Preferential Flow Estimations to a Subsurface Drain with Bromide Tracer

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Introduction

The processes associated with water movement through the soil layers involve both the flow through the macropores (preferential flow) and flow through the micropore (diffused, matrix, or Darcian flow). The significance of the preferential flow is currently unknown. Temporal effects caused by swelling of the clay in structured soils like Grenada and Loring series and drying to produce cracks need to be assessed. Further, macropore differences caused by tillage operations need to be ascertained. Thus, the purpose of this work was to separate the water reaching a subsurface drain during rainfall simulation into its matrix porosity and macroporosity components. Once the magnitudes of the two flow components were estimated, the relative importance of each in solute transport could be assessed.

Ground water contamination by agricultural chemicals has been reported in over 800 of the 1437 counties in the U.S. (National Research Council 1989). This may indicate a significant adverse impact on the environment. The need for more research and management practices that produce profitable yields while minimizing environmental contamination is great. Pesticide use in agriculture has increased dramatically. Currently, one billion kilograms of more than 400 different types of pesticide chemicals are sprayed each year on America's croplands (National Research Council 1989).

Rapid fluxes through continuous preferential paths in soils caused by tillage management, worm holes, root holes, macropores, and/or cracks may play an important role in chemical pollutants reaching ground water. Consequences of preferential flow (non-Darcian or macropore flow) include: 1) recharge of the ground water before the soil reaches field capacity; 2) less moisture for crop development because some of the water may move out of the influence of the root zone; and 3) the movement of some of the chemicals applied at the soil surface to greater depths than predicted by Darcian flow (piston displacement or matrix potential). Chemical pollutants may bypass the biologically-active root zone through these preferential paths, thus reducing their residence time (time which would allow for degradation) before reaching the ground water (Thomas and Phillips 1979; Everts and Kanwar 1990; Oosting et al. 1987; Priebe and Blackmer 1989; Logsdon et al. 1990; and others). Leaching may occur when chemicals diffuse from the smaller pores to the surface of the macropores (Thomas and Phillips 1979).

Although these macropores provide pathways for deeper penetration of water into the soil profile by gravity than the wetting front established by Darcian principles or mass transport at field capacity, their overall contribution to ground water contamination is likely to be insignificant due to the fragipan layer found in many soils of north Mississippi. This layer, characterized by high bulk densities, very low hydraulic conductivities, brittleness, compactness, and absence of fine feeder roots in the brittle portion (Soil Survey Staff 1975), impedes the vertical movement of water into the soil profile. Rhoton and Tyler (1990) and Römkens et al. (1986) showed higher bulk densities of the fragipan layer when compared to the layer above the pan. As bulk density increased, the number and size of pores decreased which reduced the saturated hydraulic conductivity. Römkens also noted a decrease in silt content and an increase in clay content in the deeper parts of the soil profile which would further retard Darcian flow. Lateral water movement along the surface of the fragipan is suspected (Römkens and Grissinger, personal communications 1991). The excess water (difference of Darcian flow in layer above fragipan to that into the fragipan) either enters large cracks in the fragipan to continue its downward movement or exits down slope onto the soil surface to enter streams as surface runoff. If these cracks are not continuous through the fragipan, the water in the cracks enters into the soil matrix of the unsaturated soil layer above the pan to be used by the growing crop or into the slower moving Darcian flow in the fragipan layer.

Soil properties such as texture, porosity, organic matter content, clay mineral content, and moisture content influence the fate and transport of water and subsequently, dissolved pesticides in the subsurface environment (Römkens et al. 1986). Sandy soils with low clay content provide a higher potential for pesticide leaching than silt soils (Baver 1966). However, silts and clays, which have a number of macropores and fissures, enhance the potential for preferential flow (short-circuiting Darcian flow) of water and dissolved pesticides to ground water.

The movement of water through a given volume of soil is dependent on the soil pore space. This movement is brought about by the action of gravity or capillary pull, either alone or in combination. The type of water movement is influenced by the dominance of the moving force. Water moves in the large pores primarily through the action of gravity characterized in saturated soils. Water also moves primarily by the action of capillary forces from surface to surface or in small pores in the presence of numerous air-water interfaces characterized in unsaturated soil (Baver 1966; Campbell 1985). Greater detail into these types of movement is given in these references.

Only recently have the large continuous openings (macropores) in soils been recognized as an important factor in the movement of soil water. While macropores may make up only a small portion of the total soil voids, they may dominate vertical flow rates during infiltration (Beven and Germann 1982). Thomas and Phillips (1979) pointed out gravitational flow of water occurred readily in soils that were below field capacity. The presence of macropores may cause different responses from predictions based on Darcian principles when the macropores conduct water rapidly through the unsaturated soil ahead of the wetting front and the flow in the macro pores is turbulent in either saturated or unsaturated zones (Beven and Germann 1982).

