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Effect of Aquifer Heterogeneity on Non-pumped, Reactive Well Networks for Removing Pollutants in Groundwater

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Abstract This purpose of this study was to evaluate the impact of heterogeneity in aquifer hydraulic conductivity on configurations of non-pumped wells filled with reactive media for removing contaminant plumes in groundwater. Among one homogeneous and three heterogeneous simulated aquifers, 2–16 wells were necessary to contain a plume, with no clear relationship between degree of heterogeneity and number of wells. Generally, heterogeneous aquifers with initial plumes having broad rather than narrow downgradient margins required more wells and showed greater tendency for plumes to move around wells. Cleanup time increased up to 181 % with degree of heterogeneity in hydraulic conductivity.

Keywords Reactive well · Heterogeneous aquifer · Mass transport model

Many cases of contaminated groundwater have been documented globally. Of several approaches for cleaning polluted groundwater, those not consuming large amounts of energy and other resources have become popular over the past two decades. A typical example of a low-energy approach is the permeable reactive barrier (PRB) – a trench filled with reactive media designed to filter or decompose contaminants traveling with groundwater into them (NRC 1994). Previous studies showed capability of PRBs for lowering concentrations of various categories of pollutants in groundwater: heavy metals (Puls et al. 1999; Ludwig et al. 2002; Conca and Wright 2006); petroleum hydrocarbons (Guerin et al. 2002); chlorinated solvents (Vogan et al. 1999; Lai et al. 2006); radionuclides (Blowes et al. 2000); and nutrients (Robertson et al. 2000).

Due to technical difficulties and high costs, most installed PRBs are less than 20 m deep; in deeper settings, wells without pumps and filled with reactive media may be a suitable alternative for treating contaminated groundwater (Freethey et al. 2002). Such wells may be drilled to greater depth and equipped with replaceable porous cartridges filled with appropriate media for a particular application (USGS 1999). While a greater hydraulic conductivity draws groundwater and contaminants into these wells, their discontinuous nature may enable portions of contaminant plumes to migrate between them and eventually offsite; modeling investigations can evaluate this tendency.

Previous studies documented the capability of certain non-pumped, reactive well networks in different settings to lower contaminant concentrations and contain plumes, with some plumes migrating offsite (Hudak 2008). Given the importance of containing plumes onsite, it is useful to examine minimum-well configurations necessary to accomplish this goal. The objective of this study was to examine the effect of degree of aquifer heterogeneity on minimum-well configurations for plume containment, in addition to remediation timeframe.

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Materials and Methods

A numerical, three-dimensional, multi-species model (Zheng and Wang 1999) simulated groundwater flow and contaminant transport in four hypothetical unconfined aquifers (Figs. 1, 2). Models consisted of a block-centered,

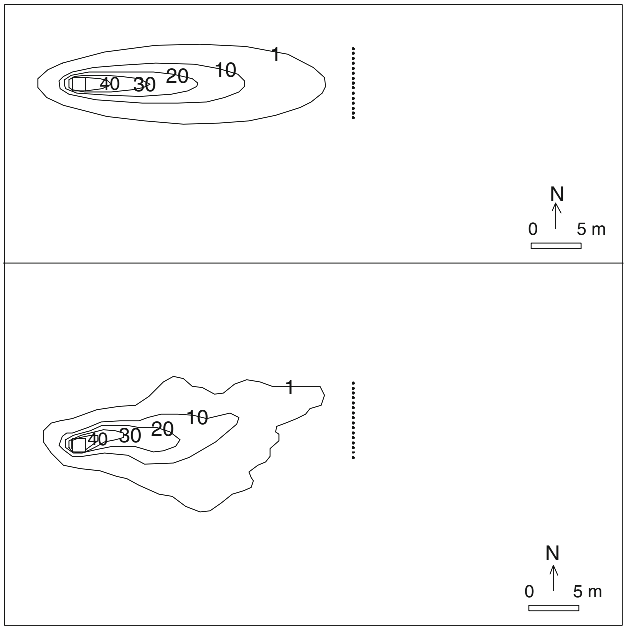

Fig. 1 Initial contaminant plumes and minimum well configurations for Cases 1 (*top*) and 2 (*bottom*); *black dots* reactive wells; *contours* in mg/L

