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PACE WATERSHED MODEL (PWM):
VOLUME 2, WEATHER MODIFICATION SIMULATIONS

by
Ali Durgunoglu, H. Vernon Knapp,
and Stanley A. Changnon, Jr.

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Illinois State Water Survey
2204 Griffith Drive
Champaign, Illinois 61820

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INTRODUCTION

To understand the potential impact of precipitation augmentation on agricultural productivity and freshwater resources, it is necessary to evaluate the effects of these precipitation changes on soil infiltration and moisture, shallow ground-water movement, and streamflow. The moisture brought by increases in rainfall (or other sources such as irrigation) can potentially be distributed into one of four hydrologic processes: 1) runoff into a stream, 2) seepage into ground water, 3) evaporation into the atmosphere, or 4) abstraction from the soil into plants for eventual transpiration into the atmosphere. Only the last of these processes is of primary benefit to the plant.

A quasi-distributed-parameter model was developed to simulate soil moisture and baseflow conditions for agricultural areas in Illinois. The development of this model was described in the preceding report: *PACE Watershed Model (PWM): Volume 1, Model Development.* The model was designed with components sensitive to water movement processes in order to provide the potential for evaluating the effects of increased amounts of rainfall, thus offering some answers as to the usability of potential precipitation augmentation. These strengths of the model allow it to be applicable to a wide range of hydrologic investigations.

This report describes 1) the calibration and validation of the model for the Kaskaskia Ditch watershed in central Illinois, 2) subsequent simulation studies performed to evaluate the hydrologic effects of precipitation augmentation in this watershed, and 3) special simulation studies performed to analyze the effects of both early-season augmentation and irrigation on crop stress reduction. Several levels of precipitation increase are evaluated to determine the overall benefit to agriculture in terms of crop water status. Results are presented on changes in soil moisture, crop water use, shallow ground-water, and streamflow conditions over periods of years representing both wet and dry climatic conditions in the watershed. Included is a brief analysis of the characteristics of crop water supply needed to improve the crop condition.

Acknowledgments

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WATERSHED SELECTION

The PACE Watershed Model (PWM) is capable of simulating watersheds with a wide range of drainage areas. The major factor considered in selecting the watershed used for calibration of the model and for weather modification simulations was the drainage area of the watershed. The size of the watershed would determine the amount of time needed for data preparation and computer execution for each simulation case. Selecting a large watershed area is undesirable because of the large amount of time needed to develop data files and the excessive amounts of computer time required for each simulation case. On the other hand, selecting a very small watershed has its problems as well. For example, there is a lesser chance that a precipitation gage exists within a small watershed, and we would have to rely on precipitation records from neighboring gages. This may be especially important if heavy but localized thunderstorms pass over small and ungaged watersheds and are not recorded by the neighboring precipitation gages. The opposite of this situation is also possible, and either case may cause problems in calibrating the model.

Among other things which influenced the selection of the sample watershed was the availability of data. Although the model was intended to be used with relatively ungaged watersheds, considerable amounts of data are required for initial calibration and testing of the model for certain soil and crop types. The data considered vital for calibrating and testing the PWM are climate data (precipitation records in or around the watershed area, temperature, wind velocity, relative humidity, cloud conditions, etc.); soil moisture observations for the soil and crop types in the selected watershed area (these observations do not need to be taken within the watershed of interest, but can be from different locations with similar conditions); and streamflow records. Soil moisture and streamflow records are not needed once the model is calibrated and tested for a particular soil and crop type.

Considering all these factors, it was decided that it would be more feasible to devote more time to model development and to run as many simulations as possible during the limited research period than to invest time in data collection and preparation. Therefore a medium-sized watershed in east central Illinois was selected for calibrating and verifying the PWM. The same watershed was also used for weather modification simulations.

The selected watershed drains an area of 12.4 square miles of the most upstream portion of the Kaskaskia River Basin at Bondville, Illinois. A streamflow gaging station (USGS Gaging Station 05590000, Kaskaskia Ditch at Bondville, IL) is located one mile east of Bondville and 3.8 miles west of Champaign, at river mile 289.6. Flow is virgin and records are good except for some winter months. The soils in the watershed are of two major soil association types: Flanagan silt loam and Drummer silty clay loam. The subsoil is basically glacial drift with low permeability. The land is flat with slopes varying from 3.6% (uplands) to 0.2% (lowlands). Drainage is improved by the Kaskaskia Ditch and drainage tiles. Com is the predominant plant cover during the growing season.

MODEL CALIBRATION

Data Used for Calibration

A computer-generated contour map of the Kaskaskia Ditch at Bondville is presented in figure 1. Channel drainage consists of one main ditch flowing from north to south and two ephemeral tributaries joining from the east Average annual discharge at the outlet is 10.6 cfs, or 11.6 inches per year. The watershed has been transformed into a grid map with square elements 1/16 square mile in size. The grid map of the basin (figure 2) shows the computer-generated land-slope directions of each square element (indicated by arrows). Channel elements are indicated by asterisks.

Soil moisture data used for calibrating the PWM were obtained from two locations in Illinois. A soil moisture monitoring station located two miles south of Bondville was used for collecting data for a Flanagan silt loam between 1981 and 1985. For that period, precipitation records were obtained from Bondville, and other climatic information was obtained from Urbana except for the percent cloudiness, which came from Springfield. Limited cloud-condition data from Urbana were correlated to the percent cloudiness data from Springfield, so that the limited cloud-condition data from Urbana could be converted to percent cloudiness data for the simulation studies. This procedure was used because earlier Springfield records, which were needed for weather modification simulations, did not have percent cloudiness records, and Urbana's limited cloud-condition records had to be used. For the period of soil moisture monitoring, the dominant crop cover was com.

Soil moisture information on Drummer soil for the period 1981–1984 was obtained from a monitoring station located 8 miles southwest of DeKalb, Illinois. Precipitation and temperature records

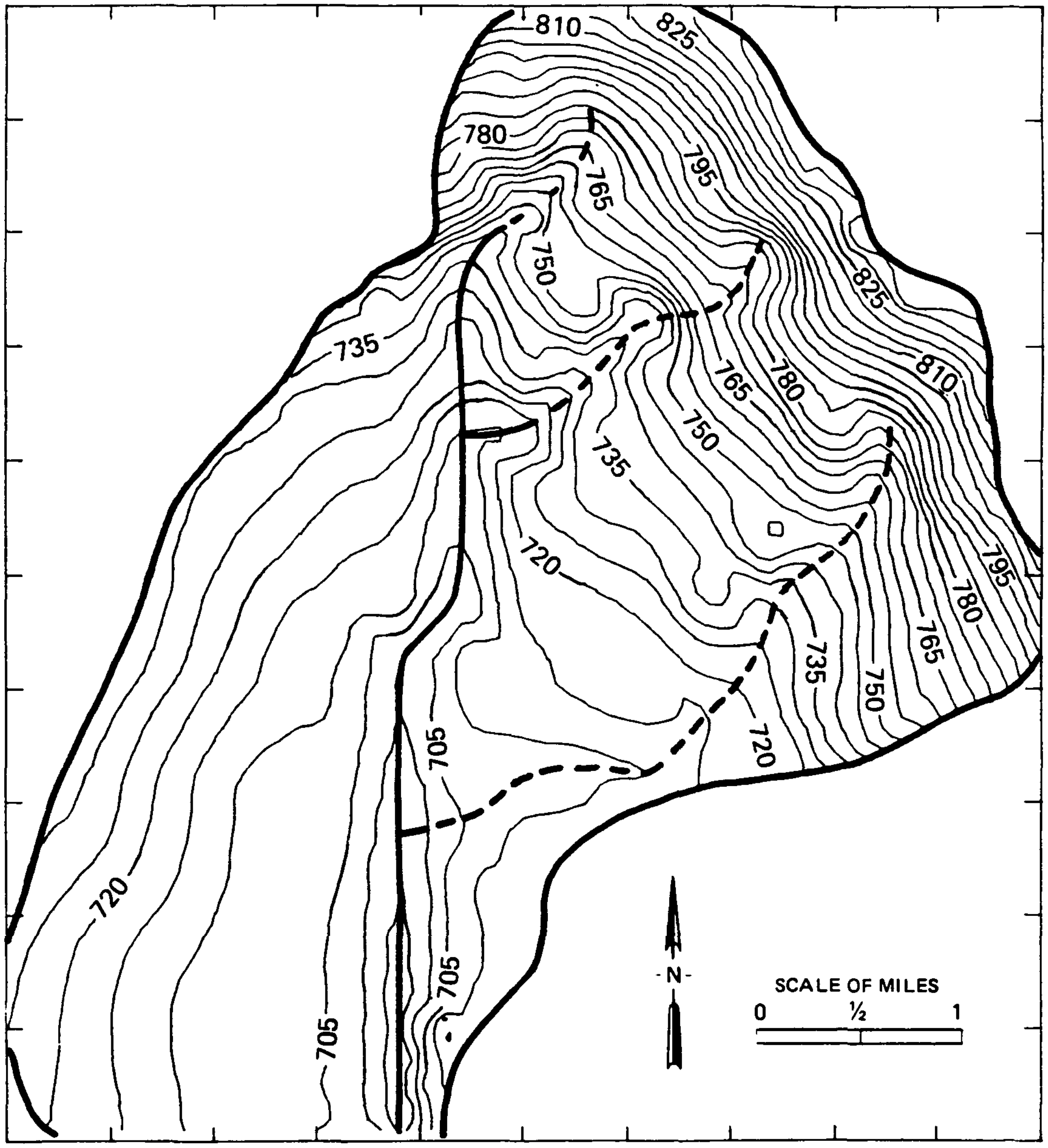

Figure 1. Computer-generated contour map of the Kaskaskia Ditch at Bondville, Illinois

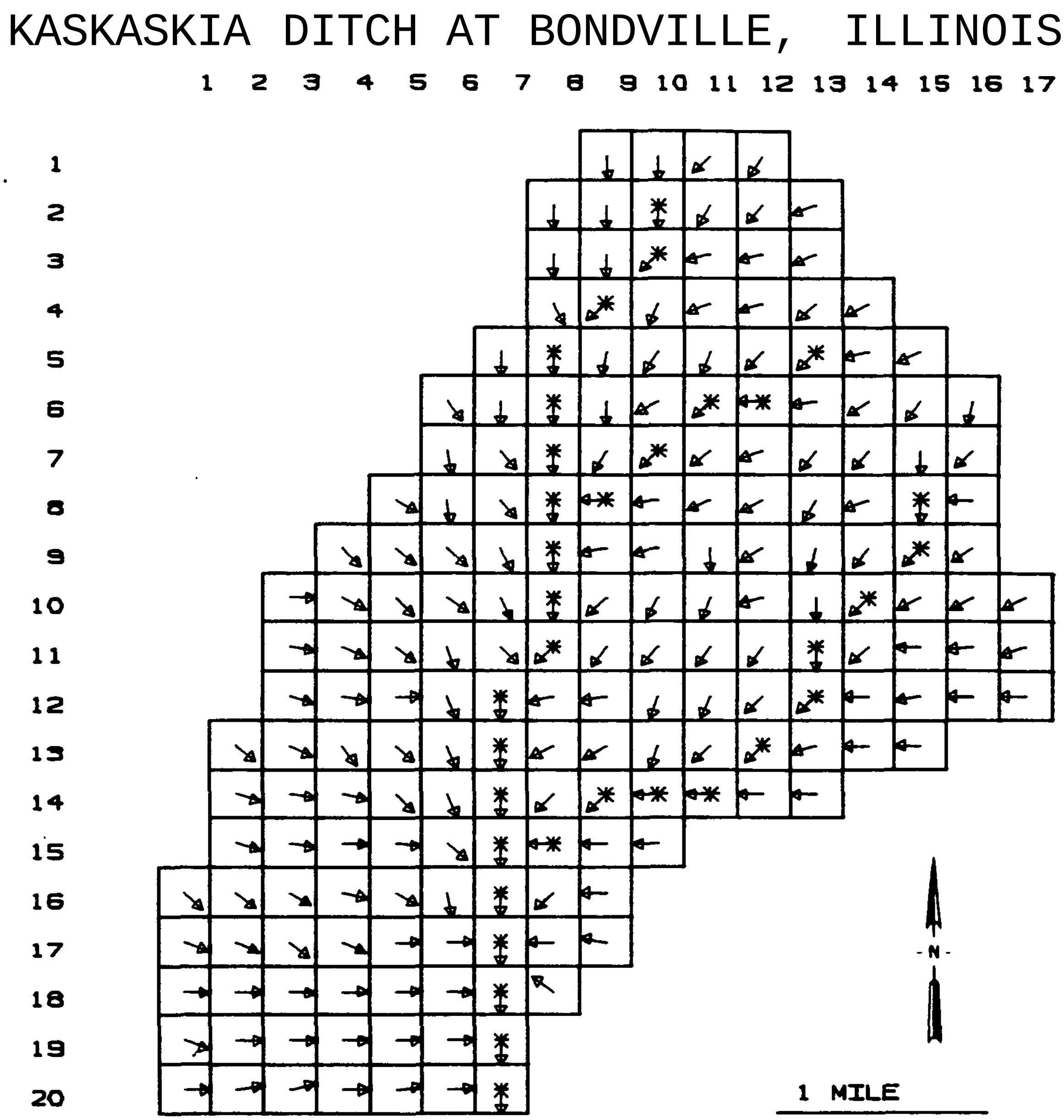

Figure 2. Grid map of the Kaskaskia Ditch Basin

for that period were taken from Waterman, which is 5 miles south of the monitoring site. Wind, relative humidity, and percent cloudiness data were obtained from Rockford (about 20 miles northwest of DeKalb). Corn was the major plant cover at that time, with some periods of bare soil.

Distribution of these two major soil association groups (Flanagan and Drummer) over the Kaskaskia Ditch Basin is illustrated in figure 3. The Flanagan soil predominantly covers the upper lands, and the Drummer soil covers the lower lands. The percent distribution of these soil types over the entire watershed area is approximately equal (52% for Flanagan, and 48% for Drummer). The entire watershed area was assumed to have drainage tiles except for the channel elements (i.e., 83% of the watershed was assumed to be tiled).

Daily streamflow records were obtained from USGS Gaging Station 05590000, as mentioned earlier. A ground-water observation well located 5 miles south of Bondville had ground-water elevation records for the period 1982-1984. Since no ground-water elevation records were available within the watershed, records of this well were used for making qualitative comparisons.

A layout of the channel drainage is illustrated in figure 4. Channel physiography, such as width, depth, and roughness of the channel, was determined by observations and measurements of the main ditch and tributaries during a field trip. Near the outlet the main ditch has a trapezoidal cross section with a bottom width of 12 to 15 feet and side slopes of 1:1. About 3 miles upstream of the outlet, water flows in a trench 4 to 5 feet wide, which has been cut through the original channel bottom. The north tributary is a V-shaped ditch 3 feet deep and 7 feet wide. The south tributary is actually a shallow grassway and has no established channel. For modeling purposes, channel elements are classified under three types, according to their width, roughness, and permeability of bottom deposits. The distribution of these channel types over the watershed is shown in figure 4. Each channel element was assumed to have a rectangular cross section.

The widths used for the channel elements on the basis of field observations are as follows: type 1 = 5 feet; type 2 = 15 feet; type 3 = 50 feet (grassway). Data were not available on the thickness of the channel bottom deposits (TC and their permeability coefficients (PERM), which were needed for channel infiltration computations. Therefore these values were determined through calibration studies.

The subsurface consists of three layers of glacial drifts (Stephenson, 1967; Visocky and Schicht, 1969). Only the most recent (Wisconsinan) drift was considered for ground-water modeling since leakage between the Wisconsinan and its underlying drift (Illinoian) is negligible. Therefore the bottom of the Wisconsinan drift was assumed to be an impermeable layer with Wisconsinan drift contributing to the major part of the water-table flow. The elevation of this impermeable layer lies between 640 and 650 feet MSL within the watershed. The land elevation is between 850 feet (uplands) and 690 feet (outlet),

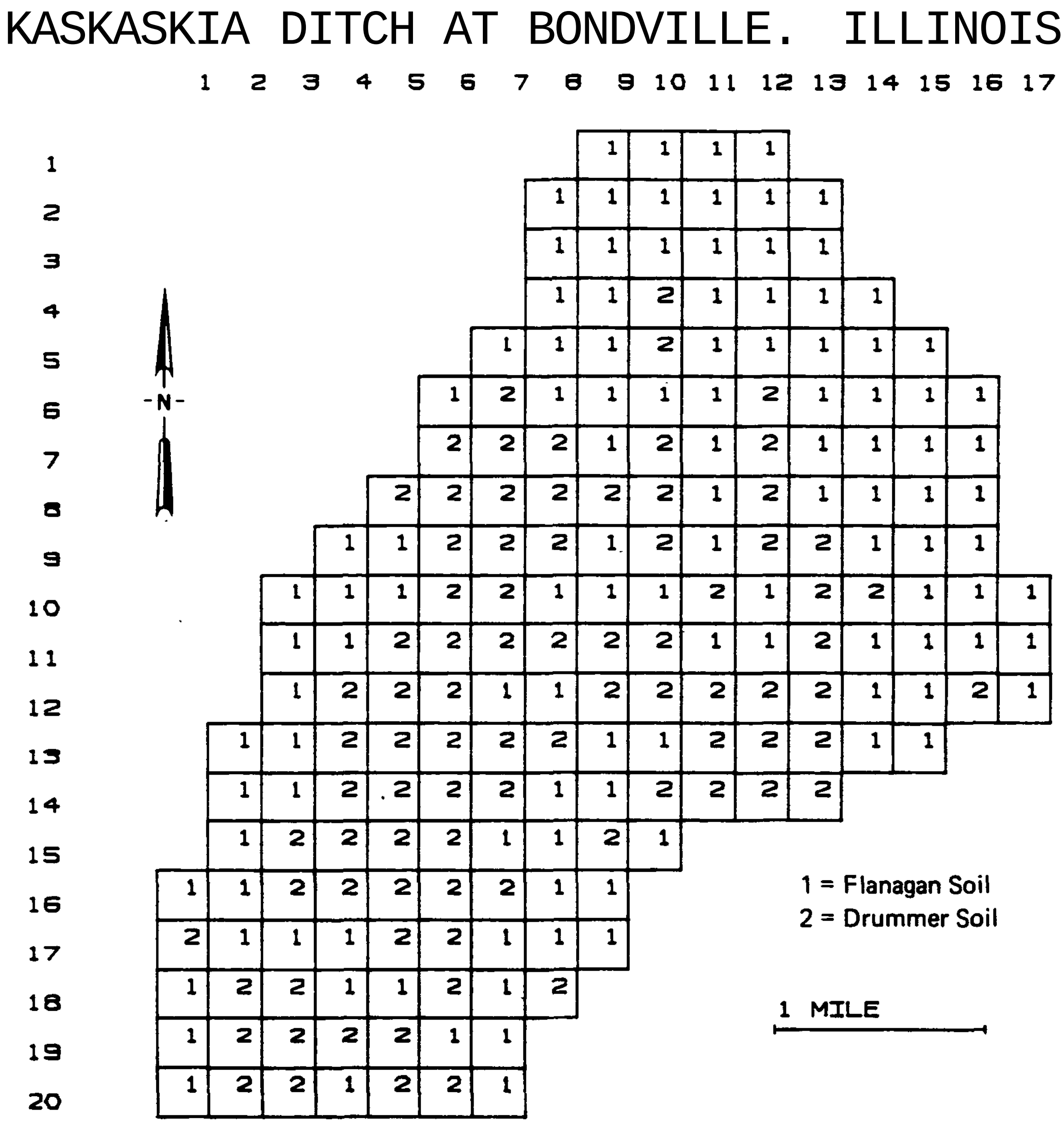

Figure 3. Distribution of the two major soil association groups over the Kaskaskia Ditch Basin

