Potential for Establishing Nonvertical Flow within the Vadose Zone

Laboratory experiments and numerical studies are used to study the potential to induce water flux in the vadose zone, which is characterized by significant horizontal components of the water velocity. Specifically, a question is addressed as to whether water can be injected or withdrawn from lenses or layers of fine sediments (bordered by coarse sediments), thus establishing flow in those portions of the vadose zone commonly associated with higher moisture contents and a higher mass of dissolved contaminants. Laboratory experiments provided the base-line proof of concept of the ability to induce horizontal components to flow in unsaturated sediments through use of suction-cup lysimeters, but were limited to ideal media and short distance scales (<0.5 m). A numerical model was used in combination with published moisture retention and relative permeability parameters for a variety of sediment types to study conditions under which such horizontal flow components might be induced over substantially greater distances (e.g., 10 m). While these numerical results support arguments that flow induction is theoretically possible, induced flow will generally result in slow transport velocities such that application will likely be limited either to short flow distances (e.g., less than a meter) or long-term (>50 years) time scales, and only with thorough knowledge of subsurface heterogeneity. Implications of this work beyond the present study may include continuing discussions of constructed capillary barriers and development of improved technologies for removal of water from the vadose zone.

It is widely recognized that flow within the vadose zone is relatively complex and very much dependent on the distribution of sediment heterogeneities. While the mean direction of water movement through the vadose zone (below the root zone) tends to be vertically downward, a number of authors have demonstrated that physical heterogeneity can result in substantial variability in local flow, including fingering, preferential flow, and horizontal migration of water and chemical constituents (e.g., Kung, 1990a,b; Sassner et al., 1994; Afyuni et al., 1994; Iqbal, 2000; Onsoy et al., 2005; Vereecken et al., 2007).

Among the phenomena associated with physical heterogeneity in the vadose zone are “capillary barriers,” which have been studied extensively since the 1990s as a means of isolating regions of coarse sediments from infiltrating water. Argued to exist in the vadose zone where fine-grained sediments overlie coarse-grained sediments, these barriers were reported to lead to flow with a significant horizontal component along the base of the finer-grained sediments. The lack of penetration of fluid into coarser sediments was argued to be related to the difference in unsaturated hydraulic conductivities, air-entry pressures, and moisture contents in the coarse-grained versus fine-grained sediments. A number of authors explored the hydraulics of capillary barriers through numerical and experimental methods (e.g., Ross, 1990; Kung, 1990a, 1990b; Oldenburg and Pruess, 1993; Yeh et al., 1994; Selker, 1997; Ho and Webb, 1998; Schroth et al., 1998; Iqbal, 2000). These early studies led a number of authors to consider the impact of capillary barriers on flow and chemical transport through experimental or mathematical analyses (e.g., Aubertin et al., 2009; Boateng, 2007; Tidwell et al., 2003; Ho and Webb, 1998; Schroth et al., 1998).

While significant literature has been dedicated to the investigation of observed variation in flow patterns within the vadose zone and the potential for capillary barriers to isolate coarse-grained sediments, substantially less attention has been paid to the topic of artificially manipulating water flux in fine-grained sediments within the vadose zone, particularly to manipulating this flux to establish significant horizontal components to flow. Through experimental and numerical analysis we explore the potential for simple technologies (suction-cup lysimeters) to provide an opportunity to induce flow within...
fine-grained sediments in the vadose zone, particularly in regions where these sediments form continuous layers or lens bounded by coarser-grained sediments. While a primary conclusion presented below is that the technology studied may be impractical beyond short flow distances (meters or less), simple heterogeneities, or relatively long time scales, this discussion provides theoretical arguments that induced, nonvertical flow might be possible under select field (natural or engineered) conditions.

Conceptual Basis

Flow at any point within an unsaturated porous medium is commonly quantified via the unsaturated version of Darcy’s law, which for horizontal isotropy, a z axis being positive in the vertically upward direction, and a free air phase at atmospheric pressure can be written (following the notation of Hillel, 1982)

$$
\begin{align*}
q_x &= K_{H}(\Psi) \frac{d(\Psi)}{dx} \\
q_y &= 0 \\
q_z &= 0 \quad \text{(1)}
\end{align*}
$$

where $q_i$ is the flux component in the $i$th direction, $\Psi = P_c/\rho g$ where $P_c$ is the capillary pressure, and $K_{H}(\Psi)$ and $K_{Z}(\Psi)$ are the unsaturated hydraulic conductivities in the horizontal and vertical directions, respectively. The relationship of the unsaturated hydraulic conductivity with capillary pressure has been studied by a number of authors (e.g., the early studies of van Genuchten, 1980, and a significant number of studies since that time) and generally takes on a form similar to that shown for a number of sediments in Fig. 1a (as adapted from data provided in the database of the modeling software, HYDRUS; Šimunek et al., 1999, 2006); that is, the magnitude of the conductivity drops multiple orders of magnitude as the capillary pressure increases (and therefore the moisture content decreases). Significant to the present discussion, it is expected that coarser-grained sediments will show rapid decline in conductivity at relatively low capillary pressures, whereas finer-grained sediments will tend to maintain moisture (and therefore conductivity) until significantly larger capillary pressures. This rapid decline in the conductivity of a coarse sediment versus a fine sediment is evident, for example, in two sieved sands used in a number of prior laboratory experiments (Accumin Sands as used, for example, by Schroth et al., 1996, 1998; Dunn and Silliman, 2003), as well as in the experiments described below. It is observed in Fig. 1b that, while the coarser of these two sands has a saturated hydraulic conductivity approximately an order of magnitude higher than the fine sand, the unsaturated hydraulic conductivity of the coarse sand at a capillary pressure of 15 cm is several orders of magnitude less than that of the fine sand. Similar to these sieved sands, it can be expected that heterogeneous distributions of sediments that are near steady-state flow at relatively high capillary pressures will be characterized by higher unsaturated hydraulic conductivities in zones of finer-grained sediments than in zones of coarser-grained sediments.

