INTEGRATED GEOPHYSICAL CHARACTERIZATION OF THE WINTHROP LANDFILL SOUTHERN FLOW PATH, WINTHROP, MAINE

C.B. Dawson, U.S. Geological Survey, Storrs, CT
J.W. Lane, Jr., U.S. Geological Survey, Storrs, CT
Eric A. White, U.S. Geological Survey, Storrs, CT
Marcel Belaval, U.S. Geological Survey, Storrs, CT

Abstract

The U.S. Geological Survey (USGS), in cooperation with United Technologies Corporation, used an integrated suite of borehole, surface, and water-borne geophysical methods near the site of the former Winthrop Landfill, Winthrop, Maine, to investigate the hydrogeology controlling the transport of leachate from the landfill to nearby Annabessacook Lake. During the fall of 2000 and summer of 2001, the USGS conducted borehole electromagnetic (EM) induction and gamma logging, and inductive terrain-conductivity, two-dimensional (2D) resistivity, continuous seismic reflection, and magnetic surveys.

The objectives of this integrated geophysical study were to provide constraints on the location and extent of the southern flow path(s) of contamination from the landfill to the lake; identify shoreline seep geophysical signatures; identify potentially hidden seeps in the lake; and determine depth to bedrock below Annabessacook Lake in the study area.

Interpretation of surface 2D resistivity, magnetic, and inductive terrain-conductivity data and borehole EM logs delineates an electrically conductive anomaly consistent with a leachate plume moving from the current landfill boundary southward through the overburden to the shores of Annabessacook Lake. Surface and borehole geophysical data collected south and southeast of the landfill indicate the presence of discrete, shallow conductive anomalies at the southeastern edge of the landfill and near the lakeshore. The conductive anomalies appear at increasing depths closer to the lake. Magnetic anomalies offshore confirm the presence of iron-rich landfill leachate discharging into the lake south of the landfill. High-resolution swept-frequency seismic data used to map sediment and grain size distribution in the lake sub-bottom along the shoreline identified sediment-infilled bedrock lows that may act as conduits for contaminant migration.

Introduction

The Winthrop Landfill in Winthrop, Maine, is an inactive waste-disposal site that was used from the 1930's until 1982 (E.C. Jordan Co., 1990). The 13-acre site originally was used as a sand-and-gravel pit until the 1930's, after which it accepted municipal, commercial, and industrial waste. Hazardous substances, including resins, plasticizers, solvents, and other processing chemicals, were disposed of at the site from the early 1950's until the 1970's (U.S. Environmental Protection Agency, 2001). In 1980, the Maine Department of Environmental Protection and the U.S. Environmental Protection Agency initiated an investigation of the site as a result of reports from the landfill operator about leaking buried drums and complaints from local residents about odors in private drinking-water wells (U.S. Environmental Protection Agency, 1983). Preliminary investigations identified contaminants, including iron and arsenic, indicative of landfill leachate in water samples from wells screened in the overburden southeast of the landfill and in seeps on the bottom of nearby Annabessacook Lake.

Citation: Dawson, C.B., Lane, J.W., Jr., White, E.A., and Belaval, Marcel, Integrated geophysical characterization of the Winthrop Landfill southern flow path, Winthrop, Maine, in Symposium on the Application of Geophysics to Engineering and Environmental Problems, Las Vegas, Nevada, February 10-14, 2002, Proceedings: Denver, Colo., Environmental and Engineering Geophysical Society, CD-ROM, 22p.

The U.S. Geological Survey (USGS), in cooperation with United Technologies Corporation (UTC), used an integrated suite of borehole, surface, and water-borne geophysical methods near the site of the former Winthrop Landfill (Figure 1) to investigate the hydrogeology affecting the transport of leachate from the landfill southeast to Annabessacook Lake. During the fall of 2000 and summer of 2001, the USGS conducted borehole electromagnetic (EM) induction and gamma logging and inductive terrain-conductivity, two-dimensional (2D) resistivity, continuous seismic reflection, and magnetic surveys. The objective of this integrated geophysical study was to provide constraints on the location and extent of the southern flow path(s) of contamination from the landfill to the lake; identify shoreline seep geophysical signatures; identify potentially hidden seeps in the lake; and determine depth to bedrock below Annabessacook Lake in the study area.

Description of the Study Area

The Winthrop Landfill and Annabessacook Lake are in the town of Winthrop in Kennebec County, Maine. The current southeastern boundary of the Winthrop Landfill is within 300 meters (m) of the lake's western shore. The study area extends from the southeast corner of the landfill east and southeast to the lakeshore (Figure 1).

The western shore of Annabessacook Lake primarily is Pleistocene marine deposits of silt, clay, and fine to very fine sand with layers of sand and gravel. The landfill overlies a narrow, northwest-southeast trending unit (Prescott, 1969) identified as Pleistocene ice-contact deposits of poorly- to well-stratified sand, gravel, and cobbles with some clay, silt, and boulders. The north-south trending meta-sedimentary bedrock trough below the landfill is filled with three distinguishable stratigraphic layers comprising 1) clayey silt and very fine sand; 2) poorly graded fine sand; and 3) medium to coarse sands and silty, gravelly sand (E.C. Jordan Co., 1990). Regional reconnaissance of the surficial geology (Thompson, 1977) indicates that the landfill and part of the southern flow path study area are on a glacial end-moraine deposit, composed primarily of sand and gravel, and glacial marine deposits of silt and clay.

The permeability of glacial end-moraine deposits in the study area is highly variable, and the glacial marine deposits have low permeability (Thompson, 1977). The landfill is on a sand and gravel aquifer with moderate to good yield potential (Nell and Locke, 1999). This aquifer extends south to Annabessacook Lake. Areas directly to the east of the landfill and northeast of the study area are underlain by surficial deposits with less yield potential than at the landfill.

