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Effects of Two-Dimensional Mass Transport Modeling on Groundwater Monitoring Configurations

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Landfills are a principal source of contamination to aquifers. With the proliferation of environmental laws over the past few decades, there has been a shift from small, poorly-designed landfills to large waste storage facilities equipped with liners and leachate collection systems. Although most modem landfills contain measures to prevent subsurface contamination, they are still susceptible to leaking in time. For example, clogged leachate collection pipes and deteriorated liners can lead to groundwater contamination. Large landfills have significant contamination potential due to a substantial volume of stored waste. Consequently, they warrant sound strategies for detecting contaminant releases. Groundwater monitoring is a key component of contaminant release detection systems. Well-designed groundwater monitoring configurations can identify pollutants before they inundate broad areas of aquifers and contaminate water supplies.

Previous authors have devised sampling strategies for toxic material buried in abandoned landfills (Parkhurst 1984), contaminated aquifers (Rouhani 1985; Loaiciga 1989; Hudak and Loaiciga 1992), and clean aquifers at risk of contamination (Meyer and Brill 1988; Wilson et al. 1992; Hudak 1994). The latter problem, positioning wells to detect future contamination, is difficult because the contaminant-release locations are unknown. An efficient configuration of detection wells must intersect plumes initiating anywhere within the footprint of a landfill. Furthermore, the plumes should be detected before reaching a downgradient compliance boundary (Domenico and Palciauskas 1982).

Two-dimensional mass transport models are often used to design detection monitoring networks in aquifers. Not accounting for solute variations along the vertical dimension, these models can potentially yield inadequate sampling configurations. The purpose of this study was to ascertain problems with groundwater monitoring configurations devised by two-dimensional mass transport models.

MATERIALS AND METHODS

Ten candidate groundwater monitoring transects were defined between a hypothetical landfill and downgradient compliance boundary (Figure 1). Oriented

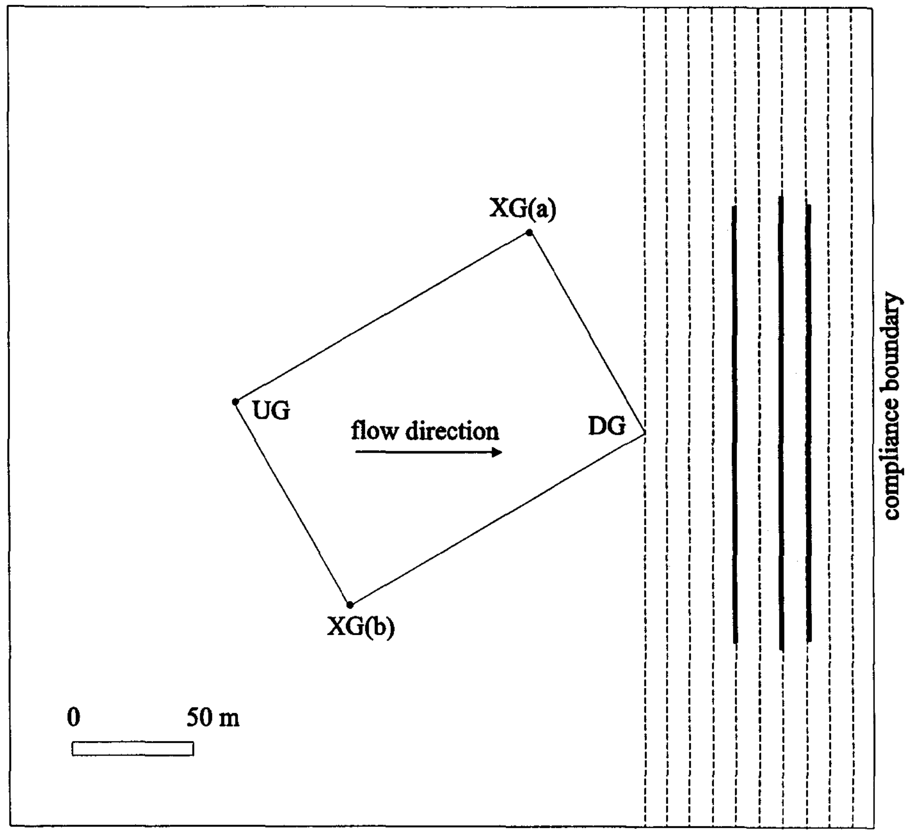

Figure 1. Problem layout showing downgradient (DG), cross-gradient (XG), and upgradient (UG) corners of landfill. Bold lines delineate monitoring segments for 5-m aquifer with 3-D model (closest segment to landfill), 15-m aquifer with 3-D model (closest segment), 5-m aquifer with 2-D model (middle segment), and 15-m aquifer with 2-D model (furthest segment).

perpendicular to groundwater flow, each transect was a potential locus for monitoring wells. Mass transport modeling was used to identify the monitoring transect with the highest detection efficiency (Hudak 1994). This quantity was defined as the width *(S)* of the smallest plume that could traverse a transect (when the plume has just reached the compliance boundary), divided by the entire width *(w)* along the transect that could be crossed by all potential contaminant plumes. A (conservatively narrow) plume emerging from the downgradient corner (DG) of the landfill established *S* for each transect. Plumes originating at the cross gradient (XG) corners of the landfill defined endpoints of *W:*

The monitoring transect having the highest detection efficiency requires the fewest wells to ensure a spacing that does not exceed S. The minimum number of wells *(N)* required along a monitoring transect to ensure a spacing that is equal to or less than S is

$$N = \left\lceil \frac{W}{S} - 1 \right\rceil \quad (1)$$

where the brackets denote the least integer that is equal to or greater than the quantity inside.

