Berichte Geol. B.-A., ***93***, *ISSN 1017-8880 – Applications in Hydrology*

Sensitivity and resolution of ERT for soil moisture monitoring in contour hedgerow intercropping systems: a methodological analysis

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Introduction

Contour hedgerow intercropping is a simultaneous agroforestry system which involves planting hedgerows along the contour lines of a slope at a distance of 4–6 m (TANG, 2000) and is extremely effective in controlling erosion on steep slopes (LAL, 1989; CRASWELL et al., 1997; MORGAN, 2004). However, sometimes a negative impact on crop response in the alley has been observed (AGUS et al., 1997; TURKELBOOM et al., 1997; DERCON et al., 2006) due to competition. To get a more detailed understanding of the competition for water, 2- or 3-D monitoring of the water fluxes in the soil-plant-atmosphere system is necessary. Electrical resistivity tomography (ERT) may be an appropriate tool for this. The measured apparent electrical resistivity depends amongst others on soil moisture content and soil water salinity (ARCHIE, 1942; WAXMAN et al., 1968; REVIL and GLOVER, 1998; LINDE et al., 2006; LALOY et al., 2011), temperature, and in some cases on root biomass (AMATO et al., 2008; ZENONE et al., 2008; AMATO et al., 2009; AL HAGREY and PETERSEN, 2011). Changes of these variables with time, such as soil moisture changes, can thus be followed performing resistivity measurements at several times provided a good calibration relationship between electrical resistivity and the variable under consideration. In this work, we present a methodology to design an experimental ERT survey for soil moisture monitoring in the field, looking at the specific characteristics of the system under consideration and the research questions posed. The objectives are to (i) generate realistic soil moisture distributions and resulting resistivity as can be expected under a monocropping and intercropping systems, (ii) analyze the performance of different measurement arrays using measures looking at spatial variability and classical geophysical measures like e.g. recovery, coverage and resolution radius; and (iii) identify an optimal survey design to capture the generated patterns with ERT during a growing season.

Material and methods

General approach

The following approach was adopted to identify the optimal ERT survey design for studying water fluxes under two different agricultural systems. Firstly, a hydrological model is created approaching the soil, relief and climate conditions at a field site near Suan Phung, Ratchaburi

Province, Thailand. Two cases are simulated: a field plot with only maize and one with contour hedgerow intercropping with *Leucaena leucocephala L*. After a spin-up period of 30 days, the model was run for 130 days starting from maize sowing. Secondly, a pedo-physical relationship was used to convert the water content distribution of a few characteristic timeframes to a resistivity distribution. Thirdly, virtual ERT measurements were conducted by forward modeling using different measurement configurations and the simulated 2-D distribution of resistivities.
The data were inverted and the resolution and sensitivity matrix were analysed. Finally, we compared the original resistivity distributions with the inverted ones in order to obtain the model recovery. Measures for spatial variability as well as the resolution matrix, sensitivity matrix and model recovery were then used to judge the performance of the measurement arrays.

Hydrological model

The hydrological model was set up using a modified version of Hydrus2D/3D (ŠIMŮNEK et al., 1996), which allows modeling of root water uptake by two different crops simultaneously. The simulations were run on a soil cross section of 13 m length and 3 m depth with an inclination of 15%. Two cases were simulated: maize monocropping and contour hedgerow intercropping with rows of *Leucaena leucocephala*, maize and bare soil strips accounting for a few chili plants with low soil coverage. Figure 1 gives an overview of the model for the intercropping case. The soil consists of three horizons: Ap (loam), B (sandy-clay-loam) and C (clay loam) (CARSEL and PARRISH, 1988). We used the Van Genuchten model (VAN GENUCHTEN, 1980) for the hydraulic behavior of the soil and the Feddes model (FEDDES et al., 1978) for the root water uptake. Rainfall and potential reference evapotranspiration were taken from an on-site weather station for the growing season of 2009. The reference evapotranspiration for a grass reference surface was calculated for hourly time intervals using the Penman-Monteith equation (ALLEN et al., 1998) and then used to calculate the crop evapotranspiration rates. We selected three distinct timeframes of the growing season (0, 60 and 108 days after sowing) for the further analysis.

