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# Procedure for Upgrading Contaminant-Detection Networks in Aquifers

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Properly located monitoring wells contribute definitive evidence of contaminants in groundwater. They can prevent widespread groundwater pollution by prompting timely cleanup efforts. Conversely, a poor configuration of wells wastes money and instills a false sense of security.

Facilities that could, but have not yet contaminated groundwater require detection monitoring wells (EPA 1994). Designing a detection network entails placing wells at strategic positions downgradient of a landfill, taking into account the direction of groundwater flow, rock and soil characteristics, and locations of neighboring properties or water supply wells. Detection monitoring is difficult due to the unknown location of future contaminant releases. The monitoring wells must be located to provide an opportunity for detecting releases from anywhere within the footprint of a landfill.

Many existing monitoring networks contain wells that are too close to the downgradient boundary of a landfill, and/or too far apart from one another. These deficiencies make it difficult to detect contaminant plumes. Previous investigators have devised methods for configuring new monitoring networks (Loaiciga et al. 1992; Meyer et al. 1994; Hudak 1998). The objective of this study was to devise an empirical method for improving existing monitoring networks with supplemental wells.

## MATERIALS AND METHODS

Figure 1 shows a five-well monitoring network near a hypothetical rectangular landfill, oriented oblique to regional groundwater flow. The network was established by arbitrarily locating wells near the landfill's downgradient boundary, at roughly even spacing (thus mimicking what is often done in practice). In practice, the number of monitoring wells may be based upon the size of a landfill, financial resources, and environmental regulations. The landfill in Figure 1 is located 100 m from a buffer zone boundary.

Monitoring efficiency determinations were based on whether enclaves of contaminated groundwater (plumes) passed through a monitoring well before crossing the buffer zone boundary. A computer using a conservative tracer (for example, chloride) generated the contaminant plumes. In practice, tracer concentrations could be measured by analytical methods such as high-pressure liquid chromatography. Domenico and Palciauskas (1982) discuss criteria for defining a buffer zone boundary. In this case, it represents the maximum limit of transport before a plume must be detected. In practice, the buffer zone boundary should be defined based upon site-specific conditions, considering such factors as property boundaries, neighboring dwellings, water supply wells, surface water bodies, groundwater velocity, and the relative costs and benefits of providing early release detection.

MAP (Wilson et al. 1993) was used to calculate the detection efficiency of the monitoring network in Figure 1 and networks devised by the upgrade method. The computer program uses a two-dimensional analytical transport function for solute released along a line source in an aquifer with a uniform flow field (Domenico 1987).

Plume boundaries were defined by a dilution contour, equal to the quotient of the concentration at a downgradient point and the original concentration of the line source. Hydrogeologic characteristics input to MAP are listed in Table 1. The listed values are representative of a conservative contaminant in an unconsolidated, silty-sand aquifer (Gelhar et al. 1992; American Petroleum Institute 1995).

Contaminant releases were simulated at 9,960 potential source nodes distributed uniformly throughout the landfill's footprint. Detection efficiency was computed as the number of landfill nodes from which leaks were detected divided by 9,960. A leak was detected if the contaminant plume passed through one or more monitoring wells before reaching the buffer zone boundary. For example, a detection efficiency of 60% implies that releases over 40% of the landfill were not detected.

A five-step upgrade method was devised to locate additional wells. Locations of existing wells were fixed, but wells added by the upgrade method may shift until it reaches a target detection efficiency, or 100%.

(1) Calculate the detection efficiency of the existing monitoring network (Figure 1). If it attains the target detection efficiency, or 100%, stop the upgrade. Otherwise, produce a map of undetected source nodes within the landfill's footprint (Figure 1).

(2) Establish a locus for additional wells by measuring the distance (lag), parallel to groundwater flow, between the landfill's downgradient boundary and each existing monitoring well. Groundwater may exit the footprint of a landfill at any point along its downgradient boundary. Draw the monitoring locus through the furthest well, maintaining a constant lag to the monitoring locus from all points on the

