CHAPTER 2

SOIL WATER AVAILABILITY

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Accurately evaluating the available soil water reservoir is vital to developing optimum management for rainfed crop production in marginally dry regions. However, the soil water reservoir is not like a bucket. Some water may percolate down out of the root zone under the influence of gravity or other forces. All water remaining in the root zone reservoir cannot be taken up by the plant as rapidly as needed because it is held too tightly by the soil particles.

Much attention has been given to problems of available water limits throughout the history of physical soil science. During the past four decades, the traditional approach to evaluating the limits of available water has been to measure the 'wilting point' and 'field capacity' of soil samples removed from the field through use of pressure chambers, usually measuring soil water contents at potentials of -15 bar for the wilting point and -0.33 bar or -0.10 bar for field capacity. Samples are taken from the soil at various depths to the measured or estimated rooting depth and the difference between the upper and lower limits of availability are summed over the rooting depth to determine the total plant available water.

Several criticisms have been made of the rather static definitions of available soil water limits mentioned above. Using theoretical and lower limits of water availability were not 'sufficiently precise or general to be much more than a rough index'. Water above the upper limit can be taken up while drainage is occurring. Plant growth can be retarded before the lower limit is reached, but water extraction by roots may continue beyond the -15 bar range in some instances. Also, where root density is low, especially in deep soils, it is difficult to separate the effects of root distribution from the effect of water flow through the soil on available water.

I have found that a major problem in defining limits of water availability to use in modelling the soil water balance is not so much related to relevant soil water potentials at the upper and lower limit as much as it is to obtaining accurate estimates of soil water potentials from soil samples removed from field sites. A series of excellent experiments done at Phoenix, Arizona, U.S.A., illustrates the point (van Bavel *et al.,* 1968a; van Bavel *et al,* 1968b; Brust *et al.,* 1968). The

Plant and Soil 58, 327–338 (1981). 0032-079X/81/0583-0327$01.80.

distribution of irrigation water in an Adelanto clay loam profile was studied in a field plot by periodic observation of water content. Successive measurements were made following an irrigation with the plot bare and covered with a plastic film, and also with the plot planted to a sorghum crop.

The successive water content profiles for the two plot conditions are shown in Figs. 1a and b. Fig. 1a shows that considerable drainage occurs after three days

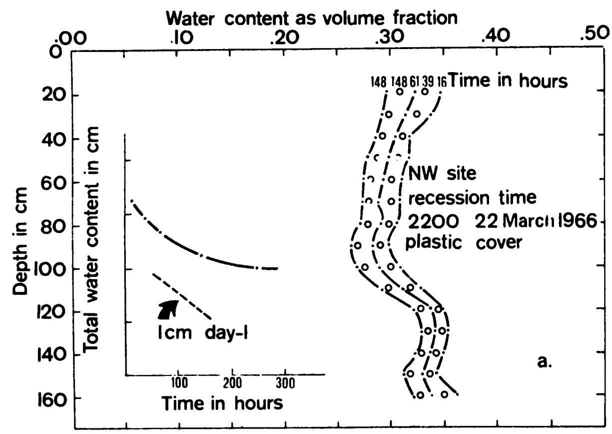

Fig. 1a. Successive water content profiles and total profile water content vs. time at the NW site of Adelanto clay loam. Surface covered with plastic after recession of irrigation water.

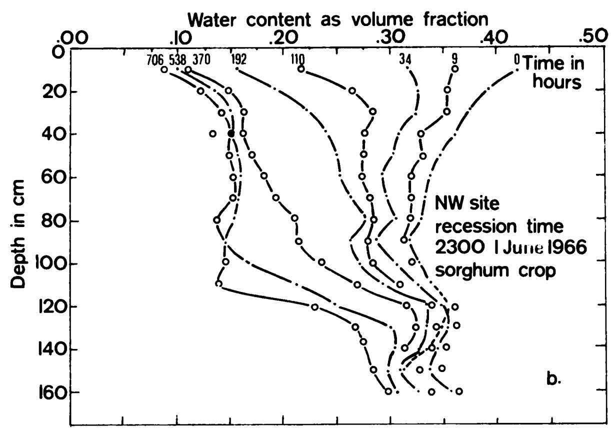

Fig. 1b. Successive water content profiles at the NW site following irrigation of a crop of sorghum. (From van Bavel *et al.*, 1968a.)

