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APPLICATION OF GEOGRAPHIC INFORMATION SYSTEMS TO GROUNDWATER MONITORING NETWORK DESIGN[1]

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ABSTRACT: Effective monitoring configurations for contaminant detection in groundwater can be designed by analyzing the spatial relationships between candidate sampling sites and aquifer zones susceptible to contamination. Examples of such zones are the domain underlying the contaminant source, zones of probable contaminant migration, and areas occupied by water supply wells. Geographic information systems (GIS) are well-suited to performing key groundwater monitoring network design tasks, such as calculating values for distance variables which quantify the proximity of candidate sites to zones of high pollution susceptibility, and utilizing these variables to quantify relative monitoring value throughout a model domain. Through a case study application, this paper outlines the utility of GIS for detection-based groundwater quality monitoring network design. The results suggest that GIS capabilities for analyzing spatially referenced data can enhance the field-applicability of established methodologies for groundwater monitoring network design.
(KEY TERMS: groundwater monitoring network design; geographic information systems; pollution monitoring.)

INTRODUCTION

Groundwater quality monitoring can play an important role in preventing degradation of underground water supplies from waste facilities, such as landfills. An effective monitoring program can rapidly identify a pollution problem, enabling timely remedial action. Designing a groundwater quality monitoring network involves selecting a set of sampling sites based upon a monitoring objective. Typical monitoring objectives include early detection of a contaminant release and protecting water supply wells. For a given objective, an appropriate monitoring strategy can be identified. Monitoring strategies can be implemented by weight schemes that rank the relative value of candidate sampling sites. Depending on the objective of a monitoring program, several distance variables may dictate the value of a candidate sampling site. These variables express distances between candidate sites and various spatially-distributed objects, such as waste facility boundaries, zones of potential contaminant migration, and water supply wells. Geographic information system (GIS) are well suited to processing spatially distributed data pertinent to the monitoring network design problem. The objective of this study is to integrate GIS capabilities for managing spatially referenced data with a groundwater quality monitoring network design methodology. We illustrate the integration process through an application to a municipal landfill.

BACKGROUND

GIS is an important water resources management tool for analyzing spatial variations in pollution susceptibility. In this context, the utility of GIS stems from its capability to analyze multiple spatially distributed variables. Others have applied GIS to assess pollution susceptibility for surface and groundwater resources. For example, Hession and Shanholtz (1988) presented a GIS for delineating areas of nonpoint source pollution from spatially indexed data. Tim *et al.* (1992) coupled GIS and water quality monitoring to identify areas of nonpoint source pollution at the watershed level. Areas of pollution susceptibility were identified on the basis of spatially distributed control factors, including soil erosion rate, sediment yield, and phosphorous loading. Several studies have

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integrated GIS with the DRASTIC rating scheme (Aller *et al.*, 1987) to generate maps illustrating spatial variations in groundwater pollution potential (Evans and Meyers, 1990; Halliday and Wolfe, 1991). These studies employed GIS capabilities for overlaying multiple "information layers" (each corresponding to one of seven spatially referenced susceptibility factors) to derive composite indices of groundwater pollution potential throughout a study region. The present study describes an application of GIS to groundwater quality monitoring in the vicinity of a contaminant source. We integrate GIS with a ranking approach to groundwater quality monitoring network design. As discussed below, the ranking approach is one of three approaches to detection-based network design.

Detection-based groundwater quality monitoring network design involves selecting a set of monitoring wells in an uncontaminated aquifer at risk of contamination from an overlying waste facility. We distinguish this problem from characterization-based network design in which wells are located within an existing field of contamination. The few approaches that have been developed to address the detection-based network design problem can be classified as simulation, qualitative, and ranking.

Simulation approaches utilize computer models to simulate the evolution of contaminant plumes (Massmann and Freeze, 1987; Meyer and Brill, 1988; Ahlfeld and Pinder, 1988). The results are then incorporated into an optimization model which derives a monitoring well configuration. In addition to generating multiple hydraulic conductivity distributions, mass transport models are needed to derive numerous contaminant plumes. Numerical modeling of contaminant transport, especially in three dimensions, is considerably more difficult than simulation of groundwater flow. Transport modeling not only is more vulnerable to numerical errors such as numerical dispersion and artificial oscillation, but also requires much more computer memory and execution time, making it impractical for many field applications.

