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FUNNEL-TYPE FLOW AND ITS IMPACT ON CONTAMINANT TRANSPORT IN UNSATURATED SOIL

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ABSTRACT

Results from many recent field experiments have indicated that groundwater contamination by pesticides is not associated with the bulk soil matrix flow which occurred throughout the entire vadose zone. A small amount of pesticide can be transported very expeditiously through certain pathways in unsaturated soils. A generic term "preferential flow" became popular during the last decade to describe this bypassing phenomenon. The objective of this paper is to review the mechanisms and properties of funnel-type preferential flow and discuss its impact on contaminant transport in unsaturated sandy soils. Soils deposited by rivers, lakes, glaciers, oceans, or wind or weathered from different natural parent materials consist of strata laid down at different times and under different circumstances. Different strata generally have different porosities and permeabilities and are often inclined. It was observed that inclined very coarse sand or clay and silt layers/lenses in a sandy vadose zone could funnel uniform unsaturated matrix flow into congregated flow paths. The congregated pathways bypassed most of the soil matrix as they moved to the groundwater. The funnel flow was triggered by a macroscopic Haines' jump across the boundary. Numerical simulation were conducted to determine how contaminant transport was influenced funnel flow paths. Results showed that it took only one-fourth of the time for a contaminant to leach out from profiles through funnel-type preferential flow paths as compared to that through a homogeneous profile. There was enough contaminant to leach out from the 2-D profiles through funnel flow paths to contaminate groundwater even at very low infiltration rate. This implied that care-fully control water budget to minimize excess leaching alone might not help preventing groundwater contamination in a sandy profile with funnel-type preferential flow paths.

Keywords: Funnel-type preferential flow, contaminant transport

INTRODUCTION

Results from many recent field experiments have indicated that, unlike nitrate problems, groundwater contamination by pesticides with concentrations on the order of one to ten parts per billion is not associated with the bulk soil matrix flow that occurs throughout the entire vadose zone. A small amount of pesticides (yet enough to contaminate groundwater) could bypass the vast soil matrix and be transported very expeditiously through certain pathways in unsaturated soils. For example, Kladivko et al. (1991) found that, after only 1 cm of net infiltration, a short pesticide pulse with concentrations more than ten times higher than the j US EPA health hazardous level were detected in water samples collected from tile drains buried at 75 cm in a silty loam soil, while the vast majority of the uniformly applied pesticide was still in the topsoil. One pore volume of this soil profile is approximately 30 cm of water. Very similarly, in a heavily-instrumented field experiment conducted in a layered soil, Roth et al. (1991) found that a uniformly-applied pulse of tracer split into a slow front

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and a fast front. The initial fast front reached the 2.2-m depth after only 3.1 cm of precipitation. At the end of the experiment, the slow front moved with matrix flow only reached the 0.84-m depth after 85.3 cm of net infiltration.

A generic term, "preferential flow," became popular during the last decade to describe this bypassing phenomenon and many examples of contaminant transport through preferential paths were reviewed by Luxmoore (1991). In the literature, three preferential flow mechanisms have been identified experimentally, i.e., macropore flow, fingering flow, and funnel flow (Helling and Gish, 1991). The objective of this paper is to review the mechanisms and properties of funnel-type preferential flow and discuss its impact on contaminant transport in unsaturated sandy soils.

MECHANISM AND PROPERTIES OF FUNNEL-TYPE PREFERENTIAL FLOW

Soils deposited by rivers, lakes, glaciers, oceans, or wind or weathered from different natural parent materials consist of strata laid down at different times and under different circumstances. Different strata generally have different porosities and permeabilities and are often inclined. In field experiments conducted in central sand area of Wisconsin, Kung (1990a) observed that inclined, very coarse sand or clay and silt layers/lenses in a sandy vadose zone could funnel uniform unsaturated matrix flow into congregated flow paths. The congregated pathways bypassed most of the soil matrix as they moved to the groundwater. It was observed that water flowing through the entire root zone was channeled to about 50% of the soil matrix from 1.5 to 2.0 m, less than 10% from 3.0 to 3.5 m, and less than 1% from 5.6 to 6.6 m. The term "funnel flow" was coined to describe this flow phenomenon (Kung, 1990b).