(72 hr), although about 70 per cent had occurred by then. After 10 days (240 hr), drainage had practically stopped and the water content profile at that time was near the drained field capacity. Data in Fig. 1b for 706 hr (about 30 days) after irrigation, show that sorghum roots practically stopped taking up water in the upper 100 cm of soil due to the soil water deficit. Water content changes were still apparent below 100 cm, although at a diminishing rate when considering the whole profile. Therefore the water content in the upper 100 cm could be practically taken as the lower limit. Had the measurements been continued until the plants were practically dead or dormant, the lower limit for the profile below 100 cm would have been determined for that cropping situation.

The drained upper limit profile (248 hr) from Fig. 1a and the approximate lower limit profile (760 hr) from Fig. 1b are replotted in Fig. 2. Also shown in Fig.

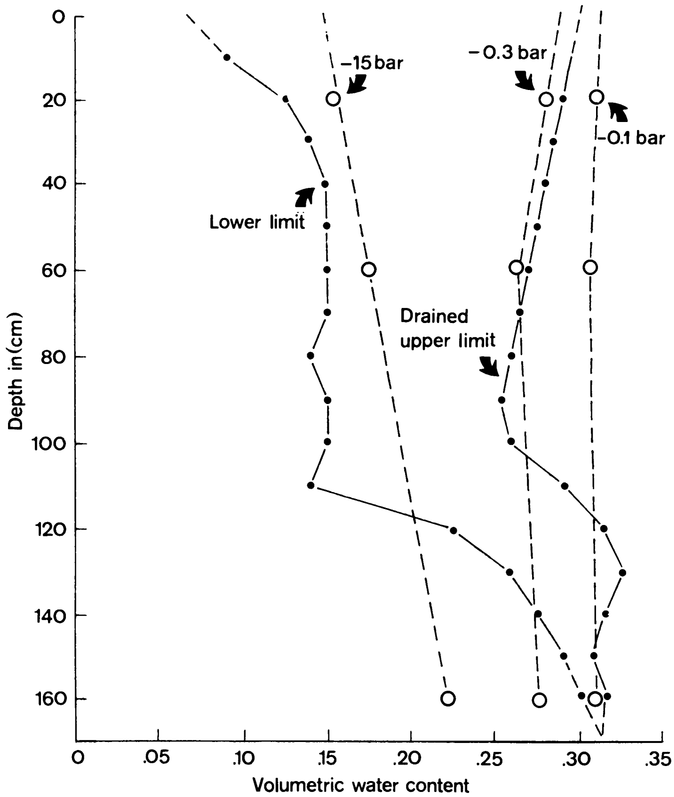

Fig. 2. Soil water content profiles for various estimates of the lower and upper limits of water availability for a sorghum crop on Adelanto clay loam. (From van Bavel *et al.*, 1968a.)

2 are the water contents at three potentials measured on samples removed from three depths near the site of the water content measurements, using laboratory pressure extraction equipment. Taking 160 cm as the reference rooting depth, available water can be calculated from data in Fig. 2 in several ways. Using the measured and interpolated -15 bar potentials as the lower limit, available water figured from the -0.1 bar potential is about 19.4 cm, from the -0.33 bar potential about 15.3 cm, and from the field measured drained upper limit about 17.5 cm. The amount actually extracted between the drained upper limit and the minimum measured value was 19.2 cm, but that value would undoubtedly be larger by 1 to 3 cm if the measurements had continued because of the apparent active depletion of water below 120 cm at the time the study was terminated (Fig. 1b).

Although the various estimates of available water are in fair agreement, errors could be much larger in other soils. The potential measurements at 160 cm fail to show the increase in water content below about 130 cm for the drained upper limit that was probably the result of a compacted horizon containing calcareous deposits and concentrations at those depths (van Bavel *et al.*, 1968b). Also note the consistent error in estimating the lower limit with the -15 bar values above 100 cm. I doubt that the water potentials between 30 and 100 cm were less than -15 bar as implied by the field and pressure extraction data.