In a qualitative approach, the monitoring network is designed from calculations and judgments made without the use of quantitative mathematical methods (Loaiciga *et al.*, 1992). Sampling locations are determined by the hydrogeologic conditions near the source of contamination. The ultimate configuration of monitoring wells is subject to the investigator's understanding of: (1) the key properties of the groundwater flow system, (2) how these properties influence the movement of contaminant and resulting contaminant distributions, and (3) what constitutes an "optimal" monitoring well configuration given probable contaminant migration pathways. Qualitative approaches are easy to implement, but often highly subjective and poorly defined.

Ranking approaches utilize weight schemes that express the relative monitoring values of candidate sampling sites distributed throughout a model domain (Hudak *et al.*, 1993). The value of a potential monitoring site can be ranked by assessing its spatial position relative to zones of contamination susceptibility, such as the contaminant source, water supply wells, and probable zones of contaminant migration. The term "advection envelope" has been used to describe a zone of contamination susceptibility that encompasses probable pollutant migration pathways (Hudak *et al.*, 1993). Groundwater flow lines originating from the hydraulically downgradient margin of the contaminant source define the geometry of this zone (Figure 1).

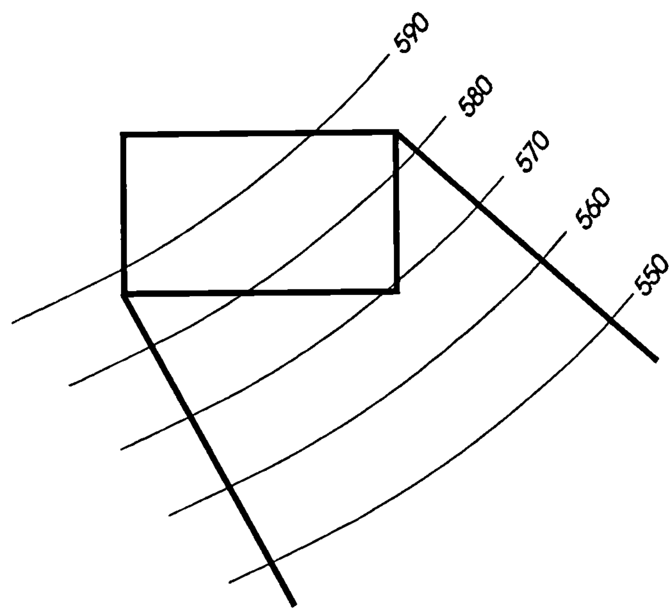

Figure 1. Advection Envelope (rectangular area represents contaminant source) (contours in units of length).

If the head configuration is highly uncertain, networks derived using a range of advection envelopes can be developed and compared. A GIS can effectively implement a ranking approach to network design by: (1) registering the spatial coordinates of candidate sampling sites and various zones of contamination susceptibility, (2) calculating distances between candidate sites and zones of susceptibility, and (3) using the distance values to rank relative monitoring value. In the following sections, we develop a ranking approach to groundwater quality monitoring network design and illustrate the role of GIS in implementing the methodology.

NETWORK DESIGN METHODOLOGY

In a ranking approach to network design, alternative weight schemes can be used to express the relative value of candidate monitoring sites (nodes) for a given monitoring objective. For example, weights can be expressed as a combination of one or more of the following distance variables:

$D(s)_j$ = distance from node j to contaminant source;

$D(e)_j$ = distance from node j to advection envelope; and

$D(w)_j$ = distance from node j to nearest water supply well.

Consider the monitoring objective of early contaminant release detection (objective A). An appropriate design strategy would be to site detection wells near *both* the contaminant source and advection envelope(s). This strategy can be implemented by weight schemes which employ the distance variables $D(s)_j$ and $D(e)_j$, as expressed in Equations (1)-(3) below.

$$A1_j = \frac{1}{D(s)_j D(e)_j} \tag{1}$$

$$A2_j = \frac{1}{D(s)_j + D(e)_j} \tag{2}$$

$$A3_j = \frac{1}{D(s)_j} + \frac{1}{D(e)_j} \tag{3}$$

where $A1_j$, $A2_j$, and $A3_j$ are alternative weights for node j.

