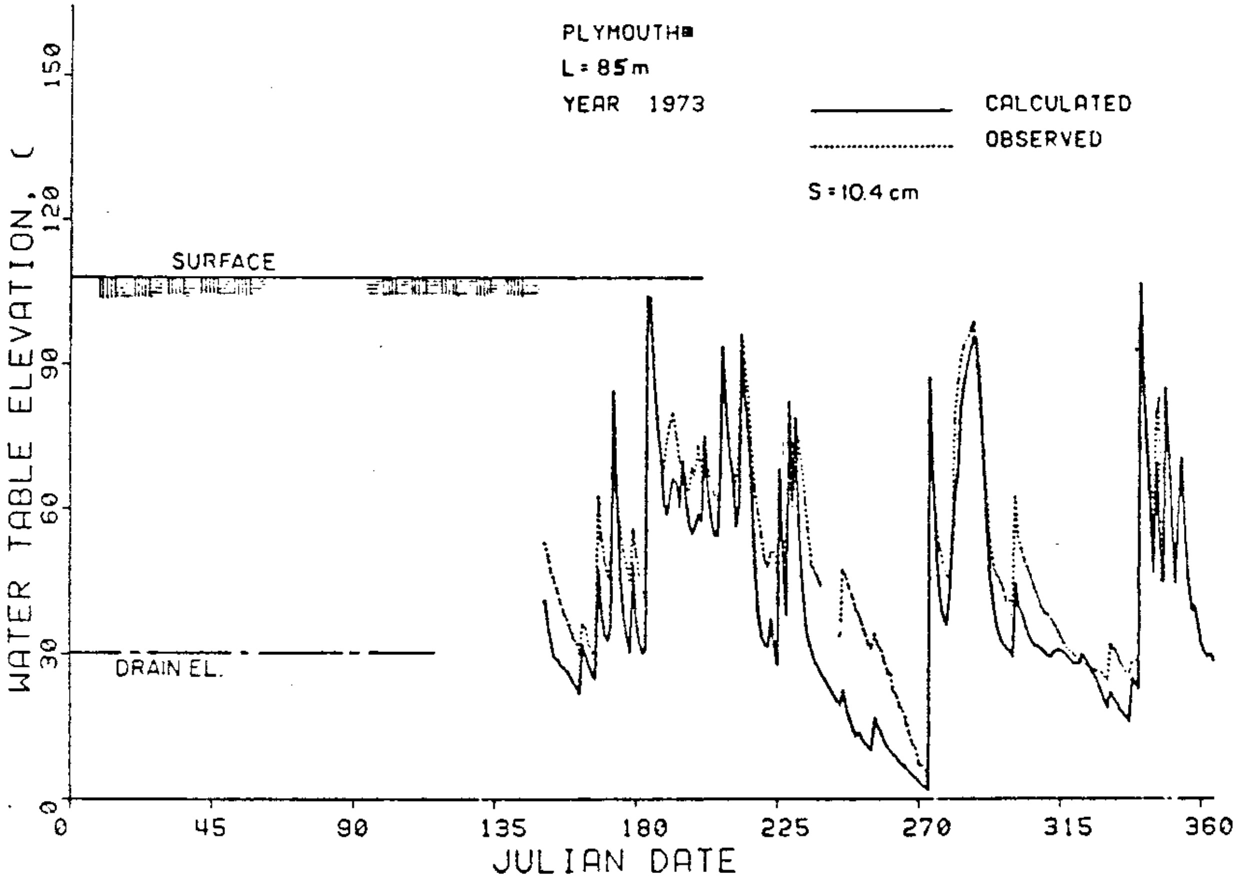
It should be emphasized that the plots given on the following pages are not the results of a data fitting exercise. In every case the agreement between measured and predicted results could be improved by changing one or more of the model inputs. However the values required to optimize the fit could not be determined *a priori* so juggling the various inputs to improve the agreement with observed data would not provide a meaningful test of the model reliability. Instead, each input parameter was determined independently as discussed in previous sections of this report. In a few cases the parameters will be varied to determine the sensitivity of the model to errors in parameter determinations. However, comparison of predicted results with values measured in the field using independently measured input parameters is the only true test of the reliability of the model. This is the method used herein to determine the suitability of DRAINMOD for application to design and analysis of water management systems.

Plymouth

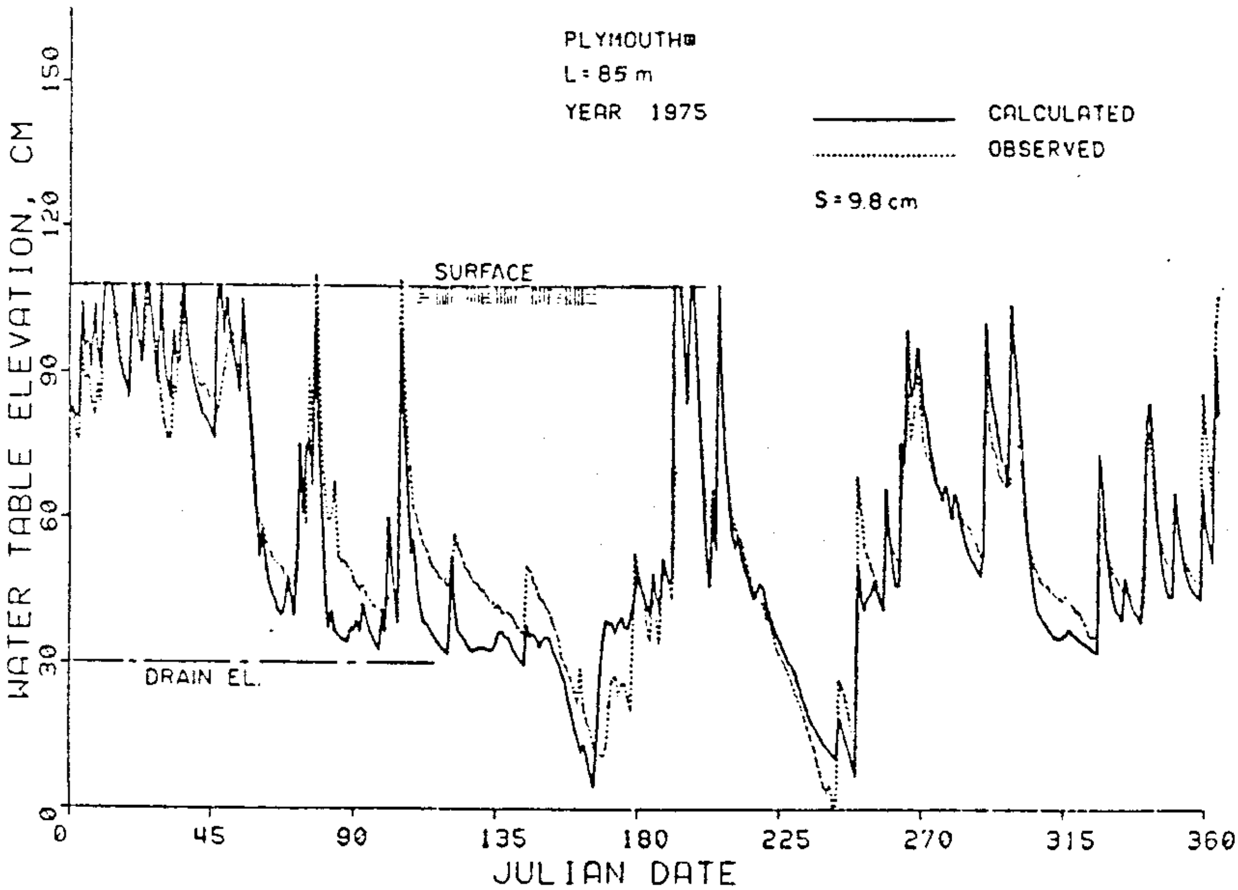
Predicted and observed water table elevations from the Tidewater Experiment Station near Plymouth are given in Figures 10-8 through 10-12. The agreement between predicted and observed results is very good with standard errors of estimate (s values) ranging from 8.6 cm (1977) to 9.8 cm (1975). The agreement is particularly good during periods when the water level in the drainage ditch is raised by controlled drainage or subirrigation. This is due to the high conductivity of the profile, especially the sandy layer below a depth of approximately 1.1 m, which permits the water table to respond quickly to changes in the observed ditch water level. The net effect is that the high K values makes the water table more sensitive to ditch water elevation than to some of the other input parameters such as those used in predicting infiltration, upward water movement and ET. Controlled drainage was used during most of 1974, the first 60 days of 1975, and for a two month period from Dec., 1976 to Jan., 1977. Subirrigation was also used for short periods in 1973 and 1975 by pumping water into the drainage outlet from a deep well. However, for most of 1973, 1975, 1976 and 1977, the system was operated as a conventional drainage system and still gave excellent agreement between measured and predicted results.

Aurora

Water table elevations are plotted for the 7.5 m drain spacing at Aurora in Figures 10-13 (1973) through 10-17 (1977). Results are plotted for the same years for the 15 m spacing in Figures 10-18 through 10-22 and for the 30 m spacing in Figures 10-23 through 10-27. The standard errors of estimate (s) are given on each plot and summarized, along with corres-



ure 10-8. Observed and predicted water table elevations midway between drains space 85 m apart on the Plymouth site during 1973.



igure 10-9. Observed and predicted water table elevations midway between drains spaced 85 m apart on the Plymouth site during 197[illegible]

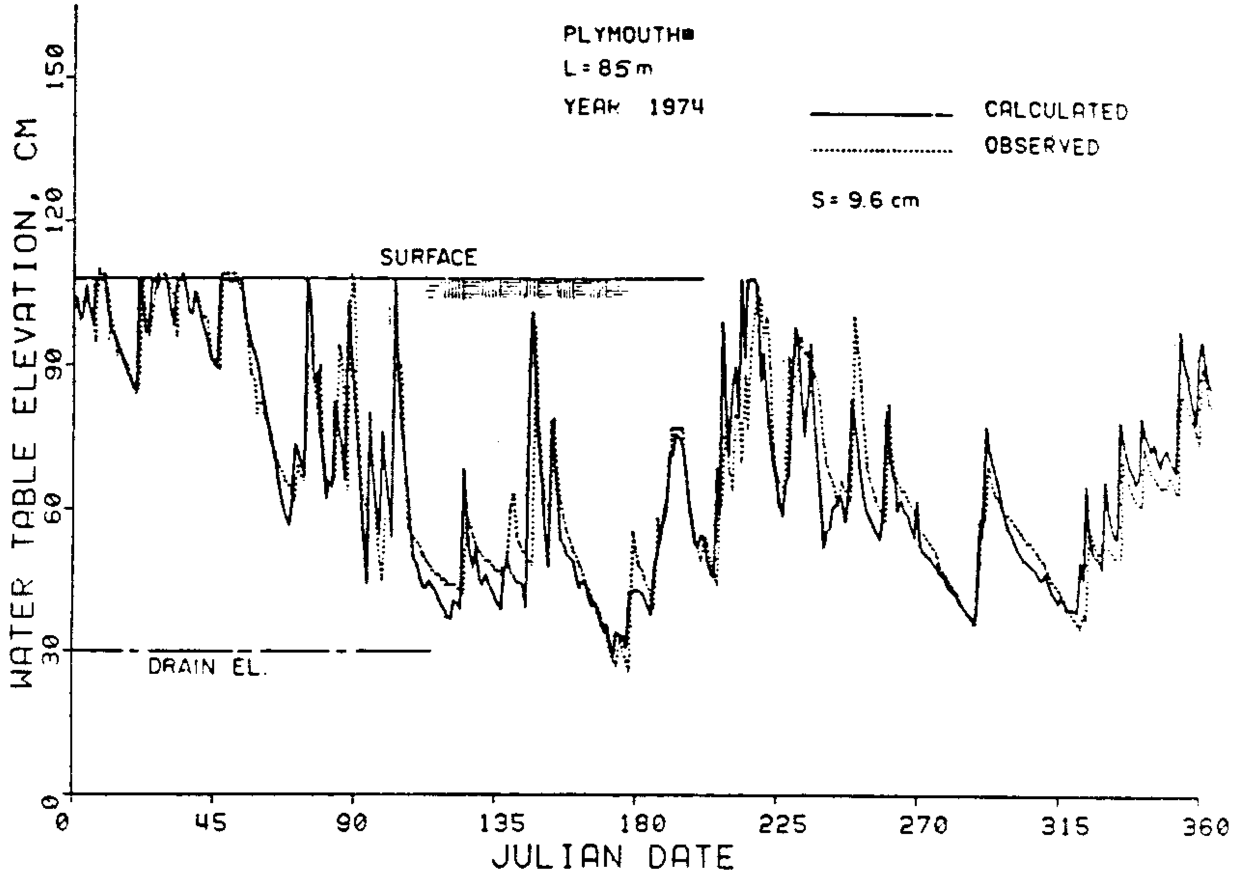


Figure 10-10. Observed and predicted water table elevations midway between drains spac
85 m apart on the Plymouth site during 1975.

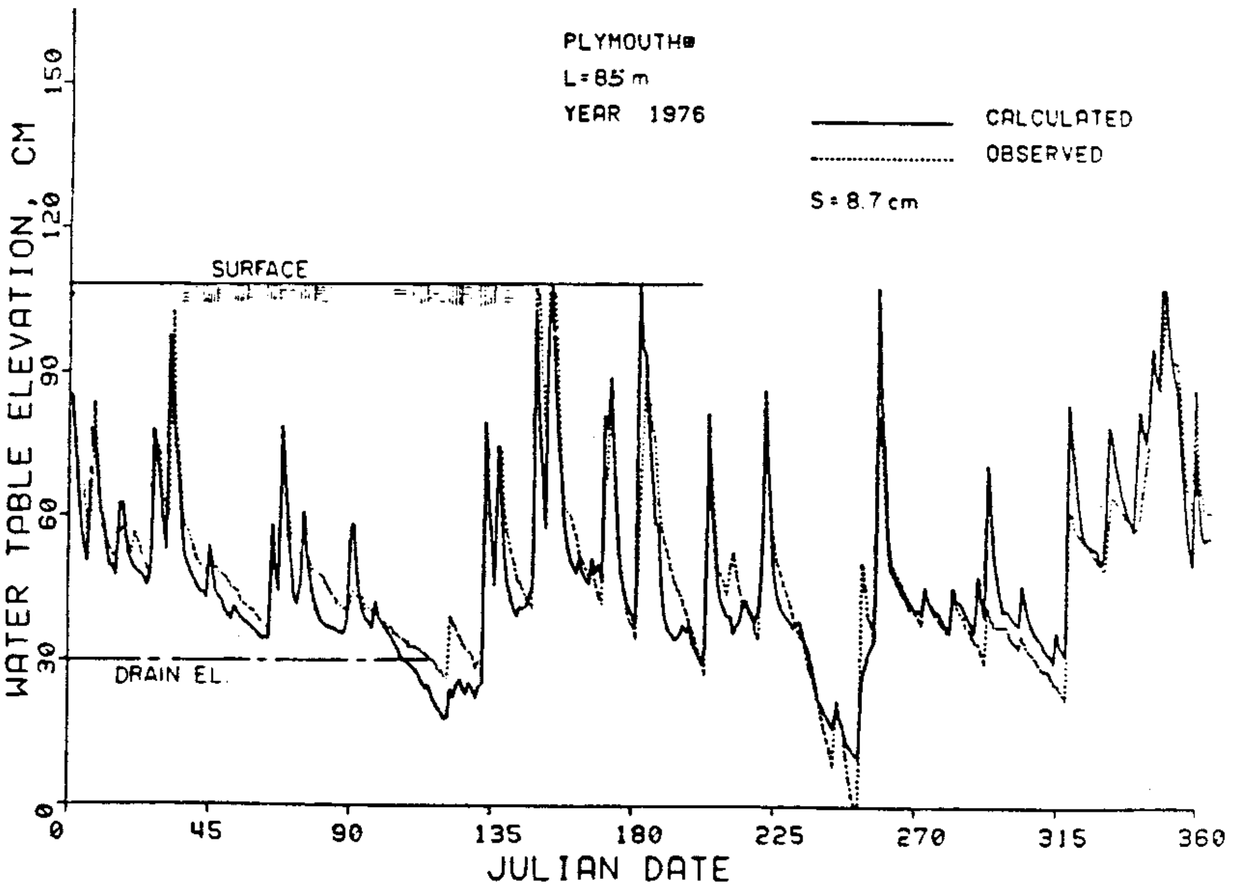


Figure 10-11. Observed and predicted water table elevations midway between drains spac

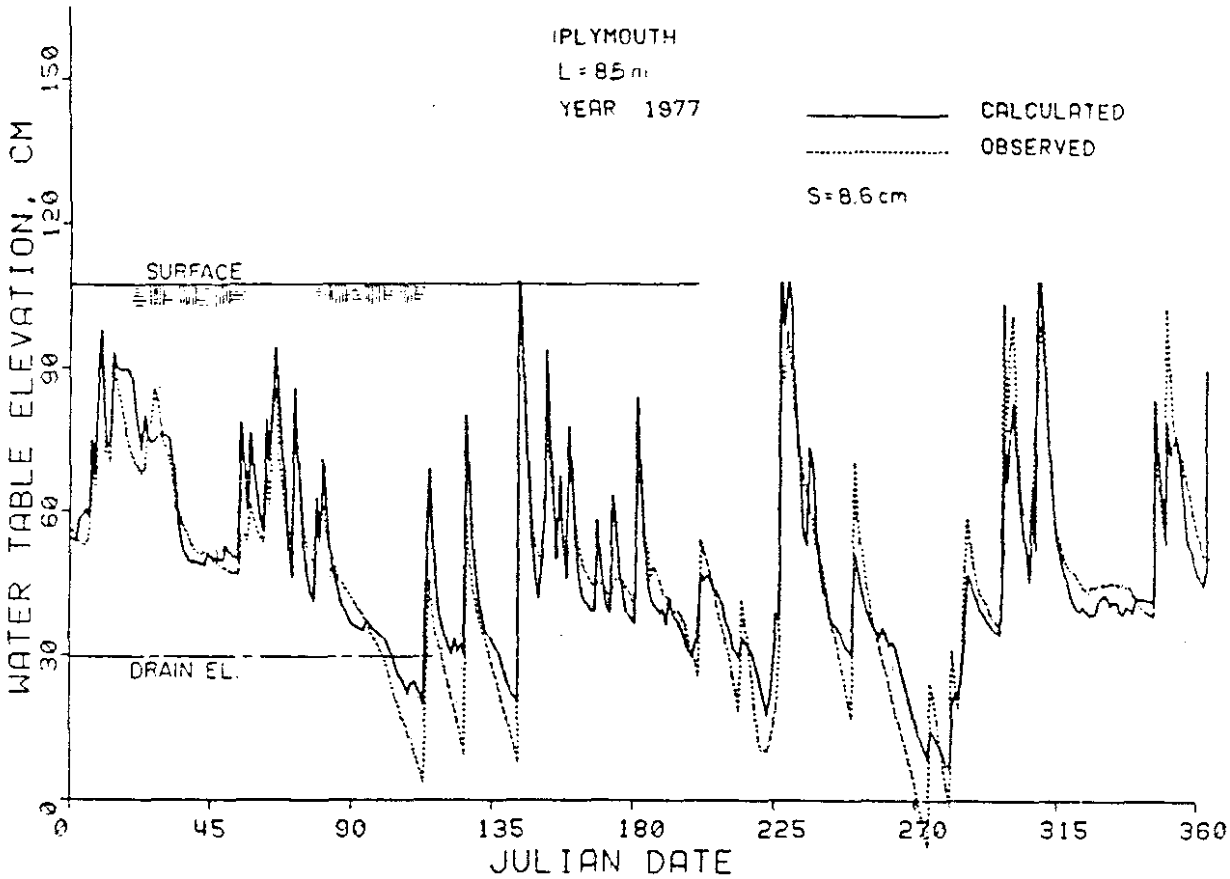


Figure 10-12. Observed and predicted water table elevations midway between drains spaced 85 m apart on the Plymouth site during 1977.

ponding values from the Plymouth and Laurinburg tests, in Table 10-3.

The Aurora system was operated in the drainage mode during most of the five year period. Subirrigation was used for relatively short periods in 1973, 1974 and 1975 as indicated by the outlet ditch water level elevations included in plots for the 30 m spacing (Figures 10-23 through 10-27). One of the weaknesses of the model is demonstrated by the subirrigation event starting on Julian day 150, 1975 (Figure 10-25). DRAINMOD predicts an upward water table response at the midpoint between the drains immediately after the water level in the outlet ditch is raised. However, it has been previously demonstrated (Skaggs, 1973) by theory as well as by laboratory and field experiments, that there may be a considerable time lag between a rise in the ditch water level and a water table response midway

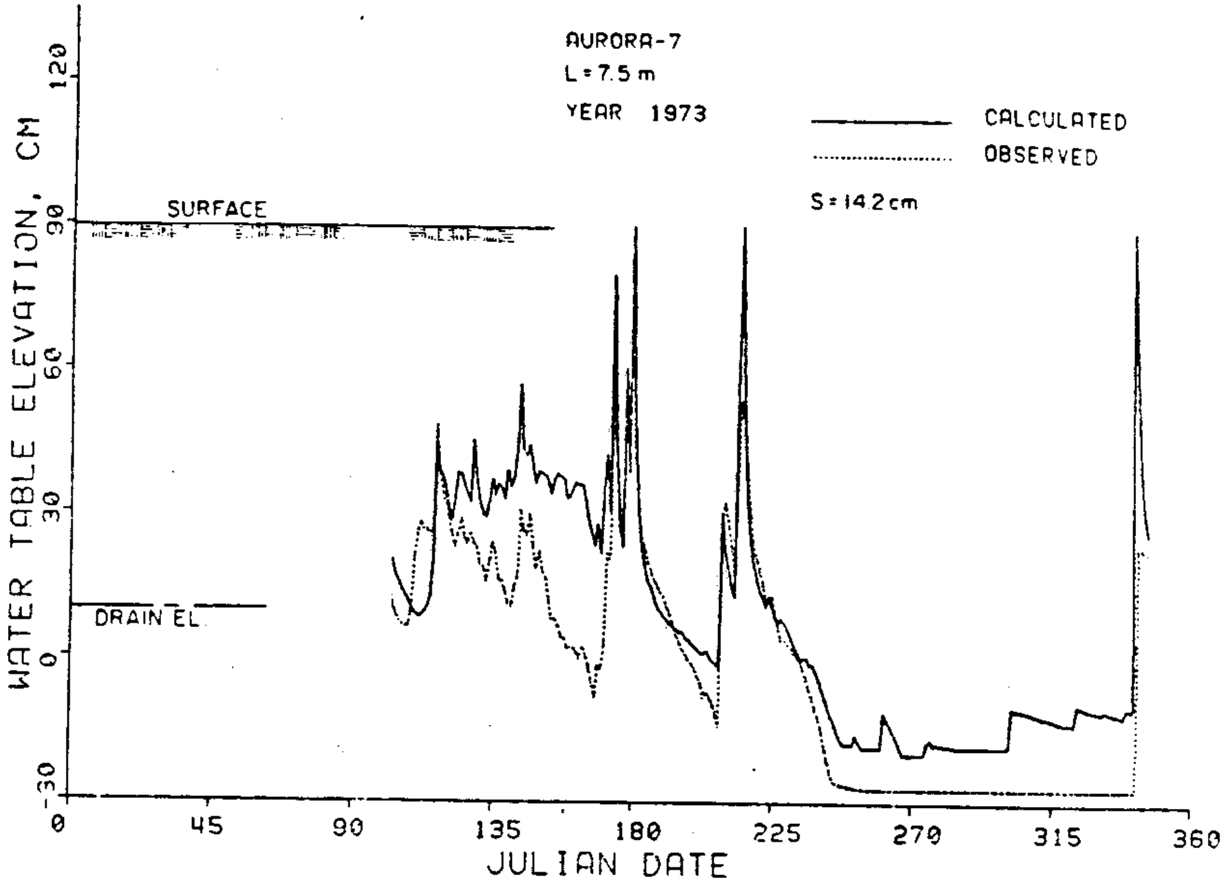


Figure 10-13. Observed and predicted water table elevations midway between drains spaced 7.5 m apart on the Aurora site during 1973.

