Generalization and Testing of a Soil Moisture Budget for Different Drainage Conditions[1]

R. F. DALE, WM. L. NELSON[2], K. L. SCHEERINGA, R. G. STUFF[3] AND H. F. REETZ[4]

Agronomy Department, Purdue University, West Lafayette, IN 47907

(Manuscript received 16 January 1982, in final form 8 May 1982)

ABSTRACT

An empirical site-specific water balance model was generalized to account for cropland drainage effects on soil moisture and evapotranspiration (*ET*). In predicting soil moisture for well-drained (WD) soils, usually total water use is equated to infiltrated precipitation, stored soil moisture, and *ET*.

In much of the eastern U.S. Corn Belt, however, row crop production is on soils which are poorly drained (PD) and underlain with perched water tables. These provide an additional source of soil water, capillary flow (*C*) into the crop root zone. Consequently, *ET* from PD soils is usually greater than that from WD soils. At West Lafayette, Indiana, from 1970 through 1974, for a PD soil the shallow water table furnished about a fourth of the total water used by late-planted corn (*Zea mays* L.) and a fifth of the water used by early-planted corn. A soil moisture budget model accounting for shallow water table influences, developed experimentally for a tile-drained Typic Argiaquoll soil, was generalized for use with other PD soils and, by voiding the capillary component, also for WD soils. For PD soils the *C* component was estimated as a function of the depth (*G*) to the shallow water table and a relative soil moisture gradient, or deficit, $1 - PAV$, where PAV is the fraction of plant available soil water in the corn root zone. In turn, changes in depth of the water table were predicted as a function of *C* and *G*, assuming a fixed basal leakage. For both PD and WD soils, daily *ET* was estimated and the pattern of relative soil moisture extraction from each 15 cm soil layer was established as a function of the relative soil moisture deficit in the top 30 cm and the age of the corn crop. The generalized simulation of the soil moisture balance (SIMBAL) model provided excellent results when tested on independent experimental data. It provided reasonable agreement when tested over a large area, using measurements taken at 108 location-dates in July and August in Indiana, Illinois, Minnesota and Nebraska in 1978–80, in cooperation wih the Control Data Corporation AGSERV project. Scatter in the predicted versus measured PAV comparisons was attributed mainly to sampling errors in estimating the daily precipitation and pan evaporation inputs needed for the model predictions of soil moisture.

1. Introduction

Evapotranspiration (*ET*) from soil and vegetation influences climate at every scale, from microclimates to worldwide atmospheric circulation patterns. *ET* depends upon both the atmospheric potential evapotranspiration (*PET*) and the soil moisture supply available to furnish that *PET*. Shukla and Mintz (1982) used a numerical model to simulate the atmospheric circulation under two different constraints on land-surface *ET*, one in which $ET/PET = 1$, and the other in which $ET/PET = 0$. Their results showed two distinctly different global patterns of July precipitation, temperature and sea level pressure. They concluded that observations of soil moisture are necessary for climate predictions. For many agricultural purposes precipitation measurements are primarily of interest as they reflect the soil moisture situation for crop production and range and forest management. Consequently, many soil water budgeting techniques have been used for predicting soil moisture. Almost all of these, however, have been developed for well-drained soils. In the eastern portion of the United States Corn Belt, much of the row crop production is on soils which are poorly drained and underlain with perched water tables. These poorly-drained soils usually have to be drained artificially to permit crop production, but generally they support higher *ET* and have higher crop yield potentials than well-drained soils.

For well-drained soils, the sources of water for evapotranspiration are stored soil moisture and precipitation. For poorly-drained soils, there is an additional supply source, capillary flow from perched

---

[1] Journal Paper No. 8857. Purdue University Agricultural Experiment Station, West Lafayette, IN 47907. Partially supported by NSF Atmospheric Sciences Section Grant ATM 8021075 and Control Data Corporation AGSERV project. Preliminary version presented at American Meteorological Society 14th Conference on Agriculture and Forest Meteorology, Minneapolis, MN, 2–4 April 1979.

[2] Present affiliation: Business Information Services, Control Data Corporation, Box 0, Minneapolis, MN 55440.

[3] Present affiliation: Climate Assessment Technology, Inc., 11550 Fuqua St., Suite 355, Houston, TX 77034.

[4] Present affiliation: Potash and Phosphate Institute, Rt. 2, Box 13, Monticello, IL 61856.

0021-8952/82/101417-10$06.50

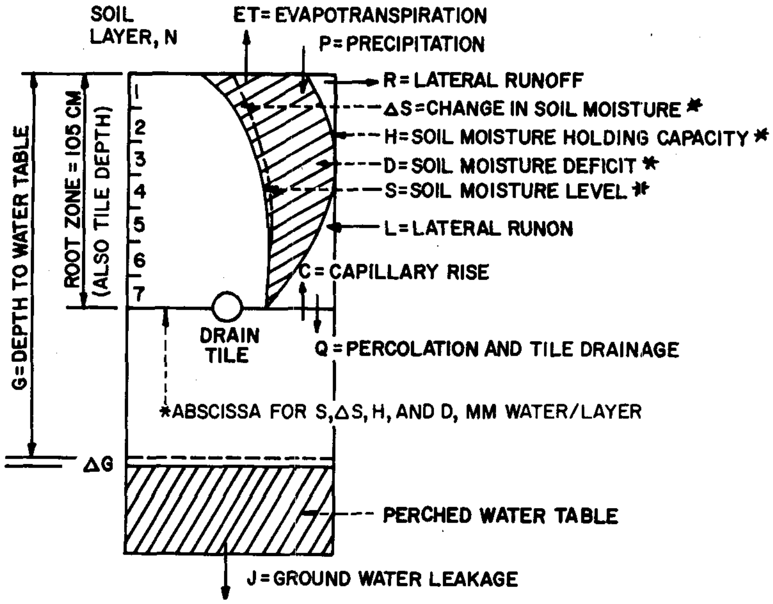

FIG. 1. Schematic profile of a poorly-drained soil, water balance components, and soil moisture expressions. Solid arrows are used for vector water balance components. Dashed arrows are used to identify the volumetric soil moisture scalars of S, ΔS, H and D, plotted on the abscissa (105 cm root and tile depth) against the respective soil layer N as the ordinate.

water tables. From measurements made under corn on poorly-drained soils at West Lafayette, Indiana, Stuff and Dale (1978) found that capillary flow from the perched water table furnished an average of 26% of the total water used by late-planted corn (*Zea mays* L.) during a 100-day period centered at date of corn silking, and 20% of the total water used by early plantings. This capillary source is not included in most soil moisture models, including that currently used to prepare the Palmer (1965) Drought Index and Crop Moisture Index used to characterize the national soil moisture status in the *Weekly Weather and Crop Bulletin* (Strommen, 1981).

