DETECTION OF CONTAMINANT PLUMES IN GROUND WATER OF LONG ISLAND, NEW YORK, BY ELECTROMAGNETIC TERRAIN-CONDUCTIVITY SURVEYS

by Thomas J. Mack and Paul E. Maus

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 86-4045

Prepared in cooperation with the

SUFFOLK COUNTY DEPARTMENT OF HEALTH SERVICES

SUFFOLK COUNTY WATER AUTHORITY

NASSAU COUNTY DEPARTMENT OF PUBLIC WORKS

TOWN OF BROOKHAVEN

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

U.S. Geological Survey
5 Aerial Way
Syosset, New York 11791
(516) 938-8830

Copies of this report may be
purchased from:

U.S. Geological Survey
Books and Open-File Reports Section
Federal Center, Bldg. 41
Box 25425
Denver, CO 80225
(303) 236-7476

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (continued)

TABLES

CONVERSION FACTORS AND ABBREVIATIONS

For readers who prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by the following factors:

Multiply inch-pound unit	by	To obtain SI (metric) unit
foot (ft)	0.3048	meter (m)
acre	4,047	square meter (m^2)

Detection of Contaminant Plumes in Ground Water of Long Island, New York, by Electromagnetic Terrain-Conductivity Surveys

by Thomas J. Mack and Paul E. Maus

Abstract

Electromagnetic terrain-conductivity surveys were conducted at four landfills in Suffolk County and at an artificial-recharge site in Nassau County to assess the feasibility of this technique for detecting contaminant plumes. The technique was successful at three of the landfills; results compared closely with those indicated by specific conductance of water from observation wells on the sites.

Data from the three sites for which the technique was successful--the Horseblock Road landfill, the Manorville scavenger-waste-disposal facility, and the Riverhead landfill--revealed pronounced terrain-conductivity anomalies that reflect known contaminant plumes. Plumes at the other two sites--Blydenburgh landfill and the East Meadow artificial-recharge site--could not be detected because cultural interferences were too great and, at the Blydenburgh site, depth to water was too great. The interferences included pipelines, utility cables, and traffic.

Given favorable conditions, such as high plume conductivity, lack of cultural interferences, and a depth of less than 100 feet to the plume, electromagnetic surveying can provide a rapid means of locating contaminant plumes.

INTRODUCTION

Plumes of contaminated ground water from waste-disposal sites can pose health risks to the local populace if the ground water is the sole source of supply for the area. Typically, a plume is identified through chemical analysis of water samples from several wells at the area of concern. This method can be costly in terms of the drilling, sampling, and analyses, and, in addition, the sites chosen for observation wells may miss the contaminant plume entirely.

Electromagnetic techniques have been effective in detecting contaminant plumes where the electrical conductivity of the plume differs significantly from that of the ambient ground water (Duran and Haeni, 1982). These techniques are relatively inexpensive, the equipment is portable and simple to operate, and the results are easily interpreted. Although these methods cannot determine the chemical composition of the plume, they can often delineate its extent and thereby facilitate monitoring-well placement, which, minimizes the number of wells needed.

In 1983, the U.S. Geological Survey began a study in cooperation with the Suffolk County Department of Health Services, Suffolk County Water Authority,

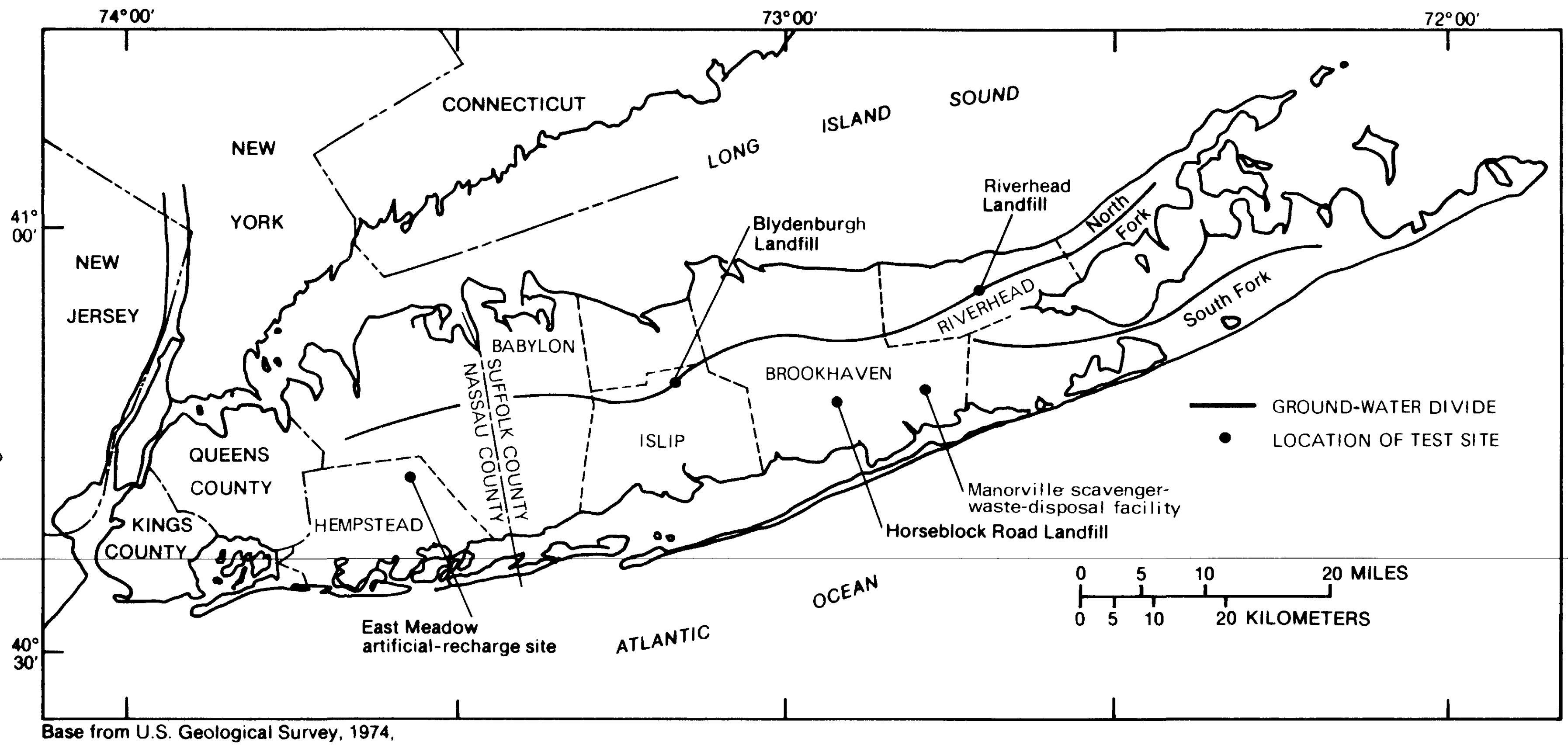


Figure 1.--Location of study sites on Long Island.

Nassau County Department of Public Works, and the Town of Brookhaven, to assess the utility of electromagnetic-terrain-conductivity surveying for detecting contaminant plumes on Long Island. Long Island is appropriate for this technique because the ground water generally has a low conductivity, and the aquifer material is highly permeable.

Five sites with varying geohydrologic and contaminant characteristics were selected for testing. The East Meadow artificial-recharge site is in central Nassau County; Blydenburgh landfill is in the center of western Suffolk County; the Horseblock Road landfill and the Manorville scavenger-waste-disposal facility are in south-central Suffolk County; and the Riverhead landfill is in northeastern Suffolk County. Site locations are shown in figure 1.

Purpose and Scope

This report presents the results of a study to assess the usefulness of the electromagnetic terrain-conductivity surveying technique for detecting and delineating contaminant plumes in ground water on Long Island and to determine the types of sites to which the technique may be applicable. The five sites were chosen to represent a variety of cultural, geohydrologic, and contamination settings typical of Long Island. Specific conductance of ground water at each site was measured for comparison with the electromagnetic terrain-conductivity data. This report describes the principles of electromagnetic-terrain-conductivity surveying and discusses results of the survey at each site.

Geohydrologic Setting

Geology

Long Island consists of a sequence of unconsolidated sedimentary deposits that rest unconformably on Precambrian to Paleozoic crystalline bedrock (fig. 2). The major units overlying the basement bedrock are, in ascending order, the Raritan Formation, the Magothy Formation and Matawan Group, undifferentiated, and Pleistocene deposits. The geology of Long Island is well documented; comprehensive reports include those by Cohen, Franke, and Foxworthy (1968) and Jensen and Soren (1974).

Only the surficial Pleistocene deposits were of concern in this study because the equipment's depth range extends to only about 100 ft below land surface. The upper Pleistocene deposits consist of till and outwash deposits of clay, sand, gravel, and boulders; the lower Pleistocene deposits consist of the Gardiners Clay along parts of the south shore, and an unnamed clay along the north shore (fig. 2). Matawan and Magothy deposits, consisting of fine to medium sand and gravel with interbedded silt and clay, occur locally within 100 ft of the land surface.

Hydrology

Fresh ground water on Long Island is stored in aquifers, which are the sole source of water supply for Nassau and Suffolk Counties (fig. 1).

Comprehensive descriptions of the hydrology of Long Island are provided by Franke and McClymonds (1972) and McClymonds and Franke (1972). The primary aquifers are the Lloyd, the Magothy, and the upper glacial (fig. 2). The Lloyd aquifer is confined by the Raritan clay. The Magothy aquifer is a major source of freshwater and the principal aquifer for most public-supply wells. Layers within this aquifer are poorly to moderately permeable and, locally, are highly permeable. The upper glacial aquifer, which is used for some water supplies in Suffolk County, ranges in composition from poorly permeable till to highly permeable outwash deposits. This aquifer is under water-table conditions and, in some areas of the north and south forks of Long Island, is the only source of fresh ground water.

Fresh ground water originates as precipitation that has percolated through the soil to the water table. Maximum ground-water recharge to the deeper aquifers occurs in a zone along the water-table divide, which runs east-west along the center of the island and the center of both forks (fig. 1). In this zone, the hydraulic gradient is predominantly downward. Ground water generally flows away from the divide toward the north and south shores, which represent areas of ground-water discharge.

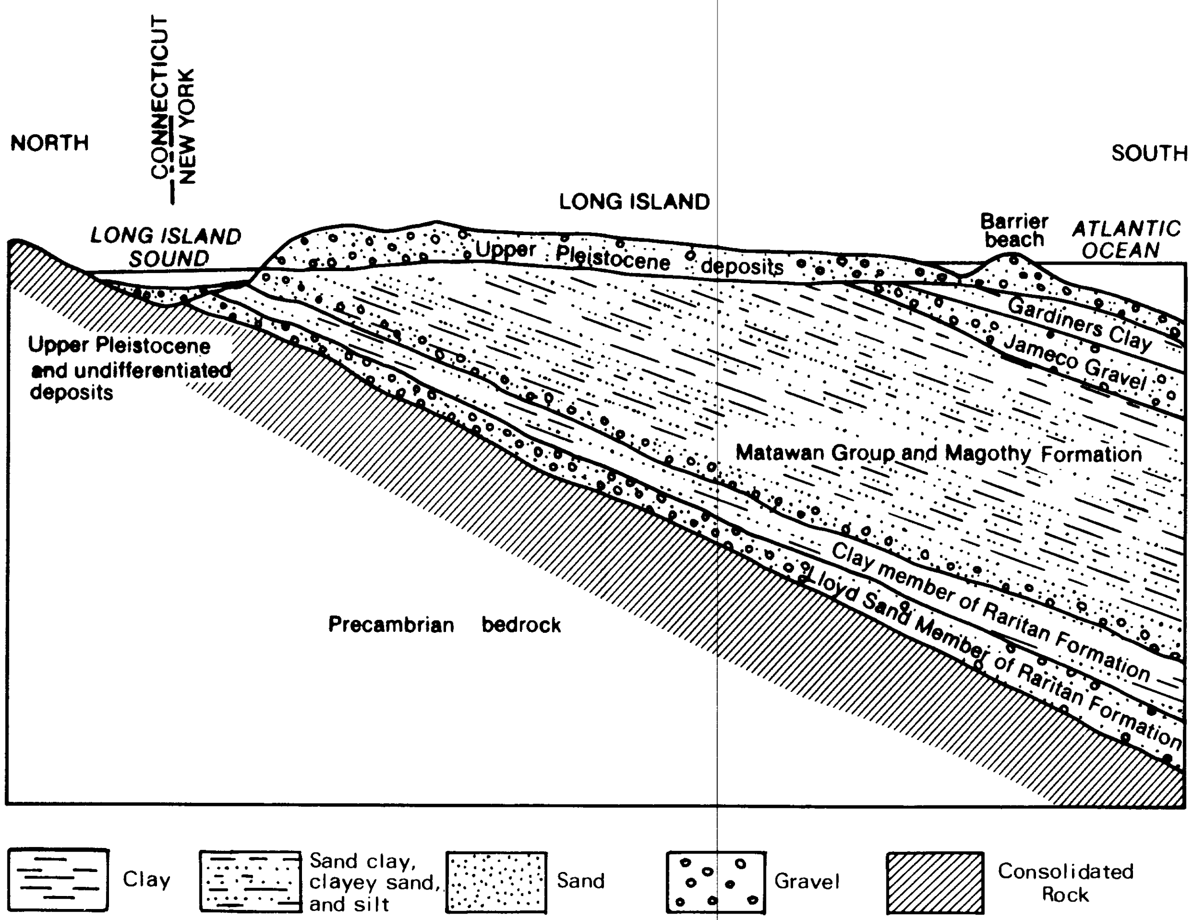


Figure 2.--Generalized geologic section of Long Island showing relative positions of the major stratigraphic units. (Modified from Cohen, Franke, and Foxworthy, 1968, p. 19.)

ELECTROMAGNETIC TERRAIN-CONDUCTIVITY TECHNIQUE

Electromagnetic techniques have been used widely for mineral exploration since the 1930's. Other uses have been developed recently--for example, Stewart (1982) has shown the usefulness of electromagnetic techniques to map the position of the saltwater interface along the Florida coast. Other investigators have applied this technique to detect contaminant plumes from various sources in several regions (McNeill, 1980a; Duran and Haeni, 1982; Greenhouse and Slaine, 1982; and Grady and Haeni 1984).

The equipment used in this survey was the EM34-3[1], manufactured by Geonics Ltd., of Mississauga, Canada. The EM34-3 consists of a transmitter and transmitter coil held by one person, and a receiver and receiver coil held by a second person. The two components are connected by a specified length of cable. Physical contact with the ground is not necessary, and the coils are simply held up or set on the ground when a reading is taken.

Principle and Methods

Electromagnetic, or inductive, techniques measure the electrical conductivity of the subsurface materials. (Conductivity is the inverse of resistivity.) Distilled water has a specific conductance of approximately 1.0 µS/cm (microsiemens per centimeter) (Hem, 1970). Ambient ground water in the upper glacial aquifer has a specific conductance of roughly 60 µS/cm in Islip and Babylon (Kimmel and Braids, 1980) and 45 µS/cm in Brookhaven (E. J. Wexler, U.S. Geological Survey, written commun., 1984). The specific conductance of water increases with the addition of ions.

Water passing through a landfill or other contaminant source typically dissolves some materials, which increases the specific conductance of the ground water. In such cases, specific conductance may become a reliable indicator of ground-water contamination. Leachate from Long Island landfills may have a conductance of more than 1,000 µS/cm (Kimmel and Braids, 1980; Wexler, in press). The sharp contrast between specific conductance of a leachate plume and that of uncontaminated ambient ground water allows the use of electromagnetic techniques in the detection of conductive plumes.