The weight schemes expressed in Equations (1) -(3) are consistent with hydrogeologic guidelines used in practice. Resource Conservation and Recovery Act (RCRA) guidelines for groundwater monitoring (U.S. EPA, 1986) specify that the placement of downgradient detection wells must consider: (1) the distance to the contaminant source and the direction of groundwater flow, (2) the likelihood of intercepting potential pathways of contaminant migration, and (3) the characteristics of the contaminant source controlling the movement and distribution of contamination in the aquifer. Distance to the contaminant source is quantified by $D(s)_j$. The direction of groundwater flow is considered in the definition of advection envelopes. In a general sense, the likelihood that a monitoring well intercepts potential contamination may be related to the distance between the corresponding node and areas of high contamination susceptibility. Finally, the characteristics of the contaminant source boundaries are considered in deriving $D(s)_j$ and in constructing advection envelopes.

Equations (4)-(6) express alternative weight schemes for a monitoring program emphasizing protection of water supply wells (objective B). In this case, an appropriate design strategy is to site detection monitoring wells near (and between) the contaminant source and water supply wells. Note that a configuration geared toward early detection of a contaminant release (objective A) is not necessarily appropriate for objective B. If a plume migrates undetected beyond a network of monitoring wells near the contaminant source, there may be no provision for confirming a pollution problem without wells located further downgradient. In a program emphasizing objective B, it is also desirable to monitor at or near water supply wells to verify the magnitude of contamination in areas where potential exposure hazard is high.

$$B1_j = \frac{1}{D(s)_j D(w)_j} \tag{4}$$

$$B2_j = \frac{1}{D(s)_j + D(w)_j} \tag{5}$$

$$B3_j = \frac{1}{D(s)_j} + \frac{1}{D(w)_j} \tag{6}$$

In some applications, it may be desirable to emphasize both objectives A and B above. Suppose that, in a given application, weight schemes A1 and B1 are utilized for objectives A and B. A sampling design which concurrently emphasizes objectives A and B could be derived with a composite weight of the form

$$C_j = \omega_1 \frac{A1_j}{A1_{max}} + \omega_2 \frac{B1_j}{B1_{max}} \tag{7}$$

where C_j = composite weight for node j; ω_1, ω_2 = weights varied between 0 and 1 ($\omega_1 + \omega_2 = 1$); and $A1_{max}$, $B1_{max}$ = maximum $A1_j$ and $B1_j$ values for all candidate sampling sites.

For a composite weight scheme, it may be desirable to give more emphasis to objective A than objective B (or vice-versa). The weights ω_1 and ω_2 can be employed for this purpose. Normalizing $A1_j$ and $B1_j$ by their respective maximum values ensures that the terms on the right-hand side of Equation (7) have equivalent, dimensionless units and take on the same range of values (0 to 1).

Given a field of candidate sites and associated weights, the monitoring network design problem can be posed as a mathematical programming model of the form

$$\text{Max } Z = \sum_{j \in J_1} W_j x_j - \sum_{j \in J_2} W_j x_j \tag{8}$$

subject to

$$\sum_{j \in J_2} x_j = P_2 \tag{9}$$

$$\sum_{j \in J} x_j = P \tag{10}$$

$$x_j = (0,1) \quad \text{for each } j \in J \tag{11}$$

where j = index of candidate well site; J = set of candidate well sites; J_1 = set of candidate detection well sites; J_2 = set of candidate background well sites; W_j = weight for node j; x_j = 1 if node j is selected as a monitoring site, 0 otherwise; P = total number of wells sited; and P_2 = number of background wells sited.

The form of the second term ensures that the nodes with the lowest weights in a designated upgradient zone will be selected for measuring background water quality. This condition is consistent with a strategy to locate background wells away from areas susceptible to contamination. All nodes outside the upgradient zone are candidate sites for detection wells. Equation (9) ensures that a specified number of wells are allocated to the upgradient zone of the model domain. Constraint (10) establishes the total number of wells to be located throughout the model domain, and constraint (11) requires that the decision variable x_j be a binary integer.

