The Third International Symposium on Soil Water Measurement Using Capacitance, Impedance and TDT (2010, Murcia, Spain), New Developments, Paper 3.5

Soil solution distribution for drip irrigation using TDR technique

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ABSTRACT

The principal objective of a drip system design is to choose the appropriate layout and components to obtain adequate soil solution distribution throughout a field. In addition to maximizing crop production, modern fertigation practices must consider environmental sustainability and rigorous water management. These often conflicting targets require significant changes in irrigation system design and operation (relative to traditional designs for maximum crop production). We conducted experiments to characterize dynamics and patterns of soil solution within the wet bulbs formed by drip irrigation. Time domain reflectometry (TDR) probes were used to monitor the distribution of potassium nitrate (KNO_3) and water distribution from drippers discharging at constant flow rates of 2, 4 and 8 L h^{-1} under field conditions. Considering results from different profiles, we observed greater solute storage near the dripper decreasing gradually towards the wetting front. About half of the applied KNO_3 solution (65%) was stored in the first layer (0-0.10 m) for all experiments, 22% was stored in the next layer (0.10-0.20 m). Comparing different dripper flow rates, we observed higher solution storage for 4 L h^{-1}, with 60, 72 and 63% of applied KNO_3 solution accumulating in the first layer (0-0.10m) for dripper flow rates of 2, 4 and 8 L h^{-1}, respectively. The results suggest that based on the volume and frequency used in this experiment, it would be advantageous to apply small amounts of solution at more frequent intervals to reduce deep percolation losses of applied water and solutes.

INTRODUCTION

In addition to maximizing crop production, modern fertigation practices must combine environmental sustainability and rigorous water management. These often conflicting considerations require significant changes in irrigation system design and operation (relative to systems for maximal crop production) (Souza & Matsura, 2004). Among the available irrigation methods, drip irrigation offers key advantages for meeting contemporary water and nutrient management efficiency standards, since it allows for accurate control of water supplied in small quantities directly to the root zone. Frequent irrigation helps maintain favorable water conditions (near field capacity) for root proliferation in the partially wetted soil volume.

The dimensions and extent of a wetted soil volume are determined by soil type (texture and structure), dripper discharge rate and spacing, and water application frequency (and initial soil water content early in the season) (Dasberg & Or, 1999). Unfortunately, these factors, which are important in both design and management, are often overlooked and current practices in Brazil and elsewhere are too often based on empirical information or on data gleaned indiscriminately from professional literature.

Characterization of the wetted soil volume in field conditions offer a practical means for gathering the relevant information required for system design (Keller & Bliesner, 1990); however, these tend to be time consuming and costly and therefore rarely performed. Alternatively, the wetted soil volume can be measured and controlled by using water content sensors such as time-domain reflectometers (TDR), which can estimate water content and electrical conductivity using a single probe within the same volume (Souza & Matsura, 2003). Thus, the purpose of this study was to characterize water and solute distribution patterns spatially and temporally in order to underpin the design and management of drip irrigation systems.

METHODS AND MATERIALS

Experiments were carried out in a 140 m^2 (7x20 m) greenhouse that is part of Experimental Irrigation Farm (ESALQ/USP), located at Piracicaba in Brazil during the 2006 and 2007. Surface layer (0-0.3 m) sandy soil classified as Oxisol was collected, air dried sieved (>2 mm) and packed in an instrumented container (0.65 m in height and 1.1 m in diameter) by compacting layers of 0.05 m to reproduce field soil bulk density (according to the methodology used by Mmolawa & Or, 2000). This procedure was repeated 9 times, using 3 containers for each dripper discharge rate of 2, 4 and 8 L h^{-1} tested. Following packing of the containers we waited two months to allow for soil settlement close to field conditions and improved contact of soil with TDR probes. Table 1 lists the soil's primary physical and chemical characteristics.

Table 1 – Physical and chemical characteristics of the Oxisol soil in field condition.

Physical characteristics						
Depth (m)	Bulk density (kg m^3)	Total porosity (%)	Texture (g kg^{-1}) Clay	Silt	Sand	K_{sat} m h^{-1}
0-0.30	1428	46	170	110	720	0.16

Chemical characteristics											
Depth (m)	pH	P mg dm^{-3}	OM (%)	H+Al	K	Ca	Mg	S	CEC	BS (%)
				Mmol$_c$ dm^{-3}						
0-0.30	4.6	5	0.69	31	1.8	24	9	35	65.6	53

K_{sat} - Saturated hydraulic conductivity; OM - Organic matter; CEC - Cation exchange capacity; BS - Percent base saturation.