A rather large decrease in water content near the surface on the lower limit profile is also shown in Fig. 2. This is typical of medium and fine textured soils because evaporation at the surface dries the soil to a much lower water potential than plant roots do. Although some of the surface water is not extracted by roots, it is included in the extractable water term because it affects the water balance and must be replaced to establish a favorable condition for plant growth.

It seems fair to conclude from data such as those of Fig. 2 that disturbed soil or undisturbed cores used with pressure extraction equipment to imply plant available water are subject to rather serious errors. This potential error, combined with the problem of incomplete extractions at the lower parts of the profile and the extra water loss near the surface, has led me to the conclusion that accurate water balance models need to have field-measured limits of water availability. Otherwise, during periods when plants are not freely transpiring because of soil water deficiencies, errors in estimating evapotranspiration can be large. I recommend that available water be defined in the field for the upper and lower limit for both research and modelling purposes whenever possible.

Measuring the upper limit

Since water can be taken up by plants while drainage is occurring, the drained upper limit is not always the appropriate upper limit of soil water availability. Therefore, it is necessary to measure or reasonably estimate the drainage rates while they are significant. It is possible to calculate drainage flux at the bottom of the expected root zone by use of field-measured hydraulic gradients and conductivities using Darcy's Law or the equation of continuity. From the field study at Phoenix mentioned above, van Bavel (1968a) found that an average field estimate of hydraulic conductivity for any given water content was 'in doubt by a factor of 5, and any resulting calculations of flux would be equally uncertain'. With site to site variation added to the uncertainty in flux, errors introduced by this method for calculating the soil water balance should be highly suspect.

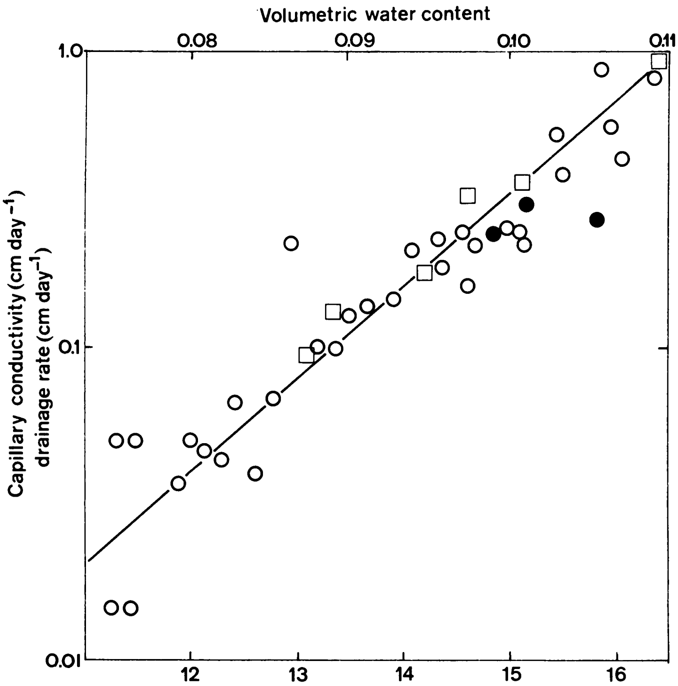

Fig. 3. Lysimeter drainage rate as a function of water storage (circles) and capilary conductivity of Plainfield sand as a function of soil water content (squares). The upper scale gives the soil water content corresponding to a given storage assuming a uniform water content distribution. (From Black *et al.*, 1969.)

Black *et al.* (1969) described useful functions to estimate drainage flux that are relatively simple to evaluate from field data. For fairly uniform sandy soil, they showed that the drainage rate at the lower part of the profile was an exponential function of the profile water storage above that depth. Their data are shown in Fig. 3 along with hydraulic conductivity data taken on disturbed samples from the profile. Although their drainage rates were measured with an accurate weighing lysimeter, data such as those shown in Fig. 1a on water content change with time and depth are accurate enough for defining drainage functions similar to those in Fig. 3. When the profile storage figures in the Black *et al.* (1969) data were divided by the soil depth to calculate an average water content, the agreement between laboratory-determined conductivities and field drainage rates at corresponding water contents was good.

