Effect of Partial Flow Reductions on DNAPL Source Dissolution Rate

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ABSTRACT

Field-scale DNAPL dissolution is controlled by the topology of DNAPL distributions with respect to the velocity field. A high resolution percolation model was developed and employed to simulate the distribution of DNAPL within source zones. Statistically anisotropic permeability values and capillary parameters were generated for 10 x 10 x 10 m domains at a resolution of 0.05 to 0.1 m for various statistical properties. TCE leakage was simulated at various rates and the distribution of residual DNAPL in "fingers" and "lenses"was computed. Variations in finger and lens geometries, frequencies, average DNAPL saturations, and overall source topology were predicted to be strongly influenced by statistical properties of the medium as well as by injection rate and fluid properties. Model results were found to be consistent with observations from controlled DNAPL release experiments reported in the literature. The computed distributions of aquifer properties and DNAPL were utilized to perform high-resolution numerical simulations of groundwater flow and dissolved transport. Simulations were performed to assess the effect of grout or foam injection in bore holes within the source zone and of shallow point-releases of fluids with various properties on dissolution rates. Borehole injection of grout-like material resulted in the greatest decreases in DNAPL dissolution rates, even for widely spaced injection points. The results indicate that measures that induced partial flow reductions through DNAPL source zones can significantly decrease dissolution rates from residual DNAPL. The benefit from induced partial flow reductions is two-fold: 1) local flow reduction in DNAPL contaminated zones reduces mass transfer rates, and 2) contaminant flux reductions occur due to the decrease in groundwater velocity.

INTRODUCTION

Monitored natural attenuation (MNA) is a remedial strategy that relies on the natural attenuation potential of aquifers (i.e. biodegradation, sorption, dispersion and dilution, chemical reactions, volatilization, etc.) as well as source control schemes. Under favorable field conditions, MNA has the potential to be an effective strategy to achieve site-specific remedial objectives for contaminated sites with chlorinated solvents. The feasibility and effectiveness of MNA at the contaminated sites with chlorinated solvents are strongly dependent on the rate of contaminant dissolution and the source longevity. The rate of contaminant dissolution to groundwater over time is a crucial factor governing the feasibility and effectiveness of engineered remediation or natural attenuation at dense nonaqueous phase liquid (DNAPL) contaminated sites. Mass transfer dependence on velocity will significantly impact the effectiveness of hydraulic controls within DNAPL source zones.

Parker and Park (2004) investigated effective field-scale mass transfer relationships. They found that heterogeneity in groundwater velocity and DNAPL distributions lead to apparent field-scale mass transfer coefficients that are much lower than those observed at the laboratory-scale. They also found that field-scale mass transfer coefficients to be linearly related to the mean source zone velocity. This linear velocity dependence significantly enhances the feasibility of controlling contaminant fluxes by hydraulic manipulation. Mass transfer coefficients were found to be proportional to relative DNAPL mass to a power less than one for laterally extensive DNAPL lenses and greater than one for more randomly oriented residual DNAPL regions.

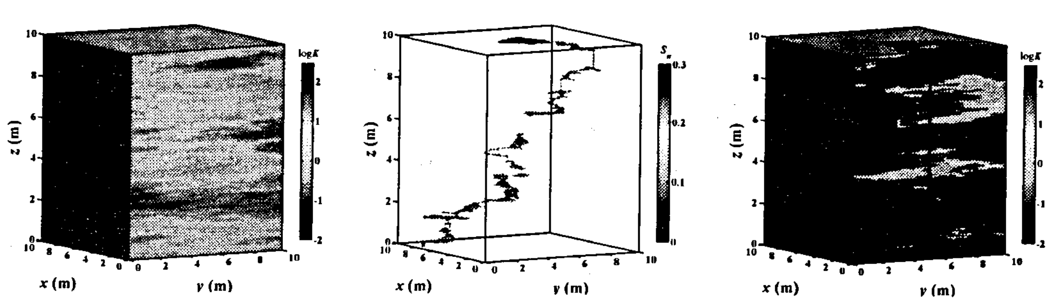
In the present study, we will investigate the effects of partial flow reductions on DNAPL source dissolution rate. For this purpose, we will generate correlated random hydraulic permeability fields, perform DNAPL percolation simulations, and simulate flow and transport from the generated DNAPL source.

SIMULATIONRESULTSANDDISCUSSION

The model domain is taken to be a 10 x 10 x 10 m aquifer region discretized into 1,000,000 cells with dimensions 0.2 by 0.2 m (horizontal) by 0.025 m (vertical). The model domain for the case study under consideration is assumed to have an arithmetic mean saturated hydraulic conductivity of 10 m d^{-1} with a $ln\ K_s$ variance (s^2_{lnK}) of 1. Correlation lengths are assumed to be 5 m in the horizontal plane and 1 m in the vertical direction (Figure 1a). A release of 279 kg (191 L) of TCE was simulated from a point near the center of the top boundary at a rate of 42 L h^{-1} (Figure 1b).

Groundwater flow simulations assume no flow through the top, bottom and two sides of the domain. Uniform hydraulic heads are employed on the remaining sides such that a lateral gradient is imposed. Simulations were performed for a hydraulic gradient of 0.01. The total simulation duration is 100 years.

a. b. c.



Figurel.