Electromagetic methods measure collectively the conductivity of the soil matrix, including any ground water or other fluid present. Air and dry sand are resistant, a given soil is more conductive saturated than unsaturated, and clay is conductive (McNeill, 1980b). The measurement of terrain conductivity is similar to measurement of specific conductance of ground water, but the two techniques measure different substances and can be compared only qualitatively and are not directly related. Conductive minerals such as magnetite, hematite, and graphite also raise the conductivity of a soil.

In inductive electromagnetic techniques, an alternating current is passed through a coil to generate a magnetic field that penetrates the earth. This

---

[1] Use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

magnetic field induces a small current in the earth, which generates a secondary magnetic field out of phase with the first. A receiver coil is placed a specific distance (the intercoil spacing) from the transmitter coil and receives the secondary magnetic field. At low transmission frequency, the ratio of the secondary to primary magnetic fields is linearly proportional to the terrain's conductivity. The terrain conductivity is thus described by McNeill (1980a) as:

$$\sigma_0 = \frac{1.2}{wus^2} \frac{H_s}{H_p} \qquad (1)$$

where:

σ_0 = terrain conductivity, in microsiemens per centimeter ($\mu S/cm$);
w = 2σ · frequency, in hertz (Hz);
u = permeability of free space;
s = intercoil spacing, in feet (ft);
H_s = strength of secondary magnetic field; and
H_p = strength of primary magnetic-field.

The instrument's depth of penetration--that is, the depth to which conductive material can be detected--depends on the instrument's intercoil spacing, its transmission frequency, and the orientation of the coils relative to the ground surface. (See table 1.) Hydrogeologic factors may affect the penetration depth and are discussed further on in the section on field considerations. Two coil orientations are used (fig. 3); the vertical dipole position has both coils flat on the ground and the horizontal dipole position has both coils upright.

The terrain-conductivity reading is a weighted measurement of the conductivity of the entire geologic column down to the penetration depth. The instrument's response to a layer of material at depth z, where z is depth to the layer divided by the intercoil spacing, is described by the two curves in figure 3. (Note that the vertical dipole position is more sensitive than the horizontal position to material at depth. To determine the contribution of a layer at depth, the column is resolved into a series of geoelectric layers. With the six settings listed in table 1, the column theoretically can be differentiated into four layers. To investigate four layers may not be practical or realistic, however, and the approach taken in this investigation was to consider the simplest or most logical representation--that of a two-layer geoelectric column in which the upper layer is the resistant unsaturated zone, and the lower layer is the conductive saturated zone.

Table 1.--EM34-3 exploration depths at three intercoil spacings.

[Data from McNeill, 1980a]

Intercoil spacing (feet)	Exploration depth (feet)	
	Horizontal dipoles	Vertical dipoles
33	25	49
66	49	98
131	98	197

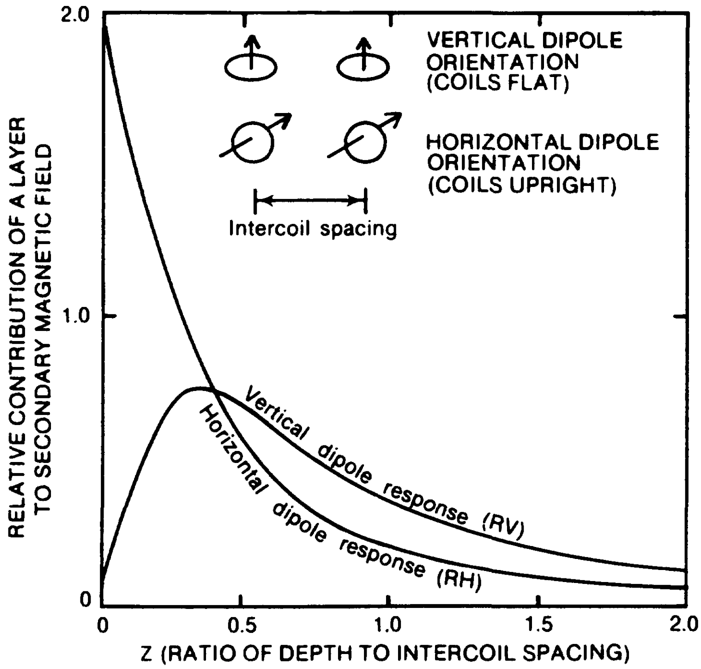


Figure 3.

Typical response curves for vertical and horizontal dipole position. (Modified from McNeill, 1980a.)

The contribution of the upper layer to the apparent conductivity is (McNeill, 1980a):

$$\sigma_1 \; [1 - R_V]$$

$$\sigma_1 \; [1 - R_H]$$

where R_V and R_H are functions of the curves in figure 3, and σ_0 , σ_1 , and σ_2 , (defined below) are the terrain conductivity and the values for the upper and lower layers, respectively. Subscripts V and H designate vertical and horizontal dipole orientations. Similarly, the contribution of the lower layer to the apparent conductivity is:

$$\sigma_2 \; R_V$$

$$\sigma_2 \; R_H$$

The terrain conductivity of the geoelectric column is the sum of the components:

$$\sigma_{0\,V} = \sigma_1 \; [1 - R_V] + \sigma_2 \; R_V \qquad (2a)$$

$$\sigma_{0\,H} = \sigma_1 \; [1 - R_H] + \sigma_2 \; R_H \qquad (2b)$$

The conductivity of the lower layer (the saturated zone) becomes:

$$\sigma_{2\,V} = \frac{\sigma_{0\,V} - \sigma_1 \; [1 - R_V]}{R_V} \qquad (3a)$$

$$\sigma_{2\,H} = \frac{\sigma_{0\,H} - \sigma_1 \; [1 - R_H]}{R_H} \qquad (3b)$$

Algebraic expressions of the relative contribution functions, the curves of figure 3, are given by McNeill (1980a) as:

$$R_V = (4z^2 + 1)^{-1/2} \quad (4a)$$

$$R_H = [(4z^2 + 1)^{1/2}] - 2z \quad (4b)$$

The conductivity of the lower layer, therefore, is readily calculated from equations 3 and 4, given the z depth, the terrain conductivity, and the conductivity of the upper layer. For example, the depth to the water table at a hypothetical station is 20 ft, and the intercoil spacing used was 66 ft. The z depth is then 20 ft divided by 66 ft or a dimensionless 0.30. Placing the z depth into equation 4a gives a vertical dipole relative contribution function of 0.86. If the measured vertical dipole terrain conductivity was 5.00 mmho/m and the unsaturated zone conductivity was 1.00 mmho/m, the conductivity of the saturated zone given by equation 3a is 5.65 mmho/m. Equations 3 and 4 can be incorporated into a simple computer routine to handle large amounts of data rapidly. This procedure was followed in this investigation, and all electromagnetic-survey results are expressed as saturated-zone conductivity. The conductivity of the upper (unsaturated) layer is most easily determined from the average of several readings where the depth to water exceeds the instrument's depth of exploration, if the conditions can be assumed consistent over the study area.

Parts of the above discussion are paraphrased from McNeill (1980a), which gives a more complete explanation of the theory and application of electromagnetic terrain-conductivity surveying and the Geonics EM34-3.

Field Considerations

A thorough terrain-conductivity survey would require a grid of orthogonally oriented stations spanning the entire study area. The land-surface and water-table altitude at each station must be known so that corrections can be made for the unsaturated zone's contribution. Ideally, the distance between stations should not exceed half the width of the suspected plume to ensure that the plume is not passed over undetected. This plan is not always practical, however; traverse lines commonly replace the grid survey, and the distance between stations is often set at a convenient value.

Measurements at each station are made in both the vertical and horizontal dipole position to give an indication of the vertical conductivity contrast. Interpretation should be made with caution when the depth to water is near the depth limit of either dipole measurement.

Before a terrain survey is begun, the investigator should be aware of both the natural field conditions and cultural features that may affect the conductance. Natural factors include the geologic and hydrologic conditions, and geophysical logs should be referred to if available. The thickness of the unsaturated zone must also be known because the maximum exploration depth of the EM34-3 used in this survey is about 100 ft. Geologic factors may have a significant effect; for example, a highly conductive zone can mask a contaminant plume beneath that zone. Therefore, a resistant upper zone is desirable. The cultural features that may affect conductivity readings include such objects as metal fences, powerlines, buried cables, pipelines, vehicles, buildings, and any other conductive structures. Above-ground structures affect measurements because the primary magnetic field extends above ground also. The effects of such interferences are readily noticed, and the station or traverse line should be relocated accordingly. If interference is suspected and the source cannot be identified or avoided, the data may need to be discarded.

The investigator should first assess what kinds of results are likely; for example, the degree of contrast between the contaminant plume and the ambient water and where the plume might be found. A computer program that yields conductivities for given hydrogeologic conditions has been developed (F. P. Haeni, U.S. Geological Survey, written commun., 1985). This prior knowledge can help to distinguish between the plume and spurious data so that appropriate actions, such as relocating a traverse line, can be taken.

SITE SURVEYS TO DETECT CONTAMINANT PLUMES

This section presents results of the 1983 and 1984 surveys at the five sites selected. Site locations are shown in figure 1.

Horseblock Road Landfill

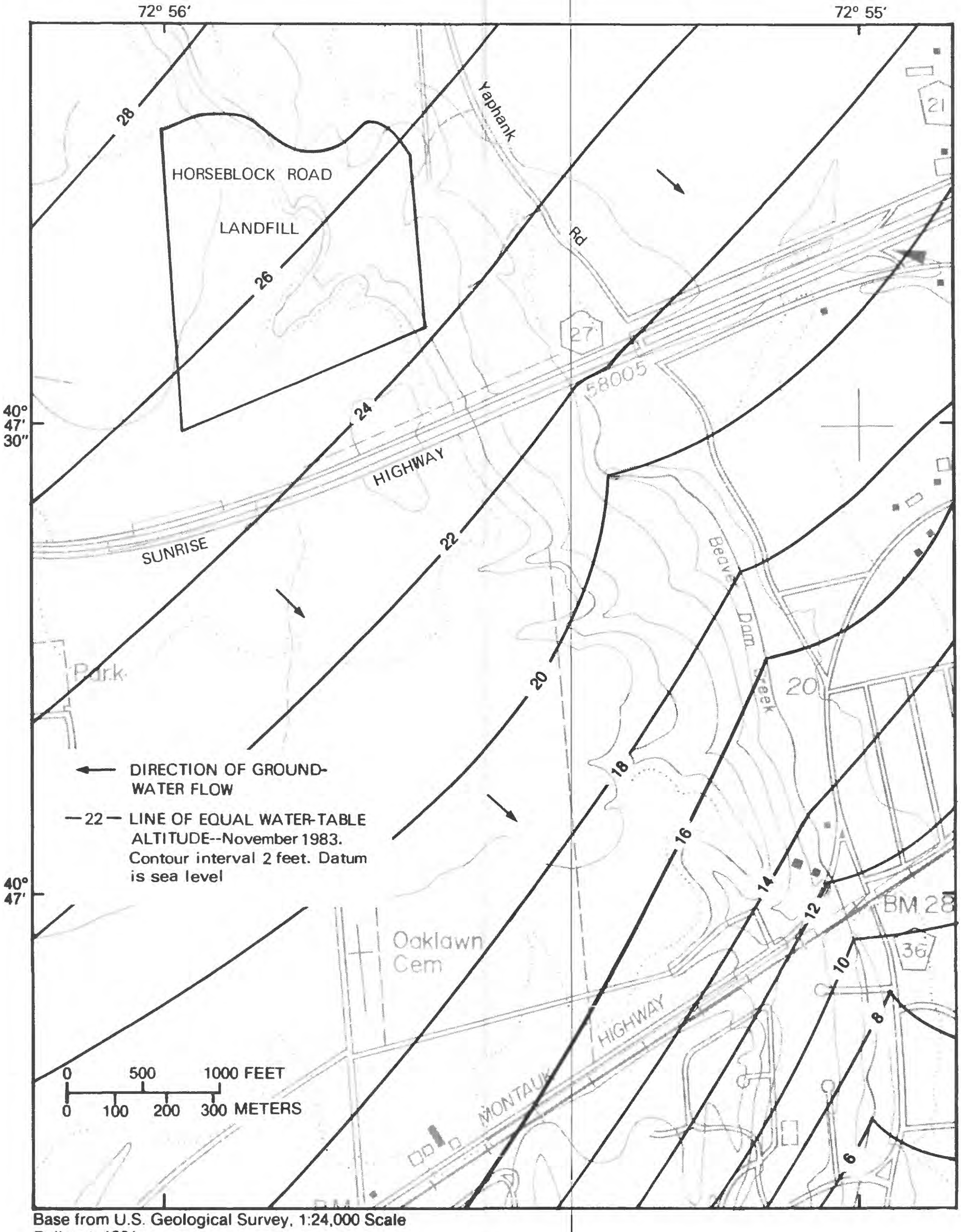
The Horseblock Road landfill, the principal landfill for the Town of Brookhaven, is a 60-acre lined landfill that was opened in March 1974. It accepts brush and mixed municipal wastes. The bottom of the landfill was excavated to approximately 10 ft above the water table and has a plastic liner.

The landfill is immediately north of Sunrise Highway and west of Yaphank Road (fig. 4). The surrounding vicinity is rural with low topographic relief and is bordered by land locally referred to as the Pine Barrens. The area is essentially in a natural state and contains scrub pine and oak.

Hydrogeology

The thickness of the unsaturated zone at this site ranges from 0 ft at Beaverdam Creek, which flows southward through the area, to 50 ft at the western edge of the landfill. This thickness represents the difference between the land surface and water-table altitude in November 1983 (fig. 4). The upper glacial aquifer has a saturated thickness of approximately 120 ft. The direction of ground-water flow is southeastward, and flow is predominantly horizontal (Wexler, 1986).

This site is underlain by glacial outwash deposits of interbedded fine to very coarse sand and gravel with lenses of clay and silty sand; the materials have a medium to high hydraulic conductivity (Wexler, 1986). Beneath the upper glacial aquifer is the Gardiners Clay (fig. 2), which consists primarily of clay and silt and forms a semiconfining unit that restricts downward flow of ground water.



Base from U.S. Geological Survey, 1:24,000 Scale Bellport, 1981

Figure 4.--Water-table altitude in November 1983 in Horseblock Road landfill area in Town of Brookhaven. (General location is shown in fig. 1.) (Modified from Wexler, in press.)

