DETERMINATION OF SOIL CONTAMINANT TRANSPORT PARAMETERS USING TIME DOMAIN REFLECTOMETRY

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INTRODUCTION

A recent study of rural shallow drinking wells found that 4.6% of the wells in the Piedmont region of Georgia had nitrate levels above the EPA recommended level of 10 ppm nitrate nitrogen (Tyson and Issac, 1991). The most likely sources of this nitrate are septic systems, fertilizers, and manures. Nitrate transport models such as LEACHN (Wagenet and Hutson, 1989) can be used to investigate the contributions of these sources to groundwater contamination, but the models require soil transport parameters that are difficult to measure. Another problem is that we are interested in predicting nitrate transport at the field scale, but transport parameters are usually measured on a much smaller soil volume.

Time domain reflectometry (TDR) has been used to measure soil water content and salinity (Dalton et al., 1984) and recently it has been shown that the method can also be used to measure contaminant movement (Kachanoski *et al.*, 1992). To use TDR, parallel waveguides consisting of a pair of stainless steel rods of a known length and 3 mm or slightly larger in diameter are installed vertically in the soil with a separation distance of about 5 cm (Dalton et al., 1984). The waveguides are connected to a time domain reflectometer that generates an electomagnetic pulse and displays or records a trace of the impedance measured in the line at the meter as a function of time. The discontinuity at the end of the waveguides causes a reflection of the transmitted pulse which appears as an increase in impedance. Kachanoski *et al.* (1992) showed that the impedance of the reflected wave (R_L) was a function of the electrical conductivity (EC) of the soil solution surrounding the rods of length L. As EC increases, attenuation of the pulse by the soil increases and R_L drops. If a salt is added under steady flow conditions to the surface of a soil where waveguides are installed vertically, the presence of the salt will cause a low initial impedance ($R_{initial}$), but as the salt leaches beyond the end of the rods, R_L will increase and eventually approach the impedance that represents the background soil solution (R_{final}). Measurements of impedance as a function of time ($R_L(t)$) can be corrected for background concentrations by subtracting R_{final} and normalized by dividing by the total change in impedance to calculate the relative mass of salt in the soil to a depth L as a function of time ($M_R(t)$) (Kachanoski *et al.*, 1992):

$$M_R(t) = \frac{(R_L(t))^{-1} - (R_{final})^{-1}}{(R_{initial})^{-1} - (R_{final})^{-1}} \quad [1]$$

A plot of M_R vs time has been called a "breakout" curve (Elrick *et al.*, 1993) and an analytical solution to the convection dispersion equation (CDE) for a nonadsorbed solute can be fit to the data to determine the dispersion coefficient (D) and pore water velocity (v):

$$M_R(t) = 1 - \left[\frac{1}{2} erfc\left(\frac{L-vt}{2\sqrt{Dt}}\right) - \frac{1}{2}\exp\left(\frac{vL}{D}\right) erfc\left(\frac{L+vt}{2\sqrt{Dt}}\right)\right] \quad [2]$$

This analysis assumes that flow is steady and only occurs in the vertical direction.

Jury and co-workers (Jury et al., 1986; White et al., 1986) have suggested that the CDE may be inadequate for predicting field-scale transport in a soil with large horizontal variation in transport because it assumes complete mixing between vertical flowpaths. They have proposed a stochastic convective lognormal transfer function model (CLT) which assumes that vertical flowpaths are completely independent. In a vertically homogeneous soil, if D increases with depth it is evidence that the CLT is more appropriate than the CDE. The CLT equation analagous to equation [2] that describes the relative mass of salt as a funtion of time is given in terms of the mean (μ) and standard deviation (σ) of the lognormal of the flowpath travel times:

$$M_R(t) = \frac{1}{2}\, erfc\left(\frac{\ln(t) - \mu}{\sqrt{2}\,\sigma}\right) \quad [3]$$

The estimated population mean (μ_p) and variance σ_p^2) of the travel times are given by (Elrick et al., 1993):

$$\mu_p = \exp(\mu + \frac{\sigma^2}{2}) \quad [4]$$

$$\sigma_p^2 = \mu_p^2 (\exp(\sigma^2) - 1) \quad [5]$$

METHODS

Our objective was to determine whether the CDE or CLT equation was more appropriate for describing field-scale contaminant movement in a Piedmont soil. We used TDR to determine CDE and CLT transport parameters (D, v, μ, and σ) of chloride (Cl), a conservative tracer for nitrate, at the "local scale" within a large plot underlain by tile drains and compared these values to the "field scale" transport parameters measured from drain effluent.

