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Purpose:
To evaluate the potential of using ground-penetrating radar (GPR) and electromagnetic induction techniques (EM) to map internal features and the thickness of the fill cap within a sanitary landfill site on Staten Island. In addition, this study attempted to demonstrate the value of integrating contemporary geophysical and computer technologies with traditional soil survey techniques to increase the number of observations, confidence levels, spatial accuracy, and cost effectiveness of soil mapping and site characterization.

Participants:
Jim Doolittle, Research Soil Scientist, NRCS, Radnor, PA
Luis Hernandez, Soil Survey Project Leader, NRCS, Staten Island, NY

Activities:
All field activities were completed during the period of 4 to 8 December 1995.

Introduction:
Increasing demands are being placed on limited land resources. In urban areas, some inactive, sanitary landfill sites are being reclaimed for other uses, most notably recreational but also commercial (JFK Airport was located on a former landfill site). The seepage of contaminants into water supplies and the emission of methane and carbon dioxide (contributors to global warming and air pollution) into the atmosphere from landfill sites have created environmental concerns.

In 1976, recognizing the environmental risks from leachates and gases escaping from landfills, the Federal Government enacted the Resource Conservation and Recovery Act (RCRA). The RCRA has become the principal law regulating the disposal of solid wastes. Subtitle D of RCRA requires landfills to be protected with a final cover of soil or a combination of soil and synthetic materials. It recommends that the thickness of this layer be at least 4 feet thick (Murphy, 1993). To be considered suitable for recreational uses, the National Soils Handbook recommends that sanitary landfills should be covered by at least 2 feet of imported soil materials. The permeability of this material should be less than 2.0 in/hr. Where the fill cap is less than two feet thick or the materials are more permeable, the risks of leachates contaminating surface and ground waters are increased and reclamation is considered impractical.

Responding to environmental concerns, public interests, and demands for improved information, soil scientists have increased research and characterization activities in areas of man-made and manmodified soils. The task of characterizing and mapping landfills and fill cap materials is not easy. Soil mapping on most landfills is unpleasant and may be unsafe. At many sites, the odors can be overwhelming. Surfaces can be irregular, densely vegetated, and littered with debris. Soil borings are intrusive and disturbances can cause further environmental damage or create potential health and safety hazards to soil scientists. Underground seepage of pollutants can contaminate the ground water. Some sanitary landfills contain toxic, carcinogenic, or corrosive chemicals that pose additional health and environmental concerns.

The mapping of landfills is not only demanding, but may challenge some established field methods and accepted models. In most areas, because of unpredictable types and arrangements of materials, anthropogentic soils and debris are highly variable. These materials may be difficult to map or inappropriately characterize if strict adherence to traditional sampling protocol and characterization methods are followed. Perhaps different properties should be mapped at different scales. Alternative procedures to collect and display data should be explored.

Consultants, environmental engineers, hydrologists, and geologists have used surface geophysical techniques in waste cleanup and monitoring projects (Greenhouse et al., 1989). Surface geophysical methods include electrical resistivity, electromagnetic induction, gravity, ground-penetrating radar, magnetic, and seismic. These techniques have been used to locate, characterize, and monitor waste sites; map stratigraphic contacts; detect anomalous subsurface conditions or features; and verify the presence and quality of groundwater. Two of these techniques, electromagnetic induction and ground-penetrating radar, were used in this study.

Electromagnetic induction techniques have been used in waste cleanup and monitoring projects to map spatial variations in apparent conductivity (Roberts et al., 1989), detect potential contaminant plumes (Mack and Maus, 1986), facilitate monitoring-well placement (Nyquist and Emery, 1993), and locate the boundaries of buried waste sites (Siegrist and Hargett, 1989). These techniques have also been used to determine the thickness of fill, identify changes in fill materials, and locate accumulations of metallic bodies (Jansen et al., 1992).

Ground-penetrating radar techniques have been used in waste-site characterization and monitoring projects to distinguish internal features within landfills (Bowders and Koerner, 1982), detect potential contaminant plumes and facilitate monitoring-well placement (Koerner et al., 1981), and locate the boundaries of landfill sites (Lawton et al. 1994). Compared with electromagnetic induction, ground-penetrating radar provides higher resolution of subsurface feature, but is more depth restricted especially in areas of finer-textured soil materials. In some areas, because of conductive and highly attenuating soil materials, GPR is an inappropriate tool for waste-site characterization and monitoring projects.

Equipment:

The radar unit used in this study was the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.* This unit is backpack portable and requires two people to operate. The use and operation of GPR have been discussed by Morey (1974), Doolittle (1987), and Daniels and others (1988). The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. The model 3102 (500 mHz) antenna was used in this investigation. The system was powered by a 12-VDC battery.

The electromagnetic induction meters used in this study were the EM38 and EM31, manufactured by Geonics Limited*. These meters are portable and require only one person to operate. Principles of

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operation have been described by McNeill (1980, 1986). No ground contact is required with these meters. Each meter provides limited vertical resolution and depth information. For each meter, lateral resolution is approximately equal to the intercoil spacing. The observation depth of an EM meter is dependent upon intercoil spacing, transmission frequency, and coil orientation relative to the ground surface.

The EM38 meter has a fixed intercoil spacing of about 40 inches. It operates at a frequency of 13.2 kHz. The EM38 meter has effective observation depths of about 30 and 60 inches in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter has a fixed intercoil spacing of about 12 feet. It operates at a frequency of 9.8 kHz. The EM31 meter has effective observation depths of about 10 and 20 feet in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

A Rockwell PLGR *, global positioning system (GPS) receiver was used to obtain field coordinates.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,* was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation.

In each of the enclosed plots of the study area, to help emphasize spatial patterns, colors and filled contour lines have been used. Other than showing trends and patterns in values of apparent conductivity (i.e. zones of higher or lower electrical conductivity) or estimated soil depths, no significance should be attached to the colors themselves.

Study Area:

The Brookfield Landfill is located in the town of Richmond, on Staten Island, New York. Figure 1 shows the approximate location of the landfill site in relation to the five counties that comprise New York City. Richmond County includes Staten Island. The entire facility occupied about 172 acres. However, only 150 acres received refuse, the other portions of the site served as a buffer zone between the landfill and residential areas located principally to the south and east.

In 1966, the New York City, Department of Sanitation began operations at the Brookfield Landfill. Until its closure in 1980, the landfill was operated as a municipal solid waste disposal facility. This waste-disposal facility served an estimated 450,000 residents of Staten Island and accepted about 1000 tons of household refuse and construction debris per day. However, illegal dumping of oils, sludges, metal plating wastes, lacquers and solvents was known or suspected to have occurred at several of New York City's landfills, including the Brookfield Landfill. Residents reported that illegal dumping had occurred beyond the boundaries of the landfill. Potential chemical contaminants within the site include alkyl phenol, cyanide, dichlorobenzene, dioctylphthalate, ethylbenzene, naphthalene, toluene, and xylene.