A soil moisture budget model accounting for shallow water table influences was developed by Stuff and Dale (1978) for a Typic Argiaquoll (Chalmers silt loam), a poorly-drained soil with a perched water table. The experimental field had drainage tiles at an average depth of 105 cm, and the depth (G) to the water table usually ranged from this tile depth in the spring to more than 150 cm in late summer. The water balance model for the poorly-drained (PD) soil was defined as

$$\Delta S = P - ET + L - R + C - Q. \qquad (1)$$

The variables are defined in Fig. 1. During periods of no precipitation, $P = L = R = Q = 0$, and

$$\Delta S = C - ET. \qquad (2)$$

For these periods without precipitation the capillary flow (C) was obtained as the residual in (2) from measurements of changes in soil moisture (ΔS) and independent estimates of evapotranspiration (ET). Increases in depth to the water table (ΔG) were assumed to be related to basal leakage (J) and C by

$$\Delta G = J + kC, \qquad (3)$$

where the inverse of k is the specific yield of capillary water per unit increase in ΔG.

Since no corn roots were found below a depth of 105 cm in the Chalmers soil, the crop rooting zone was divided into seven 15 cm soil layers, numbered (N) downward from the surface, as shown in Fig. 1. Algorithms were developed from the experimental measurements to compute C, ΔG, the pattern of extracting ET from the soil layers, and ET from PET. These algorithms were based on the volumetric soil moisture deficit (D) for the specific Typic Argiaquoll on which the experimental measurements were made.

The first objective in this paper is to generalize the model for simulating the soil water balance (SIMBAL) for any PD soil, primarily by replacing D with a relative deficit variable, $1 - PAV$, and allowing a variable tile depth and number (N) of 15 cm soil layers in the crop root zone, down to a maximum depth of 150 cm, or $N = 10$. PAV is the fraction of plant available soil moisture in a crop root zone, and is defined as $(S - WP)/(H - WP)$, where S is the actual soil water in the crop root zone, H is the soil water holding capacity, and WP is the soil water held at the plant wilting point, or at a tension of 15 bars. The second objective is to further generalize SIMBAL for use on well-drained (WD) soils, primarily by voiding the capillary and water table algorithms and by including one for estimating surface runoff R. The third objective is to test the SIMBAL model with independent measurements for both PD and WD soils. A cooperative arrangement with Control Data Corporation in its AGSERV program (Reetz *et al.*, 1979; Nelson, 1981) provided an opportunity to test a version of SIMBAL over much of the U.S. Corn Belt in 1978, 1979 and 1980.

2. Data and procedures

a. Poorly-drained soils

For Typic Argiaquoll (TA) soil, Stuff and Dale (1978) found for each layer (N) the equilibrium soil water holding capacity $[H_{\mathrm{TA}}(N)]$ decreased, and soil water tension increased, as the depth (G) to the water table increased. Accordingly, the equilibrium tension $T_Z(N)$ was estimated from the depth of the water table below the respective soil layer, $G - Z(N)$, as follows:

$$T_Z(N) = \rho g[G - Z(N)] = 0.00098[G - Z(N)], \quad (4)$$

where $T_Z(N)$ is the equilibrium soil moisture tension at $Z(N)$ [bars], ρ the density of water, g the acceleration due to gravity, G the depth to perched water table below soil surface [cm], and $Z(N)$ the depth to the center of 15 cm soil layer (N) below surface [cm].

With tensionometric and volumetric measurements of soil moisture, volumetric-tension curves were developed for the TA soil and fitted with logarithmic regressions. These were transformed with (4) to $H_{\mathrm{TA}}(N)$ on G relations for each 15 cm layer.[5] The upper limit to $H_{\mathrm{TA}}(N)$ was the total pore space in the soil layer. To extend the TA relation to other PD soils, two points were defined on the volumetric soil moisture-tension curve for each layer: the soil water holding capacity at a tension of 0.10 bar $[HC_{\mathrm{TA}}(N)]$ and the "permanent wilting point" $[WP_{\mathrm{TA}}(N)]$ at a tension of 15 bars. Note that $H_{\mathrm{TA}}(N)$ is a variable and $HC_{\mathrm{TA}}(N)$ is a constant. Note also that in (4) $HC_{\mathrm{TA}}(N)$ occurs $[T_Z(N) = 0.10 \text{ bar}]$ when the water table is 100 cm below the center of layer N.

The soil characteristics required for the modeled (M) PD soil are the volumetric soil moisture amounts held at tensions of 0.10 bar, $[HC_M(N)]$ and 15 bars $[WP_M(N)]$. The curves of $H_M(N)$ on G for any modeled soil were considered to have the same logarithmic shape, *but not scale*, as those for the Typic Argiaquoll $[H_{\mathrm{TA}}(N)]$ on G. The TA curves[5] were used to estimate $H_{\mathrm{TA}}(N)$ from G. Given $H_{\mathrm{TA}}(N)$, $PAV_{\mathrm{TA}}(N)$ was computed as $[H_{\mathrm{TA}}(N) - WP_{\mathrm{TA}}(N)]/[HC_{\mathrm{TA}}(N) - WP_{\mathrm{TA}}(N)]$. This ratio was then multiplied by $[HC_M(N) - WP_M(N)]$ for the modeled soil to estimate $H_M(N)$. The plant available holding capacity in the entire crop root zone is calculated as the difference $\Sigma H_M(N) - \Sigma WP_M(N)$, and the actual total soil moisture $[\Sigma S_M(N)]$ is used to calculate PAV_M, $[\Sigma S_M(N) - \Sigma WP_M(N)]/[\Sigma H_M(N) - \Sigma WP_M(N)]$, where the summations are for the soil layers in the variable crop rooting zone.

Soil moisture deficits from holding capacity are recharged with precipitation in successive soil layers from the surface downward. Since the PD soils have 0–2% slope, there is little to no runoff (R) and all precipitation is infiltrated. The very poorly-drained soils may even have more runon (L) from adjacent higher soils than runoff, but it was assumed that $L = R$. Precipitation in excess of that required to bring the corn root zone to the holding capacity is percolated (Q) to the water table. When the water table rises to the depth of the drain tiles ($G = T$), any Q greater than that necessary to fill the porosity for the layers below T is budgeted to tile drainage. The soil between the bottom of the crop root zone and the water table is assumed to be at the equilibrium water holding capacity so that any C or Q is reflected by (3) in ΔG. The parameters J and k, however, are extremely difficult to measure or estimate. For the TA soil, using measurements in 42 dry-down periods of 3–8 days in length (1971–73) meeting the requirements of (2), Stuff and Dale (1978) determined these parameters iteratively by testing different values of J until the highest correlation was obtained for a regression of ln $(\Delta G - J)/C$ on G:

$$\Delta\hat{G} = 0.5 + 0.3C(G/100)^{3.0}, \quad r = 0.58, \quad (5)$$

where C is in millimeters, G is in centimeters, and k [from (3)] is a function of G. Note that the final estimate of J in (5) indicates that basal leakage increased the depth of the shallow water table an average of 0.5 cm day^{-1}.

