International Water and Irrigation Journal, pp. 18-22, Vol. 20, No. 4, 2000.

INTERNATIONAL IRRIGATION

INTERNATIONAL WATER & IRRIGATION

Energy and Water Balances for Surface and Subsurface Drip Irrigated Corn

Steven R. Evett, Terry A. Howell, and **Arland D. Schneider** [1]
USDA-ARS, Conservation Laboratory, Bushland, Texas, USA

ABSTRACT

Drip irrigation using buried emitters has the potential to save irrigation water by reducing soil surface wetting and thus reducing evaporation (E). However, measurement of evapotranspiration (ET) for different combinations of emitter depth and cropping systems can become onerous. We modified a mechanistic ET model, ENWATBAL, to simulate irrigation with drip emitters at any depth and modeled energy and water balance components for corn (*Zea mays L.*, cv. PIO 3245) grown on the Pullman clay loam soil at Bushland, TX using emitters at the surface and at 0.15- and 0.30-m depths. Irrigation was daily and was scheduled to replace crop water use as measured in the field by neutron scattering. Modeled transpiration was essentially equal for all emitter depths (428 mm over 114 days from emergence to well past maximum leaf area index [LAI]) but evaporation was 51 mm and 81 mm less for 15- and 30-cm deep emitters compared with surface emitters. Predicted drainage was slight (6-, 8- and 12-mm for surface, and 0.15- and 0.30-m deep emitters, respectively), but comparisons of predicted and measured soil water profiles at season's end showed that deep drainage of over 150 mm of water may have occurred. There were minor differences in soil heat flux between the treatments because soil heat flux was a relatively minor component of the energy balance. For surface emitters, net radiation was much greater and sensible heat flux was smaller than for subsurface emitters until LAI increased past 4.2 midway through the season. Thus, almost all of the differences in ET occurred during the period of partial canopy cover. Differences in energy balance components between treatments were minor after day of year 220. The study showed that water savings of up to 10% of seasonal precipitation plus irrigation could be achieved using 30-cm deep emitters.

INTRODUCTION

Crops grown under subsurface drip irrigation may outyield those grown under surface drip (Phene et al., 1987) or use less water for the same yield (Camp et al., 1989). The differences may be related to differences in plant available water due to greater evaporation from the soil surface with surface irrigation. However for corn (*Zea mays*) grown in 1993 on the Pullman clay loam at Bushland, TX there was no significant yield difference for well-watered treatments (Howell, et al., 1994). Tarantino et al. (1982) compared microclimate and evapotranspiration (ET) of tomatoes under drip and furrow irrigation on weighing lysimeters and found no difference in seasonal ET when canopy development was similar. Drip irrigation was daily in their study while furrow irrigation frequency was about 10 days. The higher ET from furrow irrigation for the 3 days after irrigation was offset by the generally higher ET from drip irrigation on other days due to the continuously wetted soil surface under drip. Even though the loam soil surface was only partially wetted, advection from dry, hot interrow areas contributed to the energy available to drive evaporation from the wet surface. If soil surface wetting could have been reduced by using subsurface drip, the ET from drip irrigation might well have been lower than that under furrow irrigation. On a sandy soil, net radiation and ET were higher for sprinkler irrigation compared to drip irrigation of tomatoes when irrigations were daily (Ben-Asher et al., 1978).

Water flow during micro-irrigation has been variously simulated as essentially one-dimensional (Van Bavel et al., 1973), two-dimensional axisymmetric (Brandt et al., 1971; Nassehzadeh-Tabrizi et al., 1977), and two-dimensional rectilinear (Ghali and Svehlik, 1988; Oron, 1981). Lafolie et al. (1989) introduced both axisymmetric and rectilinear finite difference solutions. Although some of these studies included root uptake, none of them attempted to model the energy and water balances of the crop canopy and soil surface.