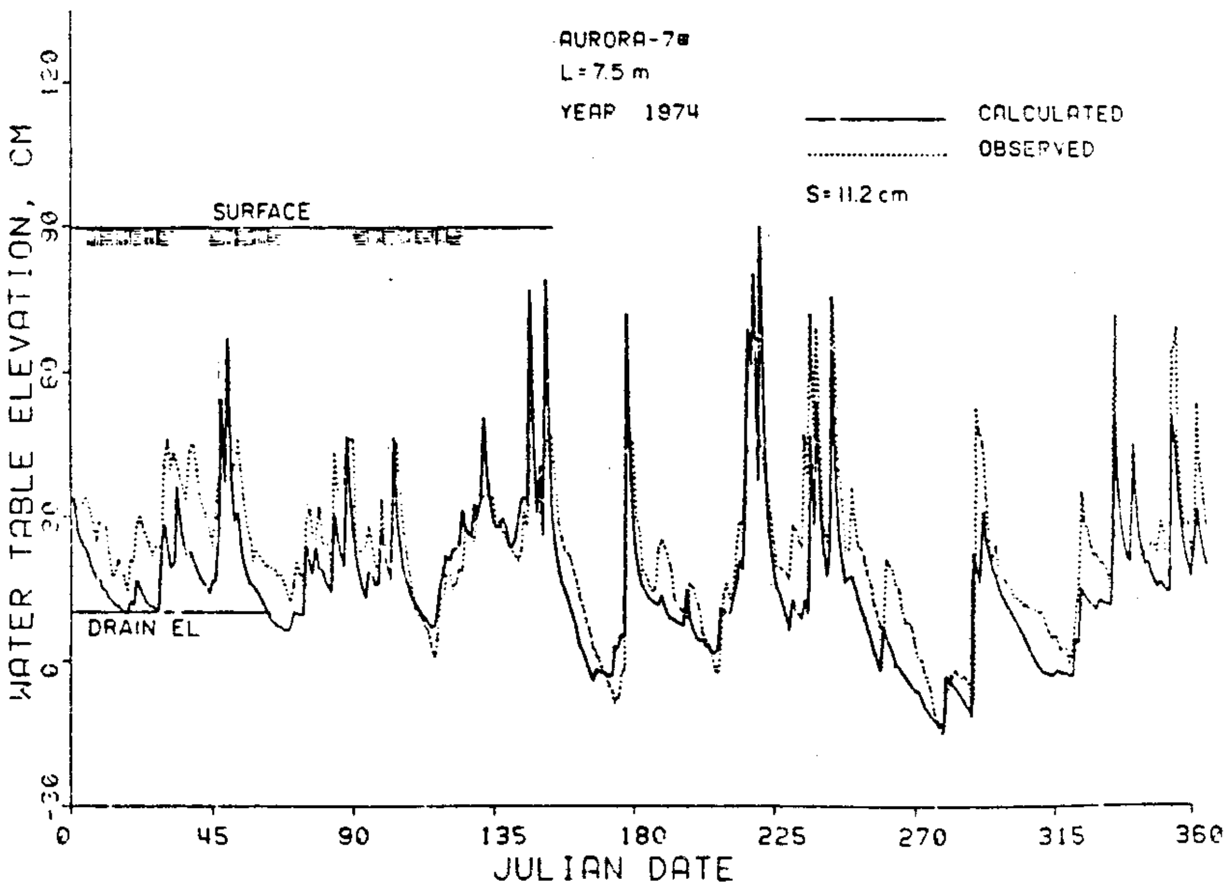


Figure 10-14. Observed and predicted water table elevations midway between drains spaced 7.5 m apart on the Aurora site during 1974.

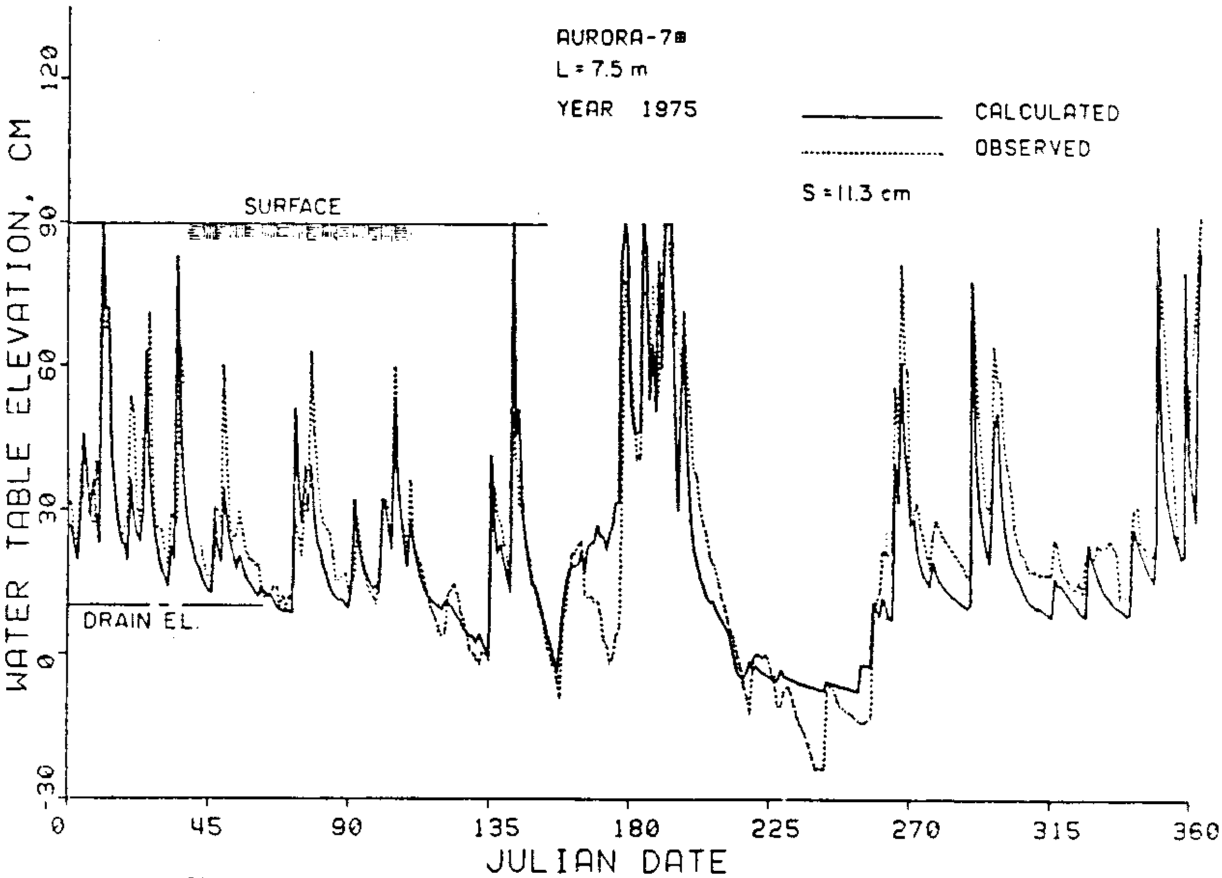


Figure 10-15. Observed and predicted water table elevations midway between drains spaced 7.5 m apart on the Aurora site during 1975.

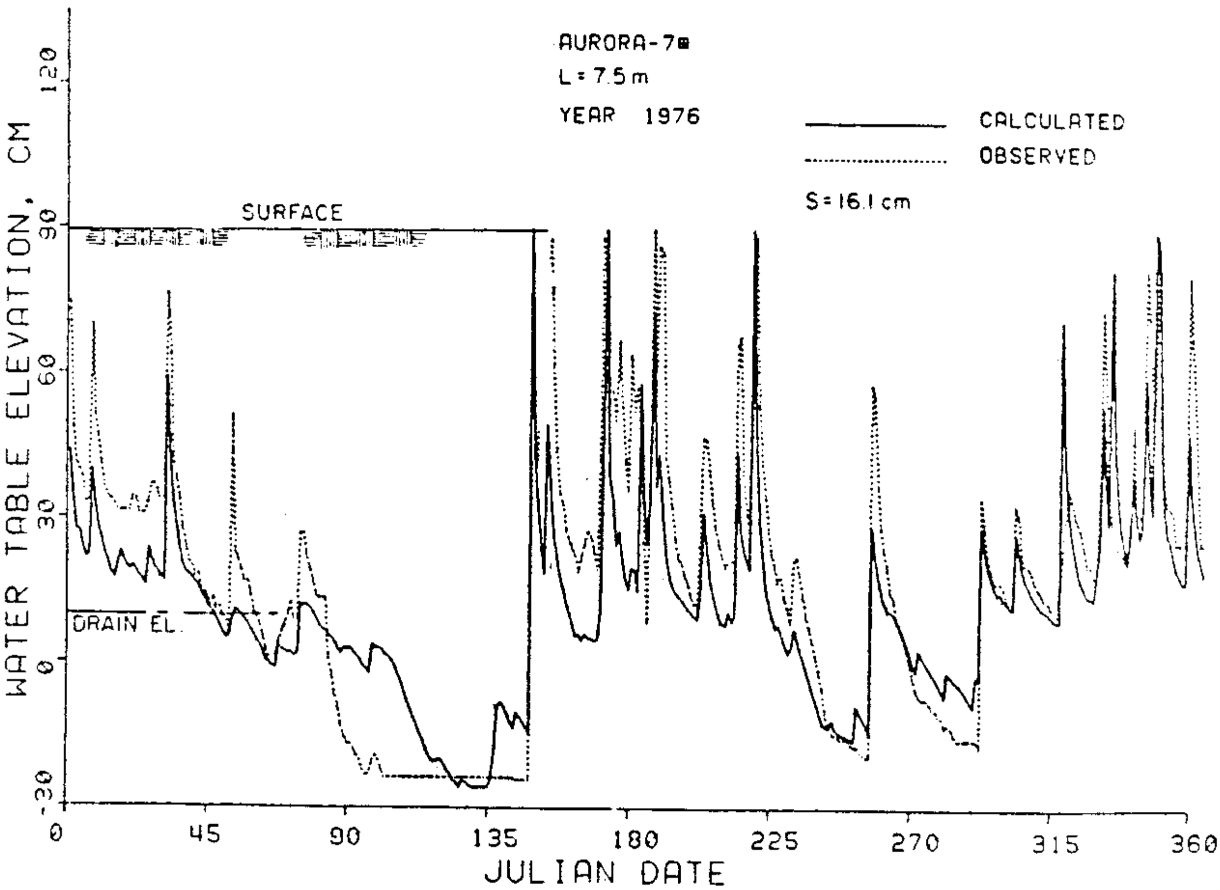


Figure 10-16. Observed and predicted water table elevations midway between drains spaced 7.5 m apart on the Aurora site during 1976.

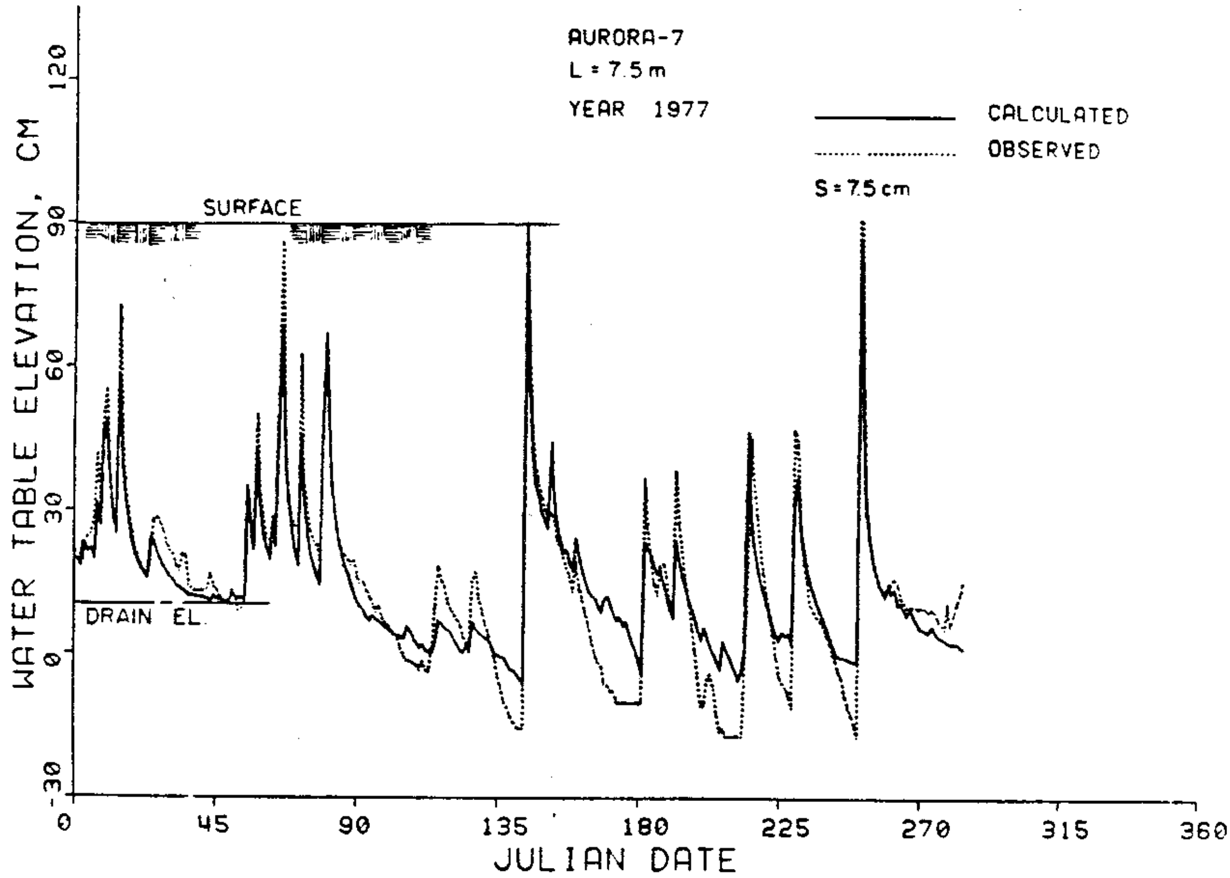


Figure 10-17. Observed and predicted water table elevations midway between drains spaced 7.5 m apart on the Aurora site during 1977.

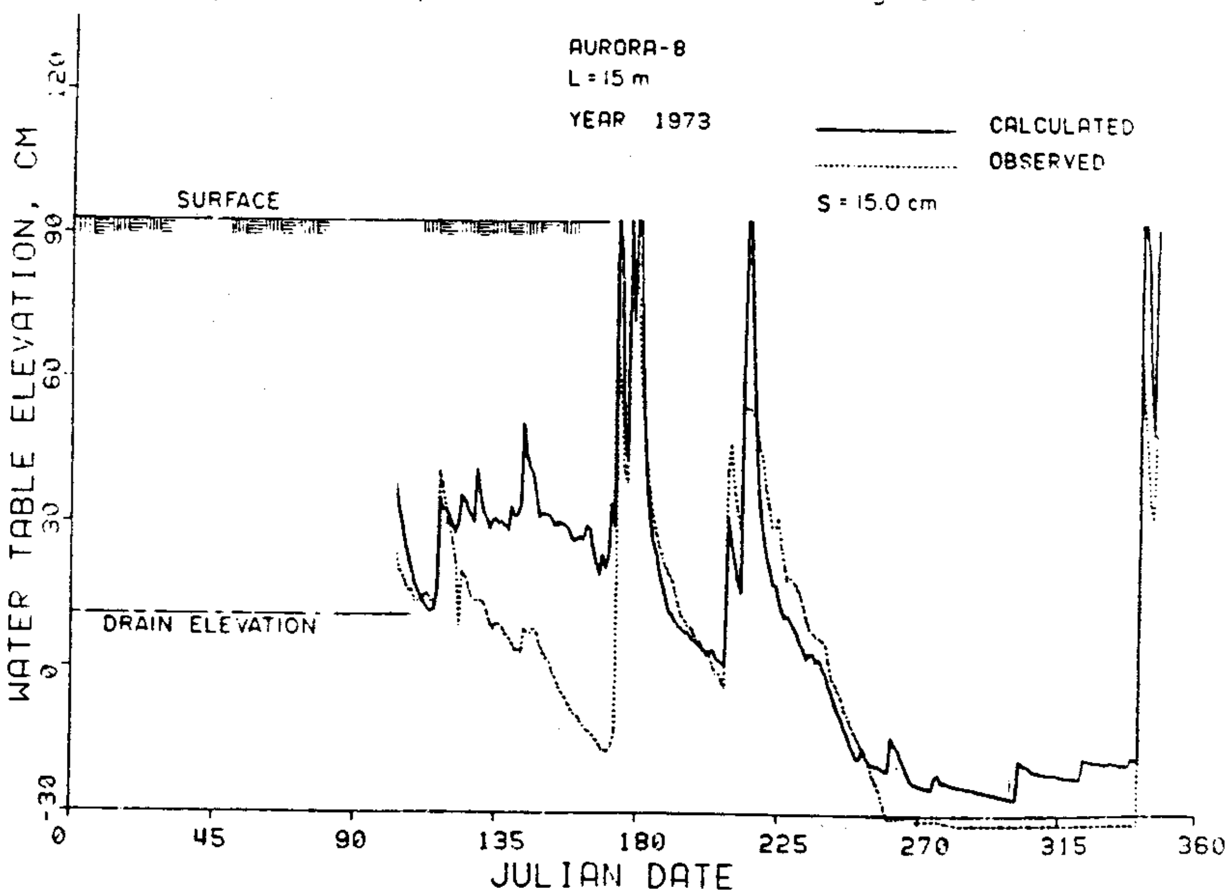


Figure 10-18. Observed and predicted water table elevations midway between drains spaced 15 m apart on the Aurora site during 1973.

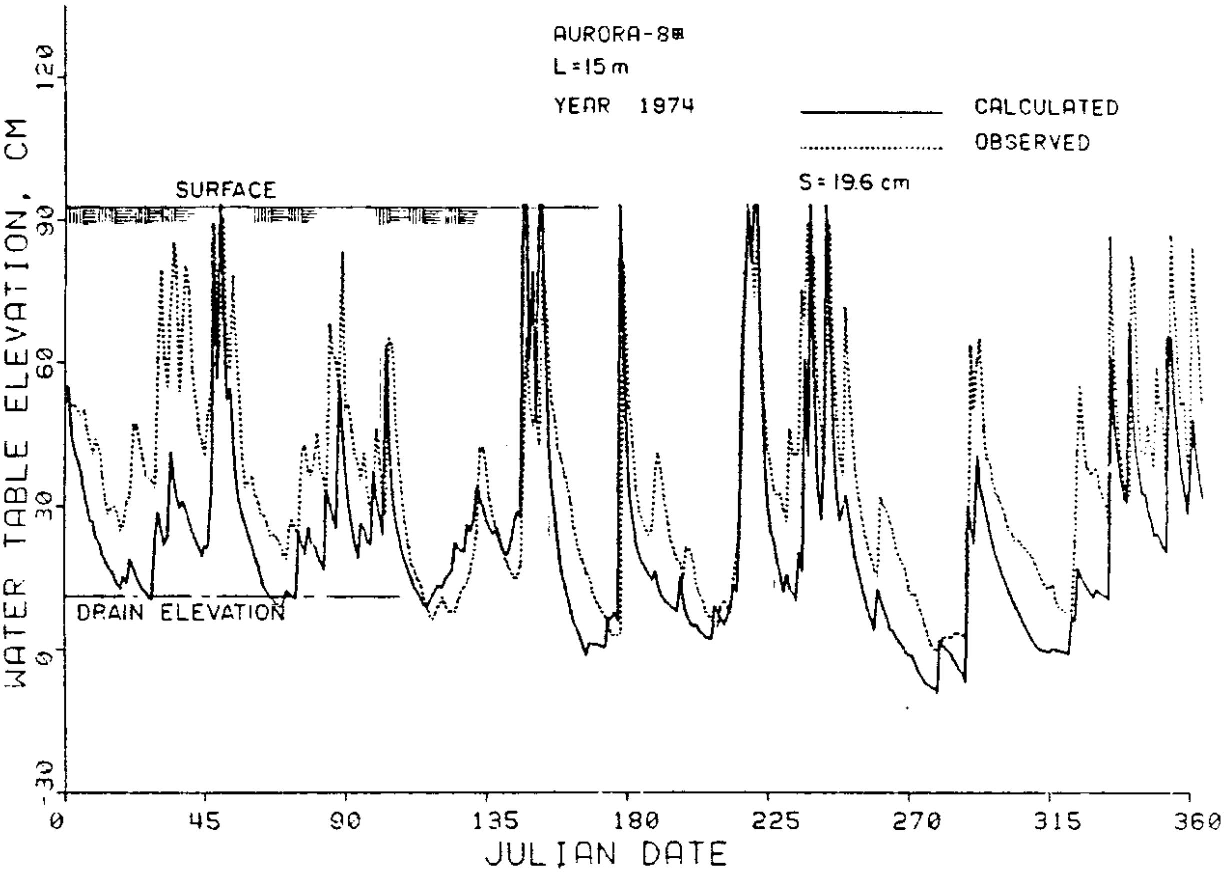


Figure 10-19. Observed and predicted water table elevations midway between drains spaced 15 m apart on the Aurora site during 1974.

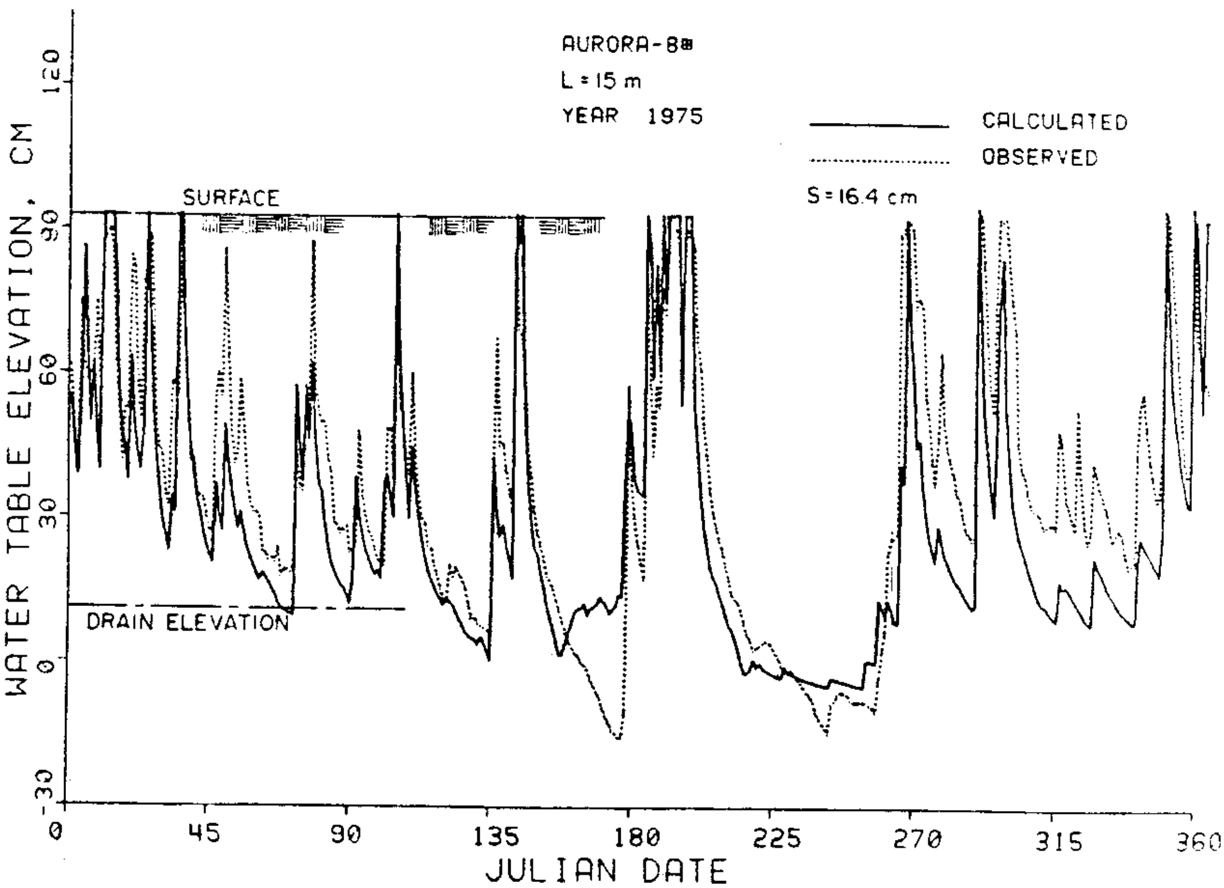


Figure 10-20. Observed and predicted water table elevations midway between drains spaced 15 m apart on the Aurora site during 1975.