Such variation in the magnitude of hydraulic conductivities combined with differences in air-entry barriers for different sediments was the basis for study of the occurrence of the capillary barrier effect as a means for isolating sediments from vertical water flux in the vadose zone (e.g., Ross, 1990; Oldenburg and Pruess, 1993; Aubertin et al., 2009). This variation is also the basis of the argument explored in the present study that nonvertical water flux can be established in the vadose zone under certain combinations of moisture content and physical heterogeneity.
To understand the conceptual basis for this work, consider the hypothetical distribution of sediments shown in Fig. 2: fine-grained sediment is embedded within a porous medium consisting predominantly of coarse-grained sediments. Under saturated conditions, the finer-grained sediment would be expected to have a lower hydraulic conductivity than the surrounding coarser-grained sediments, and, under the influence of a hydraulic gradient, flow would be expected to be concentrated predominantly in the coarser sediments.

The relationship between the coarse and fine media becomes more complicated for unsaturated porous media: four types of behavior are suggested, based on four zones which may be identified on the unsaturated hydraulic conductivity versus capillary pressure curve. These zones are illustrated through use of the example curves shown in Fig. 1b (these two sands are chosen because they provide an example in which the four zones are very distinct—in many cases, one or more of the four zones may not exist and/or may not be distinct from the other zones):

Zone 1: This occurs when capillary pressures are low relative to the air-entry barrier of both sediments (e.g., less than \( \sim 5 \) cm for the sands in Fig. 1b). Both sediments are at high moisture content, and the \( K_{\text{unsat}} \) in the coarse sediment is larger than that in the fine sediment. Any flow moving through the porous medium under these conditions will be low in the fine sediment relative to the coarse sediment, as would be experienced in the saturated zone (due to the low saturated hydraulic conductivity of the finer-grained sediments).

Zone 2: This occurs at capillary pressures where the coarse sediment is partially desaturated while the fine sediment remains at high moisture content. Over a small range of capillary pressures, this partial desaturation will result in approximately equal \( K_{\text{unsat}} \) values for the two sediments (this would occur, for example, at approximately 5 to 8 cm for the sediments in Fig. 1b). In this case, flow under a hydraulic gradient will be approximately the same in the two sediments.

Zone 3: If present, this zone occurs at capillary pressures for which the moisture content in the coarser sediment is low enough that the \( K_{\text{unsat}} \) for the coarse sediment is well below that of the finer sediment. The finer sediment remains at high moisture content and, therefore, with a \( K_{\text{unsat}} \) approximately equal to the saturated hydraulic conductivity for this sediment. While this zone may not be present in all combinations of sediments (e.g., compare the HYDRUS silt with the HYDRUS loam in Fig. 1a—there is no clear zone where the silt has a substantially higher \( K_{\text{unsat}} \) than the loam), when present, it creates the opportunity for flow approximately parallel to the primary plane of the finer-grained sediments. Such flow will be particularly likely in the presence of a significant horizontal component to the pressure gradient or when the plane of these sediments is at significant dip relative to the horizontal (such that gravity is a significant driving force along with the pressure gradient). In the case of the sediments in Fig. 1b, this zone would span approximately 8 to 20 cm.

Zone 4: This occurs when capillary pressures are high relative to the air-entry pressures for both sediments (e.g., greater than \( \sim 20 \) cm in the sediments in Fig. 1b). At this point, both sediments are partially desaturated, and the unsaturated hydraulic conductivities of both sediments are substantially lower (typically orders of magnitude lower) relative to the respective saturated conductivities. In this zone, the magnitudes of the unsaturated conductivities in both sediments are low enough that it is not expected that any substantial water velocities can be generated, except under extreme pressure gradients.

Of these zones, the third is thought to be of primary interest for consideration of options for introducing horizontal components to flow in the finer sediments without imposing substantial vertical flow that leads from the finer sediments into the underlying coarser sediments. In this situation, if water is introduced or withdrawn from the finer sediment while maintaining capillary pressures characterizing Zone 3 (specifically, keeping moisture content high in the finer sediment and low in the underlying coarser sediment), flow will occur preferentially within the finer sediment lens or layer. The laboratory and numerical experiments discussed below provide studies of the potential to accomplish such simultaneous introduction and withdrawal of water.