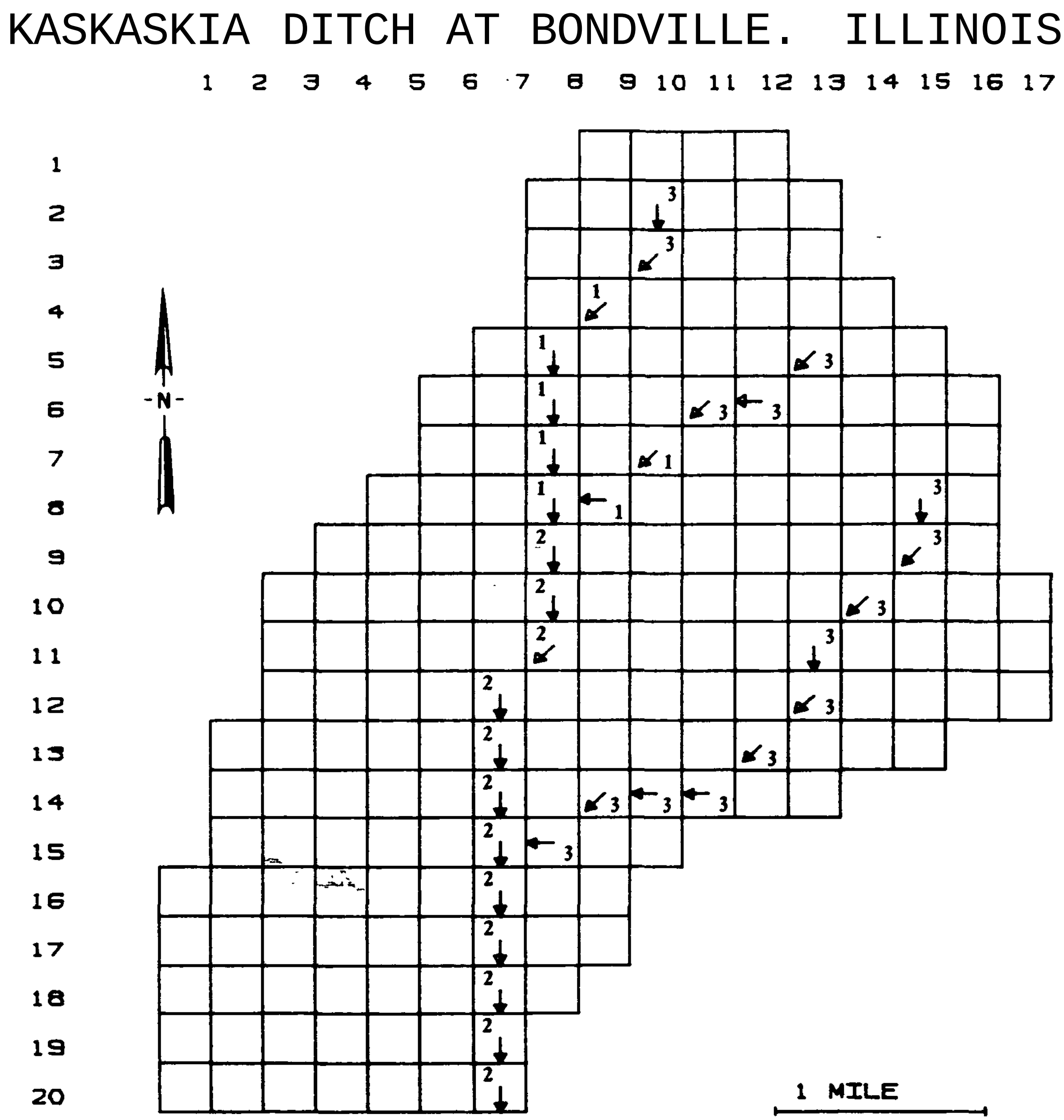

Figure 4. Layout of the channel drainage of the Kaskaskia Ditch Basin, shown on a grid map

giving a variable drift thickness of 40 to 210 feet Permeability in Wisconsinan drift is low. No actual values were available for permeability and storage coefficients. These parameters were calibrated by using the ground water component of the PWM.

Calibration of the Soil Moisture Component

The soil moisture component of the PWM handles 32 parameters, which were calibrated by using the available soil moisture data from Bondville and DeKalb. These parameters are listed in the left-hand column of table 1. The number of parameters was reduced during the calibration procedure by combining the characteristics of several adjacent soil layers. For example, the wilting point, field capacity, saturation level, and permeability of the top two layers are assumed to be equal. In this manner the original seven layers of soil were essentially reduced to four soil layers for purposes of calibration. These combinations reduced the number of soil parameters from 32 to 18.

In addition to the soil parameters, several parameters associated with the crop conditions at the Bondville and DeKalb sites have a major influence in the calibration procedure. These factors are 1) the changes in the leaf-area index (LAI) during the growing season, in terms of both total magnitude of the crop growth and the timing of growth through the year, and 2) the vertical distribution of the crop's root system throughout the different layers of the soil, and resulting effects on the distribution of water withdrawn from the soil. Without proper representation of these two factors, the calibration procedure will either diverge or reach an unacceptable local minimum. These crop conditions may have to be adjusted within the calibration procedure (e.g., after finding a local minimum) to assure a proper solution. The final leaf-area indexes and crop water-use indexes developed during calibration are shown in tables 2 and 3.

The objective function used in the optimization procedure is as follows:

$$\text{Min} \quad \sum_{i=1}^{N} \left[\left(\frac{\sum_{j=1}^{7} SMO_j - \sum_{j=1}^{7} SME_j}{\sum_{j=1}^{7} DEPTH_j} \right)^2 + \frac{1}{7} \sum_{j=1}^{7} \left(\frac{SMO_j - SME_j}{DEPTH_j} \right)^2 \right]_i \tag{1}$$

where SMO_j. and SME_j. are the observed and estimated soil moisture values for soil layer j, $DEPTH_j$, is the depth (or thickness) of soil layer j, and N is the total number of observations.

The objective function was designed to give weight to both the total amount of moisture within the soil and the distribution of the moisture within each of the four layers of the soil column. Termination criteria were developed for all parameters by predetermining a minimum change that would be accepted in a parameter between iterations. A termination criterion of change in the objective function was also adopted.

Table 1. Soil Parameters Used in Soil Moisture Calibration, and Resulting Values of the Objective Function

Parameter(s)	Flanagan Soil Initial Value	Flanagan Soil Calibrated Value	Drummer Soil Initial Value	Drummer Soil Calibrated Value
WP(1), WP(2)	0.14	0.16	0.18	0.16
WP(3), WP(4)	0.18	0.16	0.22	0.18
WP(5)	0.20	0.18	0.16	0.18
WP(6), WP(7)	0.21	0.18	0.14	0.18
FC(1), FC(2)	0.37	0.38	0.40	0.39
FC(3), FC(4)	0.41	0.41	0.44	0.44
FC(5)	0.38	0.47	0.33	0.43
FC(6), FC(7)	0.39	0.44	0.31	0.36
UL(1), UL(2)	0.52	0.56	0.53	0.54
UL(3), UL(4)	0.52	0.56	0.53	0.56
UL(5)	0.52	0.58	0.52	0.52
UL(6), UL(7)	0.52	0.56	0.50	0.49
K(1), K(2), K(3), K(4)	1.20	0.52	1.20	0.48
K(5), K(6), K(7)	0.40	0.44	1.20	0.28
CN2	80.0	82.5	80.0	82.0
EPMAX	0.60	0.40	0.60	0.30
k_o	0.0002	0.0001	0.0002	0.0003
SEP	0.138	0.177	0.138	0.130
Objective Function Value	3.6358	1.4093	1.6687	0.2273

Note:

WP(i) = Wilting point for soil layer (i) (% of total soil volume)
FC(i) = Field capacity for soil layer (i) (% of total soil volume)
UL(i) = Saturation level for soil layer (i) (% of total soil volume)
K(i) = Soil permeability for soil layer (i) (inches/hour)
CN2 = SCS curve number parameter
EPMAX = Potential transpirative uptake of the soil (inches/day)
k_o = Unsaturated hydraulic conductivity at field capacity (inches/hour)
SEP = Soil evaporation parameter (inches/day)

Table 2. Leaf-Area Index (LAI) Values Used for Calibration of the Soil Moisture Component and for Weather Modification Simulations

Grass		Corn	
Day of Calendar Year	LAI	Day of Calendar Year	LAI
1	1.15	1	0.00
15	1.15	135	0.00
56	1.50	150	0.50
79	2.00	160	0.75
100	2.25	170	1.30
122	2.35	185	2.40
156	2.45	195	3.00
212	2.45	205	3.20
253	2.35	225	3.00
278	2.20	245	2.00
300	1.95	260	1.00
329	1.55	275	0.00
366	1.15	366	0.00

Table 3. Distribution of Crop Water Uptake from the Soil for Maximum Crop Development (Percent of Total Transpiration)

	Soil Layer						
Crop Type	1	2	3	4	5	6	7
Grass	25	40	13	10	7	3	2
Corn	22	18	14	14	20	9	3

The calibration procedure used is a modified version of the Hooke-Jeeves nonlinear optimization scheme (Bazaraa and Shetty, 1979). In this technique, discrete adjustments are made individually to each of the parameters in order to search for a direction of improvement in the solution. Once a pattern of change in the parameters is found that promotes an improved solution in the objective function, a line search is conducted in the composite direction of improvement Additional iterations of the procedure are performed until either the termination criterion of the objective function is met or all the termination criteria for the individual parameters are met.

The starting values of each of the parameters for the calibration procedure were taken primarily from soil survey reports (Mount, 1982; Hinkley, 1978), and also from USDA (1970,1980) and Peters and Bartelli (1958). Table 1 lists the initial values used for each of the parameters, and the values following calibration. Both soils showed a reduction in soil permeability following the calibration procedure. The greatest amount of reduction in the objective function was caused by modifications in the parameters affecting available soil moisture (field capacity minus wilting point) and the factors controlling crop water uptake (such as EPMAX).

Soil moisture values estimated from the calibrated version of the soil moisture component of the PWM are compared to the observed data used for calibration in figures 5 and 6. The values of the objective function for the Flanagan and Drummer soils under these conditions are 1.4093 and 0.2273, respectively. These values were developed by setting initial conditions for the PWM soil moisture component and letting the component run unaffected for the duration of the soil moisture records. The ability of the model to approximate the observed soil moisture conditions at the end of three or four years as well as it does at the beginning of the soil moisture record is an indication of the model's fidelity.

When the model is run in a predictive mode (i.e., when the soil moisture status is updated to reflect the most recent measured condition), the objective function values are reduced to 0.8894 and 0.1995 for the Flanagan and Drummer soils, respectively. These values of error (as given by the objective function) for the predictive mode of simulation are 63.1 and 87.8%, respectively, of the error during the normal mode of simulation. The error that occurs during the predictive mode must come primarily as a result of short-term fluctuations between the model and the observed data, because the model is continually being reset to reflect the present soil moisture situation. When the model operates in the normal mode (without any updating of conditions), the short-term errors will be present along with long-term errors associated with the model's inability to represent seasonal and annual changes in the soil moisture. The fact that the error associated with the normal mode is not significantly greater than the error associated with the predictive mode shows that the model performs well in representing the long-term soil moisture changes.

An examination of figures 5 and 6 illustrates the ability of the model to match the measured soil moisture conditions for the Flanagan and Drummer soils. However, there are several periods for which the values estimated by the model are significantly different from the measured values. Four major factors may cause these differences between the model results and the observed values:

1. The model is not developed to simulate conditions in which the water table inundates the soil column. For this reason there may be periods in the early spring when the model underestimates the total water content of the soil. This is especially noticeable for the Flanagan soil (figure 5) for the spring months in 1984 and 1985 and for the Drummer soil (figure 6) in 1984.

2. Under normal operating conditions the neutron probe that measures the soil moisture data sometimes wanders from the original calibration setting and requires recalibration. Because calibration is not exact, the probe may provide different absolute values from one period to another for the same level of water content in the soil. This is evident from unexplained differences in the

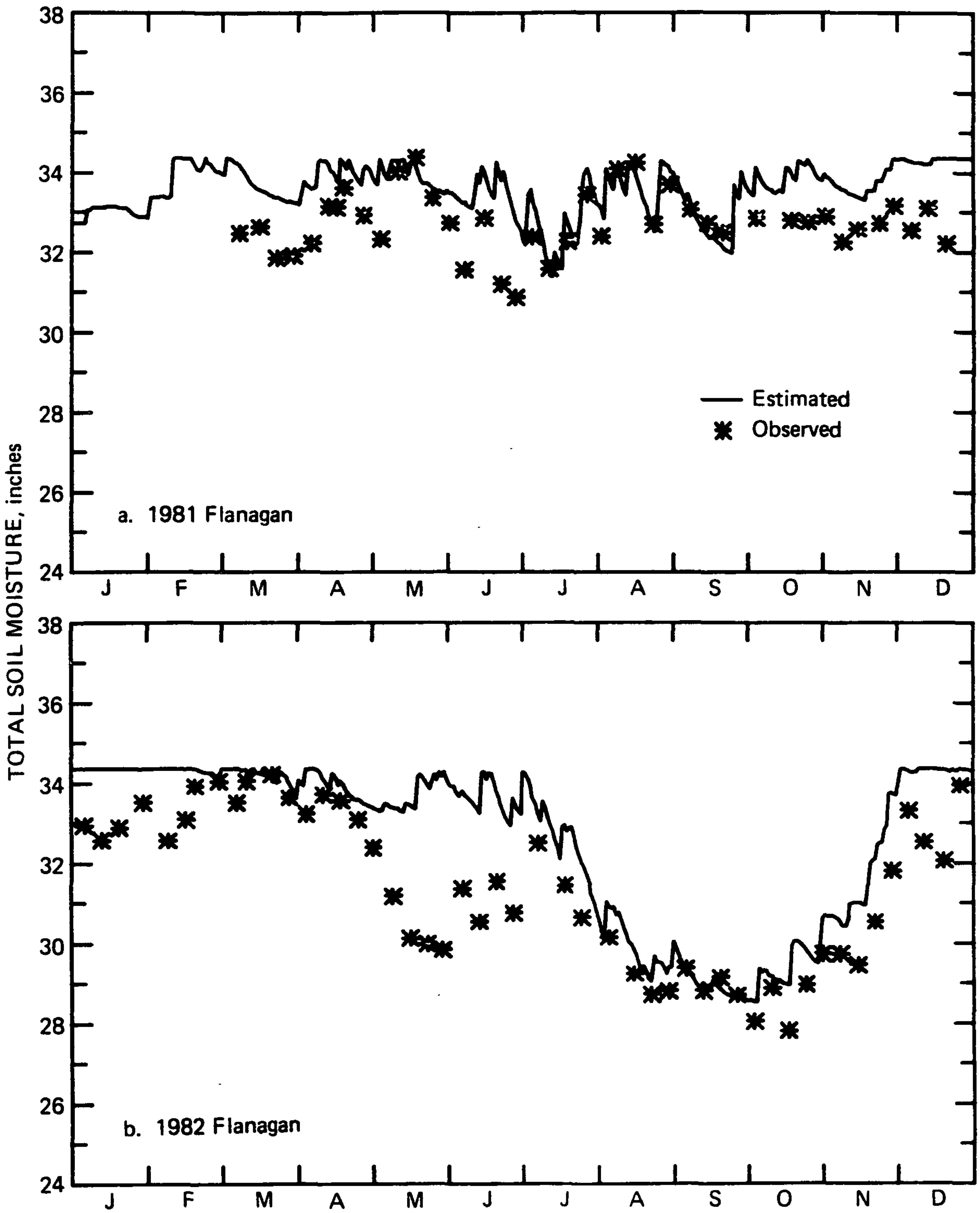

Figure 5. Estimated and observed total soil moisture values for Flanagan soil at Bondville, IL, for a) 1981, b) 1982, c) 1983, d) 1984, and e) 1985