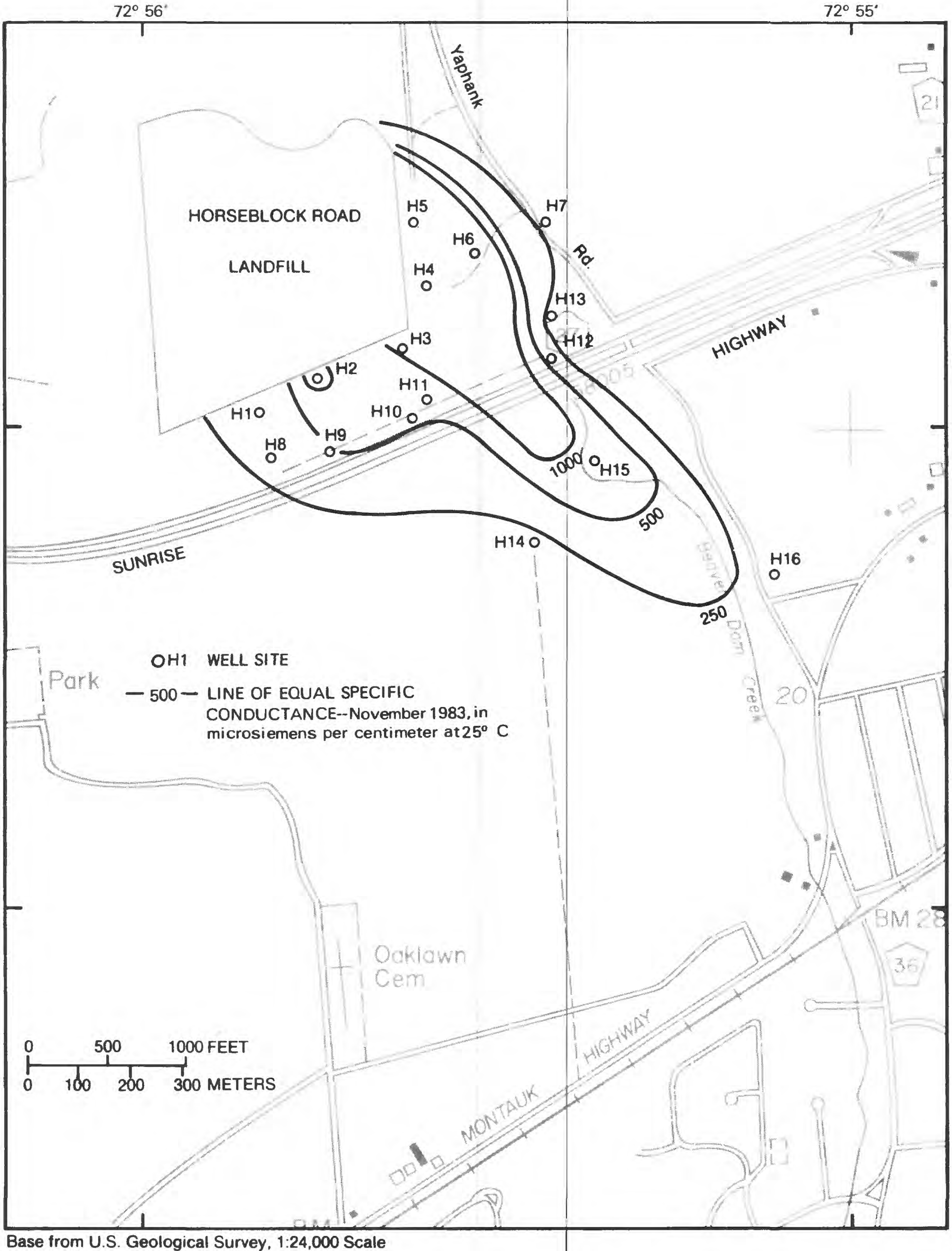
Water Quality

Specific-conductance values of ground water measured during November 1983 in the landfill vicinity are listed in table 2. The values ranged from 50 μS/cm (background level for this area) to 2,600 μS/cm at the eastern edge of the landfill. The approximate configuration of the contaminant plume, based on specific-conductance values at wells screened within 100 ft of land surface, is depicted in figure 5. The plume is elongated in the direction of ground-water flow (southeastward), and its width does not exceed the maximum width of the landfill.

Table 2.--Specific conductance of ground water in upper glacial aquifer in Horseblock Road landfill vicinity, November 1983.

[Data from E. J. Wexler, U.S. Geological Survey, written commun., 1984; well locations are shown in fig. 5]

Measurement-site number	Well number	Well depth (feet)	Measurement-point altitude (feet above sea level)	Specific conductance (microsiemens per centimeter)
H1	S73764	58	71.49	424
H2	S73760	65	71.74	235
H2	S73761	85	71.35	260
H3	S73757	73	57.35	1,050
H3	S73758	53	57.38	1,020
H4	S73753	34	38.60	1,850
H4	S73754	54	38.67	2,150
H5	S73750	34	38.27	2,300
H5	S73751	54	38.39	100
H6	S72817	22	30.25	2,600
H6	S73943	45	29	625
H7	S72130	23	27.63	223
H8	S44574	52	70	400
H8	S44575	59	70	370
H9	S72836	54	62.75	232
H9	S72837	73	62.95	480
H10	S72835	64	54.88	670
H11	S44577	50	66.59	440
H11	S44578	55	66.40	460
H12	S73946	42	24.65	268
H13	S72818	8	23.58	131
H13	S72819	23	23.95	317
H13	S72820	43	23.97	160
H14	S72131	55	47.82	230
H15	S72824	34	21.65	750
H16	S72827	14	20.09	95
H16	S72828	33	20.00	131
H16	S73955	63	21	101



Base from U.S. Geological Survey, 1:24,000 Scale
Bellport, 1981

Figure 5.--Lines of equal specific conductance at Horseblock Road landfill in November 1983 and location of observation wells. (General location is shown in fig. 1.)

Results of Terrain-Conductivity Survey

Terrain conductivity was measured in the vertical and horizontal dipole modes during January 1983. Survey lines were run along roads and trails with an intercoil spacing of 66 ft. The lines (fig. 6) included 201 measurement stations approximately 98 ft apart; their locations are shown in figures 7A (vertical dipole) and 7B (horizontal dipole). The measurements were adjusted through equations 3 and 4 to remove the effect of the unsaturated zone, as described in the methods section, and are plotted in figures 6 and 7 as saturated-zone electromagnetic conductivities. Thickness of the unsaturated zone was determined from topographic contours and the water-table-altitude map, both shown in figure 4. The conductivity of the unsaturated zone, for use in equation 3, was determined to be approximately 1.0 mmho/m.

At this site, conductivity values below 5 mmho/m can be considered within the background range because this level roughly corresponds to measured specific conductance values of 250 μS/cm or less. The elevated conductivities in traverse line H (fig. 6) clearly suggest leachate from the landfill. These peaks correspond to areas showing high specific conductance at shallow observation wells, particularly in the northeast corner of the landfill. Because no cultural sources of interference were evident, these peaks may represent areas either where the liner has a significant leak or where leachate is overflowing the liner. Two peaks in traverse H adjacent to the southeast corner of the landfill can be traced downgradient to traverse G, where they are still well defined. At traverse F, the two peaks are still evident but less defined, particularly at the shallower depths (horizontal dipole survey), where the conductivity has decreased. Further downgradient at traverse D, one peak is present but barely recognizable, and at traverse E, the conductivity has dropped to background level.

Conductivity contours based on the vertical- and horizontal-dipole surveys are presented in figure 7A and 7B, respectively. The primary axis of the plume trends southeastward from the southeast corner of the landfill, along the direction of ground-water flow (fig. 4), and is shaped much like the specific-conductance anomaly in figure 5. Values range from background lows of less than 2 mmho/m outside the plume to a high of 90.3 mmho/m at the eastern edge of the landfill. The two conductivity peaks noted earlier are evident in these maps but are less distinct. The larger peak makes up the main axis of the plume, whereas the lesser peak, which emanates from the southwest corner of the landfill, cannot be distinguished. The terrain-conductivity anomaly widens along Sunrise Highway, which probably reflects infiltration of road salt from the highway.

The anomaly revealed in the two conductivity maps is similar to that indicated by the ground-water analysis; thus, the electromagnetic technique can be considered successful at this site. Also, the electromagnetic method yields more lateral detail than the ground-water analysis because it provides a greater number of measurement points.

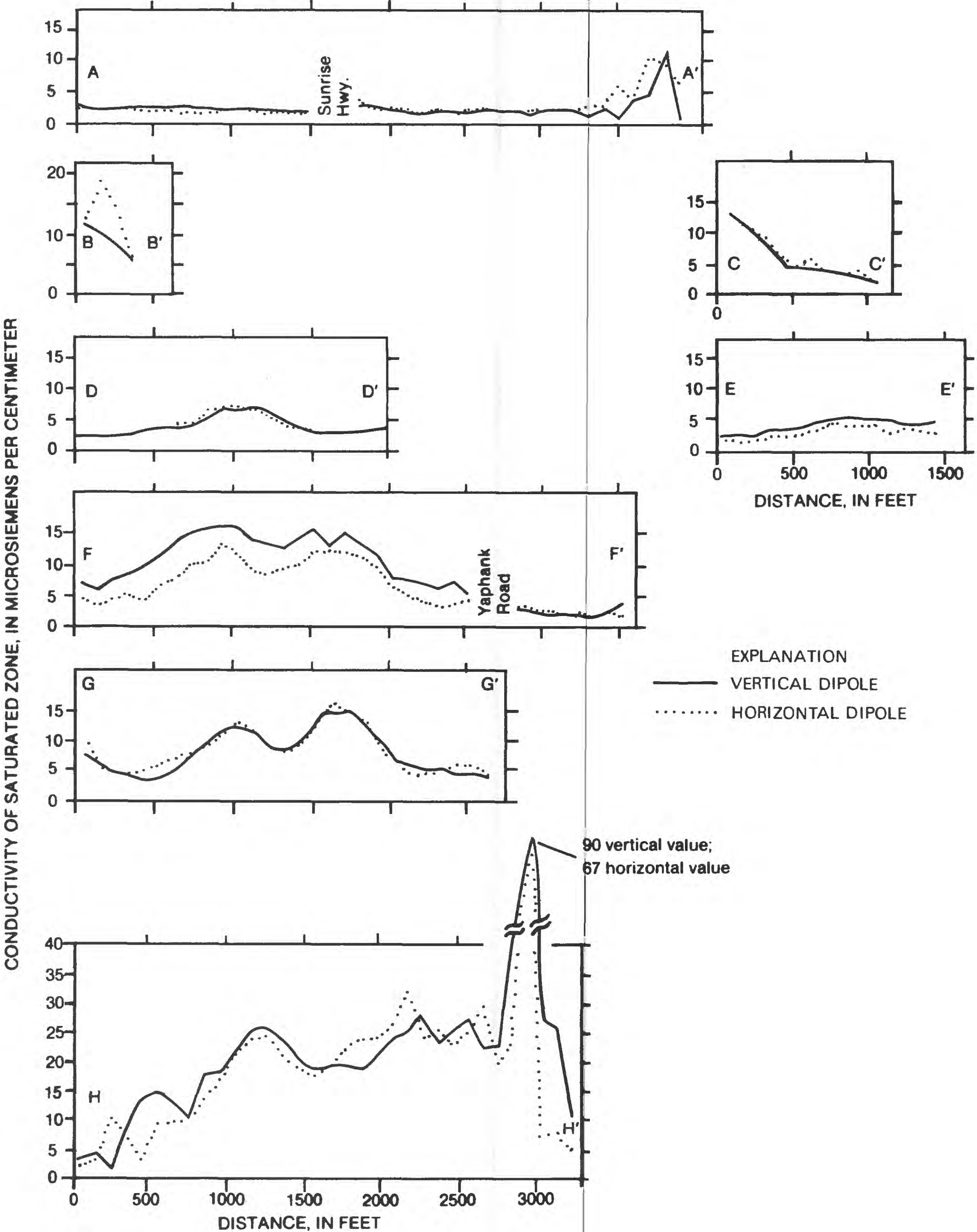
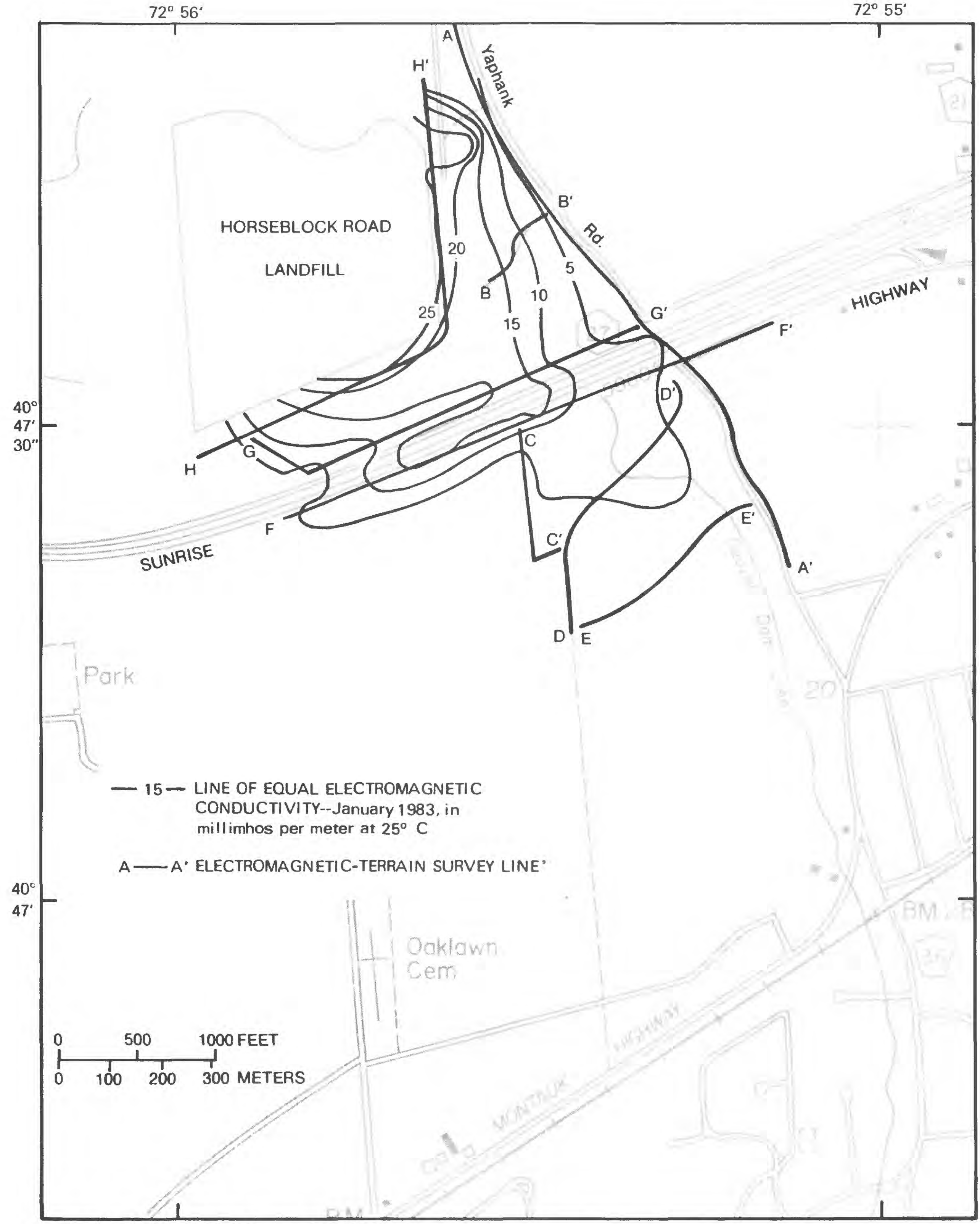
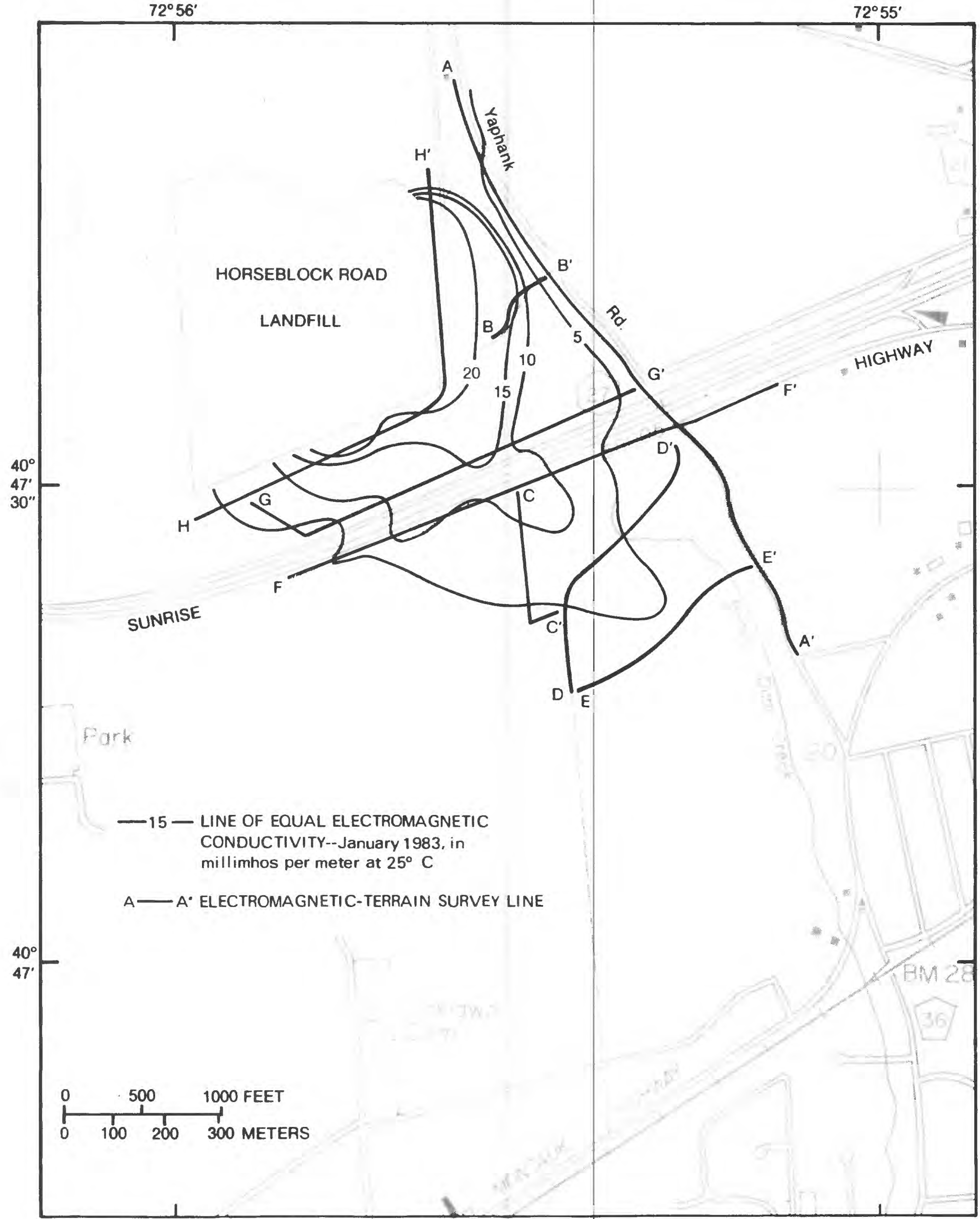


