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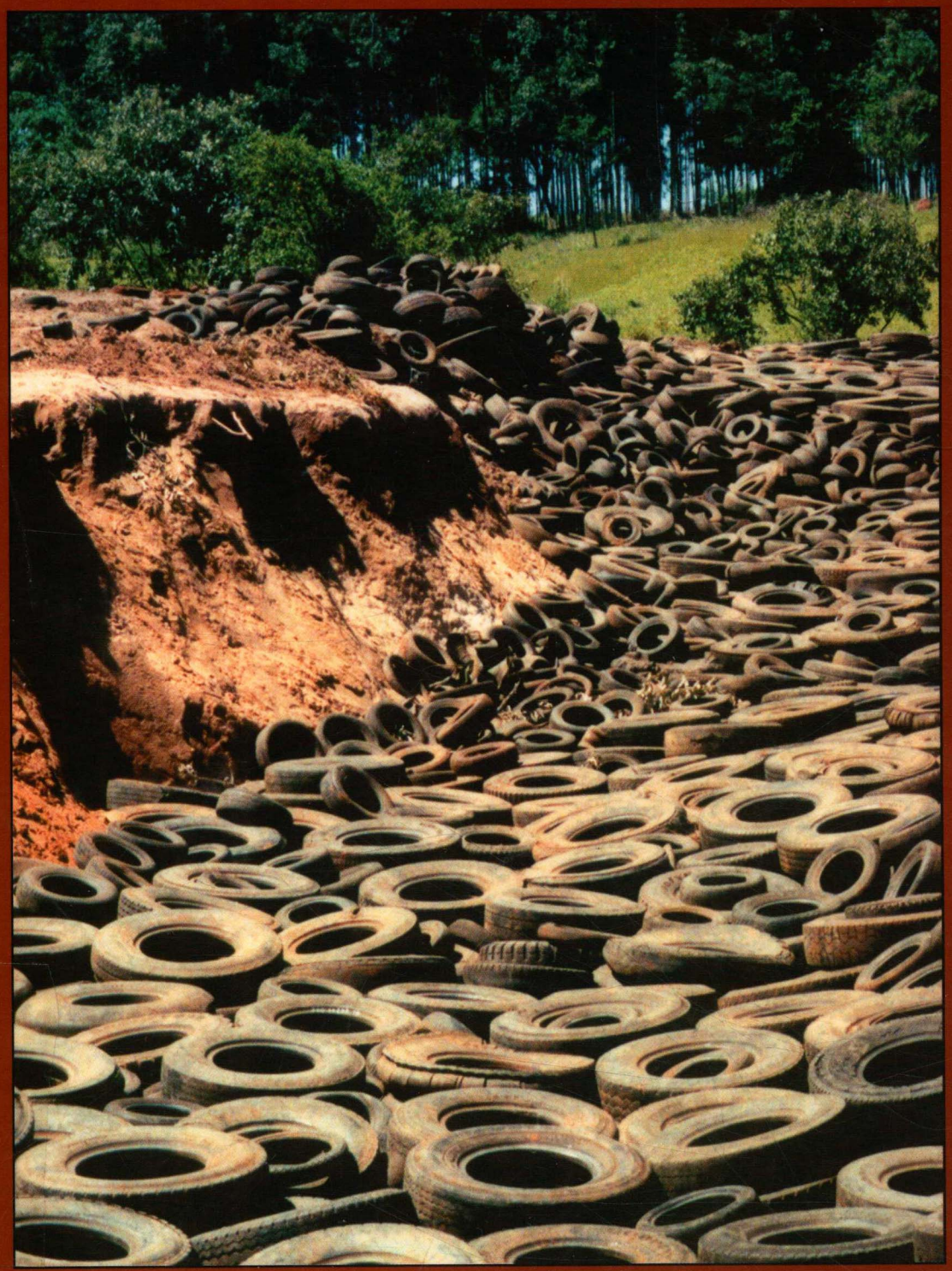

Vol. 65 No. 5 September–October 2001 SSSJD4 65(5):1351–1576 (2001)

Land Application of Agricultural, Industrial, and Municipal By-Products

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Land Application of Agricultural, Industrial, and Municipal By-Products. James F. Powers and Warren P. Dick, editors. Published by the Soil Science Society of America. Number 6 in the Soil Science Society of America Book Series. Hardcover, 653 pages, 2000. ISBN 0-89118-834-7. Price: $55.00 (members first copy $45.00). **Item No. 60901.**

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ASA Special Publication Number 63

El Niño impacts on agriculture, while typically negative, may be positive in some areas. Agricultural impacts are generally strongest in the Southern Hemisphere. In some large countries, such as Brazil and the USA, national crop yields reflect little El Niño influence, because opposite responses in different regions tend to cancel each other out.

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Impacts of El Niño and Climate Variability on Agriculture. Cynthia Rosenzweig, editor. Published by the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. ASA Special Publication Number 63. Softcover, 126 pages, 2001. ISBN 0-89118-148-2. Price: $36.00 ($30.00 members first copy). **Item No. 40325.**

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In general, four manuscript pages will equal one printed page. For space economy, Materials and Methods, long Literature Reviews, theory, soil or site descriptions, etc., footnotes, tables, figure captions, and references are set in small type. Each table and figure will usually take 1/4 of a printed page.

For tabular matter, 9 lines of typewritten matter equal 1 column-inch of type. Allow also for rules and spacing. Tables with more than 35 units (including space between words) in a horizontal line can rarely be set 1 page-column wide.

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July 2000

SSSAJ September–October 2001 Vol. 65, No. 5

Soil Science Society of America Journal

Continued on page iv

This issue's cover: Rehabilitation of a large gully erosion in Piracicaba (Brazil). Wornout tires were placed at the bottom of the gully, which are then covered with soil and reforested. The advantages of this method are an adequate destination of this waste material and a lower cost if compared with burning in special facilities or disposal in landfills. It also helps to avoid inappropriate destinations such as open air burning to recover the steel wire and open air storage which helps to develop mosquito larvae. Some mosquito species such as *Aedes aegypti* that develop extremely well in the clean water accumulated in the tires are vectors of tropical epidemic disease (Dengue Fever). Additionally, less soil is needed to fill up the gully and drainage is improved in relation to the conventional method where only soil material is used to level the area. A complete description of this method of gully erosion rehabilitation may be found in: Sparovek, G., S. Hornink, and E. Schnug. 2001. A solution for wornout tires, gully erosions, forests and dengue fever. FAL Agricultural Research. volume 51, issue 3/4 or under http://www.pb.fal.de/en/.

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SOIL SCIENCE SOCIETY OF AMERICA
JOURNAL

VOL. 65 SEPTEMBER–OCTOBER 2001 No. 5

DIVISION S-1—SOIL PHYSICS

Time Domain Reflectometry Sensitivity to Lateral Variations in Bulk Soil Electrical Conductivity

H. H. Nissen,* P. Moldrup, T. Olesen, and O. K. Jensen

ABSTRACT

It has been assumed, but not proved, that the spatial weighting and sample volume of Time domain reflectometry (TDR) regarding bulk soil electrical conductivity (EC_b) equal those determined for the relative dielectric permittivity (K). In this study, two types of experiments were carried out: (i) sensitivity experiments where the cumulative vertical weighting as a function of distance between the probe rods and the soil surface were determined for both K and EC_b at two different soil water contents and (ii) solute diffusion experiments to evaluate the discrepancies between actual and TDR-measured relative EC_b in the case where a steep gradient in EC_b passes the probe. Three-rod TDR probes and a sandy loam soil were used in both experiments. The sensitivity experiments confirmed that TDR weights K and EC_b equally in the transverse plane. Hence, previously established relationships to calculate the weighting function and sample area of a given TDR-probe geometry apply for both K and EC_b. The diffusion experiments showed that if a steep vertical solute gradient passes a horizontally inserted TDR probe, the TDR-measured EC_b profile will be more spread than the actual profile passing the probe. This phenomenon of artificial (TDR-induced) diffusion is caused by (i) TDR probes not representing a point measurement, and (ii) the nonlinear weighting of K and EC_b in the transverse plane. As the steepness of the solute concentration profile diminishes the TDR-induced diffusion decreases rapidly and becomes negligible for most applications. The effect of TDR-probe geometry on the discrepancy between actual and TDR-measured relative concentration was examined theoretically for selected two- and three-rod probe configurations.

