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Evaluation of a simple lysimeter-design modification to minimize sidewall flow

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Abstract

A common criticism of many soil lysimeter designs has been the existence of artificial flowpaths along the soil–wall interface. This artificial flow is referred to as sidewall flow. A simple lysimeter-design modification was evaluated that utilizes annular rings to divert sidewall flow near the soil surface into the soil column to minimize the occurrence of sidewall flow along the remainder of the column's length. A chloride-tracer experiment was used to evaluate the effectiveness of annular rings in minimizing sidewall flow in a mesoscale soil lysimeter (0.6 m in diameter and 1.83 m in height). The tracer-experiment data showed that even though sidewall flow may not have been completely eliminated it was reduced to an undetectable level based on chloride distributions and time domain reflectometry measurements. However, a delicate balance exists between minimizing sidewall flow and significantly altering the natural water-flow dynamics when using annular rings. The simple design modification provides a means of using a disturbed column of soil to evaluate models of solute transport, and to study preferential flow and contaminant mobility without concern for spurious data due to artificial flow along the soil–wall interface of the lysimeter. © 2000 Published by Elsevier Science B.V. All rights reserved.

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1. Introduction

A lysimeter is a container of soil intended to represent the field environment that is used to monitor soil–water–plant interactions for the purpose of studying the fate and movement of water, gases, pesticides, nutrients, tracers, trace elements, heavy metals,

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metalloids, radionuclides, viruses or bacteria. Lysimeters have been used for nearly three centuries initially to study water percolation through soil. More recently, lysimeters have been extensively used to evaluate solute transport models (Corwin et al., 1992; Klein et al., 1997; Vink et al., 1997; Butler et al., 1999), to monitor the fate and mobility of soil contaminants (Kördel et al., 1992; Burne et al., 1994; Poletika et al., 1995; Winton and Weber, 1996; Kelly et al., 1998; Corwin et al., 1999), and for evapotranspiration studies (Prueger et al., 1997). Lysimeters have two advantages over tile-drained field plots: (1) less tile-drainage bypass (Bergström, 1987), and (2) a greater degree of control over environmental factors (Bergström, 1990).

Soil lysimeter columns used in contaminant mobility studies and evaluations of solute transport models have been criticized for having artificial flowpaths along the sides of the column (Till and McCabe, 1976; Saffigna et al., 1977). This artificial flow has been referred to as sidewall flow. Sidewall flow in a soil lysimeter indicates an artificial channeling of water due to the separation of the soil from the lysimeter wall creating an airspace. These airspaces serve as artificial flowpaths that permit the rapid flow of water and the transport of solutes, which is a condition that is not representative of the field. Because of this anomalous flow behavior along the column walls, the use of lysimeters in the past to evaluate solute transport models and the mobility of contaminants through soil has been questionable.

There are direct and indirect methods for determining whether sidewall flow is occurring. Three direct approaches to account for sidewall flow include: (1) dyes, (2) tracers, and (3) collection of the sidewall flow. The use of dyes is generally not a quantitative technique. Dyes involve a visual assessment of where the sidewall flow has occurred by inspecting where the dye has accumulated. A quantitative measure of sidewall flow can be made with a guard ring at the bottom of the lysimeter that separately collects the sidewall flow. A tracer may or may not be used in combination with the collection of sidewall flow with a guard ring. However, a tracer will most likely provide a more accurate indication of sidewall flow. If a tracer is not used, then it is assumed that the drainage collected within the guard ring is the result of sidewall flow, which may not be the case. The collection of sidewall flow in a guard ring at the base of the lysimeter is not a reliable measure of sidewall flow through the entire length of the soil column. This is because substantial sidewall flow can occur in the upper portion of the lysimeter where the separation between soil and wall of the lysimeter may be the greatest due to cracking caused by shrinkage when plant roots remove soil water at the upper depths. The water involved in sidewall flow becomes redirected in the lower portion of the column where the contact between the soil and wall is closer as a result of higher water contents that expand the soil against the lysimeter walls. Tracers, on the other hand, provide a quantitative measure of where water has been flowing within the entire column. In essence, tracers provide a ‘‘snapshot’’ of the water flow dynamics.

The most common indirect approach is to use a solute transport model that accounts for preferential flow. This was done by Corwin and LeMert (1994). The preferential flow parameters are determined from an optimized fit of the model parameters to chloride distribution data over time. The problem with this approach is that sidewall flow and preferential flow are lumped together. The significance of sidewall flow in a soil lysimeter can only be inferred by comparing preferential flow parameters determined from the soil lysimeter with those where sidewall flow has been eliminated or significantly reduced.

