Comparison of two soil water models for soybeans

H. N. HAYHOE and R. DE JONG

Land Resource Research Centre, Research Branch, Agriculture Canada, Ottawa, Ontario K1A 0C6. *Contribution no. 86–57, received 31 December 1986, accepted 2 June 1987.*

Hayhoe, H. N. and De Jong, R. 1988. **Comparison of two soil water models for soybeans.** Can. Agric. Eng. **30**: 5–11. A diffusion-based soil water model and the SPAW model were tested on soybeans grown on a Caledon sandy loam soil near Simcoe, Ontario. Two different root water uptake functions in the diffusion-based model were compared with the SPAW model. Water retention curves were measured. Hydraulic conductivity and root growth characteristics were based on soil texture and observed soybean growth characteristics. The models were driven by daily evapotranspiration and precipitation data. Predicted final water contents in the root zone were all within 0.5 cm of the observed value of 5.8 cm. Changes in model estimates, as a function of soil type, were examined by using identical weather and crop input parameters but assuming a sand and a clay soil. The model cumulative evaporation values were within 2.2 cm of each other, with means of 25.6 and 37.0 cm, respectively, for the sand and the clay.

A knowledge of soil water content is important for studies of watershed hydrology, irrigation scheduling, movement of nutrients and salts and for studies of crop weather analysis modelling. Since the measurement of soil water content in the rooting zone is often costly, time consuming and complicated due to the endemic variability in the soil there has been a continuing interest in developing mathematical models which use readily available meteorological, soil and plant data (Baier and Robertson 1966; De Jong and Cameron 1978).

Simple water budget approaches use empirical algorithms based on field observations to transfer water in and out of compartments or layers. This modelling approach has proven quite versatile (Baier and Robertson 1966) since many simple assumptions appear to have a wide range of applicability. In general, however, reliable prediction at individual sites requires some calibration using observed soil water data.

Theoretical considerations suggest that water transfer in uniform soil can be modelled assuming a nonlinear diffusion process (De Jong and Cameron 1978), with water uptake by plant roots represented by a sink term (Feddes et al. 1974). This approach requires specification of the hydraulic conductivity and soil water retention curves, upper boundary conditions of potential evaporation and precipitation, and an appropriate lower boundary (Hayhoe and De Jong 1982). Although this approach has sound theoretical foundations it can still only be considered as a first-order approximation to what is happening under field conditions. Hysteresis, shrinking and swelling, or the effects of macropores can significantly influence water transfer. Other problems associated with this approach include determining representative values for soil water characteristics, specifying the sink term, and constructing an efficient and reliable numerical implementation of the model (Hayhoe 1978).

As a result of the limitations of both water budget models and theoretical diffusion-based models several attempts have been made to combine the two approaches. In one such combination called the Soil-Plant-Air-Water (SPAW) model (Saxton et al. 1974) soil water is recharged by precipitation with a dynamic time distribution of hours; it is depleted at a much slower rate by surface evaporation, plant transpiration and percolation and redistributed within the soil profile through a continual state of flux caused by hydraulic head gradients.

In this study, evaporation and soil water data for a soybean crop grown at Simcoe, Ontario (Bailey and Davies 1981b) are used to compare the diffusion-based modelling approach with the more empirical approach represented by SPAW. The effect of representing water uptake by plants in terms of root depth (Feddes et al. 1978; Carneiro da Silva and De Jong 1986) rather than root distribution (Hayhoe and De Jong 1982) is also examined using the diffusion-based model. Finally, model sensitivity to soil type is examined by assuming identical weather and crop parameters while changing the soil parameters to represent a sand and a clay soil.

METHODS

Model descriptions

(a) *Diffusion-based model.* The mathematical equation for soil-water flow and uptake by plant root systems can be written as (Hayhoe 1981):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(D(\theta)\frac{\partial \theta}{\partial z} - K(\theta)\right) - S(\theta, z) \qquad (1)$$

where θ is the volumetric water content (cm^3 cm^{-3}); t is time (min); z is the vertical distance from the soil surface (cm); $D(\theta)$ is the soil water diffusivity function (cm^2 min^{-1}); $K(\theta)$ is the hydraulic conductivity function (cm min^{-1}); and $S(\theta, z)$ is a sink term representing the water extraction rate by plant roots (cm^3 cm^{-3} min^{-1}). The latter is defined by:

$$S(\theta, z) = C(z)\, K(\theta)\, (\psi_y - \psi(\theta))\, W(z) \qquad (2)$$

where $C(z)$ is a root activity function, ψ_y is the suction head at the root-soil interface (15 000 cm H_2O), $\psi(\theta)$ is the soil-water suction head function (cm H_2O) and $W(z)$ is a root distribution function (cm cm^{-3}).