THE SAMPLE VOLUME is an important property of all measurement techniques applied to quantify a property of a medium per unit of volume. In addition, if the property of interest is unevenly distributed within the sample volume of the instrument, it is necessary to gain knowledge of the weighting function of the instrument, as well as the spatial distribution of the property in order to interpret the measurements correctly. Time domain reflectometry is a widely used nondestructive method for measuring both volumetric soil water content (θ) and EC_b in the field as well as in the laboratory. Therefore, it is important to determine the spatial sensitivity of the TDR method to soil properties.

Several studies have shown both theoretically (Ferré et al., 1996) and experimentally (Topp et al., 1982; Nadler et al., 1991) that TDR measures the length-weighted average apparent relative dielectric permittivity (K_a) if the relative dielectric permittivity (K) only varies along the probe rods. Annan (1977a,b), however, was the first to recognize the potential problem of the uneven weighting of K in the plane perpendicular to the long axis of the TDR probe rods and presented an analytical description of the effect of air- and water-filled gaps at the inner and outer conductor of a coaxial cell (Annan, 1977a) and around the probe rods of a two-rod balanced TDR probe (Annan, 1977b). He concluded that even small air- or water-filled gaps at the surface of the waveguide have a significant influence on the TDR-measured K_a in soil.

Knight (1992) conducted an analytical investigation of the spatial sensitivity of the coaxial cell and the two-rod balanced probe positioned in media of uniform or

H.H. Nissen, P. Moldrup, and T. Olesen, Dep. of Environmental Engineering, Aalborg Univ., Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark. O.K. Jensen, Dep. of Communication Technology, Aalborg Univ., Fredrik Bajersvej 7, DK-9000 Aalborg, Denmark. Received 4 Jan. 2000. *Corresponding author (i5hn@civil.auc.dk).

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Abbreviations: DC, direct current; D_p, solute diffusion coefficient; EC, relative electrical conductivity; EC_b, bulk soil electical conductivity; EM, electromagnetic; h, height; $G(x, y)$, relative sensitivity function; K_a, apparent relative dielectric permittivity; K, relative dielectric permittivity; TDR, time domain reflectometry; $W(h, B, D)$, cumulative vertical weighting function; $w(x, y)$, spatial weighting function; $w(y)$, vertical weighting function; ΔRelative EC_b, TDR-measured relative EC_b distrubution; θ, volumetric soil water content; ρ, the dimensionless radius.

close to uniform K, and derived analytical expressions for the spatial weighting function [$w(x, y)$] and relative sensitivity function [$G(x, y)$] in the plane perpendicular to the long axis of the probe rods. These functions proved that TDR weights the dielectric within the sample volume nonlinearly in the plane perpendicular to the long axis of the probe rods with local maximums at the surface of the rods. Knight (1992) also showed that $w(x, y)$ is proportional to the spatial energy density distribution of the electrostatic field and is also independent of the level but depends on the shape of nonuniformly distributed K in the plane perpendicular to the long axis of the probe rods. Hence, the sample volume of TDR is independent of θ if θ is homogeneously distributed in the soil.

Knight et al. (1994) derived a relative sensitivity function for the general case of a $N + 1$ rod probe ($N \geq 2$) showing that the energy and hence the weighting of three-rod probes is much more concentrated in the region close to the probe rods compared with two-rod probes of similar dimensions. By integrating $w(x, y)$ for the two-rod probe over the plane perpendicular to the long axis of the probe rods bounded by a surface at height (h) parallel to the probe axis passing the center of both probe rods, Knight et al. (1994) derived an expression to calculate the relative cumulative vertical energy distribution below a surface at h. The expression is referred to in this study as the cumulative vertical weighting function [W(h, B, D)] where B is the rod diameter and D is the rod spacing. This expression is very useful to estimate the necessary minimum distance to the soil surface if two-rod TDR probes are inserted horizontally close to the soil surface.

Petersen et al. (1995) carried out an empirical investigation of W(h, B, D) by gradually decreasing h above various two-rod TDR probes (different B and D). Although the theoretical expression for W(h, B, D) does not account for the effect of the steep gradient in K at the interface between air and soil, Petersen et al. (1995) showed an excellent agreement between experimentally obtained relative soil water contents and W(h, B, D) by Knight et al. (1994).

Recently, Knight et al. (1997) presented a numerical analysis enabling them to calculate $w(x, y)$ for any TDR-probe configuration regardless of the spatial K distribution. Hereby one of the big hurdles in TDR-probe design has been resolved. Using the numerical approach, Ferré et al. (1998) calculated the sample area of the majority of the TDR-probe designs used within soil science.

All the quoted studies have focused on the spatial weighting of K or on the effect on TDR-measured K_a if K varies in the plane perpendicular to the long axis of the probe rods. However, the spatial weighting and the effect of spatially variable electrical conductivity (EC) on TDR-measured EC_b is an unresolved problem. In numerous solute transport studies using TDR, it has been assumed that the spatial weighting of EC equals the weighting of K, although no actual proof has been provided. In the same studies, the TDR-measured breakthrough curves have subsequently been interpreted without paying attention to the spatial weighting of the solute within the sample volume of the probe. The objectives of this study were (i) to experimentally investigate if TDR weights K and EC equally in the plane perpendicular to the long axis of the probe rods and (ii) experimentally investigate the suitability of TDR to measure sharp gradients in EC.

THEORY

To investigate the spatial sensitivity of TDR in two dimensions, Baker and Lascano (1989) conducted a laboratory experiment in which they changed the spatial distribution of K by placing an array of water-filled glass tubes in the plane perpendicular to the long axis of the probe rods and subsequently removed one or several of the tubes. However, to measure the EC, the probe rods need to be in direct contact with the medium of interest. Thus, a simultaneous study of the spatial sensitivity of TDR towards EC and K in two dimensions calls for an electrical conductive media with a constant EC and K that can be removed in small sections in an array type pattern. In practice, it is difficult if not impossible to remove small cylinders of material parallel to the probe axis with the accuracy required to obtain a detailed description of both sensitivities. Therefore, we assume that it is possible to integrate the sensitivities over one of the axes in the plane perpendicular to the long axis of the probe rods, thereby reducing the sensitivity to a function of a single direction. We have decided to compare the integrated sensitivities as a function of a single direction as represented by the aggregate TDR-measured EC or K in order to reduce the complexity of the experiments. Therefore, if the integrated sensitivities are equal, then the hypothesis regarding the equality between the EC and K sensitivities is correct, given that it is very unlikely that two different sensitivity distributions have the same integrated values over a given direction because of the complex nature of the distribution.

Consider a TDR probe inserted with all rods in a horizontal plane close to the soil surface. A part of the sample area perpendicular to the long axis of the probe rods is above the soil surface (in the air) and another part is below (in the soil). Both air and soil contribute to the TDR-measured K_a which can be described as (Knight, 1992),

$$K_a = \iint_\Omega K(x, y) w(x, y) \mathrm{d}A \qquad [1]$$

where Ω is the region surrounding the probe, $\mathrm{d}A$ is an element of area in Ω, $K(x, y)$ is the spatial distribution of K within Ω, and $w(x, y)$ is the spatial weighting function, depending on $K(x, y)$ and defined as (Knight, 1992),

$$w(x, y) = \frac{|\nabla \Phi|^2}{\iint_\Omega |\nabla \Phi_0|^2 \mathrm{d}A} \qquad [2]$$

where $\nabla \Phi_0$ and $\nabla \Phi$ is the gradient in electrostatic potential corresponding to a homogenous and heterogenous K distribution, respectively. In the case of the horizontally inserted TDR probe, the x-axis passes the origin of the TDR-probe rods and is parallel to the soil surface. By assuming that K is homogeneously distributed in both soil and air, K reduces to a function of y. If the soil surface is positioned at $y = h$, Eq. [1] can be written as,

$$K_a = K_{soil} \int_{-\infty}^{h} \int_{-\infty}^{\infty} w(x, y) \mathrm{d}A + K_{air} \int_{h}^{\infty} \int_{-\infty}^{\infty} w(x, y) \mathrm{d}A \qquad [3]$$

where K_{soil} and K_{air} are the apparent relative dielectric permittivities of soil and air. Since $w(x, y)$ has total integral unity

(Knight, 1992), Eq. [3] can be written as,

$$K_a = K_{soil} \int_{-\infty}^{h} \int_{-\infty}^{\infty} w(x, y)\mathrm{d}A + K_{air}\left(1 - \int_{-\infty}^{h} \int_{-\infty}^{\infty} w(x, y)\mathrm{d}A\right) \quad [4]$$

Rearranging Eq. [4] and solving for the cumulative vertical weighting function gives,

$$\int_{-\infty}^{h} \int_{-\infty}^{\infty} w(x, y)\mathrm{d}A = \frac{K_a - K_{air}}{K_{soil} - K_{air}} \quad [5]$$

Thus, by changing h from ∞ to 0 and simultaneously measure K_a enables us to experimentally determine the cumulative vertical weighting of soil and air as a function of h, hereafter labeled $W(h)$.