## Laboratory Experiments

### The Flow Cell, Porous Media, and Lysimeters

Figure 3 presents an image of the flow cell used in the experimental portion of this study. Further details regarding these experiments can be found in Fisker (2009). The critical dimensions of this flow cell are shown on the image. Reservoirs were located on either side of the sediment compartment, allowing adjustment of the water table height within the sediments. The reservoirs were separated...
from the porous material by an 0.177-mm (80-mesh) stainless-steel screen supported by a plastic lattice. The base of the tank was solid plexiglass such that no flow was allowed to enter or exit through the base. The upper surface of the tank was covered loosely with a plastic sheet, allowing free flow of air to allow equilibration of changes in atmospheric pressure while minimizing evaporative loss from the upper surface.

The porous medium used in the tank experiments consisted of two grain sizes of Accumin sand (Lab Sand 1 and Lab Sand 2 in Fig. 1b) and were the same sands used in earlier experiments conducted in our laboratory by Dunn (2003, 2005). The grain sizes used were 0.30- to 0.45-mm grain size (40/50 mesh), herein termed Lab Sand 2 or fine sand, and 0.85- to 1.55-mm grain size (12/20 mesh), herein termed Lab Sand 1 or coarse sand. Schroth et al. (1996) provided characterization of these sands in terms of their hydraulic behavior under both saturated and unsaturated conditions. The air-entry pressures (assumed to be approximately equal to the capillary rise) for the sands under packing conditions used in our laboratory were estimated, based on laboratory measurements, to be 20 and 6 cm for the fine and coarse sands, respectively (Dunn, 2005).

While it is recognized that these sands are artificially sorted with an extremely uniform grain size, they were selected for this initial experimental effort for three reasons. First, our previous work with these sands has shown that it is relatively straightforward to pack these sands homogeneously into a laboratory tank. Second, the laboratory experiments were designed as proof of concept experiments. Hence, we chose an end member of the hydraulic properties of the sands (specifically, the steep $K_{\text{unsat}}$ versus capillary pressure curves shown in Fig. 1b) that would optimize the probability of inducing flow in the finer-grained sediments under laboratory conditions. Third, the unsaturated hydraulic conductivity of the fine sand at the capillary pressures used in the laboratory was high enough to allow experiments to be performed at reasonable time scales (e.g., <40 d). As discussed below, these laboratory results are extended to more complex media using the numerical model.

The sands were packed under saturated conditions to encourage consolidation and avoid trapped air. The coarse sand was initially packed to the desired location at the base of the fine-sand lens (approximately 25 cm above the base of the flow cell for horizontal lenses). Two vertical dividers were then used to separate the coarse from the fine sands during packing of the fine-sand lens. The dividers were removed after completion of the fine sand lens, and the upper portion of the flow cell was then filled with coarse sand. The coarse sand was commonly terminated approximately 10 cm above the fine sand lens due to the fact that the coarse sand was at residual moisture (during the experiments) well below this elevation. Both horizontal and angled (~15° from horizontal) lenses were studied.

Suction cup lysimeters (model 1911, SoilMoisture Equipment Corporation, Santa Barbara, CA) were used to both inject and withdraw water from the fine sand lens over a range of capillary pressure. These lysimeters (Fig. 4) include high-flow porous ceramic cups with a 0.1-MPa (1-bar) bubble pressure. The dimensions of each lysimeter included an outer diameter of 2.15 cm, an inner diameter of 0.91 cm, a length of ceramic cup of 7.5 cm, and a total length of approximately 11 cm. The lysimeter and attached tubing were all saturated before installation in the sediments.
The lysimeters were installed vertically (i.e., the 11-cm dimension was vertical) approximately 2 cm from either end of the fine sand lens with the suction cup located within the fine sand. They were installed during packing of the fine sand lens.

Monitoring of fluid migration was performed visually through injection of dyes both as instantaneous point sources introduced via syringe and needle (introduced from the upper surface of the sand) and as a continuous source through the inflow lysimeter. The dyestock used have been studied in a number of prior laboratory efforts in our laboratories and are known to be essentially conservative (i.e., do not react or sorb) in the sands used for these experiments. The movement of dye was recorded (via time-lapse photography) along the front face of the flow cell. In addition, select experiments were terminated with the dye front approximately one-half the distance between inflow and outflow. For these latter experiments, the sands were then removed in 1-cm lifts, and the distribution of the dye in the horizontal plane was recorded at each lift.

Establishing Flow

Inflow and outflow from the lysimeters was established in three ways with the intent of investigating initiation of flow under three different field conditions: (i) during a period when the elevation of the water table is dropping, (ii) within the region immediately above the capillary fringe, and (iii) within a region at relatively low initial moisture content. The first option involved initiating inflow/outflow while the sands were saturated, with subsequent lowering of the water table (through adjustment of water levels in the two external reservoirs) to its final elevation below the lens. The second option involved both lysimeters being inactive during the packing procedure and subsequent lowering of the water table to an elevation approximately 10 cm below the base of the fine-sand. The lysimeters were then activated to initiate flow. In the final option, both lysimeters were inactive during the packing procedure and lowering of the water table to the base of the tank: drainage continued for periods of up to 3 wk to ensure that no additional water was draining from the flow cell. At this point (and with the fine sand at relatively low moisture content), the lysimeters were activated and flow was initiated. The results presented below proved to be independent of which method was used to induce flow.

