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Assessment of free-flowing soil solution using zero tension samplers

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Abstract In soils containing macropores, free-flowing soil solution percolates preferentially, resulting in the rapid transport of solutes through the vadose zone. The objective of this study was to quantify the volume and estimate the velocity of free-flow under controlled rainfall rates and known initial moisture conditions. For this purpose, 45 Zero Tension Samplers (ZTS), distributed in the top 78 cm of three pits were used to collect free-flow during and after rain simulations. The initial soil-water content was monitored using Time Domain Reflectometry probes. The volume and velocity of free-flow were determined using repeated discharge measurements to construct outflow hydrographs for all the samplers. The recovery of free-flow (ratio of volume recovered divided by the volume of water applied) had a mean of 0.13 and a coefficient of variation of 0.84. The mean time lag between the application of rain and the recovery of soil solution was 0.40 h. The preferential flow was channeled through 0.57% of the soil volume. Free-flow was initiated without the soil being completely saturated, however, the volume of free-flow depended on the initial soil-moisture conditions and the rate of rainfall application.

INTRODUCTION

The rate of transport of solutes and contaminants in the unsaturated zone depends on the velocity of the infiltrating soil solution. In soils containing macropores (e.g. cracks, worm holes, or decayed root channels) free-flowing soil solution may percolate preferentially through these channels at velocities higher than those in the primary soil matrix. As demonstrated by Thomas & Phillips (1979), this preferential flow can contribute to the rapid transport of contaminants in the vadose zone.

Several researchers have monitored the transport of free-flowing solution using Zero Tension Samplers (ZTS). Barbee & Brown (1976) and Magid & Christensen (1993) compared the soil solutions collected by ZTS and tension samplers. Barbee & Brown (1976) concluded that ZTS were more efficient in sampling free flow. Magid & Christensen (1993) suggested that the soil solution collected with a ZTS represents the actual flux of solute transported through the soil. Haines *et al.* (1982) reported discrepancies between the chemical properties of samples recovered in ZTS and tension samplers. They attributed these discrepancies to the differences in residence time of the two solutions in the soil. They argued that solution sampled in ZTS has a short residence time. Shaffer *et al.* (1979) reported that preferential flow in macropores channeled a tracer of bromide rapidly to depths of 38 and 120 cm, with little change in bromide concentration.

If preferential flow is initiated, a small fraction of the soil pores will channel, by gravity, a large fraction of the flow. Indeed, the theoretical analysis of Shaffer *et al.* (1979) suggested that the pore fraction draining between 0 and -2 kpa of matric potentials (i.e. the macropores and mesopores of the soil (Wilson & Luxmoore, 1988)), contributed 90 percent of the total flux through the profile. Hence, the transport of a large percent of the solution flux through a small fraction of pore volume will result in elevated flow velocities.

The objective of the study reported in this paper was to estimate the volume and velocity of free-flow and the fraction of pores leaching solution to a ZTS under controlled rainfall rates and known initial soil-moisture conditions. The hypothesis investigated was that rainfall rates and initial soil moisture conditions may control preferential flow. This preferential flow will determine the volume and flow velocity of soil solution recovered in a ZTS. These velocity measurements are important in modeling contaminant transport through the vadose zone for two reasons. First, the knowledge of velocity can be used to explain the rapid breakthrough of solutes, e.g. nitrates and salts, in the vadose zone (Thomas & Phillips, 1979). Secondly, in the case of colloidal sized particles, e.g. bacteria and viruses, the velocity of flow controls the distribution of shear at the liquid-solid interface of the soil-water system. This shear influences the detachment and partitioning of these particles between the liquid and solid phases (e.g. McDowell-Boyer *et al.*, 1986).

METHODS

Description of the site and instruments

The experimental field site is located at Rocky Flats Environmental Technology Site (RFETS), approximately 26 kilometers northwest of Denver, Colorado. The ground surface is characterized by natural short-grass prairie and valley-side vegetation. The soils in portion of RFETS are contaminated with plutonium and americium that leaked from a storage facility (Litaor, 1993). This study is a part of an ongoing effort to understand the mechanisms of preferential flow and actinides transport at RFETS. There is some evidence that small amounts of actinides may have moved to greater depths through a network of macropores formed by decayed root channels (Litaor *et al.*, 1994).

