MEASUREMENT OF SOIL MOISTURE IN SMALL CATCHMENTS: A NEW TOOL

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ABSTRACT

Non destructive methods for measuring soil water content are based mainly on sensors permanently placed into the soil. Repetitive measurement with probes is time consuming and the volume of soil investigated is generally small. For these reasons probes are not practical for the determination of soil moisture in small water catchments. Recently, attempts have been made to use electromagnetic methods to follow the fluctuation of the water content spacially. The purpose of our paper is to demonstrate that electromagnetic induction techniques can be used also to determine the global soil water content and the soil moisture profile of any point in an area of several hectares. An application was made in Lebanon, on fersiallitic lixiviated soils, commonly found in all Mediterranean regions. Other possible applications could be calibration of remote sensing data, location of optimum planting places in watershed, rehabilitation of dry areas, and determination of ETR in small catchments.

KEYWORDS

Soil Moisture- Electromagnetic induction- ETR

INTRODUCTION

The measurement of the soil water content in the field has always been a tedious and uncertain task. Soil destructive techniques can be used to give an idea of the spatial variation of soil moisture only if one accepts to collect a great number of samples (Bardossy and al., 1998). For similar reasons, the use of probes access tubes, in the case of neutron probes, or probes left permanently in situ, as TDR or capacitances, is also limited (Chanzy and al., 1998). Therefore no really practical method is actually available to measure the global water content of the soils of water catchments despite the increasing need for such data, in remote sensing for instance.

OBJECTIVES

Our present objective is to demonstrate that it is possible to determine with a reasonable accuracy the total water content of important volumes of soils and to develop an easy-to-use method. The ultimate goal is to make possible the estimation of the actual evapotranspiration of deep soils to facilitate the calculation of the water balance of small catchments, up to 500 hectares of area and, for shallow soils, the calibration of remote sensing imagery.

THEORETICAL BASIS

The proposed method is based on the use of the Electromagnetic Induction (EI), which measures the electromagnetic conductivity of the soil. This technique has been used to determine soil salinity with indirect calibration (De Jonc et al. 1979 ; Corwin and Rhoades, 1990), or with direct calibration (Job et al., 1988). The effect of soil moisture has been demonstrated on saline soils (Job et al, 1999). Going beyond this last experiment, in the present study, we assume that for negligible soil salinity, the global apparent electromagnetic conductivity is proportional to soil moisture

Principle of electromagnetic induction

A transmitter coil (Tx), energized with a frequency f is placed on the soil surface. A receiver coil Rx is placed at a short distance s. The time varying primary magnetic field Hp produced by the alternating current induces very small curents in the soil generating a secondary magnetic field Hs which is measured through the receiving coil. If the distance of attenuation of the primary field divided by the intercoil spacing is much smaller than unity, conditions known as « low induction number », then the conductivity of the soil is proportional to the ratio of primary to secondary field (McNeal, 1980) :

$$\sigma_a = k*s^{-2}\,(Hs/Hp) \qquad (1)$$

The measured conductivity is called apparent global conductivity, because it integrates the electrical conductivity of a variable volume of soil and its intersticial liquid. It is noted σ_a , and k is a constant parameter depending on instrument construction (frequency, intercoil spacing).

The depth of soil which contributes to 90% of the secondary field, taken as depth of penetration, is approximatively equal to two intercoil spacings if the soil is homogeneous and isotrope (fig.1). The contribution of a soil layer to the secondary field Hs depends on the position of the coils. In the instrument used in this paper (EM-38 Geonics), the central axis of symetry of Tx and Rx coils are parallel and may be held either perpendicular to the soil (position said vertical mode, noted EMC_V) or parallel to it (position said horizontal mode, noted EMC_H).

