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Distance-Constrained Contaminant Detection Networks in Aquifers with Varying Hydraulic Gradients

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Strategically positioned groundwater monitoring wells enable timely detection of landfill contaminants. Identifying contaminants early in groundwater facilitates effective mitigation to protect water resources. Generally, detection monitoring networks in groundwater consist of wells in the pathways of potential contaminant plumes emerging from a landfill.

Most methods for designing detection networks in groundwater assume a constant regional hydraulic gradient, or were applied to a constant-hydraulic gradient setting (Meyer and Brill 1988; Meyer et al. 1994; Cieniawski et al. 1995; Storck et al. 1997; Hudak 1998; Angulo and Tang 1999; Yenigul et al. 2005). Meyer and Brill (1988) developed a Monte Carlo method in which the regional hydraulic gradient's orientation varied from one simulation to another, but was constant for each simulation. Morisawa and Inoue's (1991) approach, based upon Monte Carlo simulation and fuzzy utility functions, accommodated variable hydraulic gradients; however, the problem was reduced to a small number of potential leak and candidate well locations. Hudak (1996) considered nonlinear flow trajectories induced by variable hydraulic gradients, but did not constrain well offset from landifll boundaries to facilitate timely detection.

This article develops an alternative graphical approach, for which direction and magnitude of the hydraulic gradient vary across a site, and wells near landfill boundaries promote early detection of landfill contaminants.

MATERIALS AND METHODS

Alternative, six-well detection networks were constructed for the rectangular landfill and hydraulic head fields in Figure 1. The landfill measures 100 m by 120 m. The hydraulic head fields induce divergent flow in one case (Figure 1 – top) and convergent flow in the other (Figure 1 – bottom). Superimposed on the hydraulic head contours are reference contaminant plumes originating at the downgradient and cross-gradient corners of the landfill. The plumes have evolved to the point where they just reach a property boundary surrounding the landfill. Reference plume geometry reflects the character of the flow fields in which they

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evolve. Relative to the convergent case, reference plumes in the divergent flow field widen more with travel, and cross-gradient plumes follow trajectories away from the landfill. The reference contaminant plumes in Figure 1 are a subset of plumes potentially originating within the landfill's footprint.

Two alternative monitoring networks were constructed for each of the convergent and divergent flow fields. "Nonlinear networks" were derived by extending seven flow lines bounding six equal-width flow tubes through the downgradient boundary of the landfill, and placing a well along the centerline of each flow tube (Figures 2 – top and 3 - top). The nonlinear flow lines follow different trajectories, reflecting varying hydraulic gradients across the site. Wells are 20 m from the landfill's downgradient boundary, the distance measured along centerlines. Alternative, "linear networks" were constructed in the same fashion; however, flow lines were linear and parallel to one another (Figures 2 – bottom and 3 - bottom). In the linear networks, flow lines follow trajectories of the middle flow line in corresponding nonlinear networks. These middle flow lines represent average trajectories through the landfill's downgradient boundary.

In the divergent flow field, monitoring wells are slightly farther from the landfill at the cross-gradient corners than at the downgradient corner of the landfill. This pattern reflects changing flow directions along the landfill's downgradient boundary. The direction of the 20-m well offset is slightly more perpendicular to the landfill boundary at the cross-gradient corners of the landfill, thus pushing the wells slightly farther away from the landfill.

An opposite pattern is apparent in the convergent flow field. Monitoring wells are slightly closer to the landfill's downgradient boundary at the landfill's cross-gradient corners, where the direction of the 20-m well offset is slighlty more parallel to the landfill's downgradient boundary.

Numerical groundwater flow (MODFLOW – McDonald and Harbaugh 1988) and mass transport (MT3D – Zheng 1990) models were used to estimate the detection efficiency of each monitoring network. A block-centered, finite-difference model domain consisted of 96 rows and 116 columns, with a uniform 2.5 m node spacing. Models simulated the hydrogeologic conditions in Table 1. In alternate simulations, contaminant plumes evolved from single point sources coinciding with finite difference nodes in the landfill's footprint. Detection efficiency was computed as the percentage of contaminant plumes passing through at least one monitoring well before reaching the property boundary.

RESULTS AND DISCUSSION

In the divergent flow field (Figure 2), the nonlinear network detected all but four of 1,920 contaminant plumes originating inside the landfill's footprint. The network thus achieved a 99.8% detection efficiency. The linear network also performed at high efficiency, detecting all of the simulated contaminant plumes.

