Efficiency Comparison of Variably-Spaced, Non-Pumped Wells for Filtering Polluted Groundwater

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Abstract

This modeling study investigated the capability of variably-spaced arrays of non-pumped wells, filled with reactive media, to filter a hypothetical contaminant plume. Wells fully penetrated an unconfined aquifer with heterogeneous hydraulic conductivity. In one configuration, uniformly-spaced wells occupied a curve set back from the leading edge of an initial contaminant plume. In a second configuration, variably-spaced wells occupied the same curve, but were concentrated near the downgradient tip of the plume. Results suggest that variably-spaced configurations more efficiently reduce contaminant concentrations and better control off-site migration.

Keywords: Heterogeneous aquifer; Non-pumped well; Contaminant plume

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1. Introduction

Over the past few decades, permeable reactive trench technology has become a viable alternative to pump-and-treat for remediating some contaminated aquifers. Generally, reactive materials filter or decompose contaminants moving into trenches placed downgradient of contaminant plumes [1, 2]. Potentially, this energy-efficient technology can be used for a wide variety of contaminants [3-9]. However, technology and cost generally limit field applications to depths less than approximately 20 m [10].

Arrays of non-pumped wells may be a suitable alternative to reactive trench technology for deeper aquifers. In unconsolidated formations, boreholes drilled with conventional hollow-stem augers may be backfilled with reactive media [11]. Alternatively, removable porous cartridges filled with reactive media may be lowered down cased boreholes [10]. A relatively high hydraulic conductivity induces groundwater to converge toward, pass through, and diverge from individual non-pumped wells. Thus, reactive media may treat contaminants moving into wells, or release amendments into an aquifer.

A significant limitation of non-pumped arrays is the possibility of contaminated groundwater moving between wells (a problem not encountered in continuous trenches). With this limitation in mind, numerical modeling may help predict the capability of candidate non-pumped configurations for effectively containing and removing a contaminant plume.

Previous modeling studies suggest the efficiency of non-pumped configurations placed along local flow paths emerging from the downgradient boundary of a well-defined contaminant plume [12]. However, it is often difficult to define contaminant plumes with great precision in practice. The present study considers a curved locus for non-pumped wells, offset from the estimated downgradient boundary of a contaminant plume. Offsets account for uncertain plume boundaries, whereas curved loci conforming to the estimated shape of a contaminant plume facilitate timely remediation. This study evaluates the utility of relatively wide, uniform well spacing along the entire downgradient segment of a contaminant plume compared to variable spacing with a concentration of wells near the downgradient tip of a plume.

2. Methods

Two finite-difference models, MODFLOW [13] and MT3DMS [14], were used to simulate groundwater flow and contaminant transport in a hypothetical unconfined aquifer (Figure 1). The models incorporated a block-centered finite-difference grid of 125 rows and 300 columns. Rows and columns were 0.25 m wide. Constant hydraulic head values at the extreme western and eastern

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columns of the model produced a regional hydraulic gradient of 0.007 eastward. Saturated thickness was approximately 10 m, with no flow across the north, south, or bottom edges of the model.

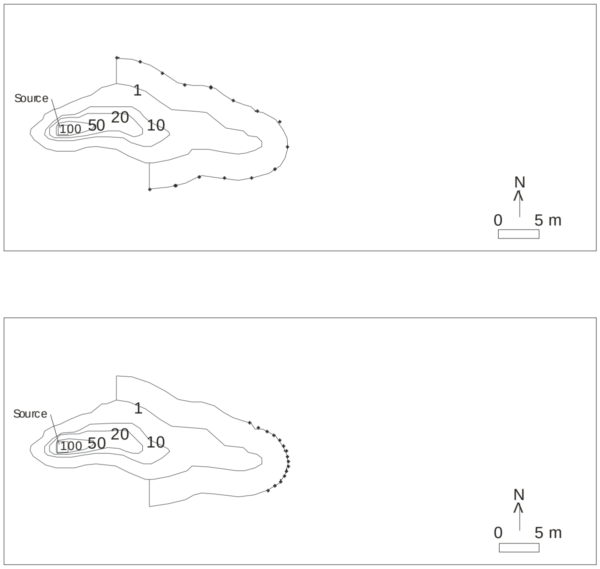

Figure 1. Configurations 1 (top) and 2 (bottom); crosses denote non-pumped wells; contours (mg/l) define initial contaminant plume.