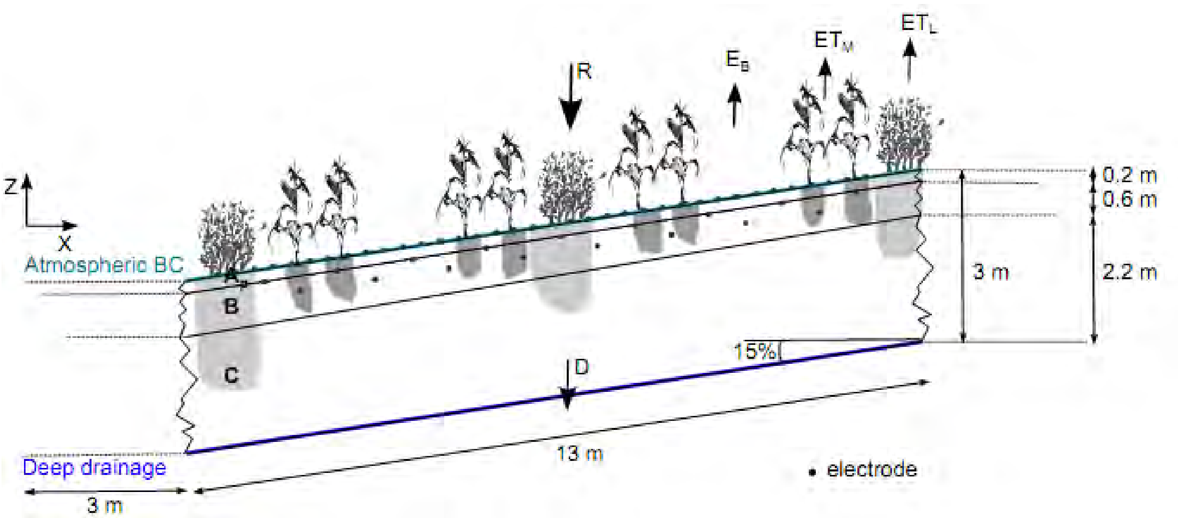

Fig. 1: Hydrological model set-up with top and bottom boundary conditions (BC) for a field plot with contour hedgerow intercropping with Leucaena, maize and bare soil strips. Three soil horizons are indicated on the scheme: Ap (0-0.2m), B (0.2-0.8m),C (0.8-3m). Symbols: ETM: evapotranspiration of maize rows, ETL: evapotranspiration of leucena strips, EB: evaporation from bare soil strip, R: rainfall, D: drainage.

Pedo-physical model

The water content of the selected timeframes was converted to a conductivity (EC) distribution using one single pedo-physical relationship for all horizons. We used the parameters of the pedo-physical model of the Bv1 horizon of GARRÉ et al. (2011) for a silty soil located in Merzenhausen, Germany. The pedophysical model is given by:

$EC = a.WC^n + b$,

with *EC* the bulk electrical conductivity (*ρ=1/EC*), *WC* the volumetric water content and *a,b,n* fitting parameters. The parameters used for our pedo-physical model are *a* = 1.20495 $S.m^{-1}$, *b* = 0.0001 $S.m^{-1}$, *n* = 3.4314.

Experimental design

The main water fluxes in the soil on a steep slope with crop rows following the contour lines are expected to be vertical, due to evapotranspiration, and along the slope, due to subsurface flow. A plane of surface and subsurface electrodes along the slope, generating a 2-D image of the subsurface along the slope, should be sufficient to capture these fluxes. On the subsurface, 36 electrodes are placed 0.33 m apart. At 0.25 and 0.50 m depth, nine electrodes were placed at each depth level with a horizontal separation of 1.32 m. Four classical measurement configurations were selected based on their distinct sensitivity distributions (Loke et al., 1996): the Wenner-array, the dipole-dipole array, the pole-dipole array and a combination of the dipole-dipole and the Wenner array. For each array, we considered data sets using only surface electrodes and datasets including also subsurface electrodes in order to assess the increase in data information due to deeper electrodes.

We conducted a smoothness-constrained inversion as in GÜNTHER et al. (2006) independently for each of the three timesteps. Several measures can be used to assess the quality of the information obtained by inversion of the measurements produced by a certain electrode array. We calculated the cumulative sensitivity (e.g. FURMAN et al., 2003; GÜNTHER, 2004), the resolution radius (FRIEDEL, 2003) and the model recovery (results not shown here). In hydrological studies, the main interest is often to capture the spatial patterns which are present in the soil moisture distribution. In order to test the performance of the different arrays to capture this spatial variability, we defined two criteria: an adjusted coefficient of determination (THEIL, 1971; p. 164, p. 175-178) and the spatial correlation using a semivariogram for each of the tested arrays.

Results

1-D water content

Figure 2 shows the 1-D water content (WC) profiles for the mono- and intercropping case at t = 0, 60 and 108 days for a profile of 2m width and 3 m depth in the middle of the simulated domain. In general, ERT predicts the 1-D profiles well. However, in the areas of sudden resistivity contrasts, the inverted profiles look smoothened and do not follow the jumps. ERT is also capable of measuring the differences between the mono- and the intercropping case. The different arrays give way to similar 1-D profiles, whereas in most cases, the combination of dipole-dipole and Wenner and the pure dipole-dipole measurements are closest to the model curve. As for the 1D profiles, there is no systematic difference between the arrays with deeper electrodes (All) and those with only surface electrodes (OS), although below -2m, many of the OS arrays end up further from the model profile than the All arrays.