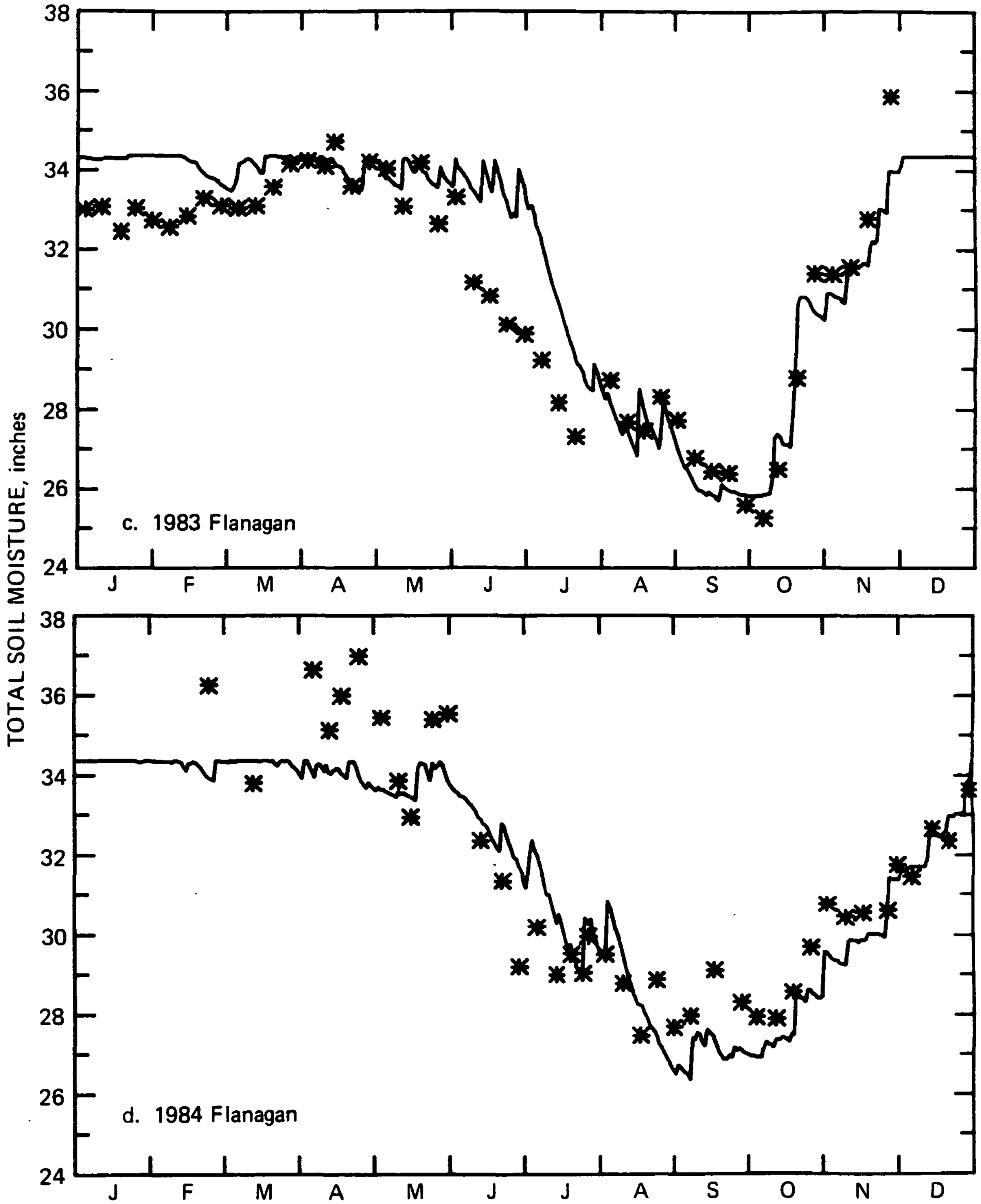

Figure 5. Continued

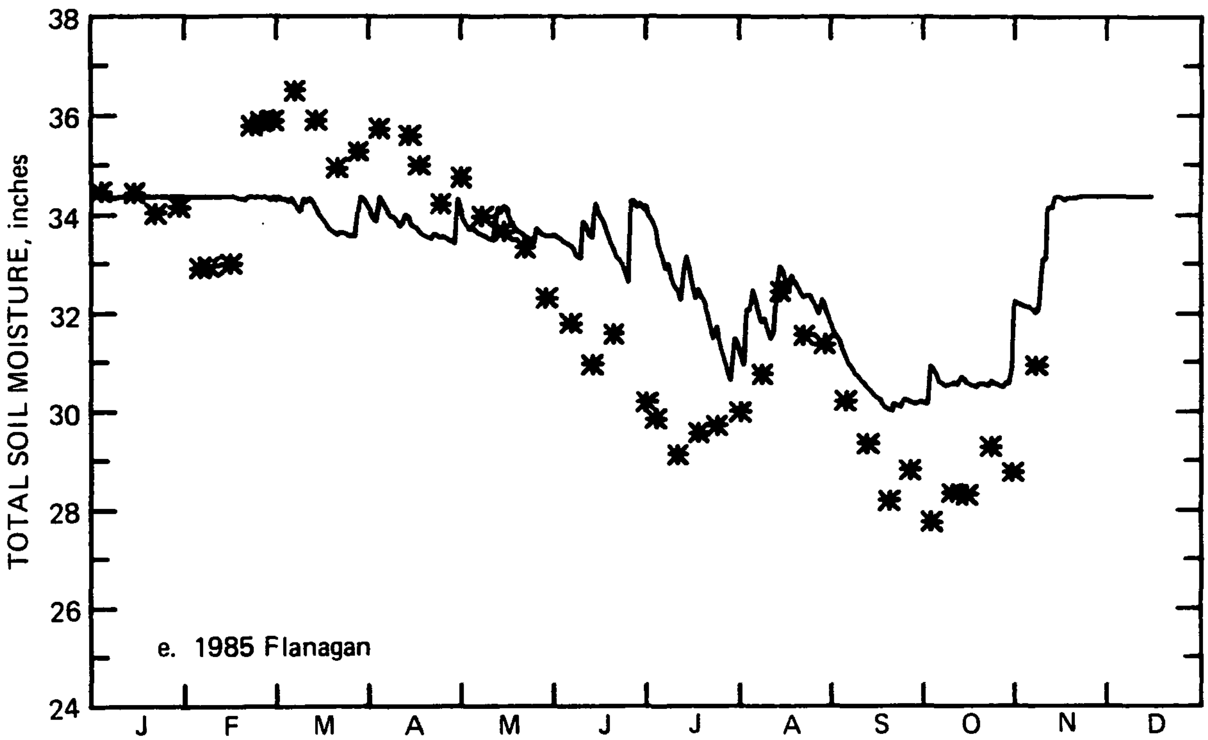

Figure 5. Concluded

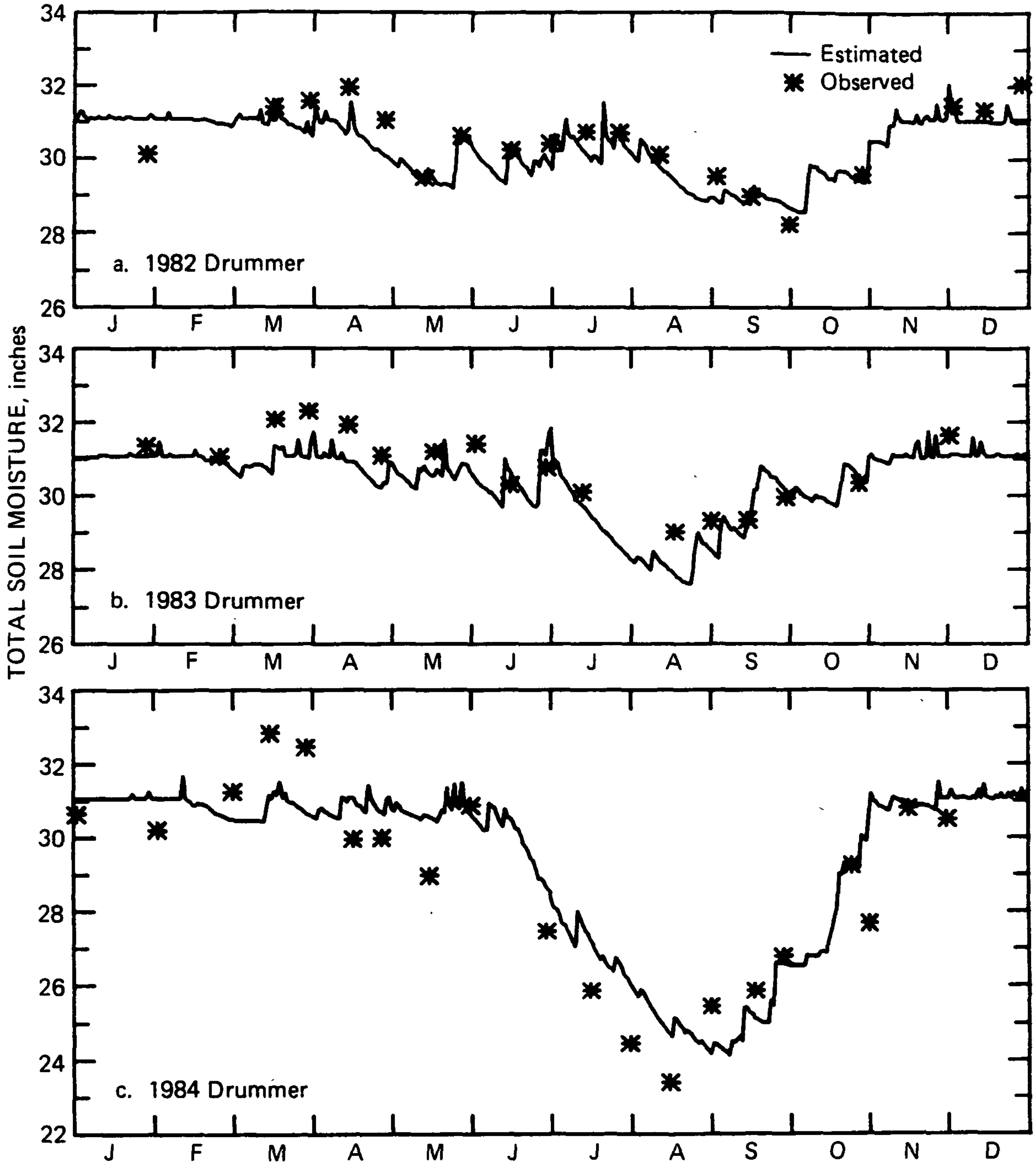

Figure 6. Estimated and observed total soil moisture values for Drummer soil at DeKalb, IL, for a) 1982, b) 1983, and c) 1984

absolute values of observations during periods in which the soil is suggested to be at or above field capacity. For example, the observed soil moisture values for the Flanagan soil at Bondville (figure 5) are markedly higher for the wet periods of 1984 and 1985 than for corresponding periods in 1981 through 1983. The model, meanwhile, provides an unvarying constant value for the major soil moisture parameters.

3. The calibration was performed by using a standard curve to describe the changes in the leaf-area index, which describes plant growth. If, in reality, the time of planting of the crop differs from the standard value, or if the field conditions result in an abnormally fast or slow crop growth, the standard representation may not be appropriate. Under conditions where the crop growth is faster than the standard value, the model can be expected to underestimate crop water use, thereby overestimating total soil moisture. In the same manner, any other incomplete information concerning crop conditions at the site of the soil moisture probe may potentially cause an erroneous representation by the model.

4. The precipitation information used by the model may not be accurate for the site where the soil moisture observations occur. This may be the case for the Flanagan soil in 1985, when the measured precipitation at Urbana is considerably higher than what appears to be the actual rainfall condition at the Bondville area, as indicated by both the soil moisture readings and the streamflow information along the Kaskaskia Ditch. In the same manner, any misrepresentation of the daily infiltration amount caused by the SCS infiltration procedure used in the model will lead to differences in the modeled soil moisture.

Any of the problems listed above may cause some calibrated values of the soil moisture model to differ from the expected values. The variance from an expected or "true" value may be reduced if the total number of soil moisture observations is increased. This would not reduce the problems, but would reduce the bias caused by any one deviation. For this reason, the calibrated model for the Flanagan soil may be expected to be superior to the Drummer soil moisture model.

Calibration of the Ground Water Component

The PWM ground water component by itself is a fully distributed-parameter sub-model and needs minimal calibration. For the execution of the ground water component, information is needed on the storage coefficient (S) and coefficient of permeability (K) (or hydraulic conductivity) for each soil type within the watershed; elevations of land and impermeable layer (Z); initial water-table levels (h0); boundary conditions; locations of the channel elements, and the recharge factor for each element; deep percolation values for each soil type (QP) (from the soil moisture component); dimensions for the watershed and grid formation; time increment; and depth of drainage tiles (d_t) and their maximum rate of drainage (C_t).

Recharge factor is a function of permeability (PERM) and thickness (TC) of the channel bottom deposits, and channel geometry. Most of these parameters are discussed in detail by Durgunoglu et al. (1987).

The storage coefficient and coefficient of permeability are measurable parameters. However, no field measurements were available in the watershed for the upper glacial drift (Wisconsinan) where our modeling interest was concentrated. These two parameters were calibrated with the soil moisture component for the top 6 feet of soil. However, subsurface conditions were expected to be different from the conditions near the surface (as also indicated by preliminary runs), and some calibration was needed with the ground water component

Other parameters calibrated with the ground water component are permeability and thickness of the channel bottom deposits (PERM and TC, and tile-drainage coefficients (C_t). In general PERM values are lower than K values since they may include values for fine material. TC values may vary between 0.1 to 0.5 foot, but with such small channel geometry and low flows, these values are more likely to be at the lower end of this range. The tile-drainage coefficient indicates the maximum amount of water that can be drained from a tiled element and usually depends on the physical condition of the tiles and the design drainage criterion.

Depth of drainage tiles was not calibrated because this parameter is usually determined by the agricultural practice and the slope of the land. Since tiles are usually placed at or around root-depth, d_t was fixed at 5 feet in the model (maximum root depth in the soil moisture component is 6 feet).

Other than all the external data input to the ground water component, there are a few parameters that are generated within the model. For example, water-table elevations are recalculated at the end of each time step and are then used as an input for the next time step. Deep percolation values are computed within the soil moisture component for each time step, and used by the ground water component as the major water intake to the component Since the ground water component uses the output from the soil moisture component as data input calibration of the soil moisture component had to precede the calibration of the ground water component

The parameters of the ground water component were calibrated to match the observed baseflow values (during low-flow periods). During low-flow periods, streamflow consists mainly of baseflow or ground-water infiltration into the stream, and flow from tile drainage. Since the ground water component computes both ground-water infiltration into the streambed and the tile drainage contribution to the stream, the combination of these two processes should match the observed baseflows. If there is surface runoff, it is estimated by the soil moisture component and added to the baseflow value to yield the total streamflow.

In flat watersheds like the Kaskaskia Ditch watershed, streamflow consists mainly of ground-water infiltration and tile drainage. Therefore ground-water levels give a good indication of the streamflows and the total soil moisture. The total soil moisture and the deep percolation values for Flanagan soil, estimated by the soil moisture component for the period 1982-1984, are illustrated in figure 7, together with the ground-water elevations of the same period obtained from an observation well near the basin. It is clear from figure 7 that the correlation between the ground-water elevations and deep percolation estimates is very good.

Streamflow records at Bondville between Water Years 1983 and 1985 were used for calibrating the parameters of the ground water component. This period was chosen because observed soil moisture values in that area were available for Flanagan soil. These years were also average years considering total precipitation, climate conditions, and streamflows. Water years were preferred over calendar years for calibrating the ground water component, because streamflows usually start and end with low flows within one water year, and this is very convenient for determining initial conditions.

Initial water-table conditions were determined by choosing an initial configuration close to the land surface and then running the model recursively over the same year. This procedure would converge to a steady water-level configuration after a few cycles. This configuration was then used as the initial water-table condition. Daily percolation values, computed by the soil moisture component, were input into the ground water component, and calibration runs were executed by changing the parameters systematically until the estimated daily streamflows matched the observed values.

In figure 8, observed and estimated daily streamflow values are illustrated for Water Years 1983 through 1985. Estimates of streamflows during winter months are not good because snow precipitation is not modeled in the PWM. This usually causes overestimation since the model cannot handle the delayed contribution of snowmelt. Unusually high estimates that are usually observed during the summer season occur because of thunderstorms that might have not passed over the entire watershed but were recorded at the Urbana station. These unusually high estimates are the result of overestimated surface runoff and have no effect on the baseflow estimates.

Estimated (Q_{est}) and observed (Q_{obs}) total streamflows at Bondville for Water Years 1983 through 1985 are given in table 4.

The values of the parameters that are calibrated and used in the ground water component are shown in tables 5 and 6. In table 5 subsurface soil and tile-drainage parameters are given. The parameters that were used in the ground water component for calculation of channel infiltration are given in table 6.

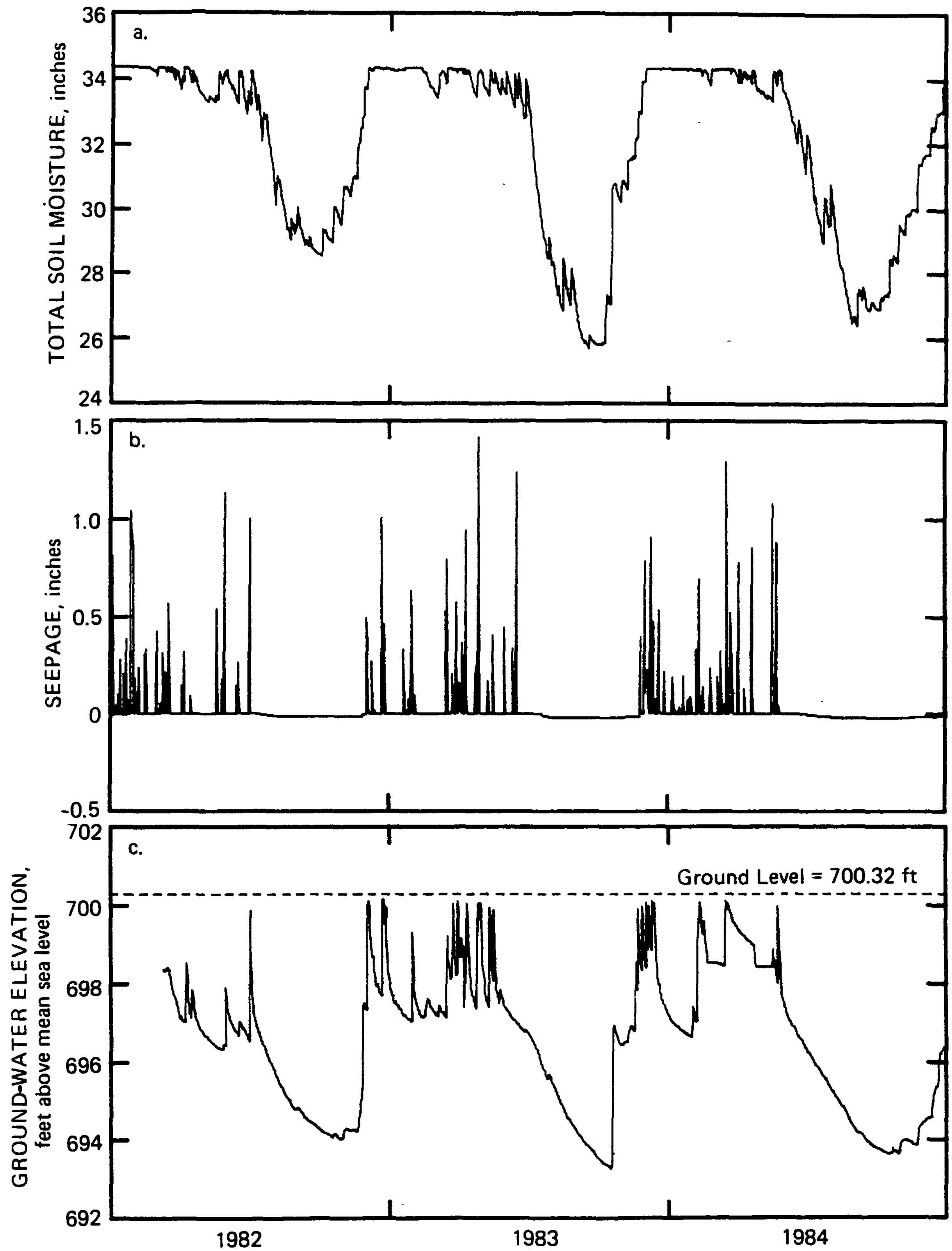

Figure 7. a) Estimated total soil moisture for Flanagan soil, b) estimated seepage for Flanagan soil, and c) ground-water elevations recorded near Bondville

