Fluid Flow and Solute Migration Within the Capillary Fringe

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Abstract

Laboratory experiments involving both homogeneous and heterogeneous porous media are used to demonstrate that fluid flow and solute transport will occur regularly in the capillary fringe (CF), including both vertical (upward as well as downward) and horizontal flow velocities. Horizontal flow above the water table appears to be limited primarily to the region of high water saturation (i.e., the CF), an observation supported by numerical modeling and consistent with the literature. Beyond observations presented in prior literature, it was observed that exchange of water within the CF with water below the water table is active, with flux both from the CF downward across the water table and from the region below the water table, upward into the CF. This flux is enhanced by the presence of physical heterogeneity. These findings strongly contrast the common conceptualization of predominantly downward vertical fluid flow through the unsaturated zone, with transition to fully three-dimensional flow only below the water table. Based on these observations, it is suggested that the CF may affect, far more significantly than is usually assumed, the natural geochemical and microbial conditions present in the region of transition from unsaturated to saturated ground water flow.

Introduction

A key question in the characterization, exploitation and remediation of ground water aquifers concerns identification of pathways traveled by water, and the impact of these pathways on the movement of solutes and the viability of microbial populations. In this study, we are particularly interested in observations of fluid flow and solute transport within the capillary fringe (CF), with emphasis on the impact of physical heterogeneity and exchange of water between the CF and the region below the water table. It is recognized, at the start of this discussion, that multiple definitions have been presented for the CF (Abdul and Gillham 1984; Ronen et al. 1997). For the present work, we define the capillary fringe as the zone immediately above the water table where the water content remains at or close to saturation. In operational terms, the top of the capillary fringe is where the pressure in the pore water is at the air-entry value (or bubbling pressure) as used in the equations of Brooks and Corey (Brooks and Corey 1966; van Genuchten 1980; Simunek et al. 1999). This definition is used here for two reasons: First, it is consistent with the discussion of air-entry contained in the latter portion of this paper; second, for the experiments described, the region of transition from full saturation to residual saturation was relatively sharp, thus making it difficult to observe behavior at heights above the air-entry point.

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A substantial body of literature exists that deals with the role of the capillary fringe as an interface between the vadose zone and the saturated zone below the water table. With respect to hydraulic aspects, several authors have investigated the influence of the CF on hydrologic response near streams and excavations in shallow phreatic systems (Abdul and Gillham 1984; Gillham 1984; Mixon 1984; Akindunni and Gillham 1992). These studies are primarily concerned with the response of surface water bodies to storms, but lateral flow within the CF is often shown to be an important mechanism of the horizontal motion of water within the subsurface. Other studies have dealt with hillslope runoff above and through the CF (Kinouchi et al. 1991), the response of ground water systems to rapid transients such as wave run-up (Li et al. 1997), pumping from wells in unconfined aquifers (Zhang et al. 1999; Nwankwor et al. 1992), and precipitation events (Abdul and Gillham 1984; Jayatilaka and Gillham 1996; Jayatilaka et al. 1996; Rosenberry and Winter 1997). In each case, the CF has been shown to have important local effects on the response of the hydrologic system to changes in local recharge, boundary conditions, or pumping. Several authors have also demonstrated the influence of such changes on vertical variations in water content and matric potential above the water table (Nielsen and Perrochet 2000; Lehmann et al. 1998).

Most relevant to the present analysis is a series of studies, based mostly on use of numerical models, which focus on the relative importance of seepage faces (Shamsai and Narasimhan 1991; Wise et al. 1994; Boufadel et al. 1999; Romano et al. 1999). These studies consider lateral flows in the CF and provide evidence that the CF plays a significant role in determining the height of seepage faces and their contribution to overall flow. One can conclude from these studies that proper prediction of flow below the water table may be reliant on inclusion of capillarity effects as an upper boundary condition on a model of saturated ground water flow (Parlange and Brutsaert 1987), or use of a fully saturated/unsaturated model of flow within the combined vadose zone, CF, and saturated ground water zone (Simunek et al. 1999).