A test container was equipped with 36 3-rod TDR probes (rod length of 200 mm and 3 mm in diameter; rod spacing of 15 mm) as illustrated in Figure 1, the probes were installed during the packing of the container. TDR probes were measured using a Tektronix 1502C (Oregon, USA) cable tester equipped with a RS 232 interface, and collected waveforms were automatically analyzed using WinTDR 6.0 software (2004) for soil water content and electrical conductivity (readings are obtained at 6 minutes interval). A calibration equation developed by Tommaselli & Bacchi (2001) was used to convert measured bulk dielectric permittivity (Ka) to soil water content (θ) as follows;

$$\theta = -0.0202 + 0.0257Ka - 0.0007Ka^2 + 1x10^{-5}Ka^3 . \quad (1)$$

For electrical conductivity measurements, we used TDR probe calibration methodology described in Souza et al. (2006a and 2006b). The resulting equations used:

$$EC = \frac{EC_{TDR} - 0.04}{(2.61\theta - 0.165)\theta} \quad (2)$$

$$C = \left[\frac{EC}{0.17}\right]^{\frac{1}{0.92}} . \quad (3)$$

where:

θ - Soil water content, m^3 m^{-3};

EC - Electrical conductivity, dS m^{-1};

EC_{TDR} - Bulk Electrical conductivity, dS m^{-1};

C - Solution concentration (KNO_3), mmol L^{-1}.

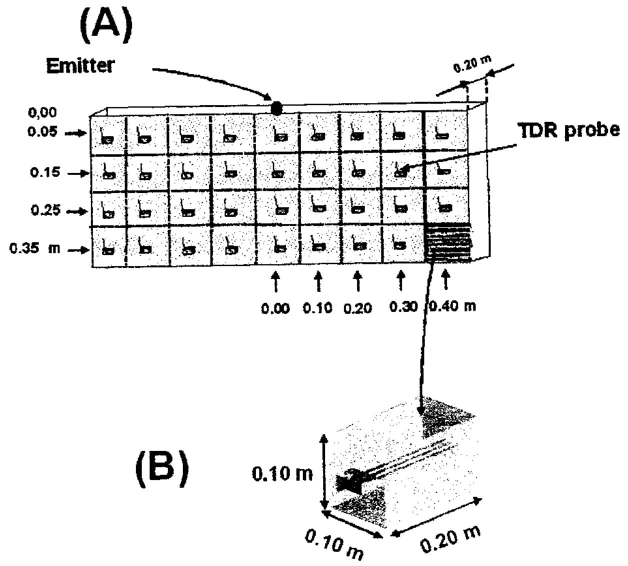

Figure 1 – A) Scheme of the experimental setup for radial symmetry; B) Volume of soil measured by each TDR probe.

TDR probes were deployed at 0.1 m spacing forming a regular grid on an axisymmetrical plane below the dripper (Figure 1A), we estimate that each probe measures a soil volume of 0.002 m^3 (Figure 1B). The solute mass stored in a soil volume was estimated from average values measured by two TDR probes positioned on opposite (symmetric) sides of a dripper representing a concentric ring of soil. The soil water content for each hypothetical soil ring was multiplied by respective soil volume to estimate water storage distribution and total (Souza & Matsura, 2004). We observed wetted soil volume formation under 2, 4 and 8L h^{-1} flow rate, with 1 L of solution application at 1-h interval. The dripper used in the experiments was Polytif (Plastro, Brazil) with a constant head maintained by a Mariotte bottle system (resulting in constant dripper discharge rate). Potassium nitrate (KNO_3) was used as test ionic solute and fertilizer (Coelho & Or, 1999) at concentration of 14.5 mmol/L in irrigation water, resulting in electrical conductivity of 2 dS m^{-1} (moderate risk of salinity).

The total amount and concentration patterns of applied solute in the soil were measured with TDR probes after each solute (fertilizer) application. Each TDR probe provided spatial and temporal information on water content and solute concentration in the soil, thus enabling detailed monitoring of soil solution dynamics. Point measurements were analyzed using a 3D surface mapping program, which presented the ion distribution profile as a function of the water content and electrical conductivity throughout the experiment.