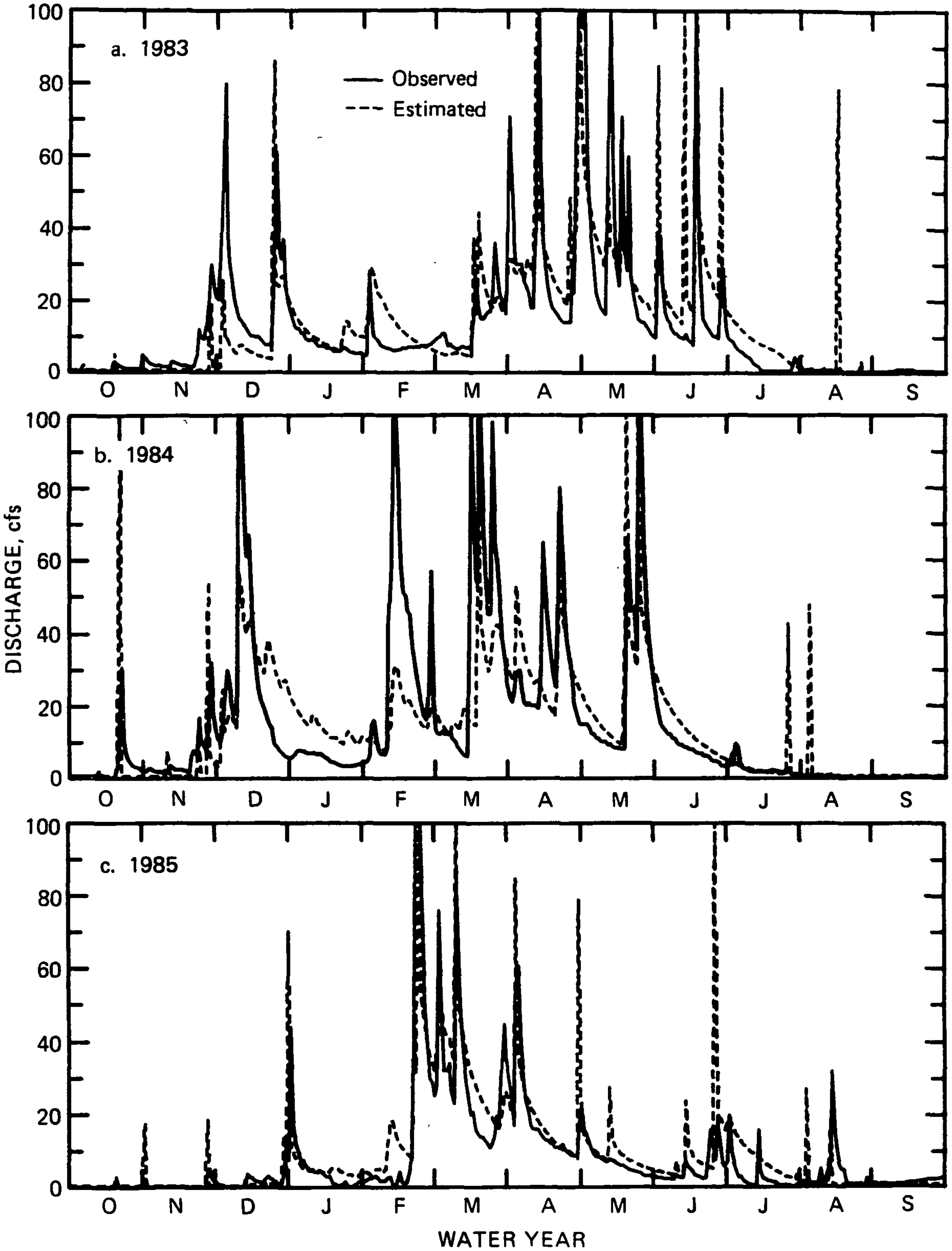

Figure 8. Observed and estimated streamflows at Bondville for Water Years a)1983, b) 1984, and c) 1985

Table 4. Estimated and Observed Total Streamflow Values at Bondville, Water Years 1983-1985

Water Year	Total Streamflow (in.) Q_{est}	Q_{obs}
1983	17.51	15.48
1984	17.90	17.52
1985	11.42	9.37

Table 5. Soil and Tile Drainage Parameters Calibrated with the Ground Water Component

	Soil Parameters		Tile Drainage Parameters	
Soil Type	Permeability Coefficient (K) (gpd/ft^2)	Storage Coefficient	d_t* (feet)	c_t (in./day)
Flanagan	16.5	0.3	5.0	0.1
Drummer	16.0	0.3	5.0	0.1

* Not a calibrated parameter
d_t = Depth of drainage tiles
c_t = Maximum rate of tile drainage

Table 6. Channel Types and Their Properties Used in the Ground Water Component

Channel Type	PERM (gpd/ft^2)	TC (feet)	Manning's Roughness*	Width* (feet)
1	10.0	0.1	0.05	5.0
2	10.0	0.1	0.05	15.0
3	25.0	0.1	0.75	50.0

* Not a calibrated parameter
PERM = Coefficient of permeability
TC = Thickness of the channel bottom deposits

The values of the permeability and storage coefficients calibrated by the ground water component are higher than the values calibrated by the soil moisture component. This is mainly due to the variation of soil properties in a typical vertical soil column. Topsoil has higher clay content and lower porosity than the subsurface soil, whereas deeper glacial drifts consist of a mixture of clay, sand, and gravel with slightly higher permeability and porosity.

MODEL VERIFICATION

Verification of the PWM was carried out to confirm that the model could perform satisfactorily outside the time period used for the calibration studies. It was also desirable that the PWM be able to simulate hydrologic conditions that represent meteorologically wet and dry periods, with durations varying from months to years. The dryer end of the hydrologic spectrum was of particular concern for this study, since most precipitation augmentation would be performed during low-precipitation periods. Considering these factors, two different periods were selected for verification of the PWM. These periods represented hydrologic conditions that had deviated significantly from normal conditions. The first period, which covers the years 1951 through 1954, represents a period that starts with a normal year (1951) and extends into drought conditions (1952-1954). The second period, on the other hand, which covers the years 1972 through 1975, represents a significantly wet period. Since the calibration studies had been performed by using a hydrologically normal period (1983-1985), using the two extremes of the hydrologic spectrum would complement the validation of the PWM.

The soil moisture, percolation, and streamflow values for the verification studies were all generated by using the parameters calibrated earlier. No dynamic or recursive updating of the parameter values was done. The only inputs to the model were the watershed properties and the climatic information. Since the model was operated sequentially (continuous mode), any error that might have been introduced through missing or incorrect data would have to propagate through time. Only a stable model would diminish the effects of error propagation and eventually converge to the actual values.

The verification of the model had to be based on daily streamflow records since there were no records of soil moisture for either soil type for the two time periods used in verification. The estimated and observed yearly total streamflow values at Bondville, and total precipitation values at Urbana, for the periods 1951-1954 and 1972-1975, are given in table 7.

Observed and estimated streamflow values at Bondville, and estimated total soil moisture in the top 6 feet of Flanagan and Drummer soils, are illustrated in figures 9 through 12 for the years 1951-1954. Streamflow records for 1951 (figure 9a) indicate that the total yearly discharge was 15.51 inches (3.91

Table 7. Estimated and Observed Total Streamflow Values at Bondville, and Corresponding Annual Precipitation Values at Urbana, for the Periods 1951-1954 and 1972-1975

Year	Total Streamflow (in.) Q_{est}	Q_{obs}	Precipitation (in.)
1951	14.66	15.51	38.39
1952	12.24	10.94	33.86
1953	5.37	4.59	26.09
1954	1.91	1.99	29.70
1972	16.07	14.26	42.95
1973	21.18	21.81	49.20
1974	20.36	22.07	43.58
1975	18.03	11.96	45.89

inches above average, or +3.91). The soil moisture was estimated to be at saturation level for most of that year, except during July through November. There are a few discrepancies between the observed and estimated streamflows in October and November 1951, as shown in figure 9a. These were caused by local thunderstorms that passed over either the Kaskaskia Ditch watershed or the Urbana weather station, but did not cover both areas.

The first six months of 1952 were normal, as indicated by the streamflow and soil moisture records shown in figure 10. Total streamflow for 1952 was 10.94 inches (–0.66), but most of this flow came during the first six months, and then the dry spell started. During the latter part of 1952 streamflows were low, and soil moisture levels did not reach saturation level until February 1953 (figures 10b and 11b). Any precipitation that came during the latter part of 1952 contributed only to replenishment of soil moisture and did not affect streamflows, since the ground-water levels were significantly low (as indicated by very low streamflow estimates).

During 1953 and 1954, the cumulative effect of the persistent drought could be seen in streamflow records and soil moisture estimates. Total streamflow for 1953 was 4.59 inches (–7.01). Streamflow estimates for 1953 (figure 11a) show very good correlation with the observed data. Soil moisture estimates indicate that saturation level of the Flanagan soil was reached only in February (about three months later than usual), as illustrated in figure 11b. Soil moisture conditions at the end of 1953 were low for both soil types (figures 11 a and 1 lb), and reached the lowest levels estimated for the entire 1951-1954 period.