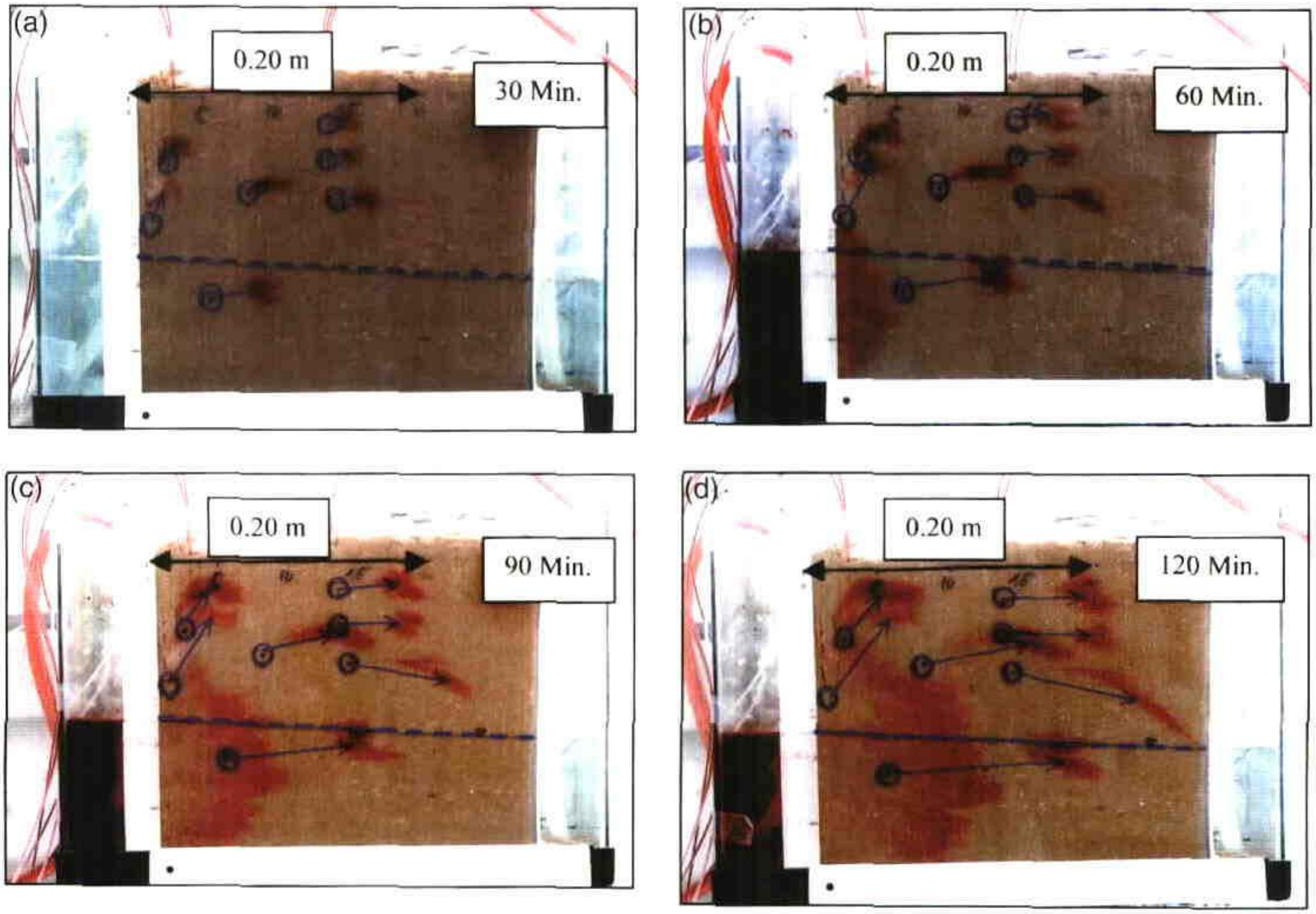

Figure 1. Transport experiment in homogeneous packing within the first tank. Overall dimensions of the sand compartment were 0.27 m in the direction of mean flow, 0.17 m width perpendicular to the mean flow, and 0.21 m from the base of the tank to the upper sand surface. Flow in these images was from left to right with the dye introduced at the locations shown by the blue circles. The movement above the water table (the water table is shown by the dotted blue line) is evident in the motion of the dye spots. The blue arrows show the association between each dye spot and the original location of injection of that spot (the arrows do not necessarily indicate the transport route). The images are in chronological order from Figure 1a through Figure 1d. The red dye invading from the left in the latter figures is a secondary front of dye entering through the inflow reservoir. For this and all later figures, the times reported on the figures are the times since the introduction of the dye tracer.

The CF is also active both biologically and geochemically, as evidenced by analysis of water collected within this region. The CF has been shown to have significant effects on the vertical motion of gas-phase transport (McCarthy and Johnson 1993), displacement of LNAPLs (Jawitz et al. 1998), degradation processes (Ostendorf et al. 1995; Zaidelman et al. 1997; Lahvis et al. 1999), CO_2 production and transport (Affek et al. 1998; Caron et al. 1994, 1998), and root water uptake and plant growth (Feddes et al. 1978). Studies also suggest that biological and geochemical activity in the immediate vicinity of the water table may be significant (Ronen et al. 1989), and that flow and transport processes in the capillary fringe are likely to be highly heterogeneous with effects ranging from variable moisture contents, to the capillary fringe forming local traps for LNAPLs in the fluid phase and dense volatiles in the gas phase (Ronen et al. 1997, 2000).

The studies mentioned lead to the conclusion that the CF may significantly affect the evolution of fluid flow and solute transport from the vadose zone to the saturated zone below the water table. Notwithstanding the literature cited, the dynamic interplay of flow and transport mechanisms across and within the CF is not well understood. Further, it is not clear that the importance of the influence of the CF on fluid flow and miscible solute transport is well recognized. Significantly, a number of textbooks on ground water hydrology virtually ignore the CF. Except near regions of discharge to surface water bodies, fluid flow and solute transport in the subsurface is commonly conceptualized as primarily vertical in the unsaturated zone. It is generally assumed that the region immediately above the water table can be characterized by predominantly vertical flow. A notable exception is the contribution by Bouwer (1978), which discusses empirical means of estimating horizontal flow and its significance in the CF.

In the present study, we qualitatively demonstrate through use of a series of laboratory experiments that flow and solute transport within the CF is strongly dependent on the nature of the physical heterogeneity of the sediments in the vicinity of the CF and likely includes horizontal and vertical (upflow and downflow) fluxes. As such, the CF may play a major role in defining the geochemistry and microbiology near the water table as it represents a zone of active mixing among waters, solutes, and microorganisms derived from recharge, influx boundaries, hydraulic exchange with ground water, diffusion, and gas exchange with both the vadose and saturated zones. Thus, the CF may have far greater impact than previously perceived on sample collection and interpretation, transport of contaminants and nutrients near the water table, and design of

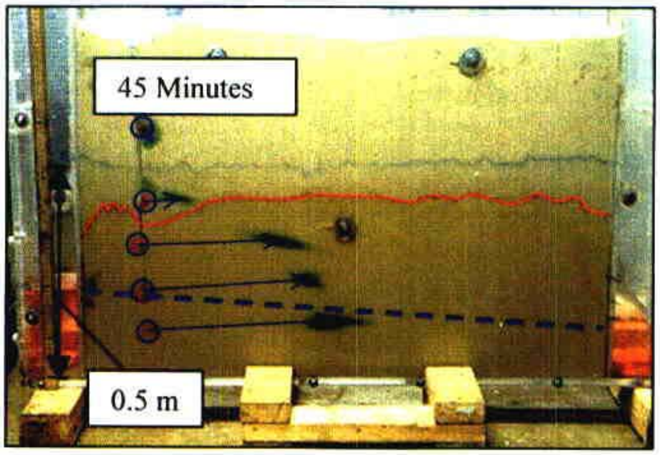

Figure 2. Transport experiment in homogeneous packing within the second tank. Overall dimensions of the sand compartment were 1.0 m in the direction of mean flow, 0.10 m width perpendicular to the mean flow, and 0.8 m from the base of the tank to the upper sand surface. Flow in this image was from left to right with approximate location of the water table marked with the dashed blue line. The upper limit of high saturation is indicated by the change in color of the sand, highlighted by the thin red line (the upper line is irrelevant to the experiment shown). Five spots were initially added to the system (see blue dots on figure): one below the water table, one approximately at the water table, two in the CF, and one above the CF. Once again, the arrows illustrate the association between dye spot and the original point of injection and are not necessarily indicative of the flow route.

remediation strategies. These assessments are critical to management and exploitation of aquifers.

Equipment Used in These Demonstrations

Two laboratory flow tanks were used to characterize the degree of fluid flow and solute transport that can occur within the CF (Figures 1 and 2). Significantly, the two flow tanks were of different size and were filled with sands with substantially different characteristics. The first tank provided for a volume of sand of dimension 0.27 m (length) × 0.17 m (width) × 0.21 m (height). The second tank provided for a volume of sand of dimension 1.0 m (length) × 0.13 m (width) × 0.89 m (height).

For both tanks, the porous medium studied was packed under saturated conditions, with the water level later lowered in the inlet and outlet reservoirs to establish a prescribed head drop across the length of the tank. For all experiments conducted, flow was allowed to reach steady-state conditions (as indicated by a lack of change in the rate of flow through the medium, constant water levels in the reservoirs and, for the second tank, constant elevation of the upper boundary of the region of high moisture content—identified through visual inspection as illustrated in the figures). The sands along the inflow and outflow reservoirs, above the level of water in the reservoirs, were horizontally confined using screens and were open to the atmosphere. For both tanks, the upper surface of the tank was covered to reduce the effects of evaporation from either the upper sand surface or the vertical surfaces of the sand above the water level at the inflow and outlet reservoirs.