Complementing the above described procedure, a central control volume was assumed inside the wetted soil volume for comparative analyses of distribution uniformity. This indicates a kind of heterogeneity due to the partial wetting of regions near the drippers. The control volume chosen was 0.50, 0.50, 0.40 m in length, width and depth, respectively, forming a cube with the dripper installed on the soil center. Thus, Christiansen's (1941) uniformity coefficients were calculated for the estimated water content and concentrations after each application of the solution, based on equation (1), following the methodology adapted by Ould Mohamed El-Hafedh et al. (2001),

$$CUC = 100\left[1 - \frac{\sum\left|X_i - \overline{X}\right|}{\overline{X}N}\right] \tag{4}$$

where:

CUC – Christiansen's uniformity coefficient, %;

X_i – Estimated water content, $m^3\ m^{-3}$; or estimated nutrient concentration, mmol L^{-1};

$\overline{X}$ – Water content average, $m^3\ m^{-3}$; or nutrient concentration average, mmol L^{-1};

N – Estimated point numbers.

The TDR-measured soil's electrical conductivity was converted to concentration of potassium nitrate in mmol L^{-1} using empirical equations 2 and 3. The data on distribution and storage of the solution in the soil provided basic information on the effects of the water-soil-solute relation, serving to underpin the design and management of drip fertigation systems.

RESULTS AND DISCUSSION

Experimental observations

A problem observed in the experiment was the contact of the wetting front with the bottom of the soil container, which occurred after the 6^{th}, 7^{th} and 4^{th} irrigations for 2, 4 and 8 L h^{-1}, respectively This problem has influenced the geometry of wetted soil volume due to the impervious soil container bottom.

Distribution and storage of the solution in the soil

Some of the parameters that influence the movement of solutes in the soil were monitored during the experiment. The parameters measured were air and soil temperature and relative humidity. However, the analyzed data did not reveal any direct influence of the parameters observed during the evolution of the formation of the wetted soil volume.

Figures 2, 3 and 4 depict measured electrical conductivity profiles during 5th, 6th and 3rd applications of potassium nitrate (KNO_3) solution, at dripper flow rates of 2, 4 and 8 L h^{-1}, respectively. These particular irrigations were chosen because the solution distribution profiles indicated that the wetting front reached the bottom of the container only following the chosen irrigation, thus the dimensions of wetted soil volume were not influenced by the boundaries in the presented results.

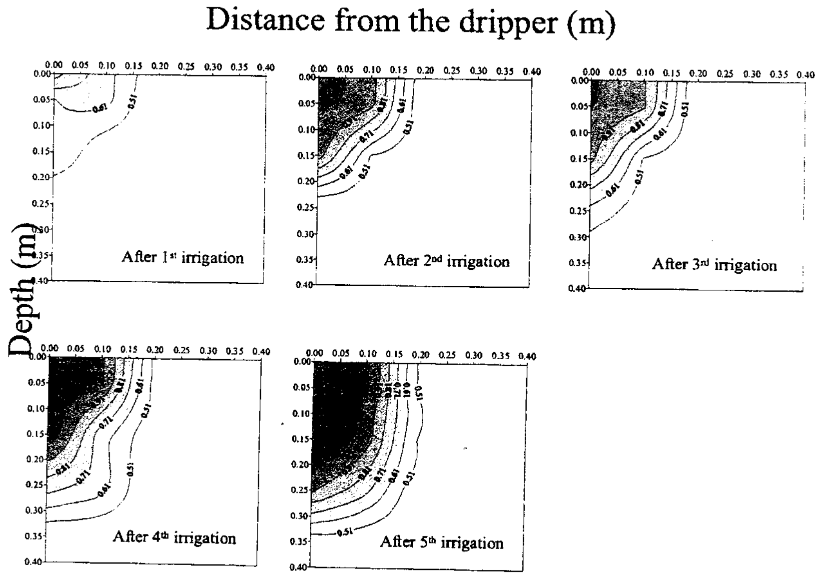

Figure 2 – Distribution of electrical conductivity in the soil, 2 L h^{-1}.