Prior to its closure, the landfill was covered with a cap of "clean fill" consisting of medium-textured soil materials. The original thickness of this material is not known. These compacted surface layers were relatively free of refuse and assumed to have moderately slow permeability. Presently, most of the survey area is covered by a dense growth of phragmites (Phragmities australias), and a few trees. In most areas, trash and debris can be readily observed on the soil surface. The long-range plan for this landfill site includes the development of a recreational park.

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The study area was located in the extreme northern portion of the Brookfield Landfill. The study area was bounded on the south by Richmond Creek, on the west by Richmond Avenue, and on the north by Forest Hill Road. The study area included a constructed ball field and a pad for model airplanes.

Field Procedures:
Prior to field work, historical data, aerial photographs, and topographic maps were reviewed by Luis Hernandez. The description and characterization of anthropogentic soils often requires historical knowledge as to the type and extent of alteration. General information was available concerning the probable location and character of buried waste from historical records and personnel interviews. The location and boundaries of many buried waste sites can often be inferred by using time-lapsed, aerial photographs. However records concerning the internal features of a landfill site, such as the location, type, and thickness of fill materials, are generally brief or nonexistent. This information is often blurred by rumors and speculation of illegal dumping (Siegrist and Hargett, 1989)

A preliminary field review confirmed site disturbance and the location of the landfill. An irregularly-shaped grid was established across the northern portion (30 acres) of the landfill site. The grid was constructed by extending eleven, parallel, profile lines eastwards from the north-south segment of a former access road (located in the western portion of the survey area) and its extension. These profile lines ranged in length from 300 to 1740 feet, and were spaced about 150 feet apart. An all-terrain vehicle was used to trample the phragmites along each line. Observation flags (115) were inserted along each line at an interval of about 100 feet. Table 1 list the coordinates of several grid points which can be used to help define the location of the survey area.

TABLE 1

Location of Selected Grid Coordinates
(obtained with Rockwell GPS)

X Axis	Y Axis	Latitude	Longitude
0	0	40°34'18.36"	74°10'04.36"
0	700	40°34'18.82"	74°09'55.39"
300	1700	40°34'17.33"	74°09'42.46"
1500	0	40°34'04.24"	74°10'04.94"
1500	300	40°34'04.06"	74°10'01.12"

The radar survey was completed by pulling the 500 mHz antenna along the eleven, parallel, east-west trending, profile lines. This procedure provided about 10450 feet of continuous radar imagery. However, interpretations were restricted to the 115 observation points. At each of the 115 observation points, measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

Discussion:
GPR Survey:
Calibration:
The suitability of GPR was assessed during field trials conducted in a portion of the study area. The purpose of these trials was to evaluate the depth of observation and resolution of the 500 and 300 mHz antennas. In addition, these trials helped to determine the dielectric constant and velocity of propagation of electromagnetic energy through the medium-textured fill cap, establish a crude depth scale for the radar profiles, and optimize control and recording settings.

A short profile line was established within the survey area. The profile line consisted of four, equally spaced (about 5 feet), observation points. Each antenna was pulled along this profile line. Recorded radar profiles were reviewed for quality of information. The thickness of the fill cap as interpreted from the radar profiles was compared with the thickness of fill cap as measured at four observation points. At these observation points, the observed thickness of the fill cap and the interpreted pulse travel time to the fill cap/garbage-layer interface ranged from 21 to 37 inches, and from 16 to 20.5 nanoseconds (two-way travel time to interface), respectively. The coefficient of determination (r^2) between the measured depth and interpreted depth (depth = speed * time) to this interface was 0.9981. Based on the averaged round-trip travel time to this interface, the velocity of propagation through the medium-textured fill cap materials was estimated to be 0.26 ft/ns. The dielectric constant was estimated to be 14.8.

When assessing the appropriateness of using GPR, a major consideration is signal attenuation at the desired antenna operating frequency (Daniels et al., 1988). The maximum depth of observation decreases with increasing antenna frequency. High frequency antennas (>500 mHz) can provide well resolved images of shallow features in soils having low conductivity. However, excessive levels of signal attenuation often preclude the use of high frequency antennas in soil having moderate electrical conductivities (Daniels et al., 1988). In these soils, lower frequency (80, 100, 120, and 300 mHz) antennas can be used to improve the depth of observation. Lower frequency antennas provide poorer resolution of subsurface features than higher frequency antennas. At the Brookfield Landfill site, for assessing the thickness of the fill cap, the 500 mHz antenna provided the best balance of observation depth and resolution.

Radar Interpretations:
With the 500 mHz antenna, the depth of observation was restricted to fill cap/garbage layer interface. As this represented the desired target and observation depth, little or no subsurface information was required or obtained below this interface.

Figure 2 is a processed radar profile from the study area (profile line 1500). This profile has been processed through the RADAN software package. Processing was limited to signal stacking, customizing color transforms and tables, and annotations. In Figure 2, the horizontal and vertical scales measure distances along the profile line and depths, respectively. These scales are in feet. Along this traverse, at an interval of about 100 feet, the radar operator impressed a segmented line, or distance mark, on the radar profile. The segmented, vertical lines indicate the locations of observation points. At each observation point, the thickness of the fill cap was interpreted from the radar imagery.

In Figure 2, the soil surface is represented by a series of dark, closely-spaced, horizontal lines which extend across the upper part of the profile. Immediately below the surface reflection is the fill cap. The fill cap consists of materials that appears relatively free of reflectors. The thickness of the fill cap was interpreted to corresponds to the depth to the first subsurface reflector.

The only other interface apparent in this profile is the fill cap/garbage-layer interface. The fill cap/garbage-layer interface appears variable in depth, expression, and thickness. At the four observation points, this interface ranges in depth from about 12.7 to 17.1 inches. The interface appears to consists of numerous, irregularly spaced, discrete, point reflectors. These point reflectors form a band which is as much as two feet wide. As many of these reflectors produce reverberated signals, they are believed to represent metallic objects.

The appearance of the fill cap/garbage-layer interface suggests that these materials are separated by either a fairly wide, transitional layer with gradual boundaries, a highly irregular interface with abrupt boundaries, or both. It is assumed that, along this interface, fill cap and refuse materials intermingle. Signal attenuation has obscured most images and limited signal penetration below the fill cap/garbage-layer interface.