To estimate C, it was assumed that capillary flow responded to the gradient between the soil moisture in the crop root zone and that in equilibrium with the water table below the crop root zone $(1 - PAV)$ and for different G this response was linear and passed through the origin. Thus, $C/(1 - PAV)$ was used as the dependent variable, and for the same 42 dry down periods ln $[C/(1 - PAV)]$ was regressed on ln $(G/100)$ to obtain

$$\hat{C} = 21.88(1 - PAV)(G/100)^{-4.0}, \quad r = 0.72. \quad (6)$$

The experimental measurements and regression relation (6) are shown in Fig. 2 for selected values of G. Note that for $G > 250$ cm $\hat{C}$ is very small. Although associated with only about half the variance in the dependent variables, the relations in (5) and (6) were

---

[5] Equations used to compute $H_{\mathrm{TA}}(N)$ in mm per 15 cm layer as a function of G [cm] for the Typic Argiaquoll soil are $H_{\mathrm{TA}}(1) = 73.3 - 3.20 \ln(G + 4)$; $H_{\mathrm{TA}}(2) = 73.6 - 3.08 \ln(G - 8)$; $H_{\mathrm{TA}}(3) = 73.6 - 2.95 \ln(G - 21)$; $H_{\mathrm{TA}}(4) = 72.5 - 2.96 \ln(G - 37)$; $H_{\mathrm{TA}}(5) = 70.1 - 3.15 \ln(G - 56)$; $H_{\mathrm{TA}}(6) = 66.8 - 3.17 \ln(G - 74)$; $H_{\mathrm{TA}}(7) = 62.4 - 2.94 \ln(G - 93)$; $H_{\mathrm{TA}}(8) = 62.0 - 3.00 \ln(G - 105)$; $H_{\mathrm{TA}}(9) = 62.0 - 3.00 \ln(G - 121)$; $H_{\mathrm{TA}}(10) = 62.0 - 3.00 \ln(G - 138)$. If the water table were above the modeled layer, $H_{\mathrm{TA}}(N)$ was set equal to the soil layer porosity, shown in Table 1.

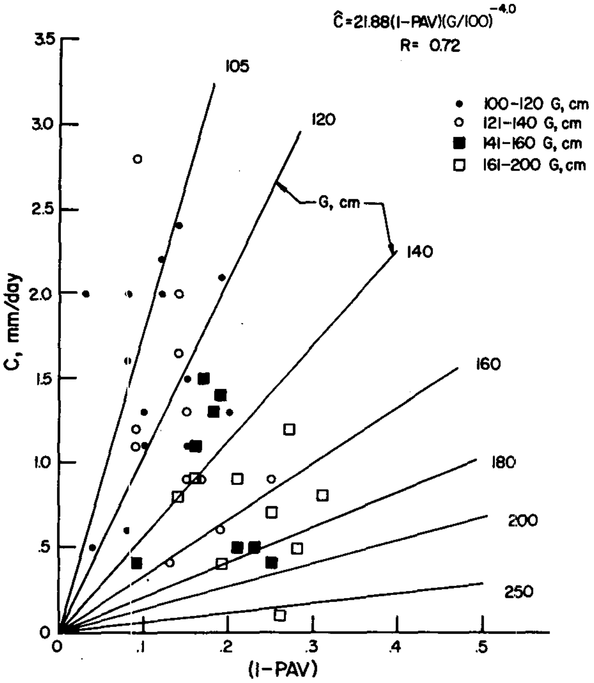

FIG. 2. Experimental determinations of capillary flow (C) on soil moisture gradient or relative deficit ($1 - PAV$) in top 105 cm for indicated depth (G) to perched water table for Typic Argiaquoll (Chalmers silt loam), West Lafayette, Indiana 1971–73. Straight lines are modeled values from (6) for indicated G.

assumed to hold for most PD soils, since usually there is insufficient information for specific soils to modify the estimated parameters. For reference purposes, the bulk density and volumetric moisture held at total porosity and at 0.10, 0.33 and 15 bars tension for each layer are shown in Table 1 for the Typic Argiaquoll at the experimental site.

The daily potential evapotranspiration (PET) for corn was obtained by multiplying the Class A pan evaporation (E_p) by a crop development factor (F), i.e., $PET = F \cdot E_p$, where

$$F = -1.58 + 0.0463W - 0.00022W^2,$$
$$0.40 \leqslant F \leqslant 0.82, \qquad (7)$$

and W is the age of the corn crop expressed in days numbered sequentially about 100 with day 100 defined as the date 75% of the plants in the field had silked. Eq. (7) was taken directly from Stuff and Dale. Daily ET was estimated by multiplying PET by a moisture stress factor, ET/PET, defined as a function of the interaction of the pan evaporation for the day (E_p) and the soil moisture deficit ($1 - PAV$) at the beginning of the day:

$$ET/PET = 1.19 - 0.169E_p(1 - PAV),$$
$$0 \leqslant ET/PET \leqslant 1. \qquad (8)$$

This moisture stress factor [(8)] was developed from the pooled field experimental data of Shanholtz and Lillard (1970) and the potometer data of Denmead and Shaw (1962), as shown in Fig. 3. The PAV in (8) was based on the corn root zone *or* the top 30 cm, whichever was greater. Based on field observations and the corn root growth measurements of Mengel and Barber (1974), the root zone was considered to consist of the top two layers (30 cm) before $W = 61$ (39 days before silking), the top three layers from $W = 61$ to 70, the top four layers from $W = 71$ to 80, and all layers after $W = 80$. For most PD soils, the maximum rooting depth for corn and the depth of the drainage tiles are less than 105 cm, so that the 7-layer model used for the TA soil usually suffices. Any depth of drainage tiles and corn root zone can be used, however, as long as the depth is not greater than 150 cm and the layers are in multiples of 15 cm.