Results from the Laboratory Experiments

Initial efforts in the laboratory demonstrated that a number of technical issues needed to be considered before successful design of a lysimeter system to induce flow. Specifically, steps were required to avoid: (i) drying of the sand in vicinity of the lysimeter at the lower capillary pressure, (ii) accidental introduction of air into the inflow or outflow tubing (thus potentially changing the intended capillary pressure within the lysimeter), and (iii) producing significant vertical flow into the coarse sand in the vicinity of the inflow lysimeter. Through laboratory efforts and use of the numerical model (discussed below), procedures were established to allow reliable and reproducible induction of horizontal or subhorizontal flow through the fine sand.

Figure 5 shows a sequence of images demonstrating induction of flow across a horizontal lens of fine sand. Outflow flux was measured and provided an average flow rate (at steady state) of $\sim 26 \text{ cm}^3 \text{ d}^{-1}$; as no other outflows were possible in this experimental design, it was assumed that the inflow rate was approximately equal to this outflow (again, at steady state). Dye inflow was initiated by adding an inert green dye (food coloring) to the inflow lysimeter. Total elapsed time for these images covers a period of approximately 10 d. The locations of the inflow and outflow

![Fig. 5. Transport of dye tracer moving across fine sand layer embedded in a coarse sand matrix. The location of the inflow (left) and outflow (right) lysimeters are shown with the dotted rectangles in Panel a. The dye was introduced with the fluid entering the sand via the inflow lysimeter. The maximum height of capillary rise in the coarse sand is visible below the lens and identified with the white line in the first image. The images were recorded: (a) early in the experiment, (b) after 1 d, (c) after 3 d, and (d) after 10 d. The images focus on the fine-sand layer and include approximately the region shown by the dashed box in Fig. 3 (the 30-cm ruler provides scale: the horizontal and vertical dimensions are approximately 40 by 25 cm).](image-url)
Lysimeters are as shown. The approximate upper edge of the capillary fringe in the coarse sand can be seen as a subtle color change below the lens in the images (and is indicated on the first image).

A significant horizontal component to flow through the fine sand is apparent in the images, based on the migration of the tracer. Common to all lab experiments and consistent with the numerical simulations, higher velocities were noted in the lower portion of the fine sand, but observable horizontal velocity was apparent at all depths in the lens. In repeat experiments run at lower flow rates, flow through the fine sand without migration into the coarse sand was maintained for periods exceeding 30 d.

These experiments provide initial proof of concept that flow with significant horizontal components can be induced (albeit within optimal sands) within the vadose zone under laboratory conditions.

**Numerical Simulations**

Numerical modeling was used both to help design and interpret the laboratory results and to extend these results into more complex systems with less idealistic sediment properties. All modeling was performed using HYDRUS\_2D/3D (Šimunek et al., 1999, 2006), a finite element solution based on the Richards equation for variably saturated flow and the advection–dispersion equation for solute transport. All modeling was performed in two dimensions to allow more rapid exploration of the potential and limitations of the proposed method of injection and withdrawal of water in fine-grained sediments. Limitations of results related to this assumption are discussed below.

Two series of simulations were completed. The first was focused on investigation of small-scale media modeled after the laboratory experiments. The second was focused on extension of these results to larger distances (length scale of 10 m), more complex geometries, and consideration of the impact of recharge.

**First Set of Simulations**

The first set of simulations was based on a numerical grid that was matched to the overall dimensions of the sediment compartment of the laboratory tank (46 × 42 cm), with the fine sand modeled as a region of 30 by 8 cm (Fig. 6a). A nodal spacing of 0.5 by 0.5 cm was utilized throughout the grid.

These simulations were run in two phases. The first phase involved developing a large-time (approximately steady state) hydraulic solution consistent with the desired boundary conditions and lysimeter fluxes. No solute transport was simulated during this phase. Boundary conditions used included a constant pressure boundary at the base of the grid and no flow boundaries at surface and along the two vertical boundaries of the grid. (While it is recognized that these conditions are not exactly the same as those used in the laboratory flow cells, these conditions can be expected to replicate the steady-state conditions in the laboratory for which there was zero net flux across these boundaries.) The pressure assigned to the lower boundary varied between 0 and −30 cm, depending on the intended hydraulic conditions within the medium during a particular run. Initial pressure conditions elsewhere in the grid were hydrostatic, with pressure declining (capillary pressure increasing) linearly with height above the bottom boundary.

Inflow and outflow from the fine sediment were modeled as two groups of 12 nodes located 2 cm from the left (inflow) and right (outflow) ends of the fine sediment lens. Equal nodal recharge was assigned to each node in these groups (positive for an injection point and negative for a point of withdrawal) with a value determined such that total inflow in the simulations was equal to the estimated rate of flux used in one of the laboratory experiments. Due to limitations related to pressure drop across the ceramic cups used in the lysimeters, accurate measurement of pressure differential was not possible in the lab experiments, but inflow and outflow fluxes were measured, so constant flux was used for the lysimeters in the numerical simulations to allow matching the numerical and laboratory results. For the results shown below, the measured total flux in the relevant laboratory experiment (transport results shown in Fig. 5) was 26 cm\(^3\) d\(^{-1}\) resulting in a flux per centimeter width of the flow cell (total width = 15 cm) of 1.71 cm\(^3\) d\(^{-1}\) per centimeter of width. This flux was distributed over the 12 recharge nodes.