Integer programming techniques, such as branch-and-bound (Land and Doig, 1960), can be used to solve the formulation given by Equation (8)-(11). Solution algorithms can be found in optimization software packages, such as LINDO (Schrage, 1991) and GAMS (Brooke *et al.*, 1988). Alternatively, the formulation can be solved as two smaller, zonal problems. In the first of these zonal problems, the (P–P_2) candidate detection well sites with the highest weights are selected as monitoring sites. The P_2 sites with the lowest weights in the upgradient zone are then selected as background monitoring sites. The zonal problems can be solved with "sort functions" available in statistical software packages. Given a set of nodes with assigned weight values, these functions arrange the set in order of ascending or descending values, and the specified number of nodes with the highest (problem 1) or lowest (problem 2) values can be extracted from the proper end of the sequence.

The zonal problems can also be solved with histogram modules commonly available in GIS software packages. In this solution technique, the numerical output is reviewed to determine two threshold numbers: the number that (P–P_2) nodes are greater than in value, and the number that P_2 nodes are less than in value. Weight values above and below these threshold values are then reclassified to a common value which can be used to identify the corresponding nodes in text or graphic output. The identification of an optimal monitoring configuration is one component of the overall utility of GIS in a ranking approach to network design. GIS are also highly effective for processing and compiling the spatial data upon which an ultimate monitoring configuration is based. The role of GIS in various stages of implementing a ranking approach to groundwater quality monitoring network design is outlined in the following section.

INTEGRATING GIS AND NETWORK DESIGN

A ranking methodology for monitoring network design was applied to the Butler County Municipal Landfill in southwest Ohio. The landfill overlies a glaciofluvial aquifer along the Great Miami River Valley (Figure 2). Underlying aquifer deposits consist of homogeneous sand and gravel. The geometric mean of hydraulic conductivity values acquired from slug tests reported in a previous study (Hudak and Loaiciga, 1991) is 210 ft/day (64 m/day). An average porosity of 0.32 was determined from laboratory measurements of bulk and particle mass density on split-spoon borehole samples. The unconsolidated deposits range from 20 to 40 ft (6 to 12 m) in thickness and overlie shale bedrock (Watkins and Spieker, 1968). Valley-wall contacts in Figure 2 denote lateral boundaries between the unconfined aquifer and upland surfaces that are underlain by glacial till or shale bedrock (Spieker, 1968). The effluent river is in hydraulic connection with groundwater in the underlying aquifer.

The region between the river and the northern valley-wall contact in Figure 2 was utilized as a model domain for monitoring network design. This region was partitioned into an orthogonal lattice of candidate monitoring sites. A raster (cell) representation of the domain is illustrated in Figure 3. Candidate monitoring sites are defined as the centers of each square cell, excluding landfill and inactive cells.

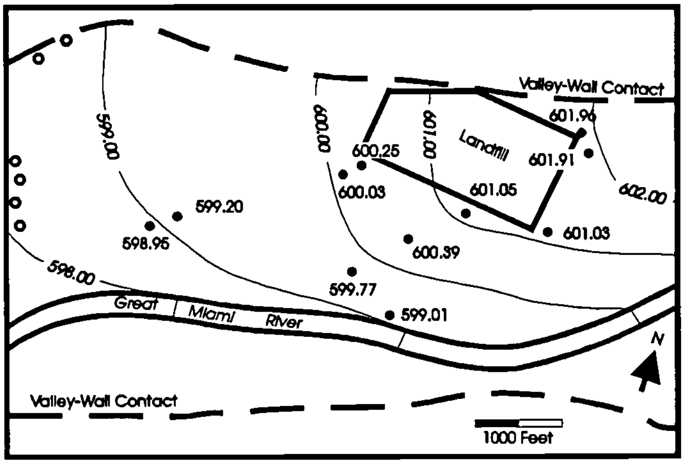

Figure 2. Map of Study Area Showing Landfill and Hydrogeologic Boundaries, Hydraulic Head Measurements (numbers adjacent to dots), Water Table Elevation Contours, and Water Supply Wells (open circles) (head measurements and contours in feet above mean sea level) (1 ft = 0.31 m).