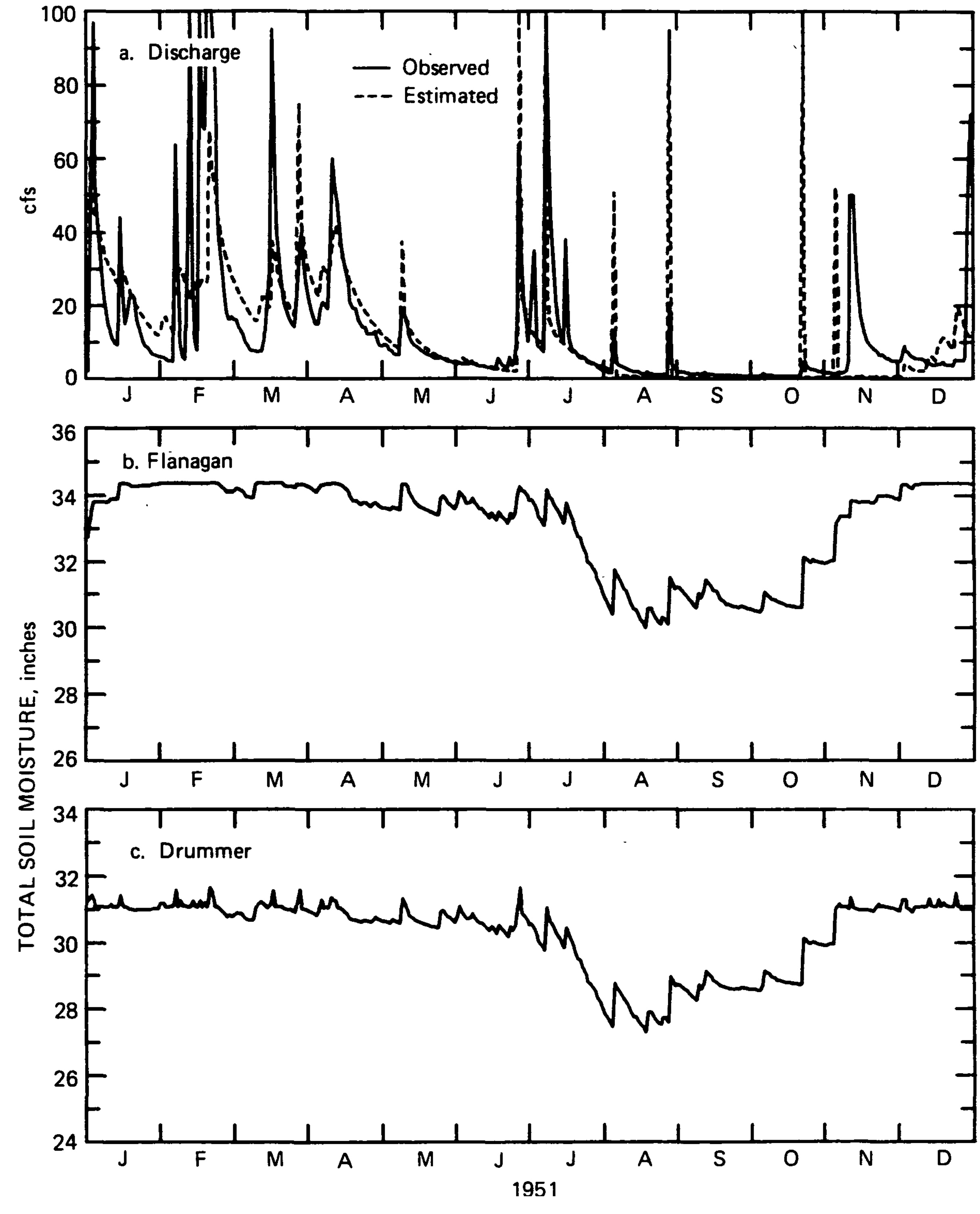

Figure 9. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1951

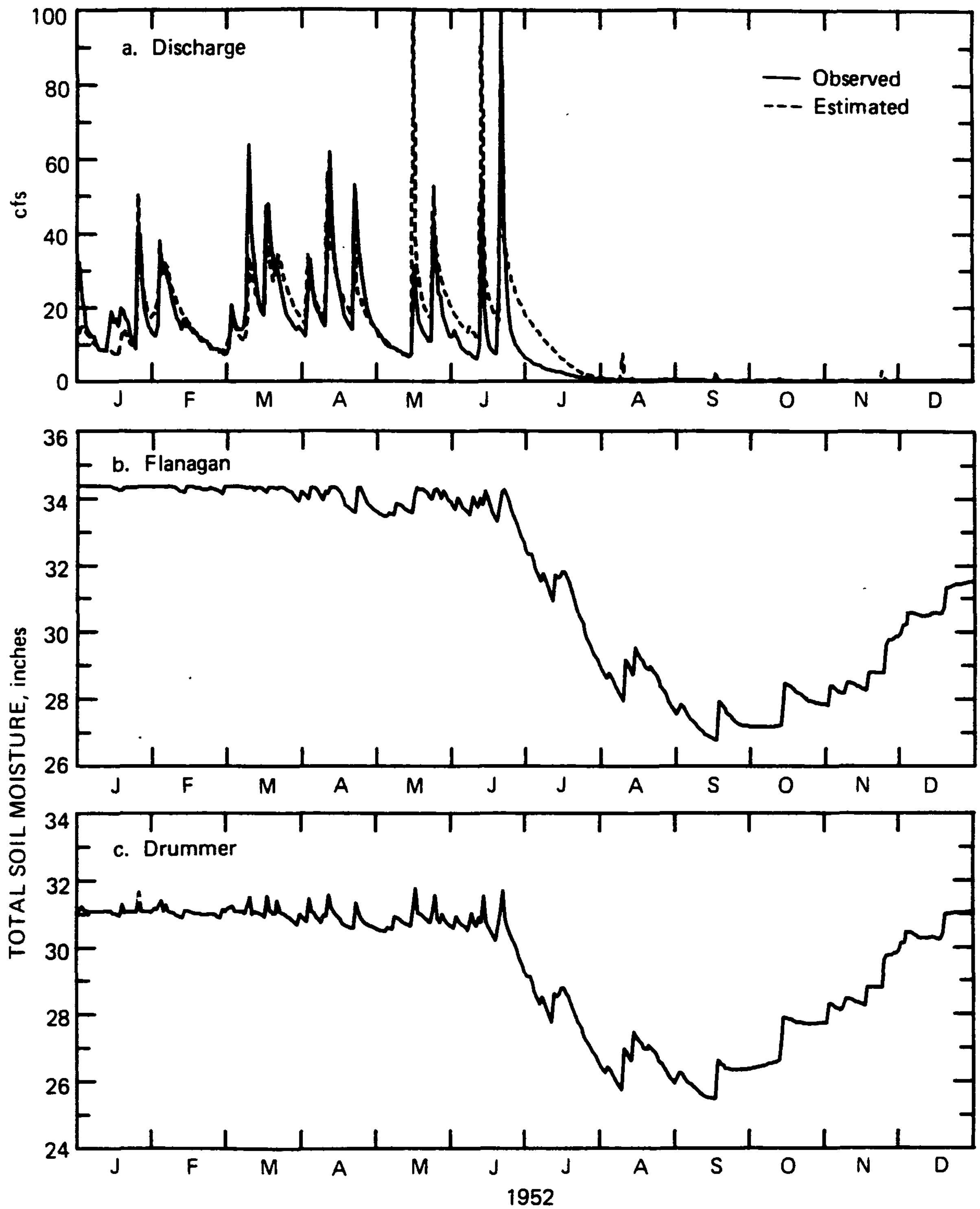

Figure 10. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1952

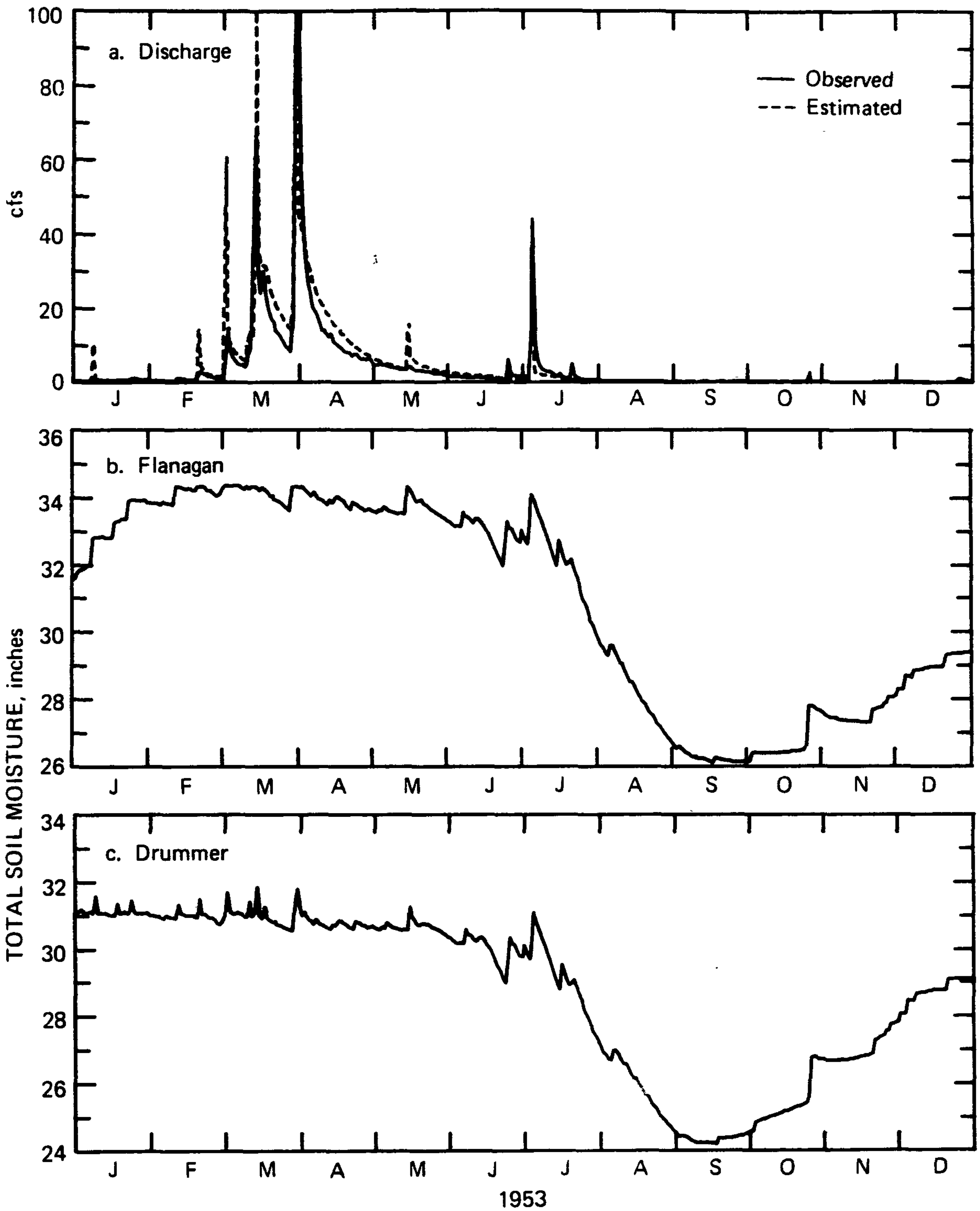

Figure 11. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1953

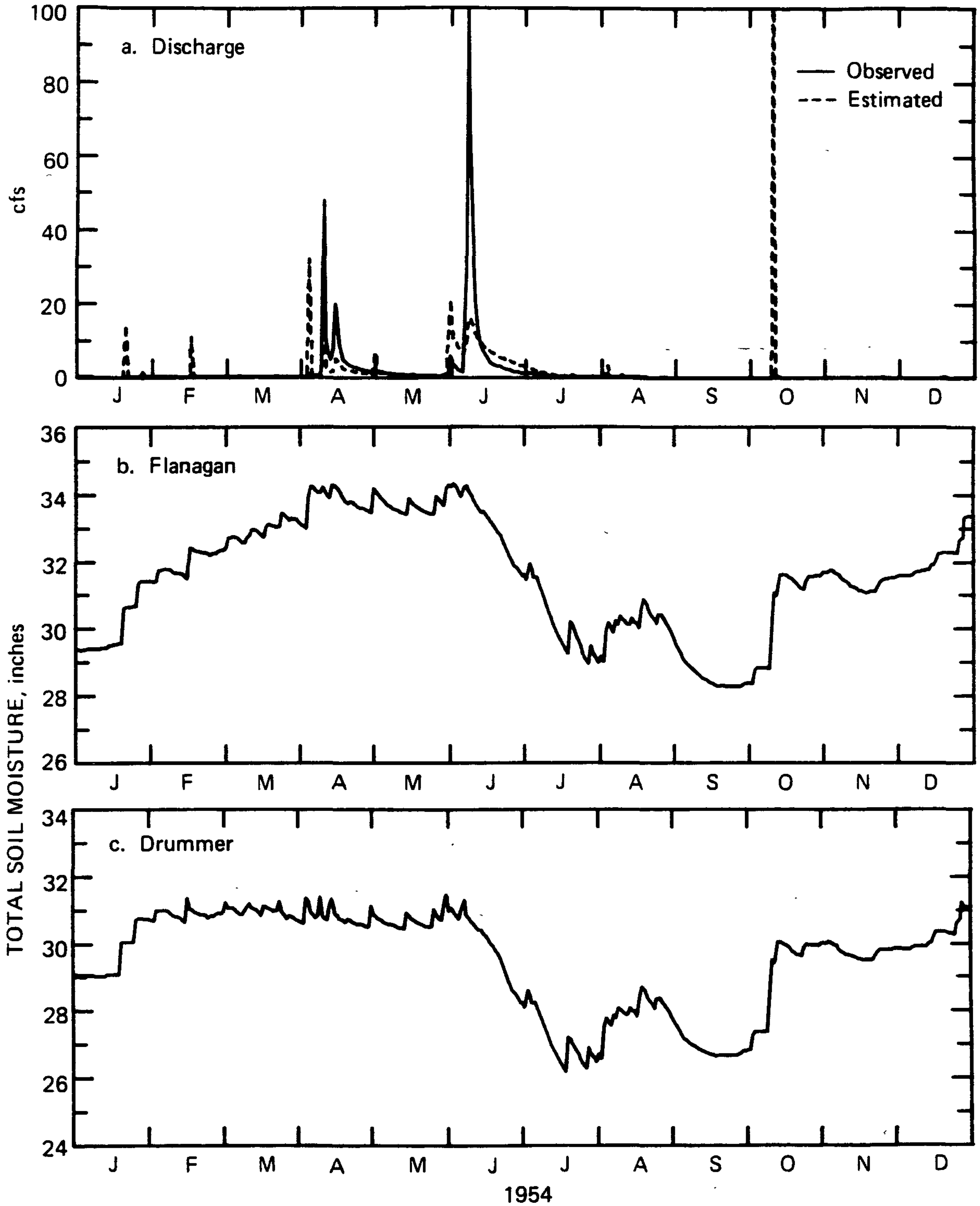

Figure 12. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1954

During 1954, a total of 1.99 inches of streamflow was observed. This is 9.61 inches lower than the average annual streamflow, and the lowest for the 1951-1954 period. Although the total streamflow in 1954 was lower than the total streamflow in 1953, there was more rain in 1954 (29.70 inches, compared to 26.09 inches during 1953). Also, total soil moisture levels did not reach saturation until April (figure 12b) and did not stay there very long. This happened because the ground-water levels were so low and the soil was so dry that the rains that came in August and after October of 1954 could only replenish the soil moisture, but could not contribute to deep percolation to feed the ground water and baseflow.

Estimated and observed streamflow values, and estimated total soil moisture in the top 6 feet of Flanagan and Drummer soils, are illustrated in figures 13 through 16 for the years 1972-1975. Streamflow estimates are good except for 1975 as shown in figures 13a, 14a, 15a, and 16a. The model showed a tendency to slightly overestimate the streamflows during long periods of saturation. This behavior is expected, since the soil moisture model was not developed to simulate conditions when soil is oversaturated. During such periods, the soil moisture component underestimates the soil moisture, and the excess water has to be directed either to streamflow by surface runoff or to baseflow via deep percolation.

A major discrepancy between the observed and the estimated streamflows is clearly visible in figure 16a. Such a discrepancy occurs if the precipitation information used by the model is not accurate for the site where the streamflow measurements are taken. Meteorological records indicate that the measured precipitation at Urbana has been considerably higher than what appears to be the actual rainfall condition at Bondville and the surrounding area. This phenomenon is illustrated by the annual precipitation values measured at Urbana and the streamflow values measured at Bondville for the periods 1951-1954 and 1972-1975, which were shown in table 7. It is clear from these values that the total precipitation at Urbana in 1975 (45.89 inches) was 2.31 inches higher than the total precipitation in 1974 (43.58 inches). Despite that, the total streamflow at Bondville in 1975 (11.96 inches) was 10.11 inches less than the total streamflow in 1974 (22.07 inches). This is a significant difference considering that the average annual flow at Bondville is 11.6 inches. Also, at Pesotum (18.6 miles downstream of Bondville) the total observed streamflow for 1975 was 16.57 inches, compared to 11.96 inches at Bondville. These facts prove the occurrence of some irregular precipitation patterns in that area during 1975.

The soil moisture and streamflow values which were simulated for model verification purposes had other uses in the weather modification simulations. The same periods (1951-1954 and 1972-1975) were also used for precipitation augmentation studies. Therefore these simulated values were used as a base for comparing the effects of precipitation augmentation on soil moisture and streamflows. All precipitation augmentations were done relative to the observed precipitation values. For example, 10% augmentation for a given day means that the observed precipitation for that day is increased by 10%. The