Since root distribution is difficult to measure, the water extraction function was modified so that only a knowledge of rooting depth was required. Equation 2 was changed so that the uptake was limited by a function of potential transpiration which we assumed decreased linearly with depth (Feddes et al. 1978). The maximum uptake by the plant root system was defined by

$$M(z) = 2\,P\,(R - z)/R^2 \qquad (3)$$

where $M(z)$ is the maximum uptake (cm^3 cm^{-3} min^{-1}), R is the

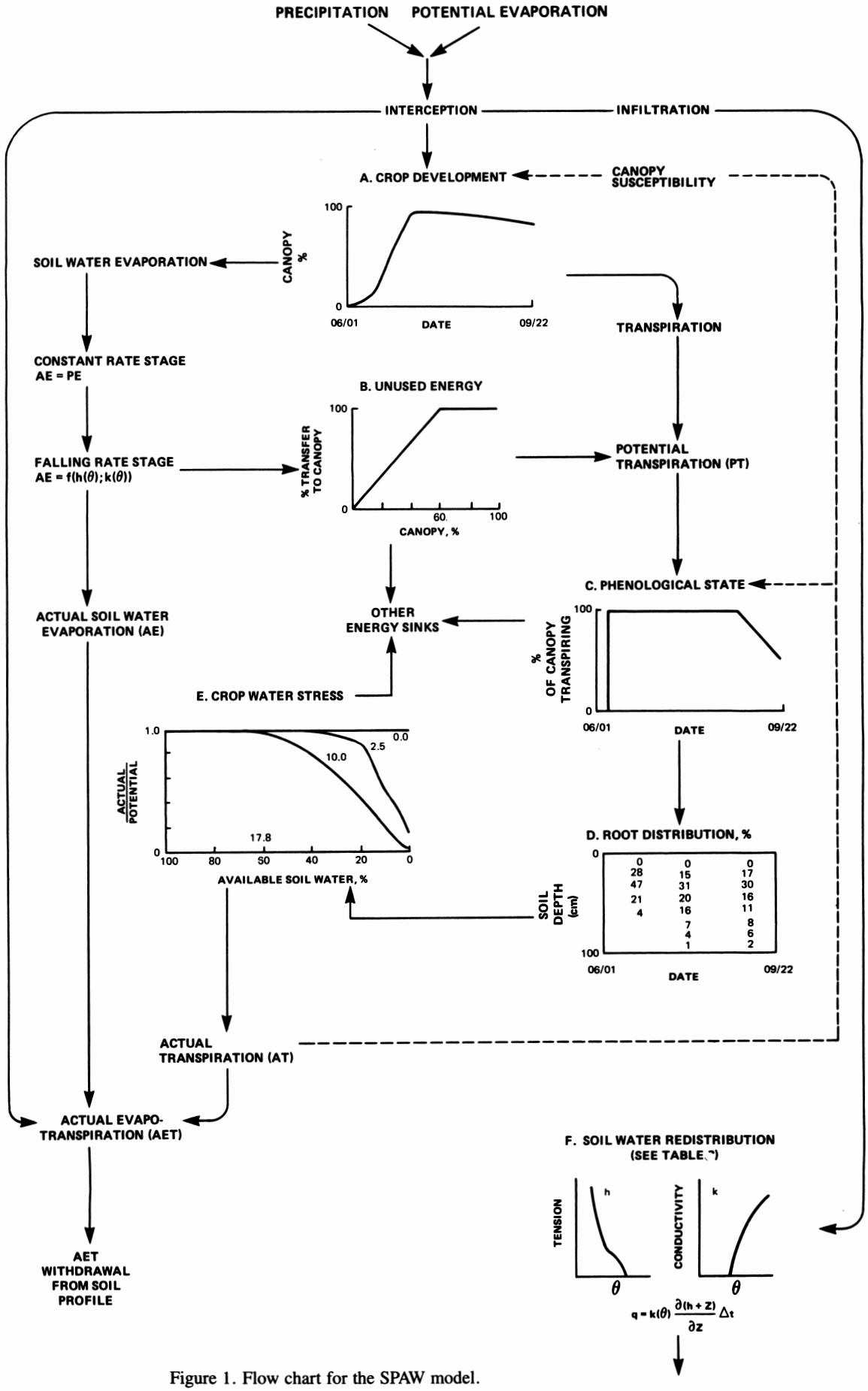

Figure 1. Flow chart for the SPAW model.

rooting depth (cm) and P is the potential transpiration rate (cm min^{-1}). The new sink term becomes

$$S(\theta,z) = \begin{cases} C(z)\,K(\theta)\,(\psi_y - \psi(\theta)) & S(\theta,z) < M(z) \\ M(z) & \text{otherwise} \end{cases} \quad (4)$$

Measured soil water contents at the beginning of the simulation period were used to specify the initial condition, $\theta(z,0)$. The surface boundary condition, $\theta(0,t)$ was specified using daily precipitation and potential evapotranspiration data, and an impermeable layer was assumed as the basal boundary condition. The total profile depth was chosen to be 100 cm.