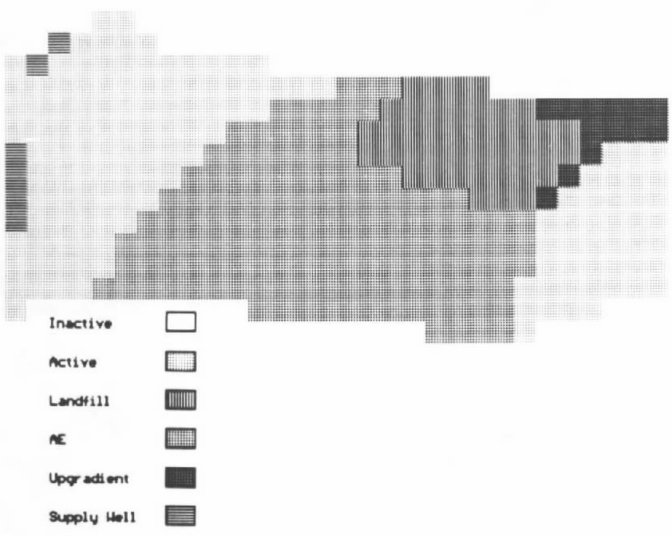

Figure 3. Raster Image of Model Domain Showing Cell Classifications; AE = Advection Envelope; Cell Width = 250 ft (76 m).

IDRISI (Eastman, 1992), a raster-based GIS, was used to process the spatial data for the network design problem. Raster boundaries for the active region of the model domain and the landfill (Figure 3) were established by converting digitized vector boundaries to their grid-cell equivalents. Rasters representing the locations of water supply wells and advection envelope boundaries were generated by an IDRISI module which converts point locations to their raster equivalents. GWPATH (Shafer, 1990), a numerical groundwater particle tracking program, was used to generate the X and Y coordinates of points along forward pathlines originating from the northwest and southeast corners of the landfill. These coordinates were used to define the boundaries of the advection envelope depicted in Figure 3. Points along the boundaries of the upgradient zone were generated by reverse particle tracking from the same corners of the landfill.

Input requirements for the groundwater particle tracking program include the aquifer hydraulic conductivity, effective porosity, and hydraulic head values at each cell in the 15-row by 30-column grid. Head values were generated from the water table elevation contours in Figure 2. The values were obtained from a GIS module that interpolates a raster digital elevation model from digitized contours. Note that the contours in Figure 2 are constructed from only 11 control points. The spatial density of these points is not sufficient to directly interpolate head values throughout the model domain. However, a reasonable interpolation could be made from contour lines that were inferred by using available control and hydrogeologic judgment. For example, the valley-wall contacts are recognized as no-flow boundaries that, in theory, meet hydraulic head contours at right angles.

Monitoring configurations were derived for objectives A through C, described in the preceding section. The GIS was used to calculate the distance variables, $D(s)_j$, $D(e)_j$, and $D(w)_j$, and to compile and display weight values. Values for the distance variables were derived from a GIS module which measures the distance between each cell and the nearest of a set of target features (i.e., landfill, advection envelope, or water supply cells). To avoid division by zero, nodes within advection envelopes and water supply well nodes were assigned $D(e)_j$ and $D(w)_j$ values equal to the respective minimum values calculated for all other nodes. An analytical overlay module was utilized to calculate nodal weight values from the distance data. Weight schemes expressed by Equations (1)-(3) and (4)-(6) were employed to derive alternative monitoring configurations for objectives A and B. For each weight scheme, Equations (8)-(11) were solved for $P = 30$ and $P_2 = 5$.

A grey-scale image (Figure 4A) exhibits spatial variations in values for weight scheme A1 through the model domain. Image display capabilities of a GIS can be used to graphically illustrate the effects of various weight schemes prior to solving the network design problem. The solution derived from weight scheme A1 is illustrated in Figure 4B. This figure was generated by overlaying a grey-scale image file of cell classifications with a vector file containing the X and Y coordinates of sampling sites. Detection well sites are clustered near the contaminant source and within the advection envelope extending downgradient from the source. This configuration has a high potential for detecting a contaminant release. Background monitoring wells are located at the points within the hydraulically upgradient area that are furthest from the contaminant source. These points have a low likelihood of becoming polluted from any landfill-derived contamination. Weight schemes A2 and A3 resulted in the identical monitoring well configuration. In general, the relative suitability of alternative weight schemes can be assessed by evaluating the resulting sampling networks, considering factors such as regulatory requirements and design strategies.

