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Modeling water table contribution to crop evapotranspiration *

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Summary. A model was developed to account for the time-dependent contribution of the water table to crop evapotranspiration. The same numerical approximation used to solve the water flow in the unsaturated zone was also modified for saturated conditions. For unsaturated flow, the hydraulic conductivity changes with water content and the specific water capacity has finite values. For saturated flow, hydraulic conductivity is constant, and the specific water capacity is zero. The proposed approach considers saturated flow as a special case of unsaturated flow with a constant saturated water content and very small but not zero specific water capacities. Thus flow can be simulated in either unsaturated or saturated zones. The contribution of upward flow to crop evapotranspiration was evaluated during lysimeter experiments in the greenhouse. Spring wheat was planted on a silty clay loam and a fine sandy loam with either no water table or constant water table depths at 50, 100 or 150 cm. Irrigation was applied whenever soil water was depleted below about 50% plant available water. Model predictions of water content and cumulative upward flux as a function of time, for the different water table depths and soils, agreed closely with measured values. The contribution of the water table to evapotranspiration (ET) was found to be 90, 41 and 7% for 50, 100, and 150 cm water table depths respectively for the silty clay loam. Corresponding computed values were 89, 45 and 6%. For the fine sandy loam measured contribution of the water table to ET was 92, 31, and 9% for 50, 100 and 150 cm water tables respectively. Corresponding computed values were 99, 29, and 11%. It was not practical to simulate the saturated-unsaturated (moving water table) predictions of the model under greenhouse conditions because of the height of the lysimeters needed. Therefore the model was also used to simulate field irrigation management options under several bottom boundary conditions where the water

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table contributions were significant to crop water use. Results from a one-year simulation were consistent with data for sugarcance grown under similar conditions in the Cauca Valley of Colombia.

The incentive for this study came from the experience of the senior author in the Cauca Valley of Colombia, S.A. which indicated significant water table buildup during the wet season could be used for crop water needs. Irrigation experiments conducted by Cenicana (1984) have indicated that upward flow from the moving water table is significant but is of unknown quantity. They found that if the water table was maintained at 120 to 150 cm there was no need for irrigation. Thus there was a desire to develop a management model to account for this situation.

The water table at many locations is so shallow during the cropping season that it contributes significantly to the water requirements of a crop. Nimah and Hanks (1973) found that there was considerable upward flow from a water table located 2.0 m below the soil surface in eastern Utah. They also found a direct relationship between the rooting depth of alfalfa and the amount of upward flow.

Computer models have been developed to describe water movement in soil under both saturated and unsaturated conditions; however, most of these models utilize simplified boundary conditions. Numerical techniques and digital computers make it possible to solve the theoretical flow equation in which natural flow involves variable top and bottom boundary conditions (Klute 1952; Hanks and Bowers 1962; Rubin 1967; Freeze 1969). A static water table seldom exists because its depth depends upon surface conditions and ground water movement. Freeze (1969) developed a comprehensive model that described the soil water flow where the water table was considered to be an isobar with zero pressure that fluctuated within the soil, depending on the top and bottom boundary conditions. Some generalized macroscale water management models, such as that developed by Skaggs (1980), assume that the water table contribution is in equilibrium with the distribution of soil moisture within the soil profile; a potential flux rate is then used for the calculations. Chang and Austin (1987) presented a one-dimensional model of water flow in the saturated-unsaturated zone using a finite difference method in which the estimated hydraulic conductivity and the specific water capacity determined whether the media was saturated or unsaturated.

Because field processes constantly change, a useful model should account for the contribution of a shallow water table, of variable depth, to a crop's water needs over time. Thus the objectives of the research reported here were: *(1)* to modify existing unsaturated flow models to account for saturated as well as unsaturated flow, *(2)* to test the model regarding how much upward flow contributed to the crop water use as related to soil properties, positions of the water table and climatic conditions.

Theory

Model development

A considerable body of literature is available on the contribution of water tables to evapotranspiration (ET) for different types of soil, climatic conditions, management, and crops. However, it is difficult to directly apply results to different locations because of the influence of the many factors involved. A model can account for many of these factors in a realistic way so that reasonable results may be simulated at different locations from those where measurements were made.

A comprehensive model of water flow was developed by Hanks and Bowers (1962), and was modified by Nimah and Hanks (1973) and Childs and Hanks (1975) to include root extraction by plants. While this model allowed for a constant water table at any given depth it has never been tested for the water table condition. It also did not allow for a moving water table. The model reported herein (WATABLE) is a modification of this model which accounts for the contribution of a water table, which may vary in depth in response to ET and irrigation or rain, under realistic conditions that may occur in the field.

The general equation of soil water flow is a second order non-linear partial differential equation of parabolic type, which in one dimension can be written as:

$$C(\theta)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] + A(z, t) \tag{1}$$

where h is the matric (or pressure) head, θ is the water content (volume), t is time, H is hydraulic head (sum of matric and gravitational head), $K(\theta)$ is hydraulic conductivity, $C(\theta)$ is the specific water capacity (the slope of the θ-h relation), z is vertical distance, and $A(z, t)$ is the root extraction term.