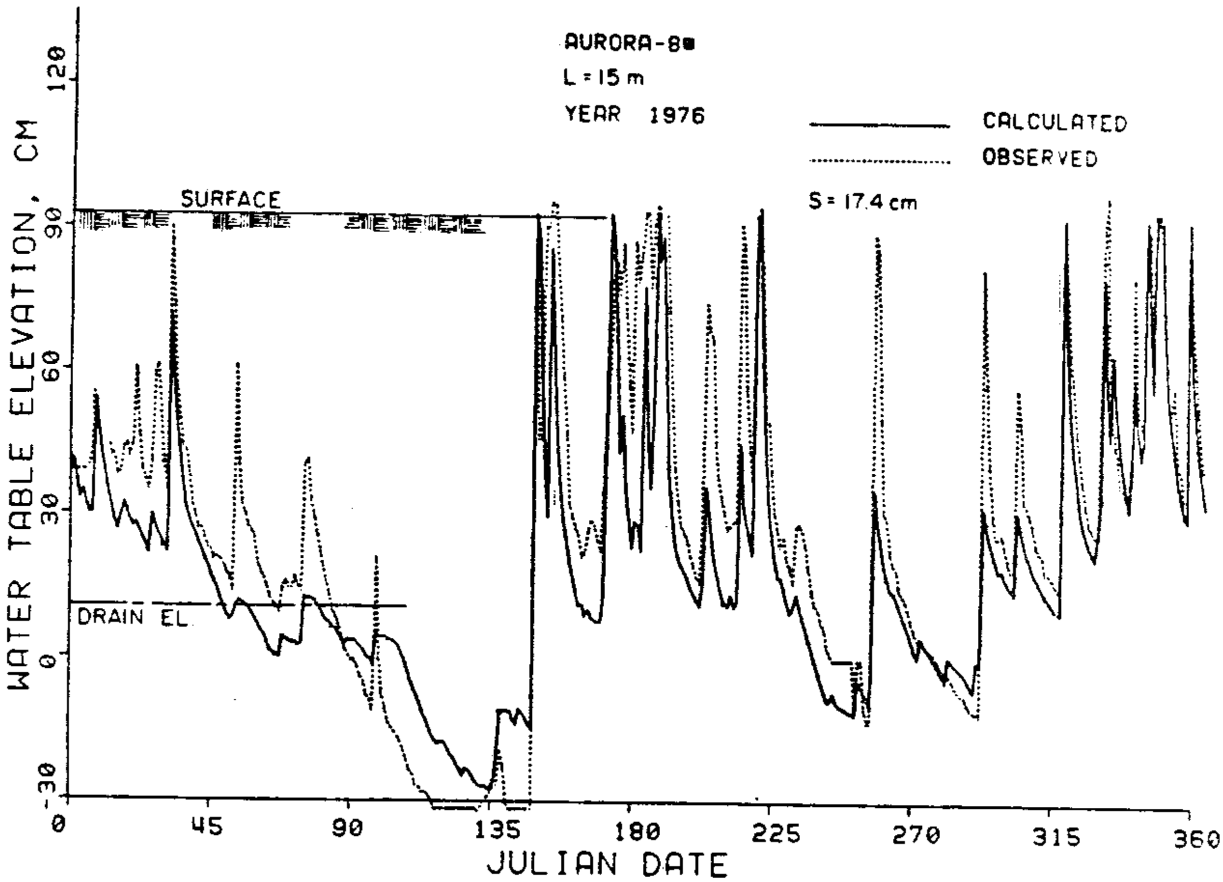


Figure 10-21. Observed and predicted water table elevations midway between drains spaced 15 m apart on the Aurora site during 1976.

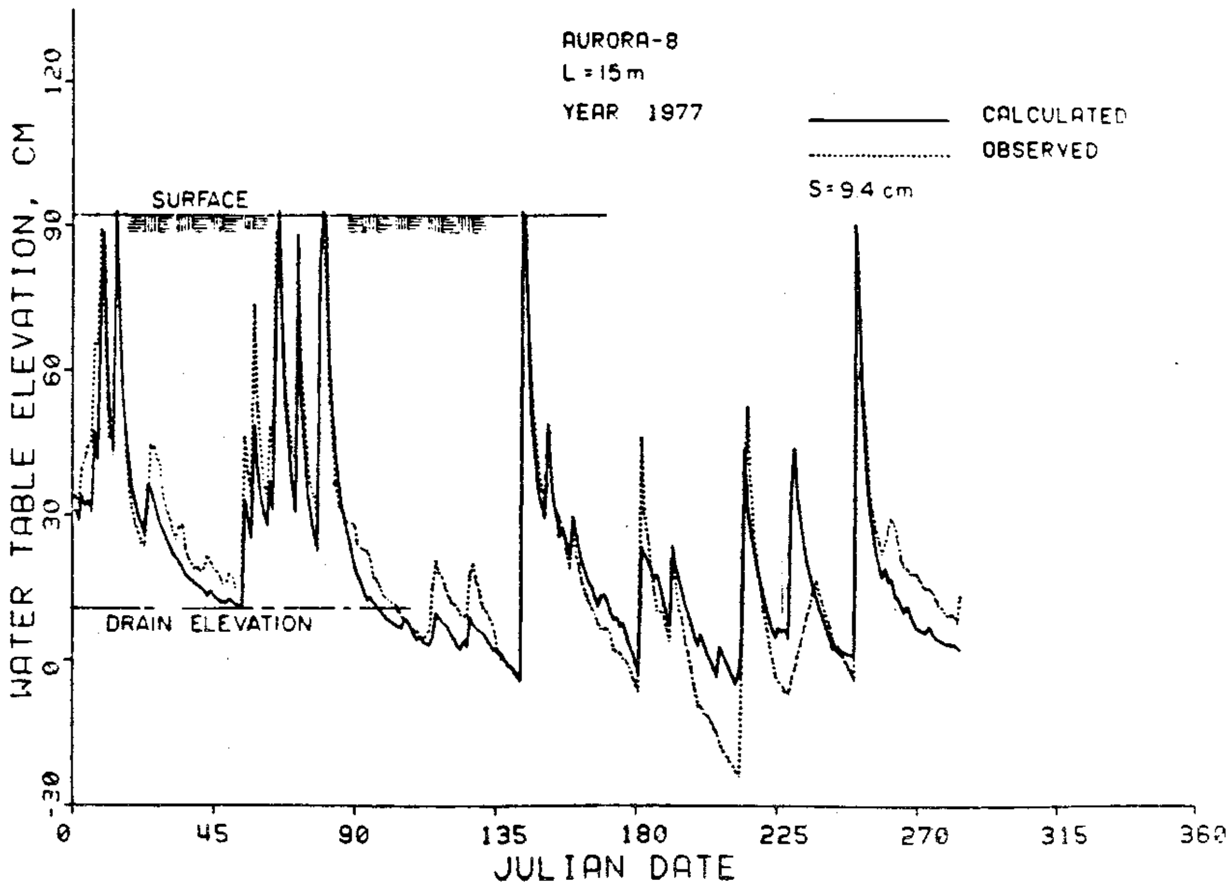


Figure 10-22. Observed and predicted water table elevations midway between drains spaced 15 m apart on the Aurora site during 1977.

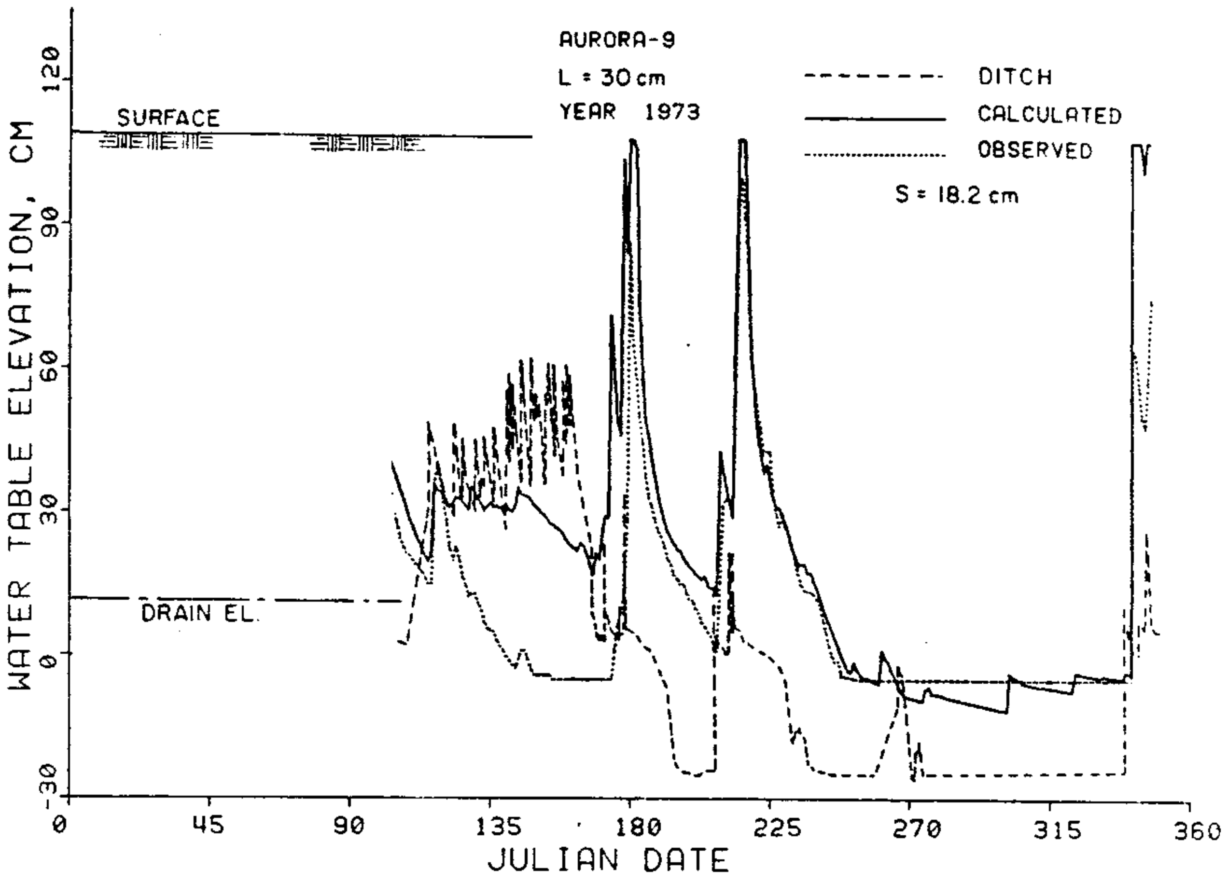


Figure 10-23. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1973.

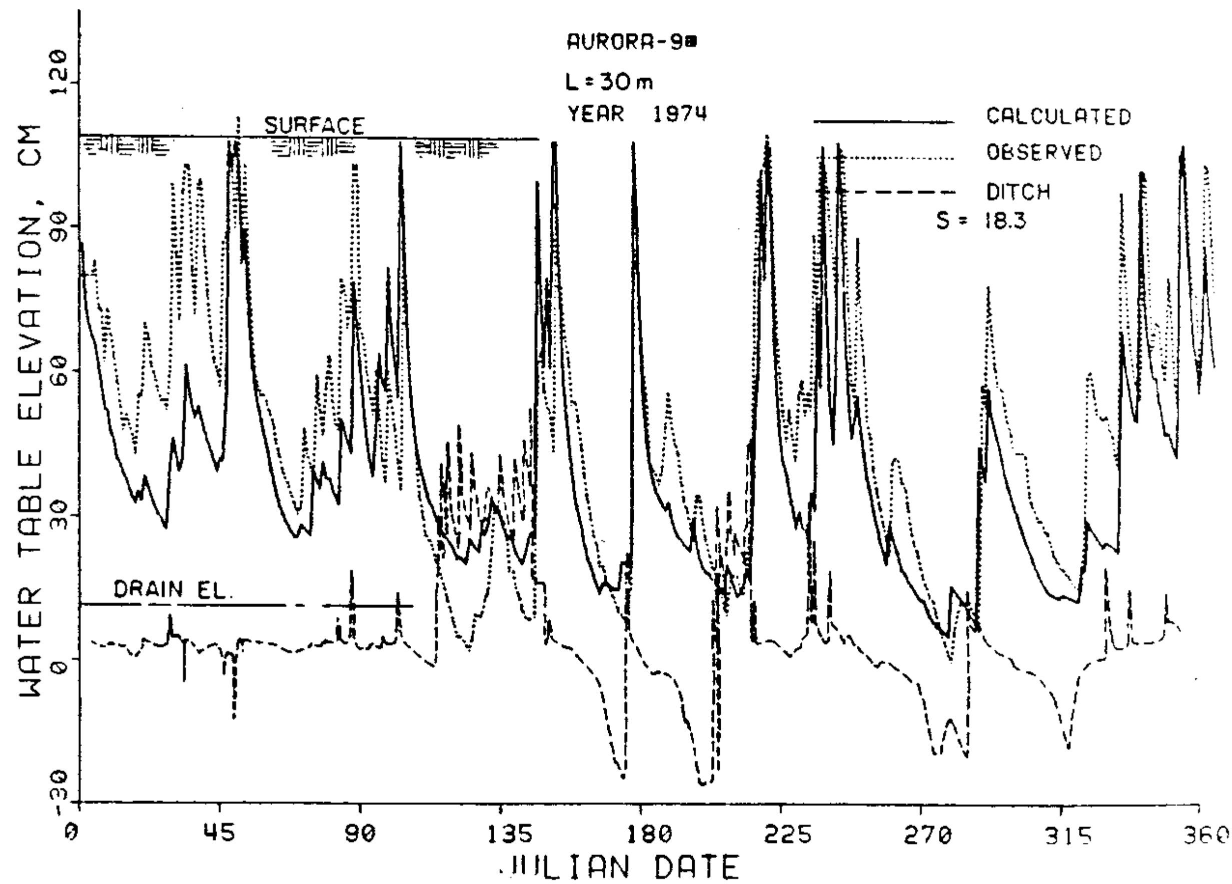


Figure 10-24. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1974.

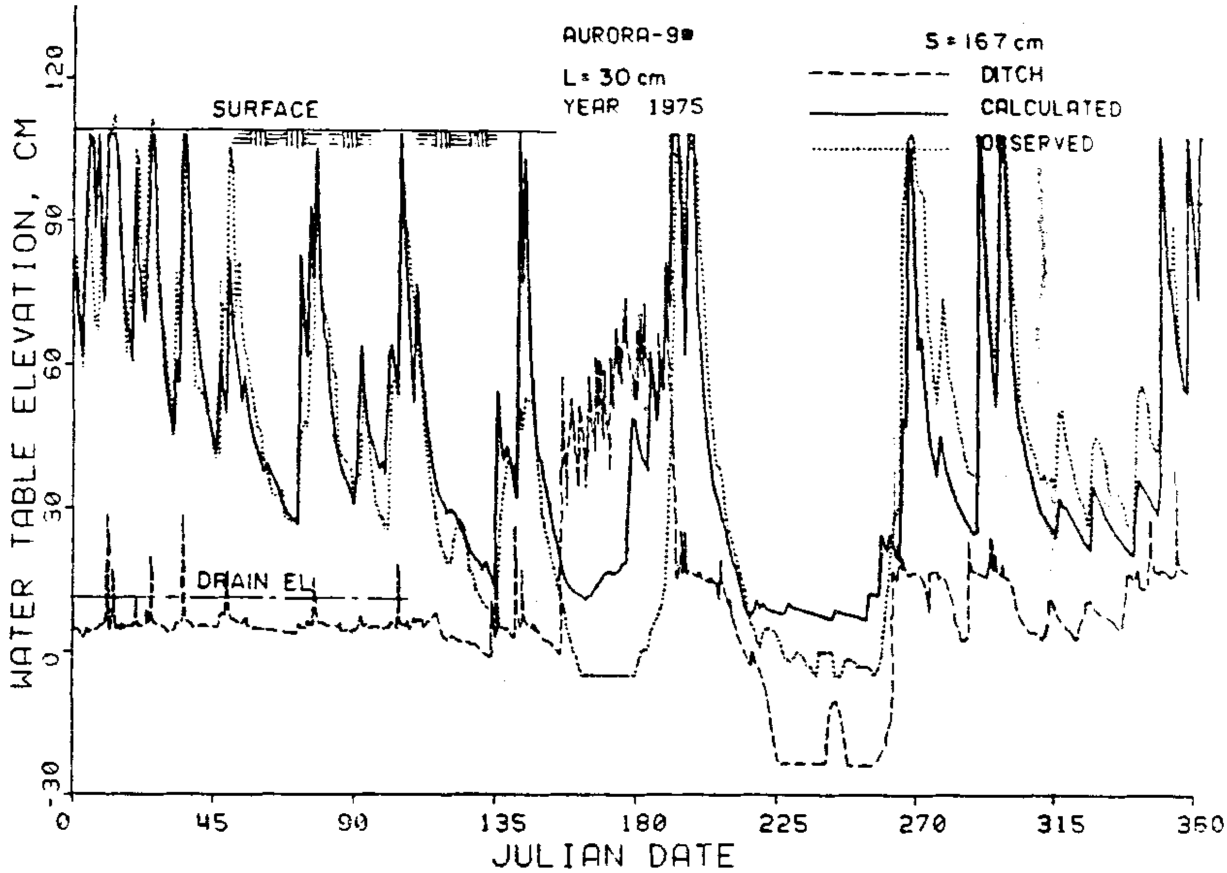


Figure 10-25. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1975.

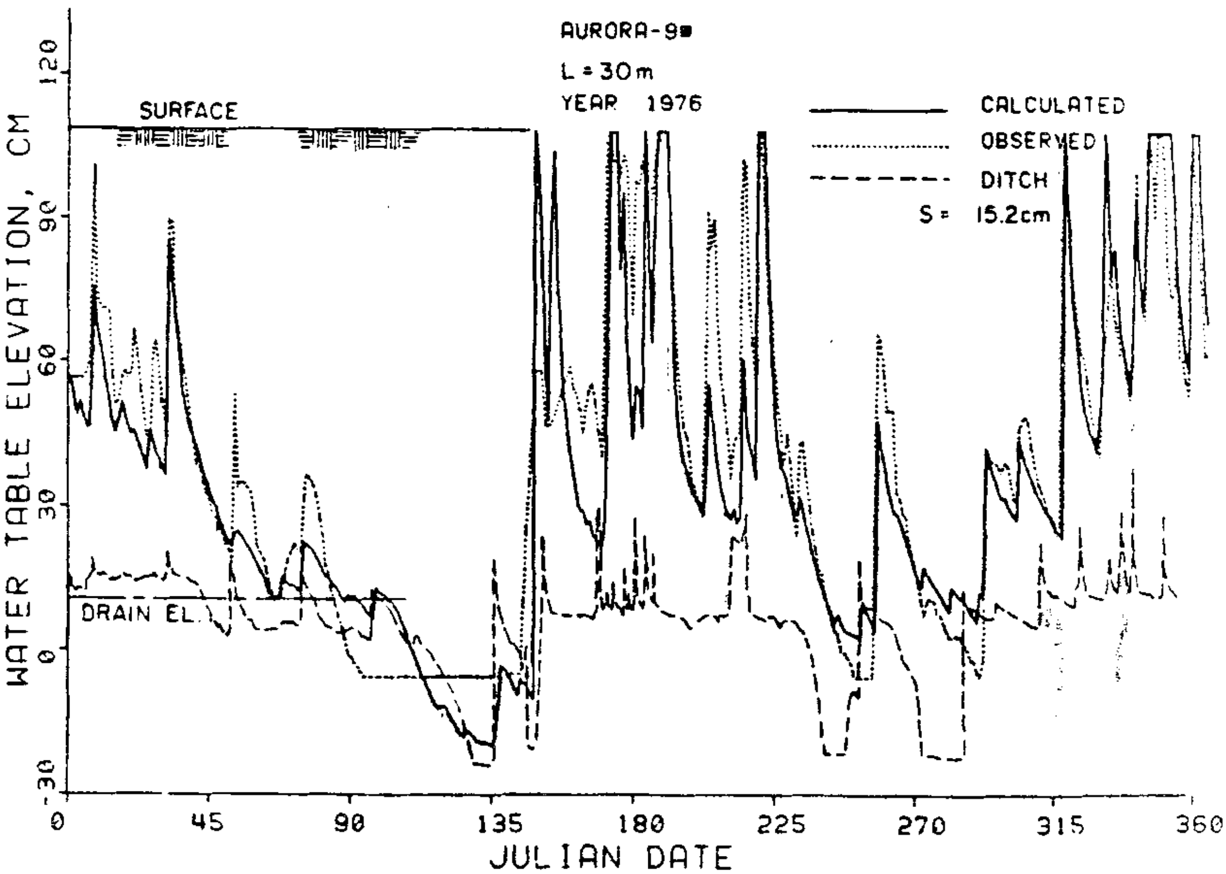


Figure 10-26. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1976.

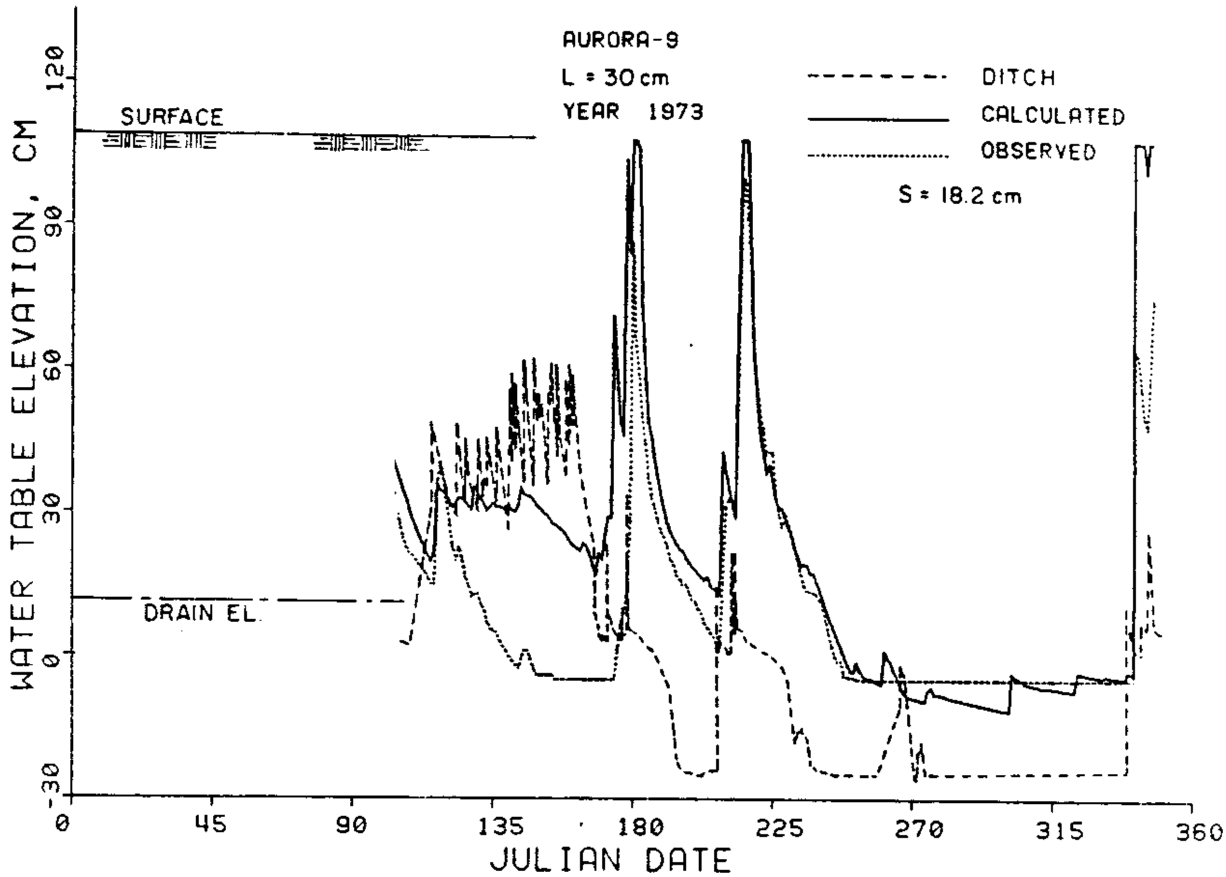


Figure 10-23. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1973.

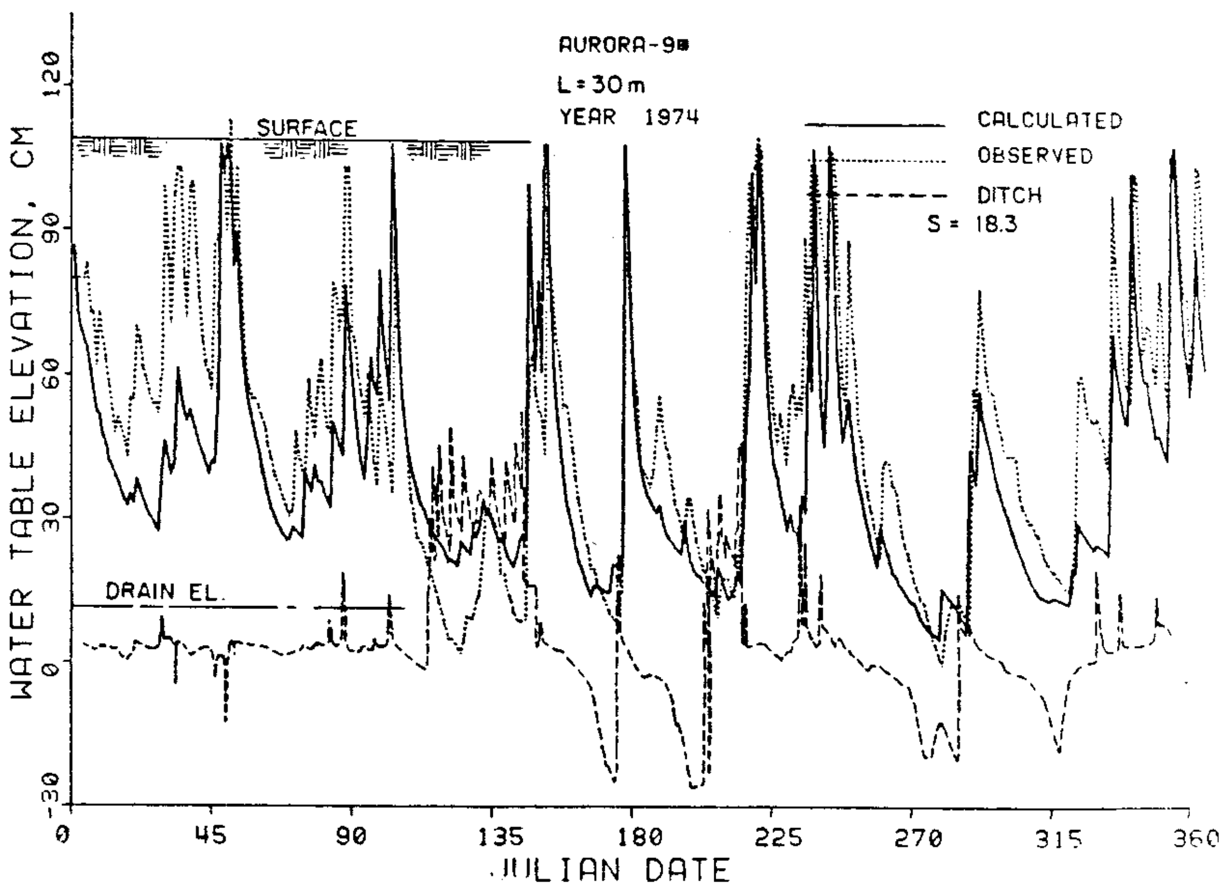


Figure 10-24. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1974.