Within the study area, based on interpretations of the radar profiles taken at the 115 observation points, the average thickness of the fill cap was 17.4 inches with a range of 0.0 to 60.6 inches. One-half of the observations had fill caps between 10.0 and 23.4 inches thick. This data suggest that the Brookfield Landfill may have been covered by a relatively thin fill cap. If the landfill was covered by an original fill cap greater than 24 inches thick, a substantial amount of settling (greater than 28 percent) has occurred as a result of waste decomposition.

Within the study area, the thickness of the fill cap was estimated to be very shallow (0 to 10 inches) at 24 percent, shallow (0 to 20 inches) at 59 percent, moderately-deep (20 to 40 inches) at 36 percent, deep (40 to 60 inches) at 4 percent; and very deep (> 60 inches) at 1 percent of the observation points. At 7 percent of the observation points, the garbage layer was at the surface.

Several series have been proposed for the anthropogentic soils formed on landfills. Series criteria are based on drainage, types of materials, and depth to garbage. In areas where the cap is less than two feet thick, reclamation is considered improbable. The Greatkills (loamy-skeletal, mixed, nonacid, mesic Typic Udorthents) and the Freshkills (coarse-loamy, mixed, nonacid, mesic Typic Udorthents) have fill caps ranging from 7 to 24 inches and from 24 to 39 inches, respectively. Taxonomically, the survey area was 63 percent Greatkills soils and 16 percent Freshkills soils. About 16 percent of the observation points had fill caps which were too thin (less than 7 inches) to be classified. About 5 percent of the observation points represented areas of included soils with fill caps greater than 40 inches thick.

Figure 3 is a two-dimensional plot simulating the thickness of the fill cap (or the depth to the refuse layer) within the survey area. This simulation is based upon radar interpretations made at 115 observation points. In Figure 3, the thickness of the fill cap appears variable across the survey area. Though variable in thickness, alternating lines of thicker or thinner fill-cap cover extend in a southwest to northeast direction across the survey area. These linear patterns are broken and partially masked by several southeast to northwest trending line segments. These patterns suggest that, if the thickness of the original fill cap materials was uniform, settling has progressed at different rates in different parts of the study area. The rates of settling could vary because of differences in the types of buried wastes and the rates of waste decomposition.

In Figure 3, the fill cap cover is noticeably thicker in two places (labeled "A" and "B") along the northern boundary of the survey area. These areas correspond to the general locations of a constructed ball field (A) and an elevated pad for model airplanes (B). For these recreational uses, additional layers of fill had been deposited on the surface.

EM Survey:

Background:

The EM survey was designed to help characterize the landfill, identify areas with anomalous electrical conductivity, and suggest dissimilar accumulations of buried materials. Variations in values of apparent conductivity were assumed to principally reflect the presence of buried metallic objects and possibly differences in the underlying materials (i.e. buried household garbage, construction debris, metallic objects, buried sludge or chemicals, and other waste materials).

Electromagnetic inductive methods measure vertical and lateral variations in the apparent electrical conductivity of earthen materials. The actual values of apparent conductivity measured are seldom diagnostic, but lateral and vertical variations in these measurements can be used to infer changes in soils and earthen materials. Interpretations of the EM data are based on the identification of spatial patterns within data sets.

Electromagnetic induction techniques are not suitable for use in all investigations. Generally, the use of EM techniques has been most successful in areas of undisturbed soils where subsurface properties are reasonably homogeneous, the effects of one property (e.g. clay, water, or salt content) dominates over the other properties, and variations in EM response can be related to changes in the dominant property (Cook et al., 1989). None of these conditions can be satisfied within landfill sites.

The use of EM techniques assumes that the area around the meter consists of relatively uniform materials arranged in horizontal layers. As landfills contain heterogeneous materials which have been dumped in various arrangements, the assumption of uniform horizontal layers can not be made. In general, compared with surrounding undisturbed areas, landfills have more anomalous values and chaotic spatial patterns of electrical conductivity. Abrupt changes in electrical conductivity can be used to locate the boundaries of landfill sites.

Measurement taken with each meter and coil orientation were influenced by the underlying refuse. Meters are exceptionally sensitive to buried metallic objects and electrolytic plumes. Where these highly conductive features are near the surface, they can cause the field intensity to approach and pass through zero. In these areas, negative values of apparent conductivity are often recorded. Although these extreme values are inaccurate measurements, they can be used to chart internal features within landfill sites and to locate areas having buried metallic objects, contaminants, or utilities.

Because of proportional reduction in induced field strength with increasing distance away from a meter, near-field materials will disproportionately influence the observed measurements. Dramatic shifts in EM response were often observed with slight horizontal changes in the position of each meter. These changes and the actual range of measured responses were greater for the EM38 meter.

It is difficult to develop accurate predictive models from apparent conductivity measurements alone. For most earthen materials, the number of conceivable models is almost infinite. Models constructed from EM data are more accurate in areas having a minimal sequence of dissimilar horizontal layers. The accuracy of models decreases with increasing numbers of layers. Electromagnetic induction methods must be sensitive to the differences existing between the layers. In other words, a meter must be able to detect differences in electromagnetic properties between the layers. Some subsurface layers have varying thicknesses and properties, but closely similar conductivity values. These dissimilar layers produce equivalent solutions which seriously reduce the accuracy and limit the effectiveness of models. In most landfills, several undesirable parameters (heterogeneous materials, metallic objects and contaminants, lateral variations in conductivity or conductivity-thickness products) fostered ambiguous EM interpretations and lessened the probability of attaining unique solutions and the appropriateness of geoelectric models.

EM Interpretations:
Basic statistics for the EM data collected within the study area are displayed in Table 2. Because of the presence of metallic objects, these statistics are perhaps meaningless. Measurements collected with the EM38 meter were the most variable, and reflects the sensitivity of the meter to near-surface, metallic objects. In general, apparent conductivity becomes less variable with increasing observation depths. For the shallower-sensing EM38 meter, one-half of the observations had values of apparent conductivity between 98 and 271 mS/m in the horizontal (0 to 30 inches), and between 18 and 135 mS/m in the vertical (0 to 60 inches) dipole orientation. For the deeper-sensing EM31 meter, one-half of the observations had values of apparent conductivity between 89 and 129 mS/m in the horizontal (0 to 10 feet), and between 102 and 129 mS/m in the vertical (0 to 20 feet) dipole orientations.

Figures 4 and 5 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 50 mS/m. Figures 6 and 7 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 25 mS/m.