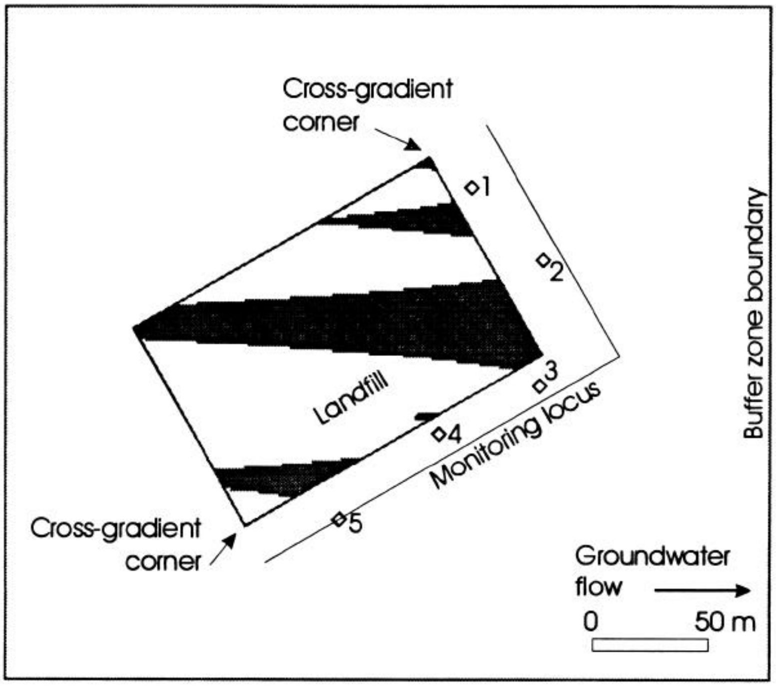


**Figure 1.** Existing groundwater monitoring network (diamonds) and undetected source nodes (shaded areas).

**Table 1.** Model Parameters

| | |
|---|---|
| Seepage velocity (m/d) | 0.01 |
| Saturated thickness (m) | 5 |
| Longitudinal dispersivity (m) | 1 |
| Transverse dispersivity (m) | 0.1 |
| Effective molecular diffusion coefficient ($m^2$/d) | $3.3 \times 10^{-5}$ |
| Dilution contour | 0.001 |
| Retardation factor | 1.0 |
| Width of line source (m) | 5 |

landfill's downgradient boundary. (This increases the chance of detecting contaminant plumes and ensures a similar lag among all wells.) In Figure 1, the lag between the landfill and monitoring locus equals 35 m (Figure 1).

(3) Evaluate the map of undetected source nodes. Bands of undetected nodes occur hydraulically upgradeint of well pairs. Find the well pair with the most undetected source nodes. Place an additional well on the monitoring locus, midway between the well pair, measuring perpendicular to groundwater flow. If the largest area of undetected source nodes is at the edge of the landfill, place the additional well midway between the closest well and cross-gradient comer of the landfill Recalculate the detection efficiency, and produce a map of undetected source nodes. If the network attains the target detection efficiency, or 100%, stop the upgrade. Otherwise proceed to Step 4.

(4) If the additional well eliminates all undetected source nodes upgradient of an existing well pair, repeat Step 3 for any remaining existing well pairs with undetected source nodes. Otherwise, determine whether there are more undetected source nodes (between the existing well pair) to one side of the additional well. Define sides by drawing a groundwater flowline through the additional well. Incrementally shift the additional well along the monitoring locus in the direction with more undetected source nodes. For each shift, produce a map of undetected source nodes, and recalculate the network's detection efficiency. Continue shifting the well until there is no improvement in detection efficiency. Stop the upgrade if the network attains the target detection efficiency, or 100%.

The shift increment should reflect site-specific conditions, such as the size of a landfill. In this case, 2 m was used as a compromise between a larger a value that would provide poor resolution and a smaller value that would make the problem computationally cumbersome.

(5) Evaluate the map of undetected source nodes. Identify the existing well pair with the most undetected nodes. If that well pair has not already received an additional well, position one by starting with Step 3. Otherwise, space an additional well and the previously added well(s) evenly between the existing well pair, measuring perpendicular to groundwater flow. (Move the previously added wells to accommodate an even spacing.) Achieve an even spacing by drawing equal-width flow tubes between the existing well pair, one tube for each additional well, Place the wells on the monitoring locus, in the middle of the flow tubes. Shift these wells per Step 4. If the monitoring network attains the target detection efficiency, or 100%, stop the upgrade. Otherwise repeat Step 5.

(6) In Steps 2-5 above, the upgrade method tracks detection efficiency with each additional well. Once the network reaches the target detection efficiency, or 100%, graph detection efficiency versus the number of wells added. The graph shows the relative benefit of each additional well.