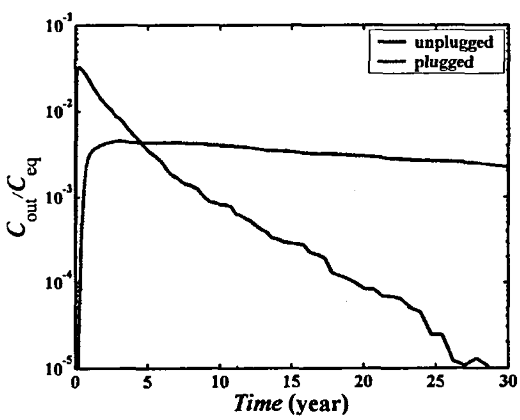
(a) Saturated hydraulic conductivity distribution in model domain.;

(b) Simulated initial residual DNAPL distribution in model domain;

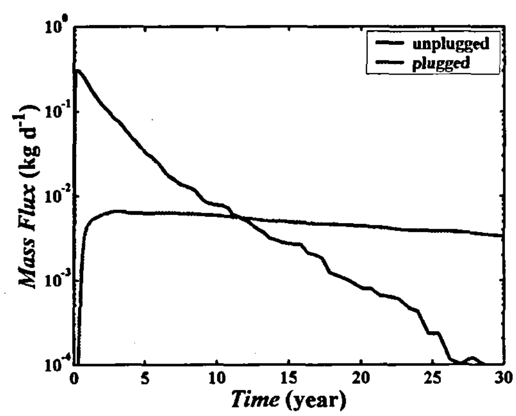
(c) Saturated hydraulic conductivity distribution after injection of plugging agent

For the simplicity of simulation, we assumed a hypothetical plugging agent. The assumed spreading distance from the injection well is 5 m, which coincides with the distance from the injection well to the nearest boundary perpendicular to the y-axis. The plugging agent is injected into the aquifer with a constant head at 0.1 m. This plugging agent covers 58% of the area on the upgradient face of the source zone and it reduces the permeability to 36% of the original hydraulic conductivity. A representation of the hydraulic conductivity spatial distribution after the injection is given in Figure 1c. Figure 2a represents the relative exit concentration versus time for plugged and unplugged domains. It shows that the effluent concentration at the downgradient boundary of the unplugged domain is less than plugged domain for most of the simulation duration except early 6 years. Higher exit mass effluent fluxes occur for the unplugged case for approximately 12 yrs (Figure 2b) where the mass fluxes is already reduced to 2% of the initial mass fluxes. Due to much higher mass fluxes leaving the source in the unplugged domain during early times, the mass of DNAPL in the unplugged domain is lower than that in the plugged domain through whole simulation duration.

a.



b.



c.

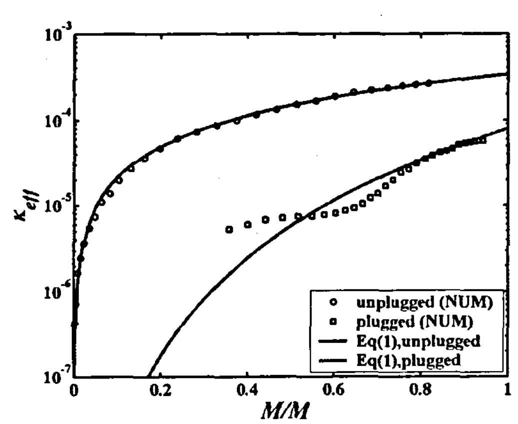


Figure 2. (a) Effect of the injection of plugging agent on the relative concentration versus time; (b) Effect of the injection of plugging agent on the mass effluent fluxes versus time; (c) Mass transfer coefficient versus relative mass for the plugged and unplugged domain;

Figure 2c shows the relationship between effective mass transfer coefficient vs. relative mass. The fitting scale parameters changes show that κ_{eff} decreases more rapidly at higher relative mass ratio and the rate diminishes with mass ratio becoming small. The effective field-scale mass transfer coefficient versus relative mass for unplugged and plugged cases is analyzed based on Parker and Park (2004, Eq. (20)),

$$\kappa_{eff} = \kappa_0 \left(\frac{q_s}{K_s} \right)^{\beta_1} \left(\frac{M}{M_0} \right)^{\beta_2} \quad (1)$$

where κ_0 is constant (T^{-1}), q_s is average darcy velocity(LT^{-1}), K_s is average saturated hydraulic conductivity (LT^{-1}), M is mass of DNAPL in source zone (M), M_0 is initial mass of DNAPL in source zone (M), and β_1 and β_2 are empirical parameters. We confirmed β_1=1 through series of simulations with different hydraulic gradients (h/x=0.1, 0.01, 0.001). Analysis shows that the value of κ_0 in the plugged domain is 26 % of that in the unplugged domain. The plugging agent increases the variance of the darcy velocity in the source domain, which increases the depletion exponent, β_2, from 1.2 to 3.8 (Table 2). The comparison of effective field-scale mass transfer coefficients shows that DNAPL mass fluxes from the plugged domain are changed even though source geometry is not altered.

Table 2. Summary of effective field-scale mass transfer coefficient analysis

	Unplugged	Plugged
κ_0	0.034	0.008
β_1	1.0	1.0
β_2	1.2	3.8

CONCLUSION

In this study, we investigated the effects of partial flow reductions on DNAPL source dissolution rate. For this purpose, we compared the mass effluent fluxes from systems with and without plugging injection. The study results indicate that the effective field-scale mass transfer coefficients for these two scenarios differ even though the source geometry is the same. The results indicate that injection of plugging agent into a source region reduces the mass flux from the DNAPL source. The benefit from injecting plugging agent is two-fold: 1) local flow reduction in DNAPL contaminated zones reduces mass transfer rates, and 2) contaminant flux reductions occur due to the decrease in groundwater velocity.

REFERENCES

Parker, J. C., and E. Park, Modeling field-scale dense nonaqueous phase liquid dissolution kinetics in heterogeneous aquifers, WRR 2004;40: W05109, doi:10.1029/2003WR002807.