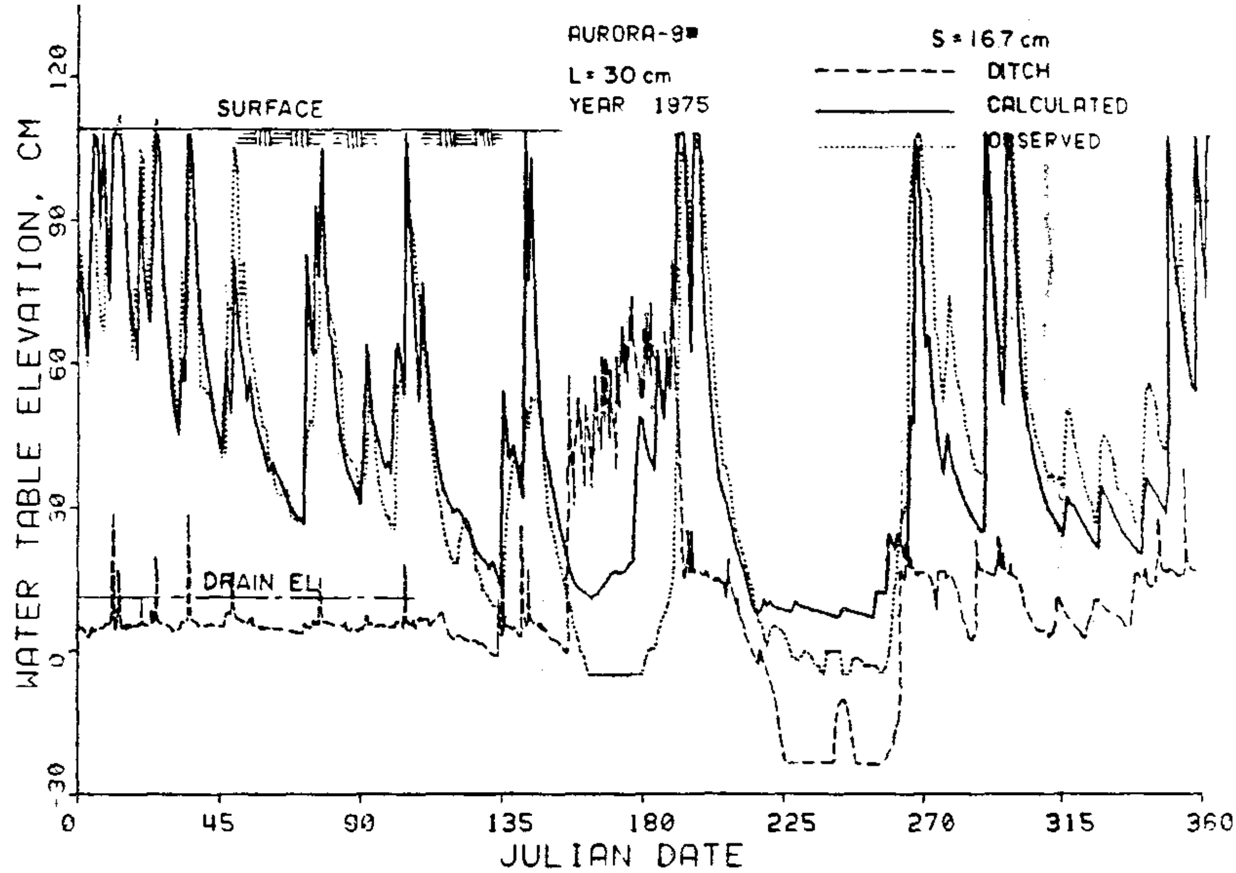


Figure 10-25. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1975.

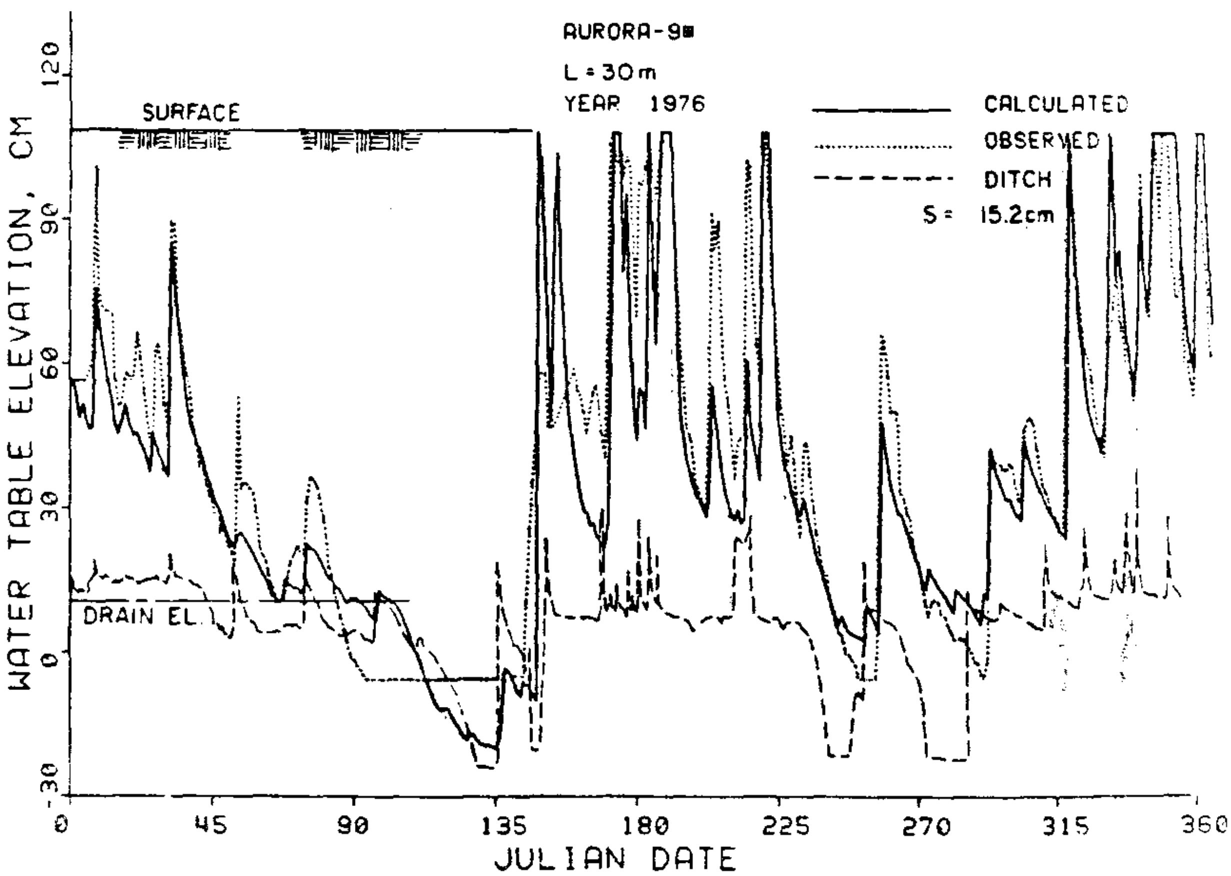


Figure 10-26. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1976.

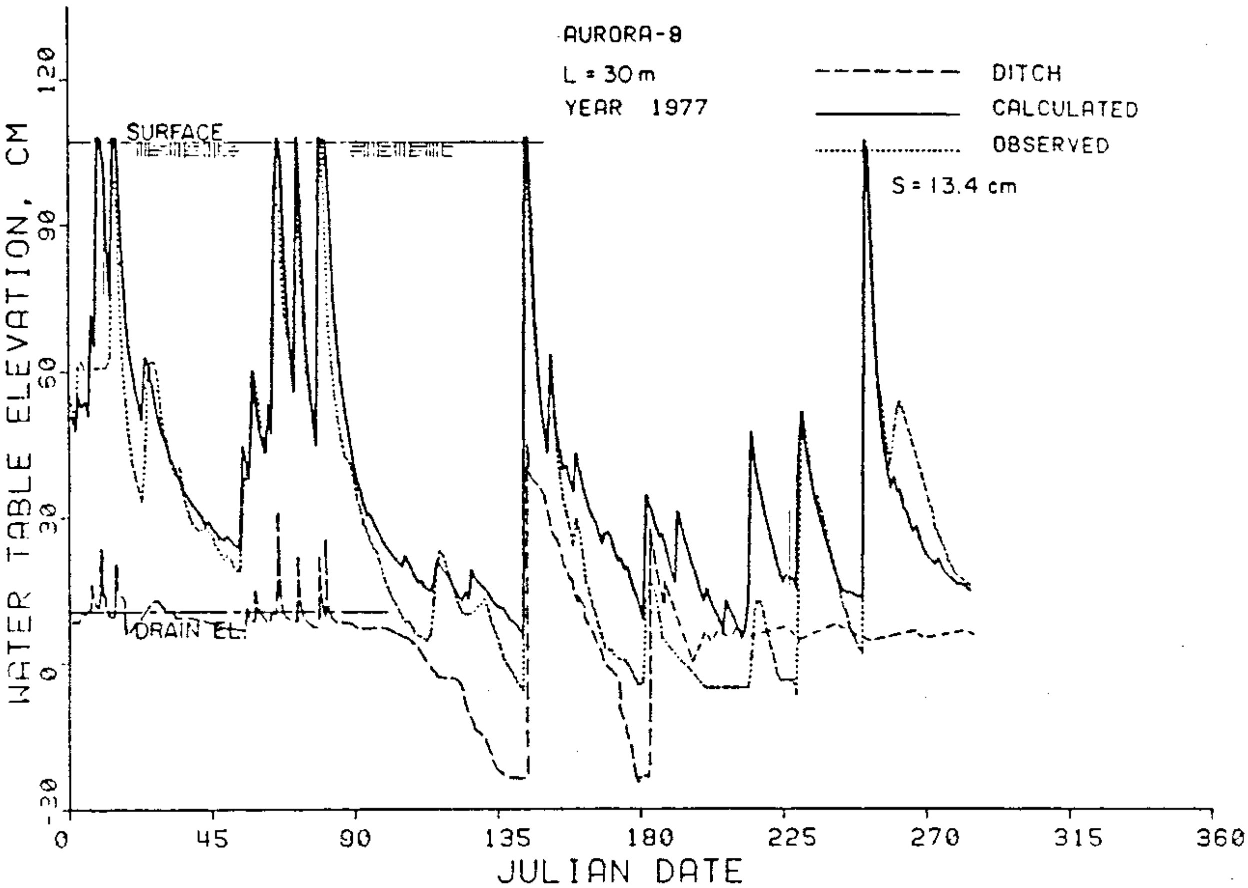


Figure 10-27. Observed and predicted water table elevations midway between drains spaced 30 m apart on the Aurora site, 1977.

Table 10-8. A summary of standard errors of estimate (cm) and average deviations (cm) for comparison of observed water table elevations with predictions by DRAINMOD.

Site	1973		1974		1975		1976		1977	
	s	a.d.	s	a.d.	s	a.d.	s	a.d.	s	a.d.
	All units in cm									
Aurora										
L = 7.5 m	14.2	11.8	11.2	9.0	11.3	8.2	16.1	12.1	7.5	5.7
L = 15 m	15.0	13.4	19.6	16.1	16.4	13.2	17.4	13.2	9.4	7.1
L = 30 m	18.2	13.3	18.3	14.4	16.7	12.1	15.2	10.9	13.4	10.3
Plymouth	10.4	7.7	9.6	6.3	9.8	7.6	8.7	6.3	8.6	6.7
Laurinburg	—	—	—	—	—	—	13.9	11.6	—	—

between drains. This is particularly true when subirrigation is initiated during dry soil conditions. This is consistent with the results given in Figures 10-25 for the 30 m spacing and Figure 10-20 for the 15 m spacing. In both cases the observed midpoint water table continued to recede, mostly due to ET, after the ditch water level was raised and did not reverse its downward trend until nearly 30 days later when rainfall occurred. This was not the case for the 7.5 m spacing which responded quickly to the raised water table as predicted by the model (Figure 10-15).

The model predicts an immediate response to subirrigation because flux is calculated with the Hooghoudt equation in terms of the water table elevation at the midpoint and the water level in the drain. No allowance is made for the time lag required to change from a drainage profile to a subirrigation profile which may be several days for large drain spacings. Everything else being equal, the time lag is proportional to the square of the drain spacing. It should be emphasized that the problem with the model in this respect occurs during the transition period from drainage to subirrigation or vice versa. Once the subirrigation profile is established, DRAINMOD will do a good job in characterizing the water table response (see for example the results for Plymouth, 1974 - Figure 10-9). Errors during the transition periods may also be negligible if the drain spacing is small or if hydraulic conductivity is high.

Predicted and observed results are in good agreement for all three spacings on the Aurora site with a maximum s value of 19.6 cm for the 15 m spacing during 1974 and a minimum s value of 9.4 cm for the 15 m spacing in 1977. The predicted water table drawdown rate was usually higher than the observed and the predicted water table elevations tended to be somewhat lower than measured for both the 7.5 and 15 m spacings (Figures 10-13 through 10-22). This could have been caused by a K value which was too high or an erroneous relationship for the drainage volume versus water table depth. However the values selected were based on actual hydraulic conductivity measurements and the same K values were used for the 30 m spacing which had about the same predicted drawdown rate as measured. Results of hydraulic conductivity tests indicated that the effective K of the profile should be smaller for the 7.5 and 15 m spacings than for the 30 m spacing (Table 10-3). These differences were thought to be due to a thicker sandy layer for the 30 m profile. The results given in 10-13 through 10-27 indicate that the conductivity of the individual layers for the 7.5 and 15 m spacings may be smaller than that for the 30 m spacing. If fact, trial runs showed that agreement between predicted and observed results can be improved considerably by using a lower K value for the 7.5 and 15 m spacings. However, such values were not obtained from hydraulic conductivity measurements so their use would not provide a fair test of the validity of the model as discussed earlier in this section. In any event, the agreement between observed and predicted results for all spacings (Figures 10-13-10-27) is considered excellent for field conditions.

Laurinburg

Observed and predicted water table elevations are plotted in Figure 10-28 for the Laurinburg site during 1976. This was a very dry year at Laurinburg and the water table did not reach the surface at any time during the year. The total recorded rainfall on the experimental site was only 780 mm versus a normal annual rainfall of about 1200 mm for this area. The agreement between observed and predicted water table depths was good with a standard error of estimate of 13.9 cm for the year. Although subirrigation was possible on the site, it was not used during 1976. The drain depth was 1.07 m so the water table was actually below the drain for a large part of the year. Cotton, which has a relatively deep root system, was grown on the site and the water table was frequently lowered below the drain elevation by ET. The rate that the water table was drawn down by ET was more rapid than observed for the early part of the year, Julian days 45 to 100, but was in good agreement with observations during the peak and latter part of the season, days 180 to 300. Trials with a range of values of hydraulic conductivity showed that, as was the case with the Aurora data, agreement could be improved by reducing K. However the results given in Figure 10-23 which were obtained with independently measured K values, are considered excellent for field conditions.

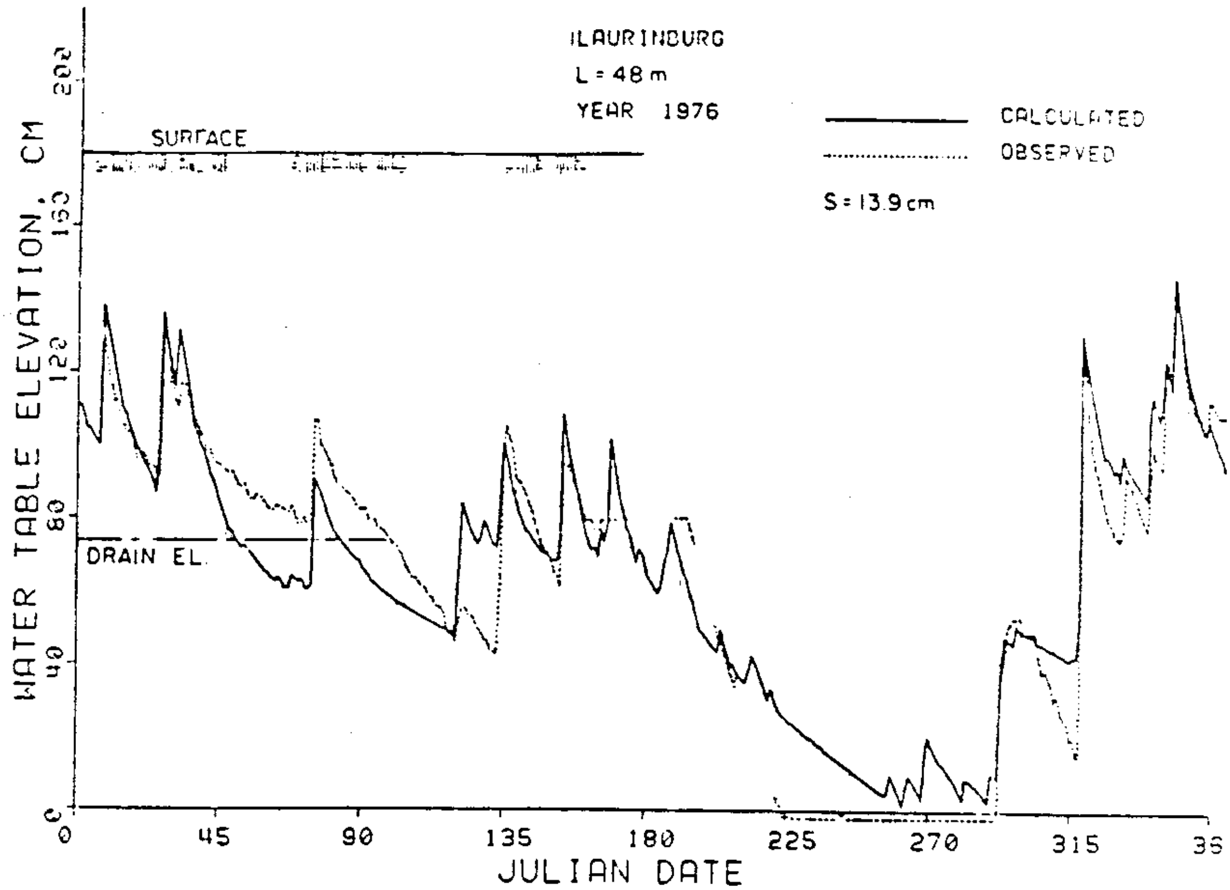


Figure 10-23. Observed and predicted water table elevations midway between drains spaced 48 m apart on the Laurinburg site during 1976.

OHIO

Experimental data were obtained from long-term field drainage experiments at the North Central Branch, Ohio Agricultural Research and Development Center near Sandusky, Ohio (Schwab et al., 1963, 1975). The experiments included replicated plots for subsurface (tile) drainage, surface drainage, and combination surface plus subsurface drainage. Therefore these data can be used to test DRAINMOD for three different drainage system designs. Inputs for DRAINMOD were obtained from soil property data and climatological records and the performance of the drainage systems was simulated for a total of eight years. Comparisons between measured and predicted surface and subsurface drainage volumes were made and used as a basis for judging the validity of DRAINMOD for North Central Ohio conditions. Results of this investigation were reported in a paper by Skaggs, Fausey and Nolte (1979) and are given in this section.

Experiments

Experimental Site

This field experiment was installed at the North Central Branch, Ohio Agricultural Research and Development Center near Sandusky, Ohio in 1958. The field installation consisted of plots having tile only, surface only, and a combination of tile and surface drainage. There were four replications. Each plot was 37 by 61 m (0.55 acres) and was surrounded with an earth dike so that surface water could not enter or leave the plots except through the flow measuring device. The tiled plots contained three 100 mm diameter concrete tile lines with a spacing of 12 m and depth of about 1 m. Tile flow was measured from the center line only. The tile-only plot had a level surface, while the surface-drained and combination-drained plots were graded to a slope of about

0.35 percent along the short dimension of the plot. The surface water was collected in a surface drain and carried to the measuring station.

Soils

The predominant soil type at the experimental site is Toledo silty clay, a Mollic Haplaquept, fine. The remaining 20 percent is classified as Fulton silty clay, which occurs at elevations 15 to 20 cm higher than the Toledo. These soils are typical of the fine-textured soils that occur in the lake region of North Central United States. They are on flat or nearly level topography, are high in clay, require drainage, and are difficult to manage. The hydraulic conductivity decreases rapidly with depth as does the 60-cm porosity.

The Toledo soil contains 45 to 50 percent clay in the plow layer. The clay contents approach 60 percent clay in the lower B horizon at about 50 to 75 cm depths. This soil is classified as being "very slowly permeable". Its hydraulic conductivity is greatly influenced by the large number of cracks that form upon drying and the rate at which they are closed by subsequent wetting. Root channels also appear to greatly influence the conductivity. The Fulton soil has a slightly higher clay bulge than the Toledo, the former having clay contents of 62 percent in the lower B horizon. It is classified as being less permeable than the Toledo, particularly in the upper B horizon. As with the Toledo, cracking and root channels also greatly influence its hydraulic conductivity.

Experimental Procedure

Tile and surface flow data were recorded continuously for the growing season (March 1 to September 30) each year. Excess water was applied twice each year in May, June, or July to provide a repeatable 10-year return period storm. Drain flow data for the eight years (1962-64 and 1967-71) were used in this analysis because the same crop (corn) was grown during these years.

Model Input Data

Climatological Data

Hourly precipitation data were recorded on the site during the months of March - September. Daily precipitation data for the remaining months were obtained from the nearby National Weather Service Station at Sandusky, Ohio. The lack of hourly data for these months was not critical because tests of the model were based on comparisons for April through September only. Daily maximum and minimum air temperatures used to estimate potential ET by the Thornthwaite method were obtained from the same station.

Soil Properties

Some of the physical and hydraulic soil properties needed in the model are available from previous publications by Schwab et al., 1963, Taylor et al., 1961. Other inputs such as infiltration equation coefficients and upward flux relationships were estimated from available unpublished data.

Soil water characteristics. Data were compiled by Fausey (1975) and are plotted in Figure 10-29. The curve obtained for the 5-15 cm depth increment was used for depths less than 30 cm and that obtained for 50-75 cm depth for profile depths greater than 30 cm. These data were used to calculate the equilibrium relationship between drained volume and water table depth (Figure 10-30) which is also a model input.

Hydraulic conductivity. The effective saturated hydraulic conductivity (K) was determined for the experimental site from drain outflow and water table draw-

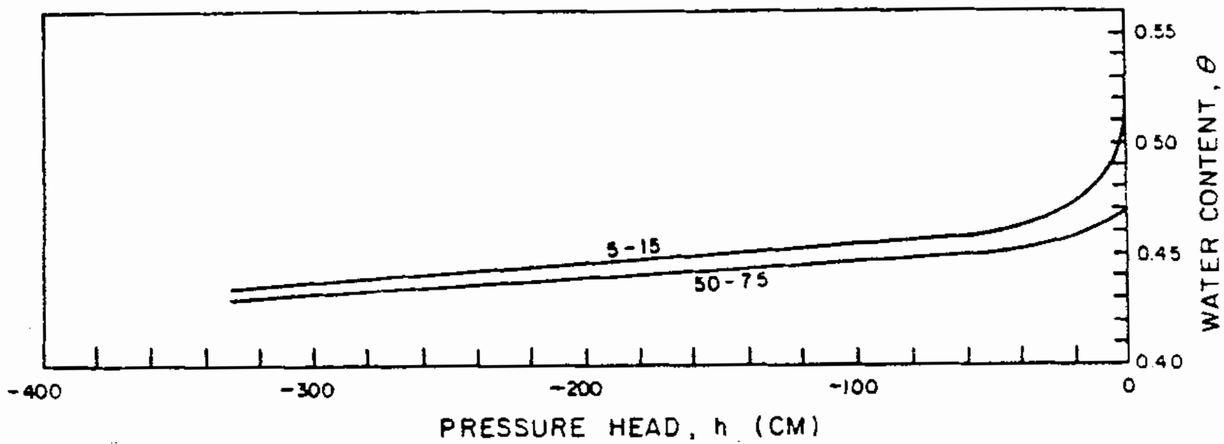


Figure 10-29. Soil water characteristics for two depths of the Toledo soil.

