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Viability of Longitudinal Trenches for Capturing Contaminated Groundwater

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Abstract Using a groundwater flow and mass transport model, this study compared the capability of trenches with permeable backfill for capturing hypothetical contaminant plumes in homogeneous and heterogeneous unconfined aquifers. Longitudinal (parallel to groundwater flow), as well as conventional transverse (perpendicular to groundwater flow) trench configurations were considered. Alternate trench configurations intercepted the leading tip of an initial contaminant plume and had identical length, equal to the cross-gradient width of the plume. A longitudinal trench required 31% less time than its transverse counterpart to remediate a homogeneous aquifer. By contrast, in simulated heterogeneous aquifers, longitudinal remediation timeframes ranged from 41% less to 33% more than transverse trenches. Results suggest that longitudinal trenches may be a viable alternative for narrow contaminant plumes under low-groundwater velocity conditions, but may be impractical for plumes with wide leading tips, or in complex heterogeneous aquifers with divergent flow.

Keywords Longitudinal trench · Groundwater · Contaminant plume

Permeable reactive trenches are a well-established alternative for remediating contaminated groundwater in shallow unconfined aquifers. In this passive approach to remediation, natural groundwater flow carries soluble contaminants into a strategically-placed trench, which filters or facilitates decomposition of contaminants (Scherer et al. 2000). Permeable backfill further enhances contaminant movement toward trenches. This approach requires much less energy than pump-and-treat systems. Moreover, the continuous character of backfilled trenches aids in capturing contaminant plumes.

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While impervious walls augment some backfilled trenches, this study focuses on trench-only configurations. Previous modeling investigations suggest the potential utility of permeable trenches in various settings (Eykholt et al. 1999; Mayer et al. 2001; Elder et al. 2002; Painter 2004; Hemsi and Shackelford 2006; Hudak 2007). Moreover, field studies showed these trenches can filter or decompose several contaminants in groundwater (Puls et al. 1999; Guerin et al. 2002; Conca and Wright 2006; Robertson et al. 2007; Turner et al. 2008).

An important design consideration is the possibility of contaminants moving around a trench. They should be long enough to contain a contaminant plume, but not arbitrarily long due to high costs. Generally, trenches are located at or beyond the leading tip of a contaminant plume and oriented transverse to regional groundwater flow. However, this conventional practice may require excessive time periods in low-groundwater velocity settings. Thus, the purpose of this study was to explore the viability of longitudinal trench configurations, in both homogeneous and heterogeneous aquifers.

Materials and Methods

Finite-difference groundwater flow (McDonald and Harbaugh 1988) and mass transport (Zheng and Wang 1999) models simulated contaminant transport in a hypothetical unconfined aquifer (Fig. 1). The model grid comprised 125 rows and 200 columns, each 1 m wide, with a saturated thickness of 10 m. Fixed hydraulic head at the west and east edges of the model produced a regional hydraulic gradient of 0.01 (Fig. 1).

Models simulated the formation and removal of contaminant plumes in each of four simulated aquifers. Case 1 was homogeneous, with a mean hydraulic conductivity of 0.2 m/d (log10 mean = −0.7). Effective porosity of the aquifer was 0.30. Cases 2–4 (Fig. 1) were heterogeneous, comprising random hydraulic conductivity distributions from a probability distribution with the following parameters: correlation length = 2.0 m; mean (log10, m/d) = −0.7, and standard deviation (log10, m/d) = 0.5.

Initially without a trench, the groundwater flow model generated a hydraulic head distribution for each of Cases 1–4. Groundwater simulations utilized the preconditioned conjugate gradient (PCG2) solver; mass balance errors were less than 0.001%. Incorporating these hydraulic head distributions, the mass transport model generated initial contaminant plumes for subsequent remediation trials. Each initial contaminant plume evolved for 5,000 d from a 1.0 m^2 source with a concentration of 100 mg/L.

Mass transport simulations utilized the following parameters: longitudinal dispersivity = 1.0 m, transverse dispersivity = 0.1 m, and effective molecular diffusion = 0.00001 m^2/d. The 1 mg/L concentration contour established contaminant plume boundaries. Further, all mass transport simulations utilized the generalized conjugate gradient (MT3DMS) solver, and mass balance errors were less than 0.001%.

After generating initial contaminant plumes, the groundwater flow and mass transport models simulated plume migration through aquifers and into trenches. First, the flow model recomputed hydraulic head fields resulting from each trench in each simulated aquifer, and these results were input to the mass transport model. Trenches were 1-m thick, with a hydraulic conductivity of 100 m/d and effective porosity of 0.35. Two trench configurations were modeled in each of the four simulated aquifers. Each trench intersected the leading tip of a contaminant plume. One configuration was transverse, and the other longitudinal, relative to the direction of regional groundwater flow. The transverse trench spanned the cross gradient width of a contaminant plume. The alternative longitudinal trench had the same length as the transverse trench.