Later, Kung (1993) demonstrated in laboratory experiments that funnel flow occurs along an inclined textural boundary if the following two conditions are both satisfied: 1) there is a macroscopic Haines' jump across the boundary (i.e., the water-entry potential of the lower, coarser soil is less negative than the air-entry potential of the upper, finer soil), and 2) infiltration rates are smaller than a certain critical rate which was exclusively determined by the saturated hydraulic conductivity of the overlain finer soil, the magnitude of the macroscopic Haines' jump, and inclination of the boundary. When both these conditions were satisfied, an inclined coarse layer embedded in medium or fine sand would behave like an impermeable wall of a funnel, i.e., water and contaminants would bypass the coarse sand layer and be congregated into column-like preferential paths.

If the first condition mentioned above is not met, water can readily penetrate into an inclined coarse sand layer. However, Kung (1993) showed that the funnel effect can still gradually augment if the unsaturated hydraulic conductivity of the coarse lens decreases much faster than that of the overlain finer soil when matric potential along the boundary decreases. Under this situation, the inclined coarse sand layer would behave like a leaky funnel, i.e., some water would penetrate into the coarse sand, while other would move laterally and bypass the coarse sand. Moreover, less and less water would enter the inclined coarse sand layer as the net infiltration rate decreased. It was also demonstrated that funnel phenomenon is not an anomaly like fingering flow that only occurred in extremely dry coarse sands. Funnel-flow phenomena can occur even when the moisture content of the whole soil profile is at its field moisture holding capacity.

Based on soil layering structures observed by Kung (1990a) during profile excavation, Ju and Kung (1993) generated 10 two-dimensional (2-D) 12 m wide by 6 m deep hypothetical soil profiles where each profile had approximately 35 coarse sand lenses randomly-distributed in otherwise homogeneous medium sand. They conducted a numerical simulation to determine the properties of funnel-type flow paths. Their results demonstrated that: 1) the flux along preferential flow paths increased more than 10 times the infiltration rate under steady-state conditions; and 2) most water and water-borne contaminants moved through less than 25% volume of the soil matrix. Their results also indicated that: 1) although the funnel-type flow paths triggered by randomly-distributed coarse sand layers/lenses were very complex, the preferential paths quickly became stochastically stationary, and 2) the vertical fluxes became log-normally distributed. The depth for the fluxes to asymptotically reach stationarity depended on the infiltration rate. The coarse sand layers/lenses in the upper part of a vadose zone alone would determine the mean and standard deviation of the log-normally distribution, while those lenses/layers in the lower profile would only determine the tortuosity of preferential flow paths.

INFLUENCE OF FUNNEL FLOW ON CONTAMINANT TRANSPORT

In field experiments conducted in central sand area of Wisconsin, Brasino (1986) installed suction-cup lysimeters in the unsaturated zone at 0.9, 1.8, and 2.7 m and groundwater monitoring well at approximately 6.0 m to study the breakthrough pattern of aldicarb applied uniformly to a potato plot. The peak aldicarb residue concentrations and their occurrence times after application are reproduced in Table 1. Note that concentrations decreased 10-fold as aldicarb moved from 0.9 to 1.8 m, yet concentrations maintained essentially the same order of magnitude at 1.8 m and 6.0 m. Moreover, the peaks took 111 and 97 days to move from the soil surface to 0.9 m, yet 25, 0, and 82 days from 0.9 to 1.8 m. The peak concentrations at 2.7 m were lower than those at the water table (i.e., 6.0 m) and did not occur until spring of the next year. Furthermore, at location 2, the peak concentration at the water table was higher than those from 1.8 and 2.7 m, and the peaks occurred on the same day at 0.9 and 1.8 m. At location 3, the peak concentration at 6.0 m occurred 13 days earlier than that at 1.8 m. These results strongly suggested that water and solute moved preferentially in the unsaturated zone.

Table 1. Peak Concentrations and Time of Aldicarb Breakthrough Curves from Three Locations and Four Depths[a]

Location of Sample	Sample Depth, m 0.9	1.8	2.7	6.0
1	1665ppb/111 days	115 ppb/136 days	--	76 ppb/166 days
2	950 ppb/111 days	47 ppb/111 days	24 ppb/308 days	68 ppb/195 days
3	650 ppb/97 days	70 ppb/179 days	24 ppb/358 days	27 ppb/166 days

[a] After Brasino (1986).