The ability to quantify sidewall flow does not in itself legitimize a soil lysimeter study unless the results indicate that immeasurable sidewall flow has occurred. In studies that attempt to determine the mobility of a contaminant in soil, the elimination of sidewall flow is crucial. The best means of eliminating sidewall flow in a column of soil is to excavate an intact, undisturbed soil core and wrap the column of soil with material that can expand and contract in unison with the soil. Without the formation of air spaces between the column of soil and the encasing material, no artificial sidewall flow will occur. However, if a large column of soil is desired (i.e., several cubic meters or more), then the sheer volume and mass of soil may make the collection of an undisturbed core prohibitive. In these situations, it may be necessary to take a disturbed soil sample and use it as fill in a lysimeter. For a soil lysimeter of this type, ideas have been proposed to prevent the channeling of water between the soil and the lysimeter wall. They include making the surface of the lysimeter wall rough (Smajstrla, 1985) and installing a barrier (Brown et al., 1985). Corwin and LeMert (1994) proposed a simple, but effective, design that significantly reduced sidewall flow with the use of annular rings that diverted sidewall flow into the column's interior.

Corwin and LeMert (1994) evaluated the reduction of sidewall flow after annular rings had been introduced into the lysimeter design. They made use of an indirect approach, which used the solute transport model TETrans (Corwin et al., 1991) to determine the reduction in bypass resulting from the introduction of annular rings. The bypass coefficient in the TETrans model represents the fraction of the volume of water entering a prescribed thickness of soil that is involved in bypass flow (see Corwin et al., 1991). The flow attributed to bypass was reduced 58% when annular rings were used. However, this approach only determined the degree to which sidewall flow had been reduced by the annular rings. It did not indicate if sidewall flow had been eliminated or if it had been reduced to an undetectable level. A direct measurement of sidewall flow is necessary to evaluate if sidewall flow is still detectable and if it has been reduced to an insignificant level. It was the objective of this study to use a chloride tracer and time domain reflectometry (TDR) to directly evaluate sidewall flow in a mesoscale soil lysimeter as effected by the introduction of annular rings.

2. Lysimeter design, methods and materials

The mesoscale lysimeter used in this study stood 1.83 m in height and 0.6 m in diameter. A schematic of the lysimeter design showing three installed annular rings is illustrated in Fig. 1. To minimize sidewall flow, annular bypass rings were inserted in the column at depths of 7.5, 30, and 60 cm below the soil surface. The annular rings were 3.75, 2.5, and 1.25 cm in width for the three depths, respectively. The purpose of the annular rings was to redirect the flow of any water passing along the column's edge into the column of soil, thereby reducing spurious sidewall-flow conditions. Fig. 2 is an idealized depiction of how the annular rings redirect water from the lysimeter column sides back into the soil to minimize sidewall flow.