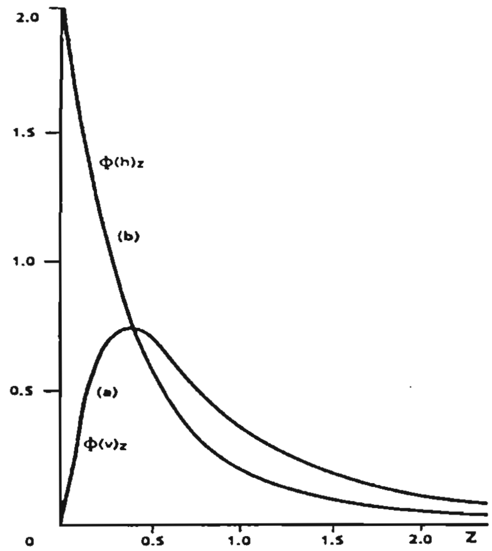

Fig.1- Contribution of a soil layer at a normalized depth z to Hs, in vertical and horizontal mode respectively (from McNeal, 1980).

METHOD

Practical sampling

The reference points used in calibration, were collected in the field using the following procedure : each point of measurement J was taken as center of a circle of 5 meter diameter, inside which ten measurements of both EMC_V and EMC_H were taken at soil surface.

In the center of the circle, the soil was sampled with an auger at an increment of 20 cm, down to p cm depth. For each sample of soil, temperature was measured during sampling. Soil moisture was determined later on in laboratory. Integrated soil temperature and soil moisture were calculated for each point as :

$$T_{0-p} = p/20(T_{0-20} + T_{20-40} + \dots T_{(p-20)-p}) \quad (2)$$

$$\theta_{0-p} = 1/6(\theta_{0-20} + \theta_{20-40} + \dots \theta_{(p-20)-p}) \quad (3)$$

Soil apparent density was determined on a separate survey on three representative profiles in order to express data of soil moisture on volume basis. Soil salinity measured at random on ten profiles averaged 0.15 dSm^{-1} with a standard deviation of 0.03, justifying the assumption of absence of soil salinity.

The specific apparent electromagnetic conductivity of the soil material, free of water, but depending on temperature, was measured simultaneously above a rock of two cubic meters and values reported as : EMC_{Vj0} and EMC_{Hj0}. It was assumed that rock temperature was equal to soil temperature at a given time.

Apparent electromagnetic conductivity of each point J (mSm^{-1}) was reported as :

$$\sigma_V j = (1/10\Sigma\ EMC_{Vi}) + EMC_{Vj0} \quad (4)$$

for measurement in vertical mode, and :

$$\sigma_H j = (1/10\Sigma EMC_{Hi}) + EMC_{Hj0} \quad (5)$$

for measurement in horizontal mode mode. In both cases, i varies from 1 to 10.

Equations (4) and (5) mean that $\sigma_H j$ or $\sigma_V j$ are equal to global apparent conductivity of the moist soil alone plus the global apparent conductivity of the soil material (i.e the dry soil).

The second term of these equations includes temperature variation, which cannot be measured in moist soil, because moisture and temperature are not independent variables. According to fig.1, the relative contribution of a given volume of soil being different in horizontal mode and in vertical mode, $\sigma_V j$ is usually different from $\sigma_H j$.

Experimental site

An experimental site representative of mediterranean soil was selected in Lebanon, in the Beqaa valley, near Aamiq. The site is situated in the lower part of a fan at the foot of Jebel Barouk, southern part of the Lebanon Mountain. The upper part of the fan is stony and as the altitude decreases, the depth of soil increases from zero to several meters at the center of the Beqaa Valley. The sequence of the soils is : rendzin - fersiallitic lixiviated - fersiallitic hydromorphic, (Lamouroux, 1976). No soil deeper than 120 cm could be investigated because the water table.

Soils were sampled as described above during a six month period, starting just after the winter. Sampling was resumed in june, the soil becoming too dry to make hand-sampling with auger easy.

Calibration of soil moisture

Calibration was made bearing in mind two constraints :

Initially, in order to measure soil moisture variation over the widest range, it was necessary to make measurement from january to june. Over this period, average soil temperature varies from 10°C up to 25°C, meanwhile soil moisture, measured on volume basis, decreases from 0.39 (field capacity) down to 0.20 (permanent wilting point).

