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# APPLICATION AND ACCURACY OF A DIELECTRIC SOIL WATER CONTENT METER

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APPLICATION AND ACCURACY OF A DIELECTRIC SOIL WATER CONTENT METER

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ABSTRACT

Accurate and instantaneous measurements of the volumetric soil water content at many depths, including the top layer, are possible with a dielectric soil water content meter. The soil profile remains undisturbed after installation of the sensors. The daily evapotranspiration was calculated from the water balance, with the water content meter to measure water storage. Simultaneous reference measurements were made with the Bowen ratio energy balance method. Comparison of these results show good agreement for the cumulative evapotranspiration over 9-day periods.

INTRODUCTION

Detailed knowledge of the water content in a soil profile is of interest for several disciplines. Dynamic hydrological processes in the soil, such as infiltration and capillary rise, can be studied. The time of irrigation and the quantity of water to be applied can be determined in water use efficiency experiments. Evapotranspiration can be calculated from the change in the water storage of the soil profile when percolation, precipitation and surface runoff are known.

During the last decades several direct and indirect methods have been used to determine the soil water content, such as the neutron-, gamma- and gravimetric methods, gypsum blocks and tensiometers (Schmugge et al. 1980). These methods have different drawbacks and most cannot be used in automatic data collection systems. The neutron- and gamma methods are dangerous and need special safety precautions. The gravimetric method disturbs the soil and is laborious. Gypsum blocks are not accurate, and tensiometers can measure only in a limited range.

Another method is the capacitive method (Smith-Rose 1934, De Plater 1955, Kuraz et al. 1970, Turski and Malicki 1974). It is based on the measurement of capacitance of a capacitor with the soil-water-air mixture as the dielectric medium. A probe with conductive plates or rods surrounded with soil constitutes the capacitor. The relative permittivity (dielectric constant) of water (80) is large compared to those of the soil matrix (<10) and air (1). A change in the water content of the soil will cause a change in the relative permittivity, and thus in the capacitance of the probe surrounded with soil. Usually, the capacitor is part of a resonance circuit of an oscillator. Changes in the water content, and thus changes in the capacitor capacitance, will change the resonance frequency of the oscillator. In this way the water content is indicated by a frequency shift. The relation between water content and frequency shift is non-linear. The relative permittivity of the soil matrix depends on its composition and bulk density and varies between 2 and 10. Therefore a calibration curve is needed for each separate soil. An important source of error with the capacitive technique is the sensitivity for the electrical conductivity of the soil which influences the resonance frequency of the oscillator. Instrumentation used in the capacitive technique consists of a read-out unit, and either a mobile probe to record at different access tube points (Kuraz 1981, Malicki 1983), or fixed probes at selected positions within the soil (Hilhorst 1984).

In this paper we describe the usefulness of the dielectric soil water content meter and its application to monitor the water content in a soil profile. The daily evapotranspiration was calculated from a water balance in which the water content meter measured the daily changes in the water storage. Reference measurements of the evapotranspiration were made simultaneously using the Bowen ratio energy balance method (Slatyer and McIlroy 1961).

MATERIALS AND METHODS

Set-up of the experiment

Before the start of the growing season the equipment was installed in the middle of a field of 125 by 200 m. The experiments were performed in a corn field in 1985. A dielectric soil water content meter, developed by the Technical and Physical Engineering Research Service in Wageningen, was used. The instrument consists of probes that have to be placed into the soil (fig. 1B) and a detachable portable read-out unit. The instrument compensates for the conductivity of the soil (Hilhorst 1984). The capacitive probes were positioned horizontally in two columns at depths of 2, 3, 4, 5, 7, 10, 20, 30, 40 and 60 cm (fig. 1A). Tensiometers were installed close to these probes at depths of 10, 20, 30, 40 and 60 cm. The capacitive probes and tensiometers were daily measured by their respective portable read-out units. The readings were manually entered into a computer for off-line analysis. Within 10 m of this research site the net incoming radiation at a height of 4 m and soil heat flux density at a depth of 2 cm below surface were measured. Also wet-bulb and dry-bulb temperatures were measured at two different heights above the bare soil or the crop. All these variables were automatically sampled every minute. The mean values of 15 minute intervals were stored on magnetic tape for analysis. The total daily rainfall was measured with standard meteorological equipment and the daily distribution with a pluviograph at a distance of approximately 150 m from the research site.