Numerical techniques make it possible to solve the flow equation for different boundary or initial conditions. A finite difference approximation solution of Eq. (1), including the root extraction term with variable ET and water application, was presented by Childs and Hanks (1975). In this model it is assumed that $C(\theta)$ and $K(\theta)$ remain constant during very short time intervals and are adjusted from one time interval to the next. A good approximation requires small time increments, especially after rainfall or irrigation. WATABLE allows for both variable depth and time increments. The time increments depend on the maximum allowable change in moisture content within the whole profile.

Single integrated solution to flow in unsaturated-saturated zones

Since roots will not generally grow into the saturated soil there is no need for the root extraction term of Eq. (1) when applied to saturated conditions. Moreover, for saturated conditions, $K(\theta)$ is a constant equal to the saturated hydraulic conductivity (Ks) and the left side of Eq. (1) is equal to zero because there is no change in h or θ with time. The resulting equation, known as Laplace's equation, evolves from the unsaturated flow equation as

$$0 = K_s\frac{\partial^2 H}{\partial z^2} \tag{2}$$

Previous models that integrated the solution for both saturated and unsaturated zones first solved Eq. (1), for unsaturated conditions, and then switched to solve Eq. (2), for the saturated zone, below the water table (Freeze 1969).

We propose to provide for a changing water table depth by solving Eq. (1) for both unsaturated and saturated conditions. To accomplish this Eq. (1) is "forced" to work under saturated conditions by providing that the specific water capacity, $C(\theta)$, is not zero but is very small. This is equivalent to assuming the water content slightly higher than saturation has a value for h very much higher than at saturation. This forces the water content below the water table to be just slightly above the saturated value. Thus there is provision for a changing position of the water table within the soil column using the same general equation for solution of particular initial and boundary conditions.

The water table is here considered to be the interface between the saturated and unsaturated zones. The bottom boundary could be set at the water table, if it is static, or at an impermeable layer below. If set at an impermeable layer and if the soil were originally quite dry followed by application of water at the surface, a condition of unsaturated buildup of water within the profile would result until saturation occurs at the bottom boundary. If water application was greater than ET the water table would rise. If ET was greater than water application the water table would lower and disappear.

This approach simplifies the mathematical formulation concerning the flow from unsaturated to saturated conditions, and vice versa, and allows simulation of either unsaturated flow only or both unsaturated and saturated flow. The modification of the model of Childs and Hanks (1975) was small with the sole addition of a provision for "above saturation" water contents. The additional computer code consisted of about six additional lines out of a total of about 560. To reflect saturated conditions, the specific water capacity can be close to but not equal zero. This is provided for in the h-θ table by including extra values for θ and h beyond saturation as shown in Table 1. The value of $C(\theta)$ assumed for the saturated condition is 2×10^{-7} cm^{-1} for both soils. For purposes of comparison, $C(\theta)$ just below saturation is 3.1×10^{-2} for Nibley silty clay loam and 2.2×10^{-2} for Kidman fine sandy loam.

A stepwise procedure to evaluate Eq. (1) at each incremental increase in depth and at each period of time was presented by Nimah and Hanks (1973) and Childs and Hanks (1975). The basic physical parameters of θ, h and $K(\theta)$ are input to the model as tabular data (Table 1). The finite difference solution results in a tridiagonal system of equations that are solved simultaneously to determine the value for h as a function of depth at the end of each small time interval. These procedures were modified, in WATABLE, to account for a moving water table at the lower boundary.

The approximate water content at the end of each time period for each depth increment is calculated according to the following equation:

$$\theta_i^{j+1} = C_i^j (h_i^{j+1} - H_i^j) + \theta_i^j \tag{3}$$

where the "i" subscripts refer to depth and the "j" supercripts refer to time. The value of C_i^j is computed from the θ-h table based on the value of h_i^j or θ_i^j. Note that the value of C_i^j that is assumed to hold during the time interval $(t^{j+1} - t^j)$ is taken from the data of θ at the beginning of the time interval. Thus time intervals must be short to make this a valid assumption.

