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Designing Equitemporal Monitoring Networks to Detect Contaminants in Groundwater

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Common goals of monitoring groundwater quality include detecting and mapping contaminants migrating from landfills. This article addresses the detection problem, in which wells intercept contaminant plumes (enclaves of contaminated groundwater) originating in landfills. Used in conjunction with vadose zone monitoring devices, strategically configured detection wells enable timely aquifer remediation.

Previous approaches to designing detection networks employed distance measures in the form of a monitoring locus (EPA 1994; Hudak 1998) or grid of candidate monitoring sites downgradient from a landfill (Hudak and Loaiciga 1993; Reed et al. 2000). However, distance measures may pose design problems in field settings with highly variable groundwater velocities. Specifically, larger distance lags (between a landfill and monitoring wells) could enhance detection capability at high-velocity segments of a landfill's downgradient boundary. This paper develops an alternative approach for siting monitoring wells based on groundwater travel times.

MATERIALS AND METHODS

Equidistant and equitemporal detection networks were devised for the rectangular landfills and hydraulic head fields in Figure 1. The networks were constructed by drawing 10 equal-width flow tubes through the downgradient boundary of the landfill and placing a well along the flow line bisecting each flow tube. In each network, the average distance lag (distance along flow line from landfill to monitoring well) was 25 m. However, the equidistant networks had a fixed distance lag, whereas the equitemporal networks had a fixed time lag (travel time along flow line from landfill to monitoring well), resulting in variable distance lags. Hydraulic gradients across the landfill's downgradient boundary varied from 0.016 to 0.047. Thus groundwater velocity varied by approximately a factor of three along the down gradient boundary.

The equitemporal networks were constructed as follows. Consider the case of N flow tubes, each bisected by a flow line. The time lag (t_1) for the first flow line is

$$t_1 = \frac{L_1}{v_1} = \frac{L_1 n_e}{K i_1} \quad (1)$$

where L_1 is the distance (measured along the flow line) between the landfill and well, v_1 is the groundwater velocity, n_e is the effective porosity, K is the hydraulic conductivity, and i_1 is the hydraulic gradient. Equal time lags among all N flow lines implies,

$$t_1 = t_2 = t_3 \ldots \Rightarrow \frac{L_1 n_e}{K i_1} = \frac{L_2 n_e}{K i_2} = \frac{L_3 n_e}{K i_3} \ldots \Rightarrow \frac{L_1}{i_1} = \frac{L_2}{i_2} = \frac{L_3}{i_3} \ldots$$
$$\Rightarrow \frac{L_i}{i_i} = \frac{\bar{L}}{\bar{i}} \quad (2)$$

where $\bar{L}$ is the average distance between the landfill and the monitoring wells, and $\bar{i}$ is the average hydraulic gradient along the flow lines. At any given flow line,

$$L_i = \frac{\bar{L}}{\bar{i}} i_i \quad (3)$$

Equation (3) was used to compute distance lags for the monitoring wells in the equitemporal networks (Figure 1).

The four networks in Figure 1 (two in Case A and two in Case B) were evaluated for detection efficiency using an analytical computer model that simulates solutes (chloride in the present study) released along a line source in an aquifer (Domenico 1987; Wilson et al. 1993). Detection efficiency was defined as the percentage of leaks detected (passing through at least one monitoring well) before reaching a buffer zone boundary located 100 m from the landfill. Leaks and resulting contaminant plumes were simulated from approximately 9,000 points distributed throughout the landfill. A dilution contour defined plume boundaries (Table 1).

RESULTS AND DISCUSSION

In each of Cases A and B, the equitemporal monitoring network outperformed its equidistant counterpart (Figure 1, Table 2). In the equitemporal networks, higher detection efficiency values were attained by positioning wells further from high-velocity segments of the landfill's downgradient boundary. This strategy was effective because contaminant plumes are narrower in higher velocity areas and, consequently, more difficult to detect. Moving the wells further away provided more opportunity for plumes to widen with transport, making them easier to detect.

Table 1. Aquifer properties

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)	3.3×10^{-5}
Dilution contour*	0.001
Retardation factor	1.0
Width of line source (m)	1

* Concentration of chloride divided by original concentration at leak.