Secondly, in order to apply our results to soils of small catchments in which the depth of soils varies, two depth of soils were investigated : 60 cm and 120 cm. Two sets of 23 and 27 points were used to establish the regression equations:

$$\theta_{0-60} = f(\sigma_V j) \text{ and } \theta_{0-60} = f'(\sigma_H j) \quad (6)$$

and also:

$$\theta_{0-120} = f(\sigma_V j) \text{ and } \theta_{0-120} = f'(\sigma_H j) \quad (7)$$

which concern soils of 120 and 60 cm depth respectively.

Two other sets of six points were sampled at random in the field in order to check the accuracy of the method.

RESULTS AND DISCUSSION

Effect of soil moisture on global apparent conductivity

The following regressions equations were found. In these equations, DW, stands for Durban-Watson coeficient which must be greater than 1.4 and smaller than 2.0 for indicating an homogeneous distribution of residuals with a degree of freedom n = 23 :

$$\theta_{0\text{-}120} = 0.6 * \sigma_V + 8.9 \qquad r = 0.932 \qquad DW = 1.7 \tag{8}$$

$$\theta_{0\text{-}120} = 0.5 * \sigma_H + 14.7 \qquad r = 0.953 \qquad DW = 1.5 \tag{9}$$

$$_{0\text{-}120} = 0.21 * \sigma_V + 0.33 * \sigma_H + 12.26 \quad r = 0.912 \qquad DW = 1.4 \tag{10}$$

And, for shallow soils, with a degree of freedom n = 27 :

$$\theta_{0\text{-}60} = 0.74 * \sigma_V + 3.1 \qquad r = 0.821 \qquad DW = 1.0 \tag{11}$$

$$\theta_{0\text{-}60} = 0.58 * \sigma_H + 10.6 \qquad r = 0.880 \qquad DW = 1.4 \tag{12}$$

$$\theta_{0\text{-}60} = 0.41 * \sigma_V + 0.29 * \sigma_H + 5.8 \qquad r = 0.912 \qquad DW = 1.2 \tag{13}$$

The error ratio : [er = average of absolute residual)/(average θ)] of equation (8) to (13) was found in the range 0.05 ± 0.01.

Residuals were distributed stochastically in each case.

Estimation of soil moisture profiles

Soil moisture profile may be calculated as :

$$\rho_{\theta,d} = \theta_{d\text{-}120} / \theta_{0\text{-}d} \tag{14}$$

where d is a depth located around 50 cm, i.e. at half distance between soil surface and water table depth. $\rho_{\theta,d}$ represents the water dynamic in the soil. Just after the first rains $\rho_\theta < 1$, then when soil is at field capacity, $\rho_\theta \approx 1$, and later on, while drying either by evaporation or internal drainage, $\rho_\theta > 1$.

From fig.1 it can be inferred that $\rho_{\theta,d}$ varies as σ_v / σ_H because σ_H emphasis the contribution of the 0-50 cm layer of soil, while in the meantime, σ_V is equally influenced by the 0-50cm and the 50-∞ layers.

This assumption was checked on the 23 soil profiles collected for soil moisture calibration.

The regression $\rho_{\theta,d} = f(\theta_{d\text{-}120} / \theta_{0\text{-}d})$ was optimized. The best fit was achieved for p = 55 cm for which :

$$\rho_{\theta,55} = 0.36 \cdot \sigma_v / \sigma_H + 0.7 \qquad n = 23 \qquad r = 0.708 \tag{15}$$

Accuracy of the method

Multiple regression equations combining σ_v and σ_H were tested for each soil depth on the two sets of soils profiles. The error between estimated moisture (θ_{es}) and moisture measured in laboratory (θ_{me}) was calculated on six soil profiles randomly distributed on similar soils of the site :

$$er = | \theta_{es} - \theta_{me} | / \theta_{me} \tag{16}$$

The error for shallow soils (p=60 cm) was : er = 0.06 ± 0.02.