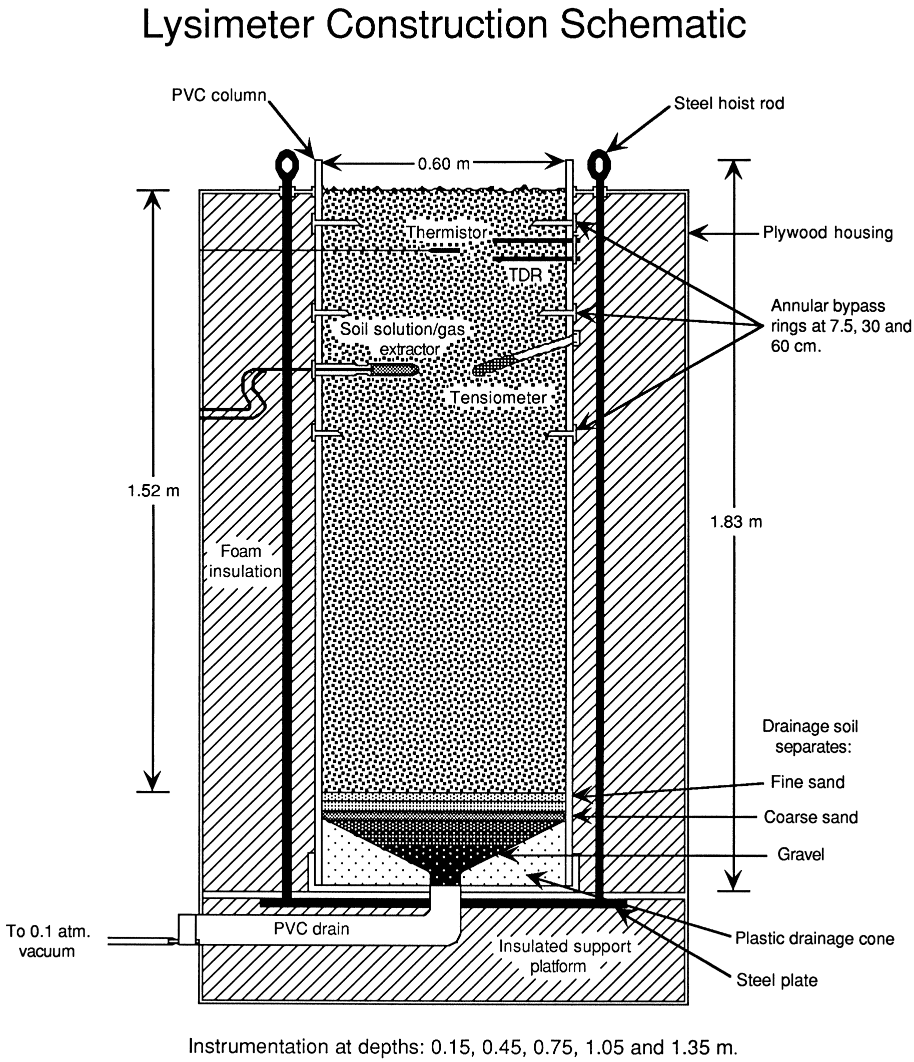

Fig. 1. Schematic of lysimeter design showing the three annular rings.

A disturbed soil sample of approximately 1.6 metric tons was manually excavated from the top 1.5 m of a site lying within the Ascalon soil series (fine-loamy, mixed, mesic Aridic Argiustoll) near Denver, CO. The soil was sieved through a 0.635-cm screen to remove any large organic debris, stones and gravel; and mixed in a concrete mixer to make it as homogeneous as possible. Physical and chemical soil properties of the homogenized Ascalon sandy clay loam are presented in Table 1.

Aside from the use of annular rings, another aspect that was crucial to minimizing sidewall flow was the way in which the soil was packed into the lysimeter, particularly at the soil–wall interface. Precautions were taken to create as closely as possible a

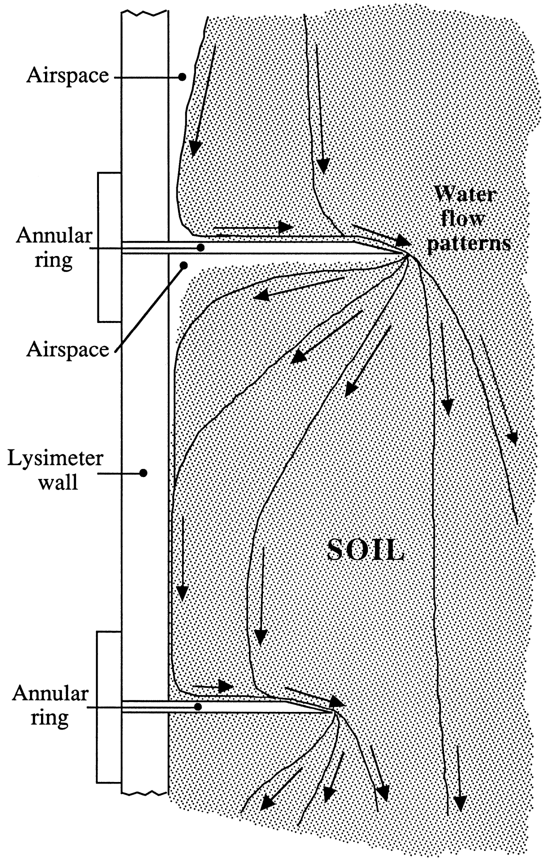

Fig. 2. Idealized depiction of how annular rings minimize the artificial flow of water along the soil–wall interface of the lysimeter by redirecting sidewall flow inward.

column of soil with naturally occurring preferential paths of flow. Care was taken to add very small increments (0.5 cm or less) of soil into the lysimeter that were compacted uniformly with applications of water rather than using the physical pressure of pounding. This was done in an effort to pack the column uniformly. After each increment of soil was added, a series of wetting-and-drying cycles were used to compact the soil. Any shrinkage away from the soil–water interface was filled in with additional soil. After approximately 0.3 m of soil was added, the soil was irrigated 4 or 5 times to further compress the soil, then the whole process was resumed again until the entire 1.52-m long space above the drainage system was filled. Filling the column with soil was a tedious process that took 6 months. The use of wetting-and-drying cycles to promote the settling and compaction of soil particles has been a common approach for packing lysimeters (Jones et al., 1974; Shih and Rosen, 1985; Bowman, 1988).