The sands used in these experiments were of similar mean grain size, but were dramatically different in terms of homogeneity and grain-size distribution. The experiments performed in the smaller tank were performed with a locally available sand from the region

Table 1
Parameters in the Head/Moisture Relationship

$$\text{Given by } \Theta = \left[\frac{1}{1+(\alpha h)^n}\right]^{\left(1-\frac{1}{n}\right)}$$

Sand	α cm^{-1}	n	Θ_S	Θ_{ir}
12/20	0.151	7.35	0.348	0.012
40/50	0.0453	12.18	0.348	0.20

Within this expression, Θ_{ir} and Θ_S are the residual and saturated water contents, respectively, Θ is the effective saturation, h is the pressure head, and α and n are shape factors (Schroth et al. 1996).

around Rehovot, Israel, that can generally be characterized as a medium-grained, unwashed sand. The experiments performed in the larger tank were based on commercially available, presieved, washed silica sands. These sands have been used in a number of previous studies of fluid flow and solute transport in both the vadose and saturated zones (Fry et al. 1997; Schroth et al. 1996; Silliman et al. 2001). Two grain sizes were used in these experiments. For the homogeneous experiments discussed later, a 40/50 mesh sand (0.30 to 0.425 mm grain size) was used. For the heterogeneous experiments discussed later, the "fine" sand is once again the 40/50 mesh sand, whereas the "coarse" sand consisted of a 12/20 mesh sand (0.85 to 1.55 mm). As the experiments run on the small tank were qualitative in nature, no measures of the mean capillary rise or saturated hydraulic conductivity were completed for this sand. The saturated hydraulic conductivities for the sands used in the large tank were measured at 7.8×10^{-4} and 4.9×10^{-3} m/sec for the fine and coarse sands, respectively (Silliman et al. 2000; slightly lower saturated conductivities were reported for the same mesh-size sands from the same source by Schroth et al. 1996). Schroth et al. (1996) state that the pressure moisture relationship for the sands used in the large tank follows the van Genuchten (1980) model with parameters as provided in Table 1. Visual inspection of Figure 3 from Schroth et al. (1996) indicates air entry heads for the coarse and fine sands of approximately 0.06 m and 0.20 m, respectively. These are consistent with observed maximum heights of high-moisture content in these two sands during our experiments.

Tracer was added to each of the porous media through a series of injection tubes installed while the tanks were being packed and/or pushed into place following the completion of packing. Tracer could also be added to the inflow reservoir, providing a dye front moving through the porous medium. Dye was used throughout all experiments as the primary tracer. NaCl was also used as a tracer in the first tank (using suction cup lysimeters to sample from within the medium) to ensure that the behavior observed with the dye was consistent with the behavior of a conservative tracer. The behavior of the dye closely matched that of the NaCl, such that it was concluded that the dye was behaving as a conservative tracer. For this reason, combined with the ease of use/detection of the dye, no chemical tracer was used in the second tank so as to avoid the necessity of installing/using suction cup lysimeters.

For all experiments, the flow field was established and allowed to come to steady-state prior to injection of dye. Dye was added in one of two fashions. In the first, dye was added to the inlet reservoir and carried into the medium by the flow from this reservoir, thus providing a uniform initial coverage over the saturated thickness bordering the inlet. In the second, dye was introduced through one or

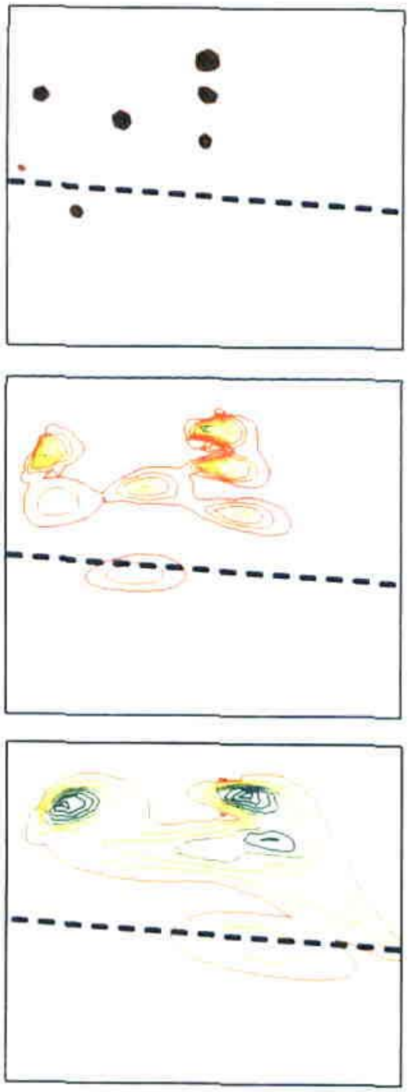

Figure 3. Motion of tracer in the first tank as predicted by Hydrus-2D (Simunek et al. 1999) showing the spread of the tracer above the water table. Flow is again from left to right. Comparison of the figures illustrates the predicted upward motion of the tracer near the inflow (left) boundary of the medium and the downward component of the tracer velocity near the outflow boundary. The dashed line illustrates the approximate location of the water table in these simulations. The time of simulation represents initial location of tracer, 30 minutes after injection, and 90 minutes after injection.

more of the tubes installed for this purpose. Dye was added in constant volume to each point to increase the uniformity of the visualization. The dye was at a slightly higher density than the water in the tanks. This change in density was intentional to avoid any concern that movement of the dyes from below the water table into the CF was driven by density.

Horizontal Flow Within the CF

Figures 1 and 2 illustrate the movement of individual spots of dye within homogeneous packings of sand in the first and second tank, respectively. Seven dye spots were released in the first tank, with all but the lowermost spot being within the CF. Five dye spots were released in the second tank with one spot below the water table, one spot approximately at the water table, two spots in the CF, and one spot above the CF. Flow is, on average, from left to right. It is emphasized that the driving force for all flow in these tanks was

Table 2
Results of Numerical Simulation of Horizontal Flux Above the Water Table for a Homogeneous Medium

Parameter	Sand	Loamy Sand	Sandy Loam	Loam
K_{sat} [$\times 10^{-5}$ m/s]	8.2	4.1	1.2	0.29
Total horizontal flux above the water table per meter width of the aquifer* [$\times 10^{-10}$ m^3/m·s]	31.3	15.0	6.1	2.0
Height below which 99% of flow in the vadose zone occurs [m]	0.10	0.25	0.50	1.00
Velocity in saturated zone [$\times 10^{-8}$ m/s]	8.2	4.1	1.3	0.26
Percent of horizontal flux carried by CF: Depth of aquifer below water table = 1 m	3.7	3.7	4.7	6.4
Percent of horizontal flux carried by CF: Depth of aquifer below water table = 10 m	0.38	0.38	0.49	0.68
Percent of horizontal flux carried by CF: Depth of aquifer below water table = 100 m	0.038	0.038	0.050	0.069

*Total horizontal flux was determined as the horizontal flow that occurred within the 3 m of sediment immediately above the water table. Horizontal flux above this height was negligible.
Calculations were carried out assuming a hydraulic gradient of 0.001. The hydraulic properties of the soil textural classes were taken from Carsel and Parish (1988).

derived from the difference in water levels in the reservoirs and that no driving force was applied in either reservoir above these water levels.

A number of observations are made regarding these results. First, as expected, the dye spots at and below the water table moved in the direction of the mean hydraulic gradient. Second, both images show strong evidence of vertical and horizontal motion of the dye spots situated within the CF. Of particular interest are the dye spots near the inlet reservoir in Figure 1 and the dye spot near the upper limit of the CF in Figure 2.

The spots near the inlet reservoir illustrate a significant upward component to flow (compare, for example, the spots near the left boundary in Figures 1a through 1c). Thus, near the inflow boundary, the pore water velocity has a significant vertical (upward) component both in the region bordering the water table and in the CF at heights up to the upper surface of the sand. Vertical components to the pore water velocity within the CF are also observed in a comparison of Figures 1c and 1d, where the flow field is converging toward the saturated zone at the outflow boundary. It is emphasized that these vertical components to the pore-water velocity are driven purely by the difference in head between the two bounding reservoirs (i.e., we have not imposed a vertical gradient via the boundary conditions).