Figures 4 and 5 represents the spatial distribution of apparent conductivity for the upper 30 inches and the upper 60 inches of the soil profile, respectively. The spatial patterns appearing in these figures are relatively complex and variable. Relatively broad, sinuous strands of significantly higher or lower apparent conductivity values can be discerned in each of these figures. These strands of extreme apparent conductivity values are separated by areas with more moderate values. Within these strands are nodes having even more extreme apparent conductivity values. As the observation depth is changed, the locations of these nodes appear to move slightly within the strands.

Table 2
Basic Statistics
EM Survey
Brookfield Landfill Study Area
(all values are in mS/m)

Meter	Orientation	Minimum	Maximum	Quartiles 1st	Median	3rd	Average
EM38	Horizontal	17.0	828.0	98.0	170.0	271.0	211.5
EM38	Vertical	-808.0	392.0	18.0	87.0	135.0	60.1
EM31	Horizontal	62.0	177.0	89.0	106.0	129.0	109.3
EM31	Vertical	56.0	183.0	102.0	114.0	129.0	114.9

The patterns appearing in figures 4 and 5 were assumed to primarily reflect the thickness of the fill cap, the concentration of metallic objects in the near-surface materials, and the composition of the underlying refuse materials. Extreme negative and positive values suggest the presence of highly conductive materials (metallic objects) near the surface. Comparing figures 4 and 5 with Figure 3, extreme values of apparent conductivity appear to correspond with areas predicted to have thinner, fill-caps (less than 18 inches). However, because of variations in fill materials and interference from metallic objects, EM surveys are generally ineffective in measuring the thickness and conductivity of the fill cap.

In general, absolute values of apparent conductivity were more moderate with the EM31 than with the EM38 meter. Compared to figures 4 and 5, the spatial patterns appearing in figures 6 and 7 are less complex and variable and values of apparent conductivity are less extreme and have a narrower range. As a consequence, patterns are more subtle and gradients are more gradual. In figures 6 to 7, areas with anomalous electrical conductivity values and presumably dissimilar accumulations of buried materials are difficult to distinguish.

Results:

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations should be verified by ground-truth observations.

2. In areas containing buried wastes, non-invasive geophysical techniques can reduce health and environmental hazards associated with soil borings and excavations.

3. Ground-penetrating radar and electromagnetic induction techniques are noninvasive. Compared with traditional survey methods, these geophysical techniques are faster and provide greater numbers of observations per unit time. These techniques are therefore more efficient and provide more comprehensive coverage. Geophysical methods can cover large areas at comparatively low costs and with minimal health and environmental risks. This report described

procedures for conducting surveys and for displaying data. Areas having a dense cover of vegetation or rough terrain impede survey operations and the placement of profile lines.

4. Ground-penetrating radar techniques were used to infer the thickness of the fill cap within the study area. No attempts were made to assess the potential of this techniques to determine the thickness of the landfill. A strong correlation was found between the observed and predicted depths to garbage ($r^2 = 0.9981$). Within the study area, the thickness of the fill cap was estimated to be very shallow (0 to 10 inches) at 24 percent, shallow (0 to 20 inches) at 59 percent, moderately-deep (20 to 40 inches) at 36 percent, deep (40 to 60 inches) at 4 percent; and very deep (> 60 inches) at 1 percent of the observation points. The garbage layer was at the surface at 7 percent of the observation points.

The accuracy of radar interpretations is based on the adequacy of auger observations. In this study, the number of ground-truth observations was exceedingly small (4). As properties (moisture, clay, and soluble salt contents) of the fill cap materials were known to vary, its is anticipated that the radar estimates contain some degree of error.

5. The EM survey was designed to help characterize the landfill. This technique identify areas with divergent apparent conductivity values, and provided a method for grouping observation points based on similarities of responses. Variations in values of apparent conductivity were assumed to principally reflect the presence of buried metallic objects and possibly differences in the underlying materials. Patterns appearing on two-dimensional plots were assumed to reflect the concentration of metallic objects in the near-surface materials and the thickness of the fill cap. Extreme negative and positive values suggested the presence of highly conductive materials (metallic objects) near the surface. It is considered impractical to develop models predicting the thickness of the fill cap or landfill from EM measurements alone. Electromagnetic induction techniques are suited to locating the boundaries of landfill sites.

6. Results obtained in this survey are not necessarily repeatable at all landfill sites within the New York City metropolitan area. Conditions present at other landfills will vary and may impose restrictions on the type(s) of geophysical methods that can be used. Under favorable conditions, GPR provides the best resolution of subsurface features. Ground-penetrating radar techniques were successfully used to estimate the thickness of the fill cap. In areas of more conductive soil materials (high clay or soluble salt contents) depth of observation will be severely restricted and the use of GPR techniques will be inappropriate. Electromagnetic induction techniques appear to be most suited to locating the boundaries of landfill sites.

7. It is recommended that similar studies should be conducted on other landfills within the New York City metropolitan area. These studies will improve our characterization and understanding of landfill sites and will help to refine the use of EM, GPR, and computer graphic techniques in areas of drastically disturbed soils.

It was my pleasure to assist your staff in this study. Luis Hernandez is commended for his preparedness, knowledge, and spirited participation in this study.

With kind regards,

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cc:

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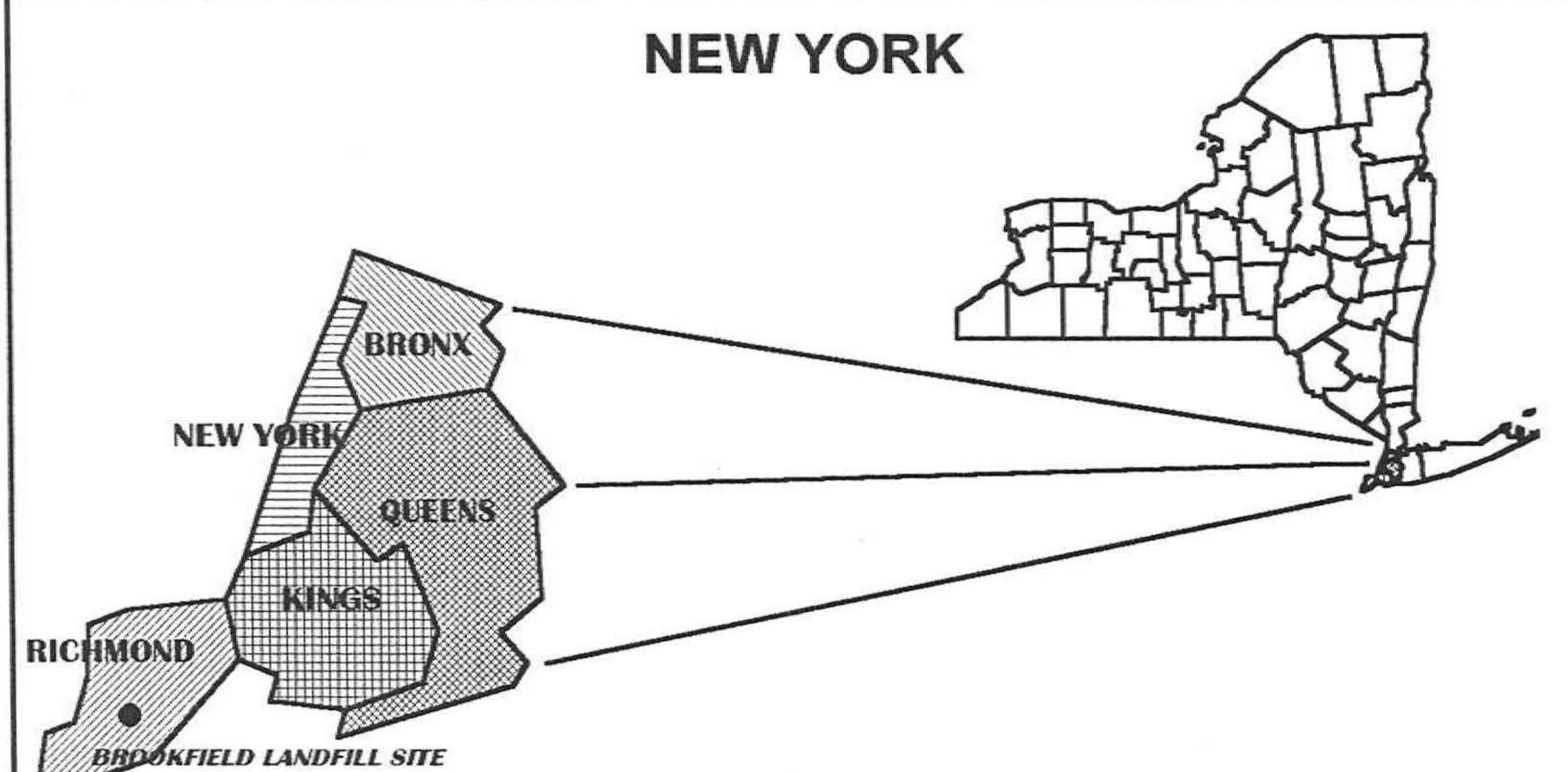
NEW YORK
BRONX
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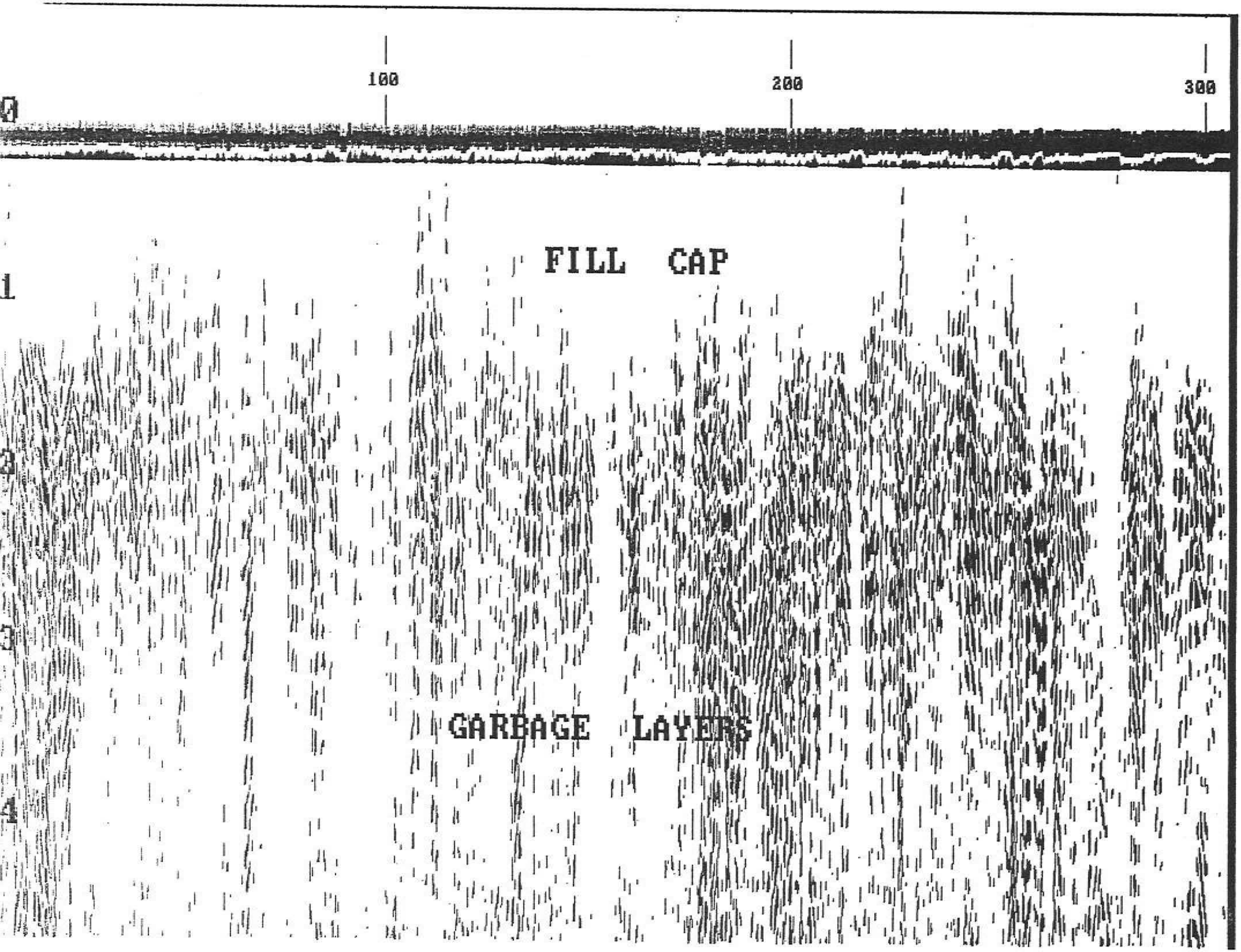
QUEENS
KINGS
RICHMOND
BROOKFIELD LANDFILL SITE