The study was conducted near Watkinsville, Ga. on two adjacent 12.5 by 30.5 m plots of Cecil sandy loam (clayey, kaolinitic, thermic Typic Kanhapludult), referred to hereafter as Plot 1 and Plot 2. Five tile drains were installed in each plot in the fall of 1991 at depths of 0.76 to 1.07 m (1 % slope) and 2.5 m lateral spacing (Fig. 1). A soil compactor was used in refilling the soil above the drains. Tipping buckets samplers were installed in collector pits at the end of each drain line. The plots were moldboard plowed, disked and covered with straw after the tile drains were installed. Groups of TDR waveguides 30, 60, and 90 cm in length were installed vertically at 80 locations in each plot (Fig. 1). Starting November 10, 1991, Plot 1 was irrigated with overhead sprinklers for 36 h at a rate of 0.78 cm h^{-1} to establish steady flow. Then a pulse of KCl was applied as a spray (100 g Cl m^{-2}) and irrigation was resumed for 213 h. After 71 h, the irrigation rate was reduced to 0.39 cm h^{-1} to reduce surface ponding. TDR impedance for each waveguide and tile drain effluent volume and Cl concentration were measured over time. The procedure was repeated on Plot 2 starting April 6, 1992. An irrigation rate of 0.38 cm h^{-1} was applied for 36 h to establish steady flow and irrigation was continued for 470 h after KCl was applied.

Impedance measurements from most of the 30 cm length waveguides were similar to those shown for position one in Plot 2 (Fig. 2a). Impedance was low just after KCl application, increased sharply during the first 100 h as Cl moved through the soil, and then leveled off at a final value representative of the background soil solution impedance. Using eq. [1], the impedance values were converted to relative mass to produce a breakout curve (Fig. 3b) and a fit of eq. [2] and eq. [3] to the curve produced CDE and CLT transport parameters, respectively, for the 0-30 cm depth at position one.

Transport parameters were also obtained from the tile drain Cl concentration vs time data by fitting the analytical solution for a pulse input using both the CDE and the CLT (Jury, Gardner, and Gardner, 1991).

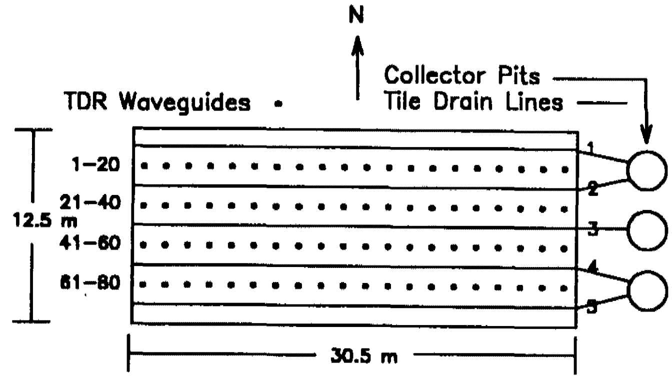

Figure 1. Diagram of plot 2 showing positions of 5 tile drain lines and 80 TDR installations. At each TDR location, waveguides 30, 60, and 90 cm in length were installed vertically.

