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Estimation of Deep Drainage and Plant Water Extraction from Soil Water Measurements

J. WILLIAMS
Senior Research Scientist, Division of Soils, CSIRO, Townsville
B.H. WALL
Experimental Officer, Division of Tropical Crops and Pastures, CSIRO, Townsville
and
R.L. McCOWN
Senior Research Scientist, Division of Tropical Crops and Pastures, CSIRO, Townsville

1 INTRODUCTION

The use of the neutron moisture meter in hydrology and agricultural applications has led to the availability of relatively accurate information on the water content as a function of both time and space for many soils. For some purposes it is necessary to further differentiate water draining beyond the root zone to recharge ground water systems from water that will be either extracted by roots or evaporated from the soil surface. Numerical simulation of the vertical flux of water in soil profiles is a potentially powerful tool for accomplishing this (Rose and Stern (1967); Van Bavel, et al. (1968); Scholl (1976); Hillel (1977)). In this paper we (a) demonstrate the performance of a simple model in predicting evapotranspiration and deep drainage as a function of both depth and time from soil profile water content estimates, (b) point out inherent problems restricting accuracy of prediction, and (c) propose a means of reducing these problems.

2 ANALYSIS

2.1 The Simulation Model

The geometric structure of the model FLUX which has been written in the simulation language ACSL (Mitchell and Gauthier 1972) is set out in Fig. 1.

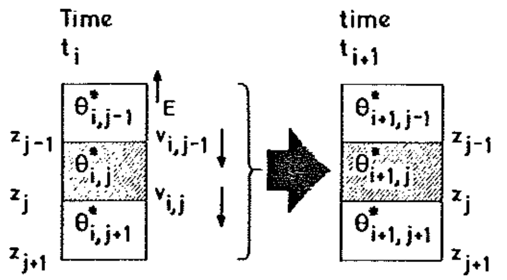

Figure 1 Structure of model to simulate flow in a one-dimensional soil profile

The profile is divided into horizons of a specified depth and thickness. The hydraulic properties, namely the $\psi(\theta)$ and the $K(\theta)$ functions, are specified for each horizon and more than one horizon may have the same hydraulic properties. An iterative procedure is used to match successive water content profiles determined with the neutron probe by calculation of the drainage between horizons and adjustment of evapotranspiration. The $\psi(\theta)$ and $K(\theta)$ functions can be set up as tables or may be generated from water content (θs) at $\psi = 0$, matric potential (ψe) at air entry, water content (θw) at $\psi = -15000$ cms, and hydraulic conductivity (Ks) at $\psi = 0$ using the procedures of Rogowski (1971) and Marshall (1958).

The water balance equation of horizon j at time t_i is given by:

$$\theta^*_{i+1,j}(Z_j-Z_{j-1}) =$$

$$\left[\theta^*_{i,j}(Z_j-Z_{j-1})\right] +$$

$$\left[(v_{i,j-1}-v_{i,j}-E_{i,j})(t_{i+1}-t_i)\right] \quad (1)$$

where $\theta^*_{i,j}$ = the mean water content ($cm^3 cm^{-3}$) for the horizon j of thickness Z_j-Z_{j-1} (cm) at time t_i (days).

$v_{i,j}$ = the mean downwards flux from the jth horizon (cm day^{-1})

and

$E_{i,j}$ = the mean evapotranspiration rate from the jth horizon at time $(t_{i+1}-t_i)$

The vertical flux downwards for horizon j to horizon j+1 at time, t_i is given by:

$$v_{i,j} = K(\theta)\left[\frac{\psi_{j+1}-\psi_j}{Z_{j+1}-Z_j} + 1\right] \quad (2)$$

where $K(\theta)$ is the hydraulic conductivity at water content $(\theta_j+\theta_{j+1})/2$ and ψ_j is the matric potential (cm) in horizon j at time t_i. This requires all horizons to be of equal thickness.

We neglect the effects of hysteresis in the $\psi(\theta)$ function and we assume that all one dimensional water movement obeys (2) and that water change other than that described by (2) can be attributed to evapotranspiration.

The water content profiles are made to fit by adjusting the evapotranspiration term in the simple water balance equation set out in (1). The performance of the model in its simple form depends on the validity of the above assumptions, and the accuracy with which we can measure the $\psi(\theta)$ and $K(\theta)$ for each horizon.