Figure 1



100
200
300
0
1
2
3
4
FILL CAP
GARBAGE LAYERS

BROOKFIELD LANDFILL

THICKNESS OF FILL CAP
INTERVAL = 6 INCHES

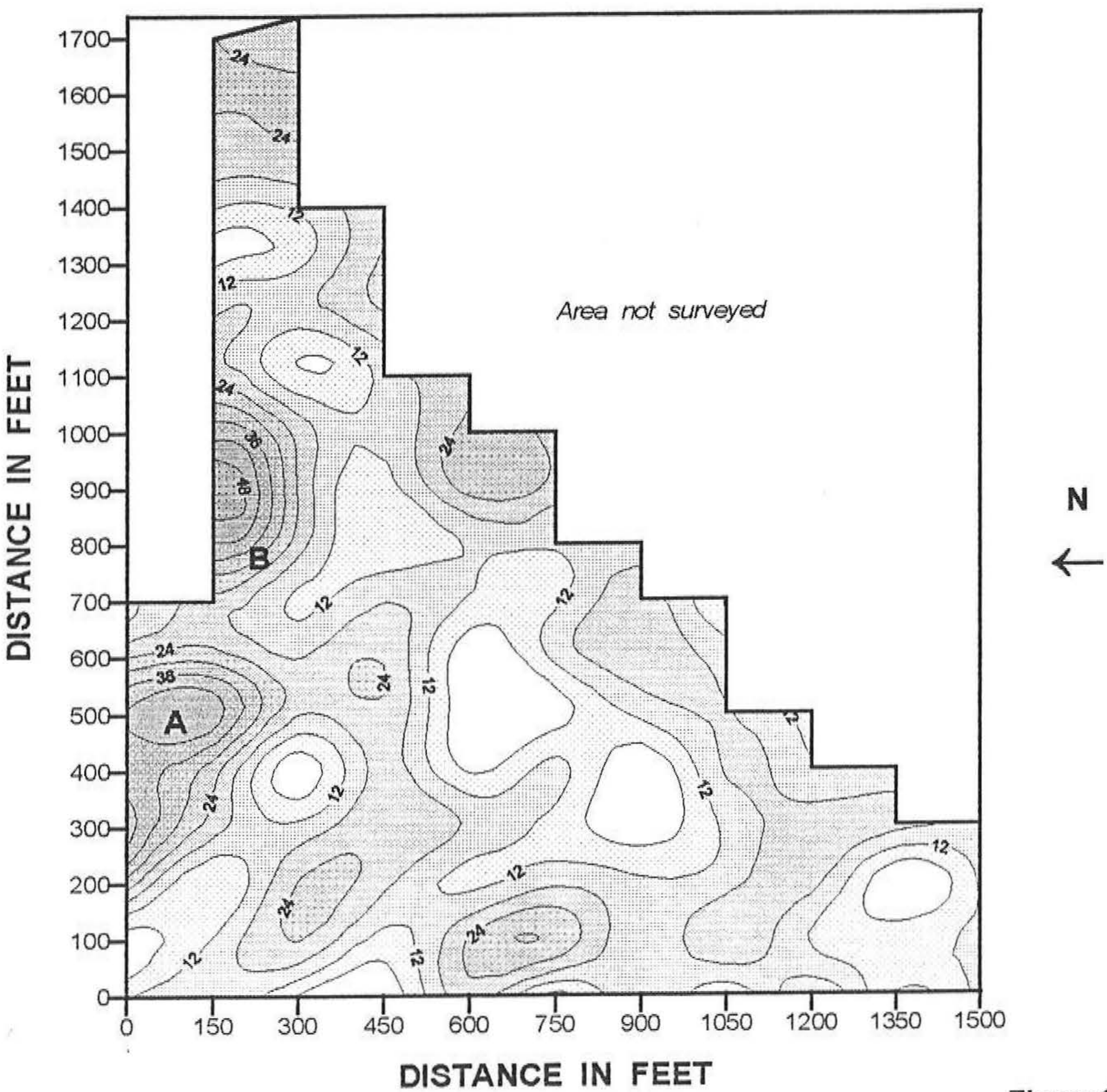


Figure 3

BROOKFIELD LANDFILL