Ground water in the region flows from areas of high hydraulic head in silty sediments to the west of the landfill to areas of lower head at the landfill and south of the landfill and discharges upward into Annabessacook Lake (E.C. Jordan Co., 1990). Thick sand-and-gravel layers are overlain by 3 to 4.5 m of alternating layers of clayey silt and fine to medium sand, which is believed to hydraulically connect the underlying permeable sand and gravels with the lake. Hydrologic studies indicate that, under typical conditions, ground water discharges into the lake year-round.

Geophysical Methods

Geophysical methods provide an efficient means of characterizing subsurface geology and hydrology. The methods used in this study measure subsurface electrical, electromagnetic, acoustic, nuclear, and magnetic properties. Iterative and integrated data collection and interpretation using multiple geophysical methods provides for a more synergistic interpretation of data that often results in a more accurate model of the complex structures and processes of the subsurface.

STUDY AREA

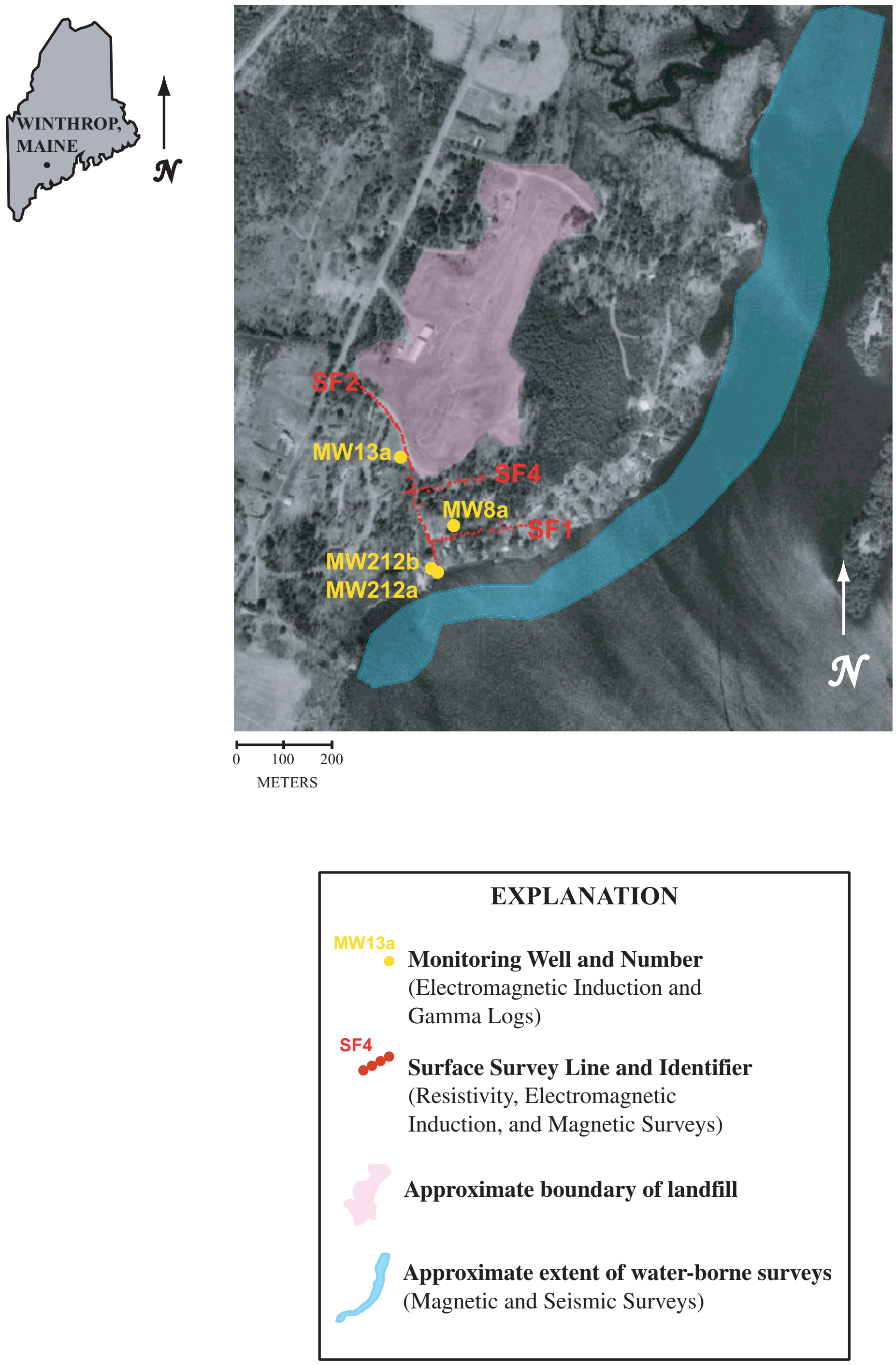

Figure 1. Location of study area and geophysical investigations near the Winthrop Landfill, Winthrop, Maine.

Electrical and Electromagnetic Methods

2D direct current (dc) electrical resistivity methods measure the apparent resistivity of the subsurface (Zohdy and others, 1974; Reynolds, 1997). Apparent resistivity data can be inverted (Figure 2) to develop a model of the subsurface structure and stratigraphy in terms of its electrical properties (deGroot-Hedlin and Constable, 1990; Oldenburg and Li, 1999; Tsourlos and others, 1999; Loke, 2001). The resistivity of the subsurface is affected by porosity, amount of water in the subsurface, ionic concentration of the pore fluid, and composition of the subsurface materials. Resistivity data can be used to identify, delineate, and map subsurface features such as electrically conductive contamination plumes, bedrock fracture zones, the saltwater/freshwater interface, the vadose zone, electrically conductive lithologic units such as clay, and sediment size distribution.