Three instrumented pits (5.5 m long) were located in areas of known actinides contamination that had the potential for preferential flow. The soil in the pits was classified as Aridic Argiustoll. The A horizon is a dark surface layer composed of humified organic matter mixed with minerals and rock fragments. The B horizon, underlying the A horizon, is a zone of pedological transformation and is richer in clay content than the A horizon. The depth to the water table fluctuates between two and three meters at the locations of the pits. The soil-texture distribution, organic matter content, and bulk density of the soil horizons in the pits were measured.

A ZTS consists of a half-section polyvinychloride (PVC) pipe (36x15 cm) capped at one end. Forty-five ZTS were used in this study. Five ZTS in each genetic soil horizon of every pit. Zero tension samplers recover soil solution in the narrow range of 0 and -5 kpa matric potential (Litaor, 1988). Water collected by the ZTS flows gravitationally to a collection bottle mounted on a load cell located below the sampler. Load cells recorded the weight and the time of water collected. The soil-water content was monitored by Time Domain Reflectometry (TDR) probes. In each pit, TDR probes were inserted in clusters of four, with two clusters per depth in three horizons, for a total of 24 probes per pit. The principles of TDR operation are discussed by Topp *et al.* (1980).

An automated spraying system was used to conduct the artificial rainfall simulations. The uniformity of the spray application was maintained by a wind skirt. The length of the frame permitted for full coverage of the pits, allowing for 30.5 cm of overhang to minimize boundary effects.

Rain simulations and data collection

Three rain simulations were performed on the three pits using an intensity of 6.75 cm h^{-1} for a 1-h duration. The simulations started at 9:00 a.m. on August 2, 3, and 9, 1993 for pits 1, 2, and 3 respectively. A second simulation on pit 3 was performed on August 24. The second simulation on pit 3 used the same volume of water (i.e. 6.75 cm), as in the first experiment, but water was applied over a thirty minute interval, thus producing twice the rain intensity of the first experiment. Sampling started immediately after the beginning of a simulation and continued for six hours. The samplers were checked on the following day (around 9:00 a.m.) for solutions recovered overnight. No solution was recovered overnight.

The TDR probes were monitored for several hours prior to the beginning of each rain simulation to determine the initial soil-water content. After the beginning of the rain simulation, monitoring of the water content continued at thirty-minute intervals.

Analysis of the outflow hydrographs of recovered soil solution

For each ZTS, the outflow hydrograph was constructed from the repeated measurements of discharge solution. Hydrograph shapes were characterized by their peak discharge rate (q_p), the mean discharge rate (q), and the time lag. The mean discharge rate (q) is the time-averaged discharge rate over the total collection time. The time lag is defined as the time difference between the center of masses of the hydrographs of applied rain and recovered solution. Hence, the mean velocity of recovered solution (v) was determined by dividing the depth to a sampler from the ground surface by the time lag (e.g. Mosley, 1982). The ratio of the discharge rate (q) to the velocity (v) is denoted θ, which represents the effective fraction of soil volume conducting the flow to the sampler. The term "effective" is meant to exclude dead-end macropores or other pores that were not activated or were not intercepted by the sampler. The area under the hydrograph gives the total volume of solution outflow expressed in cm^3/cm^2. The ratio of the total volume of solution outflow to the 6.75-cm input of rain was defined as the Recovery (RE) of a ZTS.

RESULTS

The soil textures and bulk density of three genetic horizons are shown in Table 1 for the three pits. The effective porosity of the soil was estimated from the bulk density and soil-texture measurements using the algebraic equations provided by Rawls & Brakensiek (1989). The effective porosity, Φ_e, also known as the water content at natural saturation, is the porosity corrected for air entrapment. To show the soil-moisture conditions, Table 2 shows the effective porosity of the soil (Φ_e), the initial water content, and the water content after three hours after the beginning of the rain. The monitoring of the TDR probes for several hours prior to the experiments indicated no change in the distribution of soil-water content before the simulations. This initial immobile water is presumably held by capillarity in the soil matrix. The water content increased with depth due to the increase in clay content with depth, as shown in Table 1. During and after the simulations, the water content recorded by the TDR probes remained below Φ_e, which suggests that the soil horizons remained unsaturated during the experiments. Also, ponding and surface (overland) flow were not observed on the ground surface within the test area at any time during the simulation.

Table 1 Physical properties and classification of horizons in the three pits.