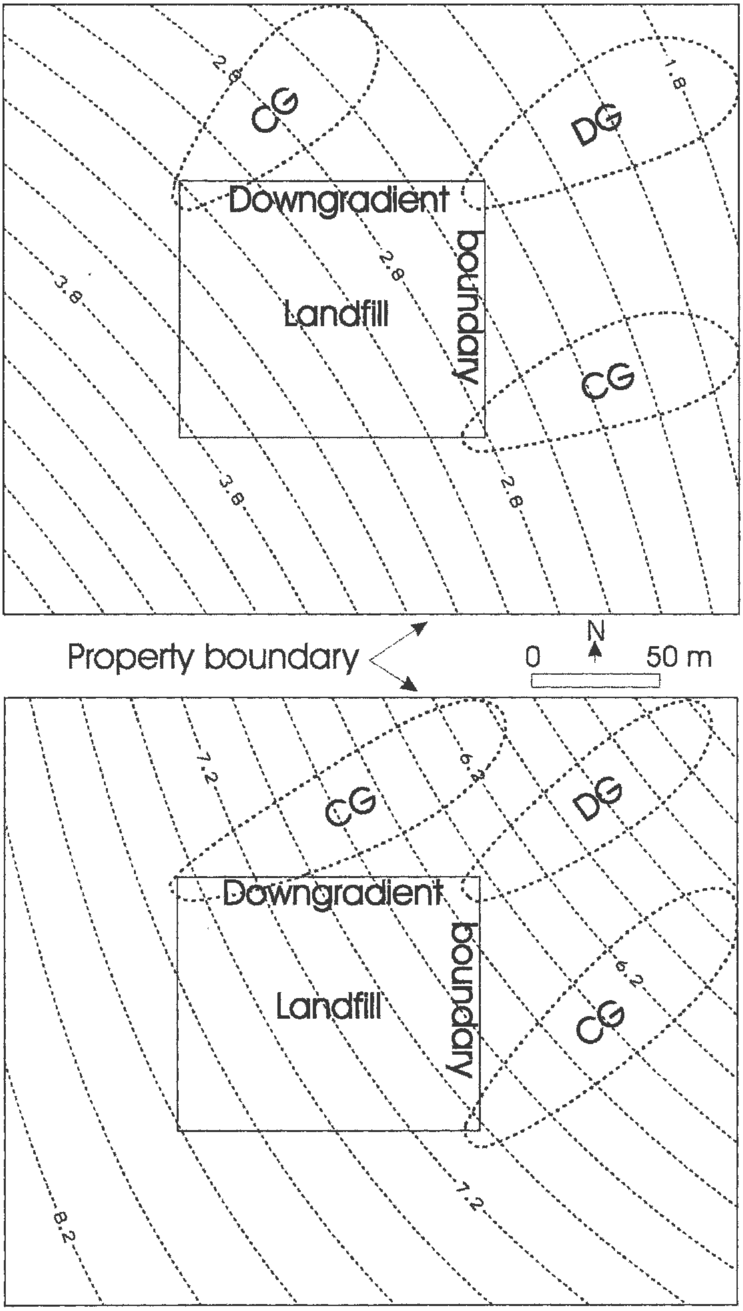

Figure 1. Landfill in divergent (top) and convergent (bottom) flow fields; dashed lines – hydraulic head contours (m); CG – cross-gradient corner reference plumes; DG – downgradient corner reference plume.