Figure 6.--Electromagnetic conductivity of saturated zone along lines A through H at Horseblock Road landfill, January 1983. (Line locations are shown in figs. 7A and 7B.)



Base from U.S. Geological Survey, 1:24,000 Scale
Bellport, 1981

Figure 7A.--Electromagnetic conductivity of saturated zone based on vertical dipole data at the Horseblock Road landfill site, January 1983, and location of survey lines. (Location is shown in fig. 1.)



Base from U.S. Geological Survey, 1:24,000 Scale
Bellport, 1981

Figure 7B.--Electromagnetic conductivity of saturated zone based on horizontal dipole data at the Horseblock Road landfill site, January 1983, and location of survey lines. (Location is shown in fig. 1.)

Manorville Scavenger-Waste-Disposal Facility

Liquid domestic and industrial wastes were deposited in a series of excavated settling basins at this site from 1964 through November 1982, when the facility ceased operation; solid wastes were buried during 1960-82. After closing in 1982, the basins were allowed to dry, and the remaining material in the bottom of the basins was removed.

The disposal site is northeast of the intersection of Paper Mill Road and Chapman Boulevard (fig. 8). Like the Horseblock Road site, the area is rural and surrounded by pine barrens, and the topographic relief is low.

Hydrogeology

The upper glacial aquifer underlying the Manorville facility consists of highly permeable Pleistocene sand and gravel similar to that at the Horseblock Road landfill (Eckhardt and Wexler, 1986). The upper glacial aquifer is approximately 160 ft thick at this site. It contains no intervening clay layers and probably rests on relatively impermeable Pleistocene clays (Eckhardt and Wexler, 1986), although no data were available to confirm this.

Eckhardt and Wexler (1986) present a water-table map of the study area, part of which is shown in figure 8. The depth to water is approximately 45 ft at the facility and ranges from 28 to 65 ft over the study area. The direction of ground-water flow is southeastward (Eckhardt and Wexler, 1986).

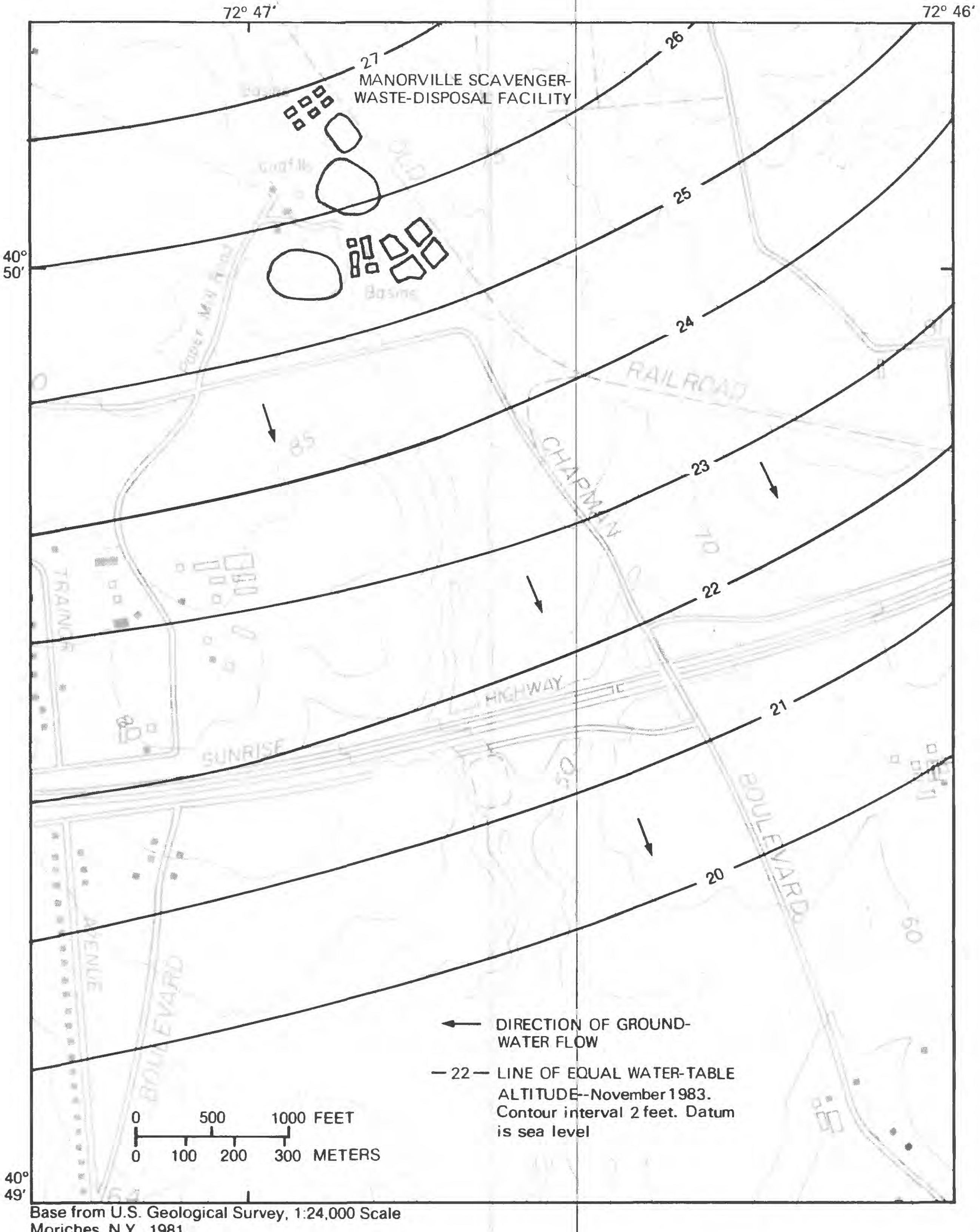
Water Quality

Chemical properties of the liquid wastes that were ponded in one of the settling basins and also of liquid wastes before their deposition in the basins are given in Dvirka and Bartilucci (1981). Specific conductance of these wastes was 793 μS/cm for the settling liquid and 1,173 μS/cm for the liquids before deposition (Dvirka and Bartilucci, 1981).

Specific conductance of water from wells screened within 100 ft of land surface (table 3) (E. J. Wexler and M. P. Scorca, U.S. Geological Survey, written commun., 1984) reveals ground-water contamination downgradient from the site. A maximum conductivity of 1,647 μS/cm was found at well site M3 immediately southeast of the site (fig. 9); water from adjacent wells also had moderately high values. Background values of 58 μS/cm or less were measured north of the site and outside the plume. The elevated conductance at well site M13 is unexplained but probably is not related to the contaminant plume.

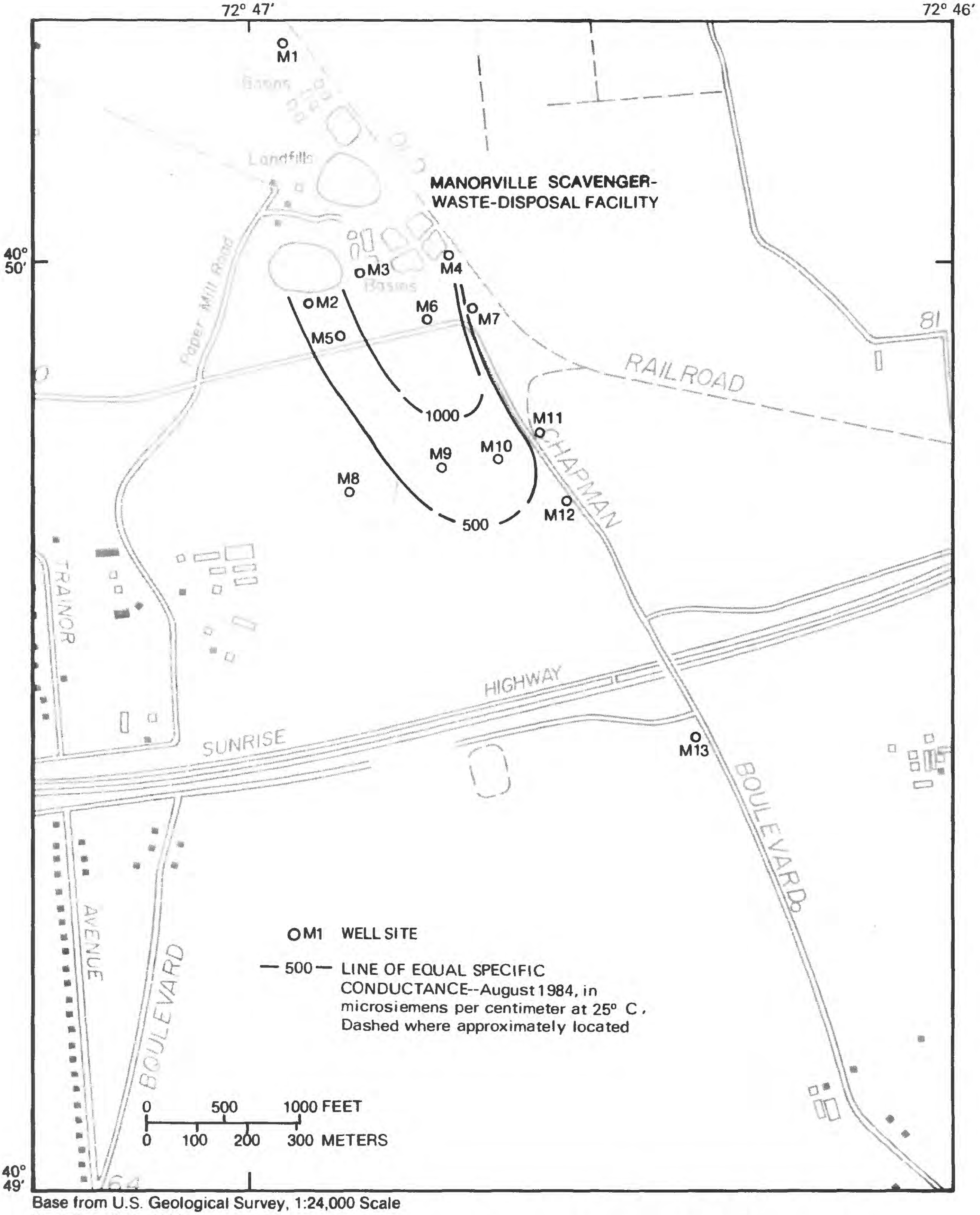
Results of Terrain-Conductivity Survey

A terrain-conductivity survey was conducted in January 1983 with an intercoil spacing of 66 ft. Survey lines were run along accessible roads and trails; their locations are shown in figures 11A (vertical dipole) and 11B (horizontal dipole). The data were adjusted through equations 3 and 4 to remove the effect of the unsaturated zone, as described in the methods



Base from U.S. Geological Survey, 1:24,000 Scale
Moriches, N.Y., 1981

Figure 8.--Water-table altitude in the Manorville area, Town of Brookhaven November 1983. (General location is shown in fig. 1.) (Modified from Eckhardt and Wexler, 1986.)



Base from U.S. Geological Survey, 1:24,000 Scale
Moriches, N.Y., 1981

Figure 9.--Specific conductance of ground water at the Manorville site in August 1984 and location of observation wells. (Location shown in fig. 1.)

section, and are plotted in figures 10 and 11 as saturated-zone electromagnetic conductivities. Thickness of the unsaturated zone was determined from topographic contours and the water-table altitude map, both given in figure 8. The conductivity of the unsaturated zone, for use in equation 3, was determined to be approximately 0.7 mmho/m.

Traverses D and C both fully bisect a conductivity anomaly. Traverse D shows a conductivity high of 7.3 mmho/m that declines to less than 2 mmho/m. The similarity between the vertical- and horizontal-dipole surveys of this traverse suggest that the vertical concentration gradients are fairly uniform in the upper water table. Further from the site, along traverse C, the anomaly is still evident but diminishes, particularly in the shallower (horizontal dipole) depths. Traverse B seems to have contained the toe of the plume, if conductivities less than 2 mmho/m are within the background range for this site. A gently diminishing conductivity gradient is seen in traverse A between traverse C and B, as expected.