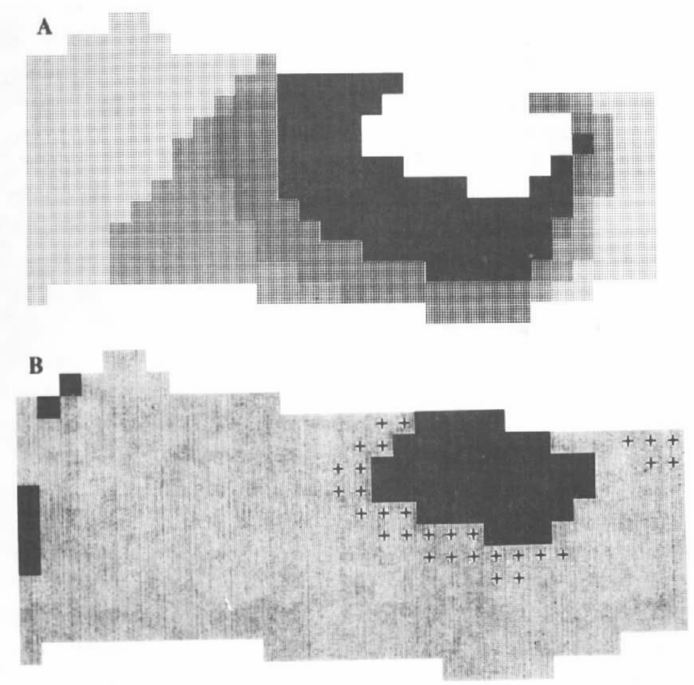

Figure 4. (A) Grey-Scale Image of Weight Values for Scheme A1. Normalized values range from zero (white) to one (black); cell width = 250 ft (76 m). (B) Monitoring Network (crosses) for Weight Scheme A1.

The orthographic projection, commonly available in GIS packages, is also effective for graphically displaying the results of alternative weight schemes. Weight surfaces generated by schemes B1 and B2 are illustrated via orthographic projection in Figure 5. The projections illustrate distinct differences between the alternative schemes. Scheme B1 generates high values at nodes near the landfill and water supply wells. In contrast, the weight values for scheme B2 are relatively uniform. The highest values occupy a narrow band extending from the western boundary of the landfill to the northern water supply well.

Figure 6 illustrates the solutions to Equations (8)-(10) for weight schemes B1 and B2. The configuration in Figure 6A is better suited to the stated monitoring objective. This configuration has capability for early detection of a contaminant release *and* verification of concentration levels near the water supply wells. The monitoring wells are strategically positioned between the contaminant source and the water supply wells. In contrast, the configuration in Figure 6B provides capability for contaminant detection only along a relatively narrow zone within the model domain. In general, scheme B2 will lead to a network distributed along a line connecting the source and the nearest water supply well. At nodes along this line, the sum of $D(s)$ and $D(w)$ is minimal and, therefore, the highest values for B2 in Equation (5) are attained. The configuration in Figure 6B provides inadequate protection for the southern water supply wells and insufficient contaminant release detection capability along the southwest margin of the landfill. This result implies that it is necessary to evaluate alternative weight schemes for a given monitoring program. The solution for weight scheme B3 (Figure 6C) is nearly identical to that for scheme B1.

