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SOLID WASTE DISPOSAL SITE CHARACTERIZATION USING NON-INTRUSIVE ELECTROMAGNETIC SURVEY TECHNIQUES AND GEOSTATISTICS

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ABSTRACT: Prior to the research reported in this paper, a site-specific hydrogeologic investigation was developed for a closed solid waste facility in Eastern Nebraska using phased subsurface characterizations. Based on the findings of this prior investigation, a surface based geoelectric survey using electromagnetic induction to measure subsurface conductivity was implemented to delineate the vertical and horizontal extent of buried waste and subsurface contamination. This technique proved to be a key non-intrusive, cost-effective element in the refinement of the second phase of the hydrogeologic investigation.

Three-dimensional ordinary kriging was used to estimate conductivity values at unsampled locations. These estimates were utilized to prepare a contaminant plume map and a cross section depicting interpreted subsurface features. Pertinent subsurface features were identified by associating a unique range of conductivity values to that of solid waste, saturated and unsaturated soils and possible leachate migrating from the identified disposal areas.

KEYWORDS: Geoelectrics, Electromagnetics, Geostatistics, Conductivity, Leachate, Hydrogeology, Vadose

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INTRODUCTION

Past landfill management and operational practices in the United States have created environmental problems and are commonly associated with soil and groundwater contamination. These landfills have either been upgraded to meet current State and Federal legislation or have closed. As a result, the number of operational landfills has decreased from over 20,000 in 1978 to approximately 3,300 in 1994. Because of strict State and Federal legislation passed dealing with closure of these landfills, the severe impact that past operations had on the environment is becoming more apparent.

For example, in 1987 the State of Nebraska required the Nebraska Department of Environmental Quality (NDEQ) to conduct a comprehensive assessment of all community solid waste disposal sites (SWDS). The purpose of this assessment was to ascertain compliance of SWDS to standards established by the Nebraska Environmental Protection Act (NEPA) and the Federal Resource Conservation and Recovery Act Subtitle D (RCRA Subtitle D)(SCS 1991).

In 1991, nearly 210 landfills in Nebraska had ceased operations or were recommended for closure by NDEQ. This recommendation was based on insufficient capacities or significant constraints imposed on owners to maintain compliance with RCRA Subtitle D requirements (SCS 1991). Due to the risk posed to Nebraska's surface and groundwater by the existence of unlicensed landfills, the NDEQ focused on closure activities. Information compiled by NDEQ identified sites located near public or private drinking water sources, that were underlain by a shallow water table surface, or were located in a 100 year flood plane.

The survey revealed that a significant number of SWDS should have further investigation. Based on this study, the NDEQ directed most of its efforts at the currently unregulated sites utilized primarily by rural communities (NDEQ 1990). These sites have not been subject to regulation since 1972 when the Whitney Amendment to the Nebraska Environmental Protection Act specifically exempted all cities within the second class (5,000 population or less) and villages from state solid waste rules and regulations (NDEQ 1990). Although these sites were exempt from state solid waste regulations, NDEQ revoked this amendment in 1991 when RCRA Subtitle D was reauthorized.

As solid waste disposal sites are forced to close over the next few years, hundreds of millions of dollars will be spent in the United States to identify, characterize and remediate sites contaminated with hazardous materials. Traditional site investigation techniques typically include compiling hydrogeologic and contaminant fate and transport information from testhole and groundwater monitoring well data. Commonly, background information is limited until the results of the first round of groundwater samples is available. Only then does it become apparent that the plume may not be completely delineated and additional monitoring wells are required.

To address this problem, non-intrusive field methods and geostatistical analysis tools were utilized to gather preliminary subsurface information pertaining to hydrogeologic features, horizontal and vertical extents of wastes and suspected leachate plumes. This information can be utilized to optimize and minimize testhole or permanent monitoring well locations.

LITERATURE REVIEW

Electromagnetic (EM) surveying techniques, combined with appropriate geostatistical analyses, are rapid and non-intrusive methods of characterizing subsurface environments. The non-intrusive nature of this technique reduces drilling or other intrusive investigative tools. The technique of EM surveying is based on the principle of utilizing varying subsurface conductivity measurements as an indication of differing geologic and or other subsurface constructs.