ENWATBAL (ENergy and WATer BALance), a mechanistic ET model, was described by Evett and Lascano (1993) and Van Bavel and Lascano (1987). It was used to predict cotton ET (Lascano et al., 1987) and sorghum ET (Van Bavel and Lascano, 1987) at Lubbock, TX. More recently Ritchie and Johnson (1990) compared ENWATBAL to the functional CERES-Maize model for predicting cotton ET. Krieg and Lascano (1990) used ENWATBAL to predict sorghum ET at Brownfield, TX, and Lascano (1991) used the model to predict the effects of N on the water use of irrigated and dryland sorghum at Lubbock, TX. ENWATBAL has successfully estimated daily corn ET ($r^2 = 0.85$ to 0.96) and net radiation ($r^2 = 0.97$) over a full season at the study site (Evett et al., 1991). Bare soil evaporation was

---

[1] *Soil Scientist, Research Leader (Agricultural Engineer), and Agricultural Engineer, respectively. USDA-ARS, Conservation and Production Research Laboratory, P.O. Drawer 10, Bushland, TX 79012. Contribution supported in part by USDA-OICD Agreement No. 03T594 60-7D15-4-023 in cooperation with the National Agricultural Research Project (NARP), Ministry of Agriculture, Agricultural Research Center, Soils and Water Research Institute, Giza, Egypt.*

also well estimated by ENWATBAL in three experiments ($r^2 = 0.84$, 0.94 and 0.99) (Evett et al., 1992). In the present study we investigated corn crop energy and water balances using ENWATBAL in order to better understand the physical differences between surface and subsurface drip irrigated corn. ENWATBAL was modified to include a source term for water application at a user chosen depth and season-long simulations were made with drip irrigation at the surface, and at 0.15 and 0.30 m below ground.

MATERIALS AND METHODS

Corn (*Zea mays L.*, cv PIO 3245) was planted on day of year 147 in rows spaced 0.76 m apart. This was about a month later than normal for this region. The soil is a Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) characterized by a dense B horizon at about 20 cm depth and a calcic horizon starting at about 110 cm depth. Fertilization, harvest, and other agronomic considerations as well as plot size and irrigation methods are given by Howell et al. (1994) elsewhere in these proceedings. Emitters were spaced at 0.45 m intervals along the tubing and lines were space 1.52 m apart. Soil water content was measured weekly by neutron scattering at depths of 0.1 through 2.3 m with 0.2 m increments using a Campbell Pacific Nuclear, Inc. model 503DR[2*] moisture gage (1 access tube per plot, 32 s counts at each depth). The gage was previously field calibrated for the A, B and calcic B horizons with coefficients of determination of 0.90, 0.96, and 0.97, respectively. There were three irrigation levels (33%, 67% and 100% of crop water use), but this paper only deals with irrigation for 100% of crop water use. A control level of 0.333 $m^3 m^{-3}$ average water content in the top 1.5 m of soil was used to calculate irrigation amounts to replenish any water used by the crop. Both daily and weekly irrigation treatments were used, but we will deal only with daily irrigations here. There were three plots with 100% surface drip irrigation and three plots with 100% subsurface drip irrigation at 0.3 m depth.

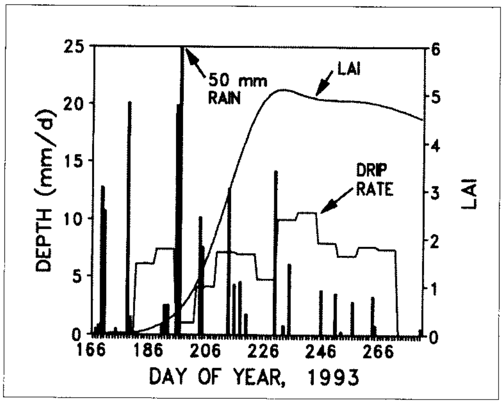

Figure 1. Rainfall (vertical bars), drip irrigation rate and leaf area index (LAI).

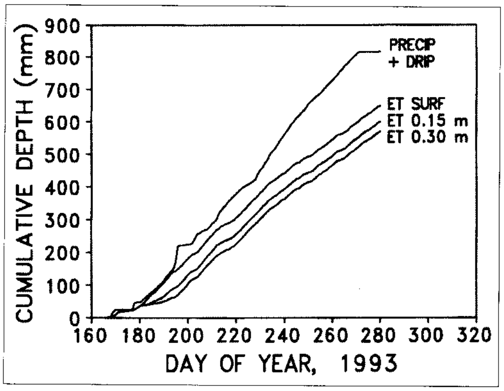

Figure 2. Cumulative precipitation plus irrigation and cumulative ET for Surface (SURF), and 0.15- and 0.30-m deep drip emitters.