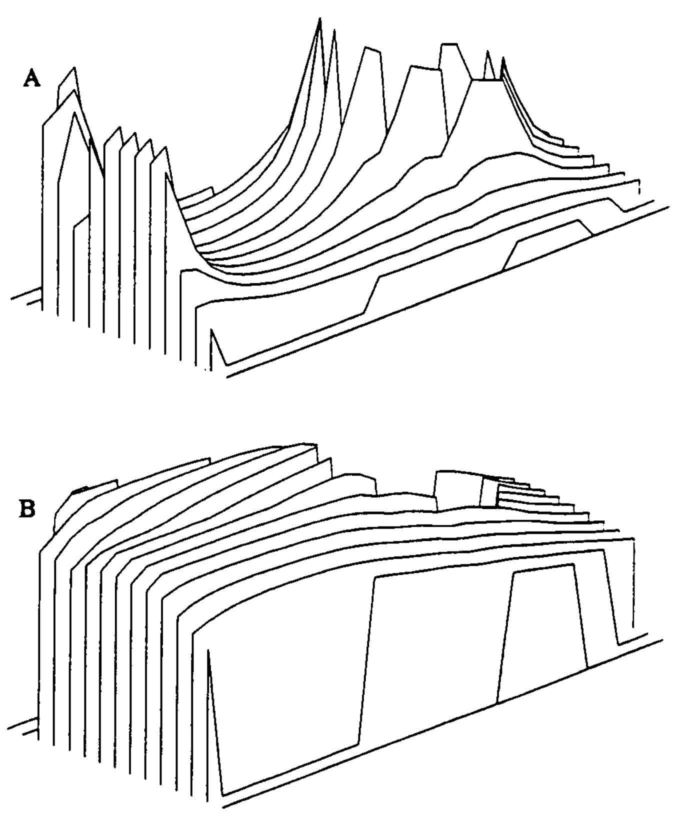

Figure 5A-B. Orthographic Perspectives of Weight Surfaces for Schemes B1 (A) and B2 (B) (view direction - northeast; view angle - 30 degrees above image plane).

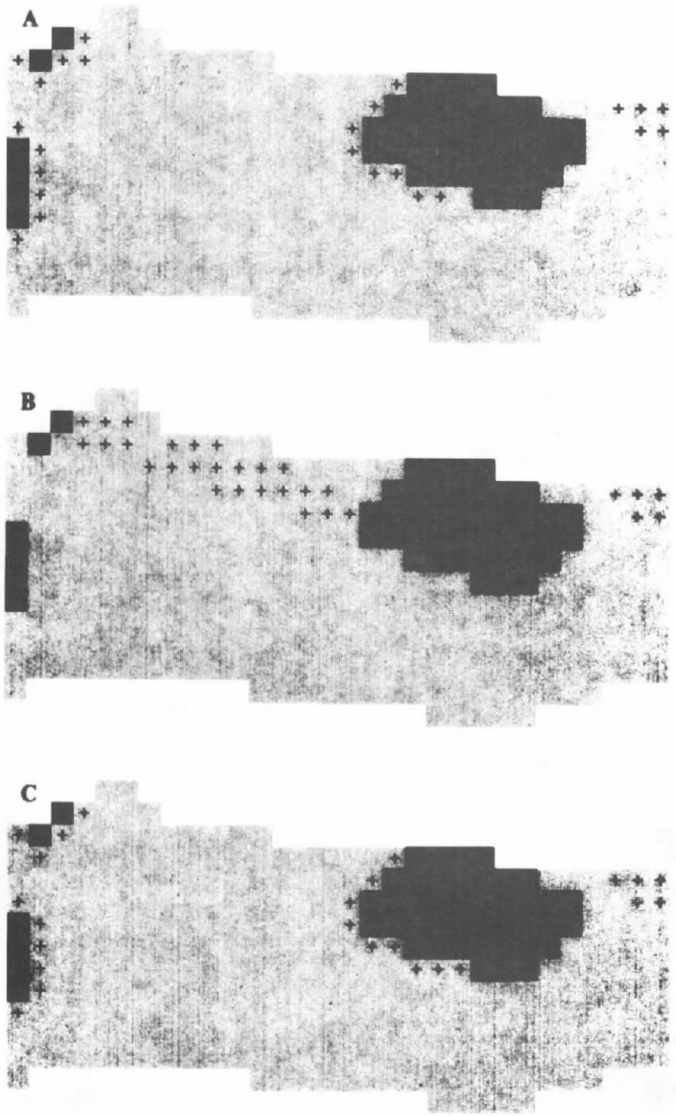

Figure 6A-C. Monitoring Networks for Weight Schemes B1 (A), B2 (B), and B3 (C).