Surface electrical methods have been used successfully in many types of subsurface investigations. Kelly (1976) showed that the d-c resistivity method can be effective in delineating a plume moving off-site from a landfill. The use of EM data sources for delineation of contaminated groundwater has been described by Greenhouse and Slaine (1986). French et al. (1988) utilized geoelectric surveying to identify anomalous regions to focus subsequent boring and sampling activities. Hagemeister (1993) identified potential waste volumes and suspected contaminant migration present at an unregulated landfill. In each case, differing electrical conductivity was interpreted as an indication of changes in the systems being investigated.

Geostatistics has been utilized in numerous investigations to estimate expected values at unsampled locations. Cooper and Istok (1988) utilized geostatistics to estimate and map contaminant concentrations and estimate errors in a groundwater plume from a set of measured contaminant concentrations. Cressie et al. (1989) prepared kriged estimate and error maps to predict a migration pathway of radionuclide contaminants from a potential high-level nuclear waste repository site. Woldt (1990) mapped the location of a suspected contaminant plume based on observed geoelectric measurements and geostatistics. Hagemeister (1993) utilized geostatistics to map subsurface electrical conductivity in two dimensional cross sections across a site. In each case, kriged estimate and error maps were prepared to assist in the interpretation of the measured data.

DATA COLLECTION

A three dimensional data set, developed by obtaining readings at several sounding depths across a gridded area, was subjected to geostatistical analyses. This data set was utilized in conjunction with available background data to identify pertinent subsurface features and approximate their general locations. The background data included boring logs, groundwater analytical reports and industrial waste disposal permits. These permits allowed the disposal of industrial wastes until the late 1970's. The methods utilized during this study consisted of establishing a sampling grid, completing an electromagnetic survey, and performing a geostatistical analysis. Each procedure was directed towards non-intrusive characterization of the subsurface environment. Existing testhole data was correlated with the predicted locations of pertinent site features for validation purposes.

Site Description

Based upon information obtained from the NDEQ, the study site was operated as a "trench and fill" SWDS from 1975 to 1987. During this time, the owner accepted domestic and industrial waste from nearby rural communities. Information pertaining to the actual quantities received are not available.

The site and the surrounding areas are located near the eastern most edge of the Nebraska Sandhills region. The topography of this region is mostly undulating to rolling. The elevation of the site is approximately 460 to 466 meters above mean sea level (MSL) near the northeast and southwest corners, respectively (NDEQ 1990). The surface geology consists of approximately 38 to 42 meters of fine to medium grain sands interbedded with coarse sand and fine gravel deposits, which is characteristic of this region.

The uppermost monitorable aquifer is located in sand and gravel deposits of the High Plains aquifer system. The water table is approximately 11 and 15 meters below grade level (BGL) in the northeast and southwest corners of the site, respectively, and the saturated thickness of the unconfined aquifer is approximately 27 meters (NDEQ 1990). Based on regional bedrock maps for this area, it appears that the top of the uppermost confining unit is the Niobrara Shale formation that underlies the water table aquifer at an approximate elevation ranging from 422 to 424 meters above MSL near the northeast and southeast corners of the site, respectively.

Under a Multi-Site Cooperative Agreement with Region VII of the Environmental Protection Agency (EPA), the NDEQ performed a Preliminary Assessment (PA) at the site to assess the threat posed by the site to human health and the environment. The NDEQ concluded that leachate from the site resulted in a leachate contaminant plume migrating in an east-northeast direction towards a river 2.5 kilometers away. Because of the low human and livestock population in the area, no evidence was found indicating that the site posed an immediate threat to human health and the environment (NDEQ 1990).

Interviews with the site owner revealed that the standard operating procedures involved excavating a 5 meter deep cell with a backhoe, depositing refuse at the toe of the working face, compacting the refuse and providing 15 centimeters of daily cover material. After each cell was completely filled, 1 to 1.5 meters of silty clay was placed on top of the waste as a final cover. Based on this information, MSL elevations were assigned to the pertinent subsurface features and are presented in Table 1.