Fig. 6. Grids for the two series of simulations: (a) laboratory-based numerical model (46 by 42 cm, top), and (b) complex geometry model (10 by 2 m). For the latter case, the grid was angled at an angle with the horizontal varying between 0 and 10°. Lighter color in each image represents the finer-grained sediment. Element geometries were constant within the grids and are shown on the images.
Given the nodal recharge, material distribution, and boundary conditions, the hydraulic simulation was run for an extended period (between 40 and 365 d depending on the simulation) to obtain an approximately steady-state hydraulic solution. This solution was then used as the initial hydraulic condition for the second phase of the simulation.

The second, transport phase of the simulation was run on the same numerical grid as the hydraulic solution. Required parameters included assumed longitudinal and transverse dispersivities for both the coarse and the fine sediments. For the results shown below, a longitudinal dispersivity of 1.0 cm and a transverse dispersivity of 0.1 cm were assumed for both media. The initial condition for the transport was arbitrarily set at 100 mg L\(^{-1}\), with flow at the recharge nodes entering the system at a concentration of 0 mg L\(^{-1}\). The lower boundary of the grid was set as a third-type boundary, while the two vertical boundaries as well as the upper boundary were set as zero mass flux.

No calibration was used for either the hydraulic or transport simulations in this series as published and/or measured values were available for all parameters except the dispersivities. Inspection of multiple simulations using different dispersivities (1.0 cm down to 0.1 cm for the longitudinal dispersivity with similar variation in the transverse dispersivity) demonstrated that the overall behavior of the transport predicted by the model was not strongly dependent on the dispersivities. Hence, 1.0 cm (longitudinal) and 0.1 cm (transverse) were assumed adequate without further calibration or adjustment.

Typical results from this series are shown in Fig. 7, the numerical approximation to the experiments shown in Fig. 5. While an exact match between the numerical and experimental was not anticipated due to the three-dimensional nature of the laboratory experiment, the degree of agreement of these numerical results with the experimental results is considered quite strong. Specifically, the tracer front advances in both speed and geometry (with more rapid flow along the lower portion of the lens) in a manner quite consistent with the lab results. This result is considered particularly strong given that the numerical model was not calibrated to these lab results, but rather was run using published properties for the sands and measured flow rates.

Additional numerical experiments demonstrated that flow at this scale could be induced for a number of combinations of sediment types (see Fisker, 2009). However, these numerical experiments also indicated that flow induction, without substantial vertical flux, becomes increasingly difficult with decreasing difference in the \(K_{unsat}\) of the two sediments at the capillary pressure of interest. These results, then, led to the question of whether flow induction was likely to be possible at larger length scales (requiring a larger range in capillary pressure to maintain a reasonable flow rate), in other sediments, and in more complex geometries.

Second Series of Simulations

The second series of simulations addressed the question of whether flow induction was likely to be scalable to field situations and consistent with a broader class of sediments and sediment geometries than studied in the laboratory-scale simulations. These simulations were run on a grid of 10 by 2 m with an orientation ranging between 0 and 10° above the horizontal (Fig. 6b). An irregular lens of finer-grained sediments was simulated as extending approximately 9 m across the grid, but not touching any boundary; the vertical dimension of this lens varied from <10 cm to >30 cm, and the lens was split into multiple fingers at several points along its length. Nodal spacing of 2 by 2 cm was used for all simulations in this series.

In contrast with the first series, the second series of simulations involved only one phase of solution. Specifically, subject to the initial hydraulic and concentration conditions outlined below, the simulations were run with both the hydraulics and transport under unsteady conditions in a single simulation run. This single phase of simulation was considered more representative of likely field conditions under which flow and transport might be induced.

Initial hydraulic conditions were defined based on a hydrostatic pressure profile relative to the lowest point on the numerical grid. The pressure at the lowest point on the grid was set equal to a value between 50 and −10 cm, depending on the desired simulation. In terms of hydraulic boundary conditions, all nodes along the bottom of the grid were set as constant pressure in time: for the slanted grids, the pressure along this boundary varied with elevation above the lowest corner of the grid. The remaining three boundaries were set as no-flow boundaries.

![Fig. 7. Numerical model of two-dimensional flow through a fine sand layer based on the experiments shown in Fig. 5 (colors represent chemical concentrations: red = 90–100 mg L\(^{-1}\), blue = 0–10 mg L\(^{-1}\)). The images shown are for Days 1, 3, and 10 to allow direct comparison with Fig. 5. The dimension of each image is 46 by 42 cm.](www.VadoseZoneJournal.org)
Initial and boundary conditions for the transport were the same as with the first set of simulations. Specifically, an initial concentration of 100 mg L\(^{-1}\) was assigned uniformly to the entire grid. The boundary condition along the lower edge of the grid was set as a third-type condition. Zero flux boundary conditions were used for all other boundaries. Dispersivities for both media were set at 2.0 cm (longitudinal) and 0.2 cm (transverse) in recognition of the larger flow distances. As with the first series, the transport solution was not tremendously sensitive to the dispersivity.