(b) *SPAW model.* The SPAW model computes the soil water balance by various steps that involve sequentially (i) calculating evapotranspiration, (ii) adding infiltration and (iii) redistributing water among the soil layers. Beginning at the top of Fig. 1, intercepted precipitation by the crop canopy has first use of the potential evapotranspiration energy. The remaining part is divided between soil water evaporation and plant transpiration according to canopy cover (Fig. 1A). Evaporation from the soil is calculated in two stages (Ritchie 1972): (i) the constant rate stage in which only the supply of energy limits soil evaporation and (ii) the falling rate stage in which water movement to the evaporating sites near the surface is controlled by the hydraulic properties of the soil. A portion of the unused potential energy for soil evaporation is returned to the plant transpiration potential (Fig. 1B).

Potential transpiration is first reduced by a seasonal relationship of the crop's phenological stage, which depicts its ability to transpire (Fig. 1C). Next, a percentage of the daily potential transpiration is assigned to each soil layer depending on the root distribution (Fig. 1D). Actual transpiration is then determined by using a family of transpiration versus available soil water content curves (Fig. 1E) as adapted from Denmead and Shaw (1962). Canopy evaporation, soil evaporation and crop transpiration are combined to provide daily actual evapotranspiration (AET) estimates.

Daily infiltration (precipitation minus canopy interception) is stored in the uppermost soil layer, until this layer reaches 90% of saturation, then the excess cascades to succeeding lower layers, with this same restriction, until sufficient storage is available. Vertical soil water redistribution among 10 soil layers is computed according to Darcy's law (Fig. 1F), with an impermeable layer as the basal boundary.

Site description

The experimental data used in this study were collected by Bailey and Davis (1981a) on a Caledon sandy loam soil near Simcoe, Ontario. Soybeans (*Glycine max* (L.) Harosoy 63) were planted on 6 June 1974, on a flat 2.6-ha plot. Volumetric water contents and hourly evaporation (measured by the Bowen ratio method) were monitored throughout the 1974 growing season. Potential evapotranspiration (Fig. 2) was estimated using the Priestley-Taylor model while precipitation (Fig. 3) was measured on-site. Water retention curves were measured as described by Wilson (1971) for three distinct soil layers (0–25 cm, 25–50 cm and 50–100 cm) and fitted by linear regression analysis to a power function of the form

$$\psi = \psi_s\,(\theta/\theta_s)^{-b} \quad (5)$$

where θ_s is saturated water content (cm^3 cm^{-3}); b and ψ_s are empirical curve fitting parameters. Equation 5 was modified according to Clapp and Hornberger (1978) to account for gradual air entry. The hydraulic conductivity-water content relationship for each of the three layers was obtained using the method of Campbell (1974).

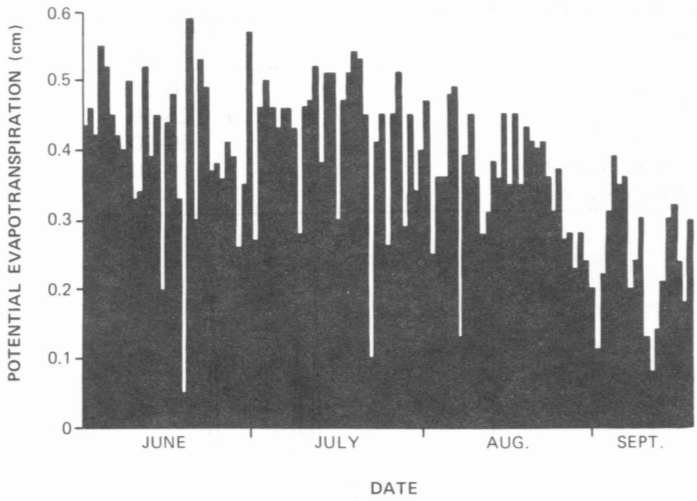

Figure 2. Daily potential evapotranspiration.

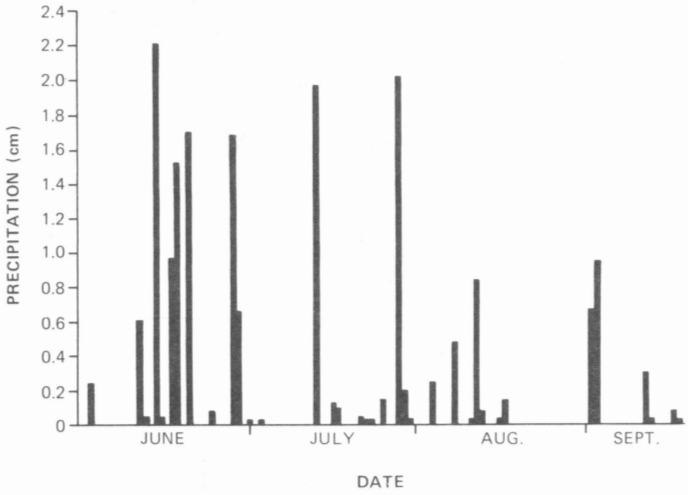

Figure 3. Daily rainfall totals measured on the site.