Detection efficiency values were calculated for the entire set of monitoring transects four times: (1) for a two-dimensional simulation of a 5-m thick aquifer, (2) for a two-dimensional simulation of a 15-m thick aquifer, (3) for a three-dimensional simulation of the 5-m thick aquifer, and (4) for a three-dimensional simulation of the 15-m thick aquifer. The monitoring transect with the highest detection efficiency was identified for each of the four cases listed above. That information was used to compare the two- and three-dimensional approaches to groundwater monitoring in the 5-m and 15-m thick aquifers.

MT3D (Zheng 1992), a numerical mass transport model, was used to obtain values for *S* and *W* along each monitoring transect. This model was employed for both two-dimensional (single layer) and three-dimensional (multiple layer) simulations. MT3D uses a mixed Eulerian Lagrangian approach to simulate advection, dispersion, and chemical reactions of solutes in aquifers. It retrieves hydraulic head values and flow terms saved by a groundwater flow model, MODFLOW (McDonald and Harbaugh 1992).

For each of the four monitoring scenarios, the aquifer was partitioned into a 75-column by 70-row block-centered finite-difference grid, with a 5-m spacing between nodes. In the two-dimensional simulations, the entire saturated thickness of the aquifer was modeled as a single layer. In the three-dimensional simulations, the aquifer was divided vertically into l-m thick layers. Releases of a conservative solute were simulated from point sources. These point sources were placed in the top layer of the aquifer for the three-dimensional simulations. Other parameters that were used in cases l-4 are presented in Table 1.

RESULTS AND DISCUSSION

In each case, the width of the downgradient plume increased away from the source, attained a maximum value, and then decreased until it reached a value of zero at the compliance boundary. The transect width *W* traversed by all potential plumes also increased away from the landfill and then narrowed near the compliance boundary, but to a lesser degree than did *S*. Because *W* is relatively uniform, *S* exerts an overriding influence on variations in detection efficiency for a set of candidate monitoring transects (Hudak 1996).

Table 1. Mass Transport Parameters

Parameter	Value
Hydraulic conductivity (m/d)	1.0
Hydraulic gradient	0.005
Porosity	0.30
Effective molecular diffusion coefficient (m^2/d)	3.9×10^{-5}
Longitudinal dispersivity (m)	1.0
Horizontal and vertical transverse dispersivity (m^2/d)	0.1
Source concentration (mg/L)	500
Plume boundary concentration (mg/L)	1

Both three-dimensional simulations identified T40 (the monitoring transect located 40 m from the downgradient comer of the landfill) the most efficient for detecting groundwater contamination (Figure 1). At T40, the detection efficiency was 0.139 for the 5-m case and 0.138 for the 15-m case. By inverting these values and applying equation 1, a minimum of 7 wells was calculated at T40 for cases 1 and 2. Moreover, the optimal monitoring transects were located in the upper layer, implying that the detection monitoring wells should also be screened in that layer. This result is consistent with the point source residing in the top layer of the three-dimensional models -- there is more initial mass which leads to wider plumes in that layer. Boreholes tapping the upper layer could also have sampling ports in lower layers, allowing for vertical profiling of contaminant concentrations.

The contaminant plumes were wider in the two-dimensional simulations. This result stems from a contrast in point sources among the two- and three-dimensional scenarios. Point sources contain more mass in the two-dimensional simulations, because they occupy the entire saturated thickness of the aquifer instead of only the upper 1 m. Larger downgradient plumes in the two-dimensional simulations yielded higher detection efficiency values than the three-dimensional simulations. Respectively, the optimal two-dimensional transects registered detection efficiency values of 0.158 and 0.153, at T60 and T70 (Figure 1), for the 5-m and 15-m aquifers. These detection efficiency values are artificially high, and the monitoring transects are too far from the landfill. Artificially-high detection efficiency values yield an inadequate number of wells (that are spaced too far apart from one another). This increases the chance of missing a contaminant plume. From equation 1, detection efficiency values of 0.158 and 0.153 would warrant only 6 wells. However, the three-dimensional simulation yielded a detection efficiency of only 0.133 for T60 (5-m case) and 0.109 for T70 (15-m case). Respectively, those detection efficiency values require 7 wells and 9 wells (see equation 1).