In a change from the first series of simulations, the inflow and outflow points in these grids (representing the lysimeters) were simulated as constant pressure nodes. This change allowed simulation of the likely approach to be used with lysimeters in the field as well as the situation in which a lysimeter cup extends substantially above or below the target sediment lens, a situation considered likely in the field. Choice of pressure at these fixed nodes was dependent on sediment type and angle of the grid, as described below. Figure 8 shows a general schematic of the location of the fixed pressure nodes used to represent the lysimeters. For the majority of simulations, one set of nodes was located on the right portion of the medium and a second set was located at the left end. For the final set of simulations (discussed below) involving recharge, a third set of nodes (simulating a third lysimeter) was added along the interior of the system. For the simulations involving a horizontal grid, 11 nodes were used for both the left and right ends. For the slanted simulations, 16 nodes were used for inflow, while 21 were used for outflow, providing opportunity to study the impact of a lysimeter extending above or below the fine-grained sediment. The third set of nodes involved 16 nodes.

Initial simulations using a mean horizontal lens with injection and withdrawal separated by 8.5 m demonstrated that induction of flow along the lens (without substantial vertical breakthrough into the underlying coarser medium) at this scale in a horizontal lens would be difficult under essentially all but the most ideal conditions. Figure 9a, for example, shows results for a silt layer within a loamy sand matrix. Typical of many of the results obtained for the horizontal lens, the horizontal component of the flow velocity was small due both to the relatively low \(K_{\text{unsat}}\) in the fine-grained sediments and the low hydraulic gradients that can be imposed (without wetting the underlying coarse-grained sediment at the inflow end or drying out the fine sediments at the outflow end). Beyond the low horizontal velocity, active flow into the lower fingers of the fine-grained sediment tended to lead to vertical flow into the underlying coarser sediment. Hence, despite simulating very large flow times (58,400 d or 160 yr), only negligible flow was predicted along the fine sediment.

The only situation in which induced flow along a mean-horizontal lens was successfully simulated was when the coarser laboratory sand (Lab Sand 1) was used as the matrix and loam from the Hydrus library was used as the fine-grained sediment. In this case, the loam remained at reasonably high moisture and \(K_{\text{unsat}}\)
(while coarse sediment was at low moisture and extremely low $K_{\text{unsat}}$ over a wide range of capillary pressures (e.g., pressure as high as −70 cm at the injection nodes on the right of the simulation and as low as −160 cm at the outflow nodes on the left), such that significant horizontal gradients could be established in the fine-grained sediment without substantially reducing the $K_{\text{unsat}}$ near the point of outflow. Figure 9b shows the resulting transport for this situation. Significantly, the time of transport shown in this image is 160 yr.

While these initial simulations indicate that flow induction would be difficult in a mean horizontal lens, a second set of simulations was run with a mean dip to the fine-grained sediments of 10° with inflow at higher elevation than the outflow. This geometry provided the opportunity to use the elevation difference along the lens to supplement the hydraulic gradient: this allows the capillary pressure at the outflow lysimeter to be minimized, thus providing higher moisture content (and therefore higher $K_{\text{unsat}}$) within this portion of the lens.

Figure 10 (a–c) shows a sequence of transport results for a lens with a mean dip of 10° and using the Hydrus sand (coarse sediment) and the Hydrus silt (fine sediment). The bottom corner of the grid is at zero capillary pressure (i.e., is at the water table). Inflow in the silt is on the right, using 16 nodes ranging in pressure from −100 to −130 cm. The outflow from the silt is 8 m to the left of the inflow and uses 21 nodes with a range of −150 to −190 cm. While the rate of migration of the invading fluid is slow (overall simulation period of ~80 yr), flow successfully passed through the silt from the upper portion to the lower portion of the lens. In this case, little flow is observed to penetrate into the underlying sand.

If the sand is replaced with loamy sand, the inflow pressure must be reduced to avoid direct flow downward toward the water table. In this case, the inflow pressures ranged from −130 to −160 cm (note that while this change reduced flow downward into the loamy sand, it also reduced the magnitude of the gradient along the silt). The resulting simulation (Fig. 10d) shows that flow is still induced within the silt. However, the rate of transport is substantially reduced, and some penetration of fluid is observed into the underlying loamy sand. Comparison of this result with those in Fig. 10 (a–c) is consistent with a range of simulations performed demonstrating that increasing the difference between the $K_{\text{unsat}}$–capillary pressure relationships for the two sediments (at the pressures of interest) will result in increased opportunity to induce flow with a significant horizontal component in the fine sediment lens. Further, these results indicate that, even when flow induction is successful, the velocity of migration of fluid along the lens will be relatively slow with transport times typically defined in terms of decades rather than years.

A final set of simulations in this series considered the impact of recharge on the distribution of flow within the fine-grained sediment. For this group of simulations, the parameters used were once again those for the loamy sand and the silt from the Hydrus library. As a simplification of this problem, the boundary condition along the upper boundary of the numerical grid was changed to a constant flux at a rate equivalent to approximately 2 mm yr$^{-1}$ uniform recharge. While this is a low recharge rate, it is argued that flow induction will be of predominant interest precisely in those situations in which recharge is so slow that flushing of lens of fine-grained sediments by natural processes is unlikely to occur within reasonable time scales. As indicated by the results below, 2 mm yr$^{-1}$ is a rate sufficiently high to lead to a degree of natural flushing of this simple system. Further, this rate is within the range of deep recharge rates estimated at select locations at the Hanford Site (Gee et al., 1992).