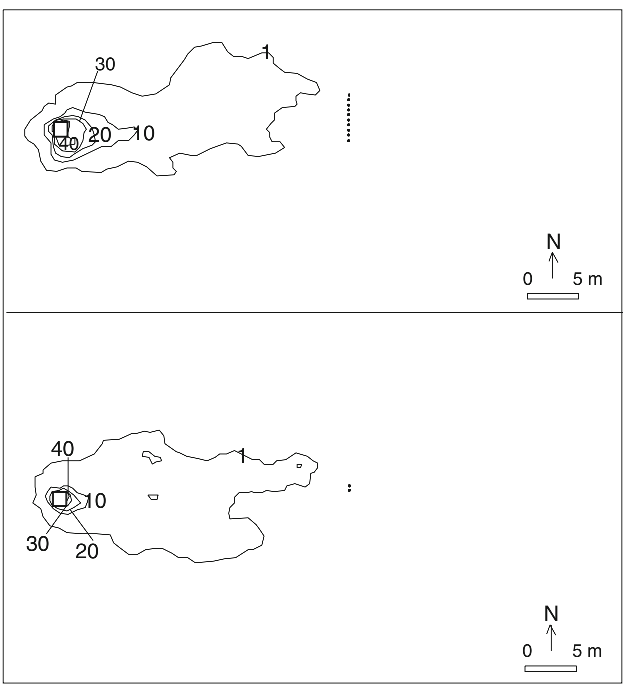

Fig. 2 Initial contaminant plumes and minimum well configurations for Cases 3 (*top*) and 4 (*bottom*); *black dots* reactive wells; *contours* in mg/L

finite-difference grid: 145 rows, 250 columns, and one layer with a node spacing of 0.25 m along rows (oriented east–west) and columns (oriented north–south). Elevation of the aquifer bottom was 0 m. Water table elevation was 10 m at the western boundary and 9.3775 m at the eastern boundary, producing a regional hydraulic gradient of 0.01 eastward. No flow crossed the northern, southern, and bottom boundaries of the model.

The study included one homogeneous (Case 1) and three heterogeneous (Cases 2–4) aquifers. For Case 1, hydraulic conductivity of the aquifer was 1 m/day. Random hydraulic conductivity fields with log-normal distributions were generated for Cases 2–4. The mean value of log10 hydraulic conductivity (m/day) equaled 0.0. Reflecting increasing degrees of heterogeneity, the standard deviation of log10 hydraulic conductivity equaled 0.4, 0.8, and 1.2 in Cases 2–4, respectively. Correlation length of hydraulic conductivity equaled 2, 1, and 0.5 m in Cases 2–4, respectively.

Effective porosity was 0.25 in the aquifer and 0.35 in the non-pumped wells, which were 0.25 m in diameter and simulated as contaminant sinks with a concentration of 0 mg/L. Hydraulic conductivity of cells occupied by wells was 100 m/day.

Without incorporating wells, the groundwater model generated an ambient hydraulic head and flow distribution for each case. All groundwater flow simulations employed the preconditioned conjugate gradient solver, producing mass balance errors of less than 0.01 %. Using the ambient hydraulic head and flow distribution, the mass transport model generated an initial contaminant plume for each case (Figs. 1, 2), used in subsequent remediation trials. Longitudinal horizontal dispersivity was 1.0 m, transverse horizontal dispersivity was 0.1 m, and the effective molecular diffusion coefficient was 0.00001 m^2/day in contaminant transport simulations. The 1 mg/L concentration contour defined contaminant plume boundaries. All mass transport simulations employed the generalized conjugate gradient (MT3DMS) solver, yielding mass balance errors less than 0.04 %.