It was slightly greater for deeper soils (p=120 cm) : 0.08 ± 0.04.

APPLICATIONS

Evolution of global soil moisture

Global soil moisture of a 2.4 ha portion of the lower part of the fan was surveyed in march 2000, when the soil moisture was near the field capacity using a 10m x10m grid. The survey was repeated in june of the same year (fig.2). During this period, the maximum soil moisture decreased from 0.36 down to 0.16, value close to the permanent wilting point of these soils.

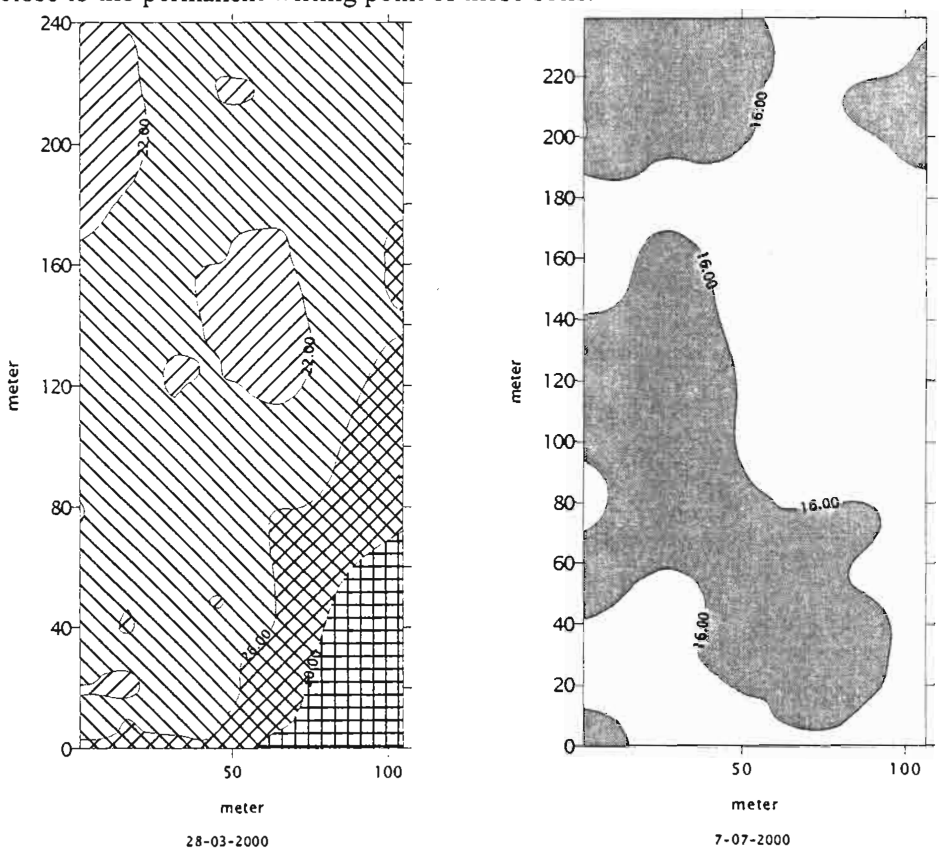

Fig.2- Evolution of global moisture of a red mediterranean soil of 120 cm depth, between march and june 2000. Isolines are reported as $100 \cdot \theta_{es}$ using equation (9).

Evolution of soil moisture profile

Soil moisture profiles were calculated on the same experimental plot, using the same field data set and calculating by equation (15). As shown figure 3 (left part), in march, just after the rainy season, soil moisutre is evenly distributed along the depth of the profile :

$\rho_{\theta,55} = \theta_{-55-120} / \theta_{00-55}$ lies between 1.0 and 1.1

After two month and a half of evaporation and internal drainage, soil moisture of the upper 55 cm decreased drastically. As a consequence, soil moisture below the first 55 cm of soil becomes 1.8 times greater than the soil moisture of the upper 55 cm (fig.3, right part). This is true at least for 60% of the volume of the plot. Within this area, no moisture is available any more for plants having a root system reaching only the first 55 cm of soil.