Evapotranspiration (ET) increases the moisture deficit in all layers of the corn root zone, but with adequate soil moisture ET is extracted preferentially from the top layers, which contain most of the plant roots. Stuff and Dale found the measured patterns of extraction of soil moisture from the profile were closely approximated with a logarithmic function,

$$X(N) = A + B \ln N, \qquad (9)$$

where $X(N)$ is the percentage of the ET extracted each day from the Nth soil layer, A is the percentage of the ET extracted from the top 15 cm layer ($N = 1$) and, since the sum of the N values of $X(N)$ is 100%, B is uniquely determined by the A value[6]. Stuff[7] calculated values for A from extraction curves for 30 dry-down periods in which the corn roots had reached their maximum depth ($W > 90$) and the requirements in (2) were met. These A values were plotted in Fig. 4 and regressed on the average PAV deficits in the top 30 cm, $1 - PAV_{30}$:

$$\hat{A} = 50.4 - 70.8(1 - PAV_{30}), \quad r = -0.67. \qquad (10)$$

With the top 30 cm at full water holding capacity, the regression (10), drawn in Fig. 4, shows 50.4% of the ET will be taken from the top 15 cm layer ($N = 1$).

Before $W = 90$ the age of the corn crop had a significant effect on $\hat{A}$. Based on 14 additional soil moisture draw-down periods before silking (the variable length periods of 3–8 days centered at $W = 71$ to 97), the following regression equation was obtained:

$$\hat{A} = 133 - 69.3(1 - PAV_{30}) - 0.92W,$$
$$R = 0.96. \qquad (10a)$$

---

[6] $\hat{B} = 11.8 - 0.84A$ for $A \leqslant 48\%$, and

$$\hat{B} = [3A^2 + A(2400A - 3A^2)^{1/2}]/(6A - 1100)$$

for $A > 48\%$.

[7] Stuff, R. G., 1975: The estimation of soil moisture under corn in a humid climate and its influence on crop growth. Ph.D. thesis, Life Science Library, Purdue University.

In (10a), note that when $W = 36$ and $PAV_{30} = 1$, all ET ($\hat{A} = 100\%$) is extracted from the top 15 cm. Eq. (10a) was used before $W = 90$. When $W < 36$ and again when $W > 152$ [after the corn roots are no longer viable (Mengel and Barber, 1974)], $W = 36$. Eq. (10) was used from $W = 90$ to $W = 152$.

Two additional controls on $\hat{A}$ were found to be necessary in early testing. For any day on which there was more moisture in the top 30 cm than in the 30–60 cm layer, $\hat{A}$ was set equal to 76%. This "upper limit" is a threshold in (9) which restricts extraction to layers $N = 1$ and 2 only. It can be seen from Fig. 4 that when $(1 - PAV_{30})$ is greater than 0.71 (beyond the experimental data range), $\hat{A}$ becomes negative. Since evaporation from the surface layer can continue below the WP, a lower bound of 10% was placed on $\hat{A}$, i.e., if $\hat{A} < 10\%$, $\hat{A} = 10\%$.

b. *Well-drained soils*

For well-drained (WD) soils, usually there are no perched water tables or drain tiles, and the C, G and variable $H_{TA}(N)$ arguments are voided. Fixed holding capacities $[H_M(N)]$ at 0.33 bar tension are assumed for each 15 cm layer. Unless there is an impervious layer, a 10-layer model generally is used to provide a 150 cm root zone for WD soils.

Precipitation runoff (R) is greater than runon (L) for WD soils, and an R correction was included in SIMBAL. For cases with daily precipitation (P) greater than 38 mm, infiltrated precipitation (PI) was estimated after Baier and Dyer (1978):

$$PI = 25.4[0.9177 + 1.811 \ln P - 0.97(PAV_{30}) \ln P]. \quad (11)$$

In (11) P is in inches, PAV_{30} in percent and PI in millimeters. Then $R = P(25.4) - PI$ [mm day^{-1}].

TABLE 1. Soil characteristics for Typic Argiaquoll (Chalmers silt loam), Field 32, Purdue University Agronomy Farm, West Lafayette, Indiana.

Soil layer			Volumetric moisture (mm per 15 cm) at total pore space and at indicated tensions			
N	Depth (cm)	Bulk density (g cm^{-3})	Porosity	0.10 bar HC_{TA} (N)	0.33 bar	15 bars WP_{TA} (N)
1	0–15	1.51	64	59	55	21
2	15–30	1.50	64	60	56	22
3	30–45	1.48	65	60	56	23
4	45–60	1.49	65	59	55	23
5	60–75	1.58	63	56	52	24
6	75–90	1.64	60	52	48	24
7	90–105	1.69	58	49	45	23
*						
8	105–120	1.71	56	48	44	23
9	120–135	1.72	55	47	44	23
10	135–150	1.72	55	47	44	23

* Average drainage tile depth and no corn roots found below 105 cm. Soil characteristics for layers 8–10 not used in SIMBAL and included only for reference.

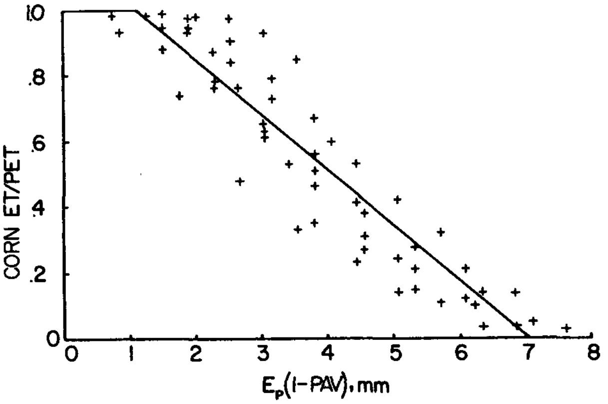

FIG. 3. Pooled experimental field measurements (Shanholtz and Lillard, 1970) and potometer measurements (Denmead and Shaw, 1962) of ratio of actual to potential evapotranspiration (ET/PET) for corn on the product of daily pan evaporation (E_p) and fraction plant available water deficit ($1 - PAV$) in corn root zone or top 30 cm, whichever greater (after Stuff and Dale, 1978). Solid line is (8).

c. *Initialization*

The soil water balance problems associated with frozen soil and snowfall have not been addressed in SIMBAL. Therefore, in areas where soil temperatures drop below 0°C in the winter, a starting soil moisture profile each spring or summer is required to initiate the SIMBAL model. For PD soils, a starting depth to the perched water table is also needed. For most of the eastern Corn Belt and areas with significant winter precipitation distribution in most years, it is satisfactory to start SIMBAL for both PD and WD soils at full holding capacities $[H_M(N)]$ and, for PD soils, with G at the tile depth, in April or May following a period of rains believed sufficient to fill any deficits in the soil profile. For the western portions of the Corn Belt and other winter-dry areas where the soil profile is not always recharged during the late fall, winter and early spring, measurements or estimates of the starting soil moisture in each layer are necessary.

d. *Testing*

The generalized SIMBAL model was tested for PD soils against our experimental measurements made in 1970 and 1974, two years which were not used in the model development. The model was started in the spring with PAV of all seven layers at 1.0 and G at 105 cm.