Subsequent to filling the lysimeter with soil, a drought-tolerant tall fescue (*Festuca elatior* L.) was planted. The tall fescue was intermittently irrigated over a 1100-day

Table 1
Chemical and physical properties of homogenized Ascalon sandy clay loam soil. Values represent averages of six subsamples for the chemical analysis and five for the physical analysis. Standard deviations are shown in parentheses

EC_e (dS/m)	pH_e	Anions (meq/l)					Cations (meq/l)				CEC (meq/100 g)	% Carbon		% $CaSO_4$ H_2O	$\%CaCO_3$	$\%Fe_2O_3$[a]	% Al_2O_3[a]	Saturation percentage (volumetric)		Particle size distribution			Texture	Bulk density[b] (g/cm^3)
		CO_3^-	HCO_3^-	Cl^-	SO_4^-	NO_3^-	Na^+	K^+	Ca^{++}	Mg^{++}		Org.	Inorg.					Paste	Pressure plate[b]	Sand 2 mm –50 μ	Silt 50 μ –2 μ	Clay < 2 μ		
0.89 (0.10)	7.84 (0.22)	*	2.95 (0.59)	1.32 (0.30)	4.15 (0.71)	0.83 (0.37)	4.29 (0.51)	0.14 (0.02)	2.66 (0.43)	2.08 (0.28)	9.56 (2.18)	0.177 (0.015)	0.29 (0.03)	*	2.48 (0.12)	1.330 (0.055)	0.104 (0.004)	33.2 (1.6)	35.6 (3.8)	55.8 (0.8)	23.7 (1.3)	20.8 (0.7)	Sandy clay loam	1.50 (0.07)

[a] Values represent an average of 3 subsamples.
[b] Determined from a packed column soil sample.
* Undetectable.

period before a chloride trace was introduced to evaluate the extent of preferential and sidewall flow. The irrigation amount and the chloride concentration of each irrigation were measured (Fig. 3). The root system of the tall fescue along with repeated wetting-and-drying cycles were the mechanisms by which natural preferential flowpaths developed in the lysimeter to recreate as closely as possible an undisturbed soil column.

The soil column was instrumented with thermistors, tensiometers, soil solution extractors, and TDR probes (for a detailed discussion of the instrumentation see Corwin and LeMert, 1994). The instruments were placed in duplicate at five depths of 0.15, 0.45, 0.75, 1.05, and 1.35 m, except for TDR probes that were installed in duplicate at depths of 0.15, 0.30, 0.45, 0.60, 0.75, 0.90. 1.05, 1.20, and 1.35 m. The TDR rods were 0.15 m in length. The duplicates were located on opposite sides (i.e., north and south sides) of the soil column. The duplicated instrumentation served as a measure of the local variability.

TDR and tensiometer measurements were taken over time to observe the wetting front of each irrigation as it moved through the soil column. The time interval between measurements varied from as little as 10 min to several days based on the time since an irrigation had occurred. The primary objective was to be able to follow the wetting front and the redistribution of water as it moved through the soil column, and the subsequent removal of soil water by the process of evapotranspiration. The TDR measurements provided additional data to evaluate the degree of water flow along the wall of the column. The TDR measurements showed that the column was well drained with no depths remaining saturated for more than a few hours.