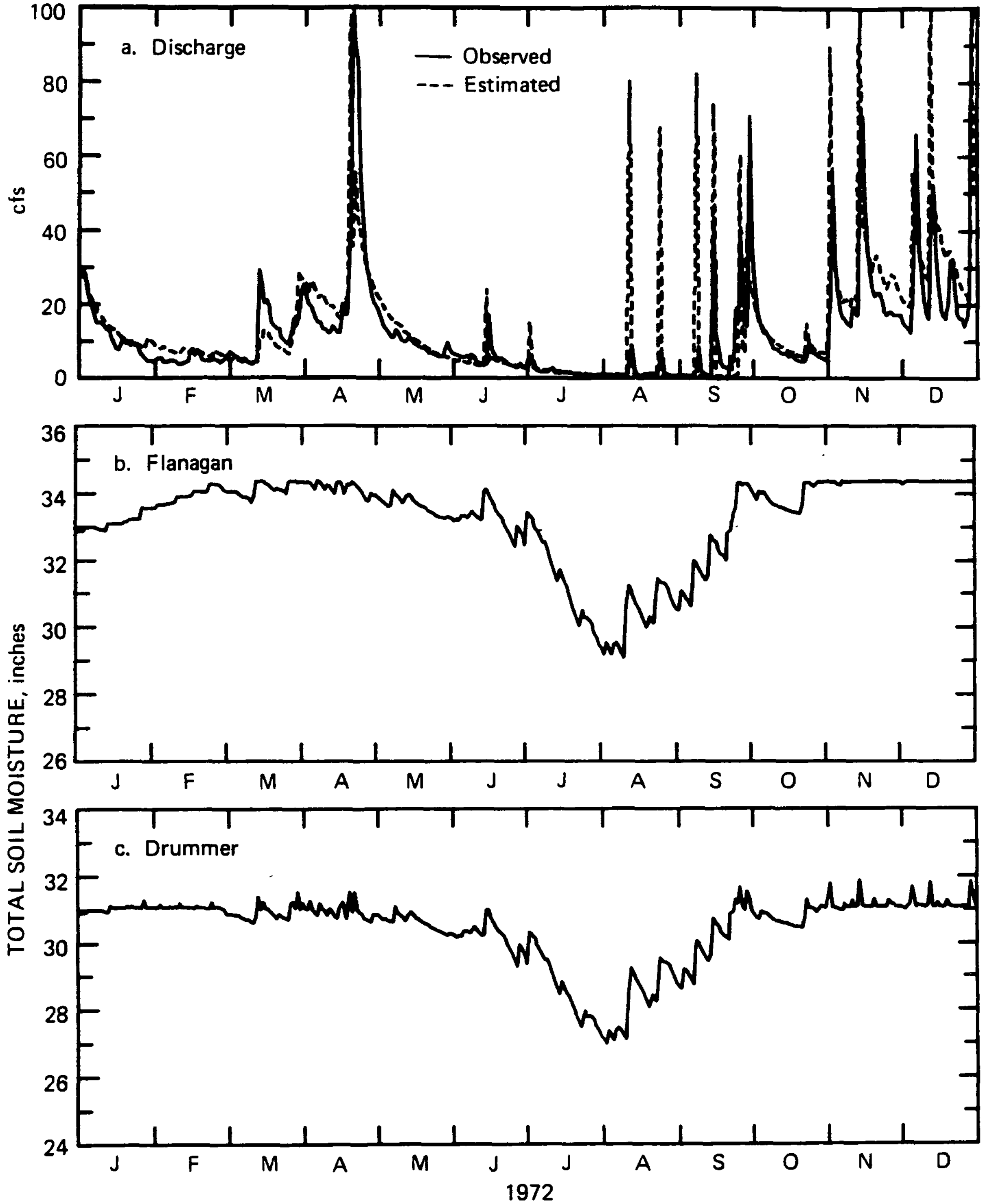

Figure 13. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1972

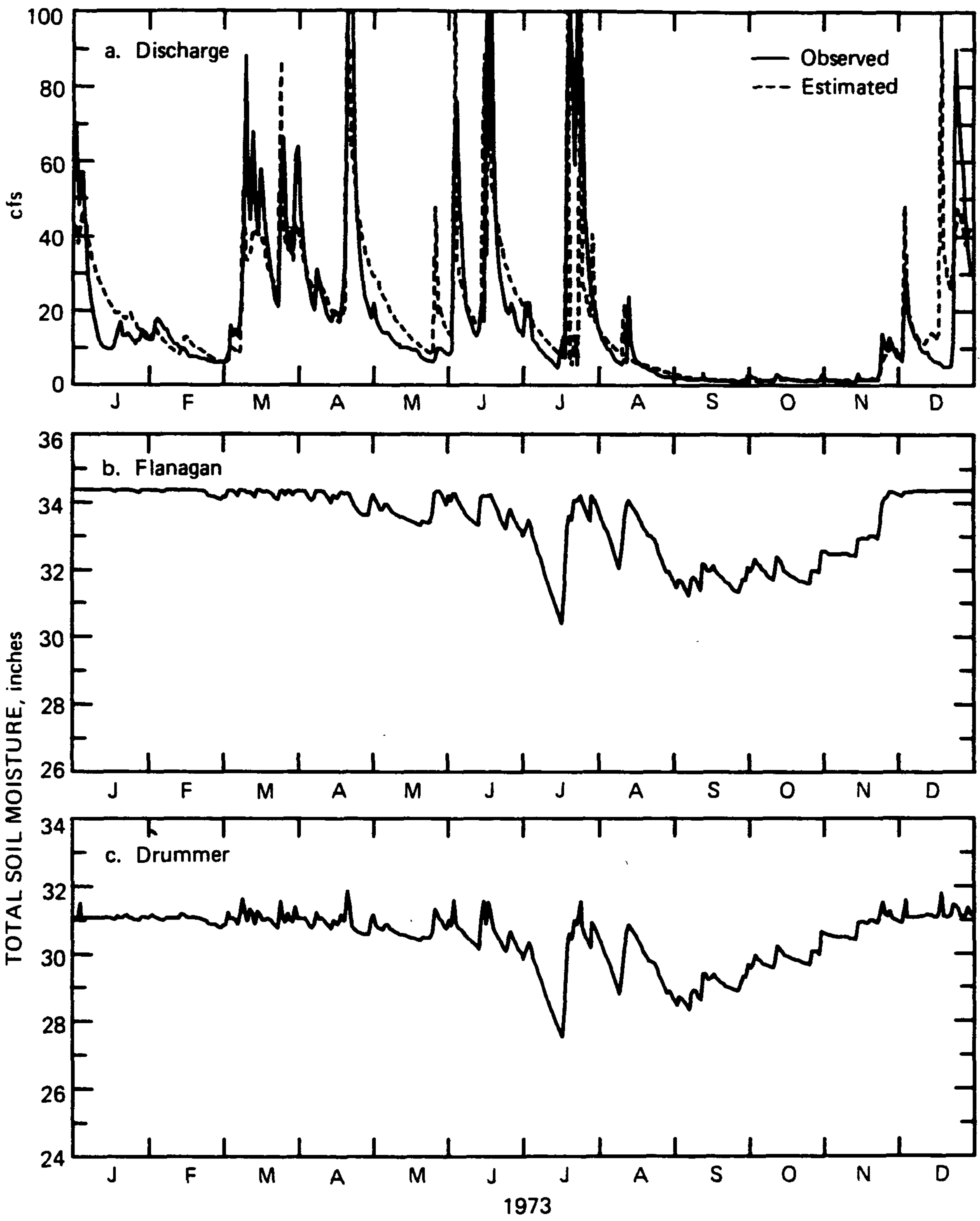

Figure 14. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1973

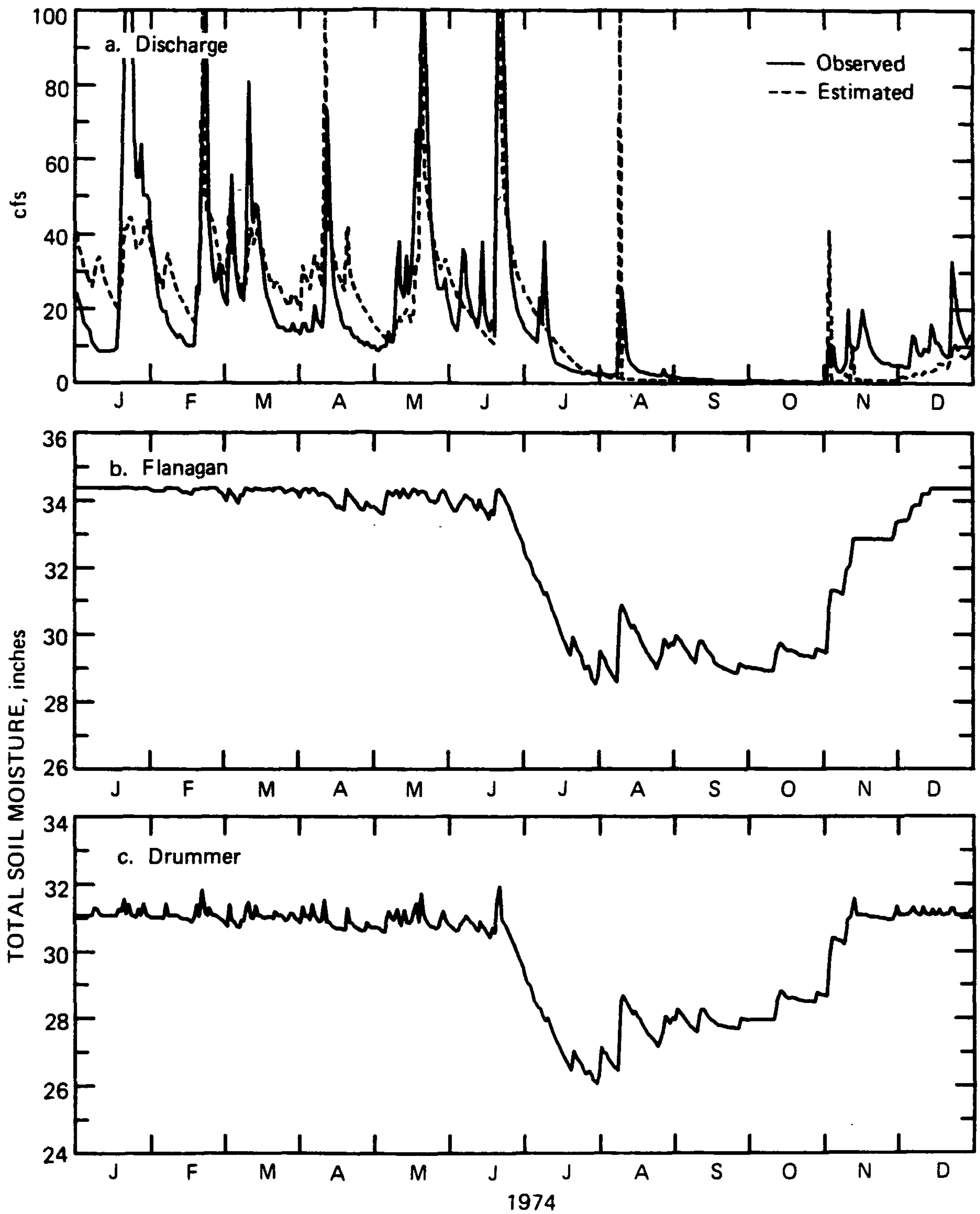

Figure 15. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1974

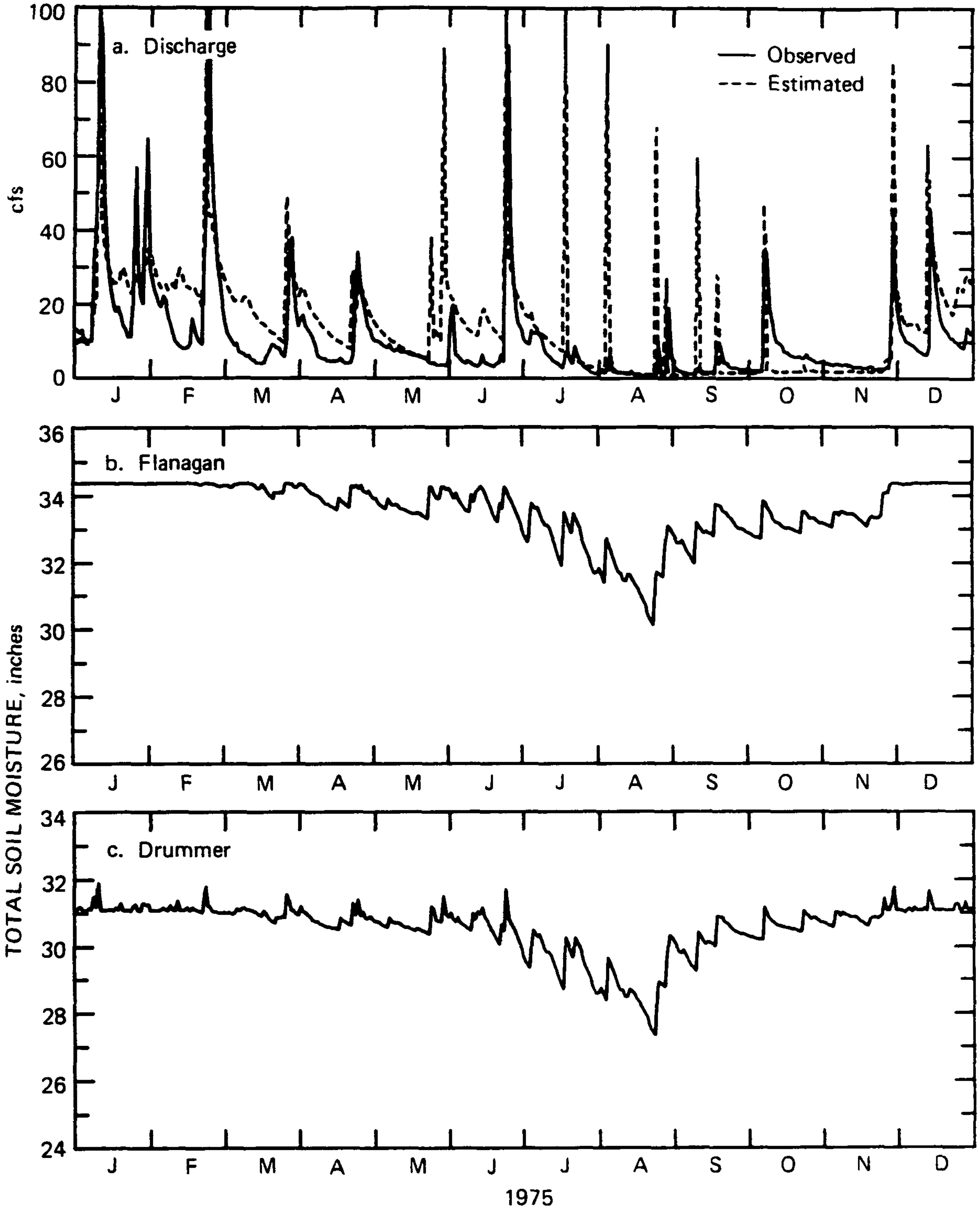

Figure 16. a) Observed and estimated streamflows at Bondville, and estimated total soil moisture values for b) Flanagan, and c) Drummer soils, for 1975

results of the augmentation simulations were then evaluated relative to the base conditions, and only the differentials between the base and the augmented conditions were considered to be important

PRECIPITATION AUGMENTATION SIMULATIONS

Precipitation augmentation was simulated for two historical periods, 1951–1954 and 1972-1975. These periods are examples of a very dry and very wet set of years, respectively, in central Illinois. For the simulations, precipitation was increased in the months of July and August for days on which rainfall was recorded. By limiting the rainfall increases to days which historically had experienced precipitation, the original distribution of rain-producing storms was maintained. Further, no evidence exists to suggest that the total number of days with rain in Midwestern convective rain conditions could be increased (Changnon and Semonin, 1975; Changnon and Hsu, 1981).

Four levels of precipitation increase were analyzed:

1. All rain-producing clouds are seeded, causing a 10% increase in all July-August rainfall.

2. All rain-producing clouds are seeded, causing a 25% increase in all July-August rainfall.

3. All rain-producing clouds are seeded (July-August), causing a 25% increase only for storms which otherwise would have daily precipitation totals in the range of 0.1 to 1.0 inches.

4. Only half of the rain-producing clouds are seeded (July-August), causing a 25% increase in rainfall for those storm events.

The range of selected increases (10 to 25%) in daily rain events is in agreement with levels used in other regions with convective rainfall regime (Weather Modification Advisory Board, 1978). Increases in 0.1- to 1.0-inch daily rain were used to match levels believed most useful to agricultural production and soil preservation (Changnon, 1981). The test of increases on 50% of the days was to measure the effect of intermittent modification.

The additional rainfall associated with each of the levels of augmentation will either 1) run off into the stream during the rainfall event, 2) evaporate from the surface or shallow layers of soil, 3) infiltrate into the soil and later be used by plants for transpiration, or 4) remain in the soil and eventually percolate down to the ground-water table. The precipitation augmentation simulation conditions and some of the processes simulated are listed in table 8.

For each of the simulated levels of precipitation augmentation, a summary has been developed describing the distribution of the additional precipitation among the various hydrologic processes. These

Table 8. Precipitation Augmentation Simulation Conditions, and Some of the Processes Simulated

Simulation Conditions:

0	No cloud seeding is done (natural condition)
1	All rain-producing clouds are seeded during July-August, causing a 10% increase in all rainfall
2	All rain-producing clouds are seeded during July-August, causing a 25% increase in all rainfall
3	All rain-producing clouds are seeded during July-August, causing a 25% increase, but only for storms which otherwise would have precipitation totals in the range of 0.1 to 1.0 inches
4	Only half of the rain-producing clouds are seeded during July-August, causing a 25% increase in rainfall for those storm events

Processes:

P =	Total Precipitation
ET =	Total Evapotranspiration
TR =	Total Transpiration
SM_{min} =	Minimum Available Soil Moisture for the Year
ASM =	Change in the Soil Moisture for the Year
Seep =	Total Deep Percolation from Soil Moisture Component
QR =	Total Surface Runoff from Soil Moisture Component
Σ(Seep + QR) =	Weighted Total of (Seep + QR) for All Soil Types
Q_{est} =	Total Streamflow Estimate from Ground Water Component
Q_{obs} =	Total Observed Streamflow

summaries are provided in tables 9 through 16, for each year of simulation, for both Flanagan and Drummer soils. Also included in these tables are the simulated values of total streamflow for the entire Kaskaskia Ditch watershed.

In each table, the increase in precipitation is distributed among four variables, as described in the following equation:

$$AP = \Delta ET + \Delta Seep + \Delta QR + \Delta(ASM) \quad (2)$$

where A represents the amount of change in the variables (as defined in table 8) from simulation condition 0. The variable of greatest concern in tables 9 through 16 is TR, the total transpiration for the year. Any increases in TR represent increased crop water use, which signifies a reduction in crop water stress. All values of transpiration are included in the total evapotranspiration value (ET). The change in the minimum soil moisture, SM_{min}, is also significant in that it represents the extent of soil moisture depletion during the growing season. The change in soil moisture for the year, ASM, will ordinarily be greater under augmented conditions, but may fluctuate from year to year since this term depends on conditions during the preceding year.

In the summary of total flows for the watershed, the term Σ (Seep + QR) is the weighted total of seepage and runoff for the entire watershed. Over a long period of time, this term will be equal to the estimated runoff of the watershed, Q_{est}. However, because of the effect of ground-water storage, these two terms will be slightly different for any one year. For example, during the drought years (1952-1954) the estimated discharge is higher than Σ (Seep + QR) because of the contribution of ground-water storage to the stream.

The simulated conditions suggest that during the wetter years (1972-1975), a great percentage of the additional rainfall will run off during storms or percolate down into ground water. For example, in 1973 the estimated increase in rainfall for simulation condition 2, the largest level of augmentation (25% for all rainfall), is 3.06 inches (table 14). Of this amount, the simulation for the Flanagan soil estimates that a total of 2.97 inches will either run off during the storm events (1.20 inches) or percolate into ground water (1.77 inches). The simulated increase in total streamflow for the Kaskaskia Ditch in 1973 is 2.86 inches. Because storm runoff is greater, potential increases in the severity of flood events should be a consideration when seeding clouds under wet-soil conditions. Virtually none of the precipitation increase is used by the crops (variable TR), and it is possible that excessively high levels of soil moisture could have a detrimental effect by inhibiting crop growth. Research has shown that overly wet summer conditions in Illinois decrease corn and soybean yields (Huff and Changnon, 1972).

For the dryer years of 1951–1954, the simulated increases in precipitation appear to be more evenly used among the various hydrologic processes. During these years, the average annual increase in summer

Table 9. Water Volumes Used in the Hydrologic Processes: Precipitation Augmentation Studies for 1951

FLANAGAN SOIL (1951)					
	Simulation Condition				
Process	0	1	2	3	4
P	38.39 (0.00)	39.23 (0.84)	40.48 (2.09)	38.93 (0.54)	38.66 (0.27)
ET	24.75 (0.00)	24.76 (0.01)	24.76 (0.01)	24.76 (0.01)	24.76 (0.01)
TR	14.01 (0.00)	14.02 (0.01)	14.02 (0.01)	14.02 (0.01)	14.02 (0.01)
SM_{min}	16.15 (0.00)	16.36 (0.21)	16.65 (0.50)	16.36 (0.21)	16.25 (0.10)
ΔSM	1.65 (0.00)	1.65 (0.00)	1.65 (0.00)	1.65 (0.00)	1.65 (0.00)
Seep	10.04 (0.00)	10.52 (0.48)	11.16(1.12)	11.49(1.45)	10.27 (0.23)
QR	1.91 (0.00)	2.27 (0.36)	2.88 (0.97)	2.00 (0.09)	1.96 (0.05)
Seep+QR	11.95(0.00)	12.79 (0.84)	14.04 (2.09)	13.49 (1.54)	12.23 (0.28)

DRUMMER SOIL (1951)					
	Simulation Condition				
Process	0	1	2	3	4
P	38.39 (0.00)	39.23 (0.84)	40.48 (2.09)	38.93 (0.54)	38.66 (0.27)
ET	23.27 (0.00)	23.28 (0.01)	23.29 (0.02)	23.29 (0.02)	23.29 (0.02)
TR	13.97 (0.00)	13.98 (0.01)	13.99 (0.02)	13.99 (0.02)	13.99 (0.02)
SM_{min}	13.18 (0.00)	13.31 (0.13)	13.54 (0.36)	13.31 (0.13)	13.25 (0.07)
ΔSM	-0.20 (0.00)	-0.20 (0.00)	-0.20 (0.00)	-0.20 (0.00)	-0.20 (0.00)
Seep	12.53 (0.00)	12.96 (0.43)	13.56 (1.03)	12.95 (0.42)	12.74 (0.21)
QR	2.67 (0.00)	3.04 (0.37)	3.70(1.03)	2.77 (0.10)	2.72 (0.05)
Seep+QR	15.20 (0.00)	16.00 (0.80)	17.26 (2.06)	15.72 (0.52)	15.46 (0.26)

TOTAL FLOWS AT BONDVILLE (1951)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	13.51(0.00)	14.33(0.82)	15.59(2.08)	14.56(1.05)	13.88 (0.37)
Q_{est}	14.66(0.00)	16.09(1.43)	17.64(2.98)	16.30(1.64)	15.61 (0.95)
Q_{obs}	15.48 (0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

Table 10. Water Volumes Used in the Hydrologic Processes: Precipitation Augmentation Studies for 1952

FLANAGAN SOIL (1952)					
	Simulation Condition				
Process	0	1	2	3	4
P	33.86 (0.00)	34.35 (0.49)	35.07 (1.21)	34.70 (0.84)	34.28 (0.42)
ET	27.19 (0.00)	27.44 (0.25)	27.73 (0.54)	27.63 (0.44)	27.41 (0.22)
TR	15.54 (0.00)	15.70(0.16)	15.90 (0.36)	15.86 (0.32)	15.70 (0.16)
SM_{min}	12.94 (0.00)	13.20(0.26)	13.59 (0.65)	13.36 (0.42)	13.15 (0.21)
ΔSM	-2.83 (0.00)	-2.62 (0.21)	-2.33 (0.50)	-2.50 (0.33)	-2.67 (0.16)
Seep	8.41 (0.00)	8.42 (0.01)	8.47 (0.06)	8.44 (0.03)	8.42 (0.01)
QR	1.07(0.00)	1.09(0.02)	1.18(0.11)	1.11(0.04)	1.09 (0.02)
Seep+QR	9.48 (0.00)	9.51 (0.03)	9.65 (0.17)	9.55 (0.07)	9.51 (0.03)

DRUMMER SOIL (1952)					
	Simulation Condition				
Process	0	1	2	3	4
P	33.86 (0.00)	34.35 (0.49)	35.07(1.21)	34.70 (0.84)	34.28 (0.42)
ET	25.22 (0.00)	25.34(0.12)	25.46 (0.24)	25.44 (0.22)	25.34 (0.12)
TR	15.59 (0.00)	15.69 (0.10)	15.80 (0.21)	15.78 (0.19)	15.70(0.11)
SM_{min}	11.36(0.00)	11.58(0.22)	11.91(0.55)	11.72(0.36)	11.55(0.19)
ΔSM	-0.01 (0.00)	0.02 (0.03)	0.02 (0.03)	0.02 (0.03)	0.02 (0.03)
Seep	6.90 (0.00)	7.16 (0.26)	7.63 (0.73)	7.38 (0.48)	7.12 (0.22)
QR	1.67 (0.00)	1.74 (0.07)	1.88 (0.21)	1.77(0.10)	1.72 (0.05)
Seep + QR	8.57 (0.00)	8.90(0.33)	9.51 (0.94)	9.15 (0.58)	8.84 (0.27)

TOTAL FLOWS AT BONDVILLE (1952)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	9.04 (0.00)	9.22 (0.18)	9.58 (0.54)	9.36 (0.32)	9.19(0.15)
Q_{est}	12.24 (0.00)	12.57 (0.33)	12.85 (0.61)	12.63 (0.39)	12.50(0.26)
Q_{obs}	10.65 (0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

Table 11. Water Volumes Used in the Hydrologic Processes: Precipitation Augmentation Studies for 1953

FLANAGAN SOIL (1953)					
	Simulation Condition				
Process	0	1	2	3	4
P	26.09 (0.00)	26.54(0.45)	27.22(1.13)	27.16(1.07)	26.63 (0.54)
ET	24.33 (0.00)	24.50(0.17)	24.70(0.37)	24.66 (0.33)	24.57 (0.24)
TR	15.90 (0.00)	16.06(0.16)	16.25(0.35)	16.22 (0.32)	16.07 (0.17)
SM_{min}	12.28 (0.00)	12.39(0.11)	12.49(0.21)	12.48 (0.20)	12.46 (0.18)
ΔSM	-2.11 (0.00)	-2.22 (-.11)	-2.43 (-.32)	-2.26 (-.15)	-2.17 (-.06)
Seep	2.86 (0.00)	3.20(0.34)	3.78(0.92)	3.59 (0.73)	3.20 (0.34)
QR	0.99 (0.00)	1.04(0.05)	1.15(0.16)	1.14(0.15)	1.07 (0.08)
Seep + QR	3.85 (0.00)	4.24 (0.39)	4.93 (1.08)	4.73 (0.88)	4.27 (0.42)

DRUMMER SOIL (1953)					
	Simulation Condition				
Process	0	1	2	3	4
P	26.09 (0.00)	26.54(0.45)	27.22(1.13)	27.16(1.07)	26.63 (0.54)
ET	23.90 (0.00)	24.01(0.11)	24.16(0.26)	24.14(0.24)	24.02 (0.12)
TR	16.40 (0.00)	16.49 (0.09)	16.63 (0.23)	16.61 (0.21)	16.49 (0.09)
SM_{min}	10.10 (0.00)	10.15(0.05)	10.25(0.15)	10.23(0.13)	10.16 (0.06)
ΔSM	-1.93 (0.00)	-0.19(1.74)	-1.89(0.04)	-1.90 (0.03)	-1.93 (0.00)
Seep	2.58 (0.00)	2.84(0.26)	3.19(0.61)	3.16(0.58)	2.88 (0.30)
QR	1.47 (0.00)	1.55 (0.08)	1.69 (0.22)	1.69(0.22)	1.58(0.11)
Seep + QR	4.05 (0.00)	4.39 (0.34)	4.88 (0.83)	4.85 (0.80)	4.46 (0.41)

TOTAL FLOWS AT BONDVILLE (1953)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	3.95 (0.00)	4.31 (0.36)	4.91 (0.96)	4.79 (0.84)	4.46 (0.51)
Q_{est}	5.37 (0.00)	6.31 (0.94)	6.91 (1.54)	6.72 (1.35)	6.32 (0.95)
Q_{obs}	4.54 (0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

Table 12. Water Volumes Used in the Hydrologic Processes: Precipitation Augmentation Studies for 1954