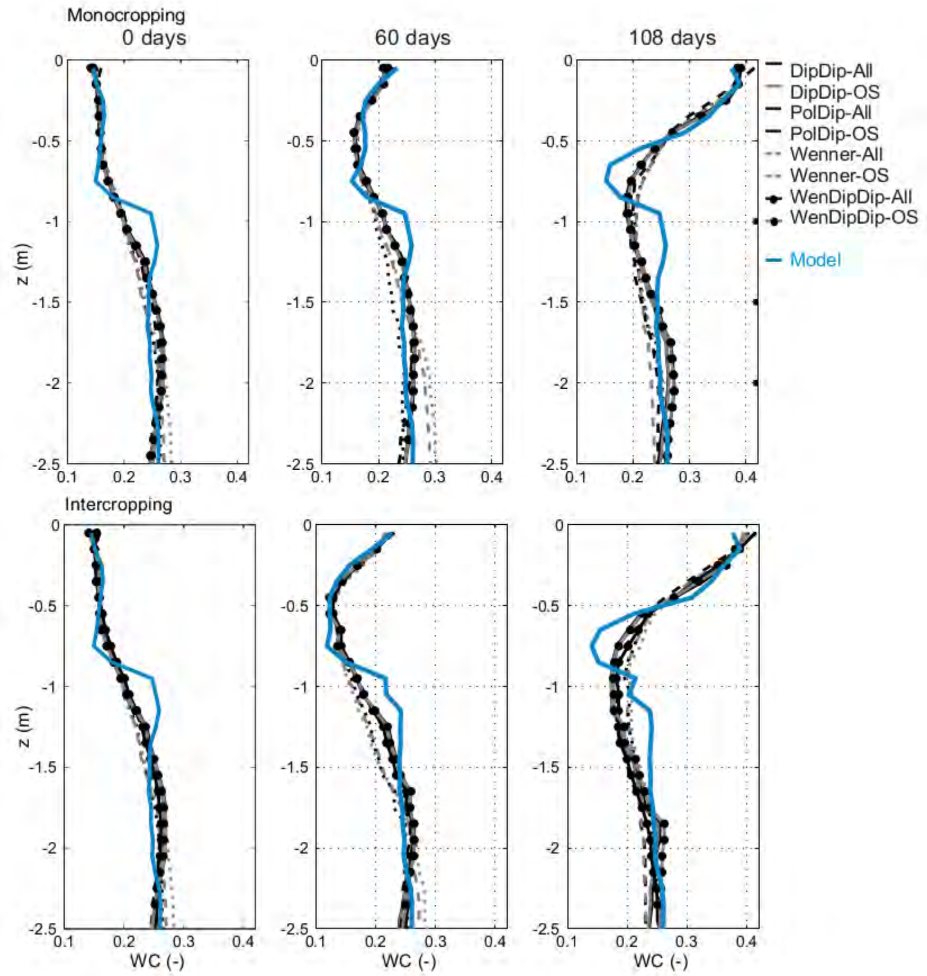

Fig. 2: 1-D water content profiles for the mono- and intercropping case at t= 0, 60 and 108 days for a profile of 2m width and 3 m depth in the middle of the simulated domain. The simulated values are represented by the thick, blue line. DipDip = dipole-dipole, PolDip = pole-dipole, WenDipDip = combination of Wenner & Dipole-dipole. Electrode arrays using only surface electrodes are marked by OS.

Spatial variability

Generally, the spatial variability of the inversion results is lower than the one of the synthetic model. All arrays capture a high variability between 0 and -1m and a decreased variability beneath 2m. For z < -1.75 m, the standard deviation was underestimated by almost all arrays. Using the WenDipDip array, the variability in 0-0.10 m was higher for the inverted WC than for the original model.

To calculate the adjusted coefficient of determination (R^2) for each electrode array under consideration, for each of the three times and for the mono- and the intercropping case, we excluded all mesh cells with a normalized coverage (log10) smaller than 0.8 from the computation. The dipole-dipole array and the combination of Wenner and dipole-dipole measurements give the best result in almost all cases and times. The pure Wenner array is inferior to the others except for the last timestep. The additional use of deep electrodes improves the result most of the time (data not shown).