The movement of the dye spot at the upper surface of the CF in Figure 2 demonstrates that there is active flow along this upper portion of the CF. It is evident that the pore water at the upper surface of the CF is in active horizontal motion. Such motion is consistent with behavior observed for all dye spots at lower elevations, but contrasts with the behavior of the dye spot that was injected above the CF (Figure 2), which shows only slight vertical movement and essentially zero horizontal motion. It is clear that the behavior above the CF is quite different from the behavior within the CF.

Numerical Analysis of Homogeneous Sands

To gain confidence that the experimental results were not experimental artifacts and to illustrate the relative importance of hor-

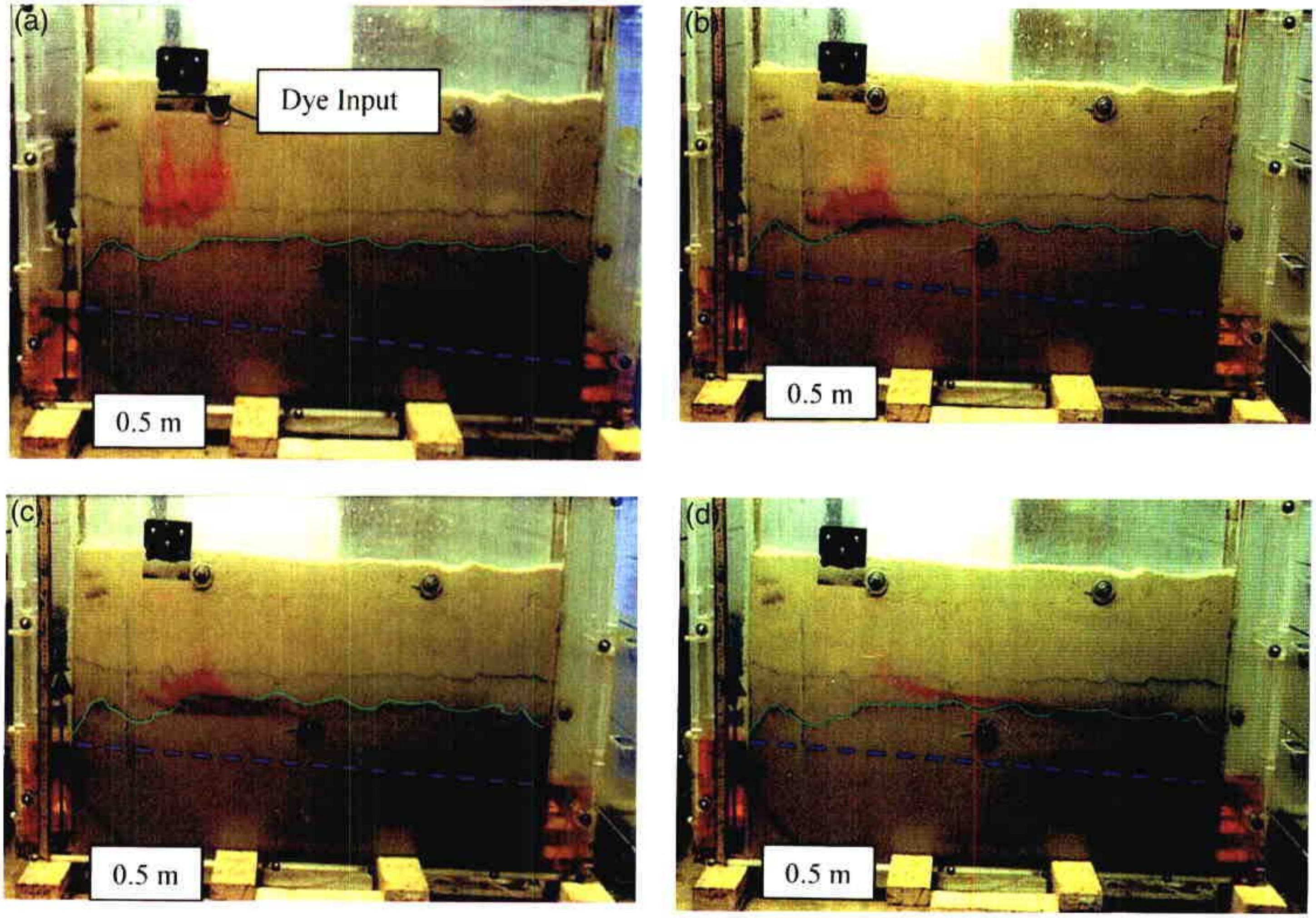

Figure 4. Infiltration experiments in the second tank. Flow below the water table is at steady state. The dye was added as a slug input within the region seen as a dark rectangle in these images. The slug was flushed into the sand with clear water applied uniformly over the entire upper surface of the sand. The images are in chronological order moving from Figure 4a through Figure 4d.

izontal flow within the CF, the flow geometry used in these experiments was reproduced numerically and the resulting flow field predicted using Hydrus-2D modeling software (Simunek et al. 1999), a finite-element solution of Richard's equation for variably saturated porous media. Hydrus-2D was applied to the flow geometry of the first tank for a range of sediment properties ranging from sand to clay. Figure 3 shows a typical result (for sand) regarding the motion of the dyes injected at locations coinciding with those used in Figure 1. The results in this figure demonstrate behavior qualitatively similar to that shown in Figures 1 and 2, including strong vertical flux near the inlet and outlet boundaries, and horizontal/vertical migration of the tracer within the CF. The qualitative agreement between the numerical and experimental results leads to the conclusion that the experimental results reliably replicate the flow and transport to be expected in these porous media under these boundary conditions.

Confidence in these experimental results leads to the question of whether flow through the CF is of significance from the standpoint of regional hydrology. Based on the empirical arguments of Bouwer (1978) regarding the relative thickness of the CF versus the underlying aquifer, we anticipate that, under the vast majority of field conditions, horizontal flux above the water table (the CF and overlying vadose zone) will be negligible compared to horizontal flux below the water table.

To address this question, we used Hydrus-2D to simulate horizontal flux through a saturated/unsaturated medium for a wide range of sediment types (e.g., a wide range of hydraulic characteristics as expressed by van Genuchten or Brooks and Corey functions (van Genuchten 1980; Simunek et al. 1999). The length of the simulated region in the horizontal direction was 100 m and the vertical dimension of the grid varied dependent on desired thickness of the saturated zone. Constant head boundaries were used at the inflow and outflow edges of the numerical grid with a no-flow boundary along the base of the grid and zero recharge along the upper surface of the grid. The total horizontal flux, Q, above the water table was estimated and compared to the flux observed below the water table for aquifer thicknesses of 1, 10, and 100 m. The calculations were completed ignoring the effects of the vertical boundaries, i.e., the same mean horizontal gradient was applied in both the unsaturated and saturated zones.