Table 1. Approximate Elevation of Pertinent Site Features (meters)

Site Feature	Southwest Corner	Northeast Corner
Surface	466	460
Bottom of Trench	461	455
Water Table	451	449
Top of Bedrock	424	422

Sampling Grid

Sampling point locations were established based on minimizing data collection efforts, maintaining minimum measurement support volumes of each instrument, and spatially defining the study area. The sampling point spacing utilized at the site was approximately 30 meters in the north and east directions and extended nearly 30 meters beyond all four property boundaries. The horizontal extent was selected based on the geology and obtaining an adequate number of sampling points beyond the limits of the suspected landfill cells to establish background subsurface conductivity levels.

Electromagnetic Survey

Electromagnetic techniques measure terrain conductivity to identify geologic and other subsurface formations. In most environmental EM applications, differing conductivity measurements are interpreted as a change in geologic formations or subsurface conditions (McNeill 1980). The EM instrument operates by generating alternating current loops with a transmitter coil (Tx). A time-varying magnetic field arising from the alternating current induces secondary currents sensed by a receiver coil (Rx) along with the primary field. The EM receiver coil intercepts a portion of the magnetic field from each loop generated by the transmitter coil and results in an output voltage which is also linearly proportional to the terrain conductivity. The resulting reading is in milli-Siemans per meter (mS/m)

The reading obtained from the EM instruments is a conductivity measurement averaged over a volume of subsurface media. Because the effective depths of penetration are small in comparison to the overall horizontal and vertical dimensions of the site, these readings were interpreted as being representative of a sampling point at the calculated effective depth.

The effective depth of penetration by the induced current is directly proportional to the intercoil spacing and depends on the orientation of the instrument. By varying the intercoil spacing, conductivity measurements can be collected at varying depths. Also, operating the instrument in the horizontal dipole mode reduces the effective depth of penetration by approximately one half that of the vertical dipole mode. Therefore, the instrument was operated in the horizontal and vertical dipole positions at four different intercoil spacings to obtain readings at eight different depths.

Theoretically, the total instrument response represents a weighted average of subsurface conductivities with a depth of infinity, but it does have practical limits. Interpretation, or modeling, of geophysical data to determine a reasonable unique solution to the nonunique problem was not performed. Although modeling this data provides a more comprehensive interpretation of the data set, the preliminary nature of this research did not warrant the level effort involved with the modeling process. Instead, Hagemeister (1993) calculated effective exploration depths of four intercoil spacings for both the vertical and horizontal dipole modes. These calculations are based on the assumption that 60 percent of the total signal contribution over a volume of subsurface media is associated with a discernible layer. Based on the small diameter and thickness of the support volume, in relation to the overall area of the site and the preliminary nature of the investigation, each instrument reading was assigned to a point located at the centroid of the calculated effective depth of penetration. Table 2 depicts the exploration depths at various intercoil spacings.

Table 2. Exploration Depths

Intercoil Spacing	Exploration Depth (meter)	
	Horizontal Mode	Vertical Mode
3.7 meters	1.0	2.5
10.0 meters	3.5	6.5
20.0 meters	8.0	13.0
40.0 meters	15.5	26.0

GEOSTATISTICAL ANALYSIS

Environmental professionals are often confronted with the problem of providing detailed information about a site based on a minimum number of sampling points. Geostatistics provides a means of utilizing spatial continuity for estimating the expected value at unsampled locations. Geostatistics is commonly utilized to describe the spatial continuity of earth science data and aims at understanding and modeling the spatial variability of the data.

The geostatistical analytical process for this study consisted of 1) describing and understanding the statistical distribution of the data, 2) modeling the spatial variability of the data, 3) estimating expected values at unsampled locations and 4) computing estimation variance values at the unsampled locations.