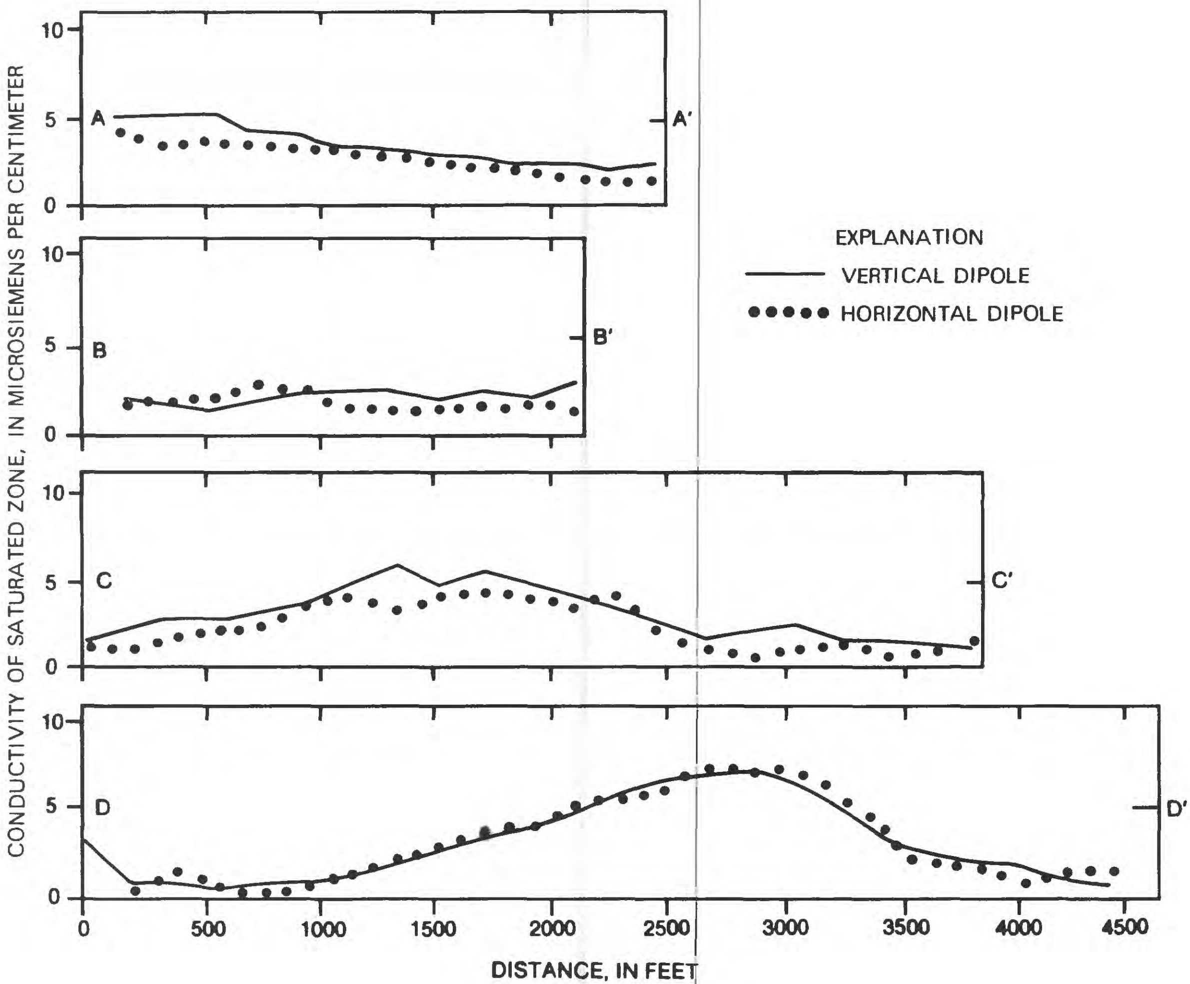


Figure 10.--Electromagnetic conductivity of saturated zone along lines A through D at the Manorville scavenger-waste-disposal facility, January 1983. (Line locations are shown in fig. 11.)

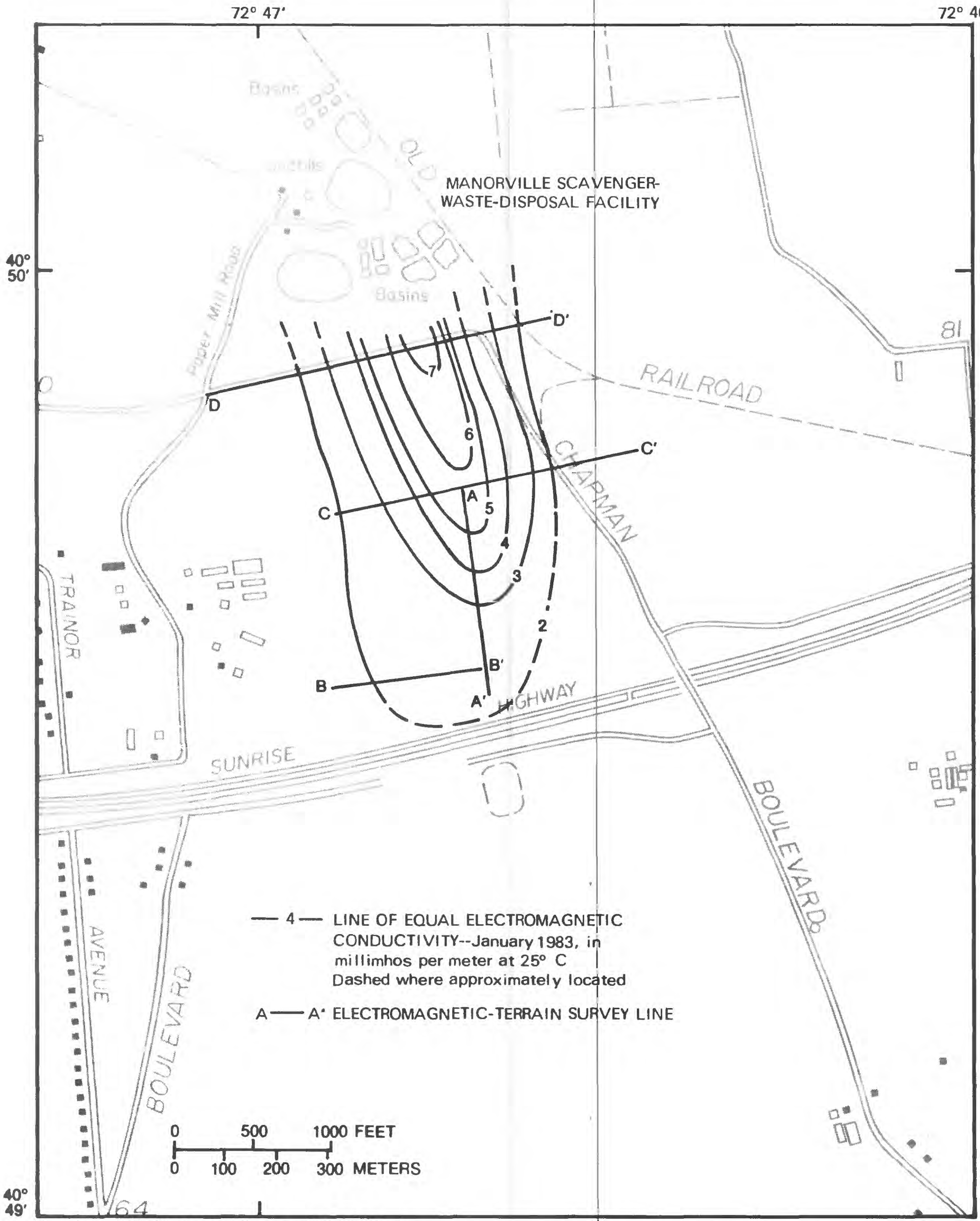
The saturated-zone electromagnetic-conductivity contours (figs. 11A and 11B) reveal the configuration of the plume emanating from the site in the direction of ground-water flow. The plume indicated on these maps extends nearly to Sunrise Highway, but additional water-quality data in this vicinity would be needed to confirm the location of the toe of this plume. The saturated-zone conductivities measured at this site, with a maximum of about 7 mmho/m, are not exceptionally high in relation to those at the Horseblock Road landfill or the Riverhead landfill (discussed in the next section). However, the specific conductance of water samples from this location confirms ground-water contamination. Greater depths to water at this site and lower specific conductance of the contaminated ground water here than at the Horseblock Road or Riverhead sites account for the relatively small magnitude of this anomaly.

The electromagnetic survey at this site can be considered successful because the results are similar to those indicated by the specific conductance of water samples from observation wells. Again, the electromagnetic survey provided greater lateral resolution than the water-sample analysis.

Table 9.--Specific conductance of ground water in upper glacial aquifer in Manorville area, August 1984.

[Data from Wexler and Scorca, U.S. Geological Survey, written commun., 1984; well locations shown in fig. 9]

Measurement-site number	Well number	Well depth (feet)	Measurement-point altitude (feet above sea level)	Specific conductance (microsiemens per centimeter)
M1	S73811	85	83.47	47
M2	S73791	61	84.27	736
M3	S73792	61	80.30	1,647
M4	S73793	56	68.77	1,480
M5	S73816	70	87.06	221
M5	S73817	90	87.35	794
M5	S73818	110	87.02	845
M6	S73813	88	64.13	676
M6	S73814	68	64.16	1,410
M6	S73815	53	64.17	351
M7	S31461	68	68.23	264
M8	S73794	73	85.56	46
M9	S73795	47	56.75	38
M9	S76402	69	57	500
M9	S76403	89	57	603
M9	S76404	109	57	548
M10	S76406	79	66	148
M10	S76407	99	66	825
M10	S73796	55	67.05	48
M11	S73797	57	68.94	52
M11	S76409	99	69	36
M12	S76412	79	71	58
M13	S73801	50	65.24	301



Base from U.S. Geological Survey, 1:24,000 Scale
Moriches, N.Y., 1981

Figure 11A.--Electromagnetic conductivity of saturated zone based on vertical dipole data at the Manorville scavenger-waste-disposal facility, January 1983, and location of survey lines. (Location is shown in fig. 1.)

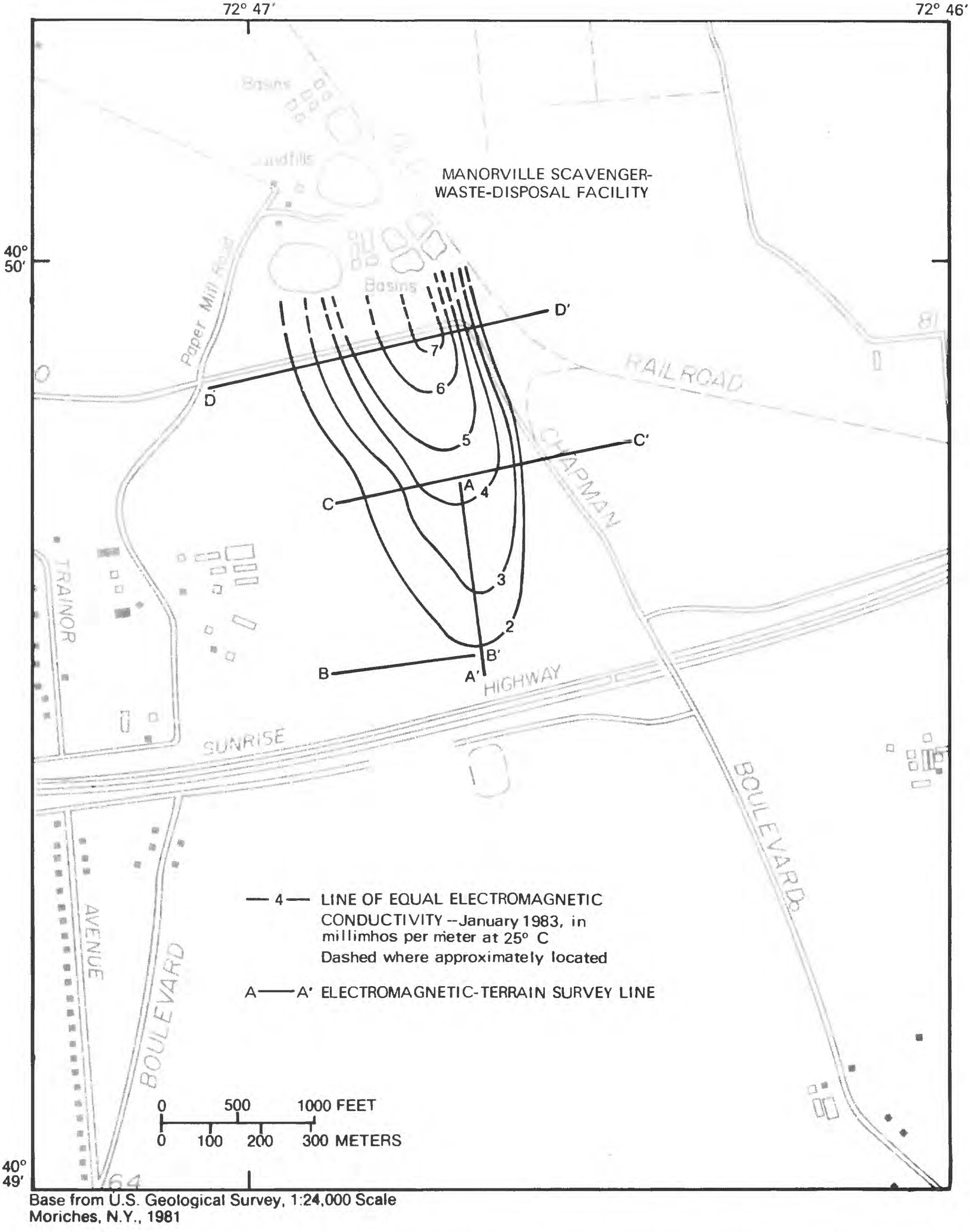


Figure 11B.--Electromagnetic conductivity of saturated zone based on horizontal dipole data at the Manorville scavenger-waste-disposal facility, January 1983, and location of survey lines. (Location is shown in fig. 1.)

Riverhead Landfill

The Riverhead landfill consists of two adjacent disposal sites on the north and south sides of Youngs Avenue, just west of Osborn Road (fig. 12). The surrounding vicinity is open farmland and wooded areas with moderate relief and few houses.

The north landfill occupies 20 acres and was operated from the mid-1920's until 1969. The type of material deposited was not recorded. The south landfill occupies roughly 40 acres and began operation when the north site closed; both are unlined. It is now the principal landfill for the Town of Riverhead. The materials accepted here are waste oil, municipal wastes, and scavenger wastes. The bottom of the south landfill is 5 to 15 ft above the water table.

Hydrogeology

The upper glacial aquifer is approximately 200 ft thick at this site and consists of fine- to coarse-grained sand and gravel with discontinuous clay layers. A silty clay 5 ft thick lies a few feet below the north end of the south landfill (Holzmacher, McLendon, and Murrell, 1975) but has not been observed in well loggings elsewhere at the site. Also underlying the south landfill is a 20-ft-thick, solid to silty clay approximately 95 ft below land surface. This layer was indicated by well logs to be continuous within the site vicinity south of the landfill, but it was not found immediately to the northeast or to the east.