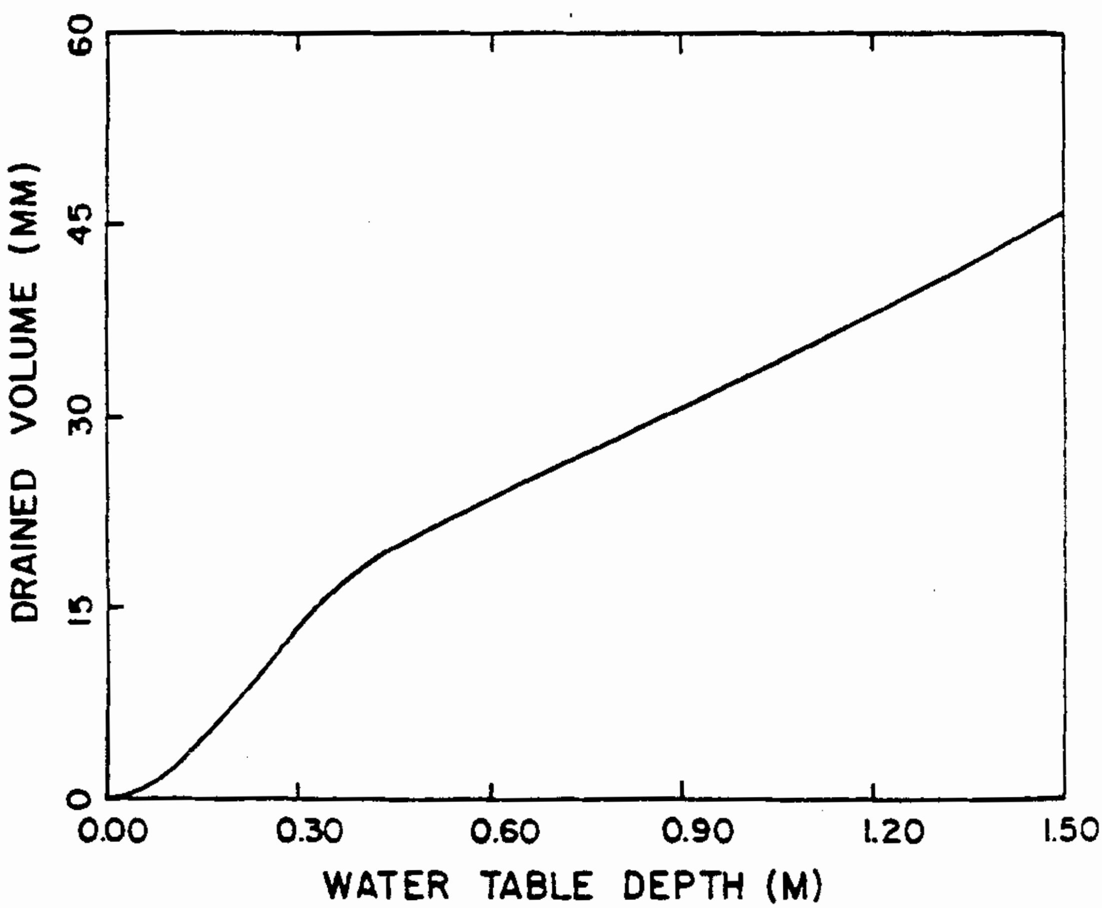


Figure 10-30. Drainage volume as a function of water table depth as calculated from the soil water characteristic.

down data by Hoffman and Schwab (1964). They also determined K by the auger hole method and from soil cores. Their results showed that the effective conductivity of the profile decreased rapidly with depth. The values used in testing the model were taken from Figure 10-32 in Hoffman's and Schwab's (1964) paper and are given in Table 10-9.

Table 10-9. Effective saturated hydraulic conductivity of the soil profile as a function of water table depth (From Hoffman and Schwab, 1964, Figure 10-32).

Water Table Depth	K (cm/h) of Profile
7.5 cm	3.0 cm/h
15	0.85
30	0.32
60	0.053
100	0.01
165	0.01

Upward flux. The relationship between steady state upward flux and water table depth is a model input. This relationship was estimated by solving Eq. 5-5 using explicit finite difference methods as discussed in Chapter 5. The soil water characteristic data (Figure 10-29) were used in the procedure of Millington and Quirk (1960) (as described in Chapter 5) to determine the unsaturated hydraulic conductivity function, K(h). The conductivity function was matched at saturation to the saturated conductivity of the subsoil which was estimated from soil core data of Hoffman and Schwab (1964, Figure 10-32) to be 0.2 cm/hr. Results are plotted in Figure 10-31.

Infiltration parameters. Parameters for the Green-Ampt infiltration equation were determined by methods proposed by Mein and Larson (1973) and Brakensiek

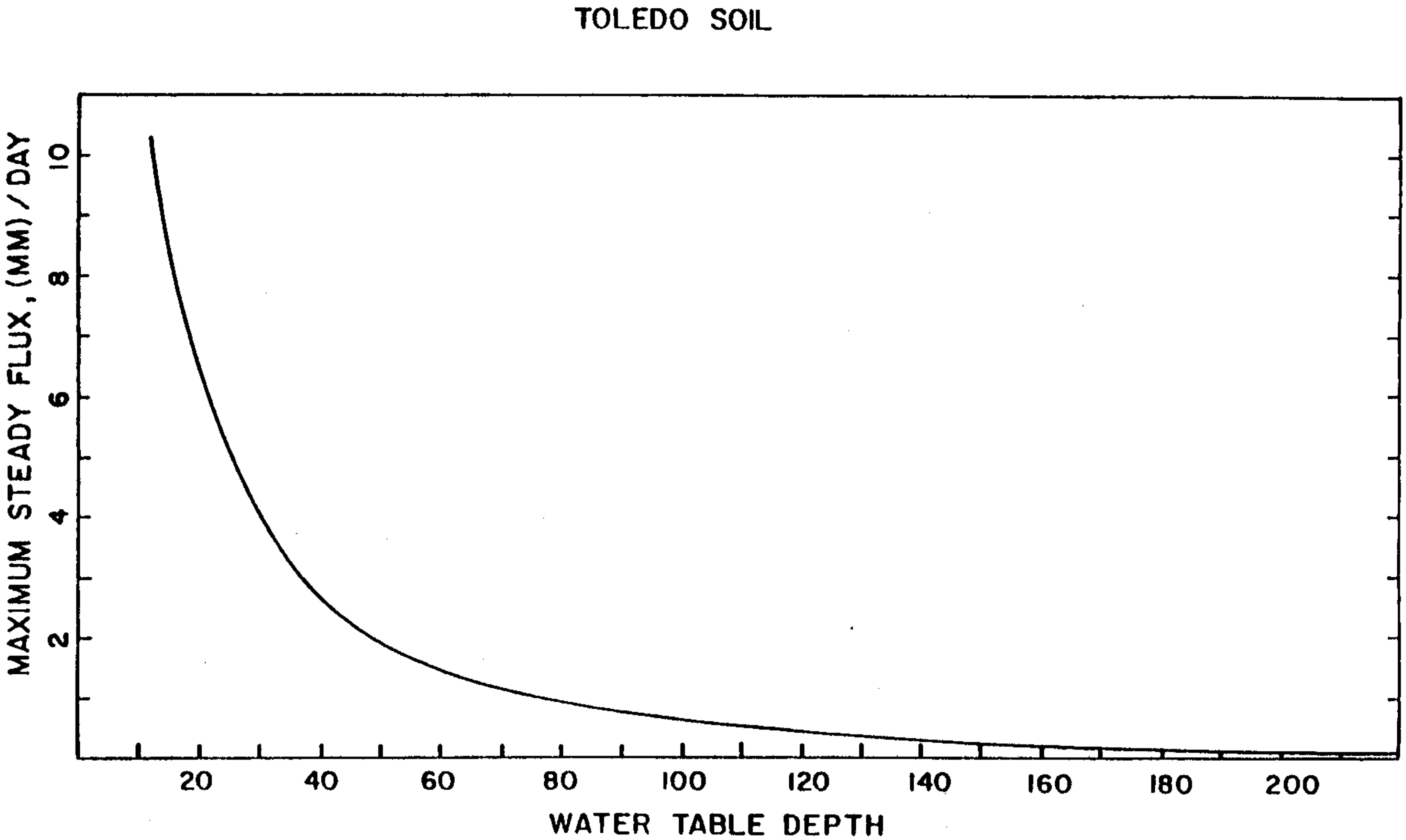


Figure 10-31. Maximum steady upward flux was calculated from numerical solutions of Eq. 5-5 as a function of water table depth.

(1977) as discussed in Chapter 5. Values for A and B are given as a function of water table depth in Table 10-10. The A and B values were determined from properties of the subsoil for initial water table depths less than 100 cm. Deeper initial water tables are usually accompanied by a dry zone at the surface so the properties of the surface layer were used to obtain A and B for water table depths greater than 200 cm.

Table 10-10. Parameters for the Green-Ampt equation for various water table depths at the start of rainfall.

Water Table Depth (cm)	$A = K_s M S_{av}$ (cm^2/h)	$B = K_s$ (cm/h)
0	0	0.4
20	0.55	0.4
50	0.70	0.4
100	0.85	0.4
200	1.90	4.1
500	1.90	4.1

<u>Crop Data</u>

Effective root depth as a function of time is a required input for the model. The effective root depth for corn was estimated from the data of Mengal and Barber (1974) and Foth (1962) as discussed in Chapter 2. The maximum effective root depth was taken as 30 cm. It was assumed that water could be removed from the top 3 cm of soil by evaporation so the minimum effective root depth was taken as 3 cm.

<u>Drainage System Parameters</u>

Input data describing the drainage system are summarized in Table 10-11. These data are used in combination with soil property data to compute drainage flux, surface runoff, etc. in the computer simulation process.

Table 10-11. Summary of input parameters for the experimental drainage system.

Parameters	Subsurface Drainage Alone	Surface Drainage Alone	Combination Surface and Subsurface Drainage
Drain Spacing	1220 cm	-	1220 cm
Drain Depth	90 cm	-	90 cm
Equivalent Depth from Drain to Impermeable Layer	75 cm*	-	75 cm*
Equivalent Profile Depth	165 cm	180 cm	165 cm
Depth of Surface Storage	15 cm	0.25 cm	0.25 cm
Surface Slope	0.0%	0.35%	0.35%
Drain Diameter	10 cm	-	10 cm

Evaluation Procedure

Surface runoff and drain flow data were recorded for the period March 1 to September 30 each year. However the March data were inconsistent due to start-up problems during some years, so the evaluations are based on the period April 1 to September 30. Precipitation data were available for all months and preliminary simulations were conducted for January 1 to March 31 to predict initial conditions for the tests beginning April 1. Simulations were conducted for all four replications on three drainage treatments (surface, subsurface and combination) for each of the eight years. Predicted and measured tile flow and surface runoff volumes were compared to evaluate the accuracy of DRAINMOD for the given conditions. Comparisons were made on the basis of both daily and cumulative runoff volumes. However, either tile flow or surface runoff occurs on only

*This equivalent depth was used by Hoffman and Schwab (1964) to obtain the K values in Table 10-9 so it is also used in the simulation.

a few days during the growing season so comparisons for daily flow volumes involve numerous zero values for both predicted and observed. This is not the case with cumulative volumes and the evaluations are mainly based on these values.

The agreement between predicted and measured cumulative flow volumes was quantified by computing the average deviation over the season as,

$$\text{a.d.} = \sum_{i=1}^{n} |\hat{Y}_i - Y_i| / n \qquad (10\text{-}3)$$

where $\hat{Y}_i$ is the predicted cumulative drainage or runoff volume and Y_i is the observed value on day i; n = 183, the number of days from April 1 to September 30. A problem with comparing cumulative flow volumes in evaluating the model is that the effect of an error early in the season may be carried over the entire duration. For example, if predicted drain flow is 2 cm too high on the first day of the test but predicted and measured values on succeeding days are exactly equal, the average deviation would be a relatively high value of 2 cm.

Results and Discussion

Means of the average deviations for cumulative flow volumes for all four replications are given in Table 10-12. Values are tabulated for each year for surface drainage plots, subsurface drainage plots, surface drainage from the combination plots and subsurface drainage from the combination plots. Agreement between measured and predicted outflow volumes was good for all treatments with values ranging from a low of 0.92 cm to a maximum of 4.3 cm. These results seem particularly good when field variability and the approximate nature of many of the model inputs are considered.

Table 10-12. Average deviations (a.d.) as defined in Equation 10-3 between observed and calculated outflow volumes. Each value is the mean of deviations for four replications.

Year	Surface Drainage		Subsurface Drainage		Combination Plots: Surface Runoff		Combination Plots: Subsurface Drainage	
	a.d.	percent of total*	a.d.	percent of total*	a.d.	percent of total*	a.d.	percent of total*
1962	1.29 cm	18.4	0.94 cm	8.1	0.97 cm	31.3	1.13 cm	12.7
1963	1.14	17.8	1.43	12.5	1.48	96.0	4.08	33.0
1964	3.70	34.2	3.92	25.0	1.02	31.0	2.08	12.4
1967	1.90	11.4	3.40	23.4	1.10	15.0	4.12	42.0
1968	2.22	13.3	1.54	9.9	1.68	21.2	1.32	13.[illegible]
1969	2.04	4.3	4.32	6.1	2.57	9.2	3.69	14.2
1970	3.52	13.0	3.97	20.0	2.96	22.0	2.15	17.2
1971	0.92	7.6	1.12	9.8	0.99	18.8	1.00	15.7

*Values given for "percent of total" were obtained by deviding the a.d. value by the mean total outflow volume for the test period (April - September).

It is difficult to judge the agreement of predicted and observed results from a single statistic such as the average deviation. Plots representing the best and worst fits of the model for each treatment are given and discussed in the following sections. The reader should note that, the model has not been fitted or matched to the observed data for the same reasons that it was not fitted to the N.C. data discussed on page 10-21. The practical use of the model depends not only on its ability to reliably predict the water table position, drainage rates, etc., but also on the premise that the required inputs can be obtained from soil property measurements, site characteristics and drainage system parameters. That is, it is not anticipated that the model requires "calibration" for a given site and drainage situation, a requirement that would severely limit its usefulness for drainage system design and evaluation. In this study, the input parameters were determined independently, as discussed in previous sections, and the results obtained should be indicative of the model's reliability for field conditions in North Central Ohio.

Surface Drainage

Observed and calculated runoff volumes from plots with surface drainage alone are plotted in Figure 10-32 for 1971. Based on the magnitude of the a.d., these plots represent the best fit of the model to observed results with a.d. = 0.92 cm. The model predicted about the right amount of runoff for all rainfall and irrigation events except for day 230 when surface runoff was predicted but none measured. Closer inspection of the results showed that the predicted water table rose to the surface during this event followed by runoff of about 1.5 cm. The error may have been caused by underestimating ET for the period prior to day 230. Low estimates of ET would have reduced

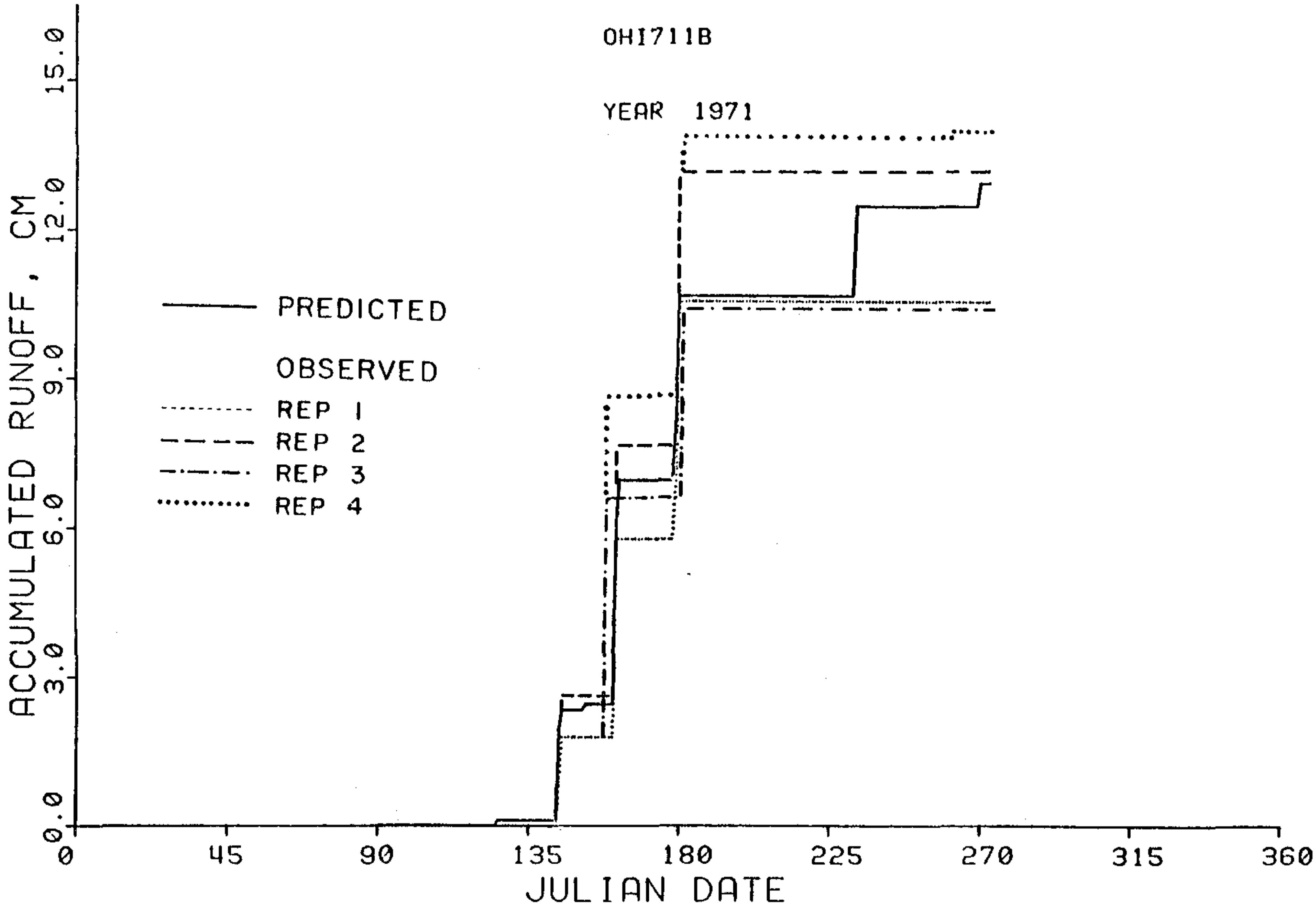


Figure 10-32. Predicted cumulative surface runoff and observed volumes from four surface drained plots during 1971. This case gave the best agreement between predicted and observed results for surface drainage with a.d. = 0.92 cm.

the unsaturated storage volume available for infiltrating water and resulted in erroneous high predictions of surface runoff.

The worst agreement for surface drainage plots was obtained for 1964 (Figure 10-33). In this case the mean a.d. was 3.7 cm which is 34 percent of the total measured runoff (10.8 cm) for the April-September test period. The deviation was mostly due to overprediction of runoff during April (days 90 - 120). April was a relatively wet month (12.95 cm of rainfall) in 1964 and no explanation is given for the low measured runoff volumes during that period. It is noted that predicted daily runoff volumes were rather low and scattered throughout the month. Such low runoff rates are difficult to measure and may not have been accurately metered by instrumentation on the site. Deviations occurring in April are carried over for the rest of the year even though good agreement between predicted and observed daily runoff volumes was obtained after day 120.

Subsurface Drainage

Agreement between predicted and observed results for the subsurface drainage plots was excellent. The best and worst fits of the model are shown in Figures 10-34 and 10-35, respectively. Although the best fit was actually obtained for 1962 (a.d. = 0.94 cm), the results for 1971 (a.d. = 1.12 cm) are plotted in Figure 10-34 representing the best fit. (Results for 1962 were not plotted because each replication was irrigated separately resulting in four separate predicted relationships.) Results for 1971 are in excellent agreement for all replications.

The worst fit for subsurface drainage, as determined from the a.d. values, was obtained for 1969 (Figure 10-35). However, agreement between predicted

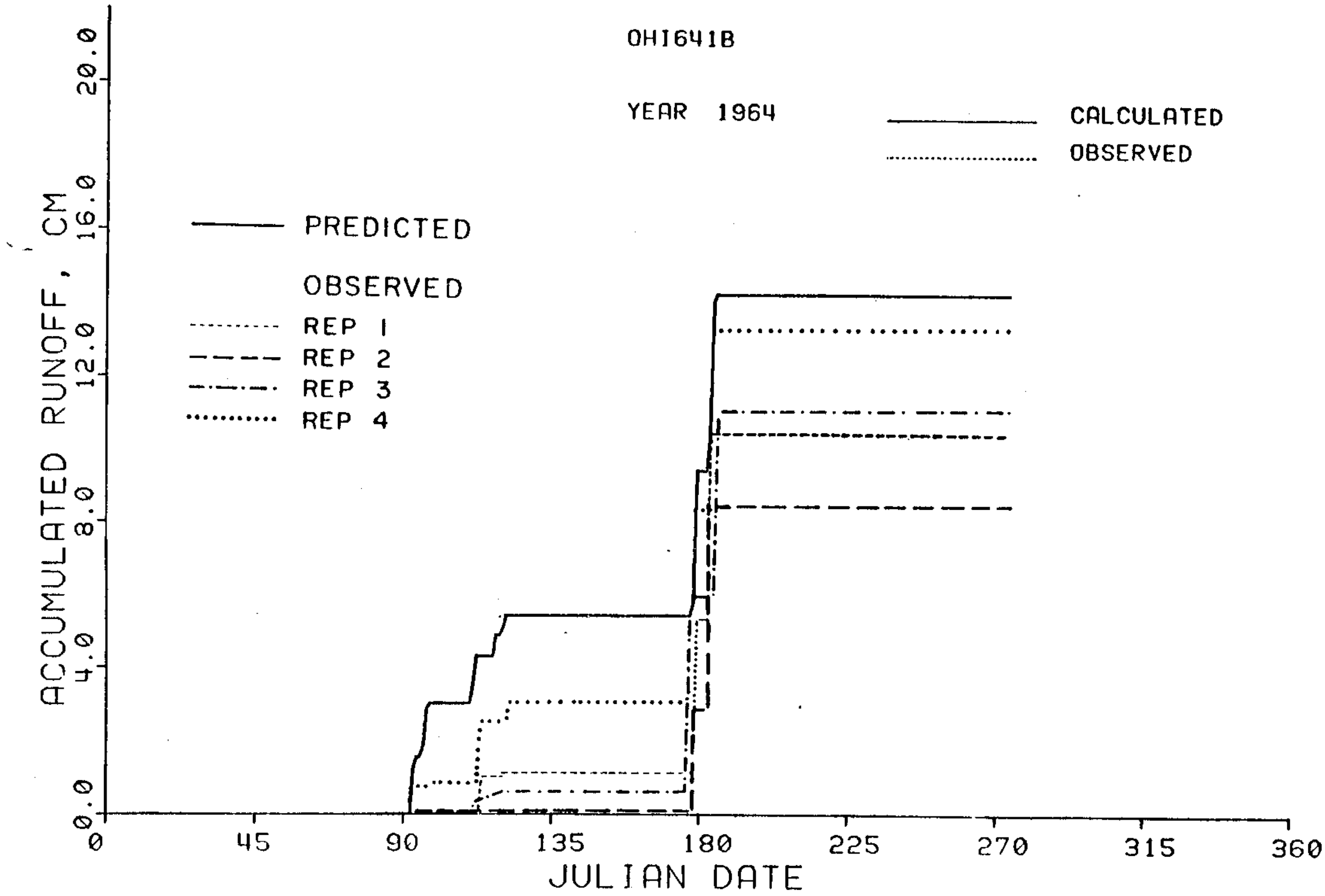


Figure 10-33. Predicted and observed surface runoff from four reps of surface drained plots during 1964. This case gave the worst agreement obtained for surface drainage with an a.d. = 3.7 cm.