For WD soils, the model was tested with soil mois-

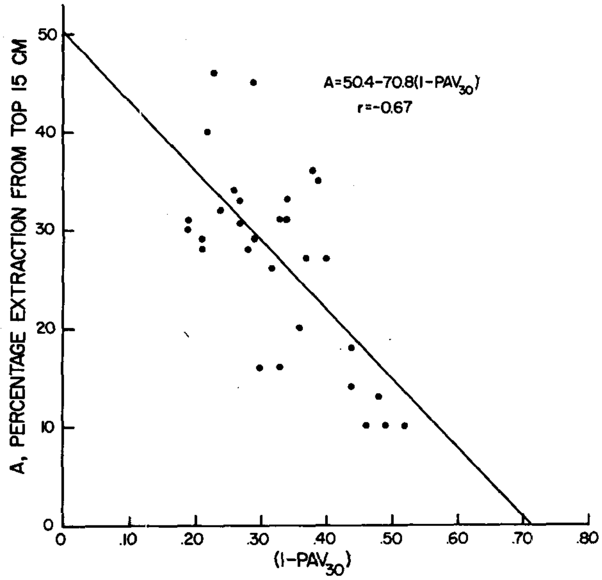

FIG. 4. Experimental measurements of percentage (A) of daily soil water use extracted from top 15 cm during 30 dry-down periods, 1971–73, on respective soil moisture deficit in top 30 cm ($1 - PAV_{30}$), and regression (10).

ture measurements made for corn following corn on a Typic Udorthent (Ida silt loam) soil at Castana, Iowa. The starting soil moisture measurements on 15 April of each year, the soil characteristics, and soil moisture measurements on the first day of each month, May through November, 1955–70, by 30 cm increments down to 150 cm, were obtained from Shaw *et al.* (1972). The daily precipitation and pan evaporation data were obtained for the Western Iowa Experimental Station at Castana from Dr. R. H. Shaw, Agronomy Dept., Iowa State University, Ames.

A large area testing was made possible as a part of the Purdue University cooperation in the Control Data Corporation (CDC) AGSERV program (Reetz *et al.*, 1979). A version of SIMBAL was used to estimate soil moisture for the predominant PD and WD soils in each of 942 counties across the Corn Belt in 1978, 1979 and 1980. Data files of the necessary soil characteristics, such as those shown in Table 1 for Chalmers, were established for each of the predominant PD and WD soils, together with their percentage of occurrence, in each county. Some counties had 100% PD and some 100% WD soils. The weather input was contracted by CDC from private meteorological firms (Weather Services Corporation, Boston, MA, in 1978, and Global Weather Dynamics, Inc., Monterey, CA, in 1979 and 1980). Based on the synoptic network reports, daily precipitation amounts and E_p estimates were provided in near-real-time, interpolated for the geographical center of each county (Nelson, 1981). The soil characteristics and weather information in the CDC files will be called "AGSERV soils and weather". These inputs were used at CDC, Minneapolis, in a version of SIMBAL to predict the PAV in the top 105 cm for the predominant PD soil and the top 150 cm for the predominant WD soil in each county. Soil moisture measurements were made in July and August at 108 selected sites in Indiana and by university cooperators[8] in Illinois, Minnesota and Nebraska, using gravimetric and neutron scattering equipment. No water table observations were made.

The soil moisture measurements were compared to those predicted with "AGSERV soils and weather" inputs, using the daily $\hat{P}$ and $\hat{E}_p$ interpolated for the county center. Since there is great spatial variability in both precipitation and soil characteristics, soil moisture predictions also were made with two other sets of data inputs for selected sites in 1978. For 53 sites, where the soil characteristics for the specific soil measured were available, the measurements were compared with those predicted with "Better soils and AGSERV weather" inputs. For 23 of the 53 sites, where precipitation and evaporation observations were available for a climatological station within a few kilometers of the soil moisture measurement site, comparisons were also made with predictions using "Better soils and weather" inputs.

3. Results and discussion

The first test of the generalized SIMBAL model was the comparison of the predicted daily soil moisture (S) in the top 105 cm and water table depth (G) for the TA soil against those measured for the two years of the experiment not used in developing the model (1970 and 1974). For both years the model simulation was started after rains in early May with the soil moisture profile at full capacity, $S(N) = H_{TA}(N)$, and G at the tile depth, 105 cm. The agreement in 1970 and 1974 was about the same as that found with the volumetric deficit model (Stuff and Dale, 1978, Figs. 8 and 9). The S and G measurements and model predictions for the early corn planting in 1970 are plotted in Fig. 5. Because of the ground water leakage and C supply [Eq. (5)], there is a characteristic drawdown of the perched water table during the summer, when ET almost always exceeds P. Usually it is recharged in the fall because of rains and reduced ET. The measurements of G were not begun until the second week in July 1970, and from about 15 August to 15 September the water table was below the access tubes used to measure G. Note that as G dropped 90 cm, from a computed 110 cm on 1 June to 200 cm on 10 September, the water holding capacity (H_{TA}) in the top 105 cm decreased from a total of 408 mm (249 mm available) to 385

---

[8] We gratefully acknowledge the cooperation of Dr. M. D. Thorne, Agronomy Dept., University of Illinois, Urbana; Dr. D. G. Baker, Soil Science Dept., University of Minnesota, St. Paul; and Dr. P. W. Harlan, Agronomy Dept., University of Nebraska, Lincoln.