Recent research illustrates the importance of macropores in the movement of water and agricultural chemicals through the root and vadose zones. Labeled water and urea were found deeper and more dispersed than predicted in a leaching study with undistributed soil columns (Priebe and Blackmer 1989). Darcian (matrix) and preferential flow were separated in a field tracer study showing preferential flow contributing less than 2% total outflow volume that carried 25% bromide and 21% nitrate in tile drainage (Everts and Kanwar 1990). Importance of preferential flow through the macropores was also documented by additional research of Germann (1988), Thomas and Phillips (1979), and White (1984).

Many hydrologic models describing infiltration and water movement in soils are based on simplifying assumptions of homogeneity and isotropic soil conditions, thus predicting water movement by Darcy's Law (Beven and Germann 1982). However, soils are not homogeneous and preferential flow has been commonly observed in structured soils (Everts and Kanwar 1990; Priebe and Blackmer 1989). The existence of preferential flow paths for water movement increases chemical transport into the soil profiles (Everts and Kanwar 1990). Chemical transport models such as GLEAMS, [Ground Water Loading Effects of Agricultural Management System (Leonard et al. 1987)], PRZM, [Pesticide Root Zone Model (Carsel et al. 1985)], and EPIC, [Erosion-Pro ductivity Impact Calculator (Sharpley and Williams 1990)]; however, do not include water and chemical transport attributed to preferential flow. A two- or possibly three-dimensional model is needed to study the solute transport under different field conditions with different tillage and management practices that would incorporate: 1) coupled heat and water flow as found in SHAW, [Soil Heat and Water model (Flerchinger and Saxton,1989a and 1989b)], 2) solute transport, 3) preferential flow of water and solutes, and 4) hydraulic and thermal properties. To date, no model exists with all these parameters.

The relationships between agricultural practices and ground-water quality have not been addressed as extensively or effectively as have other pollution processes. For instance, tillage practices can have a profound effect on the amount and transport mechanism of pesticides through the soil profile (Kanwar et al. 1985). Minimum tillage practices, which leave a greater percentage of residue than conventional tillage practices, leave the structure of surface soils largely intact, yield a greater amount of continuous macropores caused by earthworms and aging, reduce soil erosion and surface runoff, and increase infiltration. In contrast, conventional tillage practices, which include plowing, disking, and harrowing, destroy most of the preferential paths that reduce the number of pathways for water to move by gravity into the soil profile, increase soil erosion, and increase surface runoff. Limited field studies have been conducted on the transport of chemical pollutants from the soil surface to the ground water in warm surface zones. Preferential paths of water movement and subsequent pesticide movement in relation to tillage practices in the southeast region of the U.S. need to be studied because they are characterized by warm temperature and medium to heavy textured soil.

Materials and Methods

Potassium bromide (KBr) was used as a tracer in water applied as simulated rain to 1-m^2 field plots with subsurface drains installed 0.6-m below the soil surface. The plots represented undisturbed pasture and simulated-till conditions and two procedures of installing field drains (horizontal drilling and trenching).

A hydrograph-separation technique, using a mass balance and a dual porosity model, was applied to the tracer concentration and flow rate of drainage water to estimate the preferential flow and matrix flow components of subsurface drainage. Individual hydrographs of both matrix and preferential flow were constructed.

The methods of this experiment were based on using a mass balance equation that describes the transport of a solute to subsurface drain flow where:

Q_T = Total flow rate of drainage in the drain, $Q_T * C_T = Q_D * C_D + Q_P * C_P$. (1)
Q_D = Darcian flow rate,
Q_P = Preferential flow rate,
C_T = Tracer concentration in drain water,
C_D = Tracer concentration of Darcian flow component reaching drain,
C_P = Tracer concentration of preferential flow component reaching drain.

Conservation of mass yields: $Q_T = Q_D + Q_P$.(2)

By substituting Eq. 2 into Eq. 1, relationships of preferential flow and Darcian (matrix) flow are ascertained:

$$Q_P = Q_T * (C_T - C_D)/(C_P - C_D), \quad (3)$$

$$Q_D = Q_T * (C_T - C_P)/(C_D - C_P). \quad (4)$$

Initially C_P is assumed equal to the concentration of the tracer applied in the rainfall simulation and C_D is the concentration of tracer reaching the drain that increases linearly between the initial value for C_D and the ultimate concentration for C_D at the end of simulation ($C_T = C_D$). These assumptions produced two equations with two unknowns after measuring C_T with respect to time.

At the Holly Springs Experiment Station in northern Mississippi, four 1-m^2 hydraulically isolated plots with drains at fragipan depth were installed. These plots had been in native grass since 1989. A rainfall simulator was used to apply a batch mixture of KBr at 250 mg Br^-/L on the two plots where the drains were installed from the surface (trenched) and from the side (horizontally drilled). The simulation began after plots reached field capacity as determined through time domain reflectometry procedures when the soil profile was at 32% moisture. The simulations were conducted on undisturbed plots with residues removed (no-till) and disturbed plots shaped by tilling the top six inches of surface soil (conventional-till). The experimental design consisted of two tillages (conventional- and no-till), two simulations approximately 24 hours apart, and two replications. Application of 63.5 mm and 38 mm of water solution was delivered to the plots at 12.7 mm/hr for the first and second simulations, respectively. Type of data collected included measurement of subsurface drain flow and Br^- analysis of the flow at intervals during and after the two rainfall simulations.