Univariate Description

Univariate description deals with organizing, presenting and summarizing data and provides an effective means of describing the data by identifying outliers and extreme values. The univariate descriptive tools utilized to analyze the conductivity data set were:

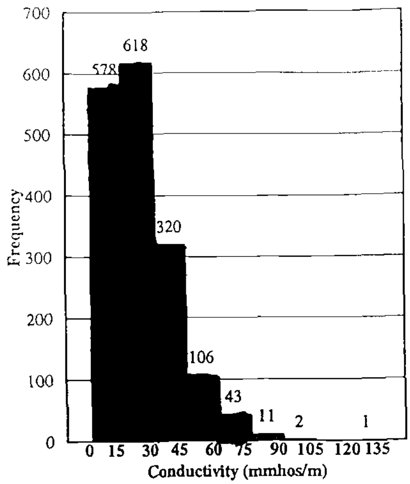

Figure 1. Histogram

1) histograms, 2) probability plots and 3) summary statistics. Because the data set is three dimensional, a descriptive scatter plot could not effectively be obtained.

Geo-EAS 1.2.1 Geostatistical Environmental Assessment Software (Englund and Sparks 1988) was utilized to prepare histograms and probability plots for both the observed data set and logarithmic transformations of the observed data set. Characteristic of many environmental data sets, the observed data exhibited a large number of low values which offset the mean of the data distribution to the left of the median. The data were transformed to prepare lognormal histograms and probability plots to determine if the data exhibits a lognormal distribution.. The tests for lognormality indicated that the data does not approach this distribution. Therefore, the observed data set was utilized for the analysis. Figure 1 presents a histogram plot for the observed conductivity data set.

The summary statistics presented in Table 3 numerically describe the location, spread and shape of the observed data distribution.

Table 3. Observed Value Summary Statistics

Number	1679	**Minimum**	0.5
Mean	23.8	**25th Percentile**	10.2
Variance	263.6	**Median**	22.7
Standard Deviation	16.2	**75th Percentile**	31.9
Skewness	1.1	**Maximum**	125.0

Experimental Variogram

A variogram is a plot of the variance, or one-half the mean squared difference, of paired data points as a function of the distance between the two points (Deutsch and Journel 1992). An omnidirectional variogram can be developed to obtain a general understanding of the spatial characteristics of the sample data. The omnidirectional variogram does not take into account spatial continuity changes due to directional changes in the data. Therefore, directional variograms are developed to identify these changes, if present. To ensure a more realistic sample variogram, the window for the lag distance did not extend greater than one-half the length or width of the data set. The lag distance between points was also restricted such that a minimum of 30 pairs per lag distance were available to increase the confidence of variogram calculations.

GSLIB - Geostatistical Software Library and User's Guide (Deutsch and Journel 1992) was utilized to develop directional and omnidirectional experimental variograms from the three dimensional conductivity data set. Generally, two sets of directional variograms were developed by restricting the paired data points to be either horizontally coplanar or vertically cocolumnar.

Attempts to identify directions of maximum and minimum continuity within a horizontal plane revealed the same structure as the omnidirectional variogram in the all directions. Therefore, isotropic conditions were considered for the horizontal plane. Paired data

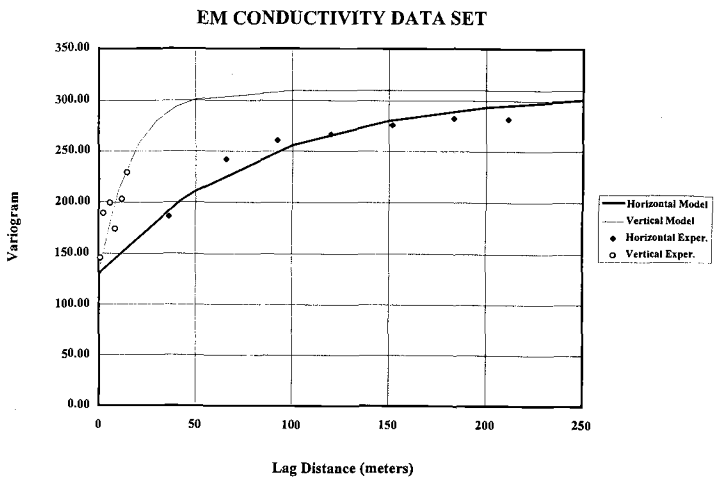

Figure 5. Schematic of Interpreted Subsurface Environment

points within a 250 meter horizontal search region generally followed the pattern of the omnidirectional variogram. This indicates that the kriging estimation process was not significantly influenced by the orientation of the principal axis of the search neighborhood and data orientation within this horizontal search region. The experimental variograms for the horizontal plane and the vertical direction are presented in Figure 2.