Now consider the soil as a conductive media separating the TDR-probe rods of the horizontally inserted TDR probe. According to Ohm's First Law, the magnitude of a current (U) is given as the ratio between the gradient in the electrostatic potential and the resistance (R). By multiplying this expression by the ratio of the surface area (A^*) to the length (L) of the body through which the current flows an expression for the flux density of charges per unit length (J) is obtained. Written for two dimensions the expression for J yields,

$$J(x, y) = \mathrm{EC}(x, y)\nabla\Phi(x, y) \quad [6]$$

where $J(x, y)$ equals $(L/A^*)U(x, y)$ and $\mathrm{EC}(x, y)$ equals $(L/A^*)R(x, y)^{-1}$. In an electrically conductive medium the magnitude of the charge flux density is proportional to the energy loss of the electromagnetic (EM) waves because of direct current (DC) conductance. So the contribution to the loss in energy of the EM waves arising from the conductivity at point (x, y) is weighted by the gradient in the static voltage distribution at the same point.

Equation [6] is analogous to the expression for the electric flux density (D) of the electrostatic field,

$$D(x, y) = K(x, y)\nabla\Phi(x, y) \quad [7]$$

where the relative dielectric permittivity $[K(x, y)]$ can be conceptualized as the ability of the media in point (x, y) to conduct electrostatic potential. It should be pointed out that $\Phi(x, y)$ is a function of $K(x, y)$, which again is a function of $\mathrm{EC}(x, y)$. However, $K(x, y)$ and hence $\Phi(x, y)$ is almost independent of $\mathrm{EC}(x, y)$ at the frequencies where K is measured by TDR. Therefore, the distribution of $\Phi(x, y)$ generally depends on the waveguide geometry (the TDR-probe rods) and the distribution of $K(x, y)$ in the region perpendicular to the long axis of the waveguide.

In conclusion, the driving force of both the charge flux density and the electric flux density is the gradient in the electrostatic potential $[\Phi(x, y)]$. Since the distribution of $\Phi(x, y)$ determines the weight by which a given K within the sample area contributes to K_a it seems reasonable to assume that this also applies for EC. The TDR-measured $\mathrm{EC_b}$ can then be described as,

$$\mathrm{EC_b} = \iint_{\Omega} \mathrm{EC}(x, y)w(x, y)\mathrm{d}A \quad [8]$$

where $w(x, y)$ is given by Eq. [2].

Now, consider the horizontally inserted TDR probe at distance h below the soil surface. By assuming a uniform EC distribution in both soil ($\mathrm{EC_{soil}}$) and air ($\mathrm{EC_{air}}$), it is possible to derive an expression for the cumulative vertical weighting function in the exact same way as was done for K,

$$\int_{-\infty}^{h} \int_{-\infty}^{\infty} w(x, y)\mathrm{d}A = \frac{\mathrm{EC_b} - \mathrm{EC_{air}}}{\mathrm{EC_{soil}} - \mathrm{EC_{air}}} \quad [9]$$

Since $\mathrm{EC_{air}}$ is ~0, Eq. [9] reduces to

$$\int_{-\infty}^{h} \int_{-\infty}^{\infty} w(x, y)\mathrm{d}A = \frac{\mathrm{EC_b}}{\mathrm{EC_{soil}}} \quad [10]$$

Thus, changing h from ∞ to 0 and simultaneously measuring $\mathrm{EC_b}$ in a medium where $\mathrm{EC_b}$ is homogeneously distributed enables us to determine experimentally the cumulative vertical weighting of soil and air as a function of h.

Three-rod TDR probes are known to have a smaller sample area in the plane perpendicular to the long axis of the probe rods compared with two-rod probes of equal rod thickness and spacing (Ferré et al., 1998). Therefore, a three-rod probe was chosen for the experiments in this study to enable the use of relatively small soil columns and hence make the experiments less labor intensive and time consuming. The chosen probe design is shown in Fig. 1a. It is specially designed for use in combination with circular (0.1 m o.d.) metal cylinders containing either repacked or undisturbed soil.

A functional description of the vertical weighting function $[w(y)]$ for the three-rod probe is needed to evaluate the impact on TDR-measured $\mathrm{EC_b}$ of the expected heterogeneous weighting of $\mathrm{EC}(x, y)$ in the plane perpendicular to the long axis of the probe rods in the case where a steep vertical gradient in EC (varying in the y-direction only) is passing a horizontally inserted three-rod TDR probe (probe rods positioned at $y = 0$). Hence, to calculate the resulting TDR-measured $\mathrm{EC_b}$, the $w(y)$ of the given TDR probe must be known. As stated above, $w(y)$ depends on $K(x, y)$ which is a weak function of $\mathrm{EC}(x, y)$. That is, an expression for $w(y)$ derived under the assumption of a homogenous $K(x, y)$ distribution is expected to be a good approximation for $w(y)$ if $\mathrm{EC}(y)$ is the only variable (constant θ). Whereas an analytical expression for the spatial weighting function (Eq. [2]) exists for two-rod TDR probes in the case of a homogenous $K(x, y)$ distribution, an equivalent expression has unfortunately never been derived for three-rod probes. Instead an empirical expression was derived which can be fitted to an experimentally determined $w(y)$ for the three-rod probe shown in Fig. 1a. The derivation of the empirical $w(y)$ expression is based on a homogenous $K(x, y)$ distribution assumption.

Knight et al. (1994) presented a relative spatial sensitivity function in polar form for the $N + 1$ rod probe,

$$G_N(\rho,\varphi) \approx \frac{1}{\rho^2[1 - 2\rho^{2N}\cos 2N\varphi + \rho^{4N}]} \quad [11]$$

where φ is the angle and ρ is the dimensionless radius given by (r/d), where r is the actual radius and d is the distance between the centre rod and one of the surrounding grounded rods. Inserting $N = 2$ (three-rod probe) into Eq. [11] and transforming to Cartesian coordinates yields,

$$G_2(X, Y) \approx \frac{1}{(X^2 + Y^2)[1 - 2(X^2 + Y^2)^2\cos(4\tan^{-1}(Y/X)) + (X^2 + Y^2)^4]} \quad [12]$$

where $X = x/d$ and $Y = y/d$. The number 4 in the cos4 term determines the number of grounded wires surrounding the center conductor; i.e., the cos2N term in Eq. [11] is in error (J. Knight, personal communication, 2000). Hence, the relative spatial sensitivity function for a three-rod probe is given by,