The ENWATBAL model was initialized with the average soil water contents measured in the 100% plots on day 167; and, with temperatures measured in a nearby weighing lysimeter which had similar surface condition in the months leading up to the experiment. Relationships of soil water content vs. soil water potential and soil hydraulic conductivity vs. soil water content were those used by Steiner et al. (1989). The relationship between soil albedo and soil surface water content (water content in the top 0.008 m of soil) was developed from measurements of albedo of Pullman soil that was freshly irrigated and air dry, respectively. Albedo was described in the model as being 0.11 from water contents of 0.49 (saturated) to 0.25, and varying linearly with water content from 0.11 to 0.20 as water content declined from 0.25 to 0. Modeling was begun on day 166 and proceeded through day 246.

The model was modified to include a drip source at a user defined depth. The emitter flow rate of 2.27 L h^{-1} was converted to an equivalent depth of water over the area covered by one emitter (0.00362 m h^{-1}). Irrigation was begun at 8:00 every day and the number of hours of application for a day were those necessary to supply 1/7 of the weekly amount required to replenish the root zone to 0.333 $m^3 m^{-3}$ water content. We ran the model for surface irrigation, and subsurface irrigation at 0.15 and 0.30 m depths. Although ENWATBAL is a one dimensional model, we considered it applicable to our problem due to the low hydraulic conductivity of the Pullman soil. Soils with low hydraulic conductivity tend to show more spreading and less deep movement of the water front than more permeable soils with the result that water fronts from adjacent emitters tend to meet and render the wetted soil volume more one-dimensional in nature. This approach is somewhat similar to the one-dimensional model of Van Bavel et al. (1973).

Input weather data for the model were collected at a weather station immediately north of the plots and included half-hourly averages of solar radiation, wind speed, air temperature, and dew point temperature, all measured at 2 m above mowed grass. Precipitation was measured with a tipping bucket raingage and totalized every half hour. Leaf area index (LAI) was measured (3 replicates) in a corn field under LEPA (Low Energy Precision Application) pivot irrigation directly north of the drip plots. The pivot field was planted a month before the drip plots so the curve of LAI vs. day required by ENWATBAL was adjusted by 30 days. Rooting depth was set equal to the depth of planting and assumed to increase by 0.01 m d-1 for 100 days. The simulations began on day 166, shortly after emergence, and ended on day 280, well past peak LAI, so surface conditions included essentially bare soil and complete canopy cover.

RESULTS AND DISCUSSION

The seasonal water balance can be written:

[1] $0 = P - ET - D - R - \Delta S - \epsilon_w$

where P is the total of precipitation and irrigation, ET is evapotranspiration (evaporation, E, plus transpiration, T), D is deep drainage, R is runoff, ΔS is the water depletion from the profile, and ϵ_w is the water balance error (all in mm). Irrigation and precipitation totaled 617 and 199 mm, respectively. Irrigation rates were adjusted to replenish soil

---

[2*] *The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.*

This space left intentionally blank.

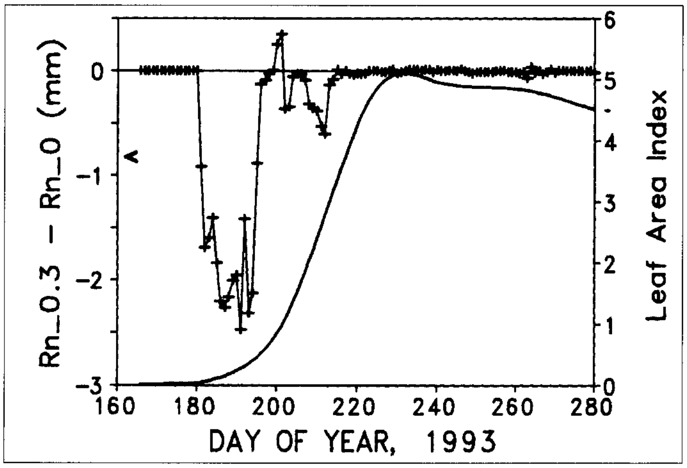

Figure 3. Net radiation for 0.30-m deep drip minus net radiation for surface drip. The plotted leaf area index curve for the season shows that net radiation differences were minor after leaf area index approached 3.