Inductive terrain-conductivity is an electromagnetic method that measures the bulk apparent subsurface electrical conductivity (McNeill, 1990). Subsurface conductivity is the reciprocal of resistivity and is affected by the same factors as resistivity. Surface inductive terrain-conductivity surveys are used to detect conductive features such as buried metal objects, ore bodies, and fluid-filled fractures and to map conductive plumes, such as landfill leachate or saltwater intrusion (McNeill, 1980; Grady and Haeni, 1984; Frischknecht and others, 1991; Powers and others, 1999). In this study, the Geonics EM31[1] terrain-conductivity meter was used for surface-conductivity surveys.

Geomagnetic Surveying

Geomagnetic surveying measures the intensity of and variations in the earth's magnetic field (Zohdy and others, 1974; Geometrics, 1996; Breiner, 1999). For near-surface magnetic surveys, the magnitude, gradient, and spatial variation of the magnetic field is used to delineate possible lithologic changes in the subsurface as well as to identify subsurface anthropogenic objects with magnetic properties. Many rocks and sediments contain varying amounts of magnetite, and certain ore bodies have strong magnetic signatures; thus, magnetic data may be used to identify certain changes in subsurface lithology. Examples of anthropogenic buried objects with magnetic signatures include metal trucks and drums, pipelines, and steel well casings.

To negate the effects of diurnal and temporal variations, magnetic gradient data are used in the analyses in this report. As a result of the geometry of the gradiometer, noise from long-wave features is suppressed and near-surface anomalies are emphasized, an advantage relative to the goals of this study (Geometrics 1996; Reynolds, 1997). Both land and water-borne geomagnetic surveys were conducted as part of this study.

Continuous Seismic Profiling

Continuous seismic-reflection profiling methods use acoustic waves to delineate the subsurface structure and lithology (Sylwester, 1983; Haeni, 1986). An acoustic wave is reflected at a material interface when there is a change in acoustic impedance across the interface. Changes in lithology or structure can result in changes in acoustic impedance. The greater the contrast in acoustic impedance across an interface, the stronger the reflected signal is at that interface. For a given survey, low-frequency signals will tend to improve depth of penetration but decrease vertical resolution, whereas high-frequency signals will increase vertical resolution and have shallower penetration. Continuous seismic-reflection profiling can be used to estimate the depth of till and bedrock interfaces, evaluate grain-size characteristics of subsurface materials, and indicate bedding planes (Haeni, 1996).

---

[1] Reference to non-USGS products is provided for information only and does not constitute endorsement by the U.S. Government.