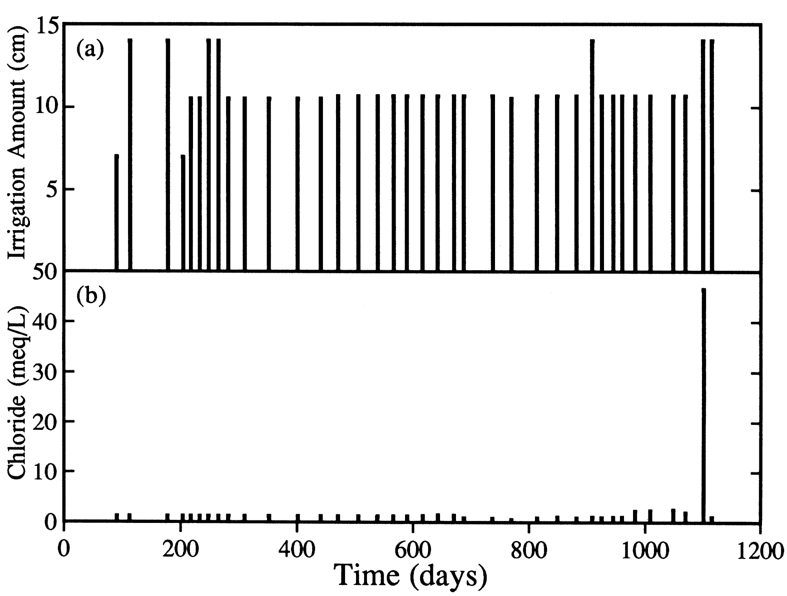

Fig. 3. Irrigation amounts applied to the tall fescue and the associated chloride concentrations in the applied irrigation water. The tall fescue was planted on day 58, which was 32 days prior to the first significant irrigation on day 90. Day 1100 is the time that the plug of chloride tracer was applied.

Table 2
Chemical composition of the water used to prepare the Cl-spiked irrigation water. Four water samples were analyzed at different times to determine temporal variation in the water composition

Sample Date (mn–day–yr)	Anions (meq/l)					Cations (meq/l)				SAR	EC_e (ds/m)	pH_e
	CO_3^-	HCO_3^-	Cl^-	SO_4^-	NO_3^-	Na^+	K^+	Ca^{2+}	Mg^{2+}			
4-17-92	*	4.378	1.160	1.471	0.124	1.627	0.038	4.357	1.074	0.987	0.628	7.92
4-20-92	*	4.260	1.226	1.278	0.128	1.609	0.036	4.288	1.066	0.983	0.630	7.65
4-27-93	*	3.960	1.186	1.504	0.135	1.602	0.049	4.021	1.162	0.995	0.611	7.52
5-4-94	*	4.100	1.136	1.470	0.123	1.575	0.062	3.914	1.172	0.988	0.600	7.35
Average	*	4.175	1.177	1.431	0.128	1.603	0.046	4.145	1.119	0.988	0.617	7.61
Std. dev.[a]		0.183	0.039	0.103	0.005	0.022	0.012	0.211	0.056	0.005	0.014	0.24

[a] Standard deviation.
* Undetectable.

Soil solution extracts were taken after the wetting front had passed and the soil water content had returned to field capacity, which was approximately 2–4 days after an irrigation. The extracts were analyzed for chloride concentration and pH. The soil solution extracts proved to be of no value in evaluating sidewall flow because the ceramic tip was too far from the column wall (Table 2).

A chloride-tracer experiment was conducted to evaluate the effectiveness of the annular rings to minimize sidewall flow. A plug of chloride (roughly 50 meq/l) was applied on Day 1100 to the soil surface of the lysimeter to observe the preferential flow dynamics (Fig. 3). The drainage from the lysimeter was monitored over the entire 1100-day period. However, following the application of the chloride plug, the drainage was monitored until an increase in chloride concentration was detected, indicating that the leading edge of the chloride-tracer plug had broken through the soil column. Further irrigation was immediately terminated. The soil in the lysimeter was excavated and sampled to get a snapshot of the distribution of chloride through the lysimeter. Two sets of soil samples were taken at 0.15 m depth increments for the entire 1.5 m length of the soil column. One set of samples consisted of a continuous 2.5-cm thick band of soil peripherally located at the soil–wall interface, subsequently referred to as the ''external soil samples''. At three depth increments (0–0.15, 0.60–0.75, and 1.35–1.50 m) the 2.5-cm continuous band of soil taken at the soil-wall interface was divided into four quadrants rather than making a composite of the entire band. This provided a measure of the variability to better isolate where sidewall flow may have occurred. A second set of samples consisted of composite soil cores taken in a concentric circle from within the center area of the lysimeter, subsequently referred to as the ''internal soil samples''. A saturation paste was prepared from each soil sample and the extract was analyzed for chloride concentration using a Cl^- titrator. Comparisons of the chloride concentrations at each 0.15-m depth increment for the set of external samples and the set of internal samples provided an understanding of the preferential flow dynamics to evaluate if sidewall flow had occurred and where.