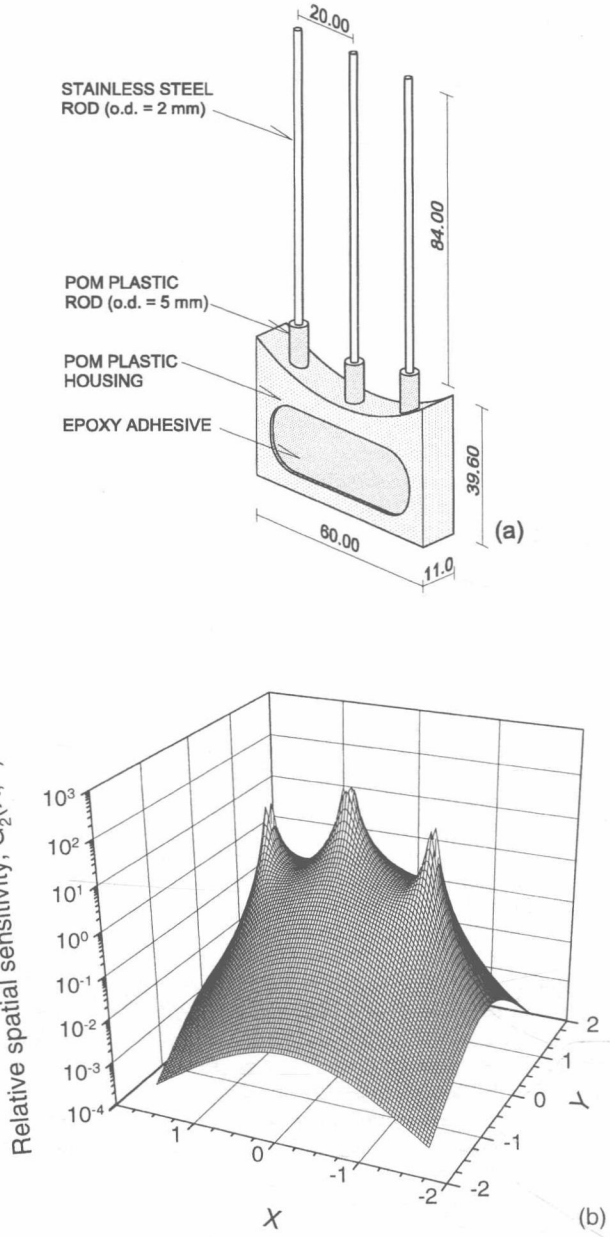

Fig. 1. Illustration of (a) the three-rod probe used in this study (all measures are in millimeters) and (b) the relative spatial sensitivity function [$G_2(X, Y)$] as a function of the dimensionless coordinates X and Y in the plane perpendicular to the long axis of the TDR probe rods of a three-rod TDR probe. Note the logarithmic scaling on the relative spatial sensitivity axis.

$$G_2(X, Y) \approx \frac{1}{(X^2 + Y^2)[1 - 2(X^2 + Y^2)^2 \cos(2\tan^{-1}(Y/X)) + (X^2 + Y^2)^4]} \quad [13]$$

and is shown in Fig. 1b. Note the logarithmic dimensionless scale on the $G_2(X, Y)$ axis and the relative $X = x/d$ and $Y = y/d$ axis. The relative spatial sensitivity function is a normalized weighting function which is independent of the ratio between probe rod diameter and rod spacing (Knight et al., 1994). Figure 1b is an excellent illustration of how a three-rod probe, as used in this study, weights a surrounding homogeneous medium. It clearly shows one of the dilemmas of TDR when applied for measuring spatially variable distributions of K and possibly EC since the dielectric and solute are given uneven weight depending on the position within the sample area. Furthermore, a heterogenous K distribution will change the weighting function compared with the homogenous case. Hence, a cumulative weighting function is a function of the direction of integration within the X–Y plane. Equation [13] does not show total integral unity which is the case for $w(x, y)$ (Knight et al., 1994). Therefore, we define the relative cumulative vertical sensitivity function [$F_2(H)$] as,

$$F_2(H) = \frac{\int_{-\infty}^{H}\int_{-\infty}^{\infty} G_2(X, Y)\mathrm{d}X\mathrm{d}Y}{\int\int_A G_2(X, Y)\mathrm{d}X\mathrm{d}Y} \quad [14]$$

where $H = h/d$. It is obvious that $F_2(H)$ does not readily describe an experimental obtained $W(h)$ for the probe in Fig. 1a because of the normalization applied in the derivation of $G_2(X, Y)$. However, the shape of $F_2(H)$ is expected to be similar to the shape of $W(h)$ and can be brought to provide a good fit of the experimental data with the right choice of d (hereafter referred to as d^*) which might differ from the real probe rod separation. Thus, the universal $W(h)$ for the TDR probe used in this study (Fig. 1a), neglecting the influence of the $K(x, y)$ distribution, is defined as,

$$W(h) = \int_{-\infty}^{h}\int_{-\infty}^{\infty} w(x, y)\mathrm{d}A = F_2\left(\frac{h}{d^*}\right) \quad [15]$$

It should be emphasized that Eq. [15] is empirical because of the optimization of d^*. It follows from Eq. [14] and [15] that $w(y)$ can be calculated as,

$$w(y) = \frac{\int_{-\infty}^{\infty} G_2(X^*, Y^*)\mathrm{d}X^*}{\int\int_A G_2(X^*, Y^*)\mathrm{d}X^*\mathrm{d}Y^*} \quad [16]$$

where $X^* = x/d^*$ and $Y^* = y/d^*$. Since $w(y)$ is defined it is possible to calculate the theoretical TDR response (EC_b) to a given EC distribution varying only in the y-direction of the plane perpendicular to the long axis of the probe rods [$EC(y)$],

$$EC_b = \int_{-\infty}^{\infty} w(y)EC(y)\mathrm{d}y \quad [17]$$

MATERIALS AND METHODS

Two types of experiments were carried out: (i) sensitivity experiments, comparing the spatial weighting of K with EC in the plane perpendicular to the long axis of the TDR-probe rods and (ii) diffusion experiments, comparing actual and TDR-measured relative EC_b in soils with a temporally decreasing gradient in EC.

In the sensitivity experiments, 16 identical stainless steel pipes (0.096 m i.d., 0.1 m o.d., and 0.1 m high) were packed with soil wetted to $\theta = 0.153$ m^3 m^{-3} or $\theta = 0.244$ m^3 m^{-3}, respectively, at a bulk density (ρ) of 1.47 Mg m^{-3}. A steel pipe packed with soil is referred to as a half-cell. In eight of the half-cells, the soil was wetted by tap water, and in the remaining eight, the soil was wetted by a 0.07 M KCl solution based on tap water, referred to as the KCl solution. Sixteen specially designed three-rod TDR probes (0.02-m rod spacing, 0.002-m rod diam., 0.084-m length of conductor) (see Fig. 1a) were inserted in the half-cells through holes in the steel pipes, one probe per half-cell, at eight fixed distances (h) below the soil surface (h = 0.0025, 0.005, 0.010, 0.015, 0.020, 0.025, 0.035,

and 0.05 m). Hence, for each value of h, two TDR probes were inserted in two different half-cells, one probe was inserted in a half-cell wetted by tap water and one probe was inserted in a half-cell wetted by the KCl solution. Subsequently, the half-cells were sealed by Parafilm (American National Can, Menasha, WI) and left to equilibrate for 24 h in a temperature regulated room at 20°C before the Parafilm was removed and K_a and EC_b were determined by TDR (four measurements per probe).

Two different experimental procedures were applied in the diffusion experiments, hereafter referred to as Method I and II. Method I was based on the sensitivity experiment. After completing the four TDR measurements per probe the half-cells were assembled in pairs depending on the position of the probes (equal h) such that the soil wetted by KCl solution came in contact with the soil wetted by tap water. Hereby eight soil columns with a steep gradient in KCl at the interface were created. Then, the columns were left for 18.9 d at θ = 0.153 m^3m^{-3} and 10.8 d at θ = 0.244 m^3m^{-3} to allow diffusion of solutes to occur via the liquid phase from one half-cell to the other. During this period, measurements of K_a and EC_b were carried out by TDR every half an hour. Only 14 half-cells were used at θ = 0.244 m^3m^{-3}; measurements were not carried out at h = 0.035 m.

Method II differed slightly from Method I. Instead of assembling two separate repacked half-cells, the soil wetted by the KCl solution was packed directly on top of the repacked soil column wetted by tap water. Three TDR probes (Fig. 1a) were inserted in each half-cell during packing at the following distances from the interface; y = 0.005, 0.015, and 0.035 m before the cells were positioned in a temperature regulated room at 20°C. The diffusion experiments following Method II was carried out at two different levels of θ (θ = 0.156 and 0.256 $m^3\ m^{-3}$) but at equal bulk density (ρ = 1.47 Mg m^{-3}) and lasted for 16.8 and 9.9 d, respectively.