While further details of these numerical experiments are beyond the scope of the present manuscript, the primary points of interest are summarized in Table 2. Two key parameters are provided: the height above the water table below which approximately 99% of all horizontal, vadose-zone flux occurs and the percentage of the total horizontal flow through the medium that occurs above the water table (for aquifer depths, below the water table, of approximately 1, 10, and 100 m). It is apparent from

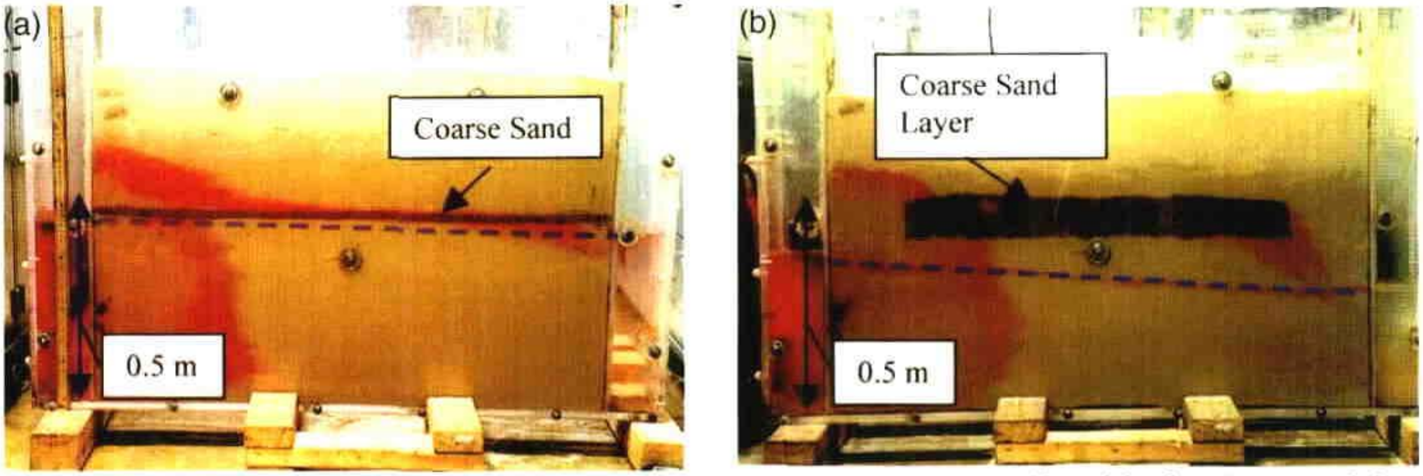

Figure 5. Motion of the dye in the presence of: (a) a continuous layer of coarse sand above the water table, and (b) a lens of coarse sand above the water table. Flow is from left to right. The approximate location of the water table is illustrated using the dashed blue lines. The coarse sand is the darker sand in these images. In Figure 5a, transport above the coarse layer is aided by flow through the coarse layer (hence the more rapid advance of the dye in the fine sand above the coarse layer than in the region below the water table).

these results that lateral flow does not extend to significant heights above the water table, nor does the CF typically contribute significantly to horizontal flow through an aquifer system. As shown from the previously mentioned experimental results and the results on heterogeneous media discussed later, however, the minimal contribution of the CF to horizontal flow through an aquifer system does not necessarily translate into a lack of transport processes within the CF.

The Flowpath of Recharge Water

The preliminary experimental and numerical results indicate that the CF represents a relatively minimal contribution to regional flow. However, vertical and horizontal flux within the CF has the potential to dramatically alter fluxes at the local scale, with possible impact on solute transport, geochemistry, and microbial dynamics. Hence, an additional sequence of experiments were focused on: (1) the role of the CF during recharge of tracers, (2) the impact of heterogeneity, and (3) the potential for unusual hydraulic behavior in the vicinity of the CF in the presence of hydraulic heterogeneity.

The first extension of the earlier results was through consideration of recharge. The experiments illustrated in Figure 2 were replicated with recharge at the upper surface of the sand. Dye tracer was added at the surface over a narrow region near the inlet reservoir. The results of this experiment are summarized in Figures 4a through 4d. At early time (Figure 4a) the dye tracer behaved much as described in the literature for solute migration through the vadose zone (Jawitz, et al. 1998; Glass and Nicholl 1996; Glass et al. 1991; Martin and Koerner 1984). Specifically, the dye fingers extensively and is subject to substantial vertical spread.

The dye behaves far differently, however, near the upper surface of the CF (Figures 4b and 4c). The vertical spread so apparent in the vadose zone is essentially reversed with the dye converging to a narrow region at the top of the CF. For the flow field simulated here (strong horizontal gradient below the water table) transport changes from predominantly vertical to predominantly horizontal. Note that this transition occurs well above the water table. In fact, the dye does not intersect with the water table until the flow field converges to the region below the water level in the outlet reservoir (Figure 4d). The implication here is that, for the flow field simulated, water flow is not vertically downward through the CF. Rather, flow will likely be predominantly horizontal in homogeneous reaches of the CF. It is anticipated that the transition within the capillary fringe will be equally important, if somewhat modified from that observed here, for other flow fields. For example, the transition is likely to be quite different when the water table is coincident with an aquitard (Keller et al. 1988, 1989). The discussion that follows is limited to consideration of the flow conditions simulated here (with horizontal gradient imposed below the water table).

The Presence of Coarse Layers Within the CF

Given the observation of substantial horizontal flow within the CF and the failure of the infiltrating dye to move vertically through the CF, we next investigated the impact of simple heterogeneity on the distribution of flow within the CF. To accomplish this investigation, we repacked the medium, adding a horizontal layer (Figure 5a) and a horizontal lens (Figure 5b) of coarse sand above the water table. As noted previously, the coarse layer used here and in all subsequent experiments involving heterogeneous packings consists of 12/20 mesh sand (0.85 to 1.55 mm) packed within a 40/50 mesh sand (0.30 to 0.425 mm grain size). The coarse sand appears as the darker layer (region) in each of the photographs.

Flow conditions were reestablished as in the previous experiments, but without infiltration. The medium was packed under saturated conditions and the water levels in the reservoirs were lowered to the final levels shown in Figures 5a and 5b. It is significant to note, and is discussed further in the next section, that the coarse sand in Figure 5b remained at high moisture content during these experiments despite its significant height above the water table.

As illustrated in Figures 5a and 5b, the impact of the coarse sand was dramatic. The high hydraulic conductivity within this sand led to high water velocities traveling through the sand and, thereby, to significant fingering/dispersion of the tracer front. Perhaps more significant, the coarse sand provided transport routes above the water table capable of transporting substantial quantities of tracer.