Test of sensitivity to soil texture

In order to compare the models' responses on a wider range of soil textures, the above crop and meteorological data were used with a sand and a clay. The hydraulic properties of soils (Table I) were taken from Clapp and Hornberger (1978). The SPAW model was also run on these data for comparison.

RESULTS

The hydraulic properties of the soils are presented in Table I. Good agreement was obtained between the measured and estimated water retention curves of the Caledon soil. Correlation coefficients (significant at the 0.01% level) exceeded 0.97 and mean absolute differences varied from 0.012 cm^3 cm^{-3} in the 0–25 cm layer to 0.018 cm^3 cm^{-3} in the 50- to 100-cm layer.

Saturated hydraulic conductivities, which are required as matching factors in Campbell's (1974) method, were taken from

Table I. Soil water retention parameters for curves of the form $\psi = \psi_s (\theta/\theta_s)^{-b}$ and saturated hyraulic conductivities

Soil	Layer (cm)	b	ψ_s (cm H_2O)	θ_s ($cm^3\ cm^{-3}$)	K_{sat} (cm min^{-1})
Caledon	0–25	3.77	26.10	0.35	0.208
Caledon	25–50	3.92	11.13	0.38	0.208
Caledon	50–100	3.23	7.14	0.38	0.208
Theoretical sand	0–100	3.0	2.1	0.38	1.06
Theoretical clay	0–100	5.3	83.8	0.51	0.0083