INVERSION OF RESISTIVITY FIELD DATA

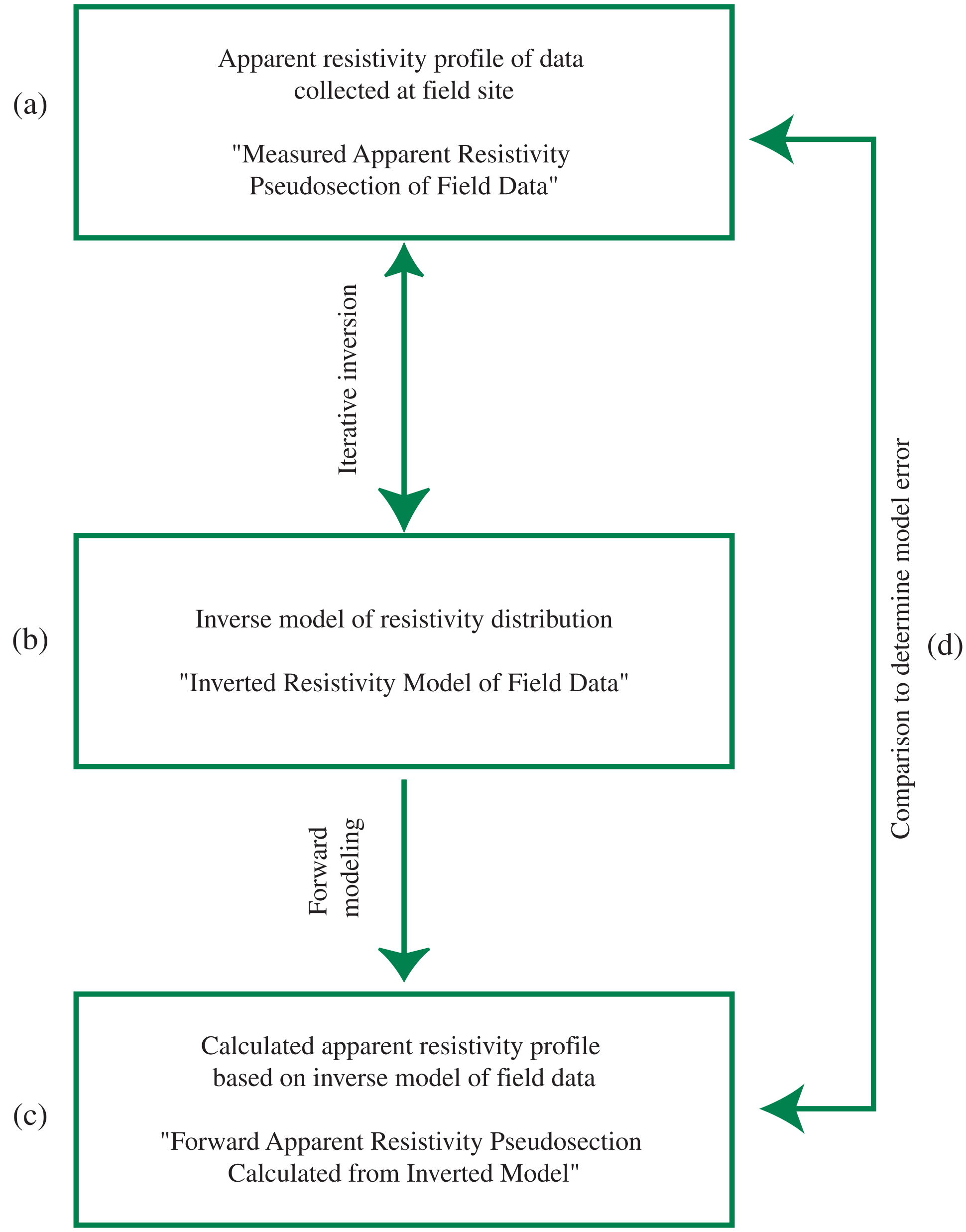

Figure 2. Overview of two-dimensional (2D) resistivity inversion process (Loke, 2001):
(a) Measured apparent resistivity data from field site are imported, and an apparent resistivity profile for the measured data is generated. The vertical dimension of the pseudosection does not have a simple relation to the geologic section or the inverted model.
(b) A non-unique model of true resistivity distribution is generated based on the actual measured field data.
(c) An apparent resistivity profile for the inverted model is generated.
(d) The two apparent resistivity profiles are compared to determine the Root-Mean-Square (RMS) error between them. RMS error is based on the percentage difference between the logarithm of the measured apparent resistivity data values and the calculated apparent resistivity values from the inverted model. Steps b, c, and d then are repeated iteratively, decreasing the error until it meets a user-defined value or the number of iterations reaches a user-defined maximum.

Borehole EM and Gamma Logging

Borehole EM induction logging (McNeill, 1986; McNeill and others, 1990) measures the bulk apparent electrical conductivity of the formation surrounding the borehole. Borehole EM induction surveys can be used to identify or confirm placement of screening in ground-water monitoring wells, monitor contamination levels outside of cased wells, and detect and (or) monitor contamination plumes in the vadose zone (Mack, 1993; Williams and others, 1993).

Natural-gamma logging records the total gamma radiation detected in the formation surrounding a borehole (Keys, 1997). Gamma-emitting isotopes are the natural products of daughter products of the uranium and thorium decay series and potassium-40. Natural-gamma radioisotopes tend to be found in higher concentrations in clays as a result of potassium-rich feldspar and mica decomposition into clay, and of uranium and thorium concentration in clay, as a result of adsorption and ion exchange. Gamma-emitting radioisotopes of anthropogenic origin cannot be differentiated from naturally occurring isotopes detected in natural-gamma borehole logging. Variations in the gamma log are used to indicate lithologic changes in the formation surrounding a borehole. Gamma logs do not have unique lithologic responses and must be interpreted in conjunction with data from other geophysical logs, drillers' records, and local geological data.

Surface and Borehole Geophysical Investigations

Surface and borehole geophysical surveys were conducted at the study area southeast of the Winthrop Landfill in the fall of 2000. Surface 2D resistivity, inductive terrain-conductivity, and geomagnetic surveys were conducted along three transects (SF4, SF1, and SF2) south of the Winthrop Landfill (Figure 1). Borehole EM and gamma logs were collected at four monitoring wells (8a, 13a, 212a, and 212b) in the study area (Figure 1).

Line SF4, oriented west-east

Line SF4, approximately 135 m long, is south of the toe of the Winthrop Landfill and is oriented roughly west-east, parallel to the shore of Annabessacook Lake in this area (Figure 1). The line is in a residential neighborhood and is approximately 90 m north of SF1.

2D resistivity profiles were collected along SF4 using Schlumberger and Wenner arrays using 28 electrodes spaced 5.0 m apart. The Wenner array measured apparent resistivity pseudosection, inverted resistivity model, and forward apparent resistivity pseudosection calculated from the inverted model are shown in Figures 3a-c. In both the Wenner and Schlumberger arrays, a near-surface low-resistivity anomaly is observed near the center of the survey line. The resistivity of the anomaly increases with depth.

Geomagnetic gradiometer measurements were recorded every 1.5 m along SF4. The moving average of the gradiometer data is plotted with the distance (Figure 3d). A small variation in the trendline occurs near the center of the survey line. A spike in the data at the end of the line (122 m) is interpreted as cultural interference from nearby power lines.

An EM31 inductive terrain-conductivity survey also was conducted along SF4. Measurements were collected at 3 m intervals in both the horizontal- and vertical-dipole configurations, and the data are shown in Figure 3d. Apparent conductivity values in both dipole configurations peak near the center of the line. Comparison of the vertical-dipole (effective penetration depth of 6 m) and horizontal-dipole (effective penetration depth of 3 m) (McNeill, 1986) data indicates that apparent conductivity values decrease with depth.

The anomaly observed in the inductive terrain-conductivity data is coincident with the location of the anomaly observed in the 2D resistivity data. This anomaly is interpreted as a near-surface conductive anomaly, with conductivity decreasing with depth.