Model Variogram

Once an acceptable experimental variogram was developed, the model variogram was constructed. Variogram modeling entailed fitting a mathematical function, using visual techniques, to the experimental variogram points by varying the model type and the nugget effect, sill and range values until the model variogram closely resembled the experimental variogram.

The exponential variogram model was fit to both the horizontal omnidirectional and the vertical variograms (Figure 2) utilizing the parameters presented in Table 4. Although the nugget and sill are identical, the range significantly decreases in the vertical direction. This is characteristic of geometric anisotropy and is commonly encountered in earth science.

Table 4. Variogram Model Parameters

Parameter	Horizontal Model	Vertical Model
Model Structure	Exponential	Exponential
Range	250	50
Sill	180	180
Nugget Effect	130	130

Cross Validation

Model variograms were cross validated to compare the sample point values to the estimated values at those locations. It is important to develop a variogram model that would minimize the standard deviation of the estimation error as determined by the cross validation process. A variogram model that produces good results does not necessarily indicate that the estimation at unknown locations will be accurate. However, good results from cross validation will suggest, with more confidence, the effectiveness of the selected model.

Cross validation consists of removing a data point from the data set and calculating an estimated value utilizing the model variogram. Once the estimate ~~are~~ is calculated, a comparison can be made between the estimated and observed values at each sampling point by calculating the difference between the two values.

The three summary statistics utilized to evaluate the cross validation results are : 1) average kriging error (AKE), 2) mean squared error (MSE) and 3) standardized mean squared error (SMSE) (Woldt 1990). The AKE provides a measure of the degree of bias introduced by the kriging process and should equal 0 if the data is unbiased. The MSE should be less than the variance of the measured values. The SMSE is a measure of the consistency and is satisfied if the SMSE is within the interval $1.0\pm[2(2/n)^{1/2}]$. The results are summarized in Table 5 along with their calculated expected values.

Table 5. Cross Validation Summary Statistics

	AKE	MSE	SMSE
Expected Value	0.0	<263.6	0.931 to 1.069
Cross validation Results	-0.03	131.0	0.89

As depicted in Table 5, the criteria meet the recommended AKE and MSE values and is just outside the range of expected SMSE values. These results are generally considered acceptable.

Ordinary kriging

Ordinary point kriging was selected to estimate expected values at unsampled locations. This method was selected because it is a linear unbiased estimator that attempts to minimize the error variance and generally has the lowest mean absolute error and mean squared error in comparison to other estimation methods (i.e. polygonal, triangulation, local sample mean, and inverse distance squared). GSLIB (Deutsch and Journel 1992) was utilized to calculate the expected values at 8,000 unsampled locations, or nodes, on a 20 x 20 x 20 grid from the three dimensional conductivity data set. The nodes were spaced at 25 meters in the north and east horizontal directions and 2 meters in the vertical direction. These spacings were selected based on the anticipated spatial orientation and depths of the pertinent subsurface features.

Search Neighborhood

The search neighborhood was established based on the following criteria: 1) selecting the greatest distance on the variogram model that closely fit the experimental variogram, 2) at least 30 pairs were utilized to calculate the experimental variogram at each point and 3) the distance did not exceed half the length of the horizontal sampling grid diagonal.

The search neighborhood was defined in the horizontal plane at 250 meters. The geometric anisotropy limited the search to within 25 meters in the vertical direction which reflects the region of the variogram with the higher level of confidence.

Background Conductivities

Generally, the expected values located west and south of the site and outside the property boundaries were considered to represent background subsurface conductivities, or expected values assumed not to be impacted by past site activities. This was established based on the groundwater flow direction. These background values generally ranged from less than 0 mS/m to 12 mS/m in the vadose zone and from 12 mS/m to 24 mS/m below the water table. These ranges of values established the basis of interpretation for identifying hydrogeologic features, landfill cells and potential leachate migrating from the cells.