2.2 The Hydraulic Properties

Initially we measured the saturated hydraulic conductivity of 75 mm diameter 'undisturbed' cores form specified depths down the profile. Smaller 50 mm cores were used to determine the moisture characteristic for the same horizons. We made the assumption that our calculations could be based on the draining moisture characterisitc, thus implying that effects of hysteresis could be neglected. We calculated $K(\theta)$ relationships using the method of Marshall (1958) and we matched the hydraulic conductivities at saturation. Greacen et al. (1974) have demonstrated the value of this technique in describing the $K(\theta)$ for a field profile. We then used these estimates of the hydraulic properties in our first analysis.

3 RESULTS

We chose to use data from a deep red earth (Tippera clay loam (Stewart, 1956)), on the CSIRO Research Station at Katherine in the Northern Territory. The measured hydraulic characteristics are displayed in Figs. 2 and 3.

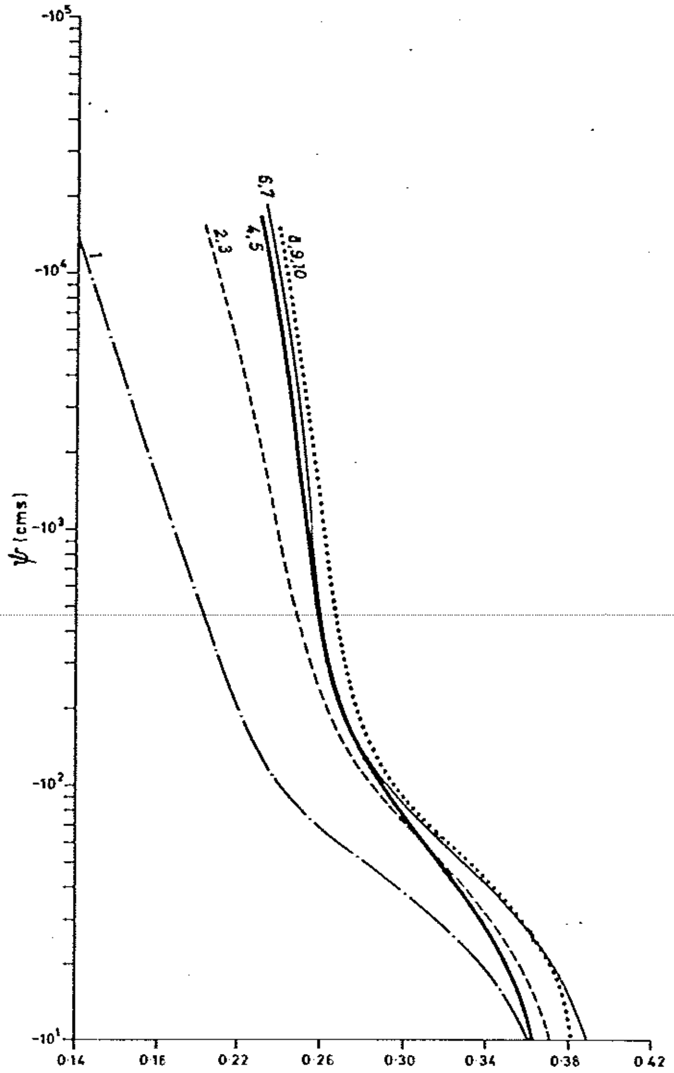

Figure 2 Measured draining moisture characteristics for the 10 zones of the Tippera red earth

For a profile undergoing redistribution and zero evapotranspiration, using the measured hydraulic properties, the agreement between actual and predicted water contents was poor (Fig. 4, Curve 1). The fact that the predicted water contents are less than observed in zones 8, 9 and 10 indicates that hydraulic conductivity is too high in these zones. Curve 2 results if the saturated hydraulic conductivity (Ks) used is decreased by a factor of 8 in the last three zones. The Ks measured was most uncertain at these depths and ranged from 1 to 10^{-3} cm day^{-1}, thus these adjustments were consistent with the range of observations. The agreement with the actual is considerably better (Curve 2).