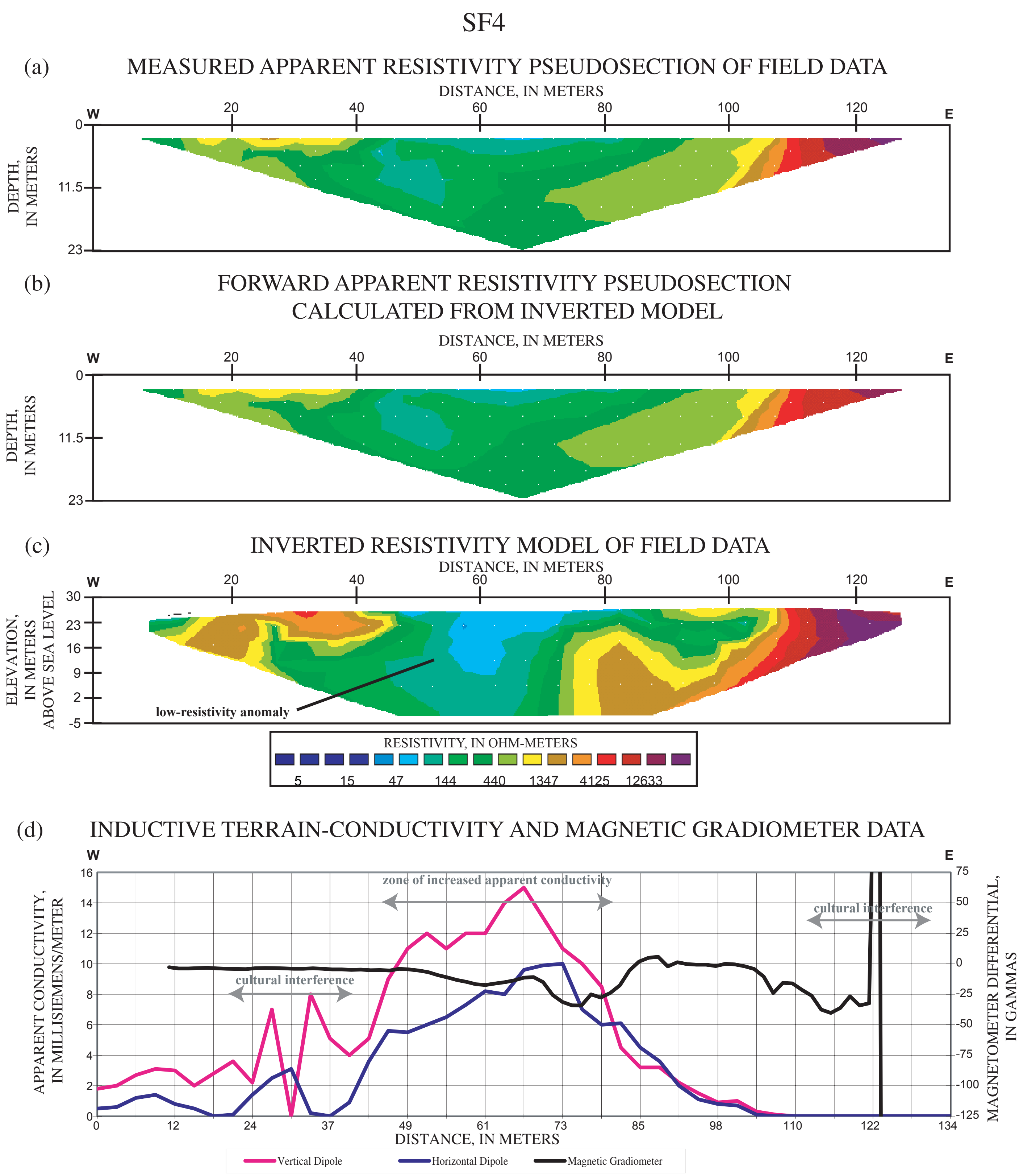

Figure 3. Surface-geophysical data for line SF4, Winthrop Landfill study area, Winthrop, Maine.
(a) 2D resistivity Wenner array measured apparent resistivity pseudosection of field data.
(b) 2D resistivity Wenner array forward apparent resistivity pseudosection calculated from inverted resistivity model.
(c) 2D resistivity Wenner array inverted resistivity model of field data with topography, iteration 6, RMS error =12.6.
(d) Inductive terrain conductivity (EM31) and magnetic gradiometer data.

Line SF1, oriented west-east

Line SF1, approximately 162 m long, is south of the Winthrop Landfill and is oriented roughly west-east, parallel to the shore of Annabessacook Lake in this area (Figure 1). The line is in a residential neighborhood and is approximately 90 m south of SF4.

2D resistivity profiles were collected along SF1 using Schlumberger and Wenner arrays with 28 electrodes spaced 6.0 m apart. The Wenner array measured apparent resistivity pseudosection, inverted resistivity model, and forward apparent resistivity pseudosection calculated from the inverted model are shown in Figures 4a-c. In the inverted resistivity models for both arrays, a bullet-like low-resistivity anomaly centered on the western half of the line at a depth of about 15 m is observed. The increase in resistivity with depth observed on the eastern side of the model is interpreted as a bedrock high in this region.

Geomagnetic gradiometer measurements were recorded every 1.5 m along SF1. The moving average of the gradiometer data is plotted with the distance (Figure 4d). A local increase in the gradiometer differential values is apparent about 50 m from the western end of the line. Spikes in the data on the eastern half of the line are interpreted as cultural interference from nearby power lines.

An EM31 inductive terrain-conductivity survey also was conducted along SF1. Measurements were collected at 3 m intervals in horizontal- and vertical-dipole configurations, and the data are shown in Figure 4d. The effective depth of penetration of the inductive terrain-conductivity survey is too small for the data to be affected by the cause of the low-resistivity anomaly seen in the 2D resistivity survey along the same line. Anomalies 61 m, 122 m, and 155 m from the western end of the line correlate with known sources of cultural interference along the line, including power lines and metal culverts. No other low- or high-resistivity anomalies are observed along SF1.

Line SF2, oriented north-south

Line SF2, approximately 345 m long, is oriented roughly north-south and is parallel to the southwestern edge of the Winthrop Landfill and normal to the shore of Annabessacook Lake (Figure 1). The line is in a residential neighborhood and is intersected by SF4 and SF1 at about 205 m and 295 m, respectively, from the northern end of the line.