The conductivity values at each incremental increase in depth were calculated as follows:

$$K_{i-1/2}^{j+1/2} = \frac{\sum_{\theta=\theta L}^{\theta_{i-1}^{j-1}} D\Delta\theta - \sum_{\theta=\theta L}^{\theta_i^{j-1}} D\Delta\theta}{(h_{i-1}^{j-1} - h_i^{j-1})} \tag{4}$$

Table 1. Soil properties used for simulation of the greenhouse results

θ	Kidman fine sandy loam		Nibley silty clay loam	
	h cm	$K(\theta)$ cm/hr	h cm	$K(\theta)$ cm/hr
0.00	−0.840E+07	0.100E−09	−0.840E+08	0.900E−10
0.02	−0.100E+07	0.800E−09	−0.100E+07	0.900E−10
0.04	−0.450E+05	0.400E−08	−0.350E+06	0.900E−09
0.06	−0.102E+05	0.300E−07	−0.122E+06	0.275E−08
0.08	−0.500E+04	0.140E−06	−0.429E+05	0.900E−08
0.10	−0.200E+04	0.950E−06	−0.150E+05	0.275E−07
0.12	−0.800E+03	0.700E−05	−0.899E+04	0.900E−07
0.14	−0.320E+03	0.300E−04	−0.539E+04	0.275E−06
0.16	−0.102E+03	0.180E−03	−0.323E+04	0.900E−06
0.18	−0.500E+02	0.110E−02	−0.194E+04	0.275E−05
0.20	−0.450E+02	0.500E−02	−0.872E+03	0.900E−05
0.22	−0.380E+02	0.200E−01	−0.523E+03	0.275E−04
0.24	−0.320E+02	0.600E−01	−0.313E+03	0.900E−04
0.26	−0.270E+02	0.120E−00	−0.188E+03	0.275E−03
0.28	−0.220E+02	0.250E−00	−0.113E+03	0.100E−02
0.30	−0.200E+02	0.500E−00	−0.675E+02	0.200E−02
0.32	−0.100E+02	0.950E−00	−0.488E+02	0.450E−02
0.34	−0.000E+00	0.150E+01	−0.360E+02	0.125E−01
0.36	+0.100E+05	0.150E+01	−0.263E+02	0.250E−01
0.38			−0.192E+02	0.500E−01
0.40			−0.140E+02	0.111E−00
0.42			−0.103E+02	0.225E−00
0.44			−0.750E+01	0.451E−00
0.46			−0.300E+01	0.125E+01
0.48			−0.000E+00	0.340E+01
0.50			+0.100E+05	0.340E+01

where D is the soil water diffusivity as defined by Klute (1952) and θL is the lowest value of θ for which a diffusivity value D has been determined. To facilitate the evaluation of Eq. (4) the model generated a table of θ vs $\Sigma D \Delta \theta$.

Boundary conditions

If the bottom boundary conditions are static, as for a water table at a specified depth, then this boundary can be characterized by a constant value of h and θ at the water table depth. Flow at the bottom boundary could then be up or down depending on the soil conditions above the water table. If θ is in the dry range, flow will be up and if in the wet range flow would be down (leaching).

A common lower boundary condition, associated with the development of a moving water table of variable depth, is an impermeable boundary at some specified depth below the water table. The moving water table may develop under these conditions depending on water application and ET. To account for this situation with both saturated and unsaturated zones within the soil profile previous models had to be modified as discussed above.

Under normal field conditions it is necessary to account for several different top boundary conditions. When the soil surface is flooded, as in basin irrigation, the soil surface is saturated, a positive matric head develops, and runoff may occur. Thus after the surface becomes saturated the matric head may be constant for some time.

The flux top boundary condition is also common. In this condition, the soil will absorb all of the water applied and infiltration will be equal to the rainfall rate or irrigation application rate. However, if the application rate is large, the soil may absorb all the water for some time until the soil surface becomes saturated, after which time the infiltration decreases similar to the ponded case. The difference between applied and infiltrated water may then appear as runoff or as ponded water.

The flux at the soil and crop surface may also be in the opposite direction to infiltration due to evaporation from the soil and transpiration from the crop (ET). If soil water content is high the flux will not be limited by soil water conditions but only by climatic conditions. As the soil continues to dry the soil surface will eventually reach air dry after which time the soil evaporation rate will be less than the climatically determined value. Soil evaporation will then be dependent on soil water flow characteristics in the top soil layers. Soil drying may also restrict plant root uptake and subsequent transpiration as the soil water content approaches the wilting water content. Transpiration will be less than the climatically determined potential rate; however, this condition will generally be found after a much longer time than when soil evaporation falls below the potential rate.

Regardless of the direction of flow the moisture content and the matric head at the soil surface are solved by an iterative procedure to determine if the potential flux is possible within the restrictions discussed above. Thus the top boundary condition is typically a flux (equal to potential ET or application rate) for some time then switches to a constant θ_{sat} or θ_{airdry} value as the soil wets or dries. The input data includes the potential flux of applied water or ET for the appropriate time period and the model computes whether the flux can be attained or a constant surface θ applies.

Materials and methods

Lysimeter-greenhouse experiment

A lysimeter experiment was conducted as a data source to compare with model predictions. It was found to be impossible to have a sufficiently high lysimeter in the greenhouse to test a practical moving water table so the tests were only for a fixed water table or no water table.