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

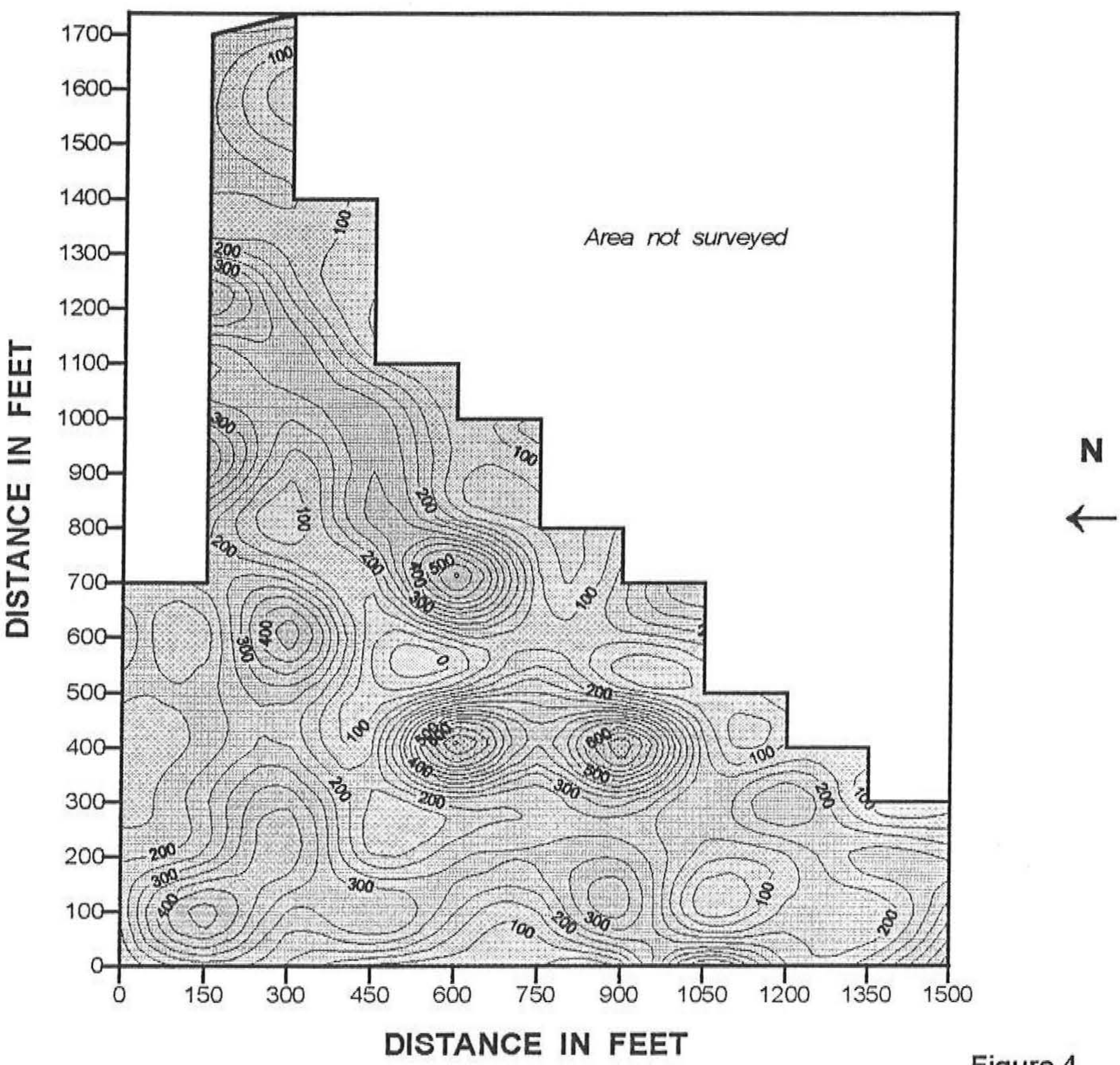


Figure 4

BROOKFIELD LANDFILL

EM38 METER
VERTICAL DIPOLE ORIENTATION

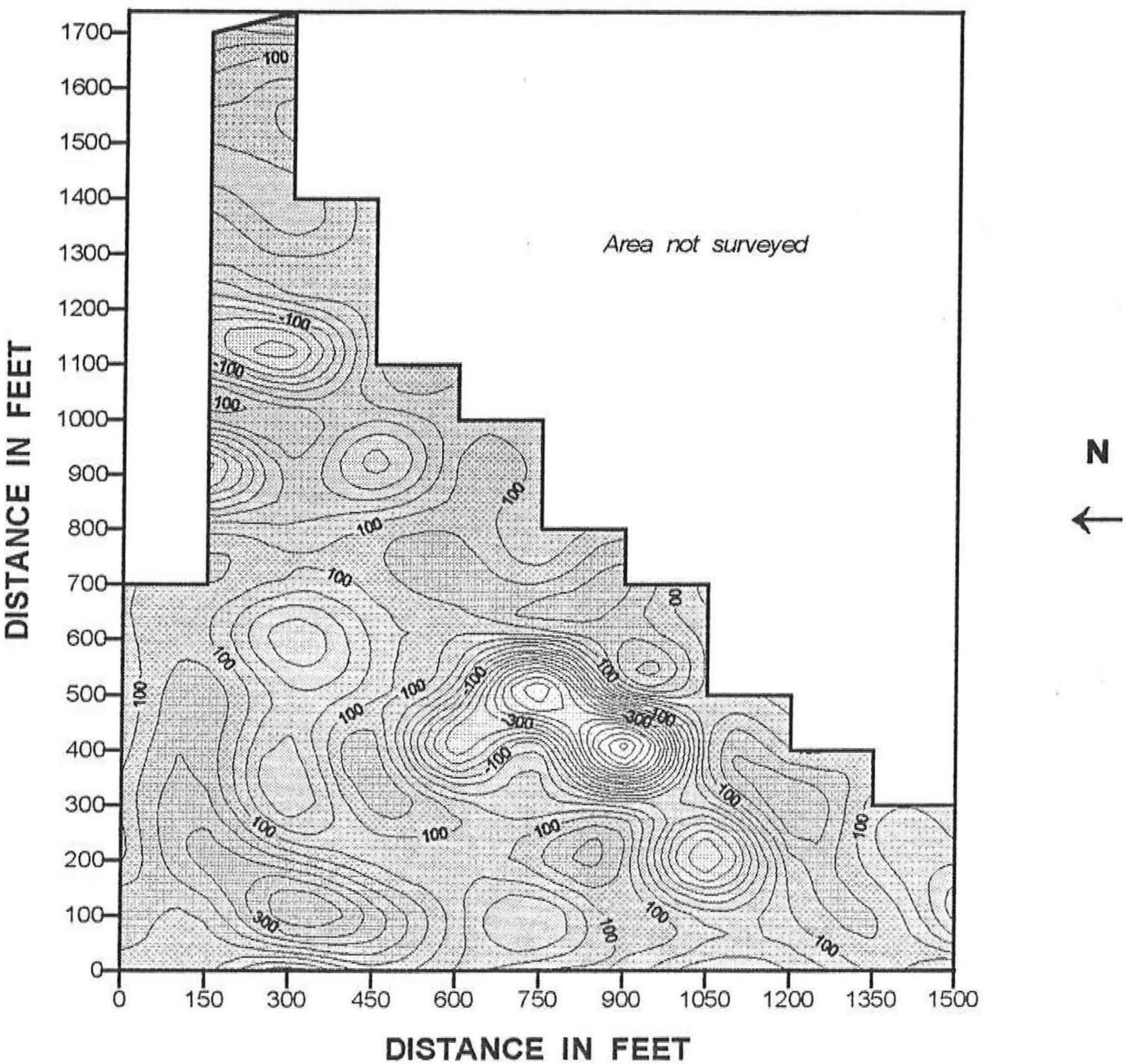


Figure 5

BROOKFIELD LANDFILL