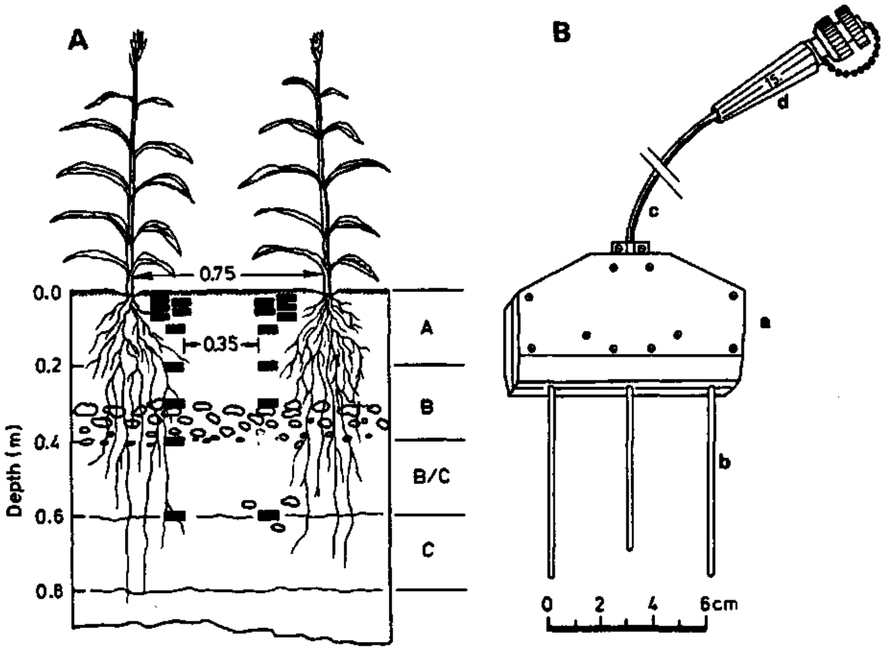


Figure 1. Soil profile at the experimental station 'Sinderhoeve' and position of capacitive probes in the profile and a schematic illustration of the capacitive probe.

A. The soil profile consists of sand, in which a humic topsoil (horizon A) has been developed by addition of farmyard manure. This topsoil consists of gravel and coarse sand of approximately 20 cm thickness. Between 20 and 40 cm there is a podzolic B horizon with less humus and iron bonds. A transition zone between the B and C horizon (B/C) is found from 40 to 60 cm. Below 60 cm the soil consists of coarse sand and gravel. The probes are placed in two columns in between two rows of corn at ten different depths (from 2 to 60 cm).

B. The capacitive probe consists of a plastic holder (a), three electrodes (b), a cable of two meters length (c) and a connector (d)

Calibration of the dielectric soil water content meter

Every probe of the water content meter needs to be calibrated. Calibrations were performed both in the field and in the laboratory (fig. 2). The calibration procedure was described earlier (Halbertsma and Przybyla 1986) and is summarized here.

During the measuring period volumetric soil samples were taken for gravimetric determination of the water content. The sampling was performed within a radius of five meters from the probes at corresponding depths. The readings of the water content meter were recorded during the sampling. A first order field calibration curve was calculated from these data points (fig 2). The scatter of the data points is the result of the spacial variability of soil characteristics, the position of sampling with respect to the crop, etc. This calibration procedure leads to data which are an average from the area considered, although the water content meter measures at one spot only.