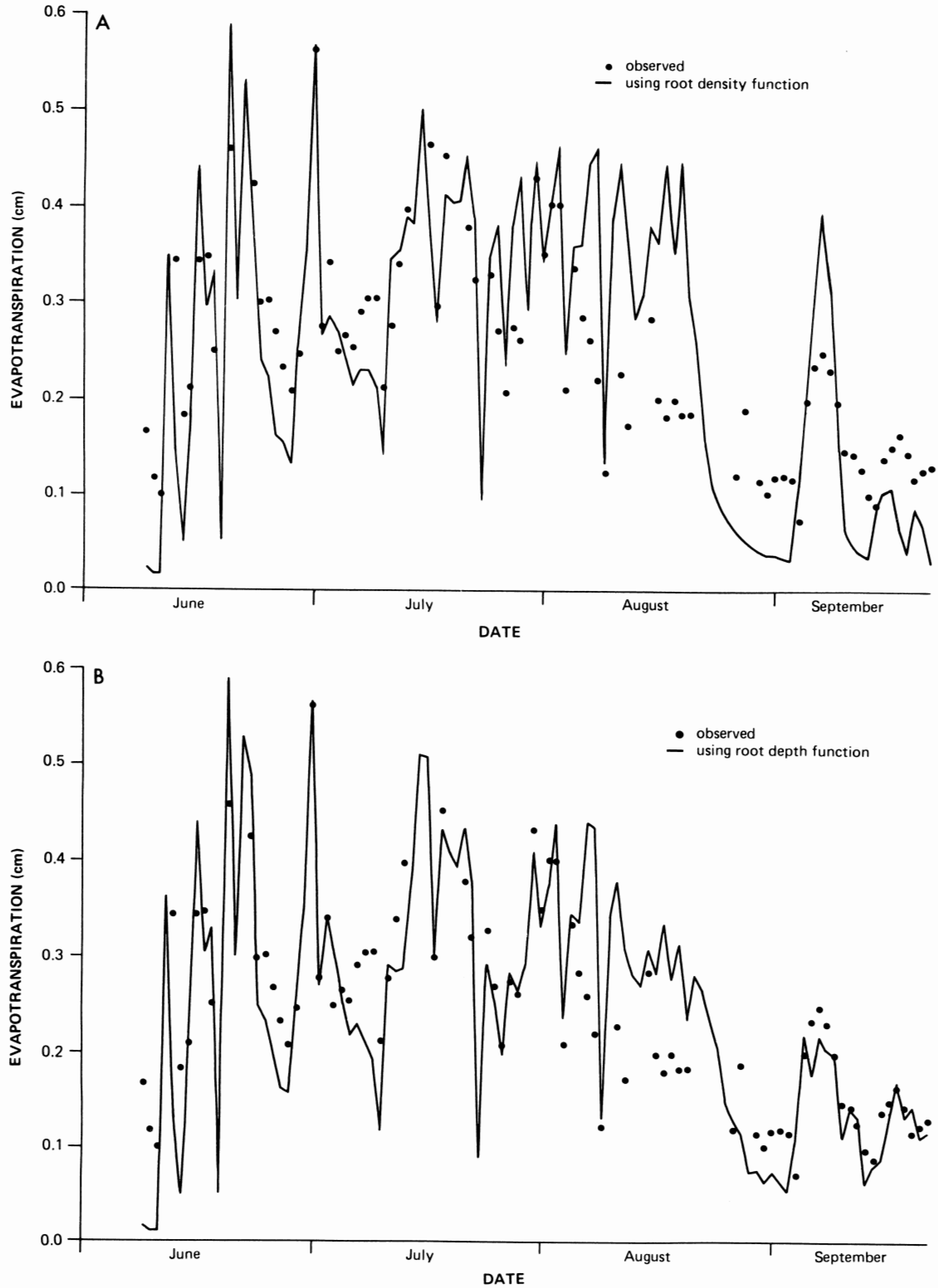

Figure 4(A). Daily actual evapotranspiration measured and simulated using the diffusion-based model with the root density function. (B). Daily actual evapotranspiration measured and simulated using the diffusion-based model with the root depth function.

Clapp and Hornberger (1978) for the appropriate textural class. For the Caledon sandy loam, field capacity was defined as the water content when ψ equalled 150 cm H_2O. For the sand and clay, field capacity was set at 100 and 333 cm H_2O, respectively. The permanent wilting point of all three soils was defined as the water content where ψ equalled 15 000 cm H_2O.

The simulation for the Caledon soil was started on 9 June 1974, 3 d after planting. The root distribution function, $W(z)$, was derived from values reported by Allmaras et al. (1975) for soybeans grown on sandy clay loam. The root activity function, $C(z)$, was used to make an empirical adjustment to match measured and predicted water uptake as a function of depth. Leaf area indices measured by Bailey and Davis (1981a) were used to partition between evaporation and transpiration (Nimah and Hanks 1973).

Figure 4 shows the observed and simulated actual evapotranspiration (AET) for the Caledon soil. During the early part of the growing season before the crop canopy and rooting system were well established SPAW gave generally higher AET values than either the measured values or those estimated with the diffusion-based model. This was the case during the period of 25–28 June and 3–9 July (Fig. 4). Total water contents estimated with SPAW during this period were lower than either measured or estimates with diffusion-based models. Estimated cumulative AET during June with SPAW was 7.4 cm but 5.3 cm with the diffusion-based models.

During July, all estimates of AET were very similar. From 9–23 July the cumulative PET was 6.0 cm while the model estimates of cumulative AET were 4.7 cm, 4.9 cm and 4.8 cm for SPAW, the diffusion model using Eq. 2 and the diffusion model using Eq. 4, respectively. As indicated by Fig. 4 the measured and estimated daily AET were also close during this July period.

Estimates of AET using SPAW were lower than the diffusion-based estimates during most of August. The SPAW estimates of AET were closer to the measured ones. The estimates of AET using the diffusion-based model with root uptake determined by Eq. 2 remained closer to PET than SPAW or the uptake function specified by Eq. 4 during most of August but dropped off more rapidly at the end of August as available water depleted (Figs. 4 and 5). During September, AET estimated with the diffusion-based model based on Eq. 4 was closer to the SPAW estimate and the measured values than were estimates with the diffusion model based on Eq. 2.

Cumulative AET for the whole growing season estimated with SPAW was 25.6 cm; with the diffusion-based model and Eq. 2 it was 25.8; and with Eq. 4 it was 25.5 cm. All three approaches produced a final total water content which closely matched the measured value (Fig. 5).

There are a number of cases where the measured drop in total soil water content was greater than either that predicted by any of the models or that predicted from calculated cumulative PET. For example, the measured water in the profile dropped from 18.0 cm on 30 June to 13.6 cm on 7 July. The cumulative PET during the period was only 3.0 cm (Fig. 2) while the change in total water content was 4.4 cm. During the period from 30 July to 6 Aug., the total soil water dropped from 12.7 to 7.9 cm. The total cumulative PET for the period was 3.1 cm. Rouse and Wilson (1972) obtained similar results on this soil with respect to estimates of evapotranspiration and infiltration from observations of soil water content. Considerable spatial variation in infiltration as well as possible lateral transfer, factors not accounted for in the models, is considered to be the cause of these discrepancies.

The simulations for the sand and clay soils were started on 1 June when the soil profile was assumed to be at field capacity.