FLANAGAN SOIL (1954)					
	Simulation Condition				
Process	0	1	2	3	4
P	29.70 (0.00)	30.46 (0.76)	31.60 (1.90)	31.00(1.30)	30.36 (0.66)
ET	25.92 (0.00)	26.12 (0.20)	26.36 (0.44)	26.26 (0.34)	26.14 (0.22)
TR	15.19 (0.00)	15.30(0.11)	15.45(0.26)	15.39 (0.20)	15.34 (0.15)
SM_{min}	14.15 (0.00)	14.67 (0.52)	15.22 (1.07)	15.02 (0.87)	14.66(0.51)
ΔSM	3.63 (0.00)	3.86(0.23)	4.24(0.61)	4.03 (0.40)	3.81 (0.18)
Seep	-0.37 (0.00)	-0.11(0.26)	0.30(0.67)	0.12(0.49)	-0.07 (0.30)
QR	0.52 (0.00)	0.58(0.06)	0.69(0.17)	0.59 (0.07)	0.56 (0.04)
Seep + QR	0.15 (0.00)	0.47 (0.32)	0.99 (0.84)	0.71 (0.56)	0.49 (0.34)

DRUMMER SOIL (1954)					
	Simulation Condition				
Process	0	1	2	3	4
P	29.70 (0.00)	30.46 (0.76)	31.60 (1.90)	31.00(1.30)	30.36 (0.66)
ET	24.71 (0.00)	24.79(0.08)	24.90(0.19)	24.85 (0.14)	24.78 (0.07)
TR	15.78 (0.00)	15.86(0.08)	15.97(0.19)	15.92(0.14)	15.86 (0.08)
SM_{min}	12.08 (0.00)	12.14(0.06)	12.23(0.15)	12.23 (0.15)	12.16 (0.08)
ΔSM	1.94 (0.00)	1.92 (-.02)	1.88 (-.06)	1.89 (-.05)	1.92 (-.02)
Seep	1.99 (0.00)	2.62 (0.63)	3.54 (1.55)	3.13(1.14)	2.57 (0.58)
QR	1.02 (0.00)	1.09 (0.07)	1.24 (0.22)	1.09(0.07)	1.06 (0.04)
Seep + QR	3.01 (0.00)	3.71 (0.70)	4.78 (1.77)	4.22 (1.21)	3.63 (0.62)

TOTAL FLOWS AT BONDVILLE (1954)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	1.52 (0.00)	2.03 (0.51)	2.85 (1.33)	2.39 (0.87)	2.00 (0.48)
Q_{est}	1.91 (0.00)	2.71 (0.80)	2.99 (1.08)	2.83 (0.92)	2.69 (0.78)
Q_{obs}	1.95 (0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

Table 13. Water Volumes Used in the Hydrologic Processes:
Precipitation Augmentation Studies for 1972

FLANAGAN SOIL (1972)					
	Simulation Condition				
Process	0	1	2	3	4
P	42.95 (0.00)	43.78 (0.83)	45.02 (2.07)	43.83 (0.88)	43.39 (0.44)
ET	25.84 (0.00)	25.91 (0.07)	25.98 (0.14)	25.93 (0.09)	25.89 (0.05)
TR	15.21 (0.00)	15.27(0.06)	15.34(0.13)	15.29 (0.08)	15.26 (0.05)
SM_{min}	15.25 (0.00)	15.52 (0.27)	15.80 (0.55)	15.59 (0.34)	15.47 (0.22)
ΔSM	1.67 (0.00)	1.67 (0.00)	1.67 (0.00)	1.67 (0.00)	1.67 (0.00)
Seep	13.08 (0.00)	13.60 (0.52)	14.32 (1.24)	13.73 (0.65)	13.41 (0.33)
QR	2.33 (0.00)	2.58 (0.25)	3.03 (0.70)	2.48 (0.15)	2.41 (0.08)
Seep + QR	15.41 (0.00)	16.18 (0.77)	17.35 (1.94)	16.21 (0.80)	15.82 (0.41)

DRUMMER SOIL (1972)					
	Simulation Condition				
Process	0	1	2	3	4
P	42.95 (0.00)	43.78 (0.83)	45.02 (2.07)	43.83 (0.88)	43.39 (0.44)
ET	24.18 (0.00)	24.23 (0.05)	24.31 (0.13)	24.26 (0.08)	24.22 (0.04)
TR	14.97 (0.00)	15.02 (0.05)	15.10(0.13)	15.06 (0.09)	15.01 (0.04)
SM_{min}	12.88 (0.00)	13.02 (0.14)	13.24 (0.36)	13.12 (0.24)	13.00 (0.12)
ΔSM	-0.18 (0.00)	-0.18 (0.00)	-0.18 (0.00)	-0.18(0.00)	-0.18 (0.00)
Seep	15.49 (0.00)	15.96 (0.47)	16.61 (1.12)	16.10(0.61)	15.80(0.31)
QR	3.37 (0.00)	3.68 (0.31)	4.19(0.82)	3.56(0.19)	3.47 (0.10)
Seep + QR	18.86 (0.00)	19.64 (0.78)	20.80 (1.94)	19.66 (0.80)	19.27 (0.41)

TOTAL FLOWS AT BONDVILLE (1972)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	17.07(0.00)	17.84(0.77)	19.01(1.94)	17.87(0.80)	17.48 (0.41)
Q_{est}	16.07(0.00)	16.77(0.70)	17.85(1.78)	16.78(0.71)	16.42 (0.35)
Q_{obs}	14.09 (0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

Table 14. Water Volumes Used in the Hydrologic Processes: Precipitation Augmentation Studies for 1973

FLANAGAN SOIL (1973)					
	Simulation Condition				
Process	0	1	2	3	4
P	49.20 (0.00)	50.43 (1.23)	52.26 (3.06)	50.52 (1.32)	49.86 (0.66)
ET	28.74 (0.00)	28.79 (0.05)	28.85(0.11)	28.84(0.10)	28.80 (0.06)
TR	15.52 (0.00)	15.55 (0.03)	15.59 (0.07)	15.59 (0.07)	15.56 (0.04)
SM_{min}	16.62 (0.00)	16.68 (0.06)	16.78(0.16)	16.78(0.16)	16.70 (0.08)
ΔSM	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Seep	17.02 (0.00)	17.77 (0.75)	18.79 (1.77)	18.09(1.07)	17.56 (0.54)
QR	3.40 (0.00)	3.84 (0.44)	4.60 (1.20)	3.56(0.16)	3.47 (0.07)
Seep+QR	20.42 (0.00)	21.61 (1.19)	23.39 (2.97)	21.65 (1.23)	21.03 (0.61)

DRUMMER SOIL (1973)					
	Simulation Condition				
Process	0	1	2	3	4
P	49.20 (0.00)	50.43 (1.23)	52.26 (3.06)	50.52(1.32)	49.86 (0.66)
ET	26.77 (0.00)	26.80(0.03)	26.85 (0.08)	26.85 (0.08)	26.81 (0.04)
TR	15.78 (0.00)	15.80 (0.02)	15.83 (0.05)	15.83 (0.05)	15.80 (0.02)
SM_{min}	13.40 (0.00)	13.46 (0.06)	13.55 (0.15)	13.55 (0.15)	13.48 (0.08)
ΔSM	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)	0.06 (0.00)
Seep	17.75 (0.00)	18.43 (0.68)	19.36(1.61)	18.74 (0.99)	18.25 (0.50)
QR	4.52 (0.00)	5.03 (0.51)	5.88 (1.36)	4.77 (0.25)	4.65 (0.13)
Seep + QR	22.27 (0.00)	23.46(1.19)	25.24 (2.97)	23.51 (1.24)	22.90 (0.63)

TOTAL FLOWS AT BONDVILLE (1973)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	21.31(0.00)	22.50(1.19)	24.28(2.97)	22.54(1.23)	22.07 (0.76)
Q_{est}	21.18(0.00)	22.30(1.12)	24.04(2.86)	22.32(1.14)	21.73 (0.55)
Q_{obs}	21.56 (0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

Table 15. Water Volumes Used in the Hydrologic Processes:
Precipitation Augmentation Studies for 1974

FLANAGAN SOIL (1974)					
	Simulation Condition				
Process	0	1	2	3	4
P	43.58 (0.00)	44.32 (0.74)	45.43 (1.85)	44.74(1.16)	44.16 (0.58)
ET	26.37 (0.00)	26.47 (0.10)	26.63 (0.26)	26.60 (0.23)	26.48(0.11)
TR	14.17 (0.00)	14.26 (0.09)	14.40 (0.23)	14.38 (0.21)	14.27 (0.10)
SM_{min}	14.74 (0.00)	14.80 (0.06)	14.91 (0.17)	14.90(0.16)	14.82 (0.08)
ΔSM	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00(0.00)	0.00 (0.00)
Seep	14.48 (0.00)	14.91 (0.43)	15.52 (1.04)	15.30 (0.82)	14.90 (0.42)
QR	2.70 (0.00)	2.91 (0.21)	3.25 (0.55)	2.79 (0.09)	2.75 (0.05)
Seep + QR	17.18 (0.00)	17.82 (0.64)	18.77(1.59)	18.09 (0.91)	17.65 (0.47)

DRUMMER SOIL (1974)					
	Simulation Condition				
Process	0	1	2	3	4
P	43.58 (0.00)	44.32 (0.74)	45.43 (1.85)	44.74(1.16)	44.16 (0.58)
ET	24.50 (0.00)	24.54 (0.04)	24.64(0.14)	24.63 (0.13)	24.55 (0.05)
TR	14.08 (0.00)	14.13 (0.05)	14.24(0.16)	14.23(0.15)	14.14 (0.06)
SM_{min}	11.96(0.00)	11.97(0.01)	12.25 (0.29)	12.24 (0.28)	12.04 (0.08)
ΔSM	0.09 (0.00)	0.09 (0.00)	0.09 (0.00)	0.09 (0.00)	0.09 (0.00)
Seep	15.30 (0.00)	15.80(0.50)	16.43 (1.13)	16.22 (0.92)	15.78 (0.48)
QR	3.60 (0.00)	3.80 (0.20)	4.18(0.58)	3.71 (0.11)	3.65 (0.05)
Seep + QR	18.90 (0.00)	19.60 (0.70)	20.61 (1.71)	19.93 (1.03)	19.43 (0.53)

TOTAL FLOWS AT BONDVILLE (1974)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	18.01(0.00)	18.67(0.66)	19.65(1.64)	18.97(0.96)	18.50(0.49)
Q_{est}	20.36(0.00)	20.83(0.47)	21.55(1.19)	20.95(0.59)	20.66 (0.30)
Q_{obs}	21.99 (0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

Table 16. Water Volumes Used in the Hydrologic Processes: Precipitation Augmentation Studies for 1975

FLANAGAN SOIL (1975)					
	Simulation Condition				
Process	0	1	2	3	4
P	45.89 (0.00)	47.02(1.13)	48.72 (2.83)	46.98 (1.09)	46.44 (0.55)
ET	27.65 (0.00)	27.65 (0.00)	27.65 (0.00)	27.65 (0.00)	27.65 (0.00)
TR	15.54 (0.00)	15.54 (0.00)	15.54 (0.00)	15.54 (0.00)	15.54 (0.00)
SM_{min}	16.29 (0.00)	16.73 (0.44)	17.28 (0.99)	16.93 (0.64)	16.61 (0.32)
ΔSM	0.00 (0.00)	0.00(0.00)	0.00(0.00)	0.00 (0.00)	0.00 (0.00)
Seep	14.56 (0.00)	15.27 (0.71)	16.27(1.71)	15.46 (0.90)	15.00 (0.44)
QR	3.65 (0.00)	4.06 (0.41)	4.76(1.11)	3.83(0.18)	3.74 (0.09)
Seep + QR	18.21 (0.00)	19.33(1.12)	21.03 (2.82)	19.29(1.08)	18.74 (0.53)

DRUMMER SOIL (1975)					
	Simulation Condition				
Process	0	1	2	3	4
P	45.89 (0.00)	47.02(1.13)	48.72 (2.83)	46.98 (1.09)	46.44 (0.55)
ET	25.35 (0.00)	25.38 (0.03)	25.39 (0.04)	25.39 (0.04)	25.37 (0.02)
TR	15.48 (0.00)	15.50 (0.02)	15.52 (0.04)	15.52 (0.04)	15.50 (0.02)
SM_{min}	13.24 (0.00)	13.49 (0.25)	13.83 (0.59)	13.61 (0.37)	13.43 (0.19)
ΔSM	-0.14(0.00)	-0.14(0.00)	-0.14(0.00)	-0.14(0.00)	-0.14(0.00)
Seep	15.70 (0.00)	16.31 (0.61)	17.19(1.49)	16.49 (0.79)	16.09 (0.39)
QR	4.85 (0.00)	5.35 (0.50)	6.14(1.29)	5.10(0.25)	4.98 (0.13)
Seep + QR	20.55 (0.00)	21.66(1.11)	23.33 (2.78)	21.59(1.04)	21.07 (0.52)

TOTAL FLOWS AT BONDVILLE (1975)					
	Simulation Condition				
Process	0	1	2	3	4
Σ(Seep + QR)	19.33(0.00)	20.45(1.19)	22.13(2.80)	20.39(1.06)	19.86 (0.53)
Q_{est}	18.03(0.00)	19.20(1.17)	21.04(3.01)	19.32(1.29)	18.69(0.66)
Q_{obs}	11.92(0.00)				

Note: Numbers in parentheses indicate increase from condition 0.
All values are in inches.
See table 8 for definitions of processes.

precipitation (given a 25% level of augmentation) is 1.58 inches. However, the maximum increase in crop transpiration during any of these years is only 0.36 inches for Flanagan soil in 1952 (table 10), and 0.23 inches for Drummer soil in 1953 (table 11). A majority of the increases in precipitation appear to stay in the soil, unused by the plants, eventually to enter the ground water through percolation (the "Seep" variable).

The average distribution of the additional precipitation into the various hydrologic processes for both the Flanagan and Drummer soils is presented in table 17. As mentioned previously, most of the additional water eventually percolates into ground water. Little of the precipitation increase tends to be used by the crop, and it is believed that this may be a result of 1) the limited amount of additional rainfall occurring during any one storm, and 2) the distribution of rainfall-producing storms within these years. This relationship between distribution of storms and crop water use is further examined in the following section.

Table 17. Average Distribution of Additional Precipitation to the Various Hydrologic Processes during Dry Years (1951-1954)

Hydrologic Process	Flanagan Soil	Drummer Soil
Soil Evaporation	6%	2%
Crop Water Use	23%	15%
Surface Runoff	16%	15%
Percolation	55%	68%

SPECIAL SIMULATION STUDIES

To study the apparently limited effect of precipitation increases on the amount of simulated crop transpiration, the model was used to simulate two special cases. In the first case, precipitation augmentation is initiated earlier in the year (during the month of June) to increase the general soil-moisture level of the soil. The second case involves the effects of irrigation on simulated crop water use. The soil-moisture component was used to simulate these cases for Flanagan soils for the three driest years analyzed previously (1953,1954, and 1983).

A crop stress index was defined for use in describing the effect of soil moisture and crop water use on crop development. The crop stress value for any one day is defined as the fractional amount of potential crop growth that is suppressed because of the lack of moisture available to the plant If, on any one day, the crop is under severe stress and no crop growth occurs, a unit value of crop stress is recorded. Severe crop stress is assumed to occur whenever actual transpiration (as limited by soil moisture) is less than 50% of the potential transpiration (Saxton et al., 1984). Partial stress is assumed to occur when the actual transpiration rate is between 50% and 80% of the potential rate. The total crop stress index is the cumulative number of crop stress values for the growing season.

Table 18 provides values of the crop stress index estimated by the soil moisture component, and the average yield for com crops in Champaign County, Illinois (obtained from the Illinois Department of Agriculture), for the years simulated by the model. A low correlation between crop stress and crop yield occurred in the period of 1950's, but these variables show a strong correlation in the 1970's and 1980's. Given these data, the crop stress index appears to be an adequate tool for evaluating the effect of soil moisture on crop yield.

Simulation of Early-Season Augmentation

For the first special simulation study, it was thought that by increasing rainfall in June as well as in July and August the soil moisture might be increased prior to the dry periods which cause the most severe stress conditions for the crops. An examination of table 19, however, indicates that the additional June

Table 18. Comparison between the Crop Stress Index and Average Com Yield for Simulated Years

Year	Crop Stress	Average Yield (bushels/year)
81	0.00	137
82	0.01	147
83	18.42	89
84	4.66	128
85	0.00	154
72	0.00	129
73	0.98	123
74	5.06	98
75	0.00	136
51	0.00	58
52	0.61	62
53	9.18	61
54	11.14	63

Table 19. Water Volumes Used in the Hydrologic Processes of the Soil Moisture Component: Precipitation Augmentation and Irrigation Simulations for Flanagan Soil

Year	Process*	No Augmentation	Irrigation (3 Inches)	Irrigation (4 Inches)	25% Augmentation (July-August)	25% Augmentation (June-August)
1953	P	26.09	29.09	30.09	27.22	27.95
	ET	24.33	26.46	27.21	24.70	24.87
	TR	15.90	17.55	17.59	16.25	16.25
	SM_{min}	12.28	13.43	13.80	12.49	12.49
	ΔSM	-2.11	-1.27	-1.04	-2.43	-2.43
	Seep	2.86	2.90	2.91	3.78	4.28
	QR	0.99	0.99	0.99	1.15	1.20
	Crop Stress Index	9.18	0.00	0.00	6.96	6.96
1954	P	29.70	32.70	33.70	31.60	32.28
	ET	25.92	27.72	27.72	26.26	26.46
	TR	15.19	16.57	16.57	15.39	15.51
	SM_{min}	14.15	15.23	15.23	15.02	15.22
	ΔSM	3.63	3.51	3.28	4.03	4.24
	Seep	-0.37	0.82	1.05	0.12	0.81
	QR	0.52	0.63	0.64	0.59	0.76
	Crop Stress Index	11.14	3.81	3.81	9.66	9.22
1983	P	50.26	53.26	54.26	51.77	54.06
	ET	30.21	32.70	33.52	30.74	30.90
	TR	18.18	20.74	21.56	18.66	18.79
	SM_{min}	12.40	12.83	12.96	12.63	13.14
	ASM	0.06	0.06	0.06	0.06	0.06
	Seep	14.29	14.63	14.76	14.86	15.58
	QR	5.65	5.82	5.87	6.05	7.46
	Crop Stress Index	18.42	3.82	1.72	14.82	14.25

* See table 8 for definitions of processes
All values are in inches

rainfall does little to increase the amount of crop water use. Even with the 2.29 inches of additional rainfall simulated for June 1983 (in addition to July-August augmentation), transpiration for that year is increased by only 0.13 inches from the July-August augmentation condition. An examination of the rainfall record for the summer of 1983 indicates that a 28-day period occurred between July 5 and August 3 in which the precipitation was only 0.30 inches. During this period there were only two days having recorded rainfall. Assuming the highest level of precipitation augmentation simulated in this study, only 0.075 inches of additional rainfall would occur during these two days. The summer of 1983 also experienced several weeks having an extremely high evapotranspiration demand.