	Pit 1			Pit 2			Pit 3		
Horizon	A	Bt	2Bt	A	AB	Bw	Bt1	Bt1	Bt2
% Sand	64.4	49.1	36.1	67.3	58.1	60.4	38.4	38.4	38.6
% Clay	16.5	34.2	36.5	15.6	26.3	25.7	40.0	40.0	37.5
Organic Matter (g/Kg)	104	13	4	100	20	0.9	1.8	1.8	0.7
Bulk Density (g/cm³)	1.01	1.46	1.4	1.63	1.36	1.48	1.20	1.20	1.50

Table 2 Effective soil porosity and measured water content[1], before and 3 hr after, the start of a rain simulation.

	Pit 1			Pit 2			Pit 3		
	Φ_e	water content		Φ_e	water content		Φ_e	water content	
		0 hr	3 hr		0hr	3 hr		0 hr	3 hr
Horizon 1	0.55	0.12	0.22	0.35	0.12	0.25	0.49	0.089	not measured
Horizon 2	0.40	0.21	0.27	0.44	0.21	0.26	0.49	0.20	
Horizon 3	0.42	0.31	0.31	0.40	0.27	0.28	0.39	0.29	

[1] Water contents are averages of at least five TDR probe readings.

Variability of RE and v, and evidence of preferential flow

The distribution of the RE, v, and θ of the ZTS in the horizons showed pronounced variability. The recovery had a mean of 13.5% with a coefficient of variation of 0.84 for the samplers. The RE varied between a maximum of 40.6 % for a sampler at the depth of 10.2 cm in pit 2, to zero for several samplers in the third horizon of pits 1 and 2. This pronounced variability was evident even for samplers within the same genetic horizon of the same pit where factors such as depth from the surface, rain boundary condition, initial moisture conditions, and soil texture were similar. For example, in pit 1, sampler 8, which was at the same depth and 81 cm distant from sampler 9, recovered 7 times more solution than sampler 9. In many cases, soil solution was recovered in the deeper ZTS earlier than in the shallower ZTS. For example, the time lag for recovery of the soil solution in sampler 6 (at the depth of 31.8 cm), was shorter than the time lag for sampler 4 (at the depth of 10.2 cm) in pit 2. The variability in RE and time lags suggest that the generation of free flow at the sampler scale will be difficult to predict because it can be controlled by networks of preferential channels. The variability of RE between the different ZTS can also be attributed to variation in the micro-topography of the soil surface, which may distribute the applied rain non-uniformly at the surface.

The average recovery of soil solution per pit and for each horizon indicate that higher initial moisture content was not a sufficient condition to generate free flow into deeper horizons of the soil profile (Table 3). For example, the RE in the third horizon of pit 3 was 12.6%, whereas the RE for the same horizon in pit 1 was 0.2% even though the initial soil moisture content was higher in pit 1 than it was for pit 3 (Table 2). Soils in horizons two and three of pits 1 and 2 had similar initial moisture conditions (Table 2) and were subjected to the same rain intensity and duration. The RE in the second horizon of pit 2 was three times the RE of this horizon in pit 1. Apparently, at the pit scale, controlling the application rate and the initial soil-moisture content was not sufficient to produce similar RE for the different pits. Hence, modeling preferential flow at the pit scale will be difficult because it may require detailed knowledge of the distribution of soil macropores and mesopores.

The average of the velocities for all the samplers was 94 cm h^{-1}. The observed rapid flow of soil solution was anticipated because gravity-driven flow in large pores is subject to less resistance than flow in the soil matrix. Similarly, the rapid flow of soil solution can be explained by the time lags between the applied rain and the recovered solution. The average time lag for the samplers was 0.40 h. This small time lag

Table 3 Mean recovery per soil horizon and pit.

	RE (%):			Mean RE per horizon
	Pit 1	Pit 2	Pit 3	
Horizon 1	24.1	27.2	9.5	20.3
Horizon 2	7.6	26.4	9.6	14.5
Horizon 3	0.2	4.7	12.6	5.8
Mean RE per pit	10.6	19.4	10.6	13.5

indicated that the flow of soil solution occurred within a short period during and after the rain.