After the measuring period the probes were removed. Soil cores were taken at several depths within 1 m distance from the probes. The soil samples were saturated in the laboratory. The probes were installed in the cores, and readings of the water content meter and weight of the soil sample were recorded at regular intervals during evaporation. The apparent non-linear relationship between the reading of the water content meter and the gravimetrically-determined water content was approximated by a second order curve (fig. 2). The advantage of this laboratory calibration over the field calibration is that the whole range from saturation to dry can be calibrated for the same soil sample. A disadvantage is that systematic errors can be introduced when the soil sample is not a representative of the soil around the probe, which was the case for several samples. For the calculation of the water content the field calibration was used only.

Calculation of the evapotranspiration from the water balance

The evapotranspiration can be calculated from the water balance. In our case there was no surface runoff and irrigation. Then the evapotranspiration during a certain period is given by:

$$ET = P - \Delta W - D$$

where:
ET = evapotranspiration (mm)
P = precipitation (mm)
$\Delta W$ = increase in water storage in the profile considered (mm)
D = drainage from the profile (mm).

The evapotranspiration was calculated on a daily basis. The increase in water storage of the profile $\Delta W$ was calculated from the changes in the water content of the soil layers measured with the water content

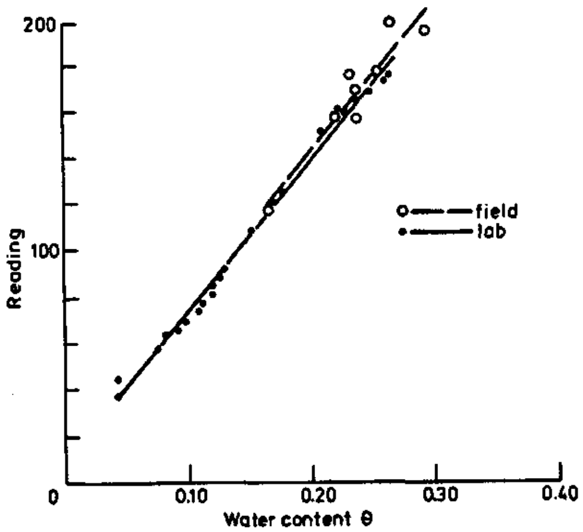


Figure 2. Calibration of the dielectric soil water content meter for the 'Sinderhoeve' experimental field at a depth of 10 cm below surface. The reading of the instrument is plotted against the gravimetrically-determined volumetric soil water content θ. The field calibration curve is the result of linear regression, the second order laboratory calibration curve of polynomial regression

meter. These changes were multiplied by the thickness of their respective layers and summed up to a depth of 50 cm. We chose that as the lower boundary of the profile. The drainage D from the considered profile into deeper layers was calculated from the flux density. The flux density was estimated from the hydraulic gradient, measured with the tensiometers at depths of 40 and 60 cm, and the unsaturated hydraulic conductivities. After the field experiments, soil samples were taken at a depth of 50 cm within 1 m from the tensiometers. In the laboratory the unsaturated hydraulic conductivities were determined from these samples with the evaporation method (Boels et al. 1978). See Results and Discussions for a discussion on the accuracy of the water balance method.