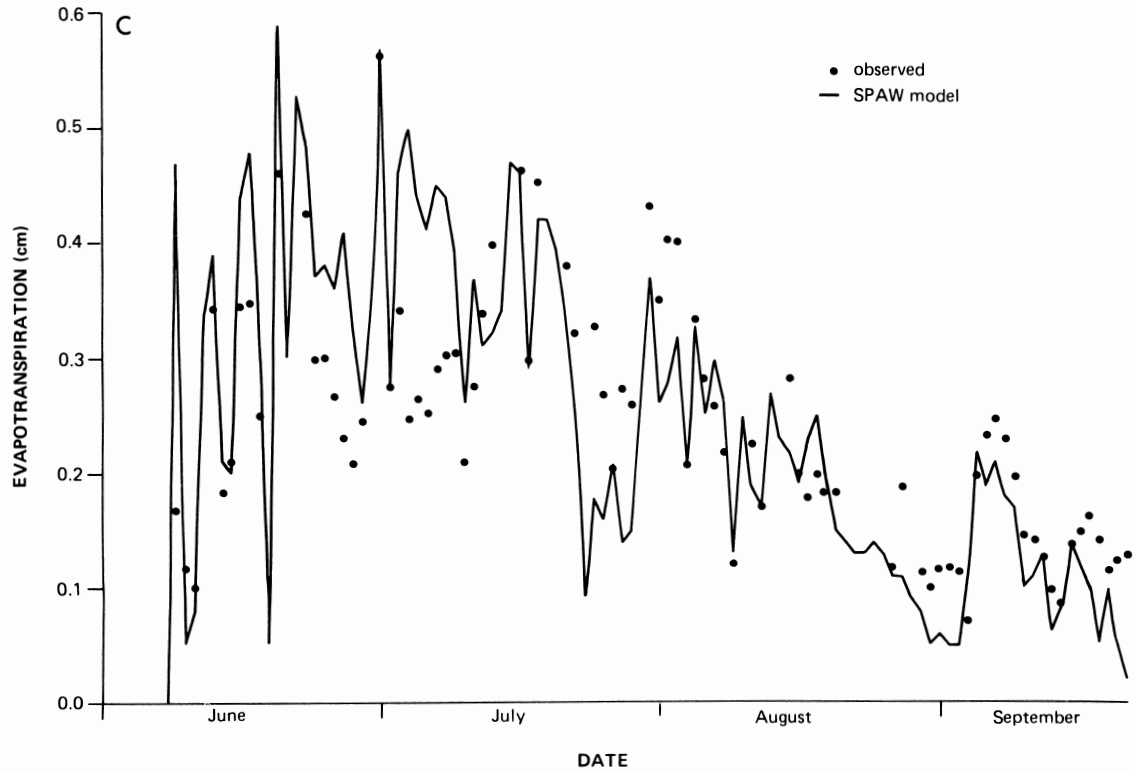

Figure 4 (C). Daily actual evapotranspiration measured and simulated using the SPAW model.

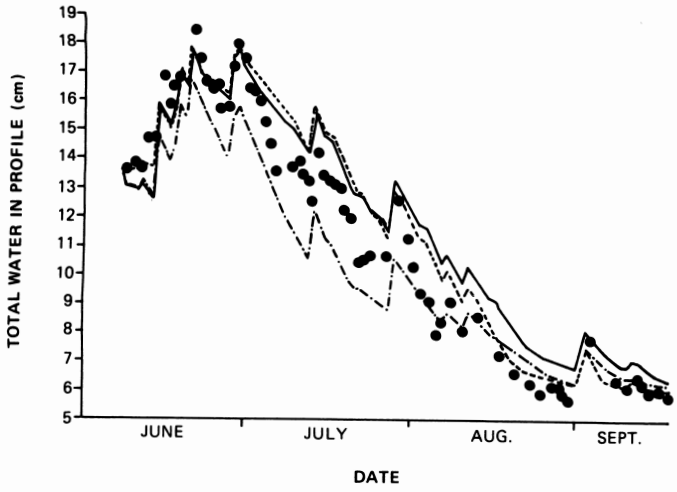

Figure 5. Total water content measured and simulated at the Simcoe experimental site. •, observed, ——using root depth function, --- using root density function, —·—·— SPAW model.