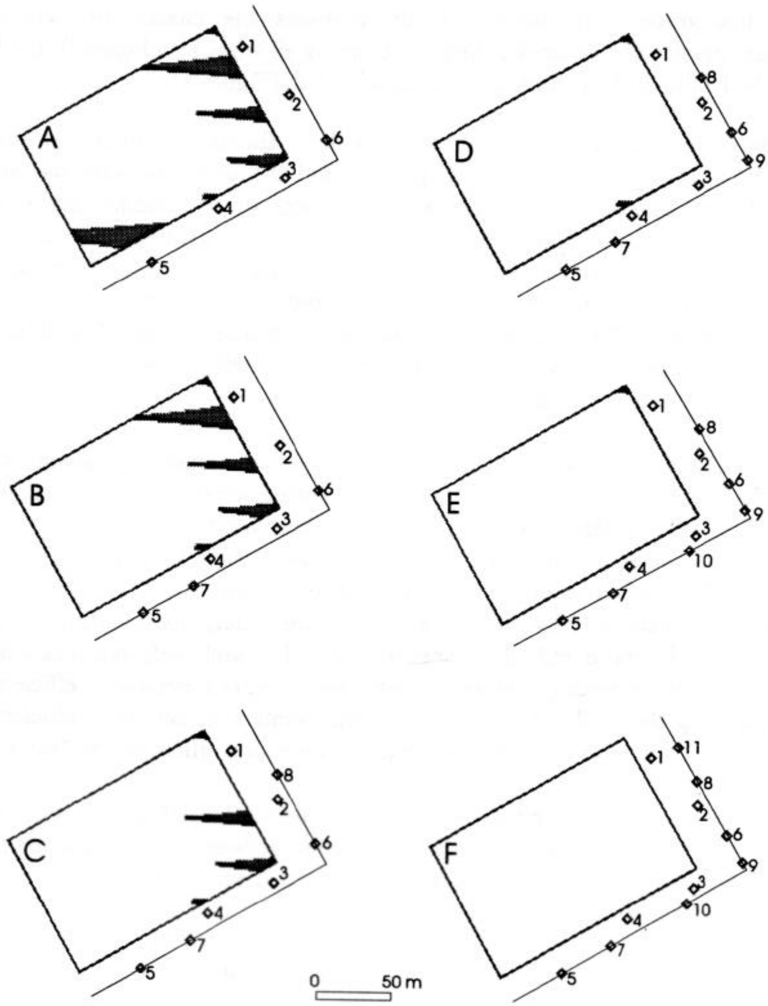


**Figure 2.** Monitoring networks (diamonds) and undetected source nodes (shaded areas) for (A) 6, (B) 7, (C) 8, (D) 9, (E) 10, and (F) 11 wells.

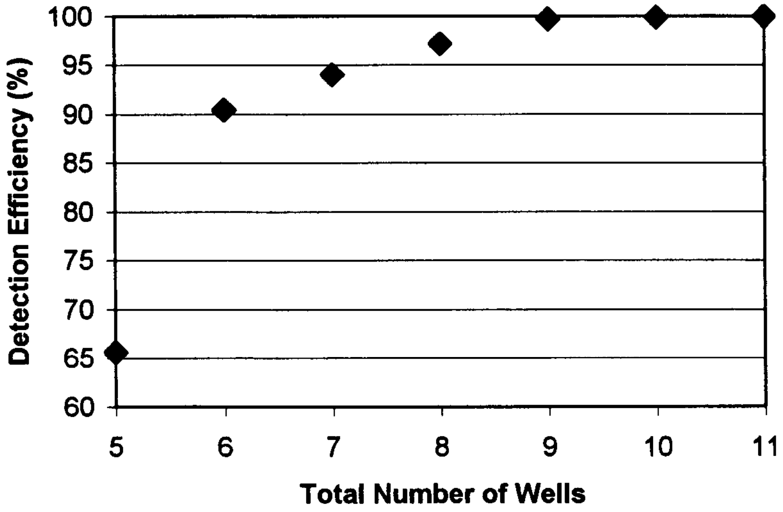


**Figure 3.** Scatter plot of network detection efficiency versus number of monitoring wells.

The upgrade method was applied to the monitoring network in Figure 1. It consists of five existing wells, numbered 1-5. Additonal wells were numbered 6 and higher.

## RESULTS AND DISCUSSION

The network had an initial detection efficiency of 65.6%. Well 6 was placed between existing well pair 2-3, increasing the network's detection efficiency from 65.6% to 90.2%. A 2-m counterclockwise shift of well 6 improved the detection efficiency to 90.4% (Figure 2).

Well 7 went between existing well pair 4-5, increasing the detection efficiency to 94.0% (Figure 2). As well 7 eliminated all undectected source nodes between existing well pair 4-5, no shifting was required. The upgrade method placed well 8 between existing well pair 1-2, increasing the network's detection efficiency to 97.2%, and eliminating all undetected source nodes between well pair 1-2 (Figure 2).

Existing well pair 2-3 received well 9. Well 6 was repositioned, so that wells 6 and 9 could be spaced evenly between well pair 2-3. A 2-m clockwise shift of well 9 increased the network's detection efficiency to 99.7%, eliminating all undetected source nodes between existing well pair 2-3 (Figure 2).

Well 10 was placed between existing well pair 3-4, detecting all source nodes between that pair, and increasing the network's detection efficiency to 99.9%

(Figure 2). Finally, well 11 was placed between well 1 and the landfill's cross-gradient comer, increasing the network's detection efficiency to 100.0% (Figure 2).

Increases in detection efficiency were much higher for wells added earlier than later. Well 6 targeted a large area of undetected source nodes upgradient of existing well pair 2-3, increasing the network's detection efficiency by 24.8 percentage points.

There were modest increases in detection efficiency up to well 9, but little improvement thereafter (Figure 3). Once the network reached 90.4% detection efficiency with well 6, there remained only small areas of undetected source nodes that additional wells could target. Many later wells required no shifting, because they could eliminate all of the undetected source nodes between an existing well pair in the middle position.

In practice, a monitoring network designer may decide to stop at well 6, or perhaps well 9, depending on budget and regulatory constraints. Well 9 increased the network's efficiency to 99.7%, and improvements thereafter were extremely low. The final two wells only produced a 0.3% increase in detection efficiency. Alternatively, 0.3% of the contaminant source nodes were detected only by wells 10 or 11. This percentage is small, considering the cost of installing a monitoring well typically ranges from U.S.$2,000-5,000.

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