Calculation of the evapotranspiration with the Bowen ratio energy balance method

The evapotranspiration can also be calculated from the differences between the energy fluxes of the net incoming radiation and the energy absorbed by the soil, together with humidity measurements at two different heights (Slatyer and McIlroy 1961). The humidity was measured with a wet- and dry-bulb type hygrometer (psychrometer). The radiation was measured with a Funck net radiometer and the soil heat flux with a flux plate. The error in temperature measurements was ±0.05°C, while the errors in radiation and soil heat flux were ±3% and ±10% of the reading respectively. The evapotranspiration during 15 minute intervals was calculated from the averaged measurements (see Set-up above). The errors of the evapotranspiration calculations were estimated in two ways with computer simulations. In the first simulation, normally distributed noise with a standard deviation of one third of the errors were superimposed on the measurements. The calculations were repeated 100 times with different realizations of the noise after which the mean evapotranspiration and its standard deviation were calculated. These simulations showed that the evapotranspiration was estimated unbiasedly and that its standard deviation was 0.2% of its daily value. So errors of ±0.6%, three times the standard deviation, are possible. In the other simulation we considered the measuring errors as systematic errors (Fuchs and Tanner 1970). The calculations were performed with these biased parameters. A bias of ±6% of the daily evapotranspiration is possible in this case. An other source of error can be that the ratio between the eddy diffusivities of heat and vapor has been taken 1 in this study. Under advective conditions large departures from 1 can occur, which, as a consequence, can lead to serious errors (Hicks and Everett 1979). However, in our study this was not the case, so this source of error can be ignored. The error in the Bowen ratio energy balance method is dominated by the bias of 6%, which is considered as the accuracy of the method.

RESULTS AND DISCUSSIONS

Water content measurements

During the measuring period from May until October 1985, water content measurements were daily made using the dielectric water content meter. Occasionally, more measurements were made to monitor the changes during the day. Soil water contents at ten different depths were calculated using the field calibration curves. The water content was determined by averaging the two water contents at corresponding depths. The water contents in the profile are plotted for three successive days in figure 3A. Moderate rainfall (fig. 4C) wetted the top 10 cm. The layers below 20 cm depth are becoming still drier. Because of withdrawal of water by the transpiring corn water movement between -40 and -60 cm is directed upwards during the whole period. Even small water content changes during the day can be observed with the water content meter (fig. 3B).

Accuracy of the water content meter

The accuracy of the measurements can be estimated from the differences in the water content of the two columns ($\theta_1$ and $\theta_2$) at corresponding depths. We assumed that all errors were stochastic. The measured water content was described as the true water content superimposed by the normally distributed noise. The standard deviation of the noise is s. So at corresponding depths the variance of the difference between the water contents is:

$$var(\theta_1 - \theta_2) = 2var(\theta) = 2s^2$$

The average standard deviation of the differences of all 10 depths was 0.01 $m^3.m^{-3}$. So $s = 0.01/\sqrt{2} \approx 0.007$ $m^3.m^{-3}$. Consequently the maximum error in the calculated water content becomes ± 3s = ± 0.02 $m^3.m^{-3}$. This is an indication of the accuracy of the water content meter. Note that all souces of error of this experiment are included, i.e. noise of the instrument, calibration errors, spacial variability of the field, temperature effects, etc. The errors in the average water content $\bar{\theta}$ of the two columns at a certain depth is figure 3 can be calculated in the same way:

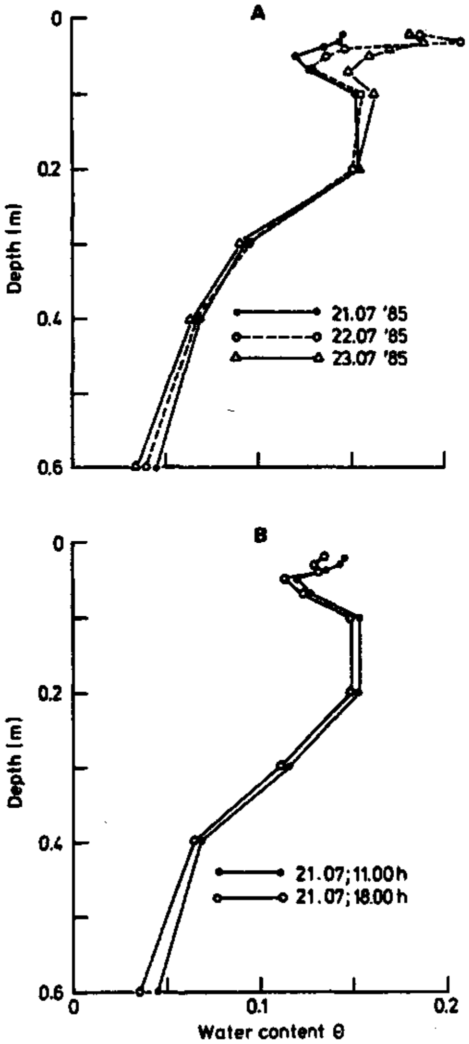


Figure 3. Volumetric soil water content of the profile at the 'Sinderhoeve' experimental field
A. Water contents θ at three successive days
B. Water contents at two different times of one day. Evapotranspiration calculated with a water balance from these data was 2.3 mm. This agrees well with the 2.4 mm found with the Bowen ratio energy balance method

$$var(\overline{\theta}) = var((\theta_1 + \theta_2)/2) = s^2/2$$

So the standard deviation was $0.007/\sqrt{2} \approx 0.005$ $m^3.m^{-3}$ and the maximum error $\pm 0.015$ $m^3.m^{-3}$.

The situation is slightly different when we consider the changes in water content at a certain depth. Systematic calibration errors were greatly reduced since we consider only relative small changes. In that case we can estimate the errors from the differences in daily water content changes ($\theta_1 n-\theta_1 o$ and $\theta_2 n-\theta_2 o$) at corresponding depths. The variance of these differences is:

$$var\{(\theta_1 n - \theta_1 o) - (\theta_2 n - \theta_2 o)\} = 4var(\theta) = 4s^2$$

So the standard deviation of these differences is 2s. Our experimental results showed an average standard deviation for the 10 depths of 0.008 $m^3.m^{-3}$. Consequently s = 0.004 $m^3.m^{-3}$. The maximum error becomes $\pm 0.012$ $m^3.m^{-3}$ which is an indication of the relative accuracy of the meter.

Calculation of the evapotranspiration

The daily evapotranspiration was calculated from the water balance (see Methods). Several problems arose with the determination of this balance. The hydraulic heads, water contents and precipitation were not measured at the same time. The data was synchronized with the measurement of the precipitation by linear interpolation. This leads to extra errors when relative rapid changes occur like rainshowers. Another problem is the drainage term in the water balance. One or two days after heavy rainfall an excessive evapotranspiration up to 20 mm/day was calculated. This was caused by the unnoticed quick percolation through the lower boundary, which consists of well permeable coarse sand. The loss is then considered as evapotranspiration in the calculations. Under these conditions automatic data acquisition systems are indispensable to sample more frequently. To evaluate the water balance method we selected a period with capillary rise only (maximum 0.03 mm/day). In this way neglectable errors were made in the drainage term.

The results of the water balance method and the Bowen ratio energy balance method are presented in figure 4. The cumulative evapotranspiration of two 9-day periods (fig. 4B) of both methods showed relative small differences, only 2.8 and 0.4 mm of the total evapotranspiration of 24 mm during those periods. The differences of the daily values of the two methods were relatively large , up to 2.75 mm/day, and were of the same order as the daily evapotranspiration (fig. 4A). These differences cannot be explained from the small errors in the Bowen ratio energy balance method and must have their origin in inaccuracies of the water balance method.

The inaccuracies of all terms of the water balance are summed in the error of the evapotranspiration. The errors in the drainage term can be neglected for the period considered and those of the precipitation term were small, less than 0.1 mm. The accuracy of the increase in the water storage of the profile ΔW can be estimated from its variance:

$$var(\Delta W) = var(\Sigma d_i\{(\theta_1 n-\theta_1 o)_i + (\theta_2 n-\theta_2 o)_i\}/2) = \Sigma d_i s^2$$