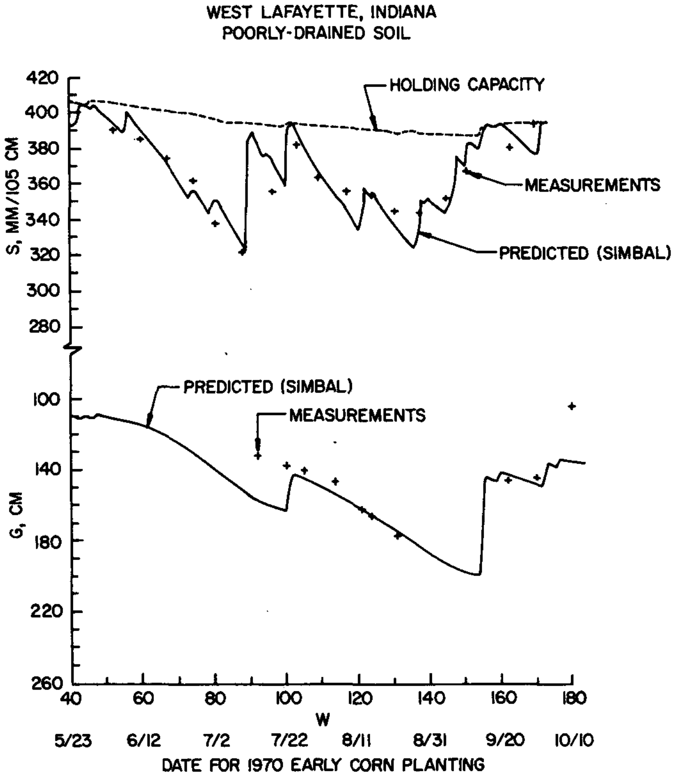

Fig. 5. Independent comparison of modeled (SIMBAL) and measured total soil moisture (*S*) in the top 105 cm and depth (*G*) to perched water table for early planted corn on PD soil (Typic Argiaquoll) in 1970. Day (*W*) is identified from silk date = 100.

mm. This is a decrease of 10% in the plant available water holding capacity in the 105 cm root zone. The downward trend in the holding capacity demonstrates the importance of the perched water table, not only in furnishing the capillary water supply [(6)], but also in supporting the higher soil water holding capacity [or lower soil moisture tension (4)]. Both the measured and computed soil moisture (*S*) show the lowest value for the summer on July 10, $S = 320$ mm ($PAV = 0.69$).

A comparison of the SIMBAL model predictions of the plant available water in the top 150 cm for a WD soil with those measured at Castana, Iowa, is shown in Fig. 6 for the driest (1968) and wettest (1962) growing seasons in the 1954–70 period. The predictions were made with a 10-layer model, the SIMBAL *C* and *G* algorithms were voided, fixed holding capacities of $H_M(N)$ at 0.33 bar (determined by Shaw *et al.*, 1972) were used, and the simulation was begun with the 15 April soil moisture measurements. Only four of the subsequent 14 measurements in May–November departed more than 10 mm from the predicted values.

The soil moisture amounts, expressed in percentage *PAV*, predicted in the AGSERV program for 108 specific dates and counties were plotted as solid circles in Figs. 7A–7D against the respective soil moisture measurements taken in Illinois, Indiana, Minnesota and Nebraska, during July and August of 1978–80 for the indicated soil drainage class and year(s). It was found that at some of the sampling locations, such as the two shown on Fig. 7B at about 40% *PAV* measured and 80% *PAV* predicted, the AGSERV estimate of precipitation for the county center was not representative of that received at the measuring site.

At the sites of all 53 measurements in 1978 (shown by the solid circles in Figs. 7A and 7B) soil characteristics were determined for the specific soil sampled, and the model was rerun with "better soils and AGSERV weather" input. The coefficient of determination (r^2) for the WD soils increased from 0.24 (shown in Fig. 7B) to 0.31 with the additional "better soils" input. The overall mean error [$\bar{e} = \Sigma$(predicted % PAV − measured % $PAV)/n$] decreased from +7.0 (Table 2) to +3.9% *PAV*. For the PD soils (Fig. 7A), however, the results were mixed, r^2 values decreasing from 0.27 to 0.24 with the "better soils" input, but $\bar{e}$ decreasing from +8.1 to +6.2% *PAV*.

There were only 9 of the soil moisture measurements shown in Fig. 7A made at sites which were within a few kilometers of a weather station, and 14 in Fig. 7B, for which "better weather" data could be

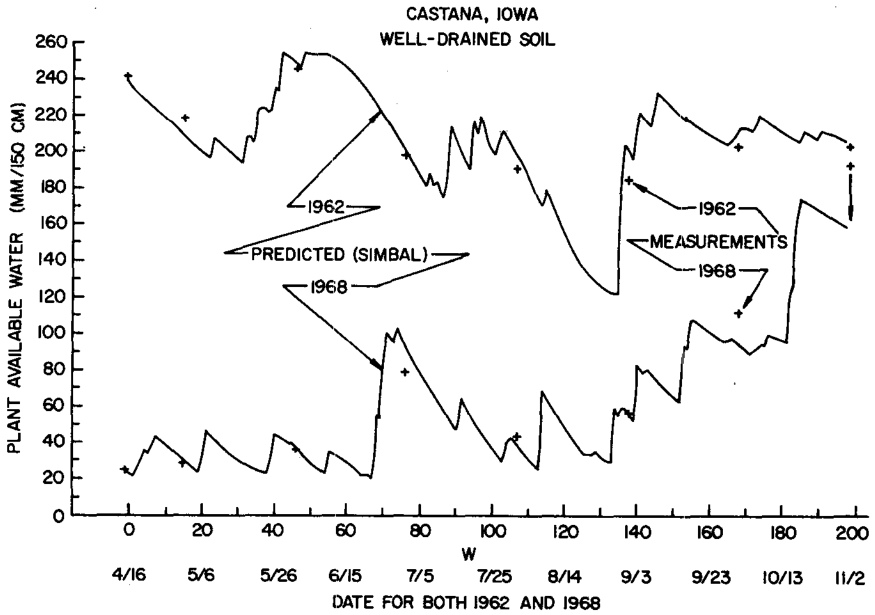

FIG. 6. Independent comparison of modeled (SIMBAL) and measured plant available soil moisture, millimeters in top 150 cm for corn, for driest (1968) and wettest (1962) years of record for WD soil (Typic Udorthent) Castana, Iowa. Corn silking date ($W = 100$) for both years was 25 July. Soil moisture measurements from Shaw *et al.* (1972).

obtained. The model predictions for these sites with "better soils and weather" inputs were plotted (squares) against the same measurements in Figs. 7A and 7B. They show less scatter about the 1:1 line for both PD and WD soils. For these smaller samples (9 in Fig. 7A and 14 in Fig. 7B), the r^2 values for the measured against predicted % *PAV*, and the mean errors $\bar{e}$ were calculated for three sets of model inputs for "AGSERV soils and weather", "better soils and AGSERV weather", and "better soils and weather". For the PD soils (squares in Fig. 7A) the r^2 values were 0.19, 0.15 and 0.60, respectively, and the $\bar{e}$ values were +12.9, +10.2 and +8.1% *PAV*. For the WD soils (squares in Fig. 7B), the r^2 values were 0.15, 0.08 and 0.41; and the $\bar{e}$ values were +12.9, +10.2 and +8.1% *PAV*. For the WD soils (squares in Fig. 7B), the r^2 values were 0.15, 0.08 and 0.41; and the $\bar{e}$ values were +12.7, +7.8 and +3.3% *PAV*, respectively. Obviously, for these samples, the "better soils" input had little effect, and the greatest improvement in the model predictions came with the "better weather", or more representative P and E_p inputs.