Temperature was continuously monitored. Even though the column was not sufficiently insulated for the soil to simulate the fluctuation of natural soil temperature conditions over a depth of 1.35 m, the insulation was sufficient to eliminate the rapid fluctuations found in daily changes; consequently, the column showed seasonal fluctuations over all depths with very little lag time from one depth to the next, but rapid daily fluctuations were minimized.

3. Results and discussion

The measurement of chloride concentration from the soil solution extracts showed no sign of the occurrence of sidewall flow. However, the soil solution extract results are inconclusive because the extractors extended too far into the soil column to provide an accurate understanding of what was actually occurring at the soil-wall interface.

Examples of typical wetting-front behavior in soil lysimeters with and without the occurrence of sidewall flow are shown in Fig. 4. Fig. 4 shows TDR measurements of water content for a single, representative irrigation in (a) a soil column with annular

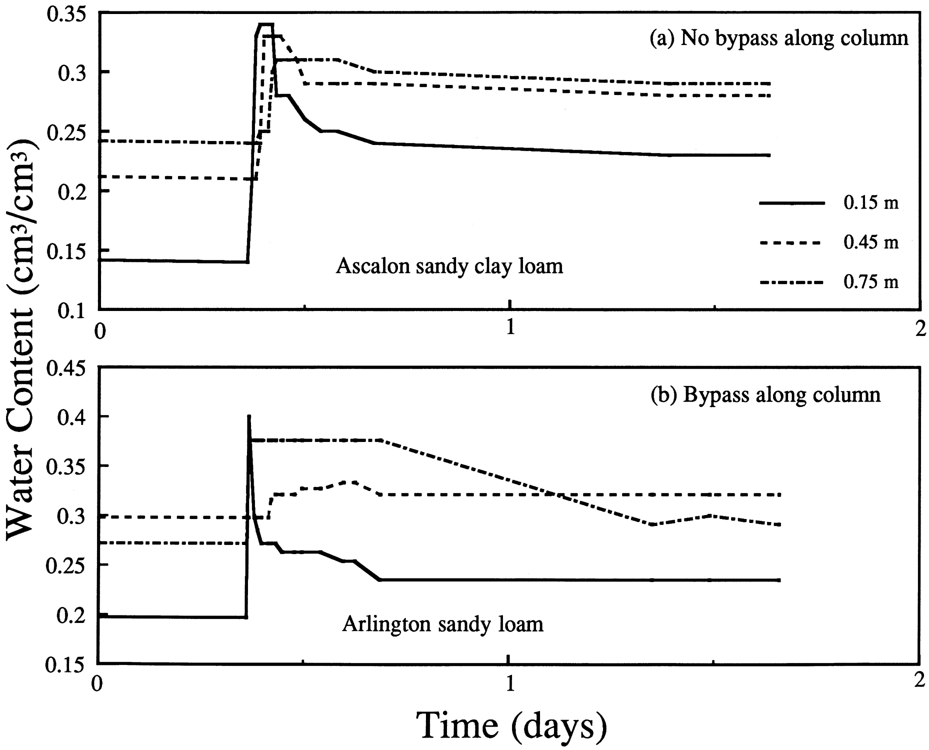

Fig. 4. TDR measurements of water content for a single, representative irrigation event at depths of 0.15 m, 0.45 m, and 0.75 m: (a) data for a soil column with annular rings installed to prevent channeling of water along the column sides, and (b) data for a column without annular rings.

rings to prevent the channeling of water along the sides of the column, and (b) a soil column without annular rings. The wetting front of the annular-ringed column shows the characteristic increase in water content at successive depths as the wetting front moves through the soil profile (Fig. 4a). In cases where channeling along the sides of the column occurs, TDR measurements of water content show either a nearly uniform increase in water content with depth over time due to the rapid filling of the crack between the column and the soil, and the subsequent lateral movement of water, or the bypassing of a depth altogether so that a lower depth increases in water content and upper depths follow (Fig. 4b). In Fig. 4a, TDR measurements of water content for the soil column outfitted with annular rings show no indication of flow along the sides of the column. The data for the soil column with annular rings show the classical progression of the wetting front through soil profile as found under field conditions, thereby suggesting that the artificial channeling effects due to the presence of a soil-wall interface had been significantly reduced. However, the measurement of water content over time with TDR by itself does not constitute proof of the absence of sidewall flow. TDR may not be sensitive enough to detect all preferential flow because TDR measures the average water content between the rods. In addition, sidewall flow may have occurred at locations outside the measurement volume of the TDR rods.