2D resistivity profiles were collected along SF2 using Schlumberger and Wenner arrays with 28 electrodes spaced 5.0 m apart. The Wenner array measured apparent resistivity pseudosection, inverted resistivity model, and forward apparent resistivity pseudosection calculated from the inverted model are shown in Figures 5a-c. The Schlumberger array data were very noisy, resulting in large inversion Root-Mean-Square (RMS) errors (Loke, 2001) of about 40; these data were, therefore, considered unreliable and were not used in the interpretation of the line. In the Wenner array inverted model, a high-contrast, bullet-like, low-resistivity anomaly is observed at a depth of about 15 m on the southern end of the line. Another low-resistivity zone is observed north of the center of the line. The anomaly extends from the surface and expands laterally with depth. The resistivity of the anomaly also decreases with depth.

Geomagnetic gradiometer measurements were recorded every 1.5 m along SF2. The moving average of the gradiometer data is plotted with the distance (Figure 5d). Magnetic gradiometer data show little variation. Two spikes in the data on the northern half of the line are interpreted as cultural interference from nearby power lines.

An EM31 inductive terrain-conductivity survey was conducted along SF2. Measurements were collected at 3 m intervals in both the horizontal- and vertical-dipole configurations (Figure 5d). Most conductive anomalies in the profiles correlate with known sources of cultural interference, including power lines and metal culverts. A conductive high observed in the horizontal-dipole data corresponds with the location of the low-resistivity anomaly that extends to the surface of the survey line in the 2D resistivity data.

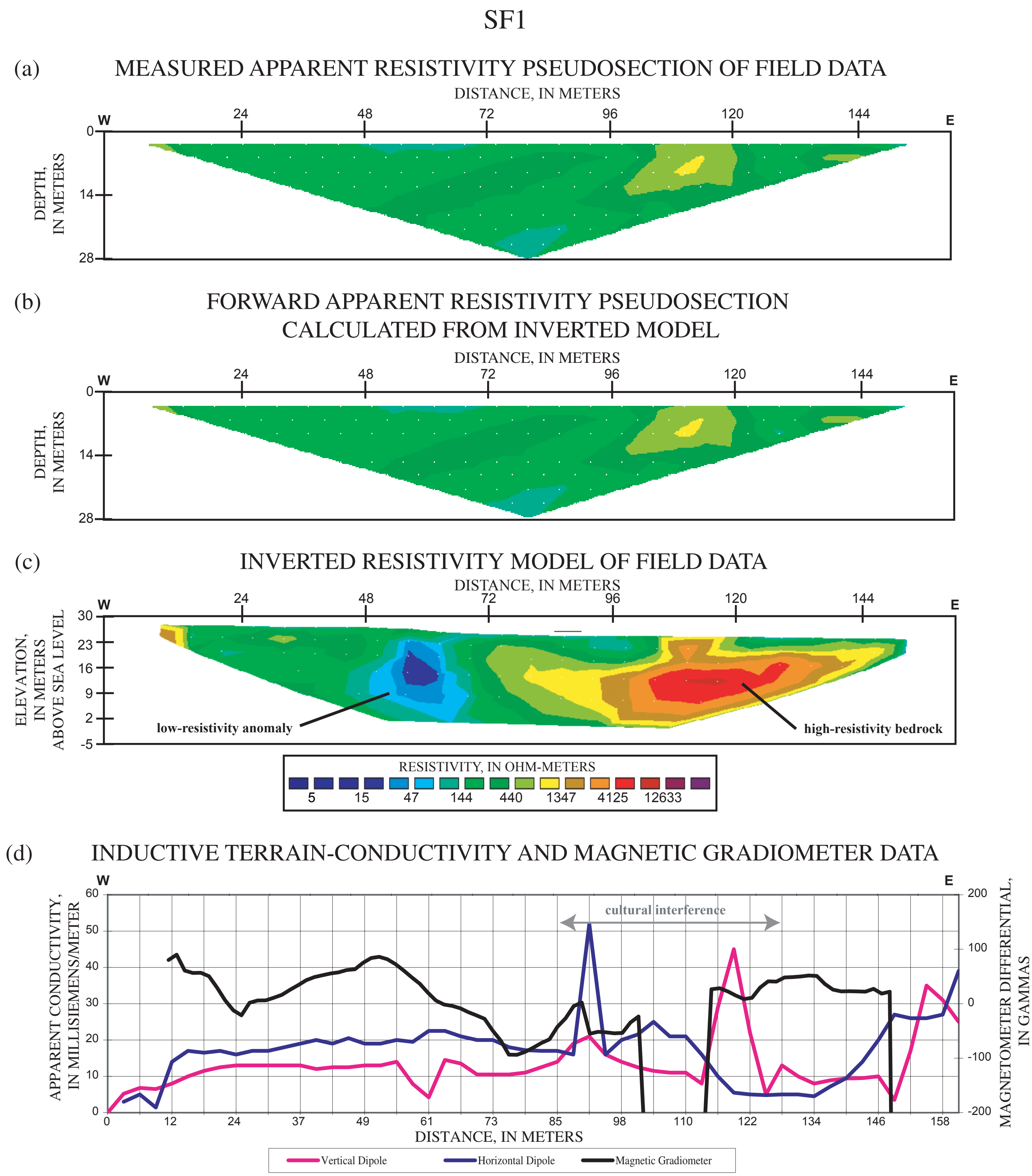

Figure 4. Surface-geophysical data for line SF1, Winthrop Landfill study area, Winthrop, Maine.
(a) 2D resistivity Wenner array measured apparent resistivity pseudosection of field data.
(b) 2D resistivity Wenner array forward apparent resistivity pseudosection calculated from inverted resistivity model.
(c) 2D resistivity Wenner array inverted resistivity model of field data with topography, iteration 6, RMS error =5.9.
(d) Inductive terrain conductivity (EM31) and magnetic gradiometer data.