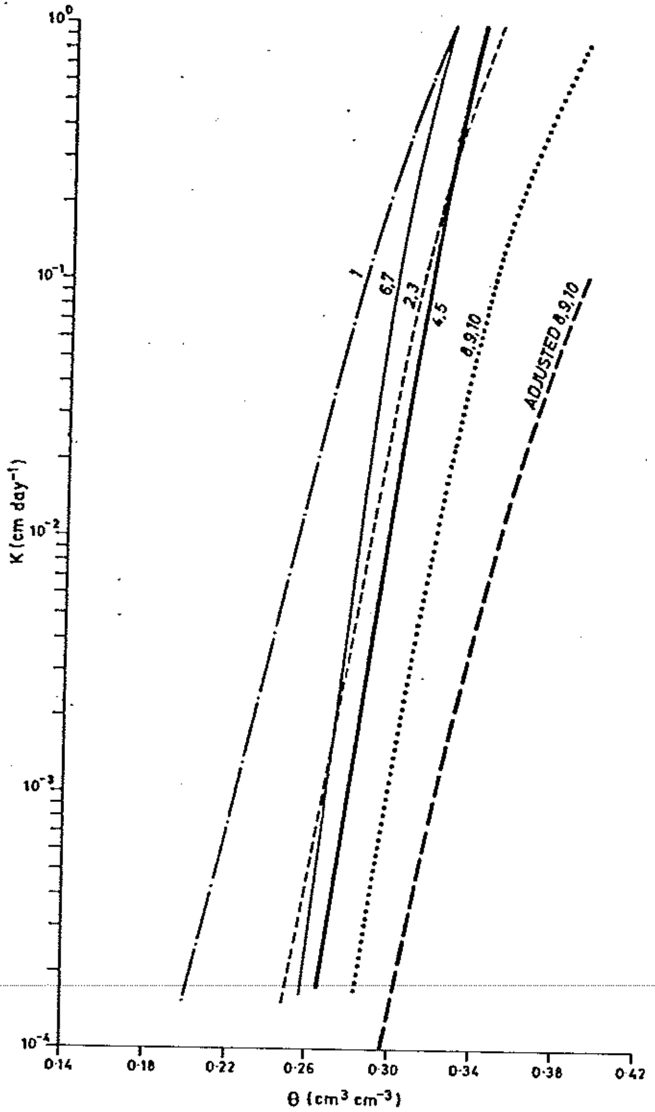

Figure 3 Estimated and adjusted $K(\theta)$ functions for 10 zones of the Tippera red earth. Solid lines are measured and the dashed lines are the adjusted functions for zones 8 to 10 used to generate Curve 2 on Fig. 4.

Curve 3 results if the Ks values used in the Marshall (1958) calculations are reduced by a factor of 8 in the remaining zones. There is a general improvement in the overall fit and it would seem that the hydraulic properties in Curve 3 may be representative of those operating in the profile. These are summarised in Table 1. The influence of an 8 fold change in Ks is seen on the movement of the water content distribution from Curve 1 to Curve 3. No adjustments were made to the moisture characteristics as we felt some confidence in these measurements. The compensation in the water content-depth function between zones 4 to 6 and zones 7 to 10 explains the reason for the very good agreement between estimated and actual drainage for Curve 2 and 3, although it illustrates how readily apparently reasonable results can often be obtained for the incorrect reasons.