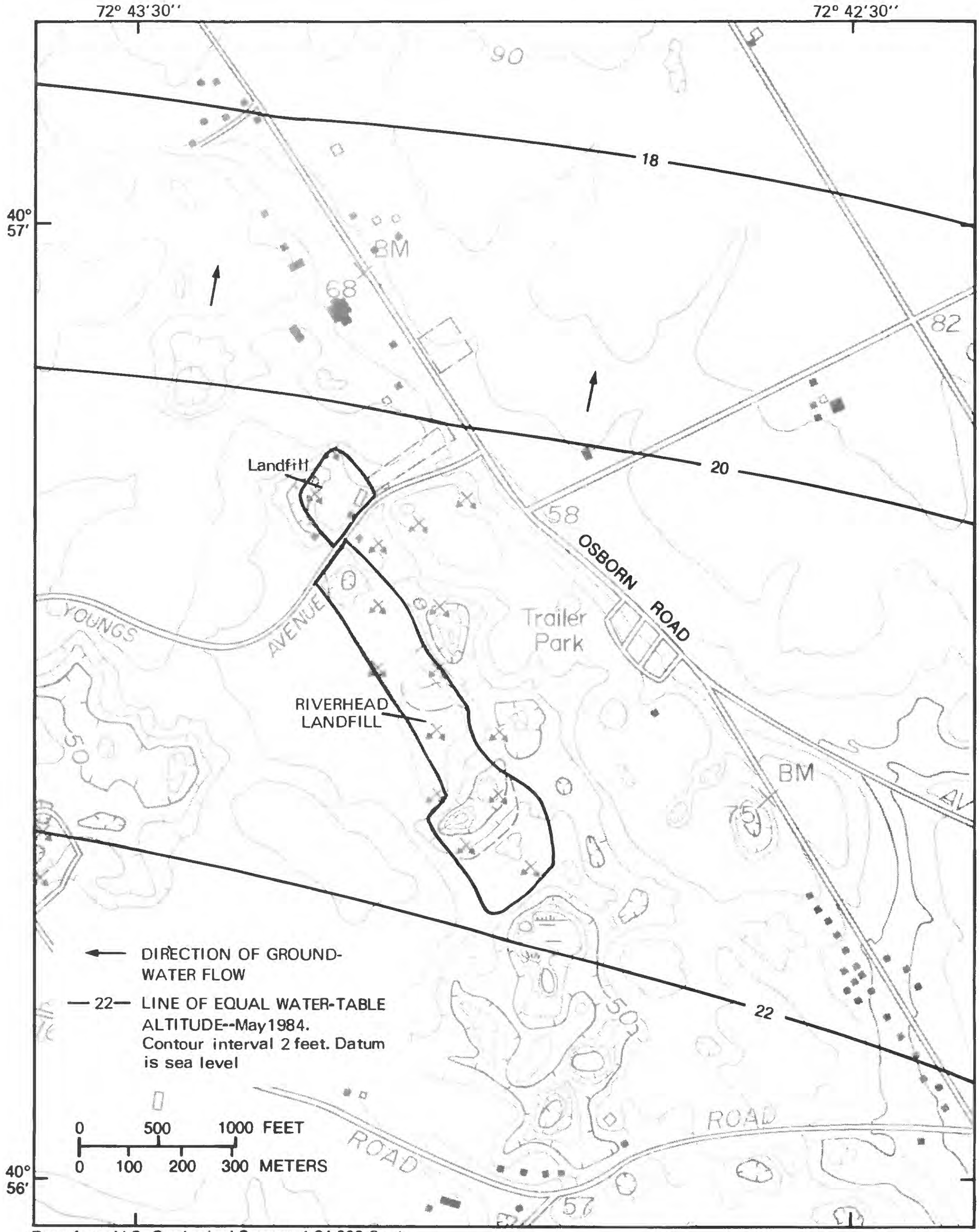
A regional water-table map by Donaldson and Koszalka (1983) indicates that the Riverhead landfill is fairly close to the regional ground-water divide and therefore in an area of deep-aquifer recharge. The local water-table contours (fig. 12) indicate the general flow direction to be northeastward. Two recharge basins are close to the landfills and may influence the local water-table altitude. The east basin collects runoff primarily from the field east of Osborn Road; the west basin serves as an overflow area for the east basin. The east basin often retains a few feet of standing water for several days after a rainfall. Water levels in nearby wells indicate that the water table beneath this basin is mounded about 1 ft above the regional water-table altitude.

Water Quality

A leachate plume in the area is indicated by high specific conductance of water from wells screened within approximately 100 ft of the land surface (table 4). Background values south of the site are low--112 μS/cm at well R9 and 78 μS/cm at well R8 (fig. 13), and immediately west of the primary recharge basin--85 μS/cm at well R2. The specific-conductance contours show the high values along the path of ground-water flow from the landfills.

Results of Terrain-Conductivity Survey

The terrain-conductivity survey at this site during April 1984 was based on a 66-ft intercoil spacing. The survey lines were run through agricultural



Base from U.S. Geological Survey, 1:24,000 Scale
Riverhead, N.Y., 1981

Figure 12.--Water-table altitude at Riverhead landfill, May 1984. (General location is shown in fig. 1.)

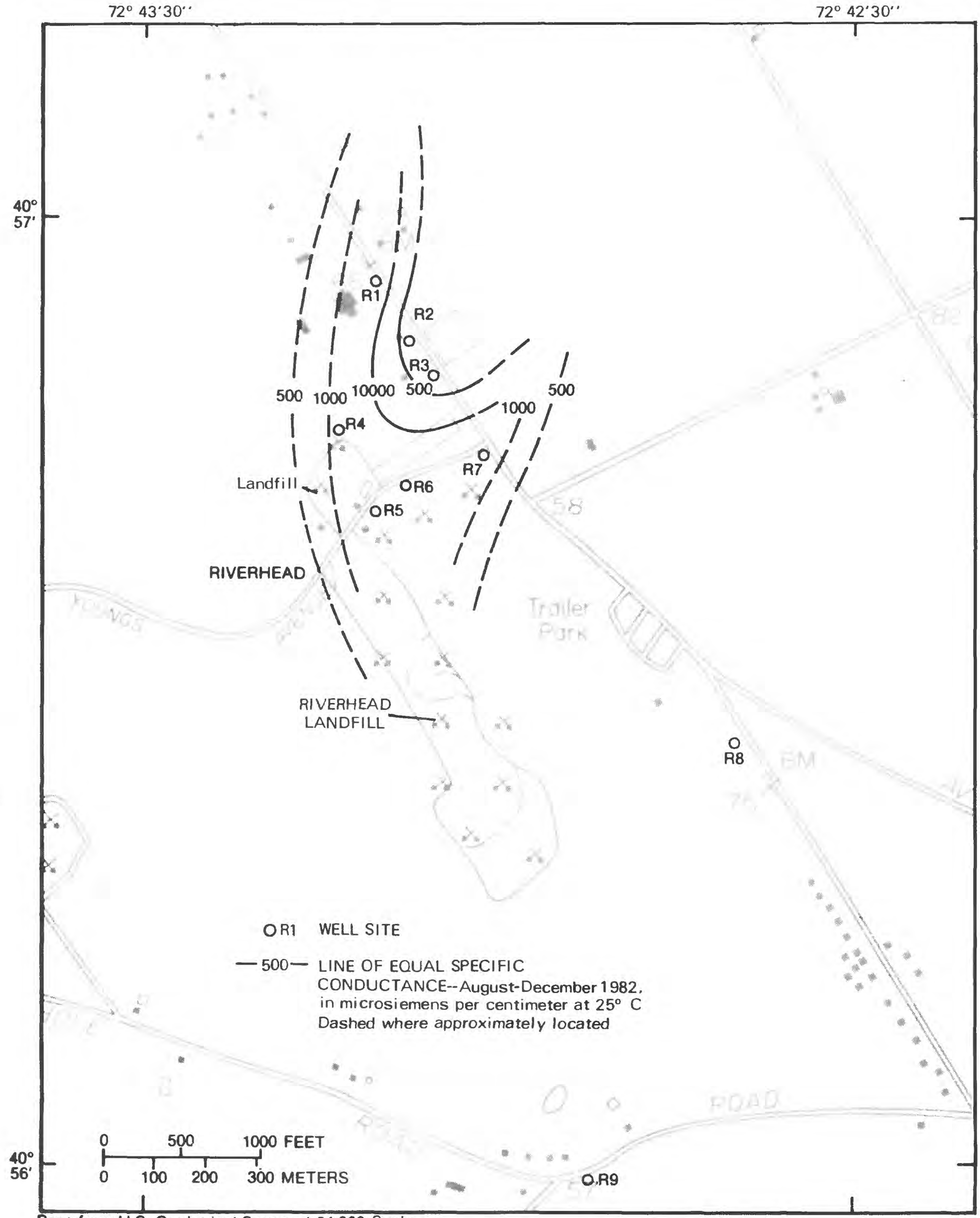
fields; the measurement stations were 164 ft apart. The measurements were adjusted through equations 3 and 4 to remove the effect of the unsaturated zone, as described in the methods section, and are plotted on figures 14 and 15 as saturated-zone conductivities. Thickness of the unsaturated zone was determined from topographic contours and the water-table altitude map, both given in figure 12. The conductivity of the unsaturated zone, for use in equation 3, was determined to be approximately 1.0 mmho/m.

Vertical and horizontal dipole values, contoured in figures 14A and 14B, respectively, reveal a conductivity anomaly similar to that indicated by specific conductance of ground water (fig. 13). A plume can be delineated, somewhat arbitrarily, at 5 mmho/m, which roughly corresponds to a specific conductance of at least 500 μS/cm in ground water at this site. The delineation is arbitrary because few specific-conductance data points are available with which to correlate the electromagnetic data. The primary axis trends north in a narrow zone along the direction of ground-water flow from the landfills, which is consistent with the observation of Kimmel and Braids (1980), who, in a study of two other Long Island landfills, noted little lateral dispersion of the leachate plumes. The conductivity decreases toward background levels to either side of the plume, as seen in lines H, E, and D of figure 15. The primary axis is marked by conductivity values exceeding 15 mmho/m; the higher values are at greater depths, as in traverses C and D (fig. 15). Of the traverses showing elevated conductivity, those nearest the landfills--for example, lines B and H--generally show small contrast in vertical dipole values, whereas at greater distances (lines A, C, and F), the contrast in dipole values becomes more apparent. This suggests that the contaminant plume is somewhat homogeneous with depth near the landfill but becomes stratified with distance.

The part of the plume that trends north may represent a "slug" of older leachate that originated from the north landfill. More recent leachate from this area seems to be diminishing in concentration. The precise location of the toe of this plume was not detected in this investigation but is probably near the area indicated in figure 14.

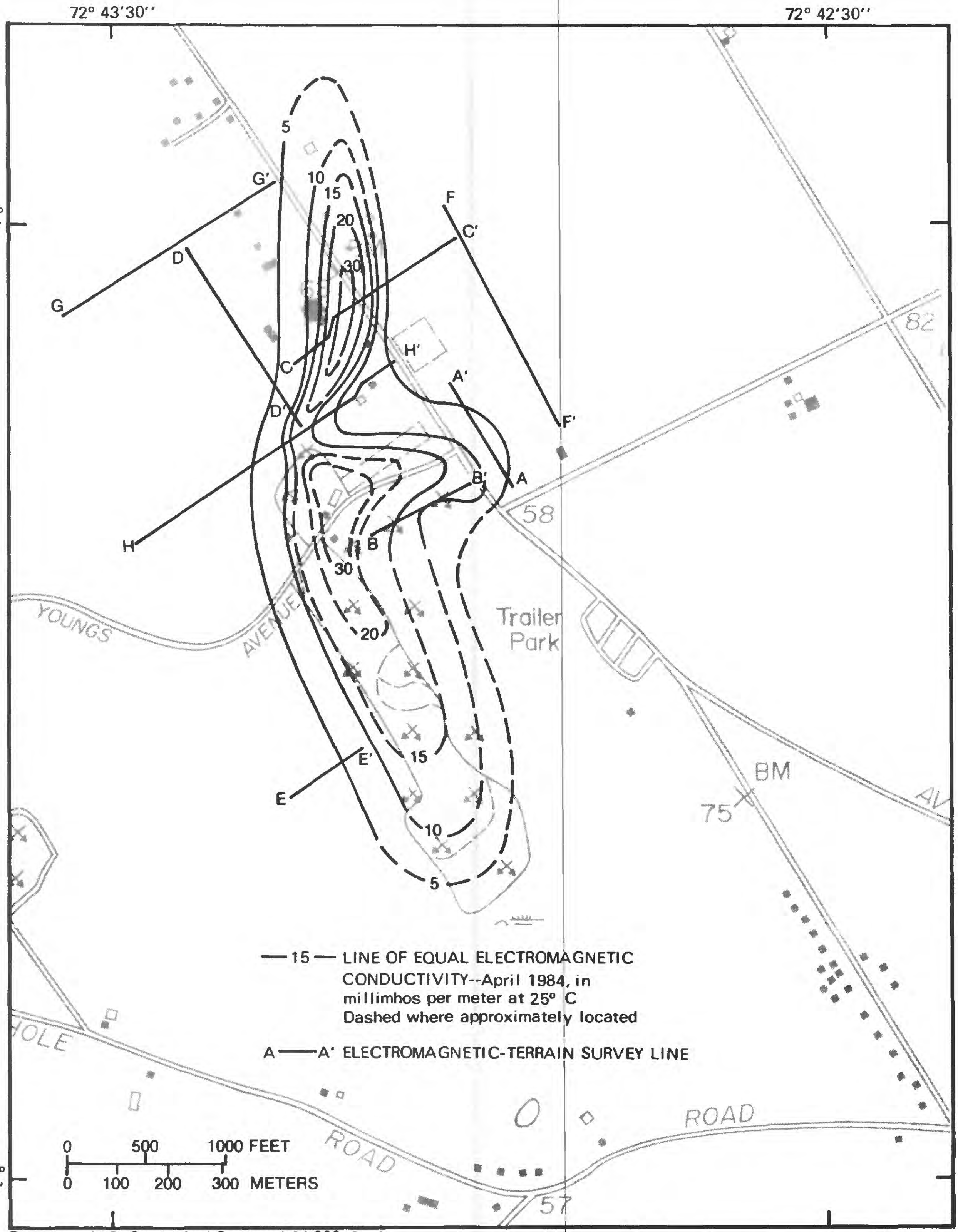
A second, more widely dispersed plume trends eastward from between the two landfills. The direction of this trend is probably the result of a locally altered ground-water flow pattern caused by the east recharge basin. Plume stratification is evident in traverses A and F (fig. 15). Saturated-zone conductivity is greater in the upper part of the ground water, where the plume apparently is concentrated. The conductivity peak of traverse A also is prominent in traverse F. Specific-conductance values at well site R7 (table 4) also are elevated, but plume stratification is slight. Large conductivity fluctuations with time have been noted in leachate plumes on Long Island (Kimmel and Braids, 1980); therefore, direct correlations between specific-conductance data and electromagnetic-survey data, which were obtained more than 1 year later, cannot be made with accuracy at this site.

The anomalously low saturated-zone conductivity around the primary recharge basin probably results from relatively clean recharge water, which diverts the flow of leachate. Traverse H (fig. 15) shows a shallow (horizontal dipole) area of low conductivity along the line of ground-water flow from this basin. This anomaly is confirmed by specific-conductance data from wells R2 and R3 (table 4) west of the basin.



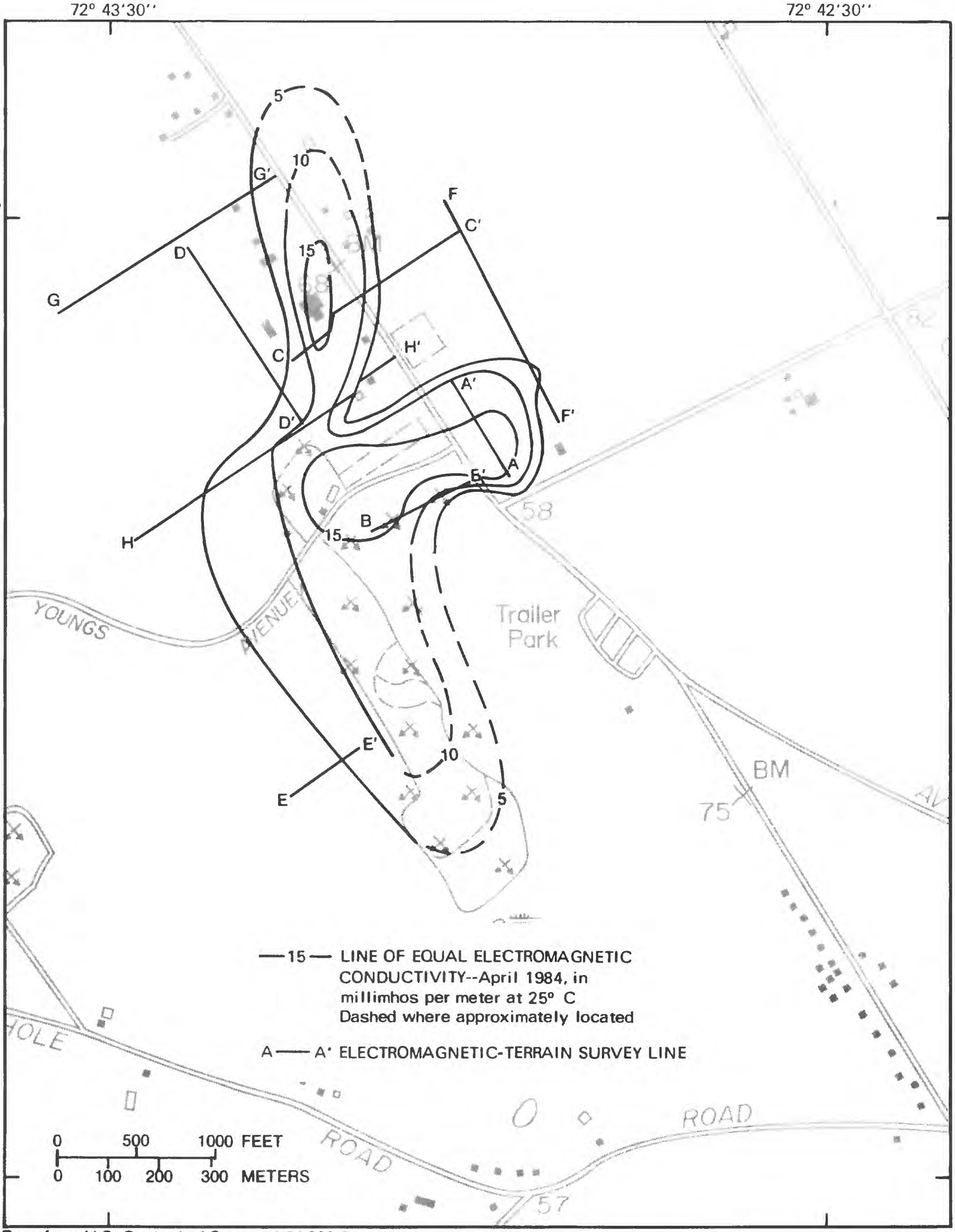
Base from U.S. Geological Survey, 1:24,000 Scale
Riverhead, N.Y., 1981

Figure 13.--Specific conductance at Riverhead landfill during August-December 1982 and location of observation wells. (Location is shown in fig. 1.)