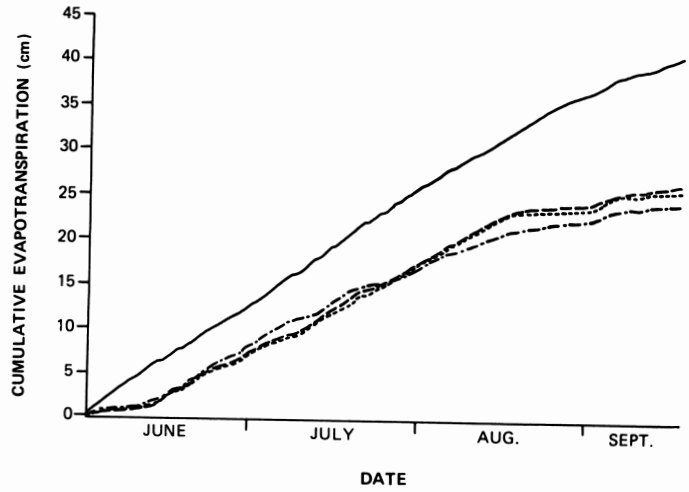

Figure 7. Cumulative potential and actual evapotranspiration simulated for a theoretical sand soil. ——potential evapotranspiration, – – – using root depth function, ---- using root density function, —·—·— SPAW model.

Cumulative PET for the period was 41.0 cm. For the clay soil (Fig. 6) the SPAW estimate of cumulative AET was 36.6 cm. For the diffusion-based approaches the cumulative AET from root depth (Eq. 4) was 37.1 cm and from root density (Eq. 2) was 37.2 cm (Fig. 6). The SPAW model again estimated higher AET than the diffusion-based models early in the growing season with AET and PET essentially equal till 18 Aug. Estimated AET then dropped off more rapidly than indicated by the diffusion-based approaches. A similar pattern occurred with the sand (Fig. 7) although prior to the establishment of the crop, there was less AET than with the clay. For the sand soil the SPAW estimate of cumulative AET was 24.4 cm. For the diffusion-based approaches the cumulative AET from root depth was 26.6 cm and from root density was 25.9 cm. For both these soils, the SPAW model yielded the highest estimates of final soil water content, which is consistent with the cumulative AET estimates. There was little difference between the two diffusion-based estimates.

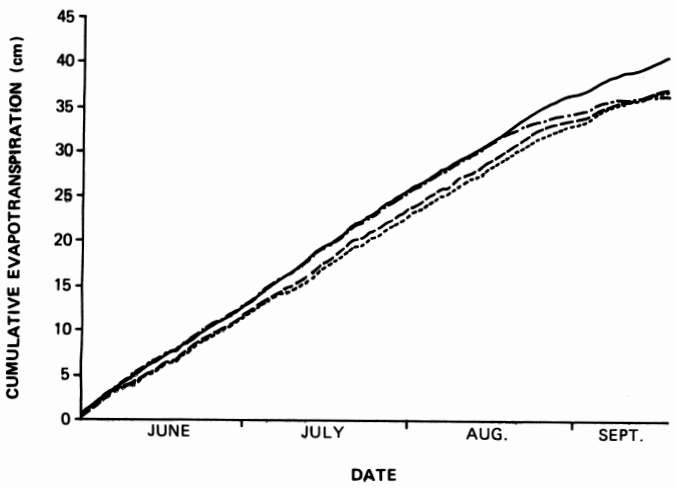

Figure 6. Cumulative potential and actual evapotranspiration simulated for a theoretical clay soil. ——potential evapotranspiration, – – – using root depth function, ---- using root density function, —·—·— SPAW model.

DISCUSSION AND CONCLUSIONS

The simulations of total water use for the growing season with different soil water models and root-water-uptake functions were all within 0.5 cm of the measured data. Real differences of up to 3.6 cm occurred in soil water contents during specific periods of the season but these differences tended to disappear by the end of the growing season. The SPAW model consistently indicated higher AET on bare or sparsely covered soil but later in the season the AET estimates were lower than the diffusion-based estimates due to the lower estimates of soil water content and the empirical assumptions of the availability of soil water to plants (Denmead and Shaw 1962). Differences between the diffusion-based estimates were generally small. When the estimates of AET during August as the soil dried were compared with measured values it appeared that the assumptions involved in using only root depth gave a better correspondence than when root densities were used.

Alaerts et al. (1985) have shown that even when root-water-uptake models predict the same uptake, soil water distribution with depth may still be quite different. The root-water-uptake function specified by Eq. 2 is formulated such that even if only a small fraction of the crop roots are in a given depth interval, the total evaporative demand of the crop can be met by extracting water from that depth if it has a relatively high water content. This feature of the model partly explains why AET may remain closer to PET until the entire profile is close to the permanent wilting point. The root-water-uptake function specified by Eq. 4, however, limits the uptake at any depth with a linearly decreasing function of evaporative demand and rooting depth. The measured data indicate that the AET estimated using Eq. 4 corresponds better than that using Eq. 2. Carneiro da Silva and De Jong (1986) also obtained satisfactory estimates using the formulation based solely on root depth. In addition, Eq. 4 is preferable as a root-water-uptake function due to the much greater difficulty in obtaining root densities as compared with obtaining root depths.