DISCUSSION

The previous sections discussed a methodology that can be utilized to interpret surface based electrical data in an effort to construct reliable maps of suspected subsurface features. Based on the selected cross sections of expected conductivity values presented in Figures 3 and 4 and limited knowledge of the site, interpretations of: 1) site specific hydrogeology, 2) horizontal and vertical extents of waste and 3) potential sources for leachate migration were developed

Hydrogeology

Station 000 North (Figure 3) depicts a vertical cross section of the background expected subsurface conductivity values for background reference. This station is located upgradient of the site and was utilized as an indication of subsurface conditions not impacted by past landfill operations. information obtained from NDEQ records, the natural subsurface environment adjacent to the boreholes consists of fine to medium sand with a static water table elevation near 450 meters. Therefore, 0 to 12 and 12 to 24 mS/m were determined to represent unsaturated and saturated fine to medium sands, respectively. A variance from these ranges was interpreted as an indication of differing subsurface structures, or impact from the landfill operation.

Landfill Cell Identification

Based on the nature of the site operations, landfill cells are expected to be located from the ground surface down to an approximate depth of 5 meters. The selected vertical cross sections (Figure 3) depicted expect conductivity values near the surface ranging in excess of 24 mS/m within the 0 to 5 meter BGL depth range.

Generally, the landfill cells appear to cover the entire site. Based on the vertical cross section maps (Figure 3), two areas exhibiting conductivity values in excess of 24 mS/m were elongated in the north and south directions with the centerlines located near stations 150 East and 300 East. Based on a personal interview with the owner, it appears that these two areas are actually several landfill cells spaced close together.

Potential Leachate Migration

The primary concern with SWDS is the potential leachate contamination associated with the nature of the operation. Leachate is a liquid that consists of refuse moisture and all precipitation that mixes with this moisture as it migrates through the landfill. Leachate migrating from a landfill naturally due to gravity or forced out as a result of the consolidation of refuse may transport contaminants from the refuse to the groundwater environment.

The presence of elevated conductivity values within the vadose and directly below the landfill cells was interpreted as potential leachate or possible instrument interference from the overlying waste. These conductivity values ranged from 12 mS/m to 24 mS/m (Figure 3).