The overall averages of the measured and AGSERV predicted % *PAV* values, together with their mean errors $\bar{e}$ have been summarized for 1978–80 in Table 2. In 1978 there appeared to be an upward bias in the predicted % *PAV* values, perhaps partially caused by a tendency for the AGSERV meteorological estimates to under predict the E_p input. Also, the AGSERV SIMBAL version did not include the runoff algorithm (11) for WD soils. For the 53 pooled comparisons in 1978, the average error was +7.4% *PAV*, and for the 9 sites with "better soils and weather" +5.2% *PAV*. For the 55 comparisons in 1979 and 1980, however, $\bar{e}$ for the PD soils was −2.0% *PAV* and for the WD soils +2.3% *PAV*, resulting in an overall error of only +0.5%. This decreased error in 1979 and 1980 may have come from improvements in the AGSERV estimates of E_p and precipitation interpolation methodology (Nelson, 1981). The tighter patterns of the squares in Figs. 7A and 7B, the higher r^2 values, and the lower mean errors (Table 2) obtained with the "better soils and weather" input suggest what most soil moisture modelers quickly come to realize: the error in soil moisture estimating stems largely from precipitation sampling.

Although characteristic soil volumetric moisture-tension curves for different soils cause departures from (8), scaling the volumetric moisture as *PAV* makes the relation more conservative, and probably (8) can be used with little error for most medium- and fine-textured soils. If pan evaporation data are not available, daily potential evaporation (*PE*) must be estimated with meteorological methods, such as those by Penman (1948) or van Bavel (1966), and it may be necessary to modify (7) and (8). Or, the *PAV* for the top 15 cm can be used from SIMBAL to predict E_p (Dale and Scheeringa, 1977), permitting the use of the same (7) and (8) relations. Over homogeneous terrain, evaporation is much more conservative than precipitation, and undoubtedly the largest source of error in SIMBAL predictions of soil moisture is the spatial variability in precipitation.

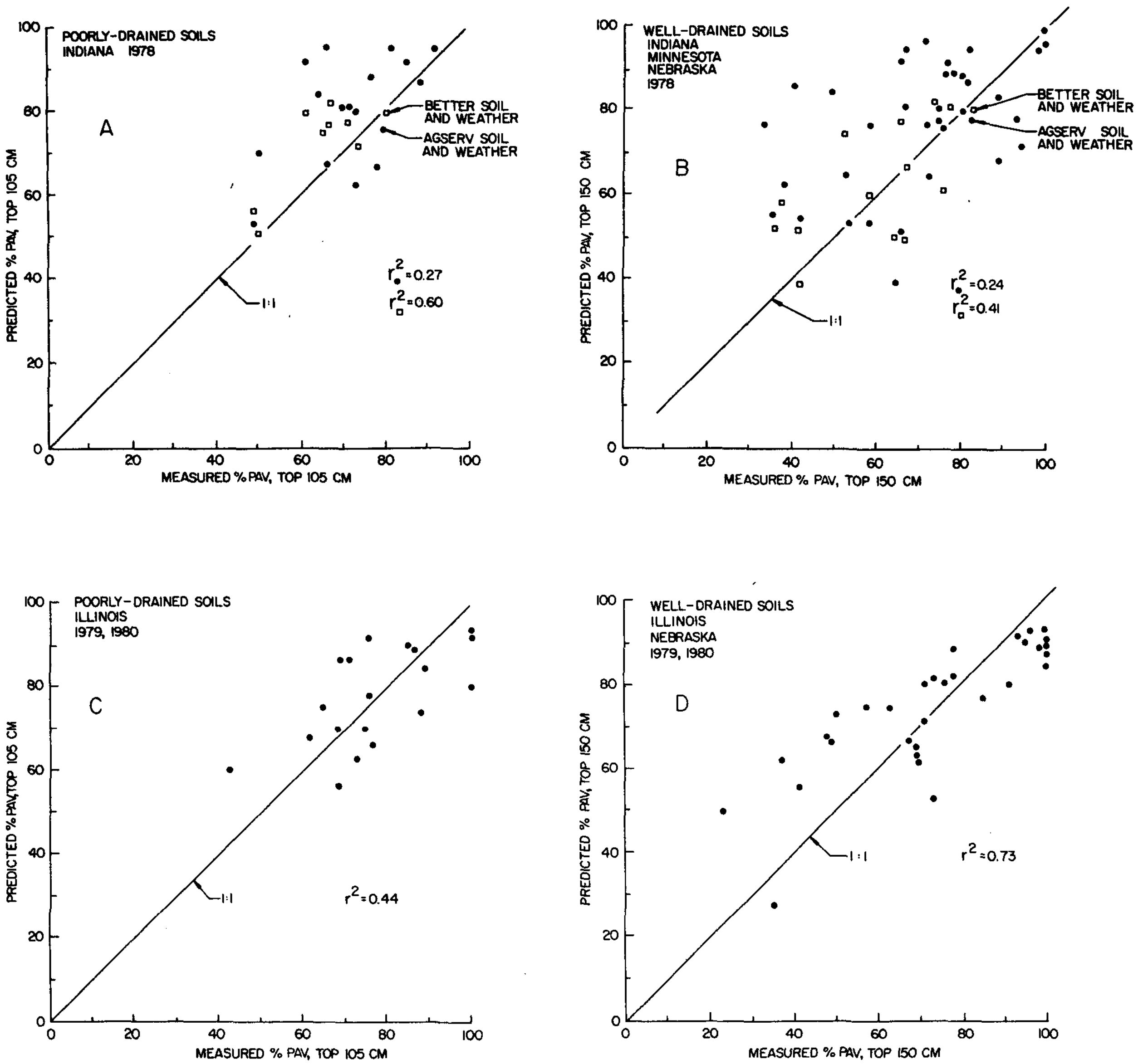

FIG. 7. Predicted and measured percentage plant available (% *PAV*) soil moisture in corn root zone for indicated soil drainage class, state(s) and year (A–D), with respective coefficients of determination r^2. "Better soils and weather" squares indicate prediction using inputs of available holding capacities for specific soil sampled and precipitation (P) and pan evaporation (E_p) measured within a few km of the sampling site, rather than the AGSERV soil factors and P and E_p estimated for the center of the county in which the soil moisture measurements were made.