Each initial plume evolved from a 1.6 m^2 source area near the western edge of the model, with a constant concentration of 50 mg/L. Initial plumes evolved over 370, 280, 430, and 1,020 days for Cases 1–4, respectively. Each resulting plume was 30 m from the downgradient model boundary.

For each initial plume, remediation trials identified a minimum-well configuration along a transect perpendicular to regional flow, approximately 3 m from the leading tip of the plume, necessary to prevent the plume from crossing the downgradient boundary. The flow model recomputed hydraulic head and flow distributions resulting from each trial well configuration; these recomputed head and flow distributions were used in MT3DMS.

Results and Discussion

The four initial contaminant plumes had different shapes, reflecting different hydraulic conductivity distributions in the simulated aquifers (Figs. 1, 2). Initial plumes in Cases 2–4 lacked symmetry about a long axis; such asymmetry typifies heterogeneous aquifers. Generally, contaminant concentration contours were increasingly irregular with complexity of the hydraulic conductivity field.

Different initial contaminant mass distributions and flow fields produced different minimum-well configurations necessary to contain a plume. Cases 1–4 required 15, 16, 10, and two wells, respectively. Wells were 0.5 m apart in each case (Figs. 1, 2). Thus, there was no clear relationship between minimum number of wells and degree of aquifer heterogeneity. Potentially, plumes with narrow leading tips (Case 4) may be contained with fewer wells, even in heterogeneous environments. However, heterogeneous environments that induce divergent flow and wide leading fronts may require more wells (Case 2). In both homogeneous and heterogeneous environments, setting the migration boundary away from wells enabled dilution and hydrodynamic dispersion to help lower contaminant concentrations.

For the same range of initial concentrations (1–50 mg/L) and monitoring transect, plumes with lower concentrations near the transect may facilitate containment with fewer wells. For example, while the 1 mg/L contour is 3 m from the transect in each case, the 10 mg/L contour is closer to the source in Case 4. With relatively low concentrations near the narrow leading tip of the plume, Case 4 required only two wells.

Figures 3, 4 show the progress of each well configuration after 500 days. While portions of plumes moved through or around transects occupied by wells, none reached the downgradient model boundary. The homogeneous case showed some tendency for plume migration through the interior of the transect, reflecting higher initial concentrations near the middle of the transect. In contrast, heterogeneous cases showed some tendency for plumes to move around transects, reflecting complex flow fields associated with heterogeneous environments.

The amount of time required to remove contaminant plumes (concentration at all model cells <1 mg/L) was: 1,170, 1,330, 1,850, and 3,290 days for Cases 1–4, respectively. Thus increased heterogeneity resulted in longer cleanup time. This pattern may be attributed to contaminants lingering in localized low-velocity zones within heterogeneous environments. The impact of these low-velocity zones increases with degree of heterogeneity – larger deviations in the magnitude of hydraulic conductivity around it's mean value create localized zones of very low (and very high) hydraulic conductivity. For example, in Case 4 contaminants lingered in the area encompassed by the 5 mg/L contour after 500 days of remediation (Fig. 4); this area sustained concentrations above 1 mg/L for nearly 3,200 days. In all cases, adding more wells could