The difference between the potential and actual transpiration simulated for this period is shown in figure 17a. Similar periods of high evapotranspirative demand and little rainfall can be seen in other dry years simulated (see figures 18a and 19a). The differences between the bottom line in these figures (unaugmented transpiration) and the middle line (transpiration with augmentation) indicate that increased rainfall does little to increase the crop water use, which would in turn decrease crop stress. Therefore, regardless of the soil moisture conditions at the beginning of these periods, significant crop stress would be expected because of lack of rainfall.

The above example indicates that simulated augmentation conditions were unable to substantially reduce crop stress because of the lack of rain-producing storm events. A conclusion from this example is that in order to be of greatest benefit during dry years, augmentation efforts will need to produce significant amounts of rainfall (for example, near 0.S inches) from conditions where little rainfall would otherwise be expected. This conclusion may be further supported by looking at the second special simulation case, irrigation, in which additional water can be brought to the plants in otherwise dry conditions.

Simulation of Irrigation

Two irrigation cases were simulated for the Flanagan soil: one in which a total of 3 inches of irrigation water is applied (1 inch applied 3 times during the year), and the other where 4 inches of irrigation is applied (1 inch applied 4 times). The applications of water were triggered when the soil moisture in the top 12 inches of the soil column fell below a threshold level. For the case involving a total of 3 inches of irrigation, a lower level of soil moisture was tolerated before irrigation was applied.

A summary of the distribution of the irrigation water to the various hydrologic processes within the soil is given in table 19. The lowest increase in crop transpiration for the irrigation simulations is 1.38 inches in 1954. This value can be obtained by subtracting the TR value with no augmentation (15.19 inches) from the TR value with irrigation (16.57 inches). On average over these three years, 64% of the water added during irrigation is used for crop water use (see table 20).

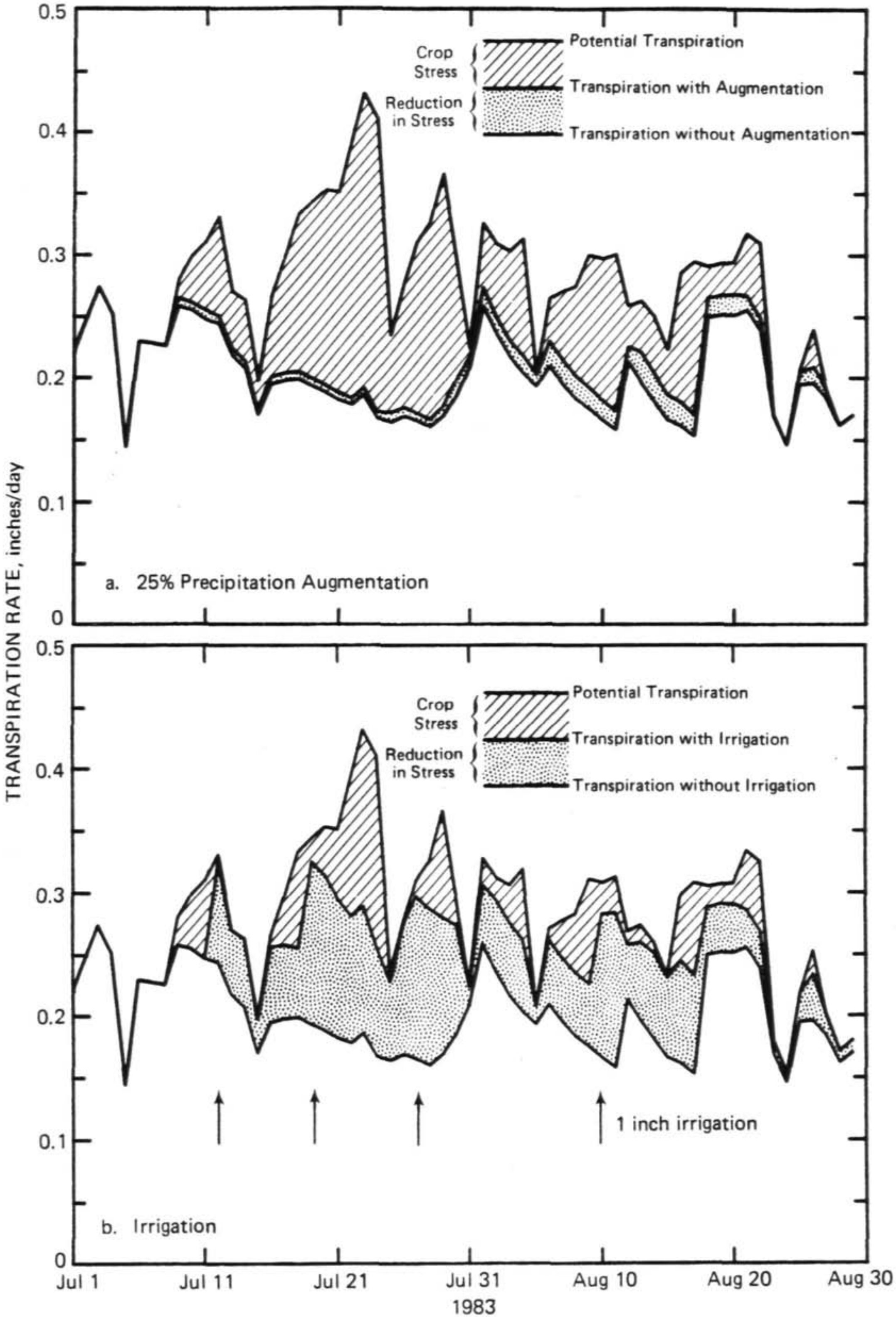

Figure 17. Change in the transpiration rate in 1983 due to a) precipitation augmentation, and b) irrigation

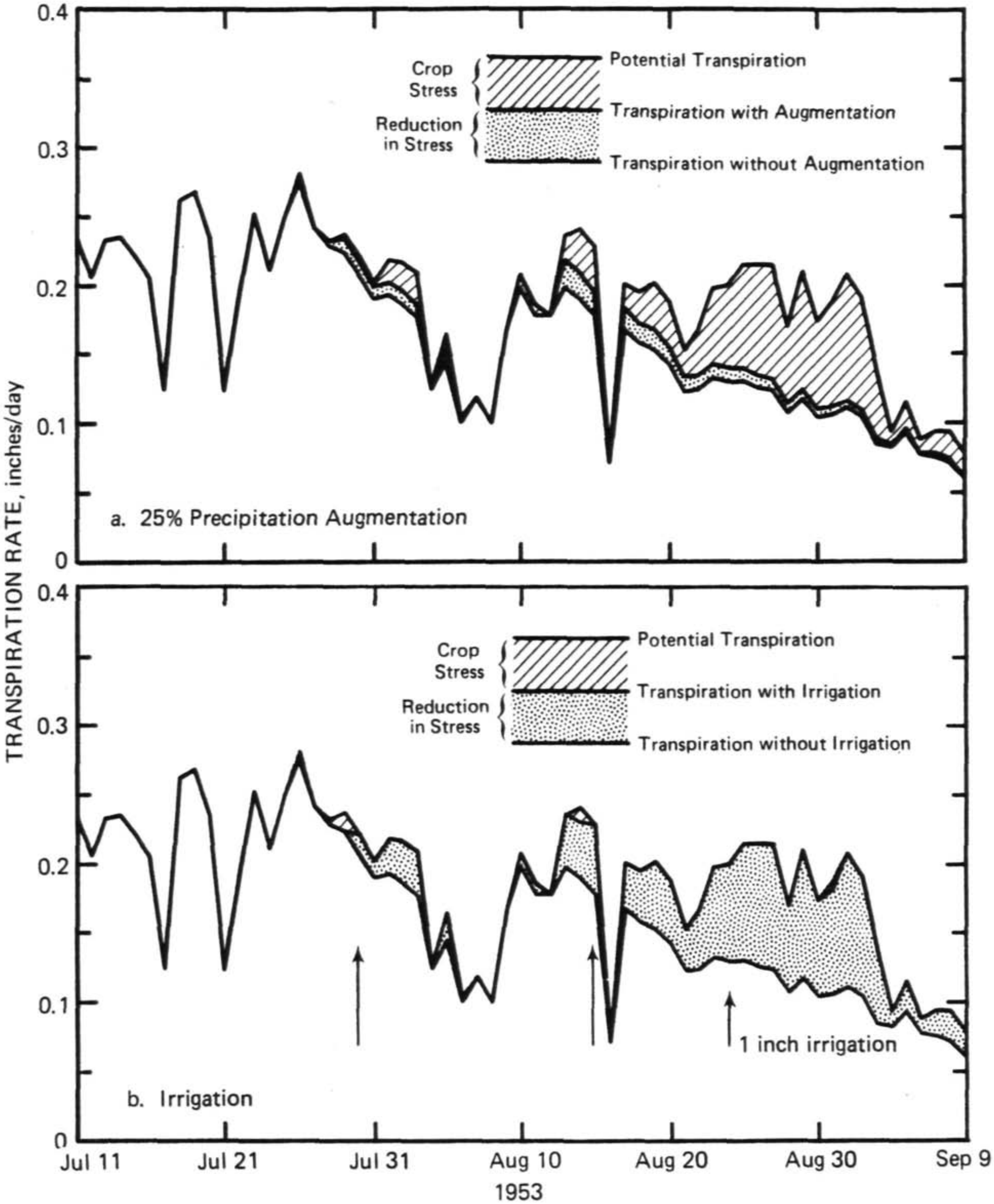

Figure 18. Change in the transpiration rate in 1953 due to a) precipitation augmentation, and b) irrigation

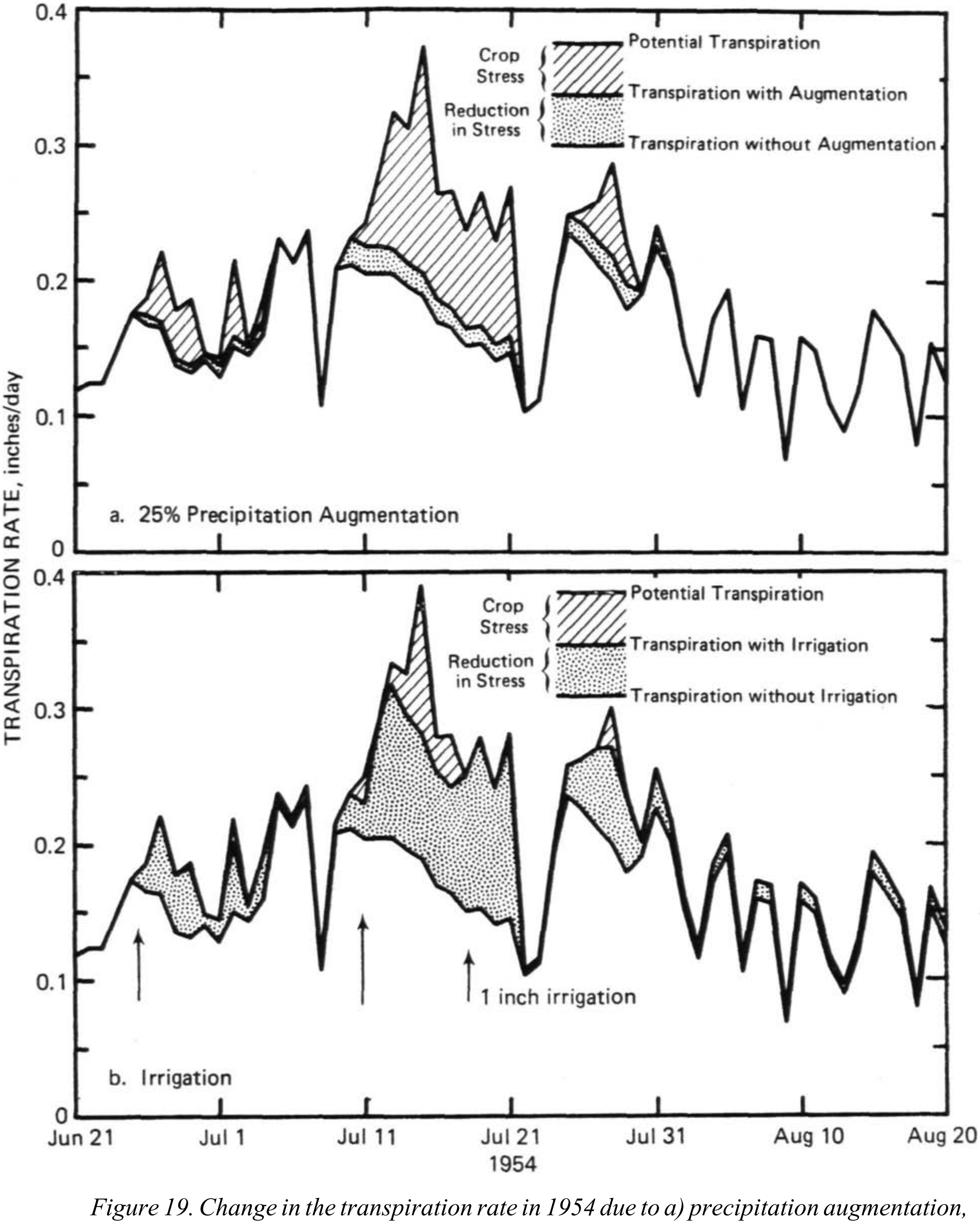

Figure 19. Change in the transpiration rate in 1954 due to a) precipitation augmentation, and b) irrigation

Table 20. Average Distribution of Irrigated Water to the Various Hydrologic Processes During Dry Years (1951-1954)

Hydrologic Process	Flanagan Soil
Soil Evaporation	8%
Crop Water Use	64%
Surface Runoff	3%
Percolation	25%

Table 20 can be compared with table 17 to indicate the major differences in the distribution of water between precipitation augmentation and irrigation. Irrigation is believed to be more efficient in supplying moisture to the crops because the water is supplied at the time when the plants need it most The irrigation events are primarily needed only during those extended periods which ordinarily would have little, if any, rainfall.

The effect of the irrigation events in improving the crop transpiration conditions is illustrated in figures 17b, 18b, and 19b. For all three years, the irrigation water reduces the differential between the potential transpiration and actual transpiration to less than half of the original differential. Because stress conditions affect the growth rate of crops, the potential transpiration rate can actually be increased by supplying the crops with sufficient moisture earlier in the year. In the same manner, a well-developed crop is more susceptible to crop stress during dry conditions simply because its transpirative demand is greater.

The reduction in the crop stress index resulting from irrigation is provided in table 19. Irrigation reduces the crop stress to zero in 1953, and the indexes for 1954 and 1983 are reduced to 34% and 9% of their respective values with no augmentation. The improvement in stress conditions resulting from irrigation helps to substantiate the claim that, in order to do the most good, precipitation augmentation would need to create rainfall within otherwise dry or marginal periods.

SUMMARY AND CONCLUSIONS

The PACE Watershed Model (PWM) was calibrated for the Kaskaskia Ditch watershed in central Illinois by using soil moisture and streamflow records for the period 1981-1985. Calibration was conducted on two scales. The soil moisture component of the PWM was calibrated by using available soil moisture records for the two dominant soil types in the basin (Flanagan silt loam and Drummer silty clay loam). The ground water component of the model was calibrated for its accuracy in modeling the baseflow contribution to the watershed streamflow. The calibrations indicate that both components of the model produce excellent qualitative representations of the hydrologic processes occurring within the basin.

The model was validated by using streamflow records for two additional periods, 1951–1954 and 1972-1975. Streamflow values simulated by the PWM agree well with the streamflow values recorded for the watershed for these periods. These two periods describe significant dry and wet periods of record for the watershed, respectively. Given the wide range of hydrologic conditions used for calibration and verification, the agreement of the estimated streamflow values with the gaging records for these two periods provides excellent support for the overall validity of the model's representation of hydrologic conditions. The processes (soil moisture, evapotranspiration, percolation, baseflow, and streamflow) simulated for these two periods were used as the base conditions for examining the effects of precipitation augmentation on soil moisture, crop water use, and streamflow conditions in the basin.

Four levels of increased precipitation were simulated for the watershed, ranging up to a 25% increase in all precipitation during the months of July and August All the simulations, which were performed by using these four different levels of precipitation augmentation, indicated that a great percentage of potential precipitation increase will add to ground water through increased percolation, and eventually will supplement the baseflow. However, only a small percentage of the increased precipitation will be used by the crops. The amounts of increased crop water use resulting from augmentation appear to be insufficient to have significantly positive effects on the total crop water stress conditions or the associated crop growth. This insufficiency is due mainly to the temporal distribution of precipitation whereby sufficient rain does not fall during periods of crop water stress.

Two alternative conditions were examined in an attempt to explain and overcome the apparent ineffectiveness of the precipitation increases. The first condition involved increasing the summer soil moisture levels by augmenting rainfall earlier in the year (June). This condition provided little benefit to the crop water status. The second alternative was a simulation of crop irrigation, activated on the basis of soil moisture levels. This simulated condition caused a significant increase in total crop water use and a reduction in total crop stress. These findings are in agreement with earlier less firm findings that indicated that rainfall increases, to be of reasonable value to crop production in the Midwest, would need to be substantial and greater than an average increase of 25% (Changnon, 1981).

Crop water stress conditions are produced by long periods of little rainfall. For this reason the temporal distribution of the rainfall is as great a concern as is the total amount of precipitation. Methods, such as irrigation, which can provide additional water to crops at any time and amount during these dry spells will produce the maximum benefit to the plant. If precipitation augmentation is to be of great use in the improvement of agricultural conditions, significant rainfall (for example, near 0.5 inches) must be produced during these periods in which little or no rainfall would otherwise occur.

Previous findings from the METROMEX study (Changnon, 1977), which showed substantial (30 to 70%) increases in certain heavy summer rain events, and subsequent measurable crop yield increase, reveal that agricultural benefits can occur from enhancement of existing rain conditions if the enhancement is sufficiently large. The impact of increased (10 to 25%) precipitation on general water resources is found to be beneficial, unless the increases occur during very wet periods. The results indicate that additional precipitation can actually increase baseflows and thus improve water quality during dry periods, without significantly increasing surface runoff.

To be of greatest use, the PWM needs to be calibrated for additional soil types and watersheds throughout Illinois. In addition, the model should be adapted for real-time operation in order to investigate the decision-making process associated with weather modification. Because of the strengths in the model for describing the physical relationships of hydrologic processes, the PWM is adaptable for modeling a wide range of hydrologic situations. In particular, the model is well suited for investigating concerns in the area of weather and climatic variability, a field of which weather modification can be considered a component

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