A composite weight, C, was derived from weight schemes A1 and B1, as expressed in Equation (7). This weight was then used to derive a network geared toward both early contaminant release detection and water supply well protection. The weights w_1 and w_2 were each set to a value 0.5 to accommodate an equal partitioning in emphasis between objectives A and B. The resulting configuration (Figure 7) has good release detection capability along the downgradient margin of the landfill. In addition, it has potential for verifying concentration levels in the vicinity of water supply wells.

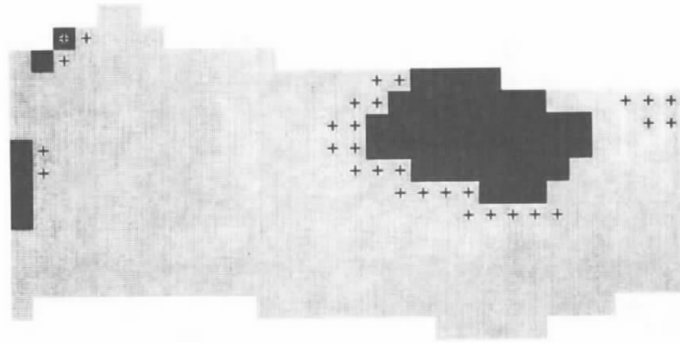

Figure 7. Monitoring Network for Weight Scheme C.

The development leading to the monitoring configurations in Figures 4, 6, and 7 suggests that GIS are ideally suited to implementing ranking approaches for groundwater quality monitoring network design. Inherently, ranking approaches to network design are computationally intensive. Typical applications require that several distance values be computed for each of over 100 candidate monitoring sites. Each distance value represents the distance between a candidate site and the nearest of a set of target features comprising a particular zone of contamination susceptibility. Several distance calculations are required to ascertain the minimum distance between a candidate site and a particular zone. Completely implementing a ranking approach may require several thousand distance calculations. These calculations can be performed rapidly with a GIS on a modern personal computer. GIS are also well-suited to expressing relative monitoring value at candidate sites by performing arithmetic overlays of information layers which store distance information. Each layer defines the nearest distance between each candidate monitoring site and a zone of contamination susceptibility. In practice, effective monitoring networks can be obtained by considering alternative configurations which reflect the objective(s) of a monitoring program. The spatial analytical capabilities of GIS allow ranking approaches to be employed as practical alternatives for generating detection-based groundwater quality monitoring configurations.

SUMMARY AND CONCLUSIONS

Our primary objective was to integrate the capabilities of GIS for analyzing spatially referenced data with a methodology for groundwater quality monitoring network design. The role of GIS in a ranking approach to network design was demonstrated through an application to a municipal landfill. Previous studies have established the utility of GIS for water pollution susceptibility assessment at the regional scale. This study extends the application of GIS to groundwater quality monitoring over locally scaled settings that encompass waste facilities. For the application demonstrated in this study, the proximity of candidate sampling sites to zones of contamination susceptibility is a primary consideration in assessing relative monitoring value.

Ranking approaches for sampling network design are based on an objective analysis in which the suitability of numerous potential monitoring sites is assessed from well-defined distance criteria. GIS enables effective computer management of spatial data pertinent to the network design problem, thereby facilitating the field application of an established methodology. A GIS can be utilized to effectively perform a number of tasks related to groundwater monitoring network design, including storing location data and object attribute information, interpolating hydraulic head values from inferred contour lines, calculating values for key distance variables, compiling and displaying weight values, and identifying optimal monitoring sites. Graphic display capabilities of GIS can be utilized to quickly assess the results of alternative weight schemes for quantifying relative monitoring value. This form of data pre-processing can discern the adequacy of various schemes prior to solving the model.

Key aspects of a GIS-assisted ranking approach to groundwater monitoring network design that may promote its application in practice include relative ease of implementation and solution, inclusion of established regulatory policy, such as background monitoring, and capacity for handling various monitoring objectives. The network design process can be carried out with commercially available raster-based GIS packages and groundwater particle tracking programs. Overall, the results of this study suggest that a ranking approach augmented with GIS is a practical and effective alternative for the problem of detection-based groundwater quality monitoring network design.

ACKNOWLEDGMENTS

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