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

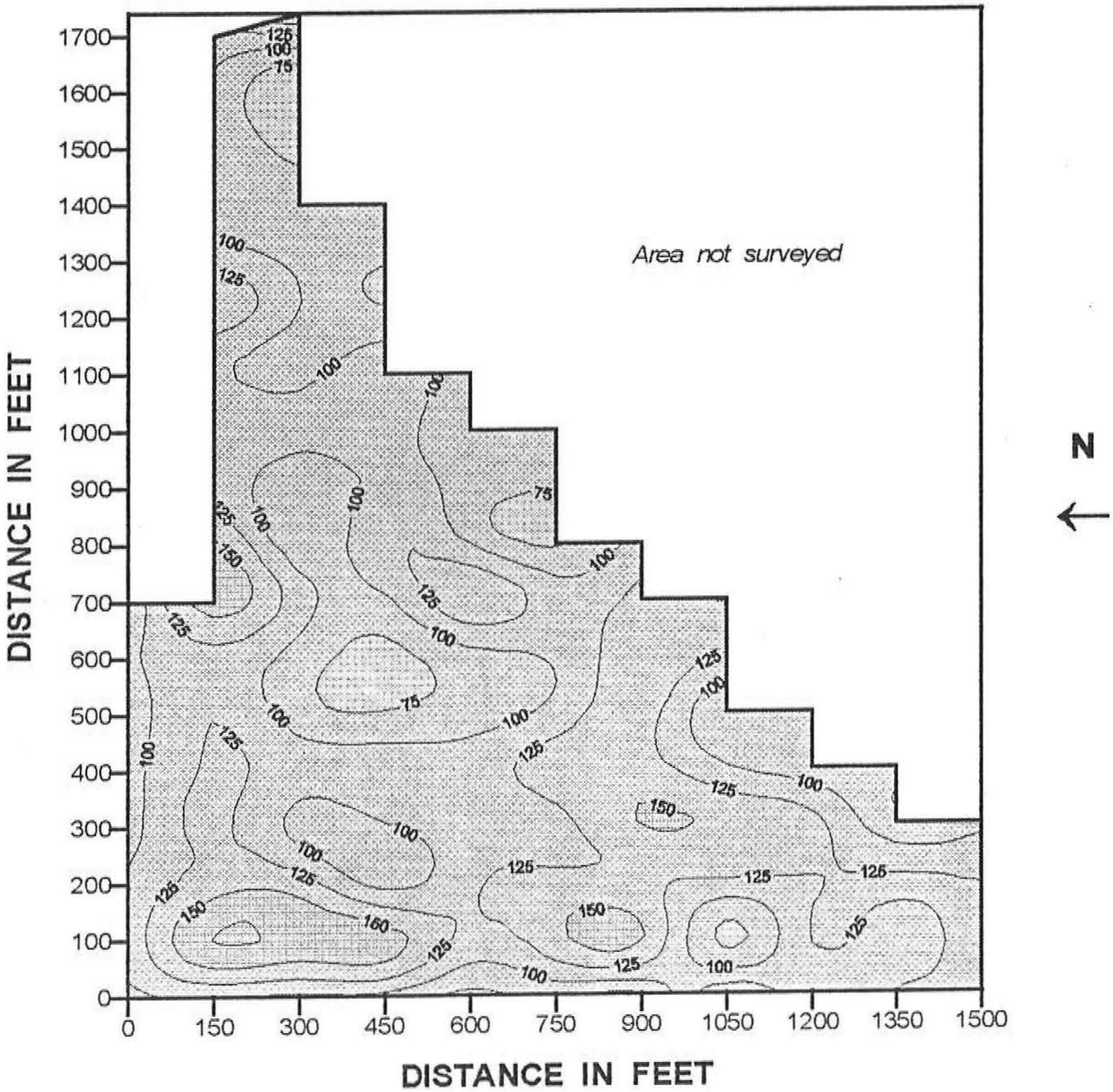


Figure 6

BROOKFIELD LANDFILL

EM31 METER
VERTICAL DIPOLE ORIENTATION

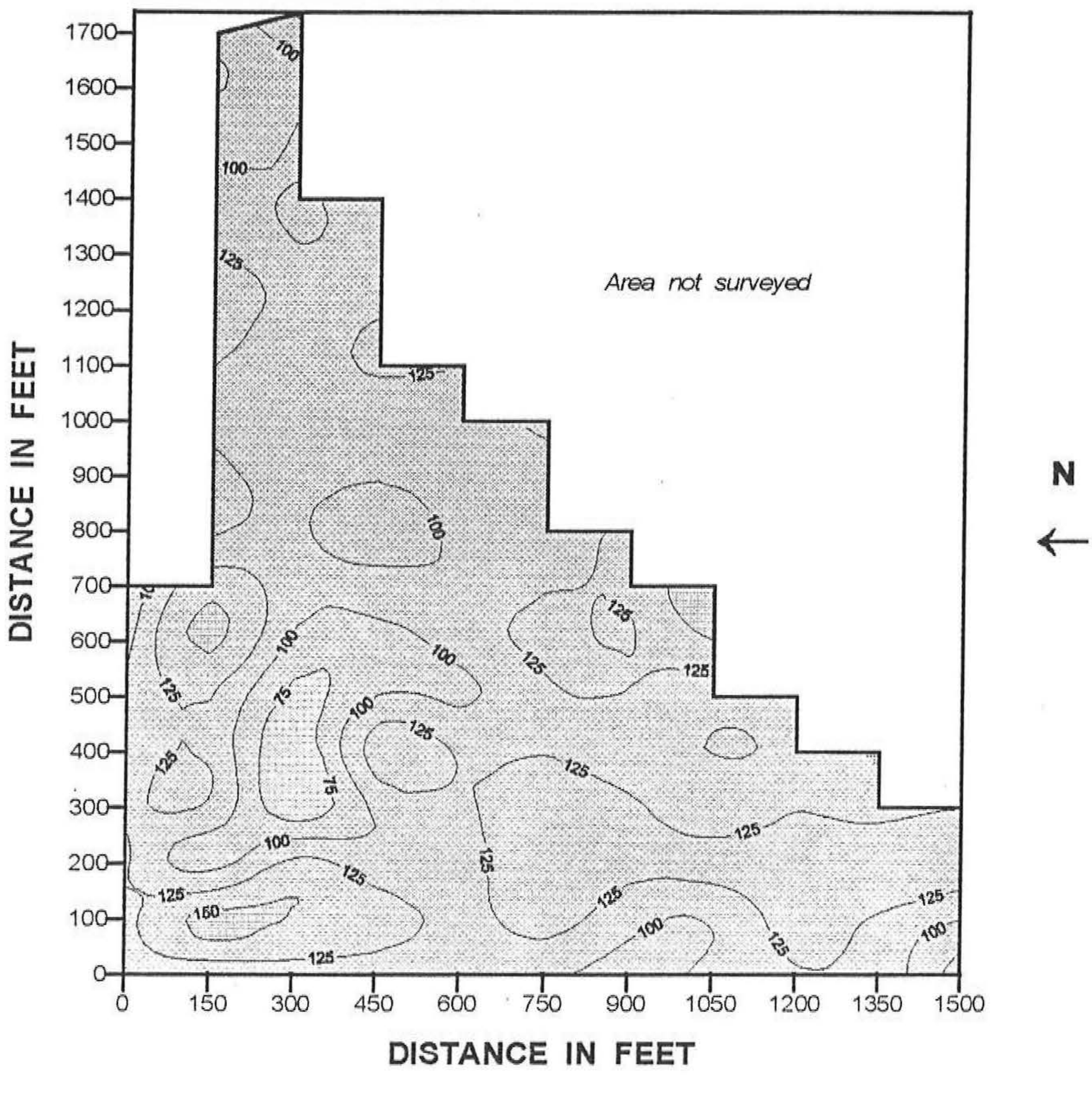


Figure 7