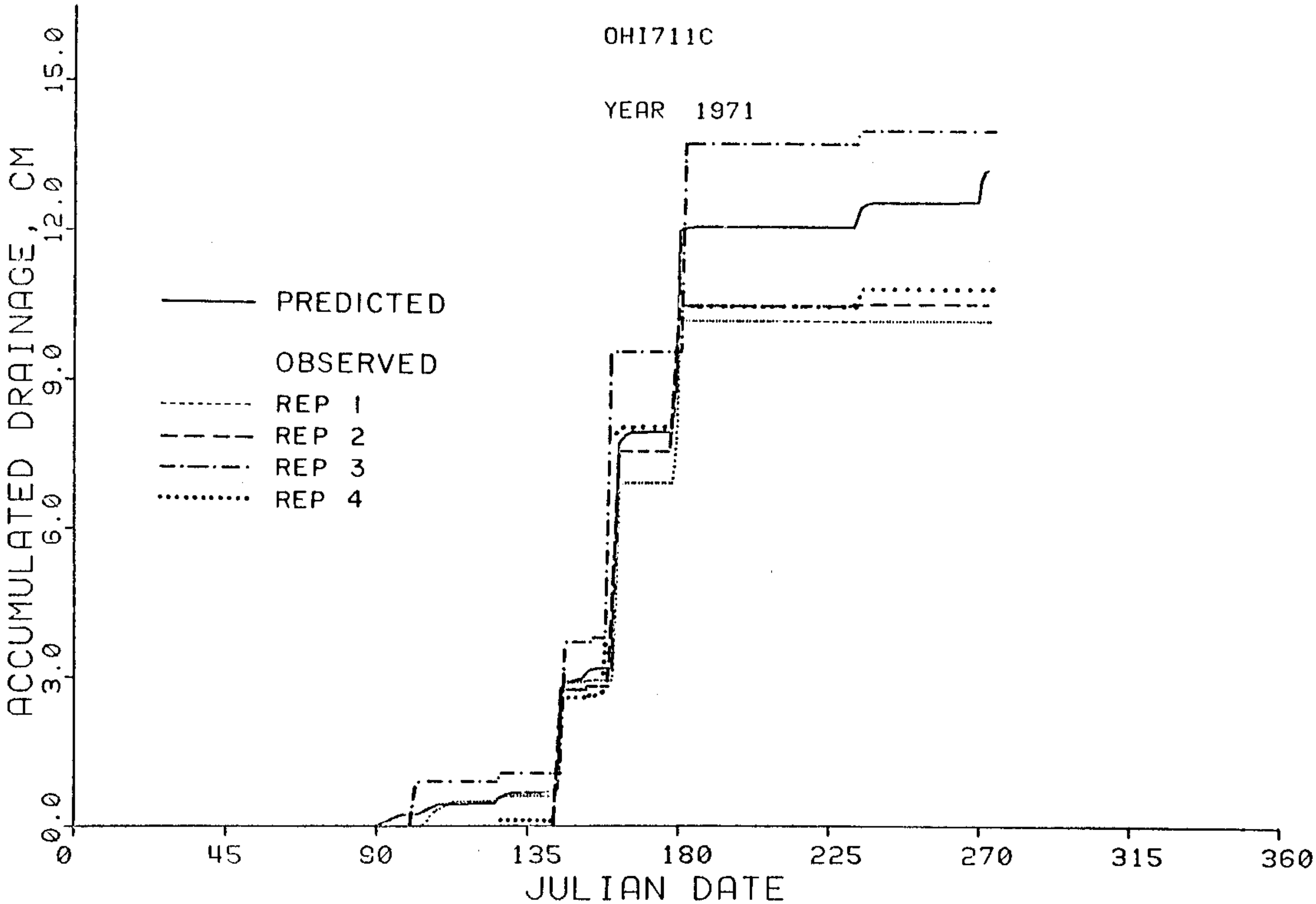


Figure 10-34. Predicted and observed drainage from four subsurface drainage plots during 1971. This case represents the second-best fit obtained for subsurface drainage with an a.d. = 1.12 cm.

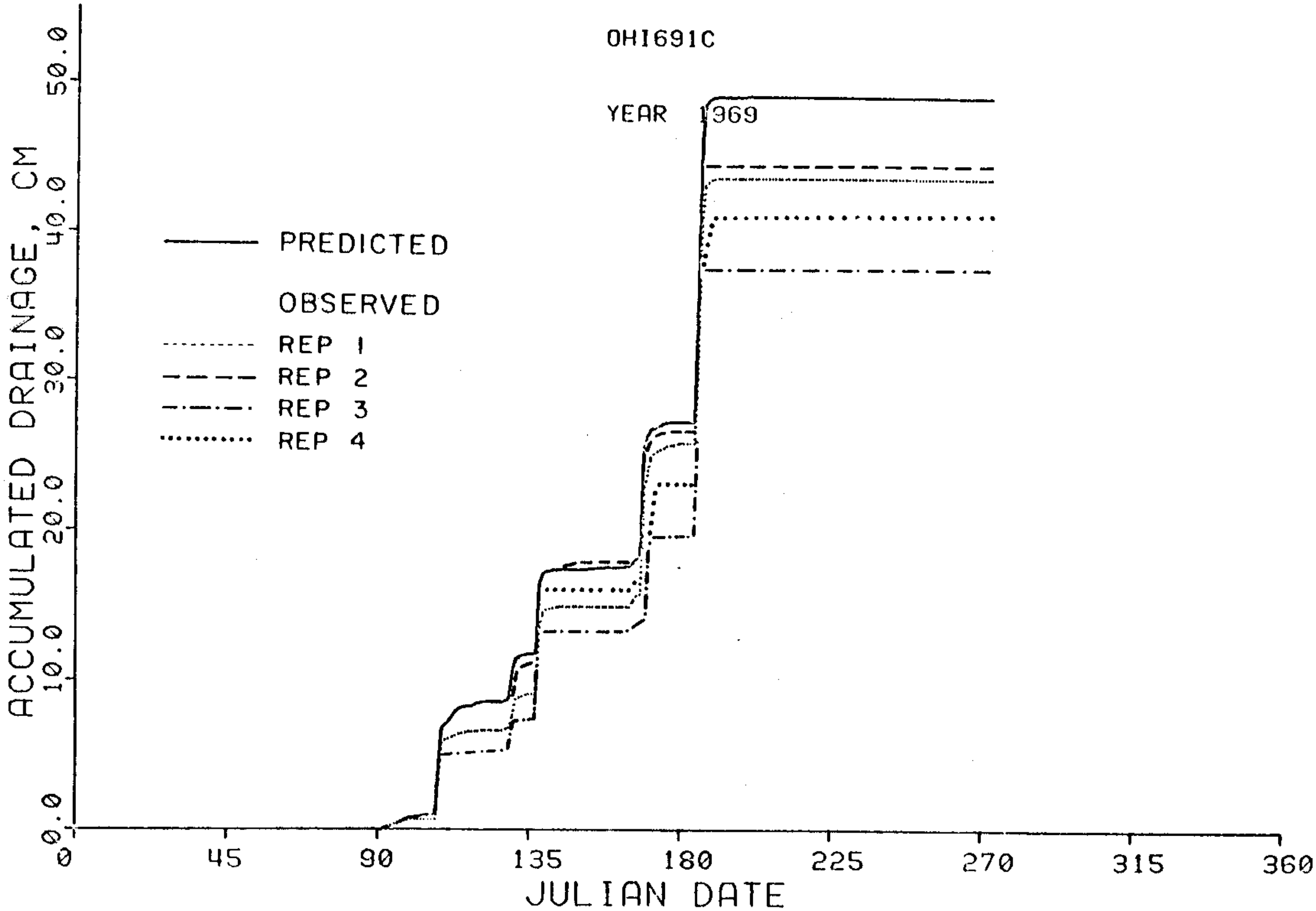


Figure 10-35. Predicted and observed drainage from four reps of subsurface drainage plots during 1969. This case gave the worst fit of the model for the subsurface drainage plots.

and observed results was excellent for most of this year as shown in Figure 10-35. Rainfall was extremely high for 1969 with over 25 cm occurring on July 4 (day 185). The major deviations resulted from that rainfall event and were carried over for the rest of the year (Figure 10-35). Although the mean a.d. was 4.32 cm, it represents only 6.1 percent of the total drainage for 1969.

Combination Surface and Subsurface Drainage

Agreement of observed and predicted results for the combination plots was determined by making comparisons for both surface and subsurface drainage volumes. The best fit of the model for the subsurface drainage component was obtained for 1971 and is shown in Figure 10-36. Corresponding plots for surface drainage for the same year are given in Figure 10-37. There were good agreements in both cases with a.d. = 1.0 cm for the subsurface component and a.d. = 0.99 cm for the surface components. For the combination plots, the overprediction of subsurface drainage was often accompanied by low predictions for the surface drainage and vice versa. Since the a.d. values are based on absolute deviations, the sum of the values for surface runoff and subsurface drainage has no significance and is not indicative of the accuracy of the model for a given year.

The worst fit for the combination plots was obtained for 1967. Results for the subsurface drainage component are shown in Figure 10-38 and those for the surface component in Figure 10-39. Replications 1 and 2 were irrigated at a different time than replications 3 and 4 so there are two predicted relationships for each plot. Predicted cumulative drainage volumes were higher than measured after day 130 for all replications (Figure 10-38). This was primarily due to predicted drainage volumes that were too high for days 129

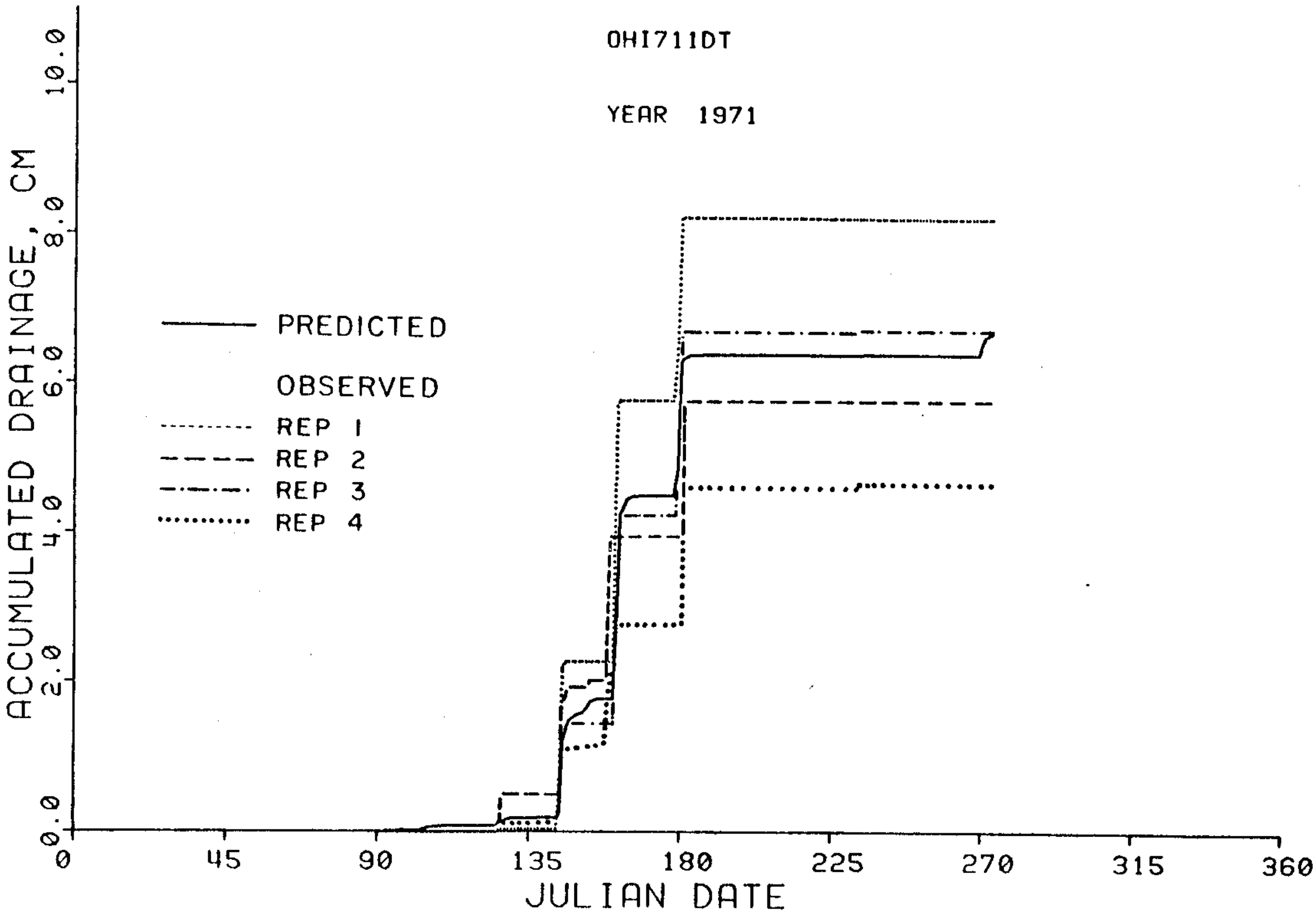


Figure 10-36. Predicted and observed cumulative subsurface drainage from combination surface and subsurface drainage plots during 1971. This case represents the best fit obtained for the combination plots with an a.d. = 1.0 cm.

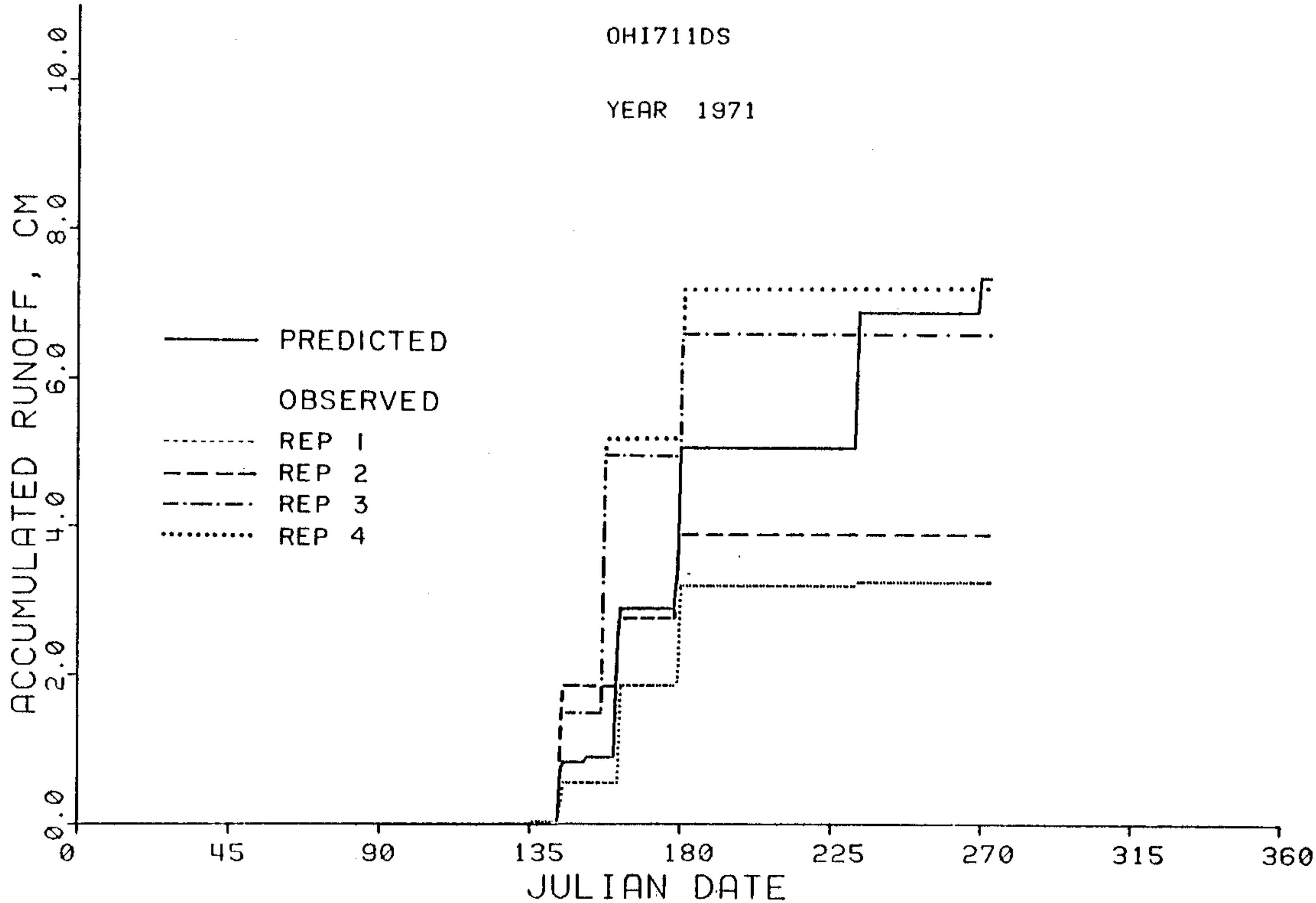


Figure 10-37. Predicted and observed cumulative surface runoff from combination surface and subsurface drainage plots during 1971. The a.d. for this case was 0.99 cm.

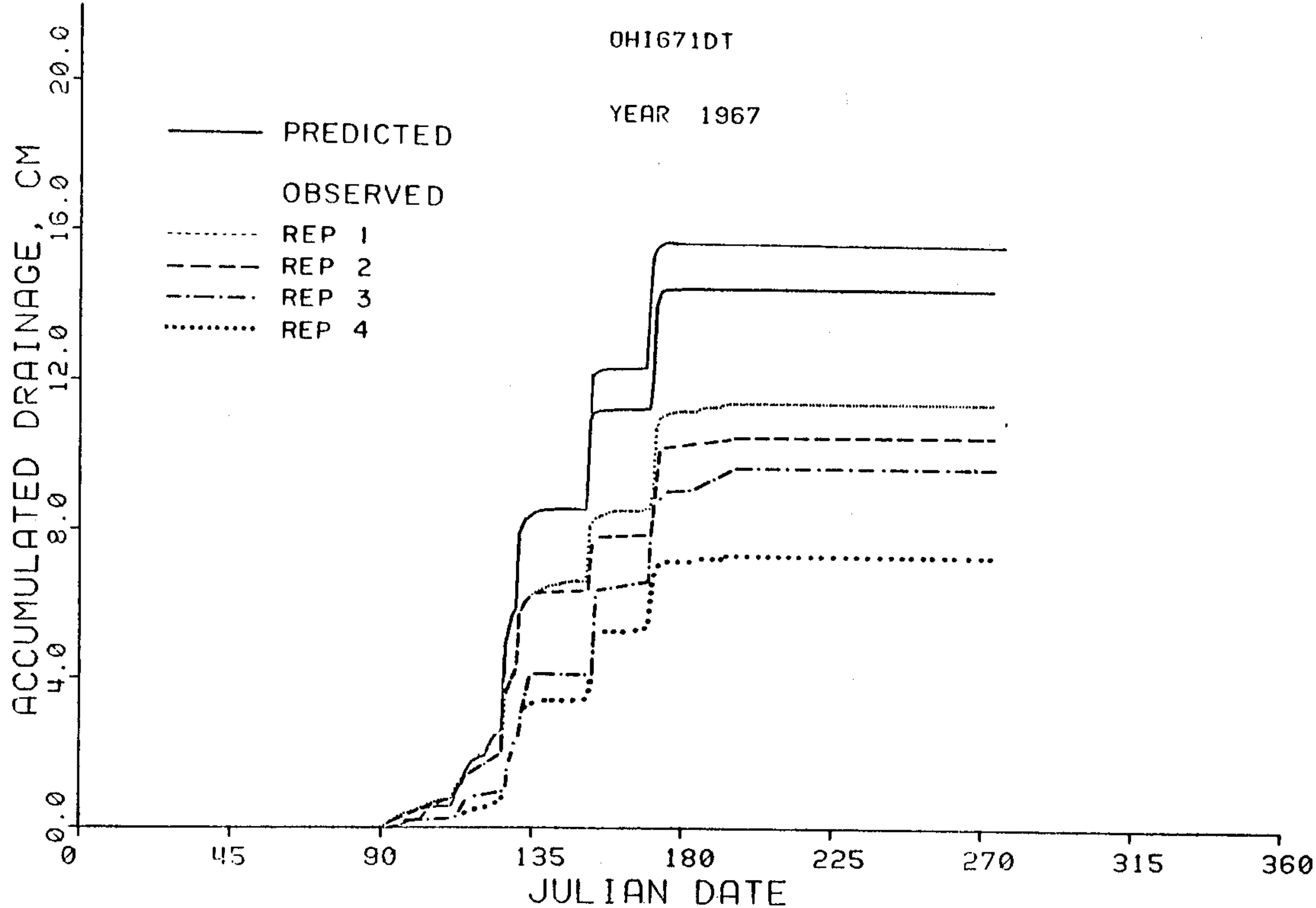


Figure 10-38. Predicted and observed cumulative subsurface drainage from combination surface and subsurface drainage plots for 1967. This case gave the worst fit for subsurface drainage on the combination plots with a mean a.d. = 4.1 cm.

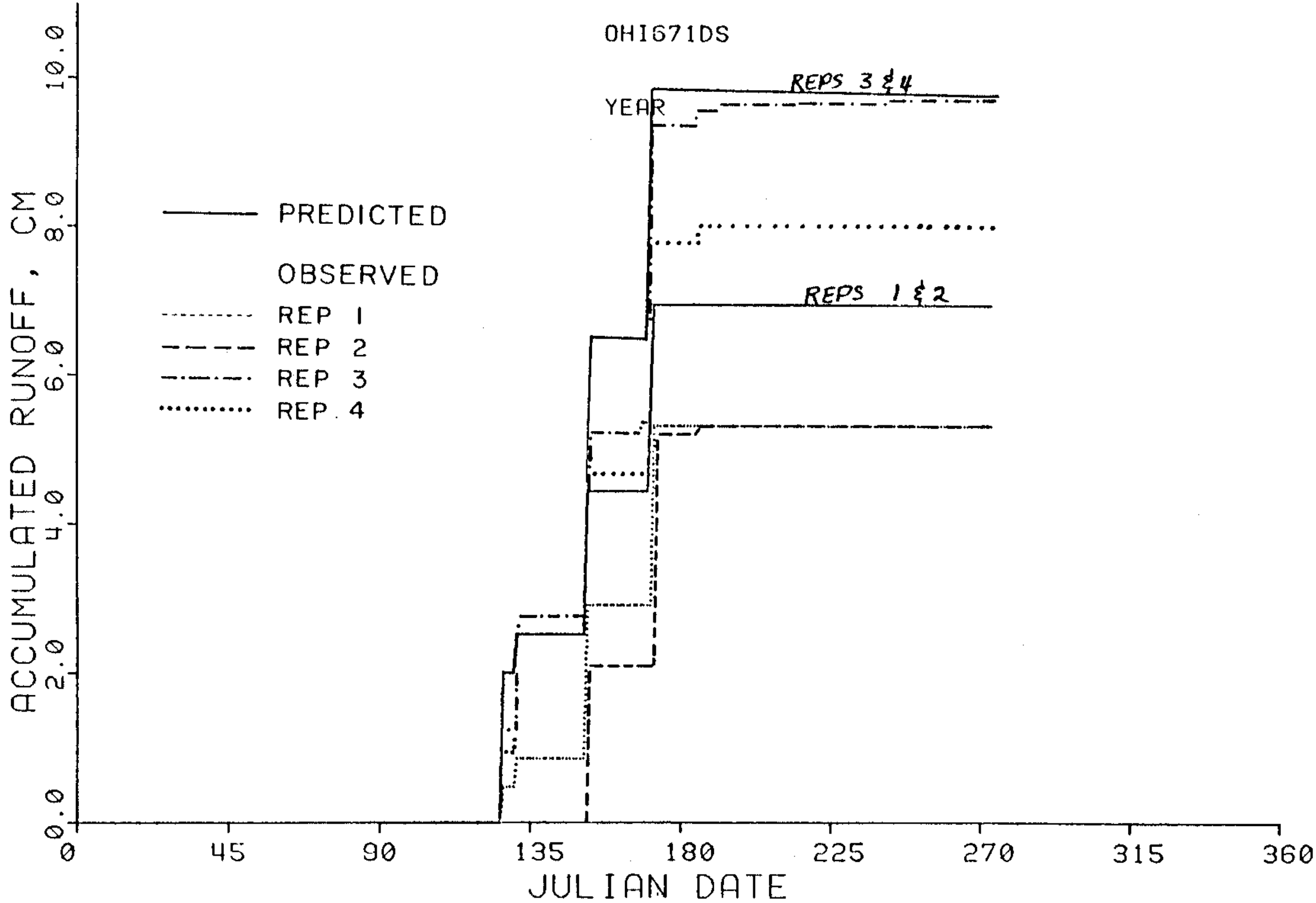


Figure 10-39. Predicted and observed cumulative surface drainage from combination surface and subsurface drainage plots for 1967. Note that there are two predicted curves because Reps 1 and 2 were irrigated at different times than Reps 3 and 4.

and 130. However subsurface drainage was also overpredicted for later events during the year, although by a smaller amount. Examination of Figure 10-39 indicates that, except for replication 3, surface drainage predictions were also too high. Therefore, the problem does not appear to be one of incorrectly partitioning the surface and subsurface drainage components. The deviations could have been caused by low estimates for ET prior to day 129 but there is no way to determine if this was actually the case.

Summary And Conclusions

The water management model DRAINMOD was evaluated for North Central Ohio conditions by comparing predicted and measured drainage volumes for eight years of record. Comparisons were made on four replications of subsurface drainage alone, surface drainage alone and combination plots having both surface and subsurface drainage. Inputs to the model were measured climatological, crop, and soil property data and drainage system parameters for each treatment. Comparisons were made for the months of April through September; corn was grown on the experimental plots for all years considered.