The results of this as well as earlier studies (De Jong and Hayhoe 1984) suggest that the diffusion-based approach can provide useful estimates of soil water and evapotranspiration. By using specified soil hydraulic properties for a range of soil

textures (Clapp and Hornberger 1978) the model became a versatile tool for simulation. The SPAW model was also found to provide a good correspondence between measured and estimated data. It required less computer time to execute a simulation (De Jong and Zentner 1985). One advantage of the diffusion-based approach is that it does not rely on the empirical relationships between the availability of soil water to plants and soil moisture content.

Simulating the soil water regime and actual evapotranspiration with either model requires a detailed input of soil hydraulic properties and seasonal crop growth characteristics. As shown in this study, with some local calibration many soil and crop data might be successfully adopted from the literature, thereby reducing the cost of field experimentation.

ACKNOWLEDGMENTS

We wish to thank Dr. W. G. Bailey (Simon Fraser University, Burnaby, B.C.) for providing the field measured data. A copy of the SPAW model was obtained from Dr. K. E. Saxton (USDA, Pullman, Washington).

REFERENCES

ALAERTS, M., M. BADJI, and J. FEYEN. 1985. Comparing the performance of root-water-uptake models. Soil Sci. 139: 289–296.

ALLMARAS, R. R., W. W. NELSON, and W. B. VOORHEES. 1975. Soybean and corn rooting in southwestern Minnesota. II. Root distribution and related water inflow. Soil. Sci. Soc. Am. Proc. 39: 771–777.

BAIER, W. and G. W. ROBERTSON. 1966. A new versatile soil moisture budget. Can. J. Plant Sci. 46: 299–315.

BAILEY, W. G. and J. A. DAVIES. 1981a. Bulk stomatal resistance control on evaporation. Boundary-Layer Meteorol. 20: 401–417.

BAILEY, W. G. and J. A. DAVIES. 1981b. Evaporation from soybeans. Boundary-Layer Meteorol. 20: 417–428.

CAMPBELL, G. S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. Soil Sci. 117: 311–314.

CANADA SOIL SURVEY COMMITTEE, Subcommittee on Soil Classification. 1978. The Canadian system of soil classification. Can. Dep. Agric. Publ. 1646, Supply and Services Canada, Ottawa, Ont. 164 pp.

CARNEIRO da SILVA, C. and E. DE JONG. 1986. Comparison of two computer models for predicting soil water in a tropical monsoon climate. Agric. For. Meteorol. 36: 249–262.

CLAPP, R. B. and G. M. HORNBERGER. 1978. Empirical equations for some hydraulic properties. Water Resour. Res. 14: 601–604.

DE JONG, R. and D. R. CAMERON. 1978. Computer simulation model for predicting soil water content profiles. Soil Sci. 128: 41–48.

DE JONG, R. and H. N. HAYHOE. 1984. Diffusion-based soil water simulation for native grassland. Agric. Water Manage. 9: 47–60.

DE JONG, R. and R. P. ZENTNER. 1985. Assessment of the SPAW model for semi-arid growing conditons with minimal local calibration. Agric. Water Manage. 10: 31–46.

DENMEAD, O. T. and R. H. SHAW. 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditons. Agron. J. 45: 385–390.

FEDDES, R. A., E. BRESLER, and S. P. NEUMAN. 1974. Field test of a modified numerical model for water uptake by root systems. Water Resour. Res. 10: 1199–1206.

FEDDES, R. A., P. J. Kowalik, and H. Zaradny. 1978. Simulation of field water use and crop yield. Halsted Press, New York.

HAYHOE, H. N. 1978. Study of the relative efficiency of finite difference and Galerkin techniques for modelling soil-water transfer. Water Resour. Res. 14: 97–102.

HAYHOE, H. N. 1981. Analysis of a diffusion model for plant root growth and an application to plant soil water uptake. Soil Sci. 131: 334–343.

HAYHOE, H. N. and R. DE JONG. 1982. Computer simulation model of soil water movement and uptake by plant roots. Land Resource Research Institute, Agriculture Canada, Ottawa, Ontario 74 pp.

NIMAH, M. N. and R. J. HANKS. 1973. Model for estimating soil water, plant and atmospheric interrelations. I. Description and sensitivity. Soil Sci. Soc. Am. Proc. 37: 522–527.

RITCHIE, J. T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8: 1204–1213.

ROUSE, W. R. and R. G. WILSON. 1972. A test of the potential accuracy of the water budget approach to estimating evapotranspiration. Agric. Meteorol. 9: 421–446.

SAXTON, K. E., H. P. JOHNSON, and R.H. SHAW. 1974. Modeling evapotranspiration and soil moisture. Trans. ASAE (Am. Soc. Agric. Eng.) 17: 673–677.

WILSON, R. G. 1971. Methods of measuring soil moisture. Intern. Field Year for the Great Lakes, Tech. Manual Ser. 1: 20 pp.