Another way to look at spatial variability is the semivariogram. As we know from the previous measures that the highest spatial variability is present between 0 and -1 m depth, we used only this part of the soil region to compute the semivariogram. Figure 3 shows the semivariograms for both the mono- and the intercropping case at t = 60 days using 70 lag distances of 0.1 m. In the monocropping case a clear periodicity can be seen in the model semivariogram, caused by the presence of maize plant roots at regular intervals of about 0.75 m. A similar, but more complex pattern represents the intercropping case. As the simulation contains not only maize, but also a Leucaena root zone and pieces of bare soil, the effects of different structures are visible. E.g. the distance between two Leucaena hedges is visible in the semivariogram (6 m). All electrode arrays produce a similar, but smoothened or flattened semivariogram. The sill of the inverted semivariograms, which is the limit of the semivariogram tending to infinity lag distances, is lower than the modeled one. The combination of Wenner and dipole-dipole arrays gives the best result. The Wenner array has the most difficulties to reproduce the spatial structure of both cases, which emerges from the very small amplitude of the periodicity in the semivariogram.

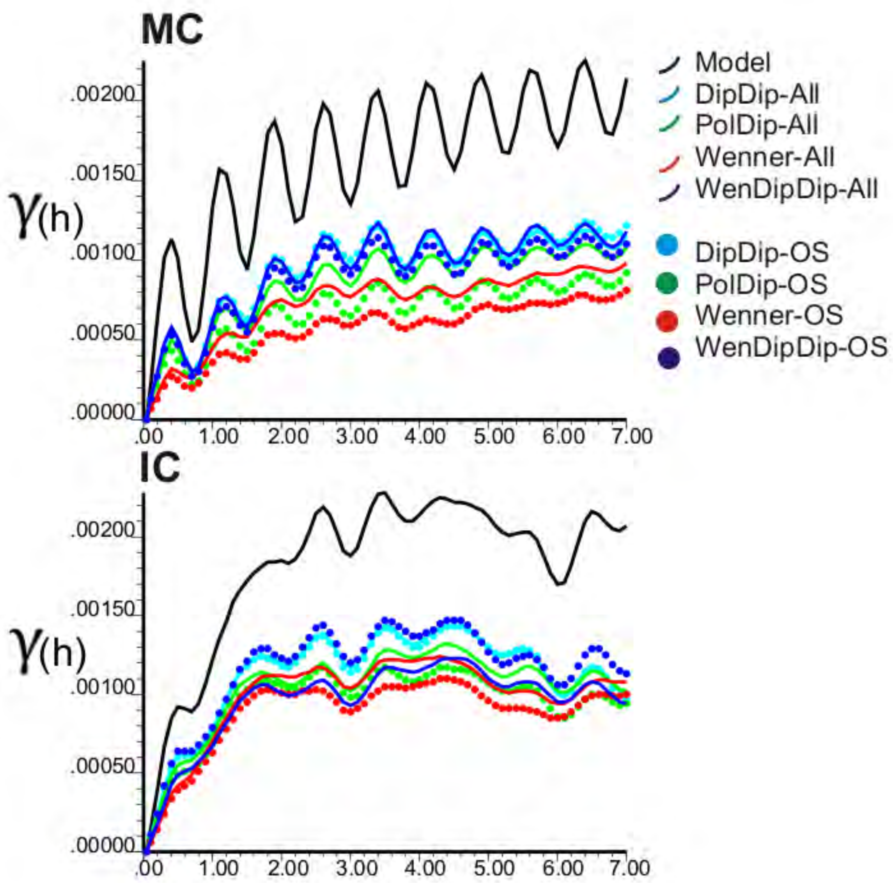

Fig. 3: Semivariograms of the water content (WC) of the synthetic and the inverted WC for the monocropping (MC) and intercropping (IC) case.

Conclusions

The general course of the 1-D WC profiles was well reproduced by the different ERT measurements. The largest deviations occurred where sharp jumps in water content occurred (boundary between two soil horizons, infiltration fronts, etc.). The resulting contrasts pose an extra difficulty for smoothness-constrained inversion of the resistivity data. All electrode arrays produce similar results in terms of 1-D profiles. The extent of the spatial variability is generally a little bit underestimated and smoothened by the ERT inversion, but the spatial structures remain present. The spatial variability is best reproduced by an array combining Wenner and dipole-

dipole quadrupoles, probably since it combines the resolving power for horizontal structures of the Wenner array with the resolving power for vertical structures of the dipole-dipole array. The standard deviations and consequently the sill of the semivariogram were underestimated more strongly by the Wenner and the pole-dipole array than by the others. We can conclude that ERT can be used to observe effects of cropping systems on soil moisture distribution. A major disadvantage of the classical smoothness-constrained inversion is the fact that sharp resistivity transitions are not well reproduced. The virtual measurements showed that it is possible to retrieve differences between 2 cropping systems on the same soil and under the same climatic conditions. Under wetter conditions, it might be difficult to distinguish single root water uptake regions below the rows by observing the spatial distribution of the data. Here, the use of a semivariogram might be the line to take, since it will reveal spatial structures which are not always clearly visible by the bare eye.

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