Other Forms of Heterogeneity and Air Entry Barriers

We had concern that the behavior shown in Figures 5a and 5b resulted, in part, from the presence of the boundary conditions (i.e., the vertical flow into the CF related to the inflow and outlet

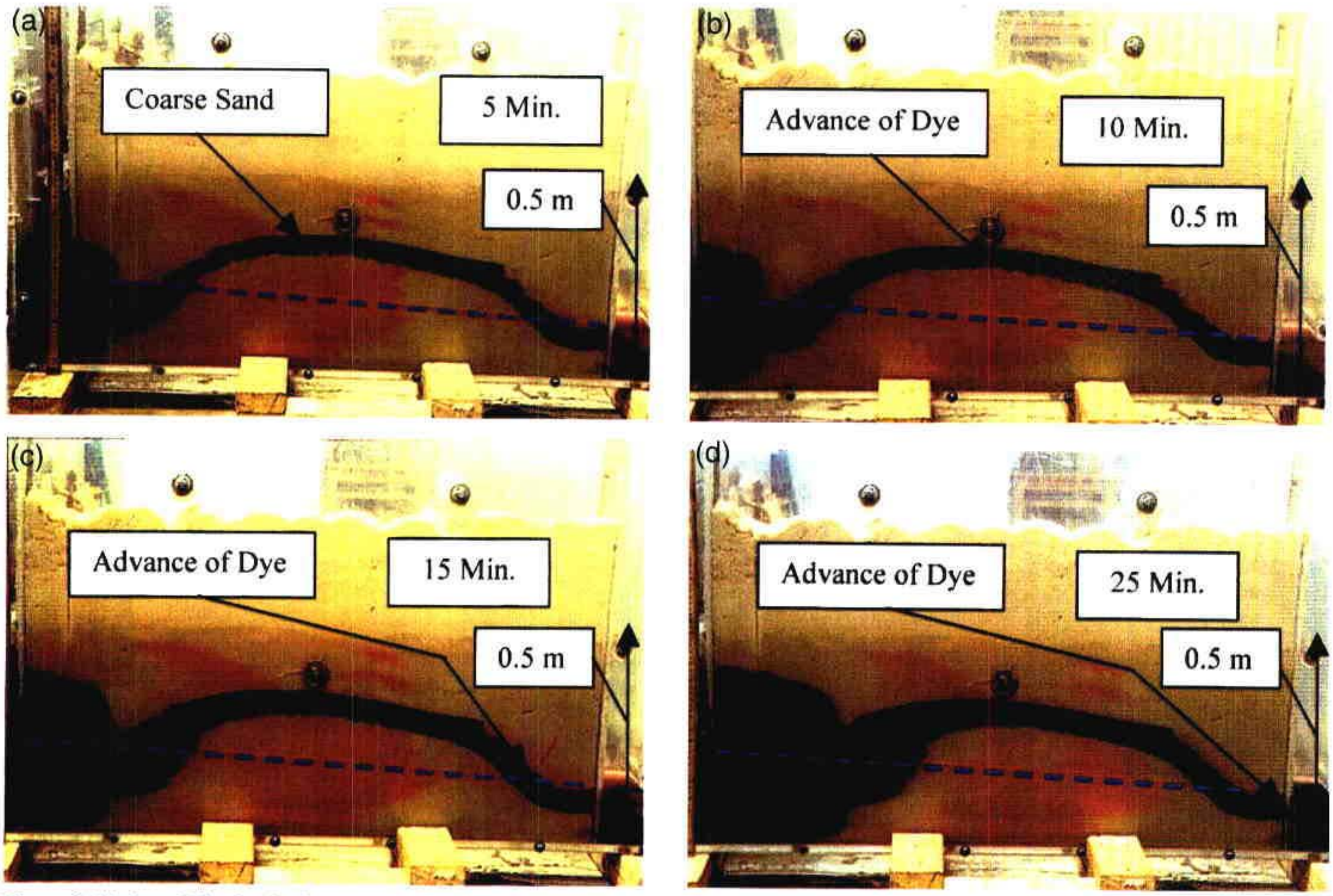

Figure 6. Motion of the dye in the presence of a nonhorizontal layer of coarse (darker) sand. Flow is from left to right. The green dye is the tracer added with the new experiment. The red dye is the remnant of a prior tracer experiment. The approximate location of the water table is illustrated with the dashed line. The movement of the green dye into the CF, horizontal across the CF, and then back below the water table is clearly demonstrated. It should also be noted that the flow route through the coarse sand in the CF was substantially faster than the route experienced by the red dye moving through the fine sand below the water table.

boundary conditions). It was not clear that, in the absence of these artificial inlet and outlet boundaries, there would be a driving force to carry the tracer from below the water table up into the coarse sand. Hence, our final investigation involved asking the question of whether a nonhorizontal heterogeneity could lead to movement of fluid from below the water table into the CF that was distinct from the effects of the boundaries.

The second tank was once again packed with a heterogeneous porous medium. For these experiments, a curved layer of coarse sand (the darker sand in Figure 6) was initiated below water level adjacent to the inlet reservoir, extended well above the anticipated elevation of the water table, and returned to an elevation below the water table adjacent to the outlet reservoir. The remainder of the tank was filled with the fine sand. The medium was packed under saturated conditions and all experiments were conducted under drainage conditions. For reasons described later, a copper tube (0.64 cm outer diameter) was packed into this medium such that the lower tip of the tube was within the upper portion of the coarse zone. The upper end of this copper tube, exposed to the atmosphere, was capped with a valve.

Initial experiments were conducted with the valve closed (such that no air could pass through the tube). Figure 6 shows a typical set of results with the water levels lowered below the coarse zone. As is seen in reviewing Figures 6a through 6d, the dye progresses rapidly along the coarse zone, crossing the water table, traveling within the CF, and then returning to a distance below the water table. These results demonstrate that, in the presence of heterogeneity, water can move from below the water table into the CF. Hence, a transport mechanism is demonstrated that will allow mixing of fluids from below the water table with fluids in the CF.

These results also illustrate an interesting phenomenon in that the water levels in the two reservoirs are low enough, relative to the top of the coarse sand layer, that the upper portion of the coarse zone should have desaturated, thus creating a low relative hydraulic conductivity in the coarse zone and an effective barrier to flow along the upper portion of the coarse zone. Clearly, this behavior is not observed in the images. This implies that the coarse zone has remained at high fluid saturation despite being at an elevation high enough to lead to desaturation.

It was hypothesized that this behavior was the result of what we now term an "air entry barrier" (AEB). By this hypothesis, the fine sand overlying the coarse sand remained, for this position of the inlet and outlet water levels, at nearly full saturation. As a result, the relative permeability to air through the fine sand was extremely small. This led to the conclusion that, during the period covered by these experiments (several days), the fine sand overlying the coarse sand prevented air from entering the coarse sand at a sufficient rate to allow significant desaturation of the coarse sand.

In an effort to test this hypothesis, the experiment was once again initiated with the valve closed on the copper tube. After