Most soils are not as uniform as the sand described in Fig. 3, and fitting a drainage function for the whole profile for conductivity data would likely produce considerably greater variability in most situations. However, if storage or

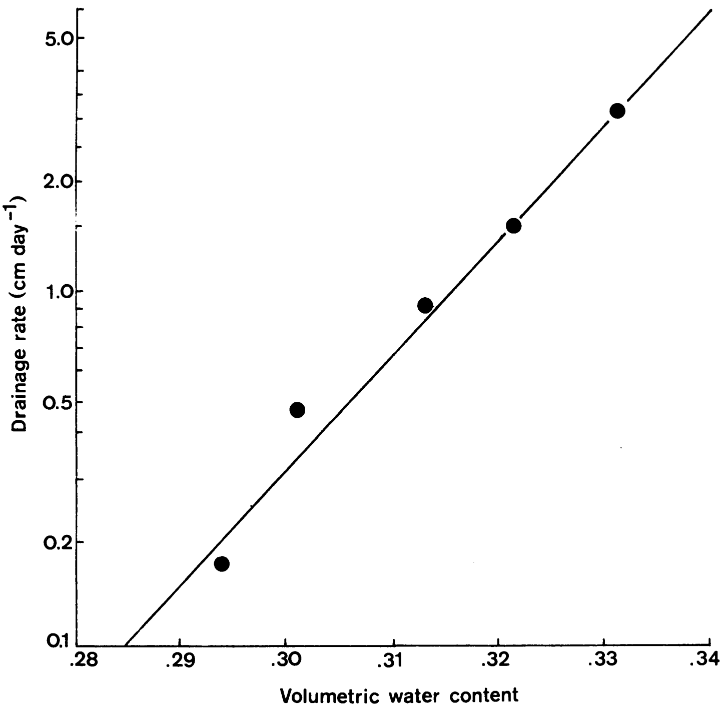

Fig. 4. Field measurements of drainage rate as a function of average soil water content for Adelanto clay loam. Average water content is for the 0 to 160 cm depth. (From van Bavel *et al.*, 1968a.)

average water contents are measured along with water contents during drainage, numbers similar to those of Fig. 3 can be calculated from field data. Fig. 4 shows a plot of drainage rates for the data of van Bavel (1968a) from Fig. 1a plotted vs. average water content, showing fairly good linearity on a semilog plot.

An equation of the form

$$D = 0.1 \exp[\beta(\bar{\theta} - \bar{\theta}_d)] \quad (1)$$

can be used to describe curves like the one in Fig. 4, where D is the drainage rate (cm day^{-1}), β is a constant related to the slope of the curve, $\bar{\theta}$ is the average soil water content at the time D is calculated (cm^3 cm^3), and θ_d is the average soil water content when D = 0.1. Data from studies of Black *et al.* (1969), Miller (1967), van Bavel *et al.* (1968a), and unpublished data I have collected for Houston black clay were used to calculate $\bar{\theta}_d$ and β values for equation (1). The results are presented in Table 1.

The $\bar{\theta}_d$ values are roughly related to soil texture, with the sand holding much less water in a near drained condition ($\bar{\theta}_d$) than a clay. However the value of β is not related to texture but is very likely a function of conditions in part or all of a soil profile restricting water flow.

Equation (2) can be used to calculate D in a daily incrementing water balance model;

$$\bar{\theta}_n z = \bar{\theta}_{n-1} z + P_n - ET_n - D_n, \quad (2)$$

where $\bar{\theta}_n$ is the average water content of an entire profile of depth z at the end of any day n, $\bar{\theta}_{n-1}$ is the corresponding water content on day n − 1, P_n is recorded precipitation or irrigation (assuming run-off), ET_n is the evapotranspiration. Black *et al.* (1969) demonstrated the successful use of (1) and (2) by independently testing with a weighing lysimeter.

Using $\bar{\theta}_d$ is a practical field measured value of the drained upper limit, water balance models can neglect D when $\bar{\theta} < \bar{\theta}_d$ and calculate its value when $\bar{\theta} \geq \bar{\theta}_d$ and retain the dynamics of water loss from a profile by D and ET simultaneously.