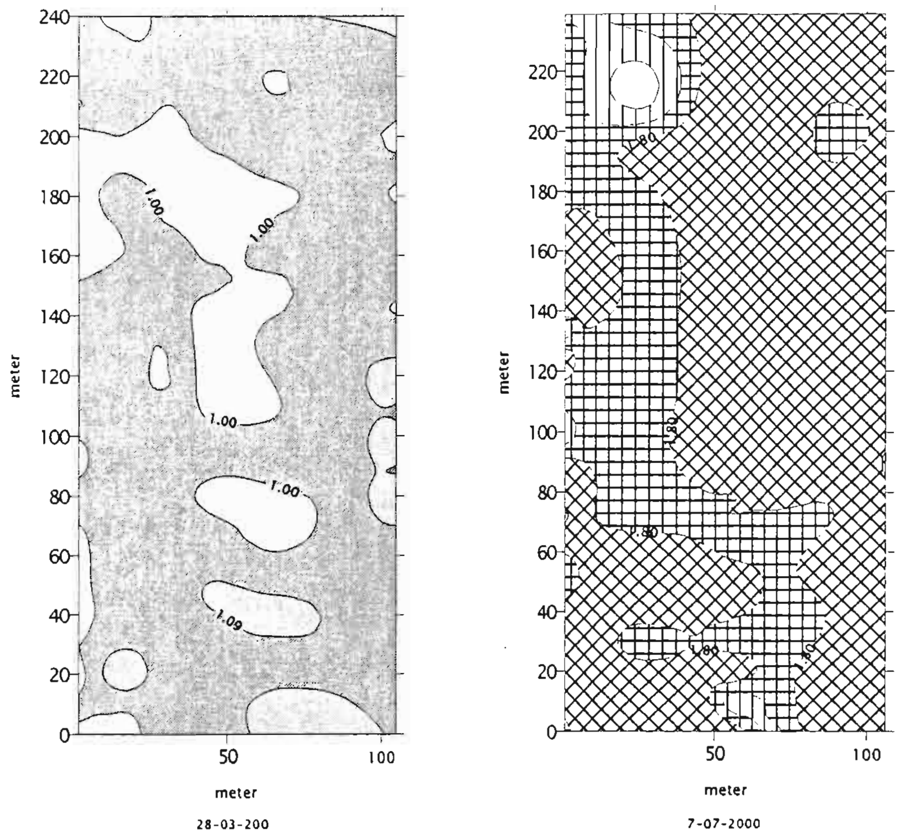

Fig.3- Evolution of soil moisture profile of a red mediterranean soil of 120 cm depth, between march and june 2000. Isolines are reported as $\rho\theta$,55 using equation (15). The part of the plot for which $\rho\theta,55 > 1.8$ is drawn with grey colour. At the top left part of the experimental plot in june the white part indicates part of the plot which has been disturbed.

CONCLUSIONS

We have demonstrated that electromagnetic induction can be used in precise evaluation of soil moisture for depth varying from 0 to 1.2 m. Monitoring in space and in time of the soil moisture of plots larger than 2 ha is possible providing a proper calibration of the soil response. The accuracy of the method is better than 8%.

Using the same data collected in the field, it is possible to give a spatial representation of a simplified soil moisture profile (ratio of soil moisture between 0 and 55 cm and 55-120 cm).

These two possibilities provide useful static and dynamic information on soil water at the scale of small wateshed. They open the way to field calibration of remote sensing radar data on one hand and on techniques of optimisation of water distribution in the soil in another hand. In dry farming areas, as well as in irrigated ones, it is also useful to follow the spatial and time variation of soil moisture profile which can be easily deduced from electromagnetic induction measurement.

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