The lysimeter system similar to that described by Hanks and Shawcroft (1965) and modified by Robbins and Willardson (1980) was used in this study. The lysimeters were made from 38 cm diameter PVC plastic pipe and were supported by liquid-filled rubber tire "inner tubes". The pressure of the fluid in the inner tubes was measured by a standpipe or pressure transducer to reflect changes in weight of the lysimeters caused by irrigation or ET. The lysimeters were filled with Nibley silty clay loam (Coarse loamy mixed mesic Calcic Haploxeroll) or Kidman fine sandy loam (Fine mixed mesic Aquic Argiustoll). The lysimeters were planted to spring wheat in late fall of 1986, and again in early winter of 1987. There was evidence of soil property changes with time for the first planting so all comparisons were made using data from the second planting. The time of good plant cover (two weeks after germination until grain development) was about 50 days. There were two "replicate" lysimeters for each treatment. All measurements were made in a greenhouse.

Lysimeters with water tables at 50, 100, and 150 cm depth were prepared as were additional lysimeters containing 100 cm of soil with no water table.

Evapotranspiration, irrigation, upward flux from the water table and soil water content-depth data were measured with time during the experiment. Irrigation was applied to the lysimeters individually when the measured soil water indicated about 50% of the available water had been depleted. Thus the experiment was designed so that ET was at potential conditions (for transpiration) throughout the experiment.

The imposed bottom boundary, where the water table was present, corresponded to a constant $h=0$ at the water table. The constant water table throughout the experiment was supplied by a Mariotte bottle arrangement connected to each lysimeter. The daily water flow at the lower boundary was measured as the equivalent amount of water needed to refill the Mariotte bottle to a marked position.

Soil water was measured at 10 cm increments with a neutron probe in an aluminum access tube installed in the center of each soil column. The neutron probe had to be calibrated individually for each soil in the same type of column because calibrations were different than in the field (probably because the sphere of influence was less than in the field).

Determination of input parameters needed to run WATABLE

One of the problems associated with using this and similar models is obtaining the necessary input parameters which can be classified as soil, crop, climatic and irrigation management data. To obtain some of the difficult soils data shown in Table 1, it was originally planned to use the method of Shani et al. (1987) as the method is very simple and gives an estimate of both θ-K and θ-h from a few simple measurements. However, in this experiment this method was found to be too crude to predict water content profiles with accuracy so it was used only to give estimates of saturated conductivity. This method is highly dependent on conditions near saturation and is essentially an "educated" extrapolation to dryer soil conditions.

Fortunately, data of θ-h were available from measurements of θ-depth in the lysimeters at the beginning of the experiment. After the lysimeters were filled with soil they were consolidated by wetting to saturation and then drained. This process was repeated several times, with additions of soil, until the soil column appeared to be stable. The data of θ-h was taken from the "equilibrium" values of θ-depth measured after drainage had ceased. This gave data from about 0–100 cm matric head. The data was extended to −15,000 cm (assumed wilting) from knowledge of θ at wilting for the soil assuming a linear θ-log (matric head) relation. A similar method was used to extend the data to −1,000,000 cm matric head (approximating air dry).

To extend the $\theta - K$ data from saturation to dryer water contents, the method of Kunze et al. (1968) was used. This method requires knowledge of the θ-h relation and K at saturation.

Besides soil property data it is also necessary to know the initial and boundary conditions to run WATABLE. The initial conditions are the water content profiles at the beginning of the simulation. For comparisons with the lysimeter measurements profiles of θ-depth measured at the beginning were used for these initial conditions.

Bottom boundary conditions are also needed. Where a water table existed the bottom boundary condition was a constant matric head at that depth. Where no water table existed an impermeable boundary was assumed at the depth of the soil (100 cm). Irrigation was such that the water content at the lower boundary never reached saturation.

The top boundary conditions needed are the potential ET for the crop, as a function of time, and the time and amount of irrigation. This data was taken from lysimeter measurements for ET and measurements of time and amount of irrigation. It was found that each lysimeter had to be considered separately because the replicates were, by necessity, at different locations in the greenhouse resulting in different ET and hence irrigation.

Information is also needed on crop factors. It was assumed that the potential plant transpiration was 0.8 of potential ET when soil evaporation was not limited. No actual measurements of root distribution were made in the lysimeters because destructive sampling would have precluded running any additional tests. The assumed root distribution was 40, 30, 20, and 10% of the total root distribution for the top, second, third and fourth quarter of the root zone respectively (Danielson 1967).

Field simulation

To apply WATABLE under field conditions, data on soil properties, rainfall, irrigation and potential ET (pan evaporation in this instance) are needed. Climatic data from the Cauca Valley in Colombia presented by Torres and Yang (1984) were used to simulate one year of sugarcane. For this simulation the model was modified to apply irrigation whenever the available soil water depletion fell below a value set at 5 cm for these simulations. Field data indicated the maximum rooting depth was 80 cm so the root distribution was assumed to follow the 40, 30, 20, 10 rule above that depth (Danielson 1967). No detailed soils data were available so the data of Millville silt loam from the USU Greenville farm was used for soil properties because this data seemed reasonable.