Base from U.S. Geological Survey, 1:24,000 Scale
Riverhead, N.Y., 1981

Figure 14A.--Electromagnetic conductivity of saturated zone based on vertical dipole data at the Riverhead landfill, April 1984, and location of survey lines. (Location is shown in fig. 1.)



Base from U.S. Geological Survey, 1:24,000 Scale
Riverhead, N.Y., 1981

Figure 14B.--Electromagnetic conductivity of saturated zone based on horizontal dipole data at the Riverhead landfill, April 1984, and location of survey lines. (Location is shown in fig. 1.)

The survey at this site can be considered successful because the results compare favorably with the observation-well analysis. As at the two sites described previously, the electromagnetic survey yields greater lateral resolution than is possible from ground-water analyses because the number of well sites is small. Even though the saturated-zone conductivity and specific conductance data cannot be correlated directly, generalized correlations are plausible in that high values of each data occur at the same locations.

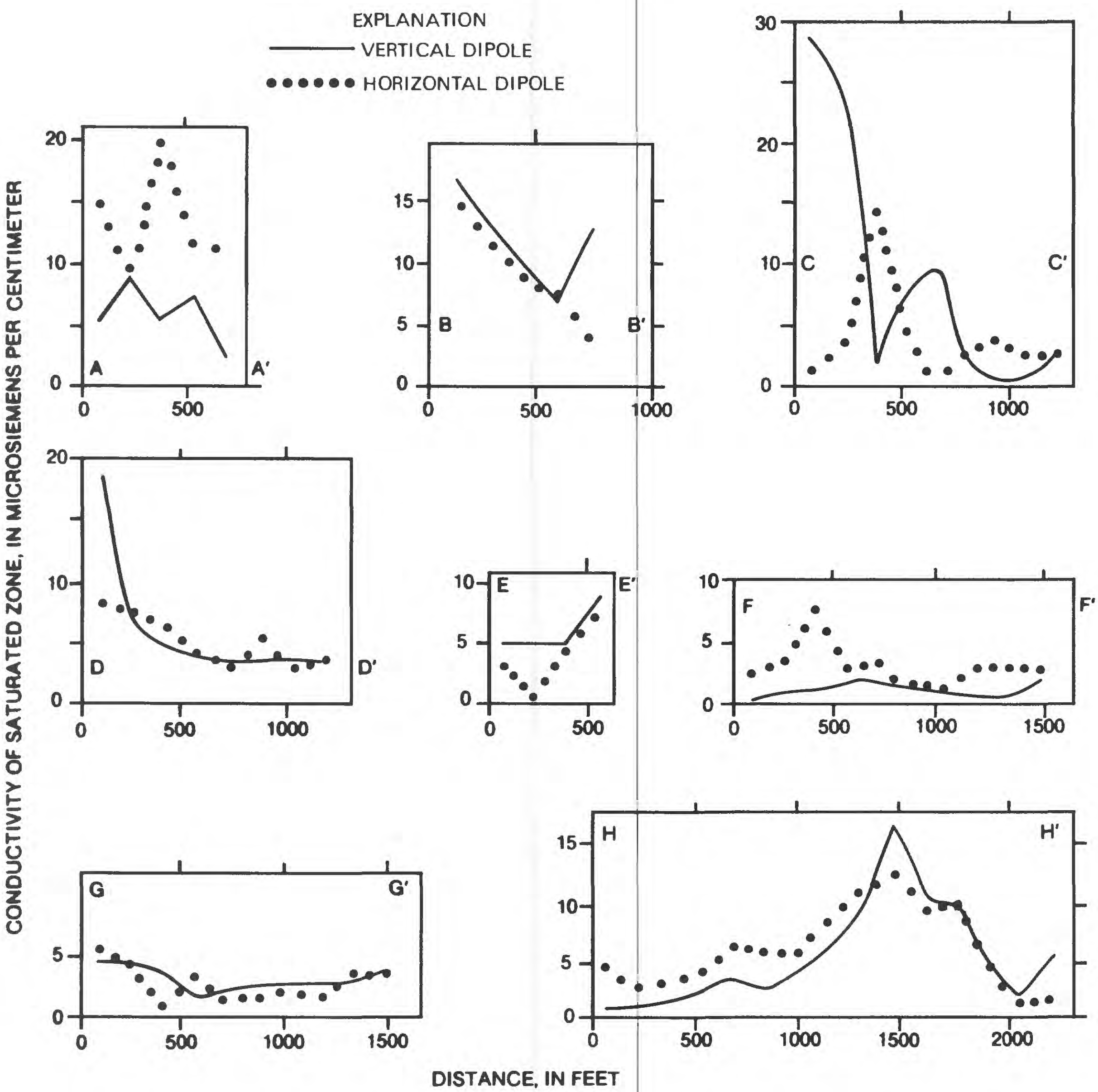


Figure 15.--Electromagnetic conductivity of saturated zone along lines A through H at Riverhead landfill, April 1984. (Line locations are shown in fig. 14.)

Table 4.--Specific conductance of ground water in upper glacial aquifer in Riverhead landfill vicinity, August through December 1982.

[Data from Suffolk County Department of Health Services; well locations shown in fig. 13]

Measurement-site number	Well number	Well depth (feet)	Measurement-point altitude (feet above sea level)	Specific conductance (microsiemens per centimeter)
R1	S73892	68	68.31	330
R1	S73892	83	68.31	1,600
R1	S73892	108	68.31	1,050
R2	S73714	63	66.56	125
R2	S73714	80	66.56	85
R2	S73714	105	66.56	220
R3	S73432	105	61.18	225
R4	S73715	83	82.19	1,350
R4	S73715	104	82.19	790
R5	S73269	62	[1]	420
R5	S73269	72	[1]	630
R5	S73269	82	[1]	860
R5	S73269	92	[1]	1,400
R5	S73269	102	[1]	760
R5	S73271	83	72.29	554
R6	S73891	60	69.67	88
R6	S73891	82	69.67	1,650
R6	S73891	103	69.67	1,700
R7	S73716	63	61.30	140
R7	S73716	83	61.30	1,100
R7	S73716	104	61.30	400
R8	S73508	104	56.92	78
R9	S51576	57	57.99	112

[1] This well has been removed.

Blydenburgh Road Landfill

The Blydenburgh Road landfill is on the west side of Blydenburgh Road north of Long Island Motor Parkway (fig. 16). This area contains several housing developments and major roads. The relief is hilly, and the land-surface altitude exceeds 150 ft.

The Blydenburgh Road landfill has been operating since 1927 and is now the principal landfill for the town of Islip. It occupies approximately 50 acres and is partly lined. The material includes mixed municipal wastes, scavenger wastes, and waste oil.

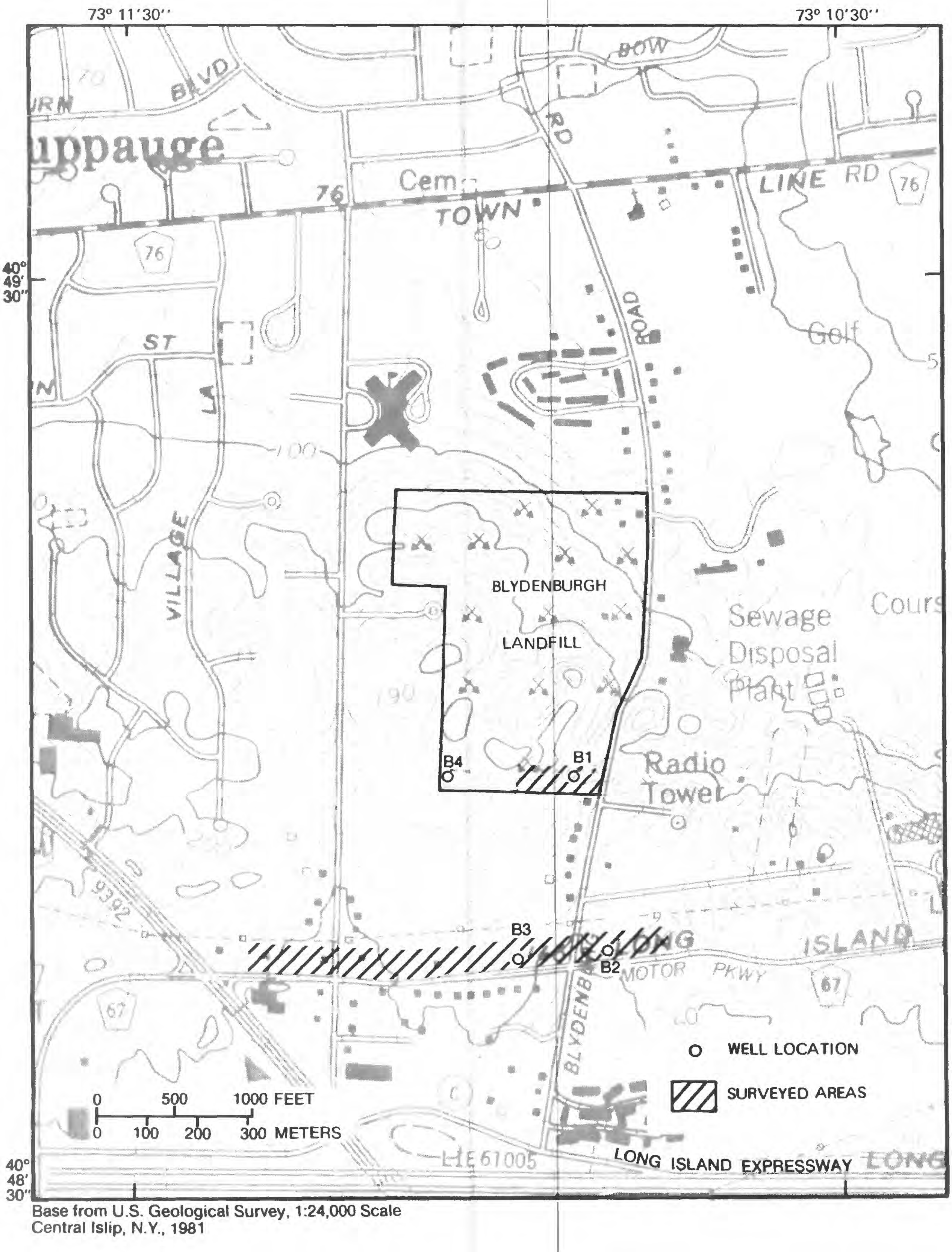


Figure 16.--Location of Blydenburgh landfill and electromagnetic-survey areas, April 1984. (General location is shown in fig. 1.)

Hydrogeology

The Blydenburgh site lies on upper Pleistocene deposits, which extend to approximately 300 ft below land surface. Drillers' logs reveal that these deposits consist of coarse- to fine-grained sand with gravel, boulders, and laminae of silty sand and clay. The hydraulic conductivity of these materials is generally low to moderate (Jensen and Soren, 1974). Depth to the water table is approximately 110 ft, and the water surface is essentially level at 40 ft above sea level within the site. A regional water-table map by Donaldson and Koszalka (1983) shows that this site is on the water-table divide and thus in an area of deep-aquifer recharge.

Water Quality

Ground water beneath the site was examined by Velzy Associates (1981) at the four well sites indicated in figure 16. Contamination was found at well B1, immediately southeast of the landfill, with a specific conductance of 1,000 μS/cm. No contamination was observed at sites B2, B3, or B4, and specific conductances were low; thus no plume could be delineated at this site.

Results of Terrain-Conductivity Survey

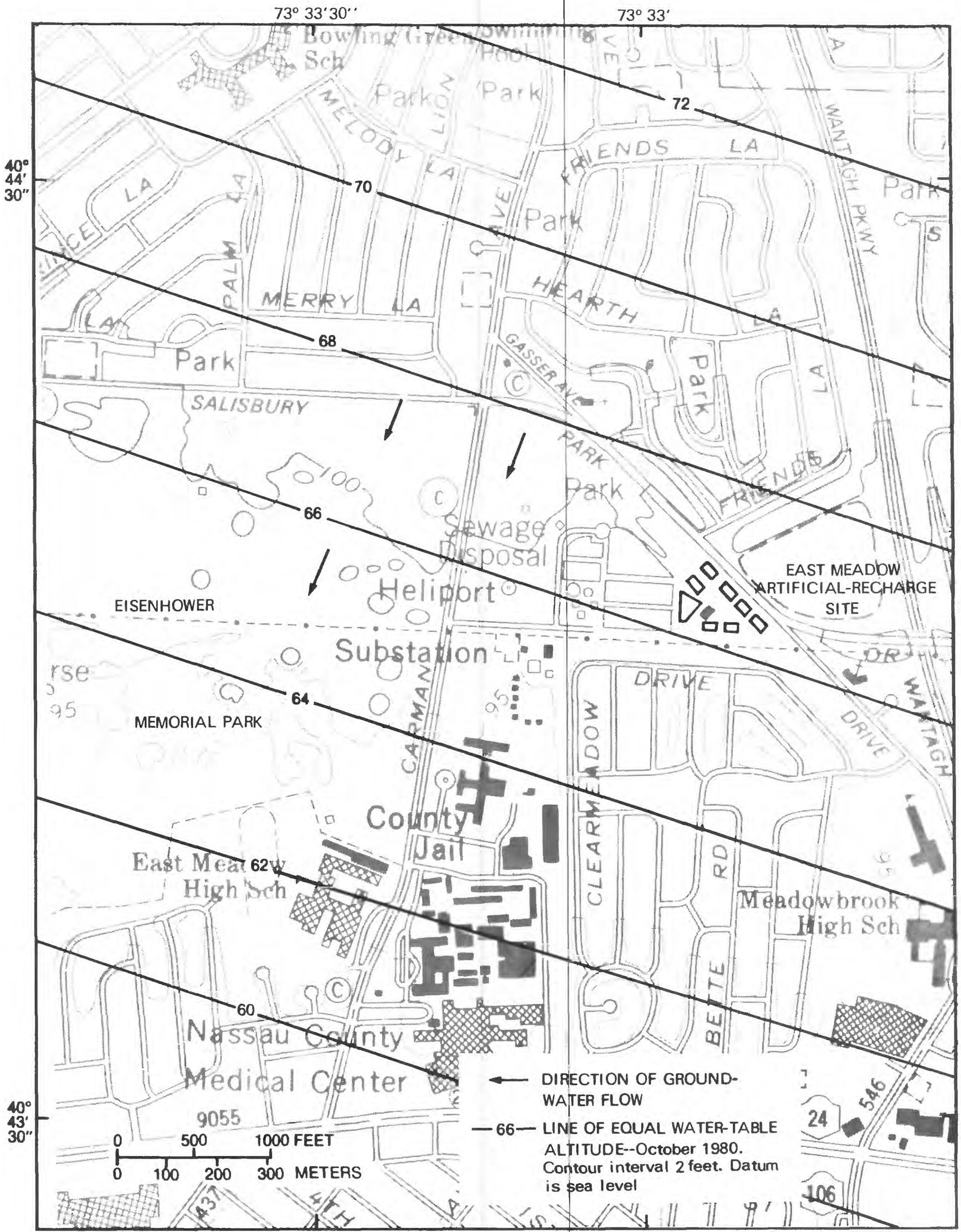
A terrain-conductivity survey was conducted at this site during April 1984. The area parallel to Motor Parkway (fig. 16) was examined because it transects the most likely path of a leachate plume and was readily accessible and because cultural interferences were least likely there. An intercoil spacing of 131 ft was used because the depth to water exceeded 100 ft.