The average error for the 23 soil moisture comparisons for PD soils in 1979–80 was only −2.0% *PAV* (Table 2) and for the 40 pooled 1978–80 PD comparisons +2.3% *PAV*. This agreement suggests that the algorithms for estimating C, developed from experimental measurements on the Typic Argiaquoll soil, provides about the right order of capillary contribution to ET for the various PD soils tested. Still, the representativeness of the parameters in (3), (5) and (6), and the assumptions that $L = R$ in (1) could easily lead to greater error for specific soils. These algorithms need further testing. For example, Harlan and Franzmeier (1974) found for another TA (very poorly drained Brookston soil) that water tended to move laterally to this soil from an adjacent Aeric Ochraqualf (somewhat poorly drained Crosby soil), or that $L > R$.

SIMBAL has been used by the Cooperative Purdue University-National Weather Service (NWS) Midwest Agricultural Weather Service Center (MAWSC) to prepare charts of *PAV* distribution over Indiana since 1976. A network of 45 stations evolved for

TABLE 2. Averages of predicted and measured percent plant available soil moisture (% *PAV*) in corn root zone [105 cm for poorly drained (PD) and 150 cm for well-drained (WD) soils] for indicated state-soil drainage groupings, July or August, 1978–80.

State	Soil drainage	Year(s)	Number of measurements	AGSERV predicted mean % $\widehat{PAV}$	Measured mean % *PAV*	Mean error % $\widehat{PAV}$ − % *PAV*	
Indiana	PD	1978	17 (9)*	80.6 (73.0)*	72.5 (64.9)*	+8.1	(+8.1)*
Indiana Minnesota Nebraska	WD	1978	36 (14)	77.6 (63.4)	70.6 (60.1)	+7.0	(+3.3)
Pooled	PD, WD	1978	53 (23)	78.6 (67.2)	71.2 (62.0)	+7.4	(+5.2)
Illinois	PD	1979–80	23	78.6	80.6	−2.0	
Illinois Nebraska	WD	1979–80	32	75.5	73.2	+2.3	
Pooled	PD, WD	1979–80	55	76.8	76.3	+0.5	

* % *PAV* averages and number of measurements in parentheses are based only on the comparisons for which "better soils and weather" information was available, i.e., using soil characteristics determined in May and June for the specific sampling site where the July or August measurements were taken and with a precipitation gage located within a few kilometers of the site.

which the necessary soils and timely weather information (Bruns and Scheeringa, 1977) could be obtained. SIMBAL has been run once-weekly[9] during each growing season, and the results have been distributed over the NWS Indiana weather wire from the MAWSC within 24 h of the weather observations used in the SIMBAL predictions. These *PAV* charts for WD soils provide much more resolution than, but generally agree with, the soil moisture patterns shown by the Palmer Crop Moisture Index used in the *Weekly Weather and Crop Bulletin* to characterize the national drought situation.

Acknowledgments. The authors much appreciate the critical reviews and suggestions given them by Dr. Bernard Silverman and three JAM referees, which we believe led to greatly improved readability and completeness of this paper. The identity of one of the reviewers became known to us during discussion of the relevance of the section on the large-area testing of the SIMBAL model. It is a pleasure to personally thank Dr. Bill Dugas, of Texas A & M, Temple, Texas, for his constructive criticisms and suggestions on this paper. Finally, we thank Mrs. Enola Ruff for her diligence and patience in typing the many developing versions of this manuscript.

REFERENCES

Baier, W., and J. Dyer, 1978: Versatile soil moisture budget. Agrometeorology Section, Land Resource Res. Inst., Research Branch, Agriculture, Canada KIA OC6.

Bruns, Warren A., and Kenneth L. Scheeringa, 1977: MICROS. *Preprints 13th Agricultural and Forest Meteorology Conf.*, Purdue University, Amer. Meteor. Soc., 41–42.

Dale, Robert F., and Kenneth L. Scheeringa, 1977: The effect of soil moisture on pan evaporation. *Agric. Meteor.*, **18**, 463–474.

Denmead, O. T., and R. H. Shaw, 1962: Availability of soil water to plants as affected by soil moisture content and meteorological conditions. *Agron. J.*, **54**, 385–390.

Harlan, P. W., and D. P. Franzmeier, 1974: Soil-water regimes in Brookston and Crosby soils. *Soil Sci. Soc. Amer. Proc.*, **38**, 638–643.

Mengel, D. B., and S. A. Barber, 1974: Development and distribution of the corn root system under field conditions. *Agron. J.* **66**, 341–344.

Nelson, Wm. L., 1981: Weather data specifications for large area crop modeling. *Computer Techniques and Meteorological Data Applied to Problems of Agriculture and Forestry: A Workshop,* A. Weiss, Ed., Anaheim, Amer. Meteor. Soc., 82–94.

Palmer, Wayne C., 1965: Meteorological drought. Weather Bureau Research Paper No. 45. Washington, DC, 58 pp.

Penman, H. L., 1948: Natural evaporation from open water, bare soil, and grass. *Proc. Roy. Soc. London,* **A193**, 120–145.

Reetz, H. F., D. A. Holt, R. F. Dale, S. E. Hollinger, C. T. Daughtry and W. L. Nelson, 1979: Physiology-based simulation, a tool for large-area crop forecasting. *Preprints 14th Conf. Agricultural and Forest Meteorology,* Minneapolis, Amer. Meteor. Soc., 148–149.

Shanholtz, V. O., and J. H. Lillard, 1970: A soil water model for two contrasting tillage systems. Bull. 38, Virginia Polytechnic Institute, Water Resources Research Center, Blacksburg, VA, 217 pp.

Shaw, R. H., R. E. Felch and E. R. Duncan, 1972: Soil moisture available for plant growth in Iowa. Spec. Rep. No. 70, Agric. Home Econ. Expt. Sta., Iowa State University, Ames, 30 pp.

Shukla, J., and Y. Mintz, 1982: Influence of land-surface evapotranspiration on the earth's climate. *Science,* **215**, 1498–1501.

Strommen, N. D., 1981: The Palmer drought index—a management tool. *Weekly Weather Crop Bull.*, **68**, No. 6, p. 19.

Stuff, R. G., and R. F. Dale, 1978: A soil moisture budget model accounting for shallow water table influences. *Soil Sci. Soc. Amer. J.*, **42**, 637–643.

VanBavel, C. H. M., 1966: Potential evaporation: The combination concept and its experimental verification. *Water Resour. Res.*, **2**, 455–467.

---

[9] Appendix 1, Use of SIMBAL-3 as an operational model, p. 9 in Stuff *et al.*, 1980: SIMBAL FORTRAN IV Version 3, Simulation of soil water balance on poorly-drained (PD) and well-drained (WD) soils. Agronomy Dept., Purdue University, 10 pp.