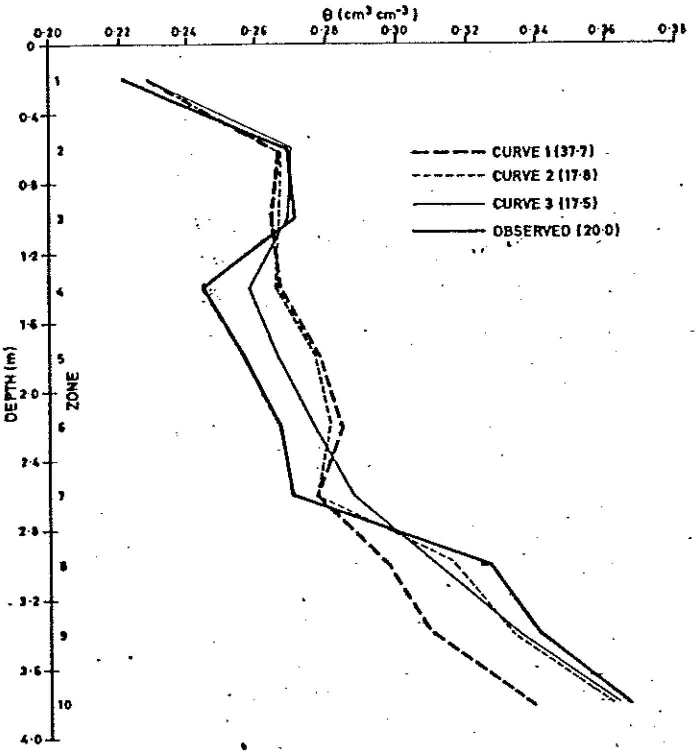

Figure 4 Observed and predicted water content as a function of depth following a period of drainage and zero evapotranspiration using measured and adjusted hydraulic properties. The drainage in mm is indicated in brackets for each curve.

These sets of measured and adjusted hydraulic properties were applied to a sequence of soil water content profiles for periods when evapotranspiration and drainage were both taking place in the profile. The best agreement between predicted and actual water contents was consistently provided by the model using the modified hydraulic properties as illustrated by Run 3 in Table 2. The actual water content profile depicted in Table 2 represents a situation when approximately equal amounts of drainage and evapotranspiration are occurring. Satisfactory agreement does not necessarily guarantee reliable partitioning. If drainage is under estimated then evaporation will be over estimated and yet this could yield good agreement between predicted and observed. On the other hand if drainage is seriously over estimated then discrepancy between predicted and observed will be apparent. The adequacy of the partitioning depends on how well the hydraulic properties used in the model reflect those operating in the profile. The measured properties (Run 1) did not yield particularly good agreement and there was a large error which could not be eliminated by further adjustment of evapotranspiration. This supports our view that drainage was over estimated by these hydraulic properties.

Using the adjusted hydraulic properties as generated from the parameters set out in Table 1, and the soil water content profiles observed towards the end of the wet season during 1975 and 1976, we estimate that evapotranspiration and deep drainage as a function of time in Fig. 5. From this we see that there is significant deep drainage from the red earth profile in the first months following the conclusion of the wet season and the proportion of deep drainage during the dry season declines rather rapidly until it becomes but a small proportion of the total water loss from the profile (and non-significant). We see that the evapotranspiration term has a value ranging from maybe 10 mm per day to less than 0.5 mm per day in the soil under this eucalypt woodland whilst the drainage is very much smaller usually less than 1.0 mm per day. Although this data is by no means conclusive it does illustrate the value of the analysis in enabling us to partition soil water content change between deep drainage and evapotranspiration.

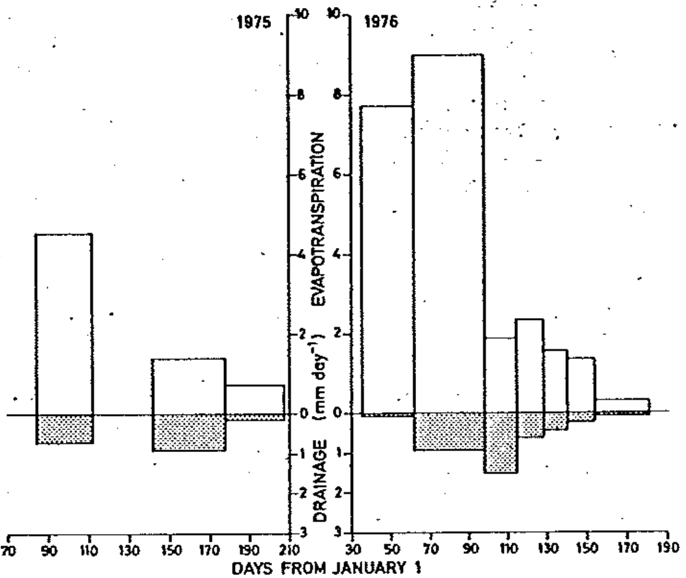

Figure 5 Estimated evapotranspiration and drainage from a Tippera red earth under woodland.