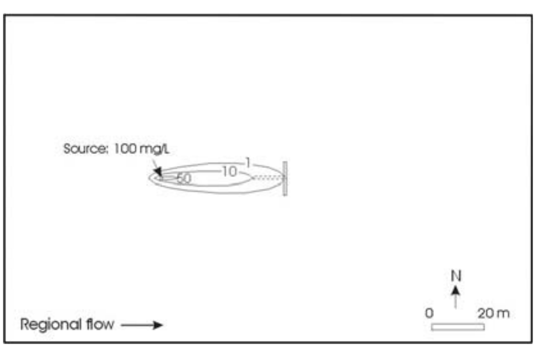

Fig. 1 Map of model domain and initial contaminant plume for Case 1; *solid rectangle*—transverse trench; *dashed rectangle*—longitudinal trench; contours in mg/L

Trenches were modeled as contaminant sinks with a concentration of 0 mg/L. A plume was "contained" if at no time the 1 mg/L contour contacted a buffer 10 m downgradient of the leading tip of the initial plume. Models also evaluated the capability of trenches to contain a plume within the entire model domain, as well as the amount of time required to reduce contaminant concentrations at all model cells below 0 mg/L.

Results and Discussion

Initial contaminant plumes had varying shapes, reflecting different hydraulic conductivity distributions in each case (Figs. 1, 2). All of the contaminant plumes in the heterogeneous aquifers had irregular shapes, an outcome of preferential flow in more permeable parts of the aquifer (Fig. 2). Trenches were 14, 22, 13, and 14 m for Cases 1–4, respectively.

In the homogeneous aquifer (Case 1), both longitudinal and transverse trenches effectively contained the contaminant plume, preventing it from reaching the 10-m buffer. However, it took 6,600 d with the longitudinal trench for contaminant concentrations at all model cells to drop below 1 mg/L, whereas it took considerably longer (9,500 d) with the transverse trench. The longitudinal trench provided contaminants quicker access to trench backfill, thus facilitating a shorter remediation timeframe.

Heterogeneous simulations produced different results. In Case 2, the transverse trench contained the contaminant plume within the 10-m buffer, requiring 9,700 d to eliminate the plume. However, the longitudinal trench enabled breaching of the 10-m buffer after approximately 4,000 d (Fig. 3). This simulation suggests that contaminant plumes with wide leading edges pose potential problems for longitudinal trenches, which have narrow cross-gradient width (Figs. 2, 3). Neither contaminant plume reached the downgradient model boundary in Case 2; however, it took an excessive amount of time, 12,900 d, for concentrations at all model cells to drop below 1 mg/L in the longitudinal simulation.

In contrast, the transverse trench performed relatively poorly in Case 3. The contaminant plume reached the 10-m buffer after approximately 10,500 d (Fig. 3). This simulation indicates that asymmetric contaminant plumes create problems for transverse trenches—the plume may move