Plume detection is delayed by the two-dimensional monitoring configurations, because the monitoring transects are too far from the landfill. The optimal monitoring transects for the two-dimensional simulations are further from the landfill because the downgradient plumes were wider near the compliance boundary (compared to the three-dimensional downgradient plumes). A key reason for this width difference is that contaminants are transferred to lower layers in the three-dimensional simulations, yielding an upper-layer plume that tapers downgradient. In contrast, there are no lower layers in the two-dimensional simulations. Mass is not transferred to lower layers, and the two-dimensional plumes maintain a larger width in the horizontal plane.

Furthermore, the two-dimensional modeling approach provides no information on vertical sampling. This opens up the possibility of using a short well screen positioned in the wrong sampling interval. For example, a l-m intake in layer 4, near the middle of T60 or T70, would miss the downgradient plume. Moreover, a l-m sampling port in layer 5 would miss the downgradient plume, regardless of which monitoring transect was deployed (Figure 2).

To alleviate these problems, a two-dimensional modeler might recommend a long screen that traverses the entire aquifer. However, that would likely lead to vertical mixing within the well casing, diluting high contaminant concentrations and hampering plume detection.

Groundwater monitoring problems induced by two-dimensional modeling increase as the aquifer thickness increases. The two dimensional, 15-m simulation (case 4) yielded a further monitoring transect. Additionally, the detection efficiency at the transect identified in case 4 was artificially elevated by 0.44, compared to 0.25 for the transect used in case 3.

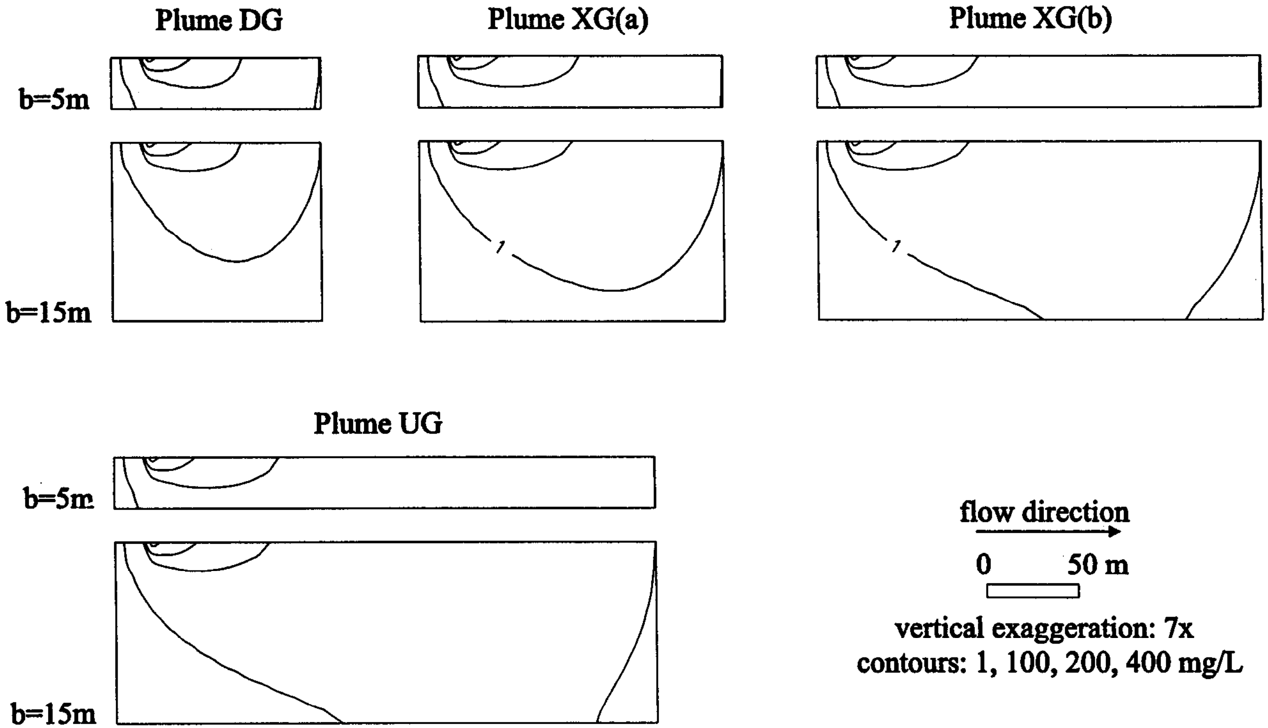

Figure 2. Longitudinal plume cross-sections for three-dimensional simulations.

In summary, a two-dimensional approach can place wells too far from the contaminant source and too far apart from one another. These monitoring configurations could miss or delay detection of contaminant plumes. Two-dimensional modeling approaches also fail to identify optimal vertical sampling horizons. This further increases the chance of missing a plume -- by positioning a short well screen in the wrong vertical interval, or by using a long well screen that dilutes contaminant concentrations. The problems induced by two-dimensional modeling magnify with increased aquifer thickness. Results of this study point to the need for simulation models that stratify an aquifer into different sampling horizons when designing groundwater-monitoring configurations.

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