The most conclusive evidence for the presence or absence of sidewall flow comes from the data for the chloride-tracer experiment. Fig. 5 shows the profile distribution of chloride in the soil samples at 0.15 m increments for the internal and external soil samples shortly after chloride had been detected in the drainage water. Ideally, the chloride distribution at the center of the column would be exactly the same as the chloride distribution in the soil adjacent to the lysimeter wall, if sidewall flow was the only process affected by the annular rings. The most obvious indication of the occurrence of sidewall flow would be the presence of high chloride concentrations in the external soil samples at the bottom depths of the lysimeter. Because the chloride concentration for the internal and external soil samples was virtually identical at the bottom of the lysimeter, then sidewall flow had probably not occurred in the lower portion of the soil column. In fact, at every depth below 0.3 m, the chloride concentration of the external soil samples was essentially the same or less than at the center of the lysimeter. The lack of chloride ‘‘hot spots’’ at the periphery indicates that sidewall flow was not occurring to any noticeable degree below 0.3 m, which further substantiates the reduction of sidewall flow to an insignificant level. This suggests that the annular rings had fulfilled their intended purpose of minimizing sidewall flow.

Aside from influencing sidewall flow, the annular rings appear to have slightly altered the water-flow patterns within the soil column. The chloride profile–distribution curves for the internal and external soil samples reflect the influence of the annular rings on the water flow. The chloride distribution curve for the external soil samples indicates

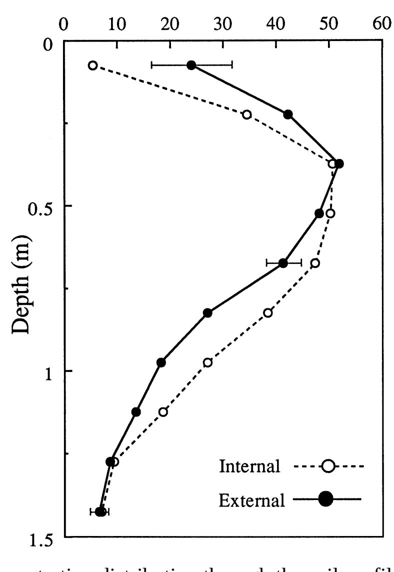

Fig. 5. Soil solution chloride concentration distribution through the soil profile at the periphery (solid line) and at the center of the column (dashed line) following the application of the chloride tracer. Variability is shown for the 0–0.15, 0.60–0.75, and 1.35–1.50 m depth increments with a standard deviation band, which is the average soil solution chloride concentration ± the standard deviation.

that the three annular rings acted as barriers that retarded the movement of chloride resulting in a curve that lags behind the curve of the internal samples. The higher chloride concentration in the top 0.30 m of soil at the periphery of the lysimeter suggests that considerable sidewall flow occurred above the first annular ring. Presumably, water moved easily and readily along the soil-wall interface until it reached the first annular ring at 0.075 m where a buildup of chloride in the soil immediately above the ring occurred due to the impeded flow (see Fig. 2). The fact that no appreciable buildup of chloride occurred below the top 0.30 m of soil suggests that the first and second annular rings sufficiently redirected the sidewall flow away from the lysimeter wall. If any preferential flow occurred it would have had to occur through natural preferential flowpaths (e.g., root channels, cracks, macropores) that had developed away from the sidewalls of the lysimeter. This is substantiated by the identical chloride concentrations at the bottom of the soil column for both the internal and external soil samples. Though it cannot be stated that sidewall flow was completely eliminated, it can be stated that preferential flow away from the column walls significantly exceeded that of sidewall flow as shown by chloride-tracer distributions.