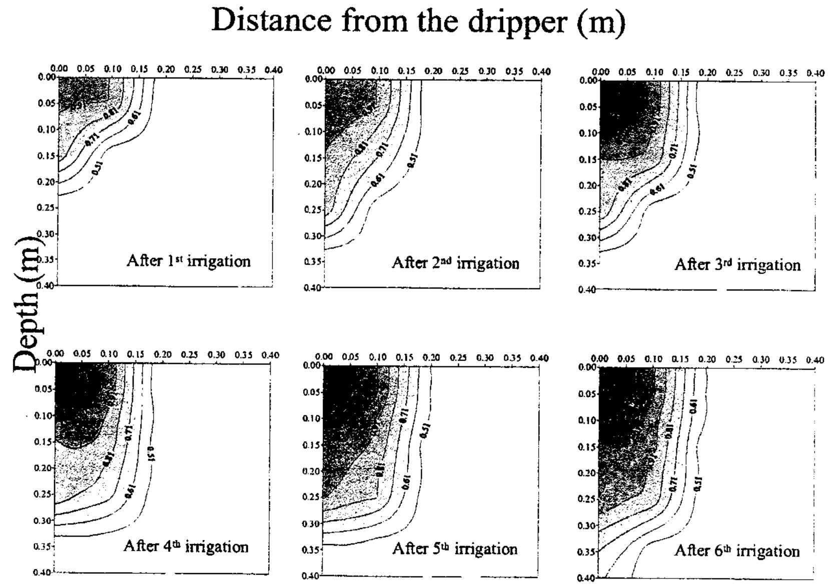

Figure 3 – Distribution of electrical conductivity in the soil, 4 L h^{-1}.

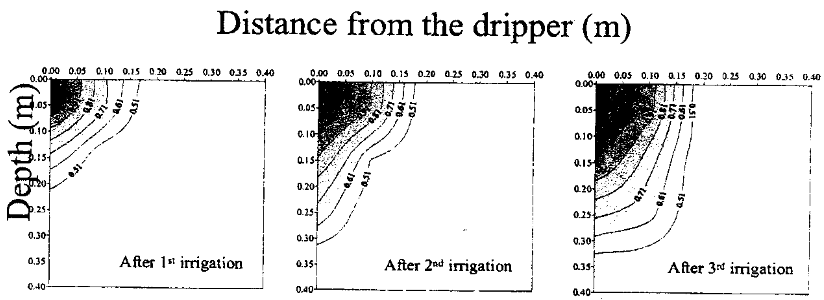

Figure 4 – Distribution of electrical conductivity in the soil, 8 L h^{-1}.

The amount of solutes in the wetted soil volume following infiltration process was quantified and reported in Table 2. For all solute applications (irrigations) the 0.10-0.20 m and 0.20-0.30 m soil layers retained most of the applied solutes (more than stored in the 0-0.10 m layer). Applied solutes tend to accumulate near the dripper source for 4 L h^{-1}, the 0 to 0.10 m layer of soil stored the highest percentage of the solution, i.e., 53%, while the 0.10 to 0.20 m layer stored 28%. Solute flow into the third layer (0.20 to 0.30 m) was observed only after the second application; this flow reached the last layer (0.30 to 0.40 m) after the fourth application. These results indicate that there is a relation between the storage and the volume of water applied to the wetted soil volume, agreeing with conservation of mass, and that increasing the volume applied causes the storage of water to descend to the deepest layer of the soil profile.

Table 2 – Volume and concentration of solution for the soil distribution profile.