where $(\theta_x n-\theta_x o)_i$ the increase of water content of layer i of column x, d the thickness of layer i and s the standard deviation for water content changes (see above). In our experiment the standard deviation of ΔW was 220s = 0.88 mm. So the maximum error becomes ±2.6 mm. The maximum error of the daily evapotranspiration is dominated by the errors in ΔW. This total error was ±2.6 mm. Note that the erorr in ΔW is independent of the period considered, in contrast with the (much smaller) errors in the precipitation and drainage terms which were summed. The latter is also the case for the Bowen ratio energy balance method. The errors in the differences between the two methods were the sum of the stochastic errors of the water balance and the bias of the Bowen ratio energy balance (maximum ±0.2 mm/day). This error is ±2.8 mm, which agrees

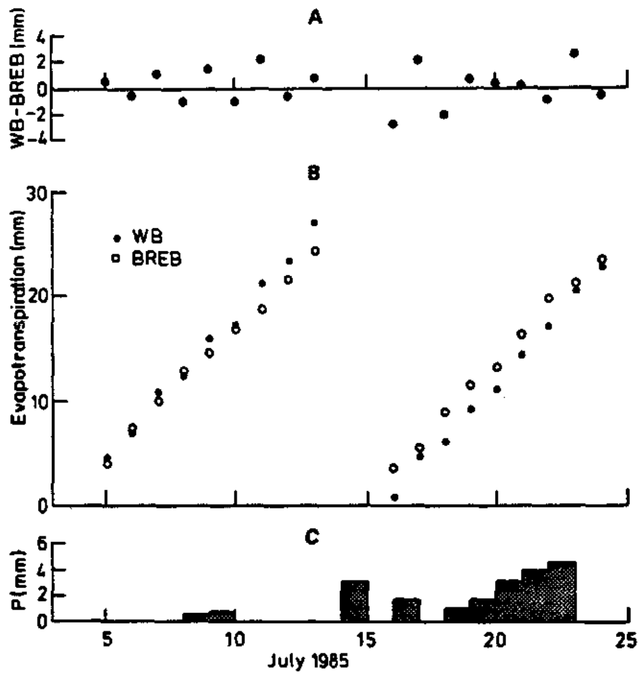


Figure 4. Evapotranspiration and precipitation from 4 to 24 July 1985
A. Differences between the daily evapotranspiration determined with the water balance (WB) and with the Bowen ratio energy balance method (BREB)
B. Cumulative evapotranspiration calculated with the two methods for two 9-day periods
C. Daily precipitation (P)

well with the experimental results (fig 4A). Note the strong correlation in the successive daily values, caused by errors in the water balance.

## SUMMARY AND CONCLUSIONS

Accurate measurements of the volumetric soil water content at many depths, including the top layer (e.g. at -2 cm), are possible with a dielectric soil water content meter. After a relatively simple calibration procedure an accuracy better than $\pm 0.02\ m^3.m^{-3}$ can be obtained, provided that no changes in the matrix-density occur as is the case in swelling and shrinking soils. After installing the probes no further disruption of the profile occurs. The response of the instrument is almost instantaneous and small water content changes can be measured. The instrument is inherently safe and can be used in automatic data recording systems.

The dielectric soil water content meter is especially suited for studies where detailed knowledge of the water content through the whole soil profile is needed, e.g. in water balance studies. Evapotranspiration can be calculated from the water balance. In our experiments we determined evapotranspiration with an accuracy of 2.6 mm, which is too less for daily measurements but satisfactory for longer periods. Comparison with evapotranspiration results obtained with the Bowen ratio energy balance method showed good agreement. The Bowen ratio energy balance and other aerodynamic methods need rather large homogeneous areas to give unbiased results. This is in contrast with the water balance method where data from one point of the field are used. This makes the method sensitive for variability of the field. However, calibrating with data obtained from a larger area can give an avarage calibrating curve for that area. In this way unbiased results can be obtained. The advantage of the water balance method is that it is also well suited for studies in a limited area like lysimeters.

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