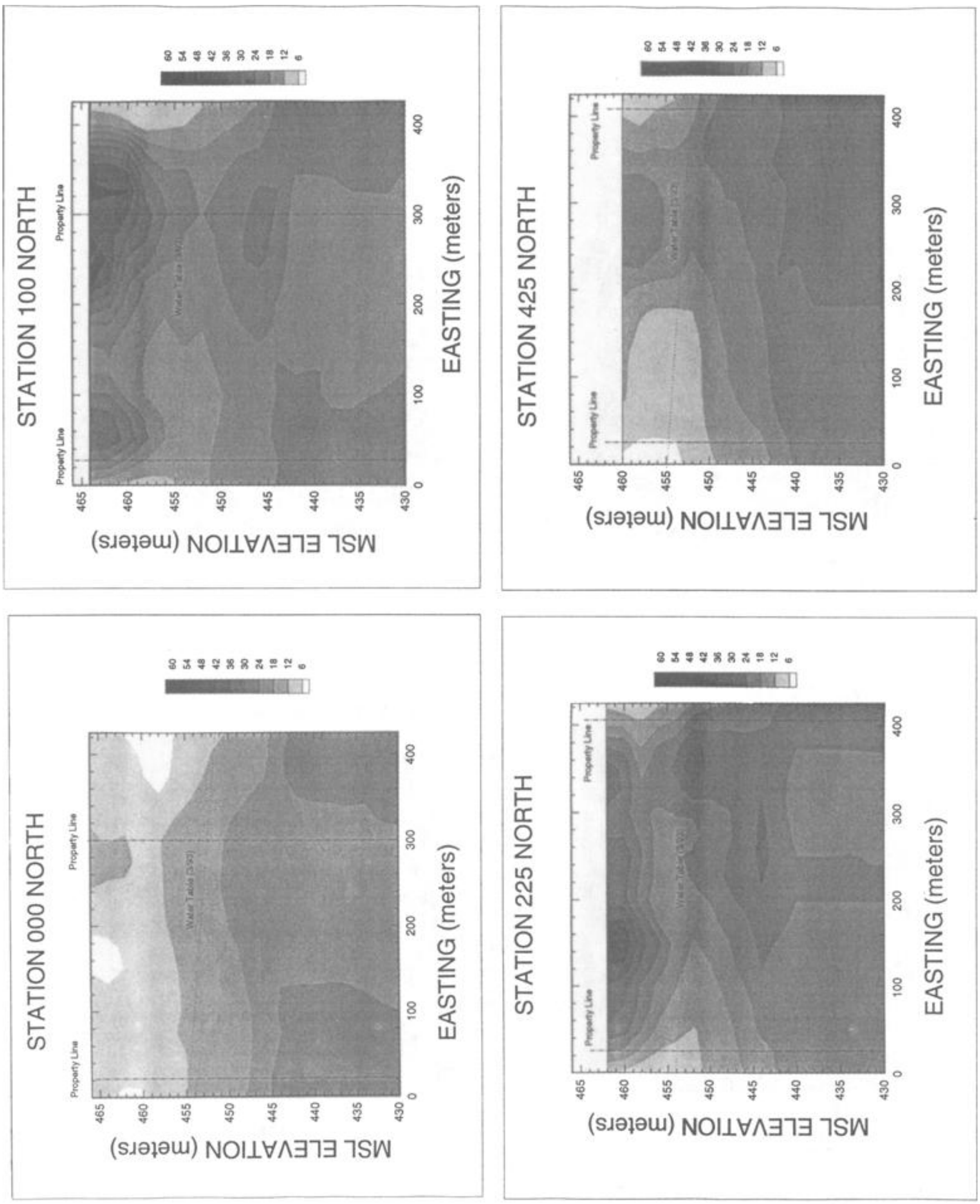

Figure 3. Vertical Cross Section of Expected Data Map

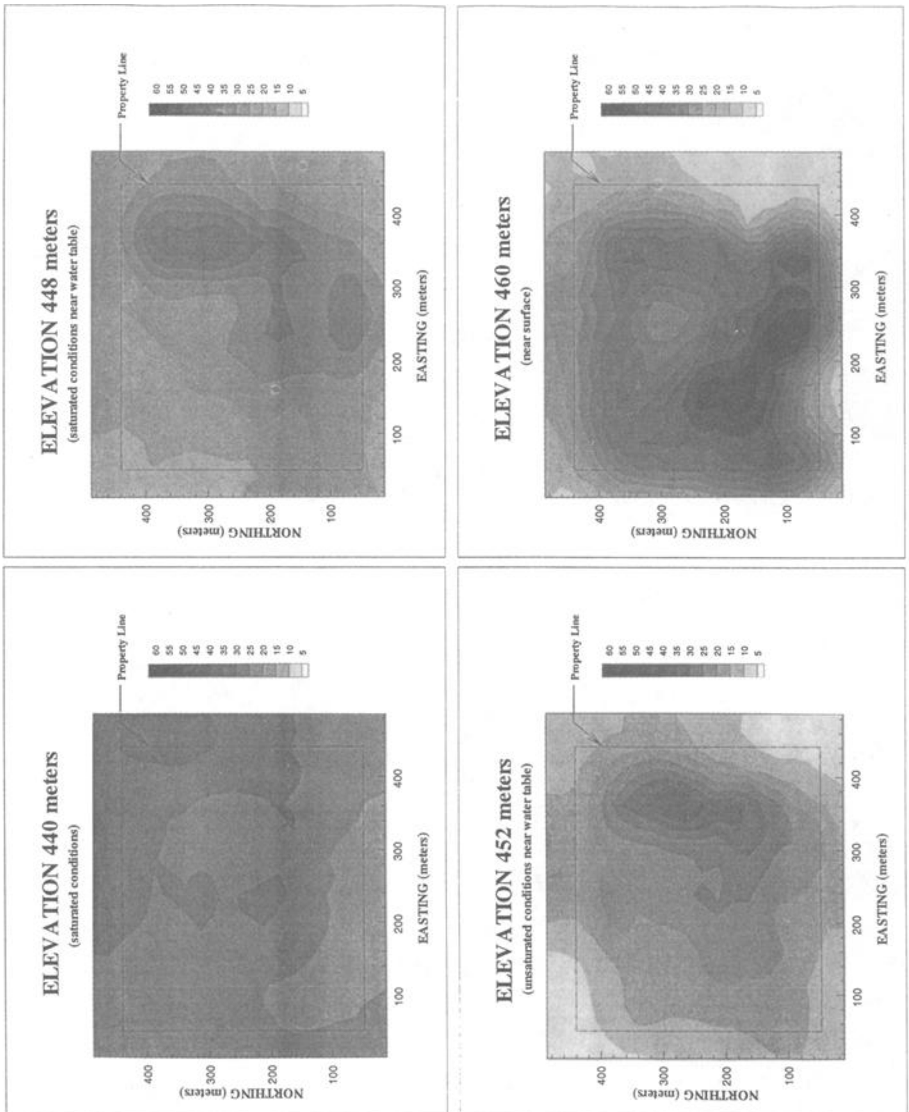

Figure 4. Horizontal Cross Section of Kriged Data Map

Interpreted Subsurface Environment

Based on the information obtained from this study, it appears that leachate may have migrated from the landfill and impacted the groundwater table. The plume appears to be migrating horizontally in the northeast direction with a vertical component. Figure 5 consists of a plan view and cross section illustrating an interpreted leachate plume located relative to the identified waste.

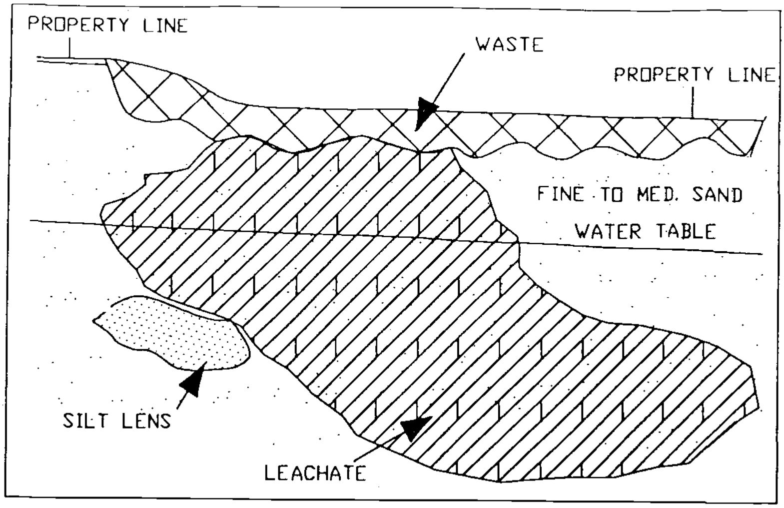

Figure 5. Schematic of Interpreted Subsurface Environment

Computer Software Support

All data description and estimation efforts requiring computer software support was completed utilizing an IBM 80386 processor. Software support utilized in this study consisted of Geo-EAS, GSLIB and TecPlot Version 6.0 (TecPlot).

Probability and histogram plots describing the 1679 observed conductivity values were prepared utilizing Geo-EAS. Geo-EAS generated on-screen plots within minutes allowing efforts to be focused on the descriptive analyses.

The expected values are presented on cross section contour maps included as Figures 3 and 4. The three dimensional expected value data set was imported into TecPlot. TecPlot utilizes linear interpolation to construct each contour line. Tecplot generated cross section maps based on a three dimensional data set. By fixing one dimension, a cross section at a desired location was generated within minutes.

CONCLUSIONS

Geostatistical analysis demonstrated that the data is spatial correlated which allowed for an interpreted subsurface model to be developed based on kriged estimated values. As an alternative to traditional intrusive characterization techniques, surface based electromagnetic surveying techniques proved to be a key non-intrusive, cost-effective element in the refinement of the second phase of the hydrogeologic investigation. Review of kriging error maps can further refine this second phase by focusing on the areas with the largest error. This study demonstrated that this methodology, as a preliminary field screening tool, can provide sufficient information to optimize the placement and minimize the number of permanent groundwater monitoring wells.

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