The same top boundary conditions were used for all simulations. It was assumed that sugarcane emergence occurred 10 days after planting and full cover and maximum root depth was reached 50 days after planting. After full cover it was assumed the potential transpiration was 0.9 of potential ET when soil water did not limit soil evaporation.

WATABLE was used to simulate changes in field irrigation requirements that would occur for three bottom boundary conditions: *(1)* a variable water table located above an impermeable barrier at 200 cm, *(2)* a shallow water table fixed at 120 cm depth, and *(3)* a deep soil with no water table.

Simulation 1 was accomplished by assuming an impervious boundary at 200 cm and initial soil water conditions as measured by Torres and Yang (1984) where the water table was about 165 cm below the soil surface. Thus from 0–165 cm depth the soil was unsaturated but from 165–200 cm depth the soil was satured.

Simulation 2 was accomplished by setting a constant water table at 120 cm throughout the season with unsaturated flow above that depth. This was done to simulate a condition (Cenicana 1984) that indicated if the water table was held constant at about 120 cm there would be no need for any irrigation. The initial water content profile was assumed to be the same as simulation 1 above 100 cm but increased to saturation at 120 cm.

Simulation 3 was accomplished by assuming an initial soil water profile as simulation 1 from 0–100 cm but which varied down to a "field capacity" water content at 200 cm. The bottom boundary was set for a constant water content of about field capacity (or constant matric head of about −100 cm) which simulates the situation for downward flow below the root zone in the field. This lower boundary condition did not allow upward flow but did allow downward flow below 200 cm, assuring no build-up of soil water and thus simulating a deep soil.

Results and discussion

Comparisons of measured and computed θ profiles are shown in Fig. 1 for Nibley silty clay loam, and for Kidman fine sandy loam in Fig. 2. The "replicate" lysimeters had different ET under greenhouse conditions so they have different simulated and measured profiles. There was generally good agreement between the measured and computed profiles for all treatments for both soils. The agreement was best for the conditions near the water table, where a water table existed, and worst near the soil surface.

The agreement was generally better for the Kidman fine sandy loam than for the Nibley silty clay loam. This is probably due to more stable soil hydraulic properties for the fine sandy loam than for the silty clay loam. The silty clay loam is more aggregated and subject to structural change than the fine sandy loam. Some of the differences in measured profiles are probably due to differences in soil properties from one lysimeter to another. However, this was not true for the simulated profiles because the same soil properties, given in Table 1, were used for all computations. The only difference in the simulated profiles was in the ET and irrigation applied (upper

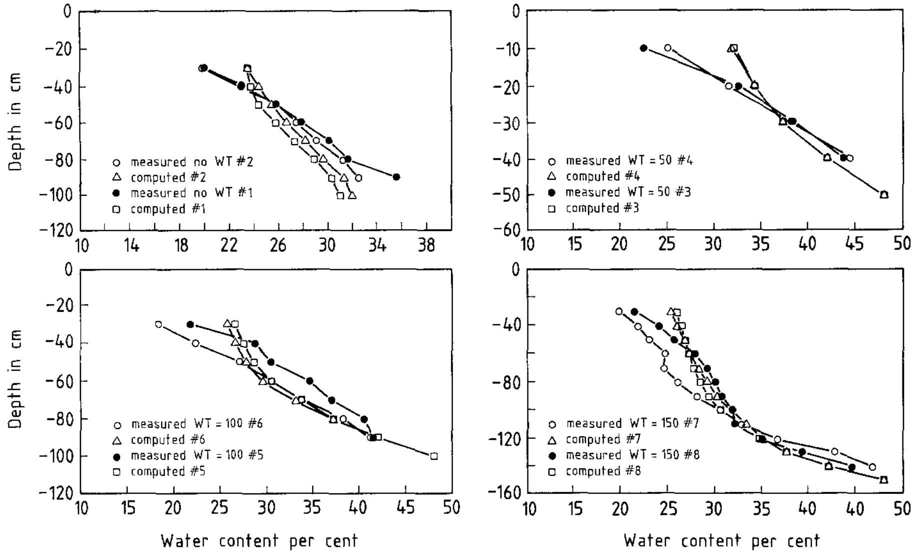


Fig. 1. Measured and computed soil water content profiles for Nibley silty clay loam at the end of 52 days