Table 1. Values of $\bar{\theta}_d$ and β fitted from field data for four soil types

Soil type	$\bar{\theta}_d$	β
Plainfield sand	0.089	109.0
Warden fine sandy loam	0.214	35.4
Adalento clay loam	0.285	74.3
Houston black clay	0.422	81.4

Measuring the lower limit

Field measurements of the lower limit of water extraction are more difficult than measuring the upper limit because root growth dynamics are different between and within crops and also because conditions for the lower limit may not often naturally occur.

The best value for the lower limit is obtained when crops reach their maximum vegetative size without stress and then grow on stored soil water until plants are visibly severely distressed. Changes in water content should practically stop at all depths when the lower limit is being approached. Because leaf senescence and natural death of many crops occur at maturity, water content changes alone are not adequate to assure that the lower limit has been reached. Therefore, it is important to be certain that plants have undergone premature severe stress for the best lower limit evaluation.

The extent of variation in the lower limit for a soil caused by crop type and management has not been well documented. The primary difference in lower limit values caused by crops should occur in deep soils where roots do not penetrate the lower levels of the soil profile in sufficient density to extract water to the approximate -15 bar limit. Thus, in shallow soils where rooting is restricted to about 1 m or less depth, the lower limit value should be practically independent of plant type unless the soil properties severely restrict root penetration.

There is limited evidence that the crop type effect on the lower limit of deep soils is not very great for many annual crops. For Houston black clay field measured extractable water amounts are almost identical for sorghum, maize and cotton (Ritchie, 1973; Ritchie *et al.*, 1972). For Adalento clay loam, the extractable water for sorghum, as shown in Fig. 2, was about 19.2, but the lower limit was not completely obtained for the measurement shown. An extrapolation of the water content curve in van Bavel *et al.*, (1968b) to approximate lower limit for the sorghum implies an extractable water content of about 21 cm between that limit and the drained upper limit. Extractable water evaluated for two varieties of wheat and one variety of barley grown in the same experimental area ranged from 19 to 21 cm extractable water (unpublished data from the U.S. Water Conservation Laboratory, Phoenix, AZ). These limited data suggest that for many annual crops, the lower limit water content for a soil may be about constant.

There are sometimes problems in using lower limit values as described above. Any stress that causes a reduction in root growth before establishment of a 'normal' rooting profile, as used in the definition of the lower limit, can cause incomplete root water extraction because of a reduced soil volume where roots take up water.

Stress resulting from nutrient deficiency that causes large differences in plant vegetative size can strongly affect the lower limit value. In an adequately fertilized winter wheat crop, soil water data of Brown (1971) indicated that extractable water on a silt loam soil was about 15.5 cm. On an unfertilized crop in the same soil, extractable water was only about 9.6 cm. The depth of extraction was about 50 cm greater in the fertilized plot, but the greatest reduction in extractable water was the result of incomplete use of the profile water below 15 cm. In the 30 to 150 cm depth increment, only about half as much water was extracted by the unfertilized crop as with the fertilized crop. This result must have been caused by an extremely low root density. Yields were 3630 and 1610 kg ha^{-1} for the fertilized and unfertilized crops, respectively. There are several experiments where fertilizers have caused significant increases in yield that did not demonstrate the dramatic difference in water extracted from a profile as the study of Brown (1971). Researchers should be aware that fertilizer or other management practices may influence extractable water for a soil.

Water stress early in the life of a plant that reduces topgrowth can also reduce root growth and, therefore, reduce extractable water. As an example, cotton growing in Houston black clay (Jordan and Ritchie, 1971) had practically stopped above ground biomass production when plants were relatively small. Although plants were not showing severe wilting symptoms, there was practically no uptake of root water below 100 cm. In other studies with cotton on the same soil, when plants were able to get much larger and develop more dense and deep root systems, extraction was obtained to 175 cm.

When poorly drained soils are near saturation in the lower part of the root zone while root systems are developing, poor aeration conditions can cause a lack of root penetration into the entire profile and cause extractable water to be reduced. R. H. Shaw in Iowa (personal communication) observed that when early season conditions are unusually wet in maize fields, crops are more drought affected later in the season than when early season conditions are drier. He attributes this phenomenon to a lack of root growth into poorly aerated soils before tasseling. When conditions improve after tasseling, no new root growth occurs and little uptake is obtained from lower parts of the soil profile when needed to sustain growth for maximum yields.