The average value of the effective fraction of soil conducting the flow, θ, was 0.0057 cm^3/cm^3. This indicates that the flow was channeled preferentially in a relatively small fraction of soil volume. On the average, as was the case with RE, decreased with soil depth, as shown in Tables 3 and 4. We hypothesize that as free flow percolates toward the ZTS, a larger fraction of moisture is diffused to the surrounding soil matrix to satisfy the capillarity or moisture-content deficit. Hence, a smaller volume of soil solution flowed freely to greater depths. The decrease in may also be due to a decrease of available preferential flow channels with depth, due to fewer plant roots penetrating to greater depths.

Table 4 Average per horizon of the effective fraction of soil volume conducting the flow to the Zero Tension Samplers.

	Average depth to Zero Tension Samplers (cm)	θ
Horizon 1	18.6	0.010
Horizon 2	32.6	0.0050
Horizon 3	53.7	0.0022

Sensitivity to application rates

The previous simulations on the different pits were performed to study the heterogeneities among the pits. On the other hand, the second simulation on pit 3 was performed to assess the impact of rain intensity and antecedent moisture conditions on the generation of free flow within the same pit. In this second simulation, the same volume of rain was applied at twice the rate of the first experiment. Surface flow due to ponding was not observed even for this higher-intensity simulation. The soil initial water content was approximately 5 % higher than the water content in the first experiment.

The recovered volume of solution for the second simulation with a higher application rate was approximately 2.3-times larger than the solution recovered in the first simulation (Table 5). This result suggests that more free flow is being generated with the increase in rain intensity and initial soil-moisture. The difference between the two simulations can be explained in terms of the infiltration capacity of the soil matrix

Table 5 Comparison of the two simulations on pit 3.

Rain intensity (cm hr^{-1})	RE (in %)	θ	v (cm hr^{-1})
6.75	10.6	0.0052	98.08
13.5	24.2	0.0058	290.63

and the theory of preferential flow. In general, macroporosity constitutes only a small fraction of the total soil porosity (e.g. Wilson & Luxmoore, 1988). Hence, when the rain was applied uniformly at the surface in the first simulation, a large fraction of the rain was captured by the capillarity of the soil matrix and was unavailable for free flow through the macropores. This captured fraction of the soil solution may not be collected by the ZTS because the flow is at too high a matric potential. However, when the rain intensity was doubled for the second simulation, the rain application rate may have exceeded the infiltration capacity in the soil matrix; a higher initial water content at the beginning of the second simulation also served to reduce infiltration capacity in the soil matrix. Hence, under the conditions of the second simulation, a larger fraction of soil solution was able to utilize the preferential channels and percolate freely to the ZTS.

As indicated in Table 5, this significantly larger volume of free flow was channeled through an effective fraction of soil volume (θ), which was only 0.0006 cm^3/cm^3 larger than θ of the first experiment. This behavior was consistent with macropore flow conditions where a small fraction of the soil is responsible for conducting most of the flow. Indeed, the increase in θ is comparable with the macroporosities suggested by Wilson & Luxmoore (1988). In theory, the flow is routed to macropore channels when the application rate exceeds the infiltration capacity of the other pore groups e.g., micropores of the soil matrix (Wilson & Luxmoore, 1988; Jardine *et al.*, 1991). In the second simulation, this condition was more likely to occur due to the intense rainfall rate. The velocity of flow increased by nearly three-fold during the second simulation (Table 5).

CONCLUSION

Free flow was observed in the vadose zone of RFETS under controlled rainfall rates and known soil-moisture conditions. Even for very similar experimental and field conditions, free-flow percolated preferentially through the soil, resulting in substantially different volumes collected in different ZTS. The spatial variability of the RE was pronounced at both the local sampler scale and the pit scale. At the pit scale, heterogeneities in preferential channels influenced the process of generation of free-flow; controlling the initial and boundary conditions at this scale was not sufficient to produce similar results for the pits.

The observed free-flow at RFETS was fast and occurred in a small fraction of the soil volume. In the first three simulations, the time lag between the applied and the recovered solution was 0.40 h. The mean velocity of flow was 94 cm h^{-1}. These elevated flow velocities should be used to explain the generally observed rapid transport of solutes due to preferential flow.

Saturation of the soil profile is not essential to generate free-flow. Indeed, free-flow was sampled while the TDR probes indicated less than full saturation in the soil horizons. However, for the same pit, increasing the rain intensity and the initial soil-moisture content caused a larger volume of soil solution to bypass capillary forces and to flow freely in preferential channels of the vadose zone.

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