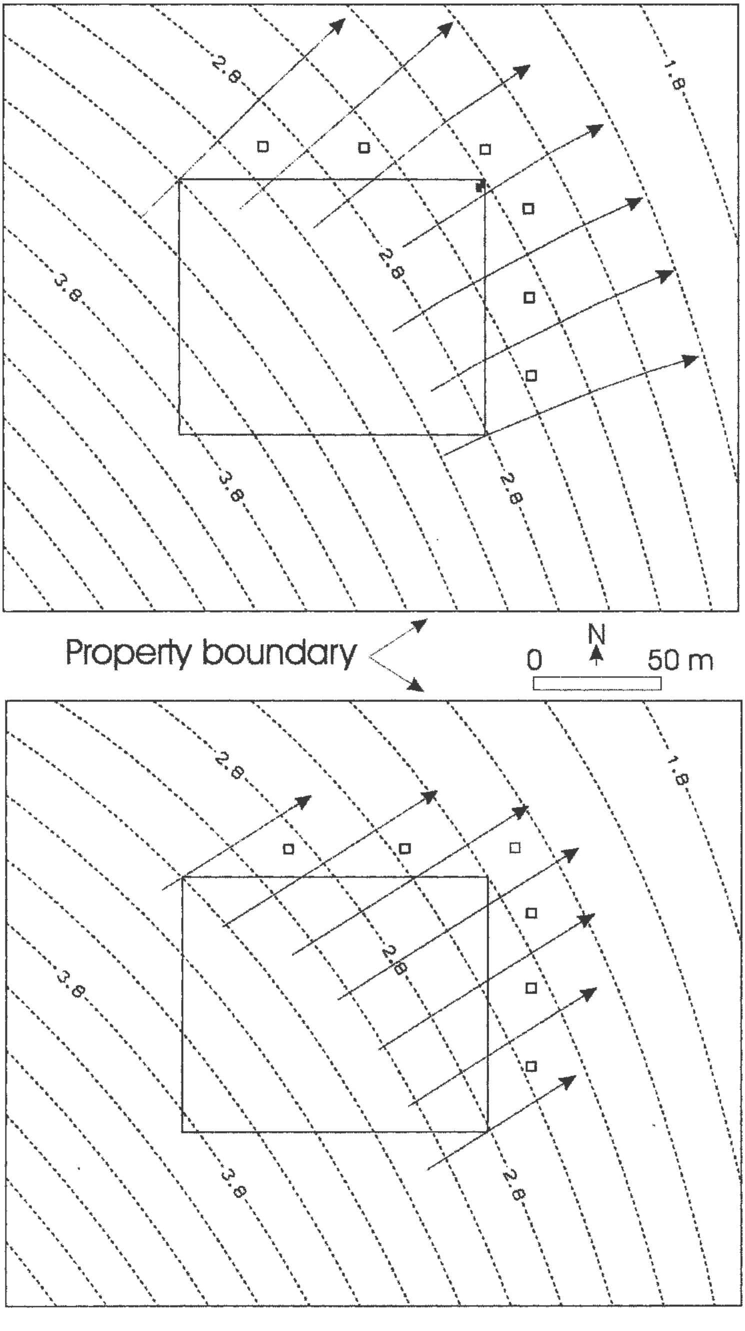

Figure 2. Nonlinear (top) and linear (bottom) networks in divergent flow field; small open squares – monitoring wells; lines with arrows – flow lines; small black squares inside landfill footprint – missed source nodes.