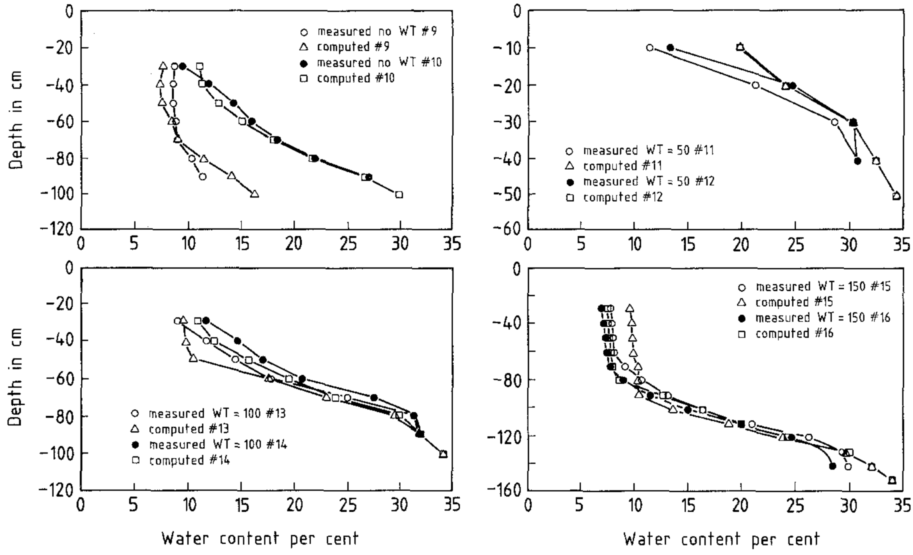


Fig. 2. Measured and computed soil water content profiles for Kidman fine sandy loam at the end of 52 days

boundary conditions) and the initial water content at the beginning of the period. The agreement is good enough that simulations of field conditions seem warranted.

Discrepancies in water content differences between measured and computed profiles could also be due to differences in actual versus assumed root distributions.

While the comparison of soil water profiles is an important consideration, of more importance for practical use is the overall water balance. If the water balance predic-

Table 2. Components of the water balance (cm) for the various treatments at the end of the 52 day growth period

Soil and lysimeter No.		ET	I	Depletion		Upflow	
				measured	computed	measured	computed
Nibley	1	33.2	30.2	3.0	3.0	0	0
	2	35.0	34.0	1.0	1.0	0	0
	3	28.3	2.4	0.5	0.8	25.4	25.1
	4	31.9	2.5	0.8	1.1	28.5	28.3
	5	41.9	20.2	4.8	3.8	16.8	17.9
	6	50.2	22.6	6.7	3.7	20.9	24.0
	7	30.7	26.5	3.4	3.6	0.8	0.6
	8	32.6	22.2	6.8	7.4	3.6	3.0
Kidman	9	31.4	26.2	5.2	5.2	0	0
	10	25.5	24.9	0.6	0.6	0	0
	11	23.1	1.4	0.7	−1.0	21.0	22.7
	12	34.9	1.0	1.1	−1.0	32.7	34.9
	13	49.3	24.5	2.4	3.2	22.4	21.6
	14	25.9	21.3	0.3	0.5	4.3	4.1
	15	34.8	27.9	3.0	2.2	3.8	4.7
	16	36.7	30.4	3.6	3.1	2.7	3.2

tions of the model are not good, then the use of the model will be much more limited. For this greenhouse tests the water balance equation can be written

$$\mathrm{ET} = I + \Delta\theta + \mathrm{UF} \qquad (5)$$

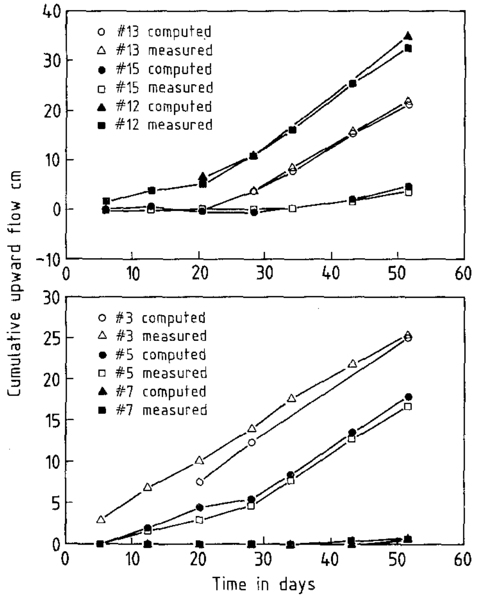
where I is irrigation, $\Delta\theta$ is changes in soil water content (depletion) and UF is upward flow (the opposite of drainage). Since ET and I are the same for measured and simulated conditions, the verification of the model is limited to comparisons of depletion and upward flow. As can be seen from Figs. 1 and 2, integration of the total water content in the profiles would result in good agreement between measured and computed total soil water content. Where a water table was maintained, UF was measured and can be compared with computed values.

Table 2 and Fig. 3 show comparisons of measured and computed cumulative upward flow, UF, over the entire growth period for all lysimeters. The data show excellent agreement. The poorest agreement was for lysimeter 6 where there is about a 15% difference. Figure 4 shows UF as a function of time for some of the lysimeters. There is excellent agreement of measured and computed UF with time.

Table 2 also shows comparisons of soil water depletion during the 52 day growth period. Depletion is less than 7 cm on all treatments and the difference between measured and computed depletion varied from 0 to 3 cm. The data show that, for this type of situation where irrigation is supplied to keep water depletion lower than a certain value, depletion is small compared to other components of the water balance.