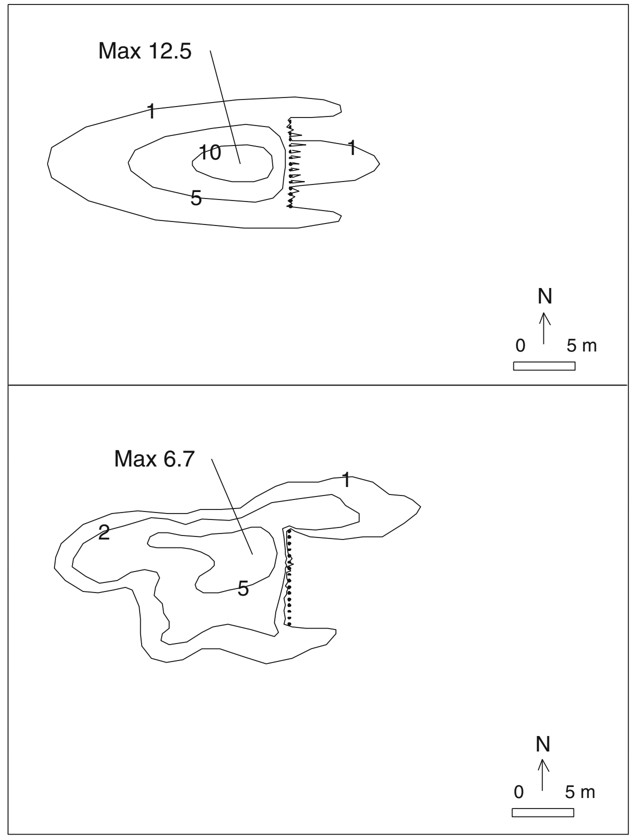

Fig. 3 Residual contaminant plumes after 500 days for Cases 1 (*top*) and 2 (*bottom*); *black dots* reactive wells; *contours* in mg/L

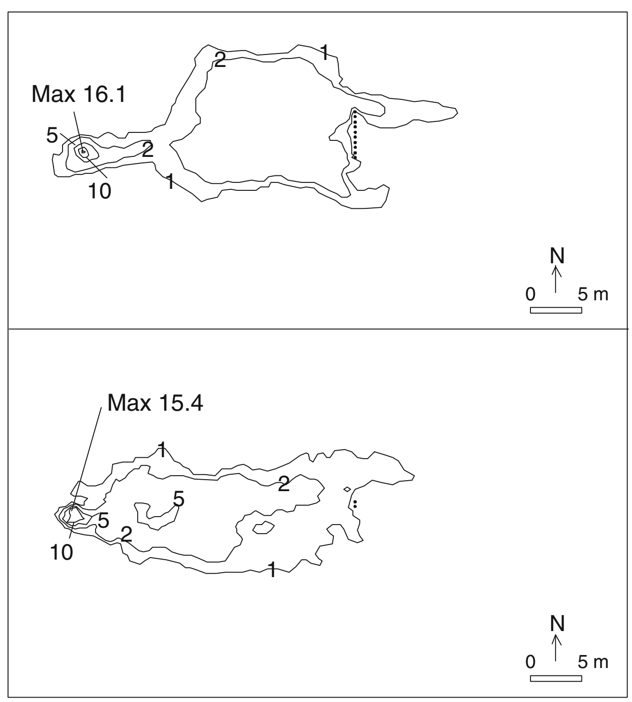

Fig. 4 Residual contaminant plumes after 500 days for Cases 3 (*top*) and 4 (*bottom*); *black dots* reactive wells; contours in mg/L

reduce remediation timeframe, but in practice would also increase cost.

In practice, settings with very low groundwater velocity and/or contaminants with low solubility could significantly delay or prevent contaminants from moving into reactive wells, rendering them ineffective. Furthermore, while this study involved computer simulations, site-specific field and laboratory studies (Morgan et al. 2005) should inform modeling investigations in practice. Field and laboratory studies should also verify the performance of operational systems, with capability for evaluating plume containment, residual contaminant levels, and the efficiency of reactive media in heterogeneous environments.

Overall, this study found that degree of heterogeneity did not strongly influence the minimum number of wells along a linear transect; some simulated plumes had relatively narrow tips that could be handled with fewer wells, and a distant migration boundary enabled natural processes to effectively lower contaminant concentrations. However, heterogeneous environments showed some tendency for plumes to migrate around the edges of transects. Moreover, cleanup time increased with degree of heterogeneity, as contaminants lingered in low-velocity zones within complex environments.

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