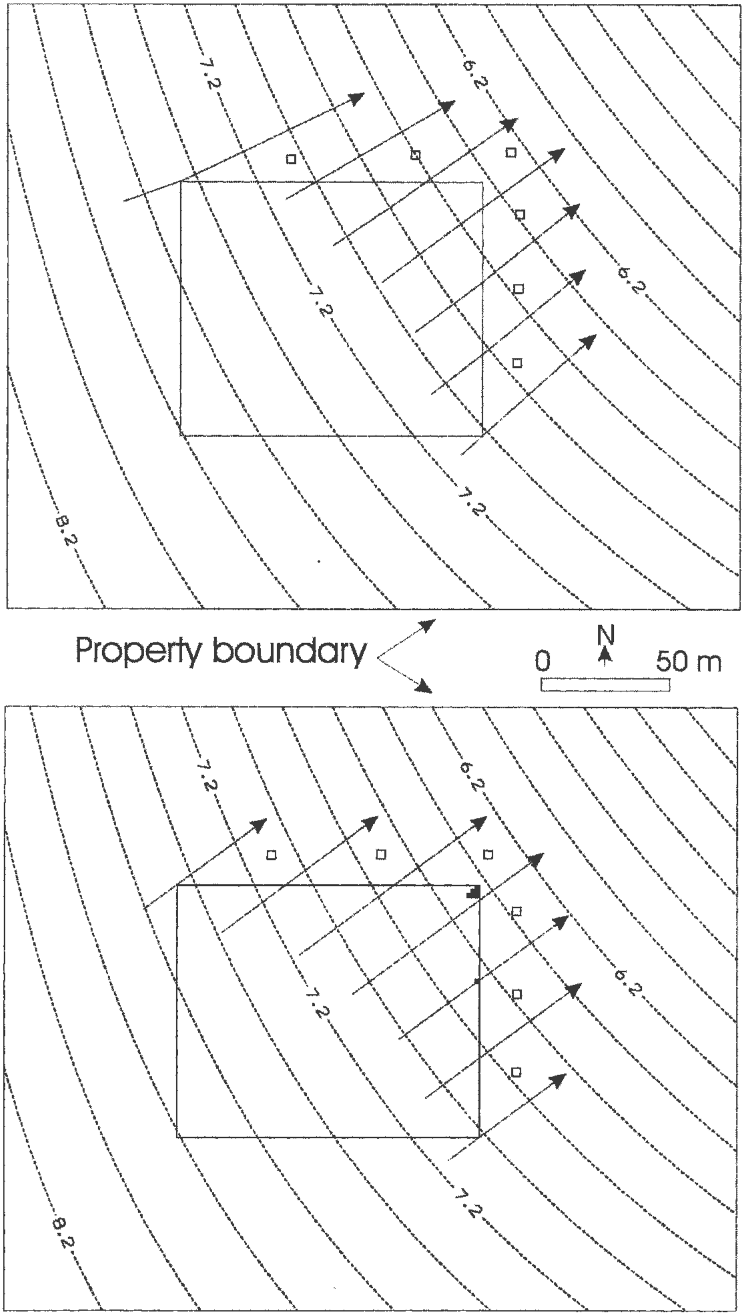

Figure 3. Nonlinear (top) and linear (bottom) networks in convergent flow field; small open squares – monitoring wells; lines with arrows – flow lines; small black squares inside landfill footprint – missed source nodes.

Table 1. Model parameters.

Hydraulic conductivity (m/d)	0.5
Effective porosity	0.30
Saturated thickness (m)	5
Longitudinal dispersivity (m)	1
Transverse dispersivity (m)	0.1
Effective molecular diffusion coefficient (m^2/d)	3.4 x 10^{-5}
Dilution contour*	0.01
Retardation factor	1.0

*Concentration of contaminant divided by original concentration at point source.

A more compact structure contributed to a slightly higher detection efficiency for the linear network. Outer flow lines in the linear network follow more inward trajectories (toward the landfill) compared to those in the nonlinear network, leading to more closely spaced monitoring wells in the linear network.

In the linear network, a closer well spacing near the landfill's downgradient corner reduced the gap through which some contaminant plumes migrated in the nonlinear network. Plumes emerging near the landfill's downgradient corner traverse a relatively narrow segment of the landfill's downgradient boundary (Figure 1 – top). By contrast, plumes emerging near the landfill's cross-gradient corners traverse a much wider segment of the downgradient boundary. A narrower traversal for downgradient plumes enables some of them to migrate between monitoring wells to the property boundary. Thus, networks with closer well spacing near the landfill's downgradient corner can potentially enhance overall detection efficiency.

Although a linear network performed at high detection efficiency in this example, more extreme curvature in hydraulic head contours would induce cross-gradient contaminant plumes to migrate away from the landfill and monitoring wells in a linear network, thus reducing overall detection efficiency.

In the convergent setting, the nonlinear network detected all of the contaminant plumes originating inside the landfill's footprint. The linear network detected all but seven plumes, attaining a slightly lower, 99.6% efficiency. Inward flow lines in the nonlinear network produced more closely spaced wells at the landfill's downgradient corner, thus contributing to a higher overall detection efficiency.

As in the divergent setting, contaminant plumes originating near the landfill's downgradient corner are more difficult to detect in the convergent setting, because they traverse a relatively small segment of the landfill's downgradient boundary (Figure 1 – bottom). By contrast, plumes at the cross-gradient corners of the landfill traverse a much wider segment of the downgradient boundary. Fewer such plumes move between monitoring wells. This trend is amplified for the reference plume at the northwest corner of the landfill (Figure 1 – bottom). Here, the hydraulic head contours are nearly perpendicular to the landfill's downgradient boundary; thus, the cross-gradient plume travels nearly along the downgradient boundary.

For the convergent flow field (Figure 3), there was more difference between nonlinear and linear networks along the northern than eastern downgradient boundary segment. More curvature in hydraulic head contours along the northern boundary segment induced more pronounced divergent flow, accounting for flow lines with markedly different orientations in the two networks, though both networks performed at overall high efficiency.

The ability of a linear network to attain high detection efficiency would diminish in more pronounced convergent flow fields. Monitoring wells near the cross-gradient corners of the landfill would be less effective, given that contaminant plumes would follow more inward trajectories. Grouping wells closer to the downgradient corner of the landfill, as in the nonlinear network, would be a more effective monitoring strategy.

Overall, results of this study suggest that both nonlinear and linear monitoring networks constructed in the manner above may perform effectively in settings characterized by slight curvature of hydraulic head contours. Such curvature induces divergent or convergent groundwater flow beneath a landfill. A linear monitoring network slightly outperformed a nonlinear counterpart in a divergent flow field. The opposite was true in a convergent setting, where a nonlinear network performed at slightly higher efficiency. With increased curvature in hydraulic head contours, nonlinear networks avoid potential problems with well placement in linear networks. Such problems include placing wells too far from cross-gradient corners of a landfill in divergent flow settings, and placing wells too close to cross-gradient corners in convergent settings.

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