water as needed and reflect major precipitation events and the increase of consumptive use with LAI (Fig. 1). Due to the well-watered condition of the crop, seasonal transpiration (T) was nearly identical regardless of emitter depth, with T of 427-, 428- and 428-mm for depths of 0-, 0.15- and 0.30-m, respectively (Table 1). However, evaporation (E) was 81 mm greater for surface drip compared to drip at 0.30 m depth. Evaporation was 30 mm greater for drip at 0.15-m depth compared to drip at 0.30m. These differences are reflected in different cumulative ET (Fig. 2). Because estimated drainage was low, the differences in E caused differences in soil moisture profiles with the profile being wetter at season's end for subsurface compared to surface drip (Table 1). The stored water at the end of the season was 69- and 48-mm greater for 0.30- and 0.15-m deep emitters, respectively, than for surface drip. Drainage, while slight, was greater for buried emitters than for surface drip (12-mm for 0.30-m deep and 8 mm for 0.15-m deep emitters compared to 6-mm for surface drip).

Table 1. Water Balance, Day 166-280, 1993.

	Depth (m)		
	0	0.15	0.30
P[a]	815.7[b]	815.7	815.7
ET	649.5	600.1	570.0
T	426.6	428.1	427.9
E	222.9	172	142.1
D	6.3	8.3	12.2
R	0	0	0
PETDR	159.9	207.3	233.5
ΔS	157.8	205.6	227.1
ϵ_w	-2.1	-1.7	-6.4
ΔS ref 0[c]	0	47.8	69.3
E ref 0	0	50.9	80.8
D ref 0	0	2	5.9

[a] *Eq. 1 defines P, ET, etc.*

[b] *Cumulative depth in mm.*

[c] *Referenced to 0-m by subtracting the value for the 0-m depth.*

The 114 day cumulative ET of 650 mm for surface drip was well over the average cumulative ET of 591 mm measured in 1989 (123 days) and 610 mm measured in 1990 (110 days) at Bushland using two weighing lysimeters. This is not surprising since daily irrigations kept the soil surface continuously moist. Moreover, the cumulative irrigation plus precipitation of 818 mm was considerably higher than the averages of 632- and 634-mm recorded in 1989 and 1990, respectively. There was considerable discrepancy between measured and modeled profile water contents by the end of the season. The model indicated little drainage but large increases in stored water of 158-, 206- and 227-mm for drip irrigation at the surface, and 15-, and 30-cm depths, respectively by day 280 (2.1 m profile depth). The measured profile water depletion was 2- and 6-mm for surface and buried drip plots for the same 2.1 m profile depth (day 167 to 278). Either there was more actual ET than predicted or there was more drainage than predicted. It is unlikely that ET was much higher than predicted. However, we did assume that the LAI data for nearby LEPA irrigated corn could be scaled to apply to our drip irrigated corn and errors in estimated ET could have resulted from this. It may be that the soil hydraulic characteristics used were inaccurate and caused underprediction of drainage. It is also possible that there was an important amount of macropore flow that would not be modeled correctly by ENWATBAL. The drainage systems in our weighing lysimeters have recorded large pulses of flow associated with large rainfalls occurring when the soil profile was wet. The surface energy balance is modeled separately for the soil and plant canopy by ENWATBAL. For this study we will consider the combined energy balance terms for both surfaces. The energy balance equation is:

[2] $0 = Rn + H + E + T + G + \in_{E}$

where Rn is net radiation, H is sensible heat flux, E and T are defined above, G is soil heat flux, and $\in_{E}$ is an error term. All terms have been converted to equivalent depth of water in mm. In Eq. 2 fluxes towards the surface are positive and fluxes away from the surface are negative.

Because ET, Rn, and G were not measured on the drip plots, direct comparisons of measured and modeled values are impossible. Subtracting daily net radiation for surface drip from net radiation for 0.30-m drip shows that the differences in modeled net radiation (converted to equivalent depth of water in mm) were confined to the period before LAI increased above 3 (Fig. 3). Thus, most of the difference in seasonal ET occurred during the period of partial canopy cover. Similar plots for E and H were very similar, differing only in magnitude of the differences. Except for minor differences in G the sum of H and Rn equaled E. Daily differences in G were always less than 1 mm and the differences in T were always less than 0.2 mm. For all energy balance terms the differences between surface and subsurface drip were less than 0.1 mm after day 220 by which time LAI had increased to 4.2. Values of, E were insignificant. In summary, the ENWATBAL model predicted a large increase in evaporation but insignificant differences in transpiration for surface compared with subsurface drip treatments. The differences developed completely during the period of partial

This space left intentionally blank

This space left intentionally blank

canopy cover and were related to the increased surface soil wetness under surface drip. There were significant predicted differences in evaporation even between the 0.15- and 0.30-m deep drip treatments. The model predicted only minor drainage, but profile water content increased by 158, 206, and 227 mm for the surface, 0.15-m and 0.30-m deep drip treatments, respectively. Since the measured change in water storage was only a few millimeters, there was probably considerable deep drainage loss during the experiment. This study indicates that up to 10% of seasonal applied water might be saved by using 0.30-m deep buried drip compared to surface drip under our conditions.