Figure 5 shows the ratio of UF/ET as related to water table depth. The data show, as reported by many others, that the UF/ET ratio was higher for the 50 cm than the 100 cm water table and was higher for the 100 than the 150 cm water table. The measured ratios were 90, 41, and 7% and the computed ratios were 89, 45, and 6%

Fig. 3. Comparison of measured and computed cumulative upward flow as related to time for Kidman (top) and Nibley (bottom) soils



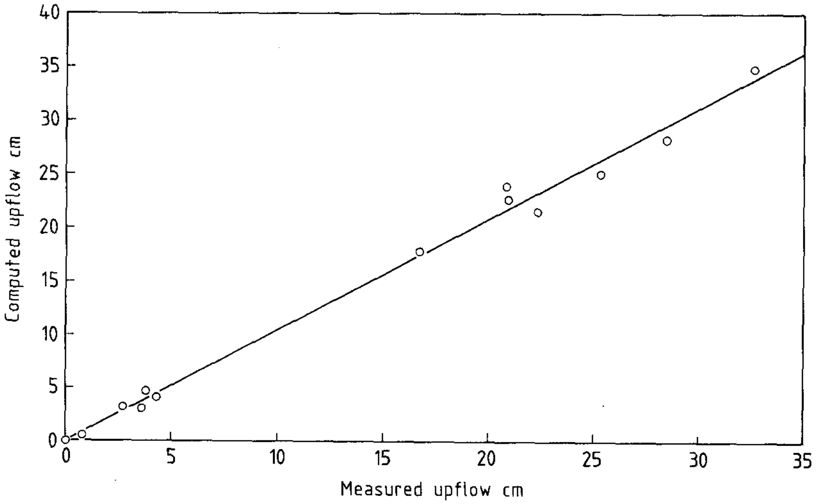


Fig. 4. Comparison of measured and computed cumulative upward flow for all water table depths and both soils at the end of the season

for 50, 100 and 150 cm water tables respectively for Nibley silty clay loam. For the Kidman fine sandy loam the measured ratios were 92, 31, and 9% and the computed ratios were 99, 29, and 11% for 50, 100, and 150 cm water table depths respectively. Thus the agreement is good between measured and computed ratios of UP/ET for all depths and both soils. There was very little difference between the results from the different soils.

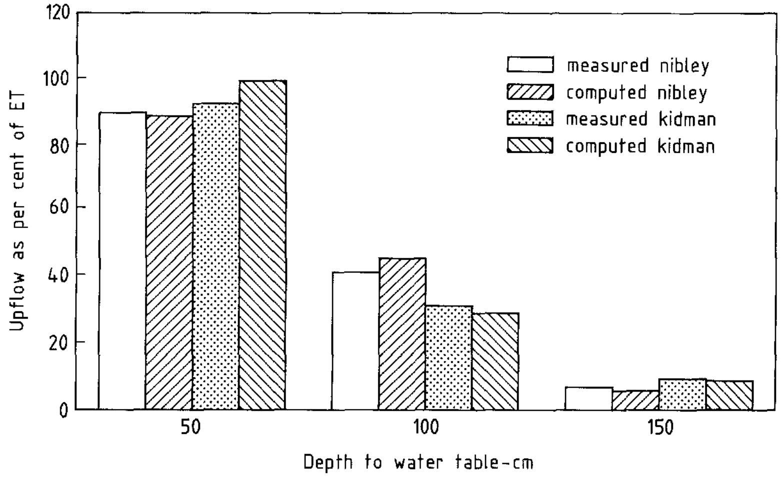


Fig. 5. Comparison of ratio of UF to ET for different water table depths and different soils at the end of the season

Table 3. Hydrologic parameters obtained from one year simulation under a moving, a shallow and no water table conditions for Cauca Valley, Colombia, S.A.

Parameter		Moving WT (120 cm)	Shallow	No WT
Pan evaporation	(cm)	153	153	153
Precipitation	(cm)	116	116	116
No. Irrigations		9	0	24
Irrigation	(cm)	45	0	105
Soil Evaporation	(cm)	27	27	27
Transpiration	(cm)	113	112	114
Drainage	(cm)	17	53	90
Upward Flow	(cm)	16	97	0

Computations have also been made using soils data derived entirely from the measurements made by the procedure of Shani et al. (1987) (but adjusted to get reasonable values at wilting and air dry water contents). These computations (data not shown) indicate much poorer agreement with water content profiles but almost as good agreement with upward flow computations. This is probably because the changes in soil water storage over long times are small compared to ET or UF from a shallow water table. If water is limited for ET these results may not apply because the amount of water coming from soil water storage is then very important. Thus this conclusion needs further testing to see under what conditions it is reasonable.