Table 2. Detection efficiency (percent)

	Case A	Case B
Equidistant	71.7	79.2
Equitemporal	74.4	80.4

Distance lags for the equitemporal networks ranged from 13.8 m to 40.5 m in Case A and 14.8 m to 42.6 m in Case B. Thus, equitemporal approaches require that some wells be shifted closer to a landfill (relative to an equidistant counterpart). However these closer wells are in lower velocity areas. It takes more time for a low-velocity plume to reach a specified distance, allowing it to widen and rendering it easier to detect. Gains in detection efficiency from placing wells further from the landfill at high-velocity areas outweighed losses in detection efficiency from placing wells closer to the landfill at low-velocity areas.

The highest detection efficiency attained by any of the four networks was 80.4% for the equitemporal network in Case B. Detection efficiency values were higher in Case B because it had a shorter segment of the landfill's downgradient boundary in the high-velocity area. In each of the four networks, detection efficiency could be increased by adding more wells, but the focus of this study was comparing differences between networks rather than attaining a specific detection efficiency. Divergent flow induced by the complex hydraulic head field contributed to low detection efficiency values.

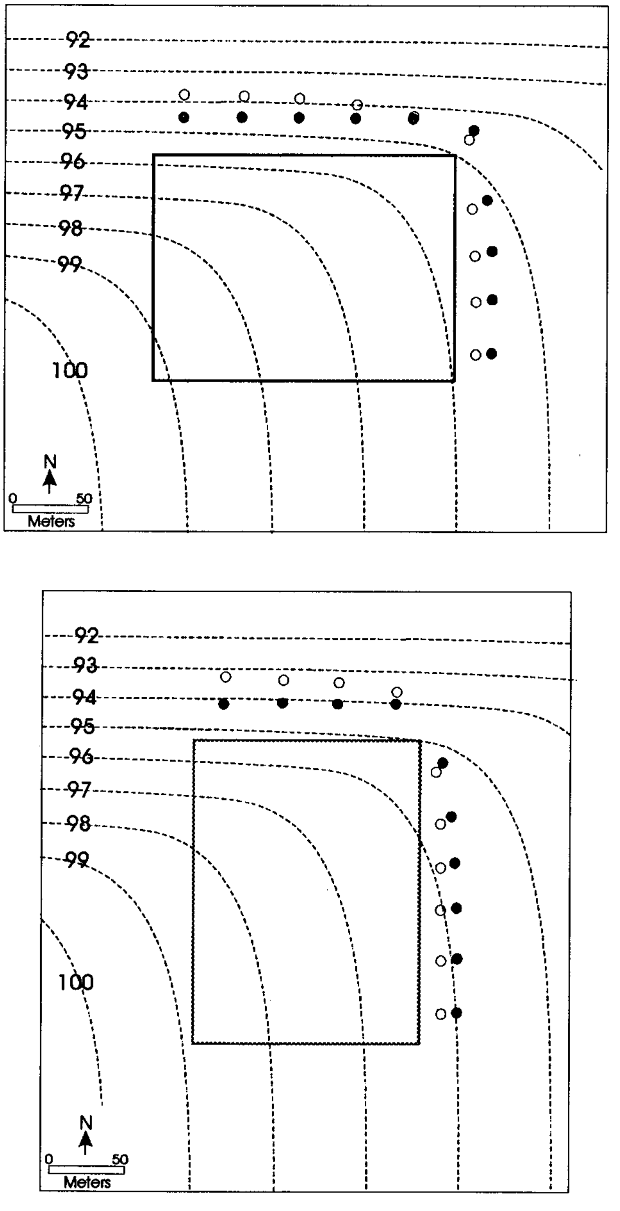

Figure 1. Map view of equidistant (dots) and equitemporal (circles) detection networks for rectangular landfill (bold) in Cases A (top) and B (bottom). Hydraulic head contours (dashed) in meters.

The difference in detection efficiency between equitemporal and equidistant networks was greater in Case A, where the longer segment of the landfill's downgradient boundary was in the high-velocity area. Field settings having this characteristic, along with highly variable groundwater velocities, warrant time-based approaches to designing contaminant detection networks in underlying aquifers.

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