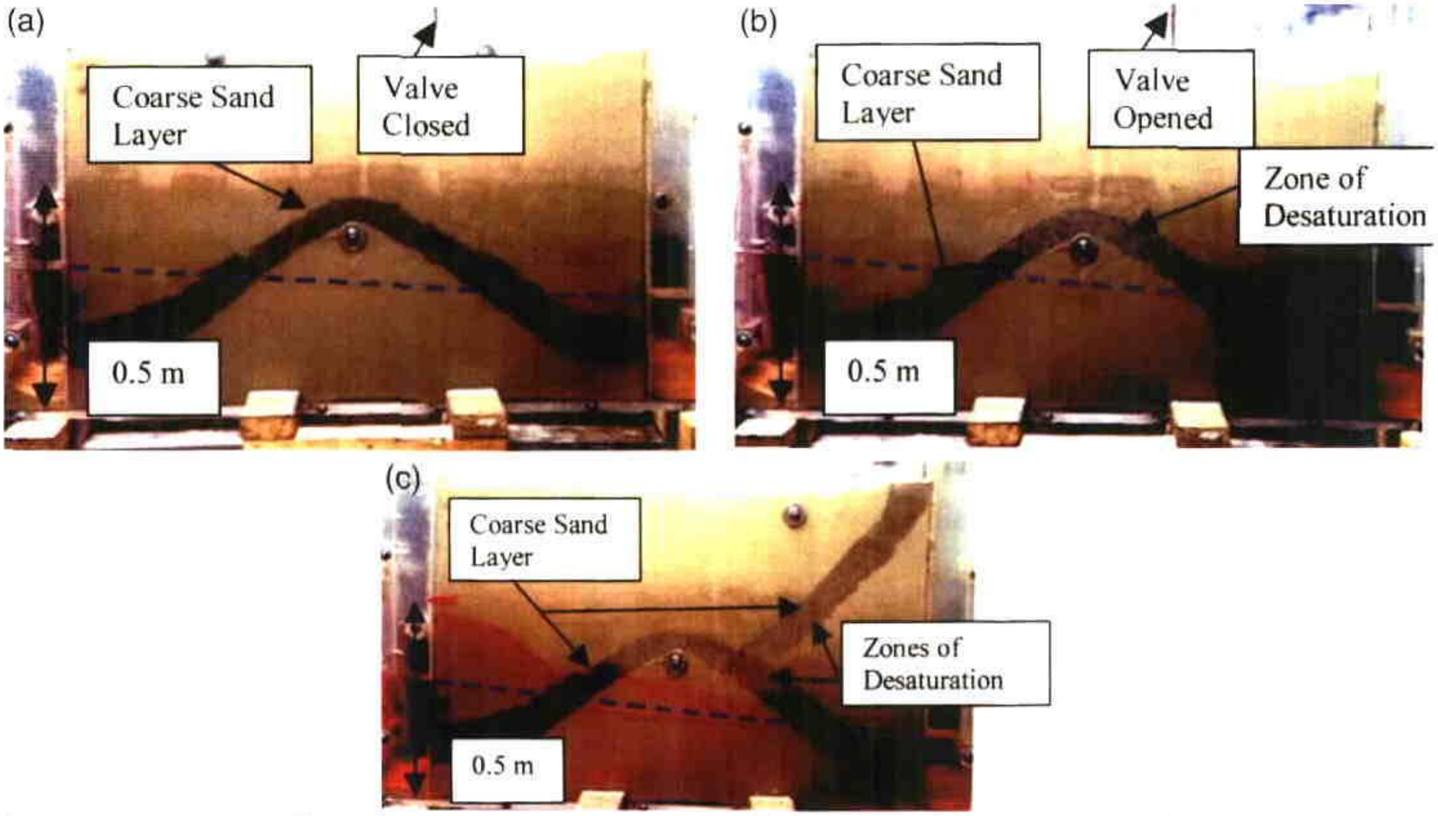

Figure 7. The experiment in Figure 6 repeated with the barrier to influx of air removed via a copper tube penetrating into the coarse layer (b) and through a continuous layer of the coarse sand to the surface (c). Comparison of Figures 7a and 7b illustrate that the mere presence of the copper tube penetrating into the coarse sand was insufficient to allow air entry. When a valve on the copper tube was closed (Figure 7a), flow continued to move through the coarse sand. Immediately upon opening of this valve, air entered the coarse sand via the tube, thus leading to desaturation of the upper portion of the coarse sand and cessation of flow in this portion of the CF (Figure 7b).

observing rapid tracer movement through the coarse sand, the valve on the copper tube was opened. The response was almost instantaneous. Within several minutes, the upper portion of the coarse sand had desaturated and the tracer was no longer transported along this route. This result is illustrated by comparing Figures 7a and 7b, showing the change in saturation of the coarse zone before (Figure 7a) and after (Figure 7b) the valve was opened. Figure 7c shows the lack of saturation during a final experiment in which the coarse sand was connected to the surface via a secondary route of coarse sand (thus breaching the AEB). It is clear in Figure 7c that the degree of saturation in the upper portion of the original coarse sand inclusion is substantially lower than in Figure 7a. No tracer migration was observed through the upper portion of the coarse sand under conditions shown in Figures 7b and 7c.

To our knowledge, these results are the first to illustrate the existence of such an AEB in the region above the water table. The implication of this result is significant as the elevation of nearly saturated pores can be quite high (1 m or more) above the water table in sediments containing continuous layers of clay or silts. Hence, in the presence of a clay or silt "barrier" above a coarse sand or gravel it is conceivable that the sand or gravel, may remain at high moisture content and, therefore, at high relative permeability at locations significantly above the water table.

Conclusion

The work presented here is exploratory in nature. The experimental and numerical results demonstrate that flow and solute transport may be far more significant in the CF than commonly assumed. These results are consistent with the theory of fluid flow in partially saturated media and with empirical laboratory and field evidence (i.e., geochemical measurements, observed movement of contaminants, stream hydrographs, and biological data). The experimental results also demonstrate that, in the presence of heterogeneity, local flow and solute transport within the capillary fringe may be extremely complex.

These results are interpreted as implying that the CF may play a far more active role than previously anticipated in the transport of solutes and the mixing of water from the vadose zone with that below the water table. The implications may be of critical importance in understanding geochemical and biological activity at the upper boundary of ground water systems, including both local (e.g., remediation) and regional (e.g., the study of subsurface ecosystems) scales. In particular, active flow and geochemical/biological activity in the 10 to 25 cm (or more) of the CF may have significant impact on (1) contaminants approaching the water table from the vadose zone, (2) biodegradation and geochemical transformation of contaminants near but below the water table, (3) the horizontal transport of contaminants near the water table, and (4) the geochemical (and isotopic) signature of mixed water entering the ground water zone.

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References

Affek, H.P., D. Ronen, and D. Yakir. 1998. About production of CO_2 in the capillary fringe of a deep phreatic aquifer. *Water Resour. Res.* 34, no. 5: 989–996.

Abdul, A.S., and R.W. Gillham. 1984. Laboratory studies of the effects of the capillary fringe on stream-flow generation. *Water Resour. Res.* 20, no. 6: 691–698.

Akindunni, F.F., and R.W. Gillham. 1992. Unsaturated and saturated flow in response to pumping of an unconfined aquifer: Numerical investigation of delayed drainage. *Ground Water* 30, no. 6: 873–884.

Boufadel, M.C., M.T. Suidan, A.D. Venosa, and M.T. Bowers. 1999. Steady seepage in trenches and dams: Effect of capillary flow. *J. Hydraulic Eng.-ASCE* 125, no. 3: 286–294.

Bouwer, H. 1978. *Groundwater Hydrology*. New York: McGraw-Hill.

Brooks, R.H., and A.T. Corey. 1966. Properties of porous media affecting fluid flow, *Journal of Irrigation Drainage* (Division of American Society of Civil Engineers) 92, 61–88.

Caron, F., S.R. Wilkinson, J. Torok, M.K. Haas, and W.N. Selander. 1994. CO_2 transport through the capillary-fringe in sand. *Waste Management* 14, no. 5: 421–433.

Caron, F., G. Manni, and W.J.G. Workman. 1998. A large-scale laboratory experiment to determine the mass transfer of CO_2 from a sandy soil to moving groundwater. *J. Geochem. Explor.* 64, nos. 1-3: 111–125.

Carsel, R.F., and R.S. Parrish. 1988. Developing joint probability distributions of soil water retention characteristics. *Water Resour. Res.* 24, no. 5: 755–769.