4 DISCUSSION

Using this simple analysis and the simulation model we are able to partition the soil water content changes into those attributable to evapotranspiration and those attributable to deep drainage. However, the analysis illustrates clearly the dependence of the methodology on reliable estimates or, at least, robust estimates of hydraulic properties for the profile. Our estimates of saturated hydraulic conductivity on 'undisturbed' cores do not generate hydraulic conductivity functions that provide satisfactory agreement between predicted and actual water content profiles. It is well established now (Nielson et al. 1973; Greacen et al. 1974; Cameron 1979) that soil heterogeneity is a very real problem in applying soil physical methods in hydrology, and the same problem is met by using this analysis.

There are two options available for dealing with the heterogeneity problem. More intensive sampling of soil physical properties would yield better estimates of the hydraulic properties in the profile. These more reliable estimates of hydraulic properties could be expected to yield more reliable partitioning of evapotranspiration and drainage; high cost of sampling and measurement mitigates against this. The alternative option is to optimize the hydraulic properties within the limits of the measured data (de Jong and Cameron, 1979) when evapotranspiration is prevented. Using the Marshall (1958) and the Rogowski (1971) methods the hydraulic properties can be optimized by methodically adjusting the four physical parameters (K_S, θ_S, ψ_e, θ_W) at each depth until simulated drainage results in a water content profile which

TABLE I

ADJUSTED HYDRAULIC PARAMETERS USED TO GENERATE $\psi(\theta)$ and $K(\theta)$ FUNCTIONS FOR THE TIPPERA RED EARTH

Zone	1	2	3	4	5	6	7	8	9	10
	40	80	120	160	200	240	280	320	360	400
Ks (cm day^{-1})	20.0	8.0	0.4	0.2	0.2	0.3	0.3	0.1	0.1	0.1
θs ($cm^3 cm^{-3}$)	0.36	0.37	0.37	0.36	0.36	0.34	0.34	0.35	0.36	0.39
ψe (cm)	-25	-30	-30	-30	-30	-50	-50	-60	-60	-60
θw ($cm^3 cm^{-3}$)	0.14	0.20	0.20	0.23	0.23	0.23	0.23	0.24	0.24	0.24

TABLE II

DIFFERENCES BETWEEN OBSERVED AND PREDICTED WATER CONTENT AS A FUNCTION OF DEPTH FOLLOWING A PERIOD OF DRAINAGE AND EVAPOTRANSPIRATION USING MEASURED AND ADJUSTED HYDRAULIC PROPERTIES

Depth (cm)	Zone	Initial Observed (cm^3 cm^{-3})	Final Observed (cm^3 cm^{-3})	Final (Observed - Predicted) x 10^3 (cm^3 cm^{-3}) Run 1	Run 2	Run 3
0-40	1	0.089	0.085	0	+1	0
40-80	2	0.260	0.230	-1	0	-10
80-120	3	0.294	0.272	-3	-3	0
120-160	4	0.299	0.283	+1	+2	0
160-200	5	0.304	0.287	-1	-1	0
200-240	6	0.320	0.301	-15	-15	-6
240-280	7	0.329	0.312	-25	-23	-2
280-320	8	0.339	0.324	-23	-21	-4
Evapotranspiration (mm)			-	6.7	8.4	31.5
Drainage (mm)			-	49.7	47.9	24.8
Total loss (mm)			57.6	56.4	56.3	56.3
Error* (mm)			-	27.8	26.5	8.8

*Error which cannot be eliminated by further adjustment of evapotranspiration.

'matches' the measured profile. Although our analysis is similar in principle to that of Rose and Stern (1967) there are a few indications that their methodology has been widely adopted because of the problems of soil areal heterogeneity (Warrick et al. 1978) and the cost and difficulties associated with the estimation of soil hydraulic properties. We suggest that the Rose and Stern (1967) analysis becomes feasible only if the problem of areal heterogeneity can be overcome.

We are currently assessing an approach whereby soil physical parameters measured at one or two positions in a 'large' area provide a first approximation of the hydraulic properties of this area. These properties are then optimized at all NMM access tube positions in the area using drainage data from a post experimental period during which the evapotranspiration is zero.

The methodology proposed here is that soil water content change in a given profile can be partitioned into evapotranspiration and drainage from a limited number of soil physical measurements along with water content distributions under one dimensional redistribution when evapotranspiration is zero. It is our hypothesis that the distribution and movement of water in a profile when evapotranspiration is zero must reflect the effective hydraulic properties of the profile.

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