REFERENCES

Camp, C.R., E.J. Sadler, and W.J. Busscher. 1989. Subsurface and alternate-middle micro irrigation for the Southeastern Coastal Plain. Trans. ASAE 32(2):451-456.

Evett, S.R., T.A. Howell, J.L. Steiner, and J.A. Tolk. 1991. Measured and modeled soil and plant evaporation. Agronomy Abstracts, p. 16.

Evett, S.R., J.L. Steiner, T.A. Howell, and A.A. Durar. 1992. Water and energy balance of bare soil: Comparison of simulation models and weighing lysimeter data. Agronomy Abstracts, p. 15.

Evett, S.R., and R.J. Lascano. 1993. ENWATBAL: A mechanistic evapotranspiration model written in compiled BASIC. Agron. J. 85:763-772.

Howell, T.A., A.D. Schneider, and B.A. Stewart. 1994. Subsurface and surface irrigation of corn - U.S. Southern High Plains. In Proceedings of the Fifth International Microirrigation Congress. April 2-6, Orlando, Florida. Amer. Soc. Agric. Engineer., 2950 Niles Rd., St. Joseph, MI 49085-9659.

Krieg, D.R., and R.J. Lascano. 1990. Sorghum. p. 719-740. In B.A. Stewart and D.R. Nielsen (ed.) Irrigation of agricultural crops. Amer. Soc. Agron., Madison, WI.

Lafolie, F., R. Guennelon, and M. Th. van Genuchten. 1989. Analysis of water flow under trickle irrigation: I. Theory and numerical solution. Soil Sci. Soc. Am. J. 53:1310-1318.

Lascano, R.J. 1991. Review of models for predicting soil water balance. p. 443-458. In Soil Water Balance in the Sudano-Sahelian Zone. Proc. of the Niamey Workshop, Feb. 1991. IAHS Public. No. 199.

Lascano, R.J., C.H.M. van Bavel, J.L. Hatfield, and D.R. Upchurch. 1987. Energy and water balance of a sparse crop: simulated and measured soil and crop evaporation. Soil Sci. Soc. Am. J. 51:1113-1121.

Nassehzadeh-Tabrizi, A., R.W. Jeppson, and L.S. Willardson. 1977. Water flow patterns in heterogenous soils under trickle irrigation. Paper no. 77-2556 presented at the 1977 Winter meeting, ASAE, Chicago, IL, Dec. 13-16.

Phene, C.J., K.R. Davis, R.B. Hutmacher, and R.L. McCormick. 1987. Advantages of subsurface irrigation for processing tomatoes. Acta Hortic. 200:101-103.

Ritchie, J.T., and B.S. Johnson. 1990. Soil and plant factors affecting evaporation. p. 363-390. In B.A. Stewart and D.R. Nielsen (ed.), Irrigation of agricultural crops. Amer. Soc. Agron., Madison, WI.

Steiner, J.L., T.A. Howell, A.D. Schneider, and R.J. Lascano. 1989. Lysimetric evaluation of evaporation prediction under full and partial canopy cover of grain sorghum. Agronomy Abstracts, 1989 Annual Meetings, American Society of Agronomy, p. 23.

Tarantino, E., H. Singh, and W.O. Pruitt. 1982. The microclimate and evapotranspiration of processing tomatoes under drip and furrow irrigation. Rivista di Agronomia, 16(1):21-29.

Van Bavel, C.H.M., J. Ahmed, S.I. Bhuiyan, E.A. Hiler, and A.G. Smajstria. 1973. Dynamic simulation of automated subsurface irrigation systems. Trans. ASAE 16(6):1095-1099.

Van Bavel, C.H.M., and R.J. Lascano. 1987. ENWATBAL: a numerical method to compute the water loss from a crop by transpiration and evaporation. Texas Agricultural Experiment Station, Texas A&M Univ., College Station, TX, 77843-2474.

I.W.I.R.