Model application

Table 3 shows a summary of the predominant hydraulic parameters from the different simulations applied to the Cauca Valley of Colombia. No irrigation was required

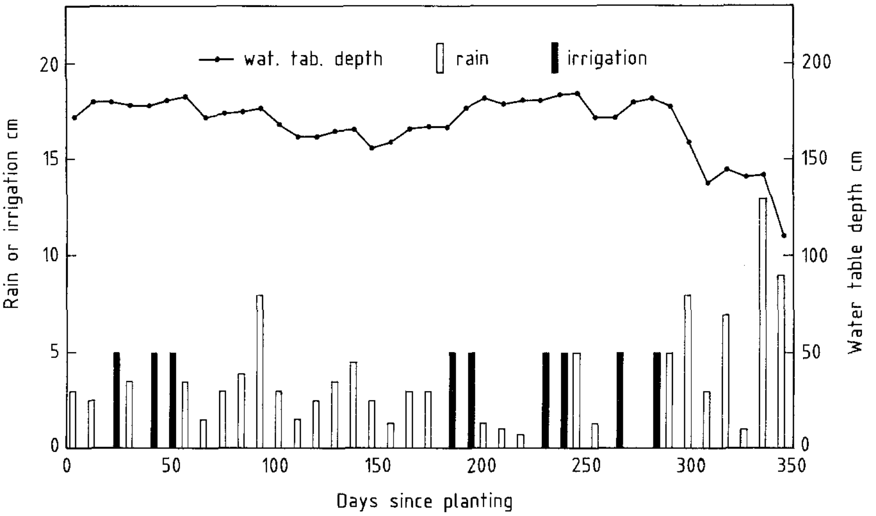


Fig. 6. Simulated water table depth vs. time for the moving water table simulation as compared to irrigation and rainfall

when the water table remained at a depth of 120 cm during the cropping season. These results are in agreement with experimental data collected by Cenicaña (1984) under similar conditions in the Cauca Valley, where water tables from about 120–150 cm depth resulted in the highest yield of sugarcance and greatest contribution of groundwater to crop ET with no irrigation required.

For the three simulated conditions, transpiration and soil evaporation (and thus ET) were essentially the same on all treatments. When irrigation was scheduled for the moving water table, there were nine irrigations that totaled 45 cm compared to 24 irrigations that totaled 120 cm where there was no water table. For the constant water table at 120 cm depth there was 87 cm of upward flow and 17 cm of downward flow. Where there was no water table there was 90 cm of drainage past 120 cm depth. The simulation for the moving water table indicated 16 cm of upward flow, at 120 cm depth, and 17.3 cm of downward flow. The difference of irrigation requirements of the moving water table compared to no water table indicate that 75 cm of irrigation was saved for later plant use by having an impermeable boundary which maintained a moving water table high enough that it could supply water to roots when needed.

Figure 6 shows the rainfall, irrigation and the simulated depth of the moving water table simulation. The simulation shows a low water table in the middle of the year during the "dry" season and maximum irrigation during that time. The water table depth decreased during the wet season. If irrigation had not been applied the water table would have disappeared during part of the season. In general, the results agree with field observation in the area but further testing is needed to verify the moving water table simulations.

Results of specific studies should not, in general, be extrapolated to other conditions. A physically based model using locally determined and identifiable soil, crop, climatic and irrigation management inputs may predict reasonable results when used for simulations for which it has not been tested. Nevertheless there is no substitute for checking specific field data before simulations are to be relied upon.

The simulations indicated that a properly managed constant water table is a potential resource for subirrigation. At many locations, proper management of the water table could reduce salinity while simultaneously decreasing the need for a drainage system. In humid areas where ground water is of good quality and sufficient to guarantee a natural salt balance the use of the water table contribution to crop needs is an important management alternative. An optimal design for a drainage system would utilize the contribution of the water table to crop water needs and would also help control salt accumulation in the soil profile. Application of the present model could help evaluate water management alternatives.

Conclusions

A previously developed unsaturated flow model was slightly modified to compute combined saturated and unsaturated flow. The results of the model simulations and measurement comparisons in the greenhouse studies indicate good predictions of soil water content profiles and upward flow where soil properties are known with fair accuracy. Simulations agree with field observation where there is a fixed water table and seem reasonable where there is a moving water table although the latter were not verified by direct measurement. Since the major modification of the model WATABLE that has not been verified is the combined unsaturated-saturated flow computation further testing is warranted.

Simulations with simplified soils data indicate good predictions of upward flow from a water table, for the greenhouse study, even though the soil water content profile predictions were less satisfactory. This is probably because the changes in soil water storage over long times are small compared to water moving out of the soil by ET or up into the soil by upward flow from a shallow water table. If water is limited for ET these results may not apply because soil water storage may then be important.

The simulations indicated that a properly managed water table is a potential resource for subirrigation. At many locations, proper management of the water table could reduce salinity while simultaneously decreasing the need for a drainage system. In humid areas where ground water is of good quality and sufficient to guarantee a natural salt balance the use of the water table contribution to crop needs is an important management alternative. Application of the present model could help evaluate these water management alternatives.

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