Figure 11 shows the results of the simulations with recharge. Figure 11a shows the predicted movement of water from the upper boundary of the grid, along the lens and to the base of the numerical grid under conditions in which no lysimeters (inflow/outflow) were active. The fact that the recharge is able to move past the lens is apparent in this result. The result shown is for 160 yr of transport (starting at the upper boundary of the numerical grid).
The laboratory and numerical results discussed above provide both 1. The finer-grained sediment forms a distinct lens or layer within a matrix of coarser-grained sediment. Further, a lens or layer with a known and approximately constant strike and dip within the region of interest will facilitate establishing and maintaining flow in the down-dip direction. Finally, the ability to establish flow uniquely within the finer-grained sediment (specifically, with minimal flow into the underlying coarse sediment) will generally increase as the geometry of the lower contact between the fine and coarse sediments becomes less intricate (specifically, in the absence of fingers of fine sediment extending into the underlying coarse sediment).

2. A significant range of capillary pressures exists at the field site for which $K_{\text{unsat}}$ of the finer-grained sediment is substantially greater (e.g., more than 2 orders of magnitude greater) than $K_{\text{unsat}}$ of the coarser-grained sediment. Particularly attractive, from the viewpoint of inducing flow, are fine-grained sediments with reasonably high $K_{\text{unsat}}$ values throughout the range of capillary pressures to be used for injection and withdrawal. As a generalization based on the van Genuchten $K_{\text{unsat}}$ versus capillary pressure relationship (van Genuchten, 1980), this condition is more likely to occur when the field site can be characterized as having a coarse sediment with high $\alpha$–low $n$ in combination with a fine sediment with low $\alpha$–high $n$ (see, e.g., Fig. 1a and Table 1).

3. Flow rates on the order of centimeters to tens of centimeters per year are sufficient for a particular field application. The material comprising the finer-grained sediment will typically not have a saturated hydraulic conductivity (and therefore a $K_{\text{unsat}}$) greater than 1.0 m d$^{-1}$. As a result, with hydraulic gradients along the fine sediment layer or lens on the order of $10^{-1}$ to $10^{-3}$ and moisture contents on the order of 0.3 (assuming that the fine sediment is close to saturation), seepage velocities along the lens will typically not be greater than 0.003 to 0.3 cm d$^{-1}$, or approximately 1 to 100 cm yr$^{-1}$. While this magnitude of velocity will not generally be acceptable for rapid remediation efforts, it may be satisfactory for long-term remediation efforts in deep vadose zone environments, such as might be observed, for example, at the Hanford Site (e.g., Truex et al., 2009; Gee et al., 2007).

In contrast to these conditions that might optimize the opportunity to induce flow, the simulations point to conditions that will generally make induction more difficult or, from a practical standpoint, impossible. Among these are:

1. Significant heterogeneity in the sediments, particularly heterogeneity that leads to vertical connection of multiple lenses

### Interpretation of Results
The laboratory and numerical results discussed above provide both support for the argument that flow induction is theoretically possible in the vadose zone using lysimeter technology and insight into significant limitations of such induction. Specifically, it appears that flow induction may be possible at a field site (subject to the limitations discussed below) under the following conditions:

1. The finer-grained sediment forms a distinct lens or layer within a matrix of coarser-grained sediment. Further, a lens or layer with

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**Table 1. Sediment parameters for the van Genuchten–Mualem model as described in HYDRUS_2D/3D for the parameters described in HYDRUS_2D/3D, and the Accumin sands used in the experiments.**

<table>
<thead>
<tr>
<th>Textural classes</th>
<th>$\alpha$</th>
<th>$n$</th>
<th>$K_{\text{sat}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab Sand †</td>
<td>0.151</td>
<td>7.35</td>
<td>423.4</td>
</tr>
<tr>
<td>Lab Sand 2†</td>
<td>0.0453</td>
<td>12.18</td>
<td>67.4</td>
</tr>
<tr>
<td>Sand‡</td>
<td>0.145</td>
<td>2.68</td>
<td>7.14</td>
</tr>
<tr>
<td>Loamy sand‡</td>
<td>0.124</td>
<td>2.28</td>
<td>3.50</td>
</tr>
<tr>
<td>Silt‡</td>
<td>0.016</td>
<td>1.37</td>
<td>0.06</td>
</tr>
<tr>
<td>Loam‡</td>
<td>0.036</td>
<td>1.56</td>
<td>0.25</td>
</tr>
</tbody>
</table>

† Source for these parameters, except the hypothetical clean silt, are derived from Schroth et al. (1996).
‡ Source for these parameters, except the hypothetical clean silt, are from the HYDRUS parameter sets as derived from Carsel and Parvish (1988).
or layers of fine-grained sediments, can lead to unexpected vertical migration of fluid. Detailed characterization of the subsurface structure combined with instrumentation allowing identification of changes of sediment moisture over time (e.g., ground-penetrating radar, tomography, neutron probes, TDR probes installed near the lysimeters) will likely be necessary to provide confidence in the functionality of the in situ process. In general, a significant probability exists that flow will migrate to regions unanticipated in the field design.