Predicted surface runoff and subsurface drainage volumes were in good agreement with measured values for all three drainage treatments. Comparisons of measured and predicted relationships showed that the times of occurrence of surface runoff and subsurface drainage events were predicted accurately in almost all cases. While there were some deviations in the magnitude of predicted and measured volumes for individual drainage events, they were usually small and, in most cases, were about the same magnitude as the differences between replications.

FLORIDA

Water table and drain outflow data were obtained from the SWAP project (a cooperative project between the USDA-ARS and the Florida Agricultural Experiment Station, Gainesville, Fla.) at Fort Pierce, Florida. The data were obtained through the cooperation of Dr. J. S. Rogers, SEA-AR, at the University of Florida. The field experiments were set up in 1968 to study problems of drainage, water control and citrus tree growth on sandy flatwoods soils. Both water table and drain outflow data for two field plots were obtained and analyzed and the results are presented in this section.

Experiments

Experimental Site

Details of the experimental layout which is located on a 20-hectare experimental watershed were given by Knipling and Hammond (1971). The soils are Wabasso and Oldsmar sands (Alfic Arenic Haplaquods) which consist of a 75 to 90 cm deep A horizon of acid sand underlain by a 10 to 20 cm thickness of an organic horizon called spodic layer, which in turn is underlain by sandy clay loam. Subsurface drains consisting of 4-inch (10 cm) corrugated plastic tubing were installed 60 feet (18.3 cm) apart. Two drain depths were used and one set of 1976 data were obtained for each depth. In one case the depth was 107 cm (3.5 ft) to the bottom of the drain and the outlet was open, i.e. above the water level in the outlet ditch. The other drain depth was 122 cm (4 ft) but the outlet end was turned up (elbowed) so that the line was submerged during drainage with an outlet water depth of 3.5 ft (107) cm. Water tables were measured midway between the drains and daily maximum and minimum water levels recorded. These values were compared to predicted day end water table depths. Citrus, with an assumed effective rooting depth of 25 cm, was grown continuously on both plots analyzed. Although the experiments included three profile modification treatments, the data analyzed here were taken for conventional surface tillage only.

Soil Properties

The physical and mineralogical characteristics of the soils were described by Hammond, et al. (1971). Factors affecting the rate of subsurface drainage were discussed by Stewart and Alberts (1971) and by Alberts, et al. (1971). Drainage characteristics of the soils were simulated on a resistance network by Rogers, et al. (1971) and the water table behavior further studied by Rogers and Stewart (1972 and 1976). Input soil property values were obtained from the above references. The soil water characteristics given by Hammond et al. (1971) were used to calculate the drainage volume-water table depth relationship given in Figure 10-40. Saturated hydraulic conductivity was obtained from cores for each profile layer and were reported by Hammond et al. (1971). The effective hydraulic conductivity was also calculated from the drain outflow data of Stewart and Alberts (1971) (their Figure 1). The conductivity values obtained from these sources and used in testing DRAINMOD are given in Table 10-13. The equivalent depth from the drain to the impermeable

Table 10-13. Effective saturated hydraulic conductivity as a function of profile depth.

Depth from Surface	K
0 - 12 cm	12.7 cm/hr
12 - 36	25.4
36 - 84	16.0
84 - 108	0.025
108 - 132	5.08
132 - 204	1.27
below 204	0.0 (impermeable)

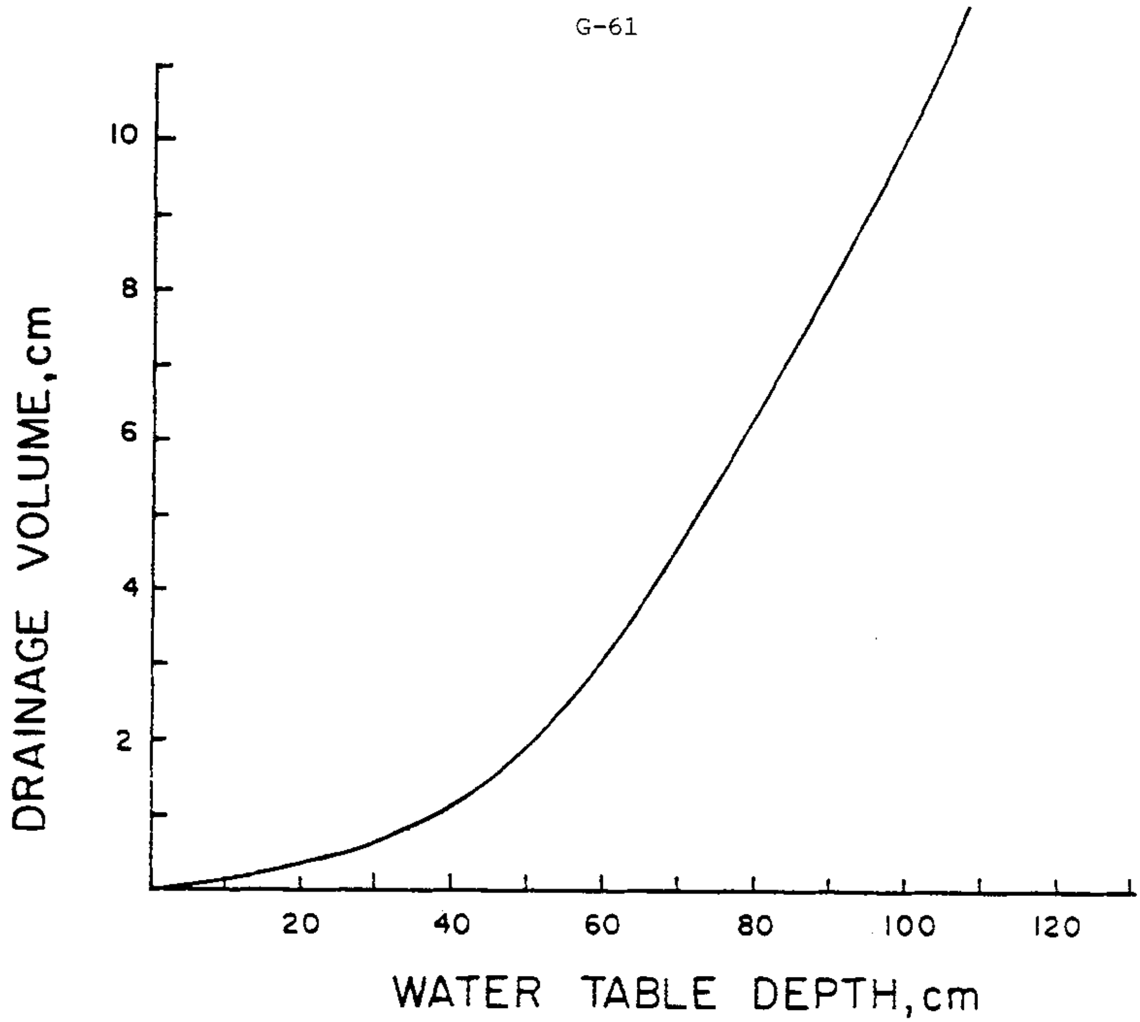


Figure 10-40. Water yield relationship for Wabasso and Oldsmar sands on the Florida site.

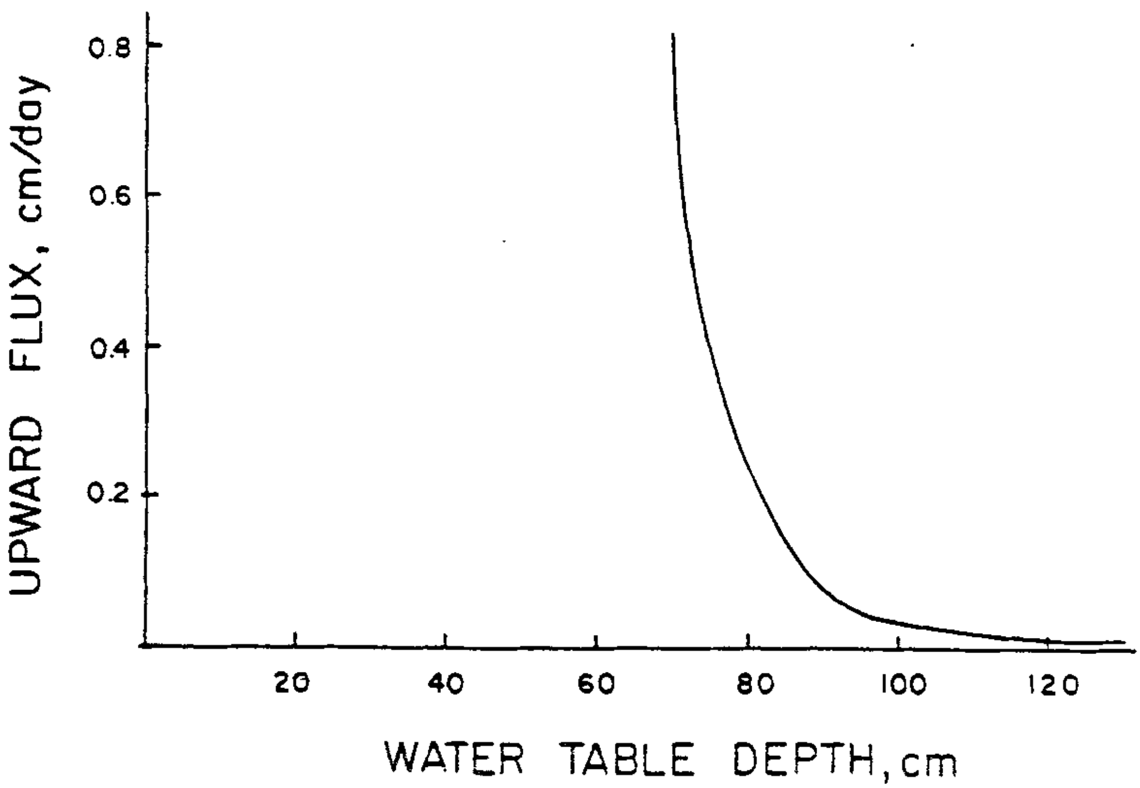


Figure 10-41. Upward flux for Oldsmar sand.

layer was calculated to be 63 cm for a drain depth of 107 cm and 57 cm for the 122 cm depth. However the methods for determining equivalent depth (Eqs. 2-13 and 2-15) assume a uniform soil. The d_e value was adjusted to account for layering as follows. The product of conductivity and depth in the bottom zone (for a drain depth of 107 cm) should be reduced by $d_e/d = 63/97$ to compensate for convergence near the drain. Therefore if we assume the region below the drain is uniform with K = 5.08 cm/hr an equivalent depth of d_e' should be used such that,

$$5.08\, d_e' = \frac{63}{97}\,(5.08 \times 25 + 1.27 \times 72).$$

Then $d_e' = 27$ cm. In like manner, $d_e' = 22$ cm for the 122 cm drain depth. These values were used as the depth from the drain to the impermeable layer with a uniform k = 5.08 cm/hr.

The upward flux-water table depth relationship was calculated using the numerical methods given in Chapter 5 and the unsaturated hydraulic conductivity values given by Hammond et al. (1971). The relationship is plotted in Figure 10-41.

Daily maximum and minimum temperatures were obtained from the National Oceanic and Atmospheric Administration (NOAA) for Fort Pierce. These data were used to calculate potential ET using the Thornthwaite method. Daily evaporation pan data were also obtained from NOAA and used in DRAINMOD for comparison purposes.

Results

The observed daily maximum water table elevations are compared to predicted day end values in Figure 10-42 for plot 12. The drain depth is 122 cm (4 ft). The outlet was raised so that the effective outlet depth is 107 cm. In general, the agreement between predicted and measured water table elevations is good

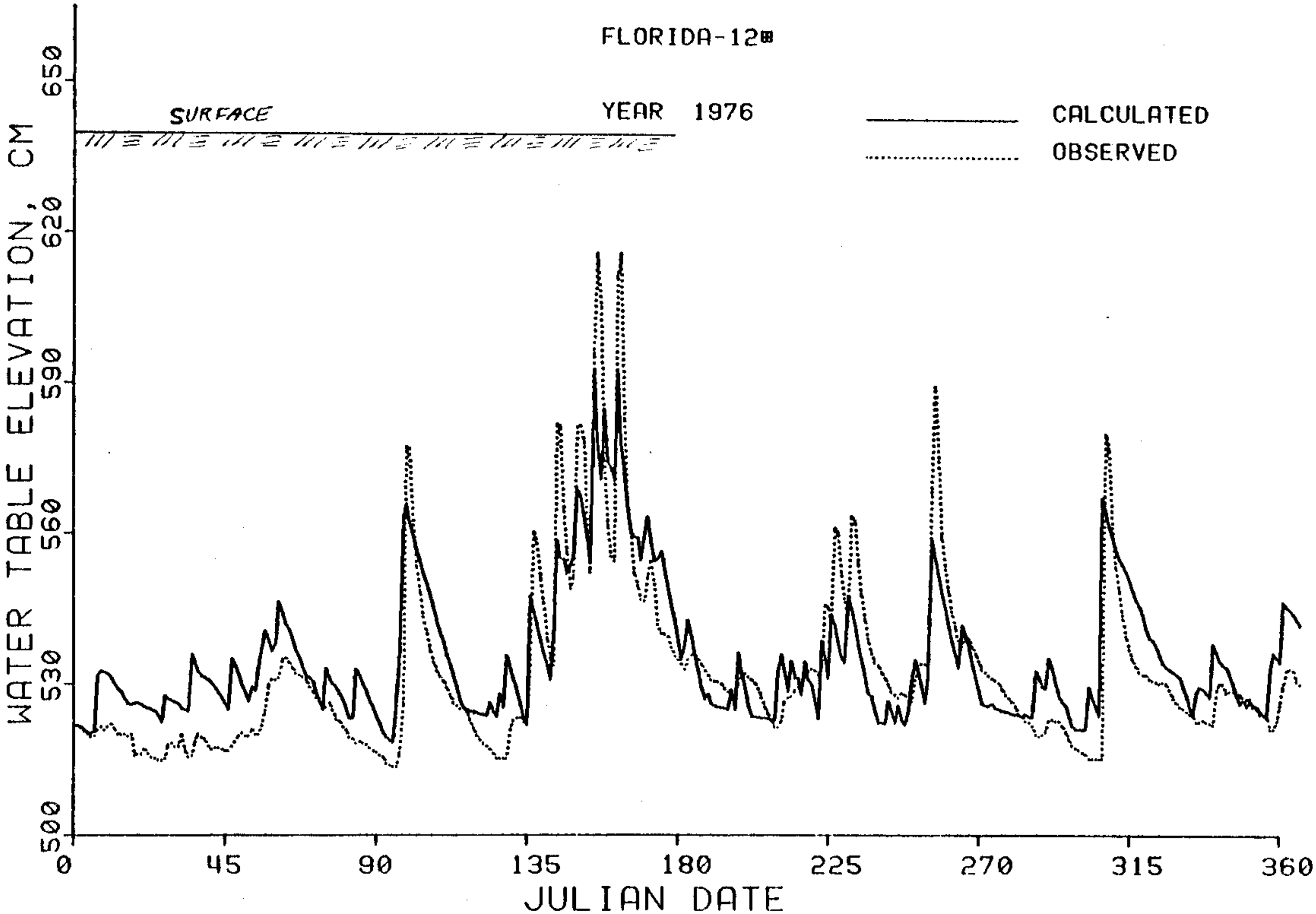


Figure 10-42. Comparison of predicted water table elevations at the end of each day with observed maximum water table elevations for a plot with drains at a depth of 122 cm. The outlet elevation is at a 107 cm depth.

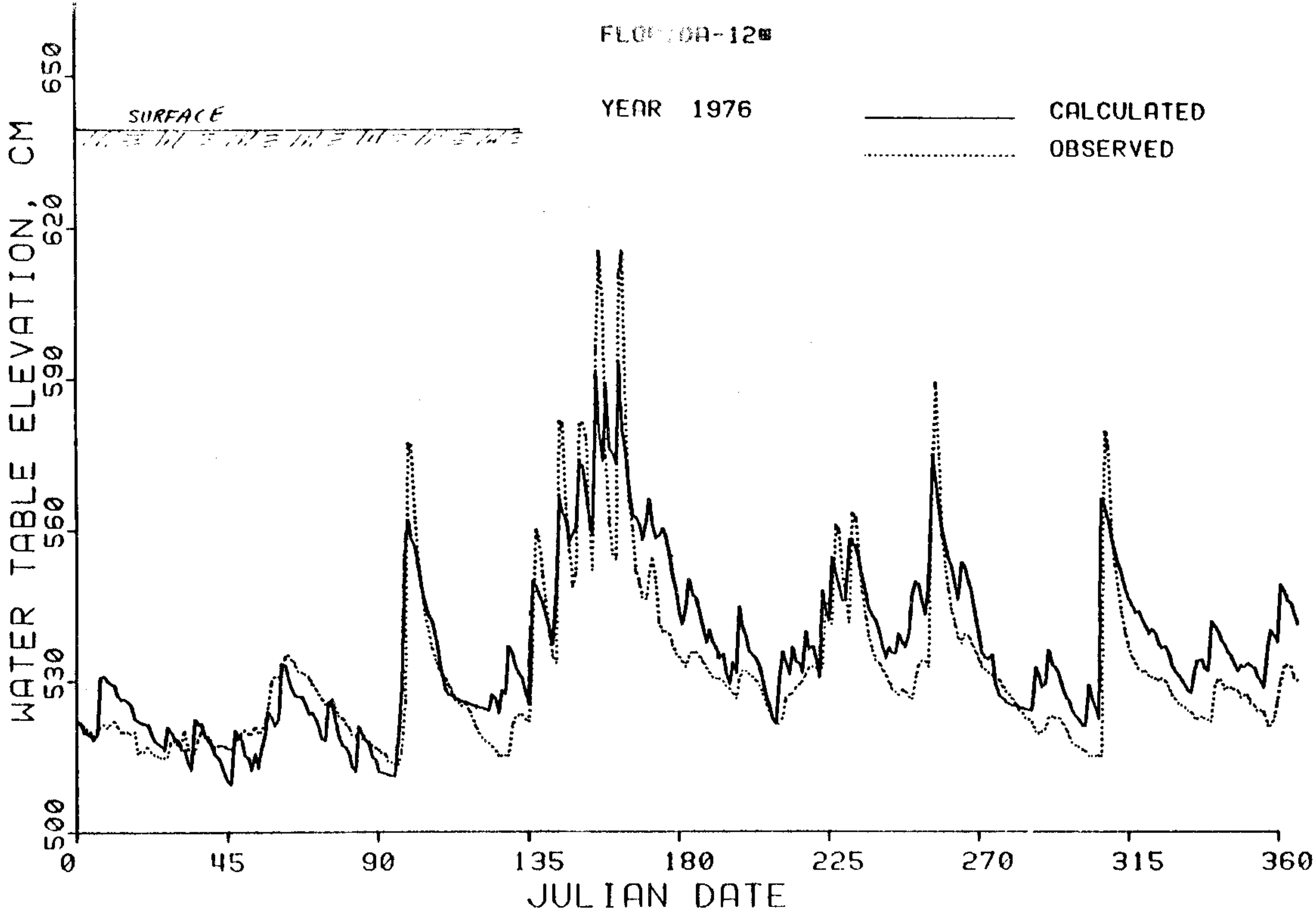


Figure 10-43. Comparison of predicted water table elevations at the end of each day with observed maximum elevations for plot 12. The potential ET used in DRAINMOD was evaluated from pan evaporation measurements.

with a standard error (Eq. 10-1) of only 10.2 cm. Predicted values are high during the early part of the test period (days 0 to 90) and somewhat low during the midsummer months. A closer examination of the simulation results showed that predicted water table elevations would have been even lower during the summer had the ET not been limited by upward water movement (Figure 10-41). These discrepancies are apparently due to high estimates of potential ET during the summer months and low estimates during the winter and early spring. Because PET predictions by the Thornthwaite method depend only on temperature and daylight hours, rather high values are obtained for the hot summer days in Florida. However the humidity is also very high and tends to limit the PET. Predicted water table elevations using daily evaporation pan readings (corrected by pan coefficient of 0.7) are plotted in Figure 10-43. Higher PET values during the spring and lower values during the summer improved agreement between predicted and observed water table elevations resulting in a standard error of 9.4 cm. Still the agreement shown in Figure 10-42 is judged acceptable for field conditions.

Predicted and observed subsurface drainage volume for plot 12 are plotted in Figure 10-44. Predictions obtained by using PET from both the Thornthwaite method and from daily pan evaporation readings are given. In this case the effects of low Thornthwaite PET values in the spring and high values in the summer are clear. High PET values during the summer months caused predicted drainage volumes to be much lower than observed while the opposite effects occurred in the winter, although to a lesser degree. Predictions using the pan ET values were in better agreement with observed drainage volumes, although they were still somewhat low.

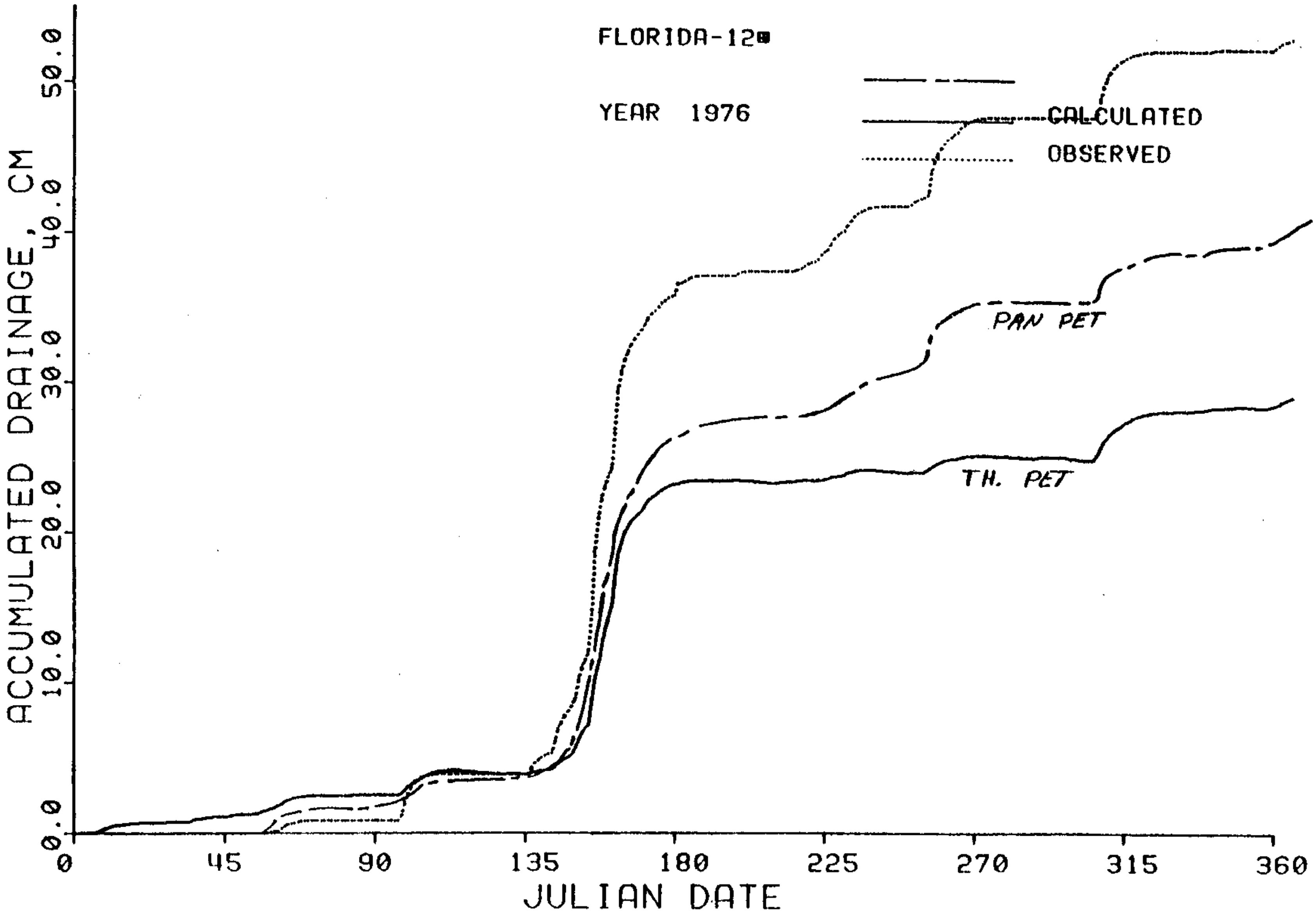


Figure 10-44. Predicted and observed drainage volumes for plot 12 (122 cm drain depth). Predictions based on both evaporation pan and Thornthwaite daily PET estimates are given.