Feddes, R.A., P.J. Kowalik, and H. Zaradny. 1978. *Simulation of Field Water Use and Crop Yield*. New York: John Wiley & Sons.

Fry, V.A., J.S. Selker, and S.M. Gorelick. 1997. Experimental investigations for trapping oxygen gas in saturated porous media for in situ bioremediation. *Water Resour. Res.* 33, no. 12: 2687–2696.

Gillham, R.W. 1984. The effect of the capillary fringe on water-table response. *J. Hydrol.* 67, 307–324.

Glass, R.J., and M.J. Nicholl. 1996. Physics of gravity fingering of immiscible fluids within porous media: An overview of current understanding and selected complicating factors. *Geoderma* 70, nos. 2/4: 133–163.

Glass, R.J., J.Y. Parlange, and T.S. Steenhuis. 1991. Immiscible displacement in porous-media: Stability analysis of 3-dimensional, axisymmetrical disturbances with application to gravity-driven front instability. *Water Resour. Res.* 27, no. 8: 1947–1956.

Jawitz, J.W., M.D. Annable, and P.S.C. Rao. 1998. Miscible fluid displacement stability in unconfined porous media: Two-dimensional flow experiments and simulations. *J. Contam. Hydrol.* 31, nos. 3-4: 211–230.

Jayatilaka, C.J., and R.W. Gillham. 1996. A deterministic-empirical model of the effect of the capillary fringe on near-stream area runoff: 1. Description of the model. *J. Hydrol.* 184, nos. 3-4: 299–315.

Jayatilaka, C.J., R.W. Gillham, D.W. Blowes, and R.J. Nathan. 1996. A deterministic-empirical model of the effect of the capillary fringe on near-stream area runoff: 2. Testing and application. *J. Hydrol.* 184, nos. 3-4: 317–336.

Keller, C.K., G. Van der Kamp, and J.A. Cherry. 1989. A multiscale study of the permeability of a thick clayey till. *Water Resour. Res.* 25, no. 11: 2299–2317.

Keller, C.K., G. Van der Kamp, and J.A. Cherry. 1988. Hydrogeology of two Saskatchewan tills. 1. Fractures, bulk permeability, and spatial variability in downward flow. *J. Hydrology* 101, nos. 1-4: 97–121.

Kinouchi, T., M. Kanda, and M. Hino. 1991. Numerical-simulation of infiltration and solute transport in an S-shaped model basin by a boundary-fitted grid system. *J. Hydrol.* 122, nos. 1-4: 373–406.

Lahvis, M.A., A.L. Baehr, and R.J. Baker. 1999. Quantification of aerobic biodegradation and volatilization rates of gasoline hydrocarbons near the water table under natural attenuation conditions. *Water Resour. Res.* 35, no. 3: 753–765.

Lehmann, P., F. Stauffer, C. Hinz, O. Dury, and H. Fluehler. 1998. Effect of hysteresis on water flow in a sand column with a fluctuating capillary fringe. *J. Contam. Hydrol.* 33, nos. 1-2: 81–100.

Li, L., D.A. Barry, J.-Y. Parlange, and C.B. Pattiaratchi. 1997. Beach water table fluctuations due to wave run-up: Capillarity effects. *Water Resour. Res.* 33, no. 5: 935–945.

Martin, J.P., and R.M. Koerner. 1984. The influence of vadose zone conditions on groundwater pollution, Part II: Fluid movement. *J. Hazardous Materials* 9, 181–207.

McCarthy, K.A., and R.L. Johnson. 1993. Transport of volatile organic compounds across the capillary-fringe. *Water Resour. Res.* 29, no. 6: 1675–1683.

Mixon, F.O. 1984. Saturated and capillary fringe ground water behavior near an excavation. *Ground Water* 26, no. 2: 148–155.

Nielsen, P., and P. Perrochet. 2000. Watertable dynamics under capillary fringes: Experiments and modeling. *Adv. Water Resour.* 23, 503–515.

Nwankwor, G.I., R.W. Gillham, G. van der Kamp, and F.F. Akindunni. 1992. Unsaturated and saturated flow in response to pumping of an unconfined aquifer: Field evidence of delayed drainage. *Ground Water* 30, no. 5: 690–700.

Ostendorf, D.W., D.J. DeGroot, and S.J. Pollock. 1995. Aerobic acetate degradation near the capillary-fringe off roadside soil—Field simulations from soil microcosms. *J. Environ. Qual.* 24, no. 2: 334–342.

Parlange, J.-Y., and W. Brutsaert. 1987. A capillary correction for free surface flow of groundwater. *Water Resour. Res.* 23, no. 5: 805–808.

Romano, C.G., E.O. Frind, and D.L. Rudolph. 1999. Significance of unsaturated flow and seepage faces in the simulation of steady-state subsurface flow. *Ground Water* 37, no. 4: 625–632.

Ronen, D., B. Berkowitz, and M. Magaritz. 1989. The development and influence of gas bubbles in phreatic aquifers under natural flow conditions. *Transp. Porous Media* 4, no. 3: 295-306.

Ronen, D., H. Scher, and M. Blunt. 1997. On the structure and flow processes in the capillary fringe of phreatic aquifers. *Transp. Porous Media* 28, no. 2: 159–180.

Ronen, D., H. Scher, and M. Blunt. 2000. Field observations of a capillary fringe before and after a rainy season. *J. Contam. Hydrol.* 44, no. 2: 103–118.

Rosenberry, D.O., and T.C. Winter. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. *J. Hydrol.* 191, nos. 1-4: 266–289.

Schroth, M.H., S.J. Ahearn, J.S. Selker, and J.D. Istok. 1996. Characterization of Miller-dimilar siilica sands for laboratory subsurface hydrologic studies. *Soil Sci. Soc. Am J.* 60, 1331–1339.

Shamsai, A., and T.N. Narasimhan. 1991. A numerical investigation of free surface-seepage face relationship under steady state flow conditions. *Water Resour. Res.* 27, no. 3: 409–421.

Silliman, S.E., R. Dunlap, M. Fletcher, and M.A. Schneegurt. 2001. Bacterial transport in heterogeneous porous media: Observations from laboratory experiments. *Water Resour. Res.* 37, no. 11: 2699–2708.

Simunek, J., M. Sejna, and M.Th. van Genuchten. 1999. The Hydrus-2D software package for simulating two-dimensional movement of water, heat, and multiple solutes in variably saturated media. Version 2.0, IGWMC-TPS-53, International Ground Water Modeling Center, Colorado School of Mines, Golden, Colorado.

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* 44, no. 5: 892–898.

Wise, W.R., T.P. Clement, and F.J. Molz. 1994. Variably saturated modeling of transient drainage—Sensitivity to soil properties. *J. Hydrol.* 161, nos. 1-4: 91–108.

Zaidelman, F.R., A.P. Shvarov, E.B. Pavlova, and S.N. Golovin. 1997. Rate of biochemical decomposition of organic matter in drained peaty soils at different sanding modes. *Eurasian Soil Sci.* 30, no. 9: 1024–1032.

Zhang, H., D.A. Barry, and G.C. Hocking. 1999. Analysis of continuous and pulsed pumping of a phreatic aquifer. *Adv. Water Resour.* 22, no. 6: 623–632.