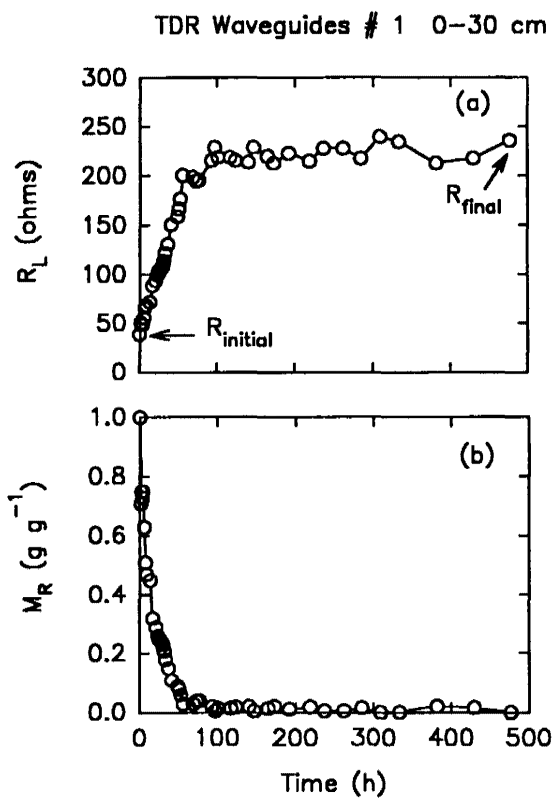

Figure 2. (a) TDR reflected wave impedance as a function of time for 0-30 cm waveguide at postiion 1, (b) relative salt mass as a function of time in the 0-30 cm depth at position 1.

Table 1. Mean Transport Parameters for Convection Dispersion Equation (CDE) and Convective Lognormal Trasfer Function (CLT) as determined from TDR and Tile Drain Data From Plot 1 and Plot 2.

Source of Curves	CDE				CLT				
	#† of Curves	D $cm^2\ h^{-1}$	v $cm\ h^{-1}$	R^2	#† of Curves	σ_p‡ $h^{1/2}$	σ_p§ $h^{1/2}$	μ_p h	R^2
Plot 1 TDR									
0-30 cm	71	7	1.76	0.90	67	9	16	25	0.90
0-60 cm	67	23	1.91	0.82	63	63	47	50	0.85
0-90 cm	40	30	2.83	0.72	44	112	96	73	0.73
Plot 1 Drain Lines	0	--	--	--	5	42		47	0.96
Plot 2 TDR									
0-30 cm	79	27	1.06	0.90	70	66	20	35	0.96
0-60 cm	72	185	1.16	0.88	48	142	96	94	0.87
0-90 cm	56	226	2.60	0.78	39	249	105	144	0.81
Plot 2 Drain Lines	5	24	0.40	0.93	5	161		164	0.92

† Number of curves in which a fit could be obtained using MATHCAD non-linear least squares.
‡ Mean of all σ_p values obtained from individual TDR breakout curves or drain line breakthrough curve.
§ Standard deviation of population of μ_p values obtained from individual TDR breakout curves.

RESULTS AND DISCUSSION

Mean values for the transport parameters computed from individual TDR breakout curves for the 0-30, 0-60, and 0-90 cm depths in Plot 1 and Plot 2 are shown in Table 1. Pore water velocity (v) increased with depth. Since saturated hydraulic conductivity decreases with depth in this soil (Bruce et al., 1983), this was probably caused by a decrease in the mobile water content as a result of greater macropore flow. Pore water velocities at a given depth were greater in Plot 1 than Plot 2 and this is a reflection of the higher application rate in Plot 1.

The TDR dispersion coefficient (D) also increased with depth which, in a vertically homogeneous soil, would be evidence that there is little horizontal mixing between flowpaths and that the CLT is more appropriate than the conventional CDE for describing field-scale transport at this site. However, in our case the soil is not vertically homogeneous (Bruce et al., 1983) and the increase in D may represent increasing macropore flow with depth.

The TDR mean travel times (μ_p) increased with depth as expected with the CLT model. The increase was nearly linear, especially in Plot 1, which would indicate that the mobile water content did not decrease with depth, contrary to the pore water velocity data. The standard deviation of the travel times (σ_p) for the TDR data was calculated in two ways. The first column for σ_p in Table 1 is the mean of the values of σ_p obtained from a fit of eq [3] to each of the TDR locations and is therefore a measure of the average variation in travel times at the local scale. The second column for σ_p is the standard deviation of the distribution of values of μ_p obtained at each location and is therefore a measure of the variation between local sites or the field-scale dispersion. The field-scale dispersion was less than the local-scale dispersion in all cases.