A random, heterogeneous hydraulic conductivity field was generated from a probability distribution with the following parameters: correlation length = 2.0 m; mean log10 hydraulic conductivity (m/d) = 0.0; and standard deviation of log10 hydraulic conductivity (m/d) = 0.5. Effective porosity was 0.30.

All groundwater flow simulations utilized the preconditioned conjugate gradient solver, producing mass balance errors less than 0.005%. First, the groundwater model generated an ambient hydraulic head field (without incorporating wells). This field was input to the mass transport model, which generated an initial contaminant plume (Figure 1). The plume evolved over 1,000 d from a 1.6 m^2 contaminant source with a concentration of 100 mg/l. A concentration of 1 mg/l defined contaminant plume boundaries. Mass transport simulations utilized the following parameters: longitudinal dispersivity = 1.0 m, transverse dispersivity = 0.1 m, effective molecular diffusion coefficient = 0.00001 m^2/d, and plume boundary concentration = 1 mg/l. All simulations employed the generalized conjugate gradient (MT3DMS) solver, yielding mass balance errors less than 0.001%.

Next, the flow model computed hydraulic head fields resulting from configurations of non-pumped wells. In separate simulations, configurations of 15 wells occupied a curve set back 3 m from the downgradient segment of the contaminant plume, defined as the segment between cross-gradient extremes and the downgradient tip of the plume. A post-processor [15] interpolated the plume boundary and other contours from contaminant concentration fields output by the mass transport model. In practice, setbacks should reflect uncertainty in mapped plume boundaries – greater uncertainty warrants a farther setback to avoid placing wells upgradient of contaminated groundwater.

Configuration 1 had a uniform well spacing of 3.3 m along the entire downgradient boundary segment of the contaminant plume (Figure 1). Configuration 2 had variable spacing, based upon the following equation (Figure 1):

$$S_i = S_{i-1} + C \qquad (1)$$

where S_i is the spacing of segment i, (i = 1 at the downgradient tip and increases toward either cross-gradient edge of a contaminant plume), and C is a constant. In this application, S_1 = 0.5 m and C = 0.1 m.

Finally, the mass transport model simulated removal of the initial contaminant plume by each non-pumped well configuration. Hydraulic conductivity and effective porosity of non-pumped wells were 100 m/d and 0.35, respectively. Non-pumped wells were simulated as contaminant sinks with a concentration of 0 mg/l.

3. Results and Discussion

The initial plume had an irregular shape, reflecting variable flow paths induced by the heterogeneous hydraulic conductivity field (Figure 1). The plume did not move around either end of Configuration 1, but did move between wells and eventually off-site (Figure 2). Maximum residual concentrations were 18.4 mg/l after 1,000 d, 5.3 mg/l after 2,000 d, and 3.6 mg/l after 3,000 d (Figure 2). Thus, wells in Configuration 1 were too far apart to effectively contain and filter the plume.

Configuration 2 featured a concentration of wells near the downgradient tip, with no wells near either cross-gradient edge, of the plume (Figure 3). This configuration effectively contained and removed the plume. Closer spacing near the critical downgradient tip of the plume prevented substantial breaching and movement to the downgradient model boundary. Residual plumes for Configuration 2 were smaller than those for Configuration 1 after 1,000 and 2,000 d. After 2,900 d, concentrations at all model cells dropped below 1 mg/l; throughout that period, concentrations remained below 1 mg/l at the eastern model boundary. Maximum residual concentrations were 18.4 mg/l after 1,000 d (identical to Configuration 1) and 3.9 mg/l after 2,000 d (less than Configuration 1).