2. Flux along the primary axis of the fine sediment will be limited both by the hydraulic gradient and the $K_{unsat}$ of the sediment. It is noted that the simulations discussed above assumed two-dimensional flow in the vertical plane. Hence, it is likely that these simulations overestimate the rate of movement of the chemical front through the lens (which will tend to be close to radial in the vicinity of the inflow and outflow points). Further analysis should be focused, for a given field site, on the hydraulic gradients anticipated from the specific site design. When multiplied by the saturated hydraulic conductivity of the sediments and divided by mean moisture content, these gradients will provide an estimate of the maximum velocity of water movement to be observed in the field. If this estimate is significantly below that required for economic application of this method, then alternative methods would need to be considered.

3. It is generally recognized that long-term use of suction-cup lysimeters is difficult at best and essentially impossible in many situations. Leakage at any point in the lysimeter or tubing, loss of contact with the sediments surrounding the lysimeter cup, or loss of saturation in the lysimeter cup can all lead to failure of a lysimeter. Hence, the concept of using and maintaining multiple suction-cup lysimeters over periods of multiple decades is recognized as impractical from the standpoint of field application. In this sense, the material discussed above would lead to a conclusion that induction of flow as suggested may never be practical under natural field conditions. While we do not disagree, we argue below that the results serve two important purposes: (i) to give caution to efforts to pursue induced flow as a practical, rapid approach to addressing remediation problems in the vadose zone over scales greater than a few meters and (ii) to encourage creative thought on alternative strategies for manipulating capillary pressure and water fluxes in the vadose zone through either modification of existing field methods or development of new field methods.

### Discussion

A theoretical argument is put forth, supported by laboratory and numerical modeling results, that manipulating horizontal components of flow in the vadose zone is theoretically possible. Specifically, by taking advantage of heterogeneity, wherein finer-grained sediments overlie coarser-grained sediments, it is theoretically possible to both introduce and extract water from the finer-grained sediments so as to induce horizontal components to the water flux. Using sieved sands under controlled laboratory conditions, it is demonstrated that such induced water flux is indeed possible at the scale of a few tens of centimeters.

Numerical modeling provides insight into the conditions under which the strategy of injection and withdrawal using suction-cup lysimeters has potential to allow induction of flow. Critical design variables include: (i) the relative hydraulic properties of the fine-grained versus coarse-grained sediments, (ii) the saturated hydraulic conductivity of the fine-grained sediments, (iii) the geometry (dip and fingering of the fine sediments), and (iv) prior knowledge of the distribution of sediments. Optimal conditions will include: (i) coarse sediments that desaturate at relatively low capillary pressure while the finer sediments maintain high moisture to relatively high capillary pressure, (ii) sufficiently high saturated hydraulic conductivity of the finer sediments so that reasonable flow velocities can be obtained under gradients in the pressure head consistent with Zone 3 of the unsaturated hydraulic conductivity—capillary pressure relationships for the two sediments, (iii) relatively smooth contact between the two sediment types (e.g., minimal fingering of the finer-grained sediments into the underlying coarse sediments and minimal interconnectivity between individual lenses of the finer-grained sediments), and (iv) a significant, and spatially consistent, dip to the contact between the sediments, thus allowing both the gradient in the pressure head and gravity to be used as driving forces for flow.

While the potential to artificially induce horizontal components to flow is considered a significant observation from this study, a major conclusion of this work is nevertheless that, even under optimal conditions, the flow velocities being discussed are small, with magnitudes typically substantially less than 1 m per year. This is recognized as a major limitation in terms of potential applications of this work from two standpoints: (i) this time scale may be unreasonably slow for many potential remediation scenarios, and (ii) this time scale results in significant challenges in terms of field operation and maintenance of equipment (e.g., maintaining suction-cup lysimeters over decades is not currently a reasonable field design). Further concerns with the practical application of this study result both from the need to provide detailed hydraulic data for the subsurface sediments (e.g., similar to the concerns with the assessment of capillary barriers; Trpkosova and MLs, 2010) and the limitation of this method to very simple heterogeneities (e.g., vertical connectivity between lens of fine-grained sediments will provide substantial potential for vertical flow and loss of horizontal continuity of the flow field).

The question therefore arises as to what can be learned from these results relative to discussion of manipulating flow and chemical transport in the vadose zone. Three contributions can be identified:

- This work adds to recent literature on capillary barriers (e.g., Qian et al., 2010; Zhang et al., 2009) and lateral flow in the vadose zone (e.g., Warrick et al., 2008) through further discussion of the mechanisms causing nonvertical fluxes in layered, unsaturated media and the potential to take advantage of natural heterogeneity similar to capillary barriers to both induce horizontal components to water fluxes and divert vertical flow.

- This work provides a documented caution that the horizontal components of induced water flux in the vadose zone are likely to be difficult to establish except under very specific field conditions and require substantial time to effectively displace pore water in fine-grained sediments over distances greater than a
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References