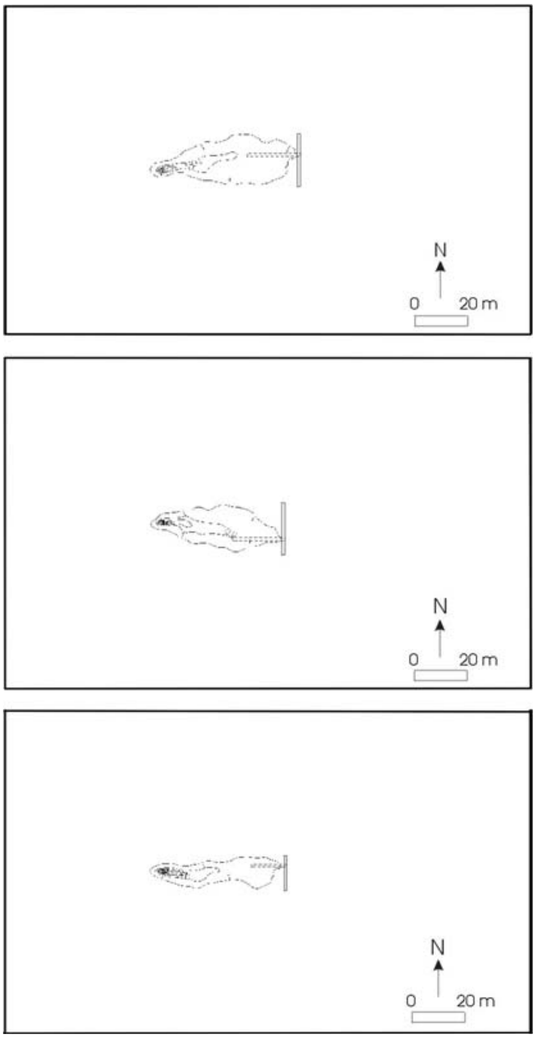

Fig. 2 Maps of initial contaminant plumes for Cases 2 (*top*), 3 (*middle*), and 4 (*bottom*); *solid rectangle*—transverse trench; *dashed rectangle*—longitudinal trench; contours in mg/L

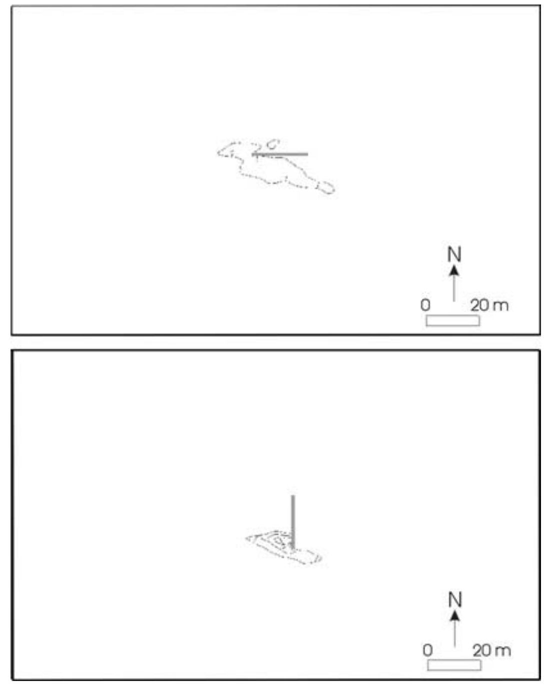

Fig. 3 Residual contaminant plumes for Case 2, longitudinal trench (*top*) and Case 3, transverse trench (*bottom*) at approximate time plume reaches 10-m buffer; contours in mg/L

around the end of the trench closest to its leading tip. The contaminant plume did not reach the downgradient model boundary; however, it took, 14,100 d to eliminate the plume in the transverse simulation. By comparison, the longitudinal configuration did contain the contaminant plume within 10 m, and it took 8,300 d to remove the plume.

Finally, both transverse and longitudinal configurations contained the contaminant plume within 10 m in Case 4. Transverse and longitudinal simulations required 9,600 d and longitudinal 9,700 d, respectively, to reduce concentrations below 1 mg/L at all model cells.

Some simulations featured contaminant movement around one end of a trench; however, only in Cases 2 (longitudinal) and 3 (transverse) did the plume reach the 10-m buffer, and in no case did it reach the downgradient model boundary. In addition to the trench, dilution with fresh groundwater and hydrodynamic dispersion helped lower contaminant concentrations throughout the model domain.

In practice, lengthening trenches facilitates containment of contaminant plumes. However, lengthy trenches are very costly. Results of this study suggest that longitudinal trenches of identical length actually outperform their transverse counterparts in some settings. In particular, aquifers with low groundwater velocity, fairly predictable flow paths, and narrow leading tips may be better suited to longitudinal rather than transverse trenches. For either trench configuration, dilution and hydrodynamic dispersion help lower contaminant concentrations in groundwater.

Simulated trenches intersected the leading tips of contaminant plumes. In practice, imprecise plume boundaries may warrant placing trenches (conservatively) farther downgradient of a plume. However, in heterogeneous aquifers with highly uncertain flow paths, placing a trench arbitrarily far away from a plume poses problems: (1) irregular flow paths may carry contaminants around the edges of the trench, and (2) contaminants take longer to reach trench backfill. For all applications, field and laboratory studies should accompany numerical modeling, and systems should be closely monitored.

In conclusion, this study examined alternative orientations for backfilled trenches in simulated homogeneous and heterogeneous unconfined aquifers. Results suggest that longitudinal trench configurations outperform conventional transverse configurations in some low-groundwater velocity settings. Longitudinal configurations provide contaminated water quicker access to trench backfill, thus facilitating more efficient remediation. However, longitudinal trenches have narrow cross-gradient width; therefore, they are not well suited to contaminant plumes with wide leading edges. Moreover, longitudinal trenches do not perform well in complex heterogeneous environments with divergent flow, which carries portions of plumes away from trenches. Natural attenuation processes working in conjunction with trenches further facilitate remediation.

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