Aside from slightly retarding the movement of chloride at the periphery of the soil column, the annular rings also appear to influence the shape of the chloride profile–distribution curves. Below 0.5 m the curve for the internal samples shows a gradual decrease in chloride concentration compared to the curve for the external samples, which decreases more sharply. If the annular rings had only acted as a barrier to slow water flow, then the shape of the curves for both the internal and external soil samples would be the same. Furthermore, the chloride profile-distribution curve for the internal soil samples below 0.5 m does not decrease as sharply as would be expected under conditions of normal water flow. The fact that the curves are different suggests that water-flow patterns had been influenced probably due to the redirection of water along the edges to the center of the column. Slightly greater water flow was occurring near the soil column's center. Ostensibly, the annular rings are complicating the water-flow patterns by introducing a lateral water-flow component directed away from the column's side at the upper depths. The greatest influence would probably be upon the faster flowing water associated with the periphery of the column (consisting mainly of the water associated with sidewall flow near the surface). This fast-flowing water is redirected inward toward the column's center and results in higher-than-expected concentrations of chloride for internal samples lower in the column as reflected by the high chloride concentrations at depths of 0.825, 0.975, and 1.125 m for the internal soil sample curve.

Fig. 5 also shows the variability of the distribution of chloride tracer at the outer edge of the soil column as reflected by the standard deviation band (i.e., ± 1 standard deviation) for the top (0-0.15 m), middle (0.60-0.75 m) and bottom (1.35-1.50 m) depth increments of the external soil samples. If chloride moved uniformly through the soil, then the standard deviation of the chloride concentration would be expected to be low and roughly the same throughout the column. However, the existence of preferential flow paths would cause considerable spatial variability in chloride concentration, thereby causing higher standard deviations where greater variability occurred. The significantly larger standard deviation for the top depth indicates a higher variability in the chloride concentration with greater uniformity existing at the two lower depths. The larger standard deviation at the surface suggests that preferential flow occurred at certain locations more than others. The occurrence of preferential flow might either be caused by naturally occurring surface cracks or by sidewall flow. Therefore, the decrease in standard deviation with depth can be due to (1) a reduction in sidewall flow with depth due to the influence of the annular rings, (2) a decrease in natural preferential flow because of fewer surface cracks extending deeper into the soil column, or (3) a combination of both decreased sidewall and natural preferential flow with depth.

4. Summary

This study has evaluated the use of annular rings for a lysimeter packed with disturbed soil. However, the impact on solute movement of artificially packing the soil is, in many cases, larger than the impact of sidewall flow. For this reason, several precautions were taken to minimize the impact of artificial packing. Specifically, the soil was packed in thin layers of 0.5 cm or less followed by repeated irrigations to settle and compress the soil particles. To develop natural preferential flowpaths, a tall fescue was planted and grown for 1100 days prior to the introduction of a chloride tracer to evaluate the occurrence of sidewall flow. This whole process was designed to reduce artificial flowpaths and develop natural paths of preferential flow in an effort to create as closely as possible a column of soil that resembled undisturbed soil. Nevertheless, the use of annular rings in an undisturbed soil column remains to be evaluated. Undisturbed soil presents additional difficulty since the annular rings must be inserted into the soil column rather than packing soil around the rings. This will require that the column of soil is irrigated prior to the insertion of the rings to make the soil less rigid in an effort to minimize the introduction of unwanted non-representative stress cracks in the soil. However, annular rings are probably best suited for situations where a disturbed soil column is required.

Previous experiments with soil lysimeters have shown that artificial flowpaths commonly occur along the soil-wall interface resulting in the rapid movement of water down the side of the lysimeter (Till and McCabe, 1976; Saffigna et al., 1977; Corwin and LeMert, 1994). This sidewall flow is generally caused by the shrinkage of soil away from the column walls during wetting-and-drying cycles, which leaves an open channel for the flow of applied water at the soil surface. The problem of sidewall flow has been addressed by the introduction of annual rings (Corwin and LeMert, 1994) and further evaluated in this study. The annular rings were effective mechanisms for minimizing sidewall flow. Though it cannot be stated that sidewall flow was completely eliminated, it can be stated that artificial flow along the column walls was significantly reduced to undetectable levels based on chloride-tracer and TDR data. However, the fact that water-flow patterns appear to have been detectably altered and that no sidewall flow appeared below the second annular ring indicates that the number and widths of the annular rings could be reduced to minimize effects on water-flow patterns without diminishing their effectiveness to minimize sidewall flow. Two annular rings at depths of 7.5 and 30 cm with widths of 3.75 and 1.25 cm, respectively, would probably be sufficient to minimize sidewall flow and alterations to water-flow patterns. In addition, an evaluation of the effectiveness of annular rings in reducing sidewall flow in high clay content soils that exhibit high shrink-swell characteristics needs to be conducted. The use of the simple annular ring modification makes lysimeters containing disturbed soil a more effective tool for studying solute transport through the root zone by minimizing the artificial flow of water and transport of solutes along the column walls.

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