Applications	Accumulated applied water	Individual applications	Distribution of the solution Layer (m) 0-0.1	0.1-0.2	0.2-0.3	0.3-0.4	CUC (%)
			Volume (L)				
2 L h^{-1}							
1st	0.94	0.94	0.74	0.18	0.01	0	74
2nd	1.89	0.95	0.51	0.34	0.10	0	64
3rd	2.84	0.95	0.41	0.36	0.15	0.03	64
4th	3.80	0.96	0.24	0.27	0.35	0.11	66
5th	4.77	0.97	0.25	0.29	0.25	0.18	65
4 L h^{-1}							
1st	0.92	0.92	0.81	0.11	0	0	74
2nd	1.83	0.91	0.53	0.23	0.15	0	68
3rd	2.77	0.94	0.46	0.32	0.16	0	66
4th	3.70	0.93	0.39	0.33	0.20	0.01	67
5th	4.66	0.96	0.41	0.28	0.20	0.07	66
6th	5.59	0.93	0.37	0.30	0.19	0.07	69
8 L h^{-1}							
1st	0.96	0.96	0.88	0.08	0	0	64
2nd	1.92	0.96	0.38	0.48	0.11	0	61
3rd	2.87	0.95	0.09	0.24	0.37	0.25	65
			Concentration (mmoL L^{-1})				
2 L h^{-1}							
1st	0.91	0.91	0.61	0.29	0.02	0	84
2nd	2.57	1.66	1.06	0.61	0.04	0.01	63
3rd	4.12	1.55	0.30	0.40	0.80	0.05	65
4th	5.05	0.83	0.09	0.22	0.41	0.11	66
5th	6.23	1.18	0.11	0.37	0.54	0.16	63
4 L h^{-1}							
1st	2.04	2.04	1.40	0.64	0	0	67
2nd	3.03	0.99	0.32	0.32	0.35	0	67
3rd	3.60	0.57	0.19	0.19	0.19	0	63
4th	3.98	0.38	0.10	0.10	0.14	0.04	62
5th	4.66	0.68	0.23	0.15	0.13	0.18	65
6th	5.90	1.24	0.26	0.25	0.32	0.41	65
8 L h^{-1}							
1st	1.88	1.88	1.48	0.40	0	0	69
2nd	2.98	1.10	0.28	0.45	0.38	0	64
3rd	3.97	0.99	0.09	0.51	0.35	0.05	65

The interactions among the different soil water content and solute concentration distribution shows spatial gradient with greater storage of solutes near the dripper and gradual decrease towards the wetting front. However, the mass distribution of potassium nitrate corrected for soil water content show uniform concentration for all analyzed points (with a slight decrease close to the dripper after fourth irrigation displacing KNO_3 towards the edge of the wetted soil volume).

Valocchi (1984) has shown that solute front is retarded relative to the wetting front. However, the modification of this initial condition resulting from the distribution of ions in the profile led to a second condition, in which the electrical conductivity of the newly applied solution and that of the solution adjacent to the dripper showed similar values, promoting the movement of the ions towards the edges of the soil container, accompanying the water flow, in search of the aforementioned stability.

Another observation is based on the soil's CEC (Cation Exchange Capacity) (Rivera et al., 2006), i.e., the potassium of the solution in the soil interacted with the cation exchange complex. This element was therefore retained in the soil adjacent to the point of application, and the solution that flowed to the furthermost regions of the wetted soil volume showed a lower ion concentration.

It is suggested that the distribution of ion concentrations should be studied in a larger number of successive events. This would allow for a better understanding of the phenomenon that occurred during the dynamics of the solution in the soil, providing objective information to help the farmer make the best fertigation management decisions.

Analysis of soil water distribution uniformity

As the initial water content in the soil volume was uniform the average of coefficient of uniformity was 66 % in the soil. From the onset of irrigation, a decrease in soil water coefficient of uniformity has been observed (Table 2). This reflects heterogeneity due to partial wetting of regions near the drippers. In intensive culture, the water content of wetted soil can reach more than 80 % of soil water distribution uniformity (Keller and Bliesner, 1990).

Ould Mohamed El-Hafedh et al. (2001) had noticed a coefficient of uniformity of 90 % indicating an improvement of the bulb moisture distribution. This value is accepted in the drip irrigation system where a strong uniformity has to be accompanied by very important values of the average water content due the saturation of zones close to the drippers.

The values of the distribution homogeneity coefficient for the potassium nitrate distribution profiles were congruous with those observed for the distribution of soil water. This confirmed the strong mobility of potassium nitrate in the soil, which accompanied the water flow in the soil, forming a gradient towards the edge of the wetted soil volume. This finding reinforces the importance of being able to change the distribution of solution in the soil through different combinations of spacing between drippers. Solution that is more evenly distributed in the soil, raising the CUC above the values observed here, spreads the fertilizer homogeneously to the plant's root system, reducing the loss of ions through leaching and contributing to nutrients transport to the roots through mass flow and diffusion mechanisms.

CONCLUSIONS

This study demonstrated the following conclusions: (1) With proper calibration, the TDR and methodology presented here are very promising in the study of the dynamics of solution in the soil; (2) The interactions between the different profiles (water content versus electrical conductivity) revealed a gradient distribution of the solution in the soil, with greater storage of solution adjacent to the dripper, gradually diminishing as it approached the wetting front; (3) For the soil conditions and based on the volume and frequency used during this experiment, it is recommended to apply small amounts of solution at more frequent intervals to reduce the deep percolation loss of water and solutes.

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