At the end of all the diffusion experiments, the soil columns were cut in sections and the Cl^- concentration determined by extraction on a Technicon TRAACS 800 Autoanalyser (Technicon Industrial Systems, Tarrytown, NY).

The soil used in this study was a Foulum sandy loam (Typic Hapludult) [Sand (20–2000 μm) = 78.9%, Silt (2–20 μm) = 11.3%, Clay (<2 μm) = 9.8%] collected from the top 0.2 m of an agricultural field at Research Center Foulum, Denmark. The soil was passed through a 2-mm sieve, and mixed thoroughly to obtain a homogenous mixture before it was packed into the steel pipes. Olesen et al. (2001) measured the soil water characteristic curve of the Foulum soil. According to their data the matric potential (ψ) in Foulum soil equals ~ −3.5 m H_2O at θ ~ 0.25 $m^3\ m^{-3}$ whereas ψ equals ~ −15 m H_2O at θ ~ 0.15 $m^3\ m^{-3}$, i.e., θ was well below field capacity in all the experiments in this study.

The TDR equipment consisted of a Tektronix 1502B cable tester equipped with an RS 232 interface (Tektronix, Beaverton, OR) and a 16-probe Dynamax multiplexing system (Dynamax Inc., Houston, TX). The K_a and EC_b were determined from the TDR trace by the TACQ software (Dynamax Inc., Houston, TX) based on the principles of Heimovaara and Bouten (1990) and Wraith et al. (1993), respectively.

RESULTS AND DISCUSSION

Figure 2 shows the cumulative weighting of the soil as a function of distance to the soil surface, $W(h)$, calculated by Eq. [5] and [10] from measurements of K_a and EC_b obtained with TDR in the sensitivity experiment. Note that K_{soil} in Eq. [5] equals K_a at h = 0.05 m and

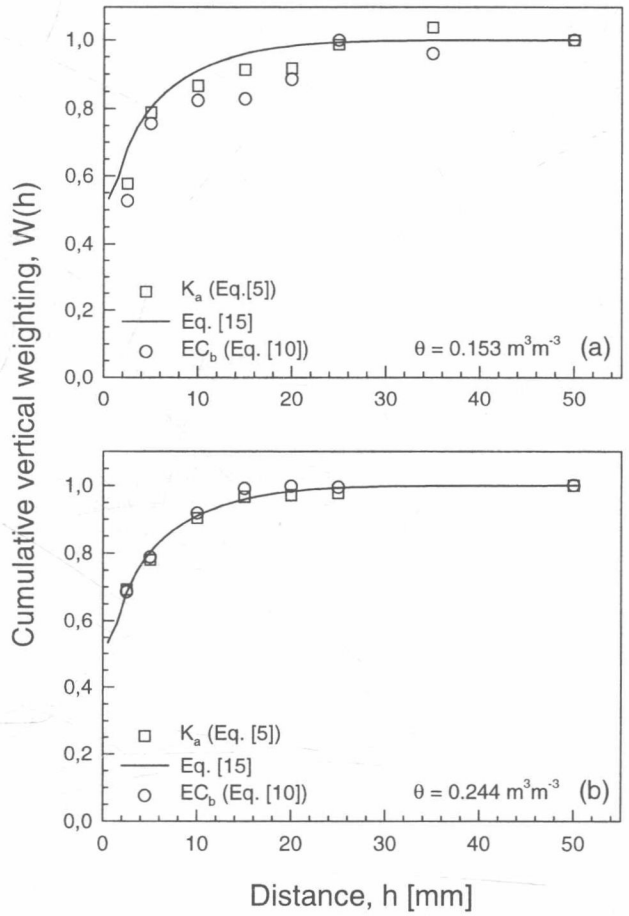

Fig. 2. Comparison between the cumulative vertical weighting [$W(h)$] calculated from TDR-measured soil water content (θ) and bulk soil electrical conductivity (EC_b) as a function of distance to the soil surface (h) at two different soil water contents: (a) θ = 0.153 $m^3\ m^{-3}$ and (b) θ = 0.244 $m^3\ m^{-3}$. Also shown is the universal cumulative vertical weighting function (Eq. [15]) for the TDR probe shown in Fig. 1a (solid line).

K_{air} = 1. A similar approach was applied in Eq. [10] were EC_{soil} equals EC_b at h = 0.05 m. Each data point in Fig. 2 represents the average of measurements obtained by two TDR probes positioned at the same h in two different half-cells prior to their assembly. There is a striking agreement between the cumulative weighting obtained by Eq. [5] [$W(h)_{K_a}$] and [10] [$W(h)_{EC_b}$] especially in the experiment carried out at θ = 0.244 $m^3\ m^{-3}$ (Fig. 2b) where differences are practically nonexistent. The minor scatter in the data obtained in the experiment carried out at θ = 0.153 m^3m^{-3} shows a trend toward a lower level of $W(h)_{EC_b}$ compared with $W(h)_{K_a}$. When calculating $W(h)_{EC_b}$ from Eq. [10] it is assumed that EC_{soil} equals EC_b at h = 0.05 m, so errors in the determination of EC_b at this depth will effect all $W(h)_{EC_b}$ values except at h = 0.05 m. However, this type of error should lead to a decreasing absolute error with decreasing $W(h)_{EC_b}$ which is clearly not the case. The error source is most likely a reduced contact area between probe rods and soil. This is supported by the difficulty to pack the soil at a uniform ρ and the difficulty to obtain a satisfactory contact between the TDR-probe rods and the soil at θ = 0.153 $m^3\ m^{-3}$, especially at h = 0.0025 m,

which is the likely cause of the major underestimation of both $W(h)_{EC_b}$ and $W(h)_{K_a}$ at this depth. It should be emphasized that $W(h)$, shown in Fig. 2, is only valid for the TDR-probe design shown in Fig. 1 and for the given spatial K distribution which changes as a function of y. Hence, theoretically $W(h)$, on Fig. 2a and 2b, should be slightly different because of the differences in $K(x, y)$ (K of soil at $\theta = 0.244$ m^3 m^{-3} is higher than at $\theta = 0.153$ m^3 m^{-3}). The magnitude of the difference is likely too small to be revealed in an experimental investigation and calls for a numerical analysis as the one carried out by Knight et al. (1997) and Ferré et al. (1998). In conclusion, despite the minor scatter at $\theta = 0.153$ m^3 m^{-3}, our measurements have proved that TDR weights EC and K equally in the plane perpendicular to the long axis of the probe rods.

The secondary objective of this study was to examine the discrepancies between actual and TDR-measured EC_b in the case where a steep gradient in EC passes the probe. This was done in the diffusion experiments where half-cells wetted with tap water and a KCl solution, respectively, and equipped with a single TDR probe (Method I) or three TDR probes (Method II) per half-cell at varying distances (h) from the soil surface were assembled and subsequently EC_b was measured by TDR as a function of time. In these experiments, the TDR probes were totally surrounded by soil, i.e., $W(h)$ was expected to differ slightly from the functions determined in the sensitivity experiment (Fig. 2). Petersen et al. (1995) compared an expression for $W(h)$, derived by Knight et al. (1994) for two-rod probes, with the relative soil water content as a function of h obtained by gradually decreasing the distance between the soil surface and various horizontally inserted two-rod TDR probes. Although the expression for $W(h)$ is derived for a homogenous K distribution, there was an excellent agreement between this expression and the TDR-measured relative soil water contents. Therefore, it was decided to use $W(h)$ determined at $\theta = 0.244$ m^3 m^{-3} in the sensitivity experiment as a universal cumulative vertical weighting function for the TDR probe shown in Fig. 1a, hereby ignoring the dependency of $K(x, y)$. A functional expression describing the data in Fig. 2b was obtained using least squares optimization of Eq. [15] (by changing d^*) to the measured $W(h)$ profile. The integration of $G_2(X^*, Y^*)$ was solved numerically by calculating the volume under the plane shown in Fig. 1b, transformed to the X^*, Y^* system of coordinates omitting the volume occupied by the probe rods. The best fit was obtained for $d^* = 0.03$ m and the result is shown in Fig. 2. By differentiating the universal $W(h)$ in Fig. 2 with respect to y, $w(y)$ is obtained. Hence, the resulting EC_b from all EC distributions varying only in the y-direction of the plane perpendicular to the long axis of the probe rods can be calculated directly.