Goodness of fit (R^2) of the CDE and CLT models to the TDR breakthrough curves were similar. The fit was poorer at the deeper depths and the number of curves for which an acceptable fit could be obtained declined sharply with depth. With the longer waveguides, almost all of the signal was dissipated in the soil due to the high water and salt content, resulting in a very low reflected wave impedance and high variability.

In Plot 1, a satisfactory fit to the tile drain data could not be obtained for any of the five tile drains using the CDE so a comparison between the TDR local-scale and tile drain field-scale CDE transport parameters was not possible. The CLT parameters obtained from the lower depths of the TDR data in Plot 1 exceeded the values for the tile drain data. In Plot 2, the CDE parameters obtained from the TDR data also exceeded the tile drain values. However, there was good agreement in Plot 2 between the CLT mean travel time (μ_p) for the 0-90 cm TDR data (144 h) and the drain line value (164 h). This indicates that the time of arrival of the peak concentration in the tile drains in Plot 1 could be accurately predicted using the TDR data. The field-scale estimate of the

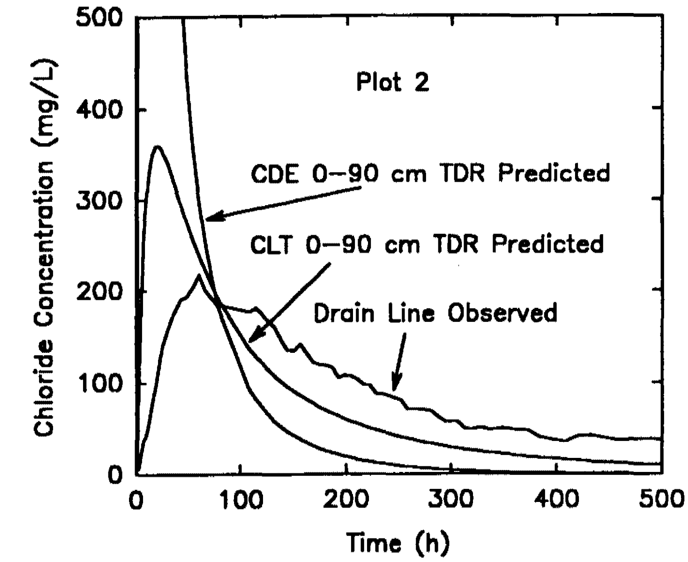

Figure 3. Comparison of observed mean Cl concentration in tile drains with predicted concentration using 0-90 cm TDR data based on CDE and CLT in Plot 2.

standard deviation of the travel times calculated from the population of 39 values of μ_p for the 0-90 cm TDR waveguides (105 h) was closer to the value for the tile drains (161 h) than the local-scale estimate of σ_p (249). This may indicate that most of the dispersion at the field-scale is caused by differences among local sites in mean flow velocities and not by differences in flow velocities within sites.

The predicted Cl concentrations using the 0-90 cm TDR data based on the CDE and the CLT are shown in Fig 3 and compared with the observed drain line concentrations in Plot 2. Both the CLT and CDE predict earlier breakthrough and higher peak concentrations than observed in the drain lines but the CLT prediction is much closer to the observed values than the CDE.

CONCLUSIONS

There is a need for a rapid non-intrusive method of measuring soil contaminant transport parameters. TDR can be used to obtain these parameters for nonadsorbed contaminants under conditions of steady flow and constant water content, but signal loss limits the depth to which reliable data can be obtained. Our results indicate that the dispersion coefficient in the CDE increases with depth. This may be evidence that the CDE is inappropriate for describing field-scale leaching in our soils or it may be due to greater macropore flow with depth. The results for one of the plots indicated that the CLT did a better job of predicting field-scale contaminant leaching than the CDE. This implies that there is little mixing among vertical flowpaths at the field scale.

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