Upward movement of water into the root zone can also be a factor contributing to the inaccuracy of lower limit measurements. van Bavel *et al.* (1968b) and Stone *et al.* (1973) made field measurements of water flux at soil depths thought to be below the root zone, and both reported sustained periods of more than 10 days with upward fluxes of 0.2 to 0.3 cm day^{-1}. Those values are subject to large uncertainties because of soil heterogenity, but both appear to overestimate the upward fluxes.

In the van Bavel *et al.* study, about 2.5 cm of water was calculated to move into the root zone by upward flow from below 170 cm. That supply of water would need an average change in volumetric water content of 0.025 for 100 cm, or 0.05 for 50 cm below the 170 cm depth, both unlikely at those depths. The largest measured change in water content below the drained upper limit at 160 cm was 0.025. Errors in their upper flux calculations could be an order of magnitude too high, and, if so, little error would have been introduced by neglecting upward flow.

In the Stone *et al.* study, measurements were made to 150 cm. Using calculated upward flux at 150 cm and the measured depletion rate, they calculated ET rates for a full cover irrigated sorghum crop of about 0.3 cm day^{-1} for more than 15 days. Those calculated ET rates are about half of usual values expected during August in South Dakota. Pan evaporation averaged about 0.7 cm day^{-1} during that time and, in a separate study, Stone and Horton (1974) reported ET rates for sorghum measured with an energy balance method at the same time of year and same approximate stage of growth to average about 0.6 cm day^{-1}. Therefore, it is reasonable to expect their upward flux calculations to be too high by about an order of magnitude.

In fact, depletion of water from the upper 150 cm profile reached about 0.1 cm day^{-1} the last few days of measurements and water contents in the depth range between 90 and 150 cm were changing quite rapidly during that time also. If plants were freely evaporating near the end of August, this is evidence of active uptake from below 150 cm if ET rates were in the range of 0.4 to 0.6 cm day^{-1}. Field measured soil water potentials in the lower part of the profile were about 0.6 bar at that time. Therefore, plants should not have been stressed to the point of a large reduction in ET.

Measurement of roots in the Stone *et al.* study indicated that 99.9 per cent of the roots were in the upper 130 cm of the profile. In the van Bavel *et al.* study, it was stated that estimates with sorghum in the same field indicated no appreciable root activity below 140 cm. Because evidence is good in both cases for active root uptake below those depths, I suspect that traditional methods of sampling roots are lacking where root densities are low. Those sparse roots deep in the profile may be highly active in uptake when the water supply is adequate.

In the absence of a water table within about 5 m of the surface, errors in the lower limit evaluation caused by upward flux can be minimized by measuring water content to a depth where there is almost no change in water content between the drained upper limit and the lower limit.

SUMMARY AND CONCLUSIONS

Definitions of the upper and lower limits of soil water availability are difficult to establish because of water flow into and out of the root zone and because of incomplete extraction by sparse roots at the lower boundaries of the root zone. Pressure extraction equipment used on soil samples removed from a field often fails to provide reliable estimates of the limits of water availability when comparing it to observations in the field. Therefore, for accurate soil water balance modelling, it is important to measure the upper and lower limits in the field.

The difference between the field-measured drained upper limit and lower limit soil water content is called the extractable water. A simple field-measured drainage function can be used to determine the time when water is available above the upper limit while soils are draining. Determining the extractable water in this way requires only soil water content measurements. For best accuracy, the neutron meter is recommended because soil measurements have much less error for determining change in water content with time because the same soil volume is measured every time.

When the field-measured drained upper limit and lower limit water contents are measured to calculate extractable water, quite general relations can be established for a function to reduce transpiration as related to soil water (Ritchie, 1973). Above about 70 per cent of the range of extractable soil water, transpiration is little affected by soil water deficit; afterwards transpiration is reduced in approximate inverse proportion to the extractable soil water below the 30 per cent threshold value. In dry regions where ET is the critical factor in soil water balance modelling, calculating transpiration accurately is important. Therefore, evaluating the soil water reservoir available for plant root extraction is paramount to evaluating systems that minimize risks in marginal dryland areas.

Hopefully, accumulated experience with different soils and crops will some day provide reasonable extrapolation of extractable water limits and field drainage functions where field data are not available. Until then, field measurements seem to be unavoidable.

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