Figure 3 shows an example of the relative Cl^- distribution determined by extraction at the end of the diffusion experiment carried out at $\theta = 0.256$ m^3 m^{-3} (Method II). Also shown is the optimized analytical solution to Fick's second law for diffusion of solutes in soil (Crank, 1975, p. 414). The solute diffusion coefficient (D_p = 10.17 cm^2 s^{-1}) was determined in a least squares optimization to the relative Cl^- concentrations in Fig. 3. There is an excellent agreement between the measured relative Cl^- concentration and the analytical solution. Similar goodness of fit was observed in all the paired half-cells. Therefore, it was assumed that the analytical solution provide an adequate description of the relative Cl^- distribution in the paired half-cells at any time during the diffusion experiments.

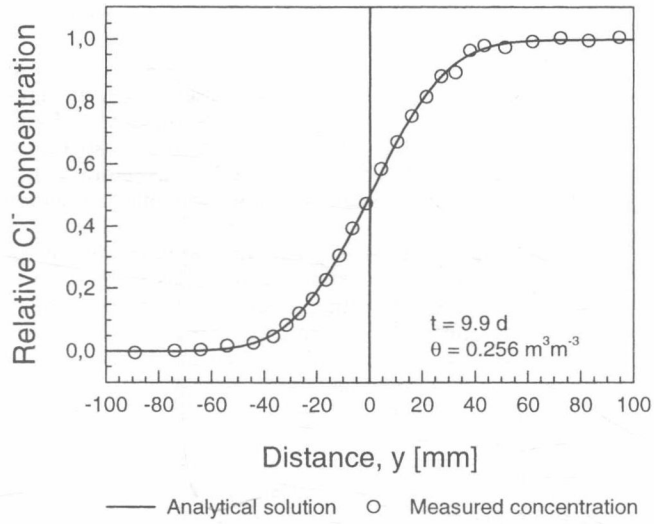

Fig. 3. Example of the relative Cl^- concentration measured by extraction of the soil solution at the end of the diffusion experiment (Method II) carried out at $\theta = 0.256$ m^3 m^{-3} as a function of distance to the interface between the two half-cells.

Figure 4 shows the relative EC_b measured by TDR in the diffusion experiment (Method I) at $\theta = 0.244$ m^3 m^{-3} as a function of distance to the interface immediately after (Fig. 4a) and 5.9 d after (Fig. 4b) the half-cells were assembled. Note that the interface between the half-cells is positioned at $y = 0$. For comparison, the theoretical relative EC_b response as a function of depth (solid line) is calculated using Eq. [17]. The actual distribution of relative $EC(y)$ needed in Eq. [17] to calculate the theoretical relative EC_b response is shown in Fig. 4 as a dotted line. At $t = 0$ d, the actual distribution is a step function rising from zero to one at the interface, whereas at $t = 5.9$ d the actual distribution was calculated using an average solute diffusion coefficient determined by fitting the analytical solution to the relative Cl^- concentration profiles measured in the eight paired half-cells at the end of the experiment. Therefore, the actual relative $EC(y)$ profile in Fig. 4b represents a relative Cl^- concentration profile. In a KCl solution the relationship between the EC and the Cl^- concentration is close to linear for Cl^- concentrations below 0.05 M (Vogeler et al., 1996). A linear relationship also exist between EC_b and the EC of the soil solution beyond a threshold level of EC at constant θ. Rhoades et al. (1976), Vanclooster et al. (1994), and Vogeler et al. (1996) reported linearity at EC values >0.25 S m^{-1} whereas Rhoades et al. (1989) reported linearity at EC values >0.10 S m^{-1}. The nonlinear behavior below the threshold level is believed to be influenced by clay con-

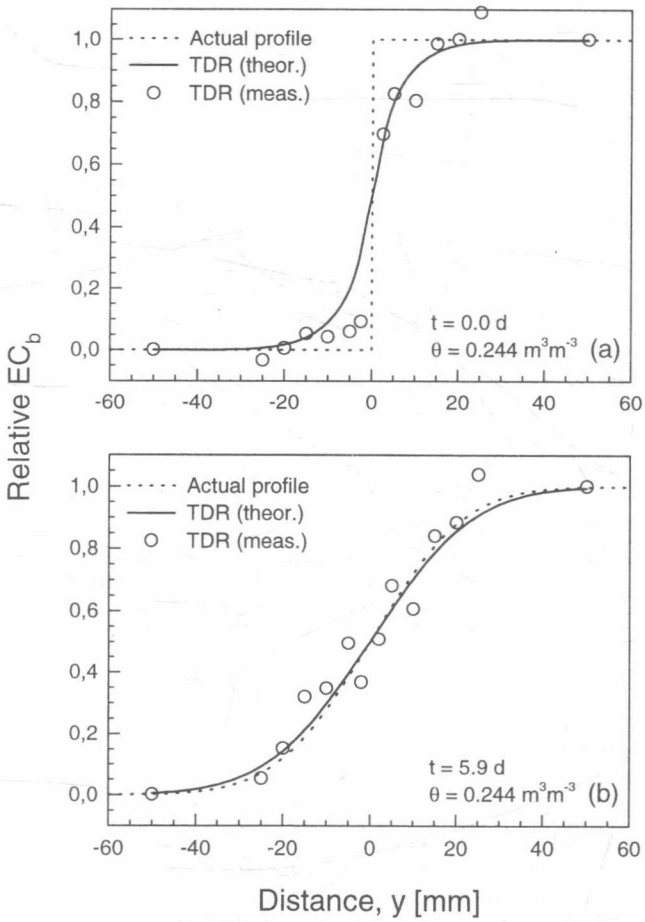

Fig. 4. Comparison between the actual distribution of relative electrical conductivity (EC), TDR-measured relative bulk soil electrical conductivity (EC_b) and the theoretical distribution of TDR-measured relative EC_b as a function of distance to the interface between the half-cells at (a) the beginning (t = 0 d) and (b) 5.9 d after the half-cells were assembled in the diffusion experiment (Method I) carried out at θ = 0.244 m^3 m^{-3}.

tent and Na^+ saturation (Shainberg et al., 1980). Since the soil used in this study is a sandy loam and EC > 0.10 S m^{-1} in all the experiments (unpublished data), linear relationships were assumed to exist between EC_b, EC of the soil solution, and the Cl^- concentration, justifying the comparison between relative EC_b and relative Cl^-concentration in Fig. 4. From Fig. 4a, it is evident that the TDR-measured relative $EC_b(y)$ provide a false image of the actual distribution of relative $EC(y)$ in the two half-cells. An increasing part of the sample volume is in the adjacent cell as the probes approach the interface hereby creating what could be denoted as artificial (TDR-induced) diffusion. There is an excellent agreement between measured and theoretical relative $EC_b(y)$ in the soil wetted by the KCl solution ($y > 0$) whereas the agreement is less convincing in the half-cells wetted by tap water ($y < 0$). A likely explanation could be insufficient contact between probe rods and soil. In addition, the measurement originates from 14 individual half-cells and although they were assumed identical there will always be small differences between the cells.

As the Cl^- spreads, the steepness of the actual relative $EC(y)$ profile decreases, which reduces the differences

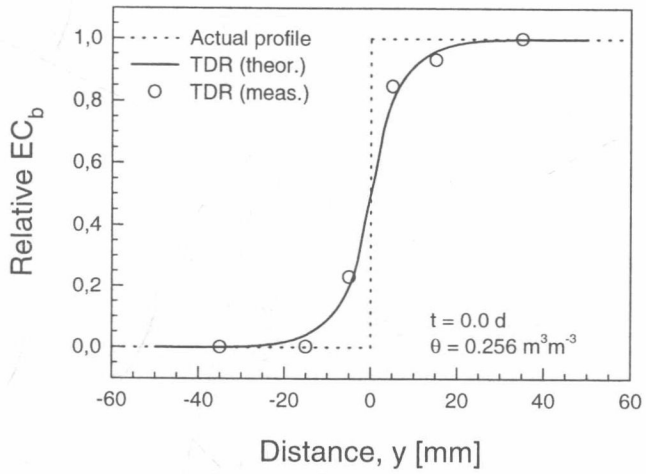

Fig. 5. Comparison between the actual distribution of relative electrical conductivity (EC), TDR-measured relative bulk soil electrical conductivity (EC_b), and the theoretical distribution of TDR-measured relative EC_b as a function of distance to the interface between the two half-cells at the beginning (t = 0 d) of the diffusion experiment (Method II) carried out at θ = 0.256 m^3 m^{-3}.

between the measured and the actual profile. This is evident from Fig. 4b showing measurements of $EC_b(y)$ obtained 5.9 d after the half-cells were assembled. The difference between the actual and theoretical profile is very small and the measurements are well described by the actual profile. The probe positioned at $y = -0.0025$ m continues to underestimate relative EC_b supporting that there was insufficient contact between probe rods and soil at this depth.