Results

If either preferential or matrix flow were the only mechanism for the transport of solutes to subsurface drainage, the concentration of Br^- in drainage would be expected to increase for as long as the tracer solution was applied or until the concentration of the tracer in the drainage water reached the same concentration as that applied in the tracer solution. Figure 1 shows Br^- concentrations measured in the drain outflow during the 5-hour simulation event for each treatment. The drain line was not flowing at the start of the simulation but flow began on the average of 50 minutes after irrigation began. During each irrigation , Br^- concentrations in drain outflow reached a peak and then began to decline. A peak in Br^- concentrations occurred between 280 to 300 minutes during the first irrigation. This increasing and decreasing concentration of tracer in drain outflow is consistent with a dual porosity model.

Hydrographs in Figures 2 and 3 are the result of solving Equations 3 and 4 for preferential and matrix flow using the Br^- concentrations in the drainage shown in Figure 1. Figures 2 and 3 show the dominant mechanism for water reaching the subsurface drain line is matrix flow. Matrix flow appears to contribute the majority of the water moving to the drain line even during the early stages of the drain flow hydrographs. Initial mixing between the macropores and matrix flow, combined with high antecedent soil moisture content at the start of the experiment, may explain why macropore flow does not show greater response during the early stages of flow. Figure 4 presents the relative contribution to drain outflow made by preferential flow during the first irrigation for each treatment . The undisturbed plots produced more preferential flow than the simulated-till plots, independent of how the drains were installed.

Total discharge and total mass of Br^- from each rain simulation are shown in Table 1. The undisturbed pasture condition with the horizontal-drilled drains showed preferential flow contributed 31% and 17% of its total discharge from the 5- and 3-hour storms, respectively, while the undisturbed pasture condition with trenched drains showed preferential flow contributed only 16% and 9% of its total discharge for the two respective storms. However, the total discharge from the undisturbed pasture condition was 6% higher for the trenched drains as compared to the horizontal-drilled drains which imply the trench may be inducing significant water movement that is non-representative of the actual water flow patterns for these soils. The simulated-till plots for both drain installation procedures produced preferential discharge of 14% and 25% of the total discharge for the 5- and 3-hour storms, respectively. The simulated-till procedures probably reduced the number of continuous macropores thus causing reduced preferential flows. Even though preferential flow contributed relatively small amounts of total drain outflow as compared to the matrix flow, preferential flow contributed on a mass basis 55% and 18% of the bromide for the 5- and 3-hour storms, respectively, under undisturbed pasture conditions and 28% and 35% of the bromide for the two storms under simulated-till.

Conclusions

Matrix and preferential flow components were separated from total flow by a hydrograph-separation technique which used the assumption of dual porosity and a tracer mass balance. An estimate of the magnitude of water and Br- transported by preferential flow to a drain line from irrigations applied by a rain simulator were shown in Figures 2 through 4. These hydrographs provide an indication of the potential significance of preferential flow in transporting water and chemicals that move like Br^- through macropores to the shallow groundwater system. These procedures should be considered a minimum estimate of the quantity of preferential flow due to the simplified assumptions of all preferential flow being intercepted directly by the drain and no dilution of tracer occurs in the preferential flow channels. Preferential flow in the drainage at any time was small as compared to the matrix flow, however it contributed a disproportionate amount of Br^- tracer. This data support the concept that mode ls used to predict mass balances using only the matrix (Darcian) flow will thus underestimate those chemicals that move like bromide into the soil profile.

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	Undisturbed, Drilled Drain	Undisturbed, Trenched Drain	Simulated-Till, Drilled Drain	Simulated-Till, Trenched Drain
5-Hour Storm				
Discharge (V)				
Preferential (ml)	4,473	1,635	2,085	2,971
Total (ml)	14,586	10,477	14,361	21,034
% Preferential	30.6%	15.6%	14.5%	14.1%
Mass (C*V)				
Preferential (mg)	81	25	39	58
Total (mg)	118	61	121	242
% Preferential	69.0%	41.0%	32.1%	23.9%
3-Hour Storm				
Discharge (V)				
Preferential (ml)	1,206	1,162	1,667	1,355
Total (ml)	7,268	12,698	6,123	5,762
% Preferential	16.6%	9.2%	27.2%	23.5%
Mass (C*V)				
Preferential (mg)	16	28	44	33
Total (mg)	89	165	110	110
% Preferential	18.4%	17.1%	40.4%	29.8%

Table 1. Total discharge and total mass of Br- in drain outflow of each treatment.