Cultural interferences in this area were found to be excessive, however, and gave inconsistent and unreliable data. Thus, the electromagnetic survey was unsuccessful at this site. The interferences included traffic on Motor Parkway and buried water mains crossed by the traverses. A nearby high-power transmission line north of the parkway, and utility-service cables south of the parkway, probably also disturbed the readings. The terrain conductivity was also examined at the south edge of the landfill. Here, too, the depth to water necessitated the 131-ft intercoil spacing, and again, the disturbances were excessive.

Use of the 131-ft intercoil spacing seems to heighten the effects of cultural disturbances. At wide spacing, the magnetic field received is weaker than that obtained from shallow depths with shorter spacings; thus background electromagnetic "noise" may outweigh the electromagnetic properties of materials being examined and produces anomalous or constantly shifting readings.

East Meadow Artificial-Recharge Site

The East Meadow recharge site encompasses 35 acres owned by Nassau County in the triangular area southeast of the intersection of Salisbury Park Drive and Carman Avenue (fig. 17). The site includes a sewage-disposal plant and an artificial-recharge site. The surrounding area is suburban with negligible topographic relief.



Base from U.S. Geological Survey, 1:24,000 Scale
Freeport, NY, 1981

Figure 17.--Water-table altitude at East Meadow artificial-recharge site, October 1980. (General location is shown in fig. 1.)

The sewage-disposal plant operated until 1979, and the recharge site discontinued its operation in 1984. The recharge operation, described in detail by Aronson (1980) and Schneider and Oaksford (1984), incorporated 11 basins and 5 injection wells designed to receive a total of 4 Mgal/d of reclaimed water. The basins are shallow (5 ft) and transmit water to the water table; the injection wells are screened 65 to 95 ft below land surface and inject water directly into the top of the Magothy aquifer.

Hydrogeology

The site is on upper Pleistocene deposits of highly permeable outwash sand and gravel (Katz and Mallard, 1980). Core borings show these deposits to extend 50 to 70 ft below land surface (Aronson and others, 1983). Magothy deposits are in hydraulic contact with the Pleistocene deposits and are within the exploration depth of this investigation, approximately 100 ft. These deposits consist of fine to medium sand, silt, clay, and gravel (Katz and Mallard, 1980). Interbedded silt and clay lenses are discontinuous and generally less than 5 ft thick (Aronson, 1980).

The local water-table configuration is shown in figure 17. The direction of ground-water flow is generally southward, and the thickness of the unsaturated zone is approximately 35 ft. A regional water-table map by Donaldson and Koszalka (1983) indicates that this is probably an area of moderately deep aquifer recharge.

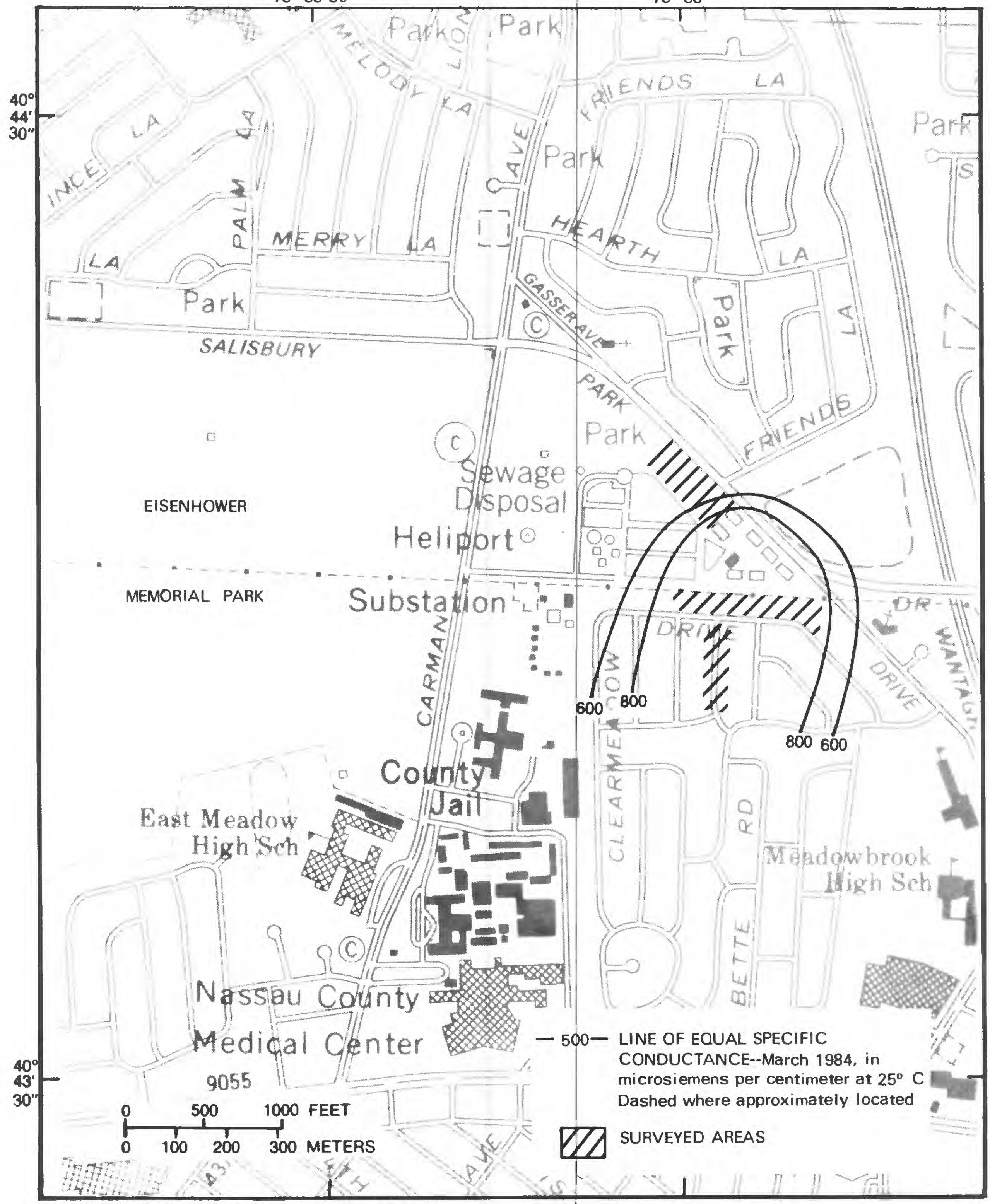
Water Quality

Reclaimed wastewater used for recharge at this site was supplied by an offsite advanced wastewater-treatment plant designed to produce potable water (Aronson and others, 1983). The chemical quality of the native ground water at this site has been described by Katz and Mallard (1980), Aronson and others (1983), and Schneider and Oaksford (1985). Specific conductance of shallow ground water ranges from 200 to 500 µS/cm; that of reclaimed water ranges from 800 to 1,100 µS/cm (Schneider, U.S. Geological Survey, written comun., 1984). Reclaimed water of relatively high specific conductance underlies the site (fig. 18), and sharp contrasts of more than 600 µS/cm have been measured between this plume and the ambient water over short lateral distances.

Results of Terrain-Conductivity Survey

Terrain-conductivity surveys were conducted in January 1983 in areas believed to be least influenced by cultural interferences (fig. 18). An intercoil spacing of 66 ft was used to penetrate the aquifer materials in question.

Electromagnetic surveying was unsuccessful because this site is heavily influenced by cultural interferences. The residential street along which an electromagnetic traverse was conducted was influenced by water mains and sewer lines under and alongside the road, and by power and telephone lines over the road. The traverses immediately south of the site were disturbed by a



Base from U.S. Geological Survey, 1:24,000 Scale
Freeport, NY, 1981

Figure 18.--Specific conductance of ground water at the East Meadow artificial-recharge site, March 1984, and location of electro-magnetic survey areas. (Location is shown in fig. 1.)

high-power transmission line and chain-link fences. The area immediately north of the site was initially expected to be more promising because it is an agricultural field. However, disturbances from nearby sources affected this region, too; these included traffic on Salisbury Drive, buried power and telephone cables adjacent to the road, and a chain-link fence.

SUMMARY AND CONCLUSIONS

Electromagnetic terrain-conductivity surveys were conducted at four landfills and one artificial-recharge site on Long Island to assess the utility of this technique in contaminant-plume detection and delineation. This technique was successful at three of the sites--Horseblock Road, Manorville, and Riverhead--where a contaminant plume was detected and confirmed by water-quality data.

This technique was ineffective in detecting plumes at the Blydenburgh landfill and East Meadow recharge site, where cultural interfences were excessive; the large depth to water at the Blydenburgh site (approximately 110 feet) was an additional limiting factor.

Cultural interferences included underground pipelines and utility cables, overhead cables, metal fences, and traffic. Therefore, investigations of this type are more effective in areas with fewer or avoidable interferences.

Depth stratification of contaminant plumes was examined, but corresponding water-quality data had been taken months before or after the terrain-conductivity surveys, which allowed only rough comparisons. Additionally, the maximum penetration depth of the present equipment (approximately 100 ft) allows examination of only the upper part of the saturated zone in most areas, and subdivision of that zone would not be realistic.

Electromagnetic terrain-conductivity surveying can be useful in contaminant-plume investigations where geohydrologic and cultural conditions are favorable. Under such conditions, a conductive plume can be delineated with finer lateral resolution than could be provided, practically, by ground-water sampling at observation wells. Electromagnetic techniques do not, however, identify the chemical constituents of the water and cannot replace observation-well sampling. Information gained through use of this technique permits selection of optimal sites for placement of observation wells to minimize the costs and manpower involved in well installation.

REFERENCES CITED

Aronson, D. A., 1980, The Meadowbrook artificial recharge project in Nassau County, Long Island, New York: Long Island Water Resources Bulletin 14, 23 p.

Aronson, D. A., Lindner, J. B., and Katz, B. G., 1983, Geology of the Meadowbrook artificial-recharge site at East Meadow, Nassau County, New York: U.S. Geological Survey Water-Resources Investigations Report 82-4084, 44 p.

Cohen, Philip, Franke, O. L., and Foxworthy, B. L., 1968, An atlas of Long Island's water resources: New York State Water Resources Commision Bulletin 62, 117 p.

Donaldson, C. D., and Koszalka, E. J., 1983, Water table on Long Island, New York, March 1979: U.S. Geological Survey Open-File Report 82-163, 2 sheets.

Duran, P. B., and Haeni, F. P., 1982, The use of electromagnetic conductivity techniques in delineation of ground-water contamination plumes, in The impact of waste storage and disposal on ground-water resources [proceedings of northeast conference, Ithaca, N.Y., June 28-July 1, 1982]: Ithaca, N.Y., U.S. Geological Survey and Cornell University Center for Environmental Research, p. 8.4.1 -8.4.33.

Dvirka and Bartilucci, Consulting Engineers, 1981, Scavenger waste landfill leachate study for Town of Brookhaven: Syosset, N.Y., Dvirka and Bartilucci Consulting Engineers, Inc., 166 p.

Eckhardt, D. A., and Wexler, E. J., 1986, Ground-water movement in the upper glacial aquifer in the Manorville area, Town of Brookhaven, Long Island, New York, in November 1983: U.S. Geological Survey Water-Resources Investigations Report 85-4035, 12 p.

Franke, O. L., and McClymonds, N. E., 1972, Summary of the hydrologic situation on Long Island, New York, as a guide to water-management alternatives: U.S. Geological Survey Professional Paper 627-F, 59 p.

Grady, S. J., and Haeni, F. P., 1984, Application of electromagnetic techniques in determining distribution and extent of ground-water contamination at a sanitary landfill, Farmington, Connecticut, in Proceedings of the National Water Well Association/U.S. Environmental Protection Agency conference on surface and borehore geophysical methods in ground-water investigations: San Antonio, Tex., p. 338-367.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Holzmacher, McLendon, and Murrell, 1975, Study of leachate at landfill sites, 1975: Melville, N.Y., Holzmacher, McLendon, and Murrell, P.C., Consulting Engineers, v. 1, 142 p.

REFERENCES CITED (continued)

Jensen, H. M., and Soren, Julian, 1974, Hydrology of Suffolk County, Long Island, New York: U.S. Geological Survey Hydrologic Investigation Atlas HA-501, 2 sheets.

Katz, B. G., and Mallard, G. E., 1980, Chemical and microbiological monitoring of a sole-source aquifer intended for artificial recharge: U.S. Geological Survey Open-File Report 80-567, 18 p.

Kimmel, G. E., and Braids, O. C., 1980, Leachate plumes in ground water from Babylon and Islip landfills, Long Island, New York: U.S. Geological Survey Professional Paper 1085, 38 p.

McClymonds, N. E., and Franke, O. L., 1972, Water-transmitting properties of aquifers on Long Island, New York: U.S. Geological Survey Professional Paper 627-E, 24 p.

McNeill, J. D., 1980a, Electromagnetic terrain conductivity measurement at low induction numbers: Mississauga, Ont., Geonics Ltd., Technical note TN-6, 15 p.

__________ 1980b, Electrical conductivity of soils and rocks: Mississauga, Ont., Geonics Ltd., Technical note TN-5, 22 p.

Schneider, B. J., and Oaksford, E. T., 1984, Design, operation, and monitoring capability of an experimental artificial-recharge facility at East Meadow, Long Island, New York: U.S. Geological Survey Water-Resources Investigations Report 84-4321, 28 p.

Slaine, D. D., and Greenhouse, J. P., 1982, The use of reconnaissance electromagnetic methods to map contaminant migration, in Nielsen, D. M., ed., Proceedings of the second national symposium on aquifer restoration and ground water monitoring: Worthington, Ohio, National Water Well Association, p. 299-315.

Stewart, M. T., 1982, Evaluation of electromagnetic methods for rapid mapping of salt-water interfaces in coastal aquifers: Ground Water, v. 20, no. 5, 538-545.

Velzy Associates, Inc., 1981, Ground water and leachate investigations Blydenburgh Landfill, Hauppauge, New York: Mineola, N.Y., Velzy Associates, Inc., 215 p.

Wexler, E. J., Ground-water flow and solute transport at the Brookhaven landfill site, Long Island, New York--Part 1, Hydrogeology and chemical quality of ground water: U.S. Geological Survey Water-Resources Investigations 86-4070 (in press).

☆ U.S. GOVERNMENT PRINTING OFFICE: 1987—887 - 181/50220