Figure 5 shows the actual, TDR-theoretical (Eq. [17]), and TDR-measured relative $EC_b(y)$ obtained immediately after assembling the half-cells in the diffusion experiment (Method II) carried out at θ = 0.256 m^3 m^{-3}. The effect of the steep gradient in relative $EC(y)$ on TDR-measured relative $EC_b(y)$ is evident and the measurements provide a false impression that the solute has already spread at $t = 0$. This again proves the phenomenon of artificial (TDR-induced) diffusion. Although the theoretical relative $EC_b(y)$ distribution is only an approximation of the real distribution, since the theoretical $EC_b(y)$ is obtained for a varying heterogenous K distribution, it is in very good agreement with the TDR-measured values.

Figures 4a and 5 have shown that because of the size and the nonlinear weighting of solute within the sample area perpendicular to the long axis of the probe rods TDR-measured relative EC_b profiles cannot be used to determine D_p in soils if the actual relative concentration profile show a steep increase in concentration. However, Fig. 4b shows that the difference between the actual and TDR-measured relative EC_b profiles diminish rapidly as the concentration profile become more spread. Therefore, it should be possible to determine D_p in soil with TDR if one waits until the profile is sufficiently spread. The question is when the error because of artificial (TDR-induced) diffusion becomes negligible compared with the solute diffusion.

In Fig. 6, the absolute difference between actual relative EC_b [calculated using the analytical solution to

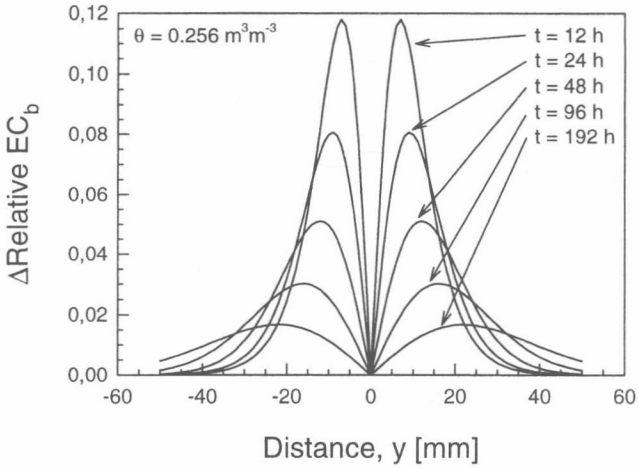

Fig. 6. Temporal development in absolute difference between the actual relative bulk soil electrical conductivity (EC_b) distribution and the theoretical TDR-measured relative EC_b distribution (ΔRelative EC_b) as a function of distance from the half-cell interface calculated theoretically from the soil data (θ and D_p) obtained in the diffusion experiment (Method II) carried out at θ = 0.256 m³ m⁻³.

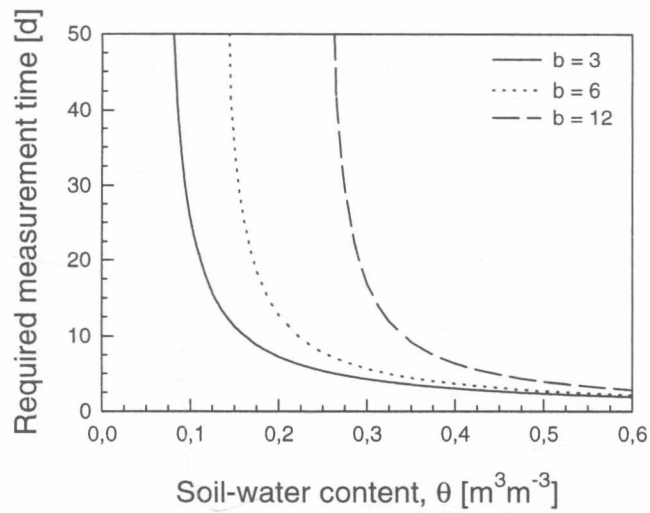

Fig. 7. Time needed to reach the acceptance criterion, the theoretical TDR-measured relative ECb distribution (ΔRelative EC_b = 2%), as a function of soil water content (θ) in three different model soils varying in the value of the Cambell parameter, *b*, where *b* = 3, 6, and 12 represents a sand, loam, and clay soil, respectively.

Fick's second law of diffusion (Crank, 1975, p. 414)] and theoretical TDR-measured relative EC_b profiles is shown as a function of distance to the half-cell interface. The difference is labeled ΔRelative EC_b. Data (θ and D_p) from the diffusion experiment (Method II) carried out at θ = 0.256 m³ m⁻³, was used to determine ΔRelative EC_b at various times after the half-cells were assembled. It is evident that the influence of artificial (TDR-induced) diffusion decreases over time as expected from Fig. 4a and b. Furthermore, the peak value in ΔRelative EC_b shows a tendency to move from the center towards the open ends of the half-cells. Consider the relative spatial sensitivity function [$G_2(X, Y)$ in Fig. 1b and assume it is independent of the solute concentration distribution in the X–Y plane. Then assume that solute diffusion occurs from a line source perpendicular to the X–Y plane and parallel to the x-axis. There is only two special cases where the TDR-measured EC_b will equal the actual EC_b at $Y = 0$ (the probe axis), that is when the concentration is totally uniform in the X–Y plane or if the line source is positioned at Y = 0, i.e., the S-shaped concentration profile is centered around the probe axis. This explains why, ΔRelative $EC_b = 0$ at $y = 0$ in Fig. 6 despite an increasing spreading of the solute. At all other positions of the line source ($Y \neq 0$), the S-shaped concentration profile is distributed asymmetrically around the probe axis and combined with the properties of $w(y)$ it leads to an erroneous EC_b estimate. The peak value in ΔRelative EC_b occurs at the distance between the line source and the probe axis where the combination of a given S-shaped concentration profile and a given $w(y)$ (depends on the TDR probe) results in the largest discrepancy between TDR measured EC_b and EC_b at the probe axis ($Y = 0$). Apparently this distance depends on the spreading of the solute.

Based on our experience from previous solute diffusion experiments using the traditional technique of sectioning and extraction to determine the solute concentration profile and D_p at the end of the experiment, the variations in the relative concentration because of measurement errors is of the order of 2%. Therefore, a maximum acceptable ΔRelative EC_b should be of the same order of magnitude, i.e., ~0.02, to make the two techniques comparable. For the case in Fig. 6, the criterion is reached after ~160 h. The time required to reach the acceptance criterion of ΔRelative EC_b is, however, a function of both soil type and θ.

Olesen et al. (2001) presented the following soil-type dependent model to estimate D_p,

$$D_P = 1.1(\theta - \theta_{th})\theta D_0 \quad [18]$$

D_p is the solute diffusion coefficient in soil, D_0 is the solute diffusion coefficient in water, θ is the volumetric soil water content, and θ_{th} is the threshold soil water content where solute diffusion approaches zero because of disconnected water films and high water viscosity close to soil mineral surfaces. Olesen et al. (2001) suggested that θ_{th} can be estimated from pore size distribution,

$$\theta_{th} = 0.02b \quad [19]$$

where b is the Cambell (1974) pore-size distribution index equal to the slope of the soil-water characteristic curve in a log-log coordinate system. By choosing b values of 3, 6, and 12, $D_p(\theta)$ values representing a sand, a loam, and a clay soil, respectively, can be calculated from Eq. [18] and [19]. Subsequently, given the 2% acceptance criterion of ΔRelative EC_b it is possible to calculate the time needed to reach the criterion for the three different soils (b values) as a function of θ and the result is shown in Fig. 7. An inherent assumption in the model (Eq. [19]) is that diffusion stops at $\theta = \theta_{th}$, i.e., the time needed to reach the acceptance criteria in Fig. 7 tends toward infinity as θ tends toward θ_{th}. That is, θ_{th} in Fig. 7 is approximately equal to θ corresponding to a required measurement time of 50 d. Based on the

curves in Fig. 7, an acceptable duration (≤2 wk) of TDR-monitored diffusion experiments can be obtained for all soil types at θ values exceeding θ_{th} with ~0.05 $m^3\ m^{-3}$.