With dye tracing and a profile excavation technique, Kung (1990a) conducted field experiments in a plot close to that of Brasino (1986) and confirmed that funnel-type preferential flow was the dominant flow mechanism that caused the unique breakthrough pattern observed by Brasino (1986). Later, Kung (1993) conducted laboratory experiments in 1.8-m wide by 1.2-m high sand box where a 1.3-m wide and 5-cm thick inclined coarse sand lens was embedded in medium sand to determine why a single coarse sand lens would influence solute transport in unsaturated sandy soil. His results demonstrated that, because water moved much faster along the congregated flow paths along the upper surface of the coarse sand lens, water-borne contaminants were significantly accelerated. The pollution potential of reactive and degradable contaminants was increased because the total time available for degradation is greatly reduced. Furthermore, because contaminant completely bypassed the soil matrix underneath the coarse sand lens, the total fraction of contaminants adsorbed is smaller when either the adsorption isotherm is nonlinear or the adsorption is rate-limited.

As mentioned in Kung (1990b), the concentrations measured by Brasino (1986) might not reflect what truly occurred in the unsaturated profile because locations of his sampling devices were randomly determined. As water and contaminants moved through a smaller and smaller fraction of soil matrix, the samplers had relatively little chance to be installed along preferential flow paths. It was important, yet, difficult to quantitatively understand how contaminant transport would be influenced in a sandy vadose zone with funnel-type preferential flow paths. Ideally, field experiments should have been conducted where the funnel-type flow paths were known a priori so that solute sampling devices could be strategically installed to collect representative breakthrough patterns. Yet, current technology could not accurately map the structures and locations of all inclined coarse sand layers/lenses in an unsaturated soil that would trigger funnel flow.

Numerical simulations were, therefore, conducted by Ju and Kung (1993) as a surrogate to study contaminant transport in 12 m wide by 6 m deep 2-D hypothetical soil profiles that they generated earlier where funnel-flow paths were known. Breakthrough patterns of conservative as well as degradable contaminants at five water application rates were simulated. Their results showed that it took only one-fourth of the time for a contaminant to leach from the 2-D profiles through funnel-type preferential flow paths as compared to that through a 1-D homogeneous profile. At approximately 50 days after application with low infiltration rate, for example, the peak of the contaminant front reached the bottom of the 6-m profile in 2-D profiles, while the contaminant front barely passed 1 m in 1-D homogeneous profile. The total mass of the degradable contaminant leached decreased exponentially as the water application rate decreased. However, there was enough contaminant to leach from the 2-D profiles with funnel flow paths to contaminate groundwater even at very low infiltration rate (i.e., 0.115 mm per day). Note that it was practically impossible to manage the water budget to achieve an average daily net infiltration rate smaller than 0.115 mm per day. This implied that a carefully controlled water budget to minimize excess leaching alone might not help prevent groundwater contamination in a sandy profile with funnel-type preferential flow paths similar to those in the hypothetical profiles. The ratio between the total mass leached from the 2-D profile and that from the 1-D homogeneous profile increased exponentially as the water application rate decreased. This implied that the impact of the funnel flow on the transport of a degradable contaminant is most significant when the net infiltration is low.

CONCLUSIONS

Funnel-type preferential flow paths could significantly accelerate contaminant transport in an unsaturated soil. Generally, the breakthrough of a contaminant pulse in a 2-D profile with funnel flow took only one-fourth of the time as compared 10 that through a 1-D homogeneous profile. The total mass leached from the 2-D profile increased exponentially as the water application rate decreased. This implies that the impact of funnel flow on the contaminant transport is most drastic when the net infiltration is low. In other words, careful control of the water budget by minimizing excess leaching alone might not prevent groundwater contamination in a sandy profile with funnel-type preferential flow paths.

In a sandy vadose zone with funnel-type preferential flow paths, the soil solution samples collected by current lysimeter-based sampling protocol significantly underestimated the pat-tern of mass breakthrough. Because preferential flow paths are not known a priori in a vadose zone, increasing the total number of samples at random locations and then averaging measured concentrations would not warrant that a more representative contaminant break-through pattern would be collected.

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