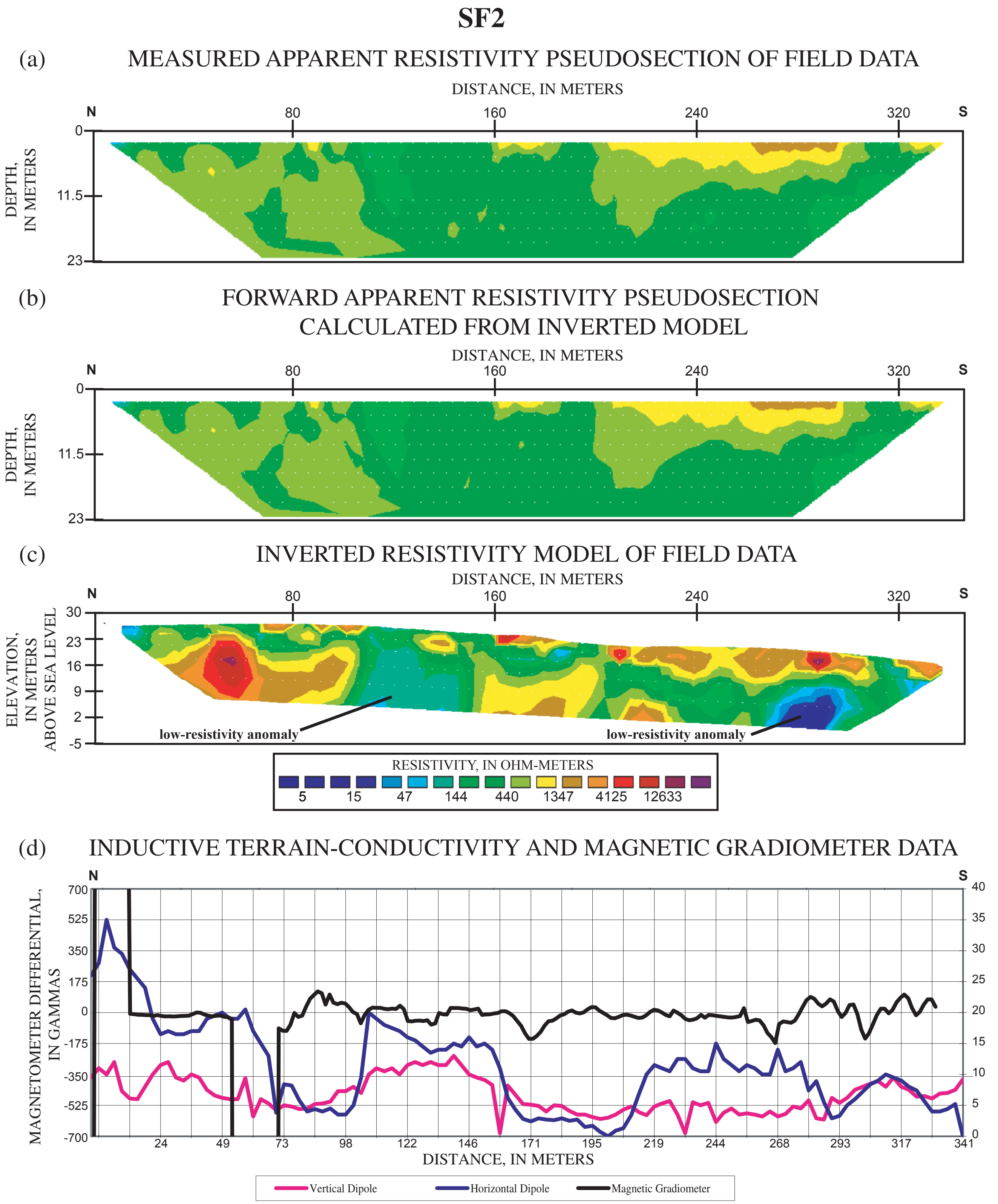

Figure 5. Surface-geophysical data for line SF2, Winthrop Landfill study area, Winthrop, Maine.
(a) 2D resistivity Wenner array measured apparent resistivity pseudosection of field data.
(b) 2D resistivity Wenner array forward apparent resistivity pseudosection calculated from inverted resistivity model.
(c) 2D resistivity Wenner array inverted resistivity model of field data with topography, iteration 6, RMS error =7.2.
(d) Inductive terrain conductivity (EM31) and magnetic gradiometer data.

Monitoring Well 8a

Monitoring well 8a (MW8a) is about 20 m north of SF1 (Figure 1). The 33.9-m deep, screened well is open to unconsolidated sediment except for the bottom 2 m, which is open to bedrock. EM induction and gamma logs were collected in August 2000. The logs (Figure 6) show a zone of increased conductivity of about 55 to 65 millisiemens/meter (mS/m) at depths of 7.5 to 22.5 m. This region of the log also has a lower gamma count, so the increase in conductivity is interpreted to be the result of increased pore fluid conductivity rather than increased clay content. Another conductivity peak is at 29 m, which also is interpreted to be the result of increased pore fluid conductivity in this zone.

Monitoring Well 13a

Monitoring well 13a (MW13a) is about 20 m south of SF2 (Figure 1). The 14.2-m deep, screened well is open to unconsolidated sediment except for the bottom meter, which is open to bedrock. EM induction and gamma logs were collected in August 2000. The logs (Figure 7) show a zone of increased conductivity at about 3.5 m, which coincides with a region of increased gamma counts and may, therefore, be a result of lithologic rather than water-quality changes.

Monitoring Well 212 Series

Monitoring well 212a (MW212a) is between the southern end of SF2 and the lake (Figure 1). The 38.5-m deep, screened well is open to unconsolidated sediment except for the bottom 3.7 m, which is open to bedrock. EM induction and gamma logs were collected in August 2000. The EM induction log (Figure 8) data increase in conductivity at about 11 m, spike off-scale at over 1200 mS/m between the depths of 13 m and 22 m, and decrease at 22.5 m. Gamma counts in the zone of the conductivity spike are lower than in the rest of the well.