The curves in Fig. 7 are calculated on the basis of the $w(y)$ of the three-rod probe used for the experiments in this study (Fig. 1a). However, the probe-rod geometry (i.e., number of rods, rod diameter, and rod spacing) influence on both the size of the sample area and the weighting of K and EC within the sample area. Therefore, the acceptance criterion can be reached faster by choosing a probe that is less sensitive to changes in EC_b in the far field. As mentioned previously an analytical solution describing $w(x, y)$ does not exist for three-rod probes. Knight (1992) did, however, derive an analytical solution of $w(x, y)$ for two-rod probes under the assumption of a homogenous $K(x, y)$ distribution and Knight et al. (1994) performed an integration of this expression over x yielding an analytical expression for $w(y)$. Using this expression, the temporal development in the maximum ΔRelative EC_b in the diffusion experiment (Method II) carried out at $\theta = 0.256\ m^3\ m^{-3}$ was calculated for five different geometric configurations of two-rod probes and the three-rod probe used in this study. The results are shown in Fig. 8a and 8b. The effect of rod spacing (D) is examined in Fig. 8a and compared with the three-rod probe used in this study (Fig. 1a) whereas the effect of rod diameter (B) for two-rod probes is shown in Fig. 8b. By comparing the curves in Fig. 8a, it is clear that two-rod probes have a larger sample area and hence larger artificial (TDR-induced) diffusion compared with a three-rod probe of equal dimensions. In fact the rod spacing need to be nearly halved to obtain equal performance. The effect of rod diameter is quite significant with a clear decrease in maximum ΔRelative EC_b as a function of decreasing rod diameter (Fig. 8b). By decreasing the sample area perpendicular to the long axis of the probe rods a decreasing bias in TDR-measured relative concentration because of artificial (TDR-induced) diffusion is obtained and a sufficiently precise determination of D_p can be derived from steeper concentration profiles. In addition, three-rod probes are preferable compared with two-rod probes of equal dimensions.

The experimental focus of this study has been on solute diffusion, since diffusion is a slowly progressing and well described process (Crank, 1975, p. 414) making the experiments and the interpretation of the results less complicated. However, also in the case of convective-dispersive solute transport during water movement in soil, the TDR measurement will not represent a point measurement and EC is weighted nonlinearly as a function of distance to the probe rods. Thus, the solute dispersion coefficient will also be overestimated when determined from TDR measured solute breakthrough curves. The error introduced depends on the steepness of the profile. Furthermore, in cases where the solute concentration is not changing monotonously, having local or global maximum or minimum peak values, TDR-measured concentrations at these peak values will be under- and overestimated, respectively. Similar considerations apply for steep gradients in K created by wetting fronts. Unfortunately, the dependency of the weighting function on the K distribution result in a temporal changing weighting function as the K gradient passes the probe, making it impossible to evaluate the error in the K estimate with the analytical solutions by Knight et al. (1994). The numerical approach by Knight et al. (1997) and Ferré et al. (1998) might prove useful for this analysis. In conclusion, if TDR is used to measure the temporal change of K or EC at a given depth or the depth profile of K and EC at a given time and if a steep gradient in K or EC is passing the probe(s) the TDR-measured profile will deviate from the actual profile and the magnitude of the error increases with the steepness of the profile.

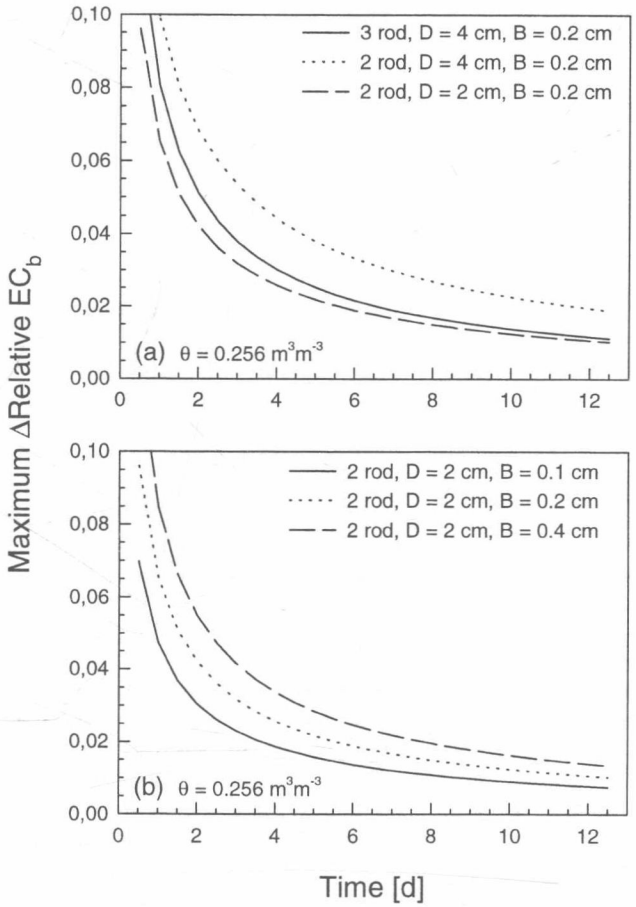

Fig. 8. Temporal development in the maximum absolute difference between the actual relative bulk soil electrical conductivity (EC_b) distribution and the theoretical TDR-measured relative EC_b distribution (Maximum ΔRelative EC_b) for (a) the three-rod probe in Fig. 1a compared with two-rod probes with varying probe rod separation (D) and (b) two-rod probes with constant D, but various rod diameter (B). Calculations were based on soil data (θ and D_p) obtained in the diffusion experiment (Method II) carried out at $\theta = 0.256\ m^3\ m^{-3}$.

CONCLUSIONS

We have presented an experimental comparison between the cumulative vertical weighting of EC and K in the plane perpendicular to the long axis of the TDR-probe rods of a three-rod TDR probe and proved that

they are equal. Thus, the sample volume of TDR-measured EC_b and K_a is identical, as expected. Well-known analytical and numerical solutions for the spatial weighting of conventional and special TDR probes positioned in a medium with a homogenous or heterogenous relative dielectric permittivity distribution also apply for electrical conductivity.

We also showed that because of the finite size of the sample area perpendicular to the long axis of the TDR probe rods, conventional TDR probes register the presence of wetting fronts or solute gradients, progressing in a direction perpendicular to the long axis of the probe rods, before they reach the probe. In addition, TDR performs a complex weighting of K and EC within the sample area, showing maximum sensitivity in the vicinity of the probe rods and depending on direction, probe type, and the K distribution. The resulting TDR-measured EC_b and K_a profiles are biased towards an increased spreading of the relative solute concentration profiles or relative soil water content profiles. This phenomenon is denoted as artificial (TDR-induced) diffusion. Solute diffusion experiments showed that the bias increases with the steepness of the profiles. At a certain degree of spreading the bias becomes small and in most cases negligible compared with other error sources and TDR-measured relative EC_b profiles can then be used to accurately determine solute transport properties such as solute diffusion and dispersion coefficients.

To reduce problems with artificial (TDR-induced) diffusion during solute transport experiments with steep concentration gradients the choice of TDR-probe design should be considered carefully. A theoretical investigation of the effect of TDR-probe design on the temporal development in the difference between the actual and TDR-measured relative EC_b profiles showed that TDR-probe dimensions generally should be minimized and three-rod probes are preferable compared with two-rod probes of equal dimensions.

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