Predicted and observed water table depths for plot 15 are plotted in Figure 10-45 for ET calculated by the Thornthwaite method and in Figure 10-46 with ET obtained from daily pan evaporation measurements. Standard errors were 13.9 cm and 13.0 cm for the relationships plotted in Figures 10-45 and 10-46 respectively. Again there is evidence in Figure 10-45 of high ET predictions (and correspondingly low water table elevations) during the summer months. This situation is improved when pan evaporation is used to estimate PET (Figure 10-46) but high ET rates during days 30 to 90 cause the predicted water table elevations to be low during that period. These observations are consistent with the drainage outflow plots given in Figure 10-47. Calculated values obtained by using both Thornthwaite and pan PET values are plotted. As was the case for plot 12 (Figure 10-44), high ET predictions by the Thornthwaite method for the summer months caused the calculated drainage outflow to be low.

The results presented for the Florida site generally confirm the validity of DRAINMOD for the conditions represented. However these results also point out potential problems with using the Thornthwaite method to predict PET at all locations. This method worked well for N.C. and Ohio conditions but may need modification for other locations. One modification that could be used is to calculate monthly PET values with the Thornthwaite method and with one of the more sophisticated models such as the Penman method. Then correction factors could be obtained for the Thornthwaite method by taking a ratio of the monthly values. Definition of the correction factors would only be required at one location within a rather wide geographic region so the necessary data could possibly be obtained. This would still allow consideration of the day-to-day variation in ET due to temperature changes as predicted by the Thornthwaite

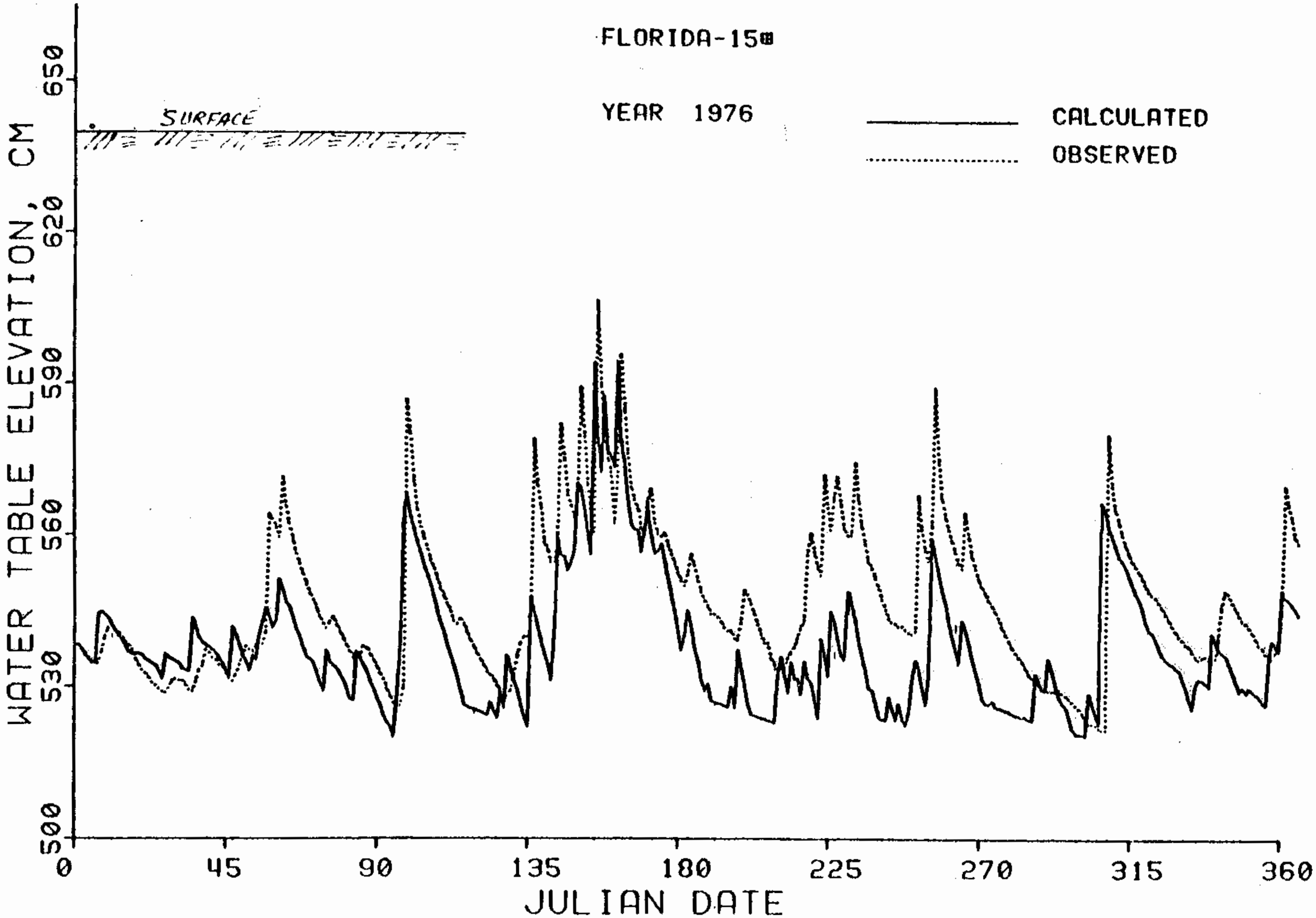


Figure 10-45. Predicted and observed water table elevations for plot 15 which has drains at a depth of 107 cm. The Thornthwaite method was used to calculate PET. The observed elevations plotted are daily minimum values.

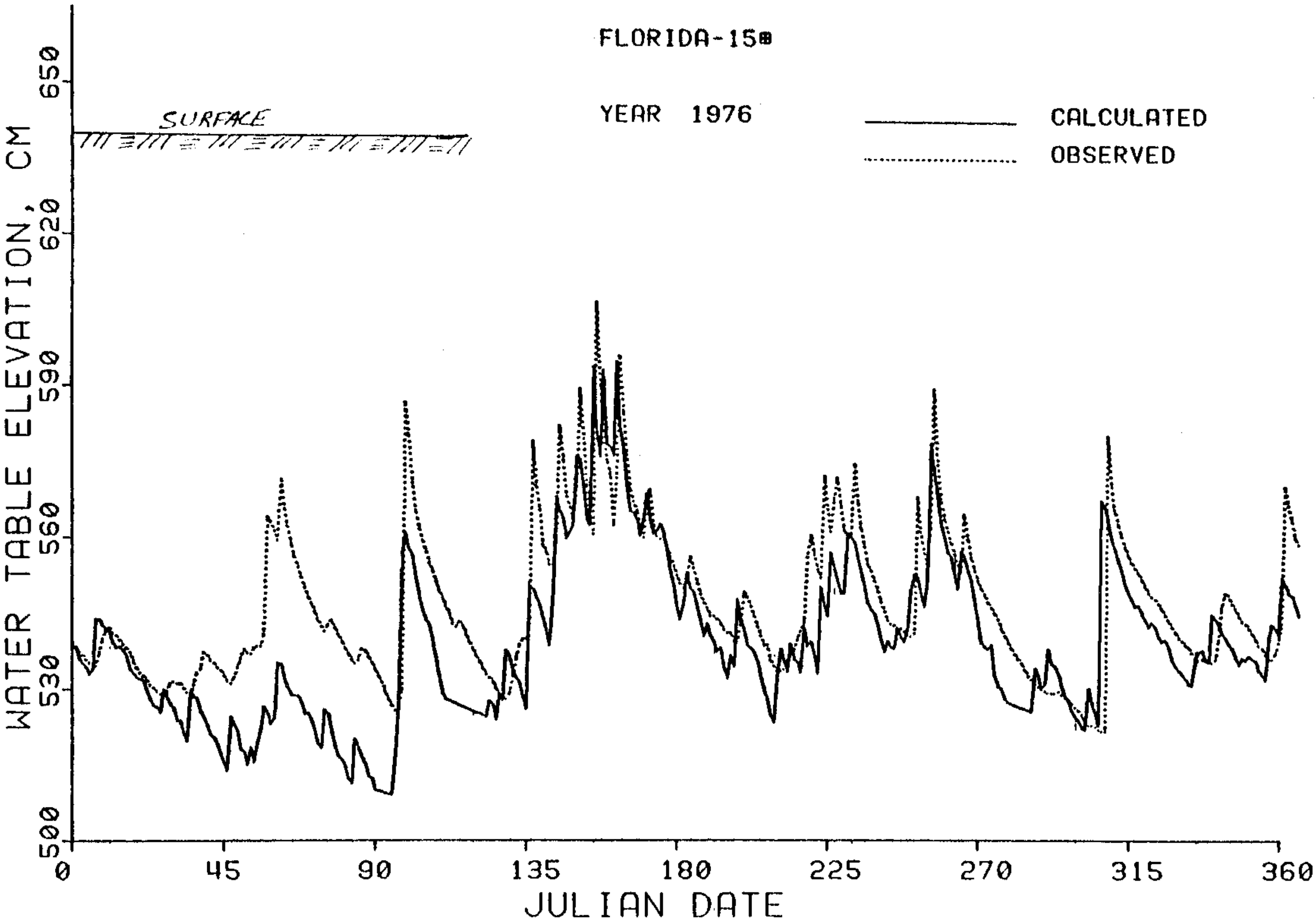


Figure 10-46. Predicted and observed water table elevations for plot 15 which has drains at a depth of 107 cm. PET was determined from pan evaporation measurements. The observed elevations plotted are daily minimum values.

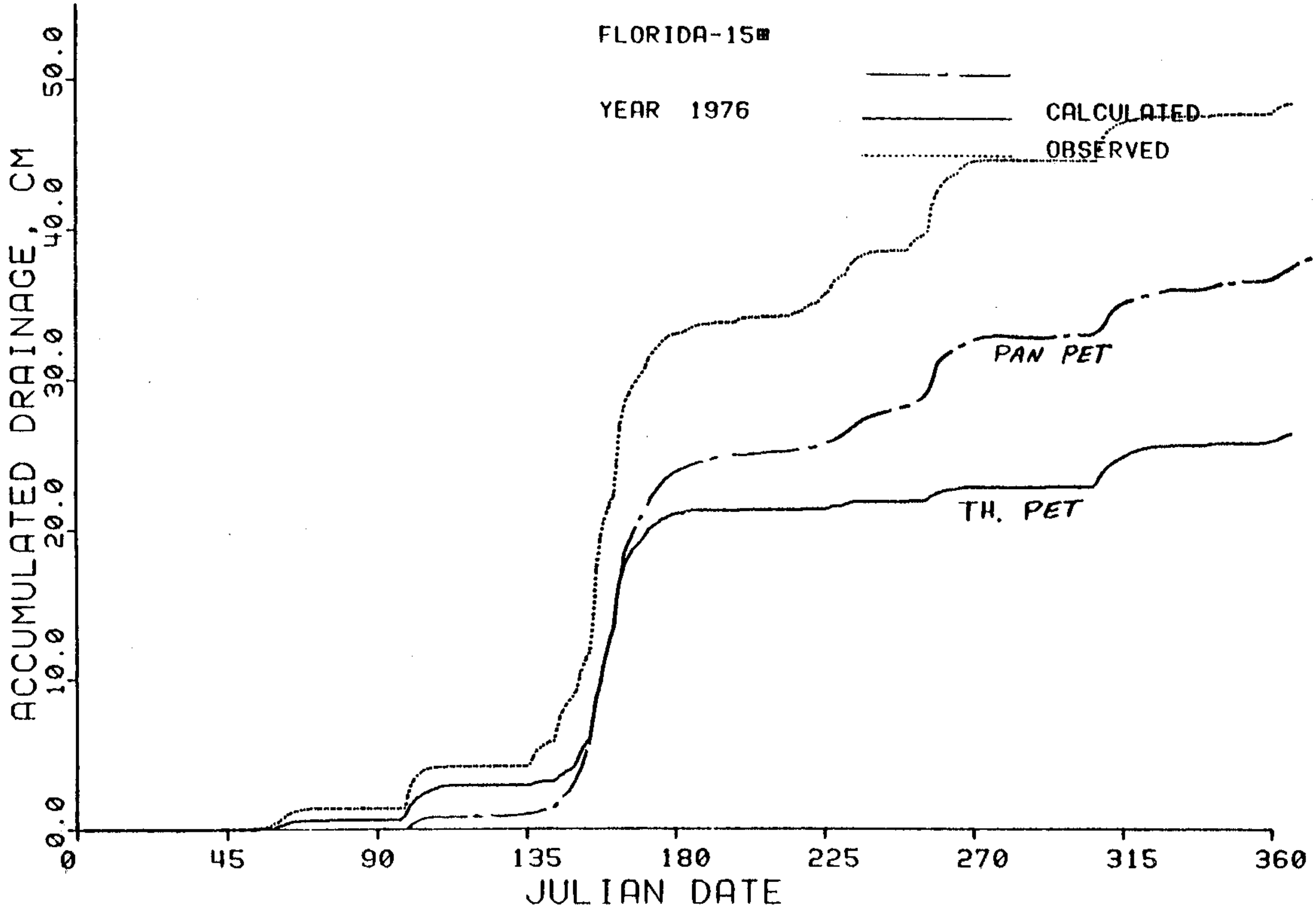


Figure 10-47. Predicted and observed drainage volumes for plot 15 (107 cm drain depth). Predictions obtained for both evaporation pan and Thornthwaite PET values are plotted.

method. Of course an alternative method for predicting PET can be easily substituted into DRAINMOD if necessary input data are available for the desired location.

CALIFORNIA

Data were obtained from results of a USDA-ARS study on drainage from an irrigated field in the Imperial Valley of California. The data were obtained through the cooperation of Mr. Lee Hermsmeier, SEA-AR, at Brawley, California.

Experiments

Experiments were conducted on a subsurface drained field on the Galleano ranch during 1968, 1969 and 1970. Barley was grown in 1968. Sugar beets were planted in the fall, 1969 and harvested in summer, 1970. The soil is a sandy clay with parallel drains placed 152 cm (5 ft) deep and 61 m (200 ft) apart. The soil is tight and the recommended drain spacing would normally be much closer than 61 m. Irrigation water was applied by the furrow method and the amount applied at each irrigation was measured and recorded. Observation wells were placed at several locations between the tile lines so that the position and shape of the water table could be measured. Wells were installed between three separate sets of tile lines at 3 locations along the lines. Measurements were made periodically (daily in several cases) to determine the change in water table with time after irrigation. Drain outflow rates were recorded continuously from both 4-inch clay tile and 3-inch plastic tubing.

The effective hydraulic conductivity was calculated from daily drain flow and water table elevation measurements. The K value obtained was K = 0.1 cm/hr. The upward flux was evaluated using the critical depth concept with CRITD = 100 cm. A drainable porosity of 10 percent was assumed and the drainage volume-water table depth relationship determined as discussed in Chapter 5. Daily irrigation volumes were input to the model as rainfall distributed over a four-hour period. Daily potential evaporation was calculated by Hermsmeier (personal communication) by the Jensen-Haise formula, the Penman method and another modified formula. Daily evaporation pan data were available and corrected values (pan coefficient of 0.7) were also used as inputs to DRAINMOD.

Results

Predicted and observed water table elevations for a point midway between drain lines are plotted in Figure 10-48 for 1968. Agreement between observed and predicted water table elevations was good for 1968. Predicted water tables frequently rise to the surface after irrigation and, in many cases, surface runoff is predicted. Runoff is predicted because the total calculated drained volume (air volume) at the time of irrigation is less than the irrigation water that was applied. The drainage volume predicted is close to that measured so the discrepancy cannot be accounted for by errors in the soil properties or drainage system parameters. Predicted runoff for 1968 was relatively small and could have been the result in errors in the field measurement of the irrigation tailwater. That is, the amount of runoff predicted could have actually left the field during the furrow irrigation process. Another explanation is that water was lost from the field by deep or lateral seepage that was not accounted for. In summary, for the 1968 data, the model did a good job in predicting the water table position with time under furrow irrigation conditions.

While predicted water table elevations were in close agreement with observed for 1968, the results were poor for 1970 (Figure 10-49). The predicted water table again rose to the surface frequently with surface runoff predicted on many occasions. However the observed water table tended to recede throughout the

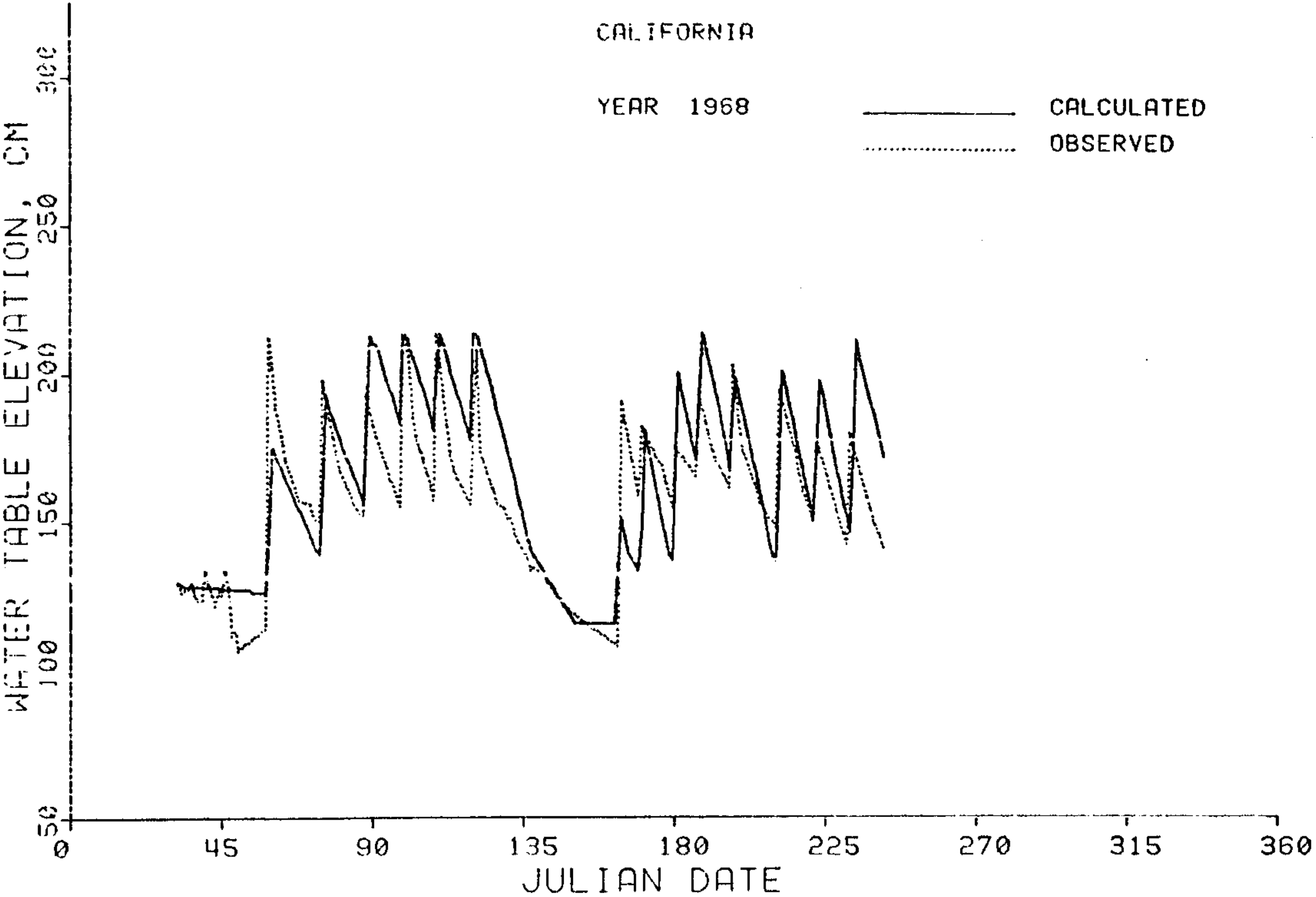


Figure 10-48. Predicted and measured water table elevations for a site near Brawley, California in 1968.

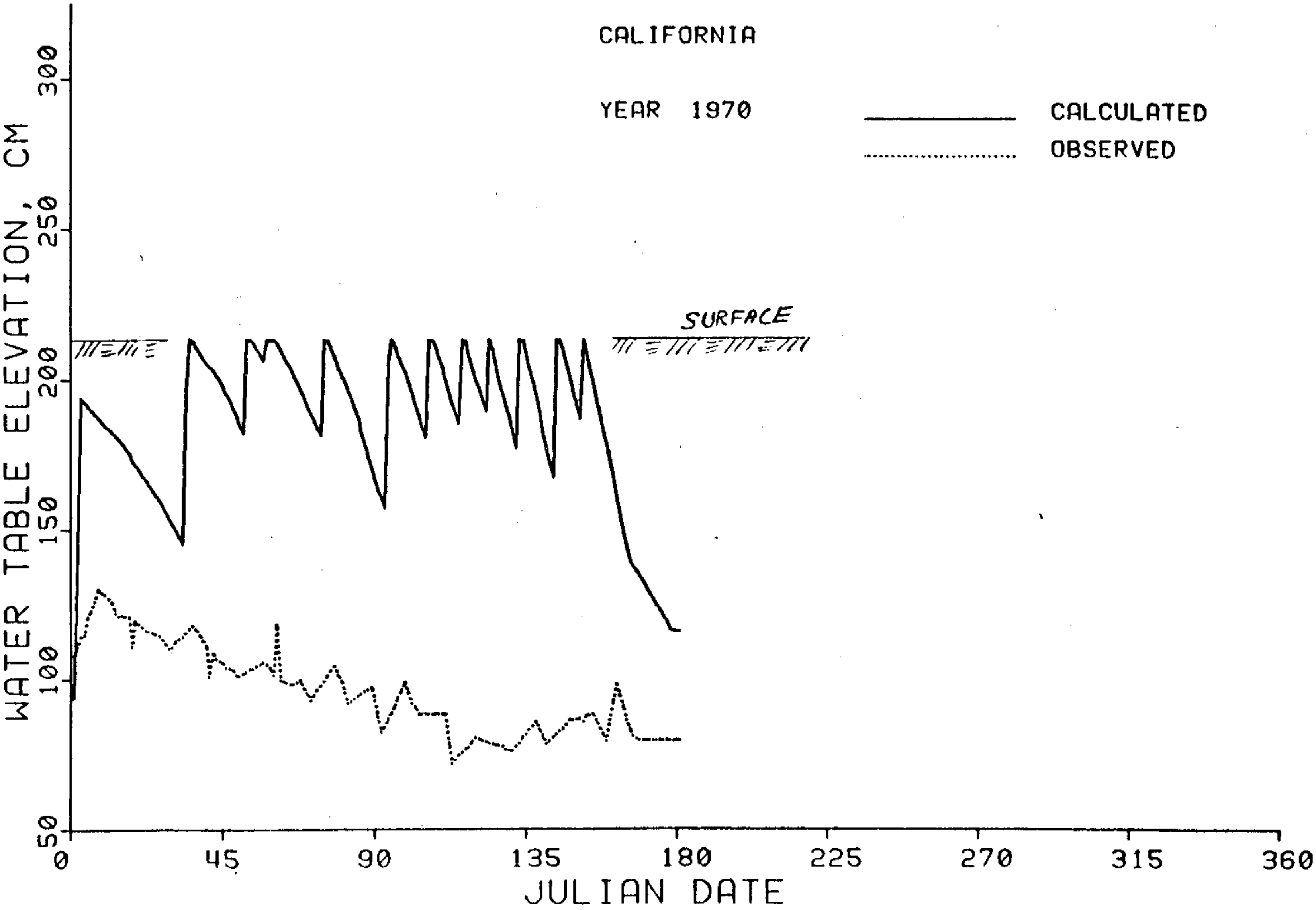


Figure 10-49. Predicted and measured water tables for a site near Brawley, California in 1970. Predicted water tables were much too high possibly because large seepage losses were not accounted for.

irrigation period with limited rises of only short duration. The data set was not as complete -- fewer measurements at fewer locations -- in 1970 as in 1968 and the trends observed indicate that differences in the measurement procedures may have occurred. Apparently a significant amount of water is lost from the system by deep or lateral seepage. Water balance calculations between irrigation periods in 1970 show water loss rates as high as 0.94 cm/day (0.37 in/day) that cannot be accounted for by ET or drainage through the tile lines.

The results presented in Figures 10-48 and 10-49 indicate that the model shows promise for application to irrigated lands, but that more work is needed to test the model for these conditions. This work is now being done under a BARD research project that is discussed in the next section. Data are being collected and processed from several field drainage experiments in California that were conducted in the 1960's. Plans are to use these data to test the model for several soils and conditions.

OTHER FIELD DATA

There are several other potential opportunities for testing the model which are being pursued in the research programs at North Carolina State University. Data on drained plots for sugar cane production at Baton Rouge, Louisiana have been obtained by Mr. Cade Carter - SEA-AR at Baton Rouge. Two or three years of data on at least two sites are available from this source. Data have been obtained for one site and the model is being tested for those conditions.

Dr. Gideon Sinai, a researcher at the Technion in Israel, is interested in testing the model for use in that country. He is now setting up field experiments to check the model validity. This work is being conducted under a BARD (Binational Agricultural Research and Development) cooperative research project between North Carolina State University and The Technion.

The SEA-AR unit at Orono, Maine has just recently completed installation of a rather large field drainage experiment. Mr. Joe Bornstein, a USDA researcher at that location, has indicated an interest in testing the model for Maine conditions. Mr. Bornstein and his coworkers are now making the necessary measurements for checking the model at that location.