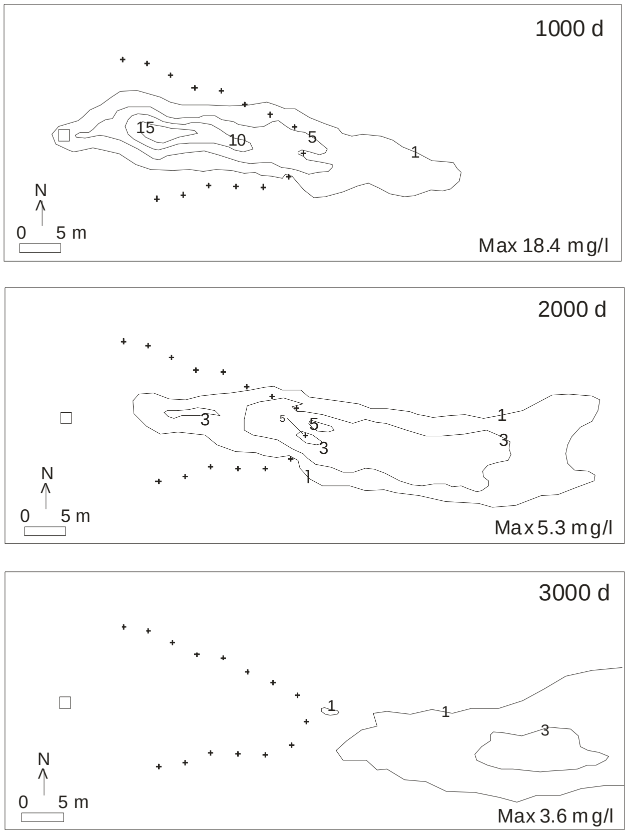

Figure 2. Residual contaminant plumes (mg/l) for Configuration 1 after 1,000, 2,000, and 3,000 d.

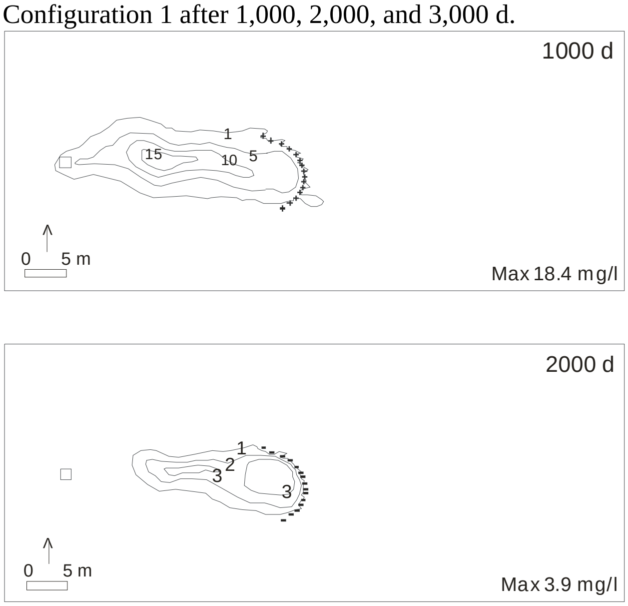

Figure 3. Residual contaminant plumes (mg/l) for Configuration 2 after 1,000 and 2,000 d.

The above results suggest that positioning non-pumped, reactive wells near the downgradient tip of a contaminant plume may be a more effective remediation strategy than spacing the same number of wells uniformly along the entire downgradient segment of the plume. The shape of a contaminant plume reflects prevailing groundwater flow conditions, with a tendency for preferential movement beyond the leading tip of the plume. Taking advantage of this tendency, even if it means sacrificing some coverage near the cross-gradient edges of the plume, can help facilitate timely aquifer remediation.

Here, the objective was comparing configurations with the same number of non-pumped wells for a simulated heterogeneous aquifer. While additional wells could enhance simulated remediation efficiency, cost considerations limit the number wells used in practice. In addition to cost, environmental regulations and site conditions dictate suitable approaches in practice. For example, strategies described above are not suited to aquifers with extremely low groundwater velocity, complex flow paths, and/or non-aqueous phase contaminants. These conditions would delay or prevent contaminant movement to the non-pumped wells.

4. Conclusion

This study evaluated alternative arrays of non-pumped wells along a curved locus downgradient of a simulated contaminant plume in a heterogeneous aquifer. Results suggest that variably-spaced wells, with a concentration of wells near the downgradient tip of a plume, may outperform wells spaced uniformly along the entire downgradient segment of a plume. The former approach better reflects mass transport tendency, as reflected in the estimated shape of the plume, in turn governed by the prevailing groundwater flow field. Thus, variably-spaced arrays of non-pumped wells may warrant consideration as a practical alternative for deep aquifer remediation at some settings.

5. References

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