Monitoring well 212b (MW212b) also was logged in order to identify the cause of the conductive anomaly in the MW212a data. MW212b is about 2 m north of MW212a. The screened well is 23.3 m deep and is completed in unconsolidated sediment. The EM induction log (Figure 8) shows a conductivity high below 11 m. Gamma counts at this depth vary but do not correlate with the increase in conductivity; the highest conductivity zone, from 18 to 22 m, also is the zone of the lowest gamma counts. The conductivity values (60-70 mS/m) in the zone below 11 m are similar to those of the conductive anomaly in MW8a.

The depth of the conductive anomaly in MW212b coincides with the depth of the conductivity spike in MW212a. Drilling records (ABB Environmental Services, 1992b) for MW212a do not note any metal debris left from drilling or any sudden lithologic change in the zone of the anomaly. However, it is unlikely that the spike would be caused entirely by pore fluid conductivity values alone and not be seen in neighboring well MW212b.

Based on the EM and gamma logs and similarity to the values seen in MW8a, the conductive anomaly in MW212b is interpreted to be the result of an increase in pore fluid conductivity in the formation surrounding the lower half of the well. The conductive anomaly in MW212a is due in part to the same pore fluid conductivity increase. The conductivity spike in MW212a is attributed to unrecorded drilling debris, an interpretation supported by the decrease in gamma counts in the same zone, which may be the result of attenuation caused by a metal pipe surrounding the borehole in this zone.

MONITORING WELL 8a

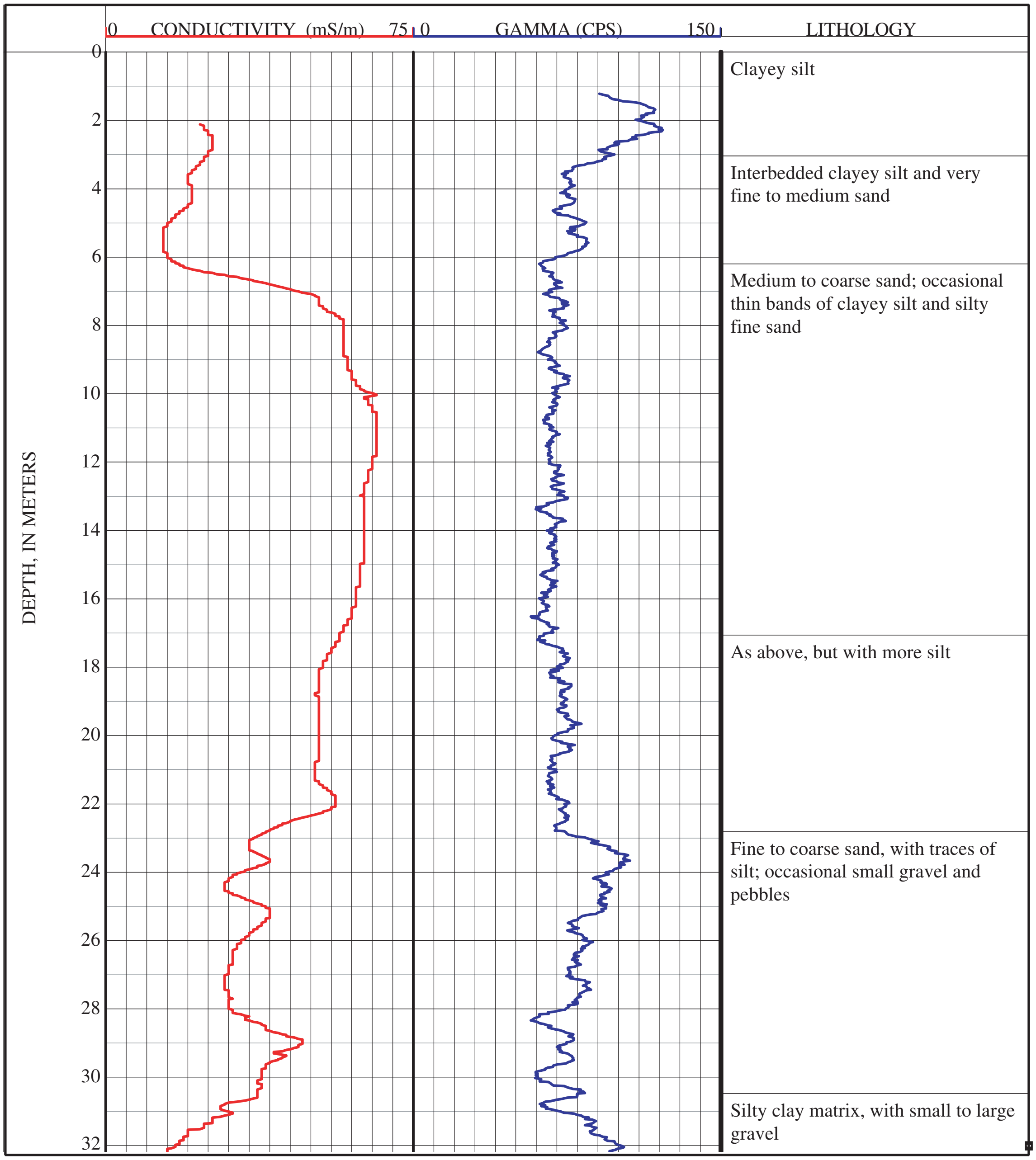

Figure 6. Borehole-geophysical logs for monitoring well 8a (MW8a), Winthrop Landfill study area, Winthrop, Maine. Left: Electromagnetic (EM) induction log, conductivity in millisiemens/meter (mS/m). Center: Natural gamma log, values in counts per second (CPS). Right: Lithology based on drillers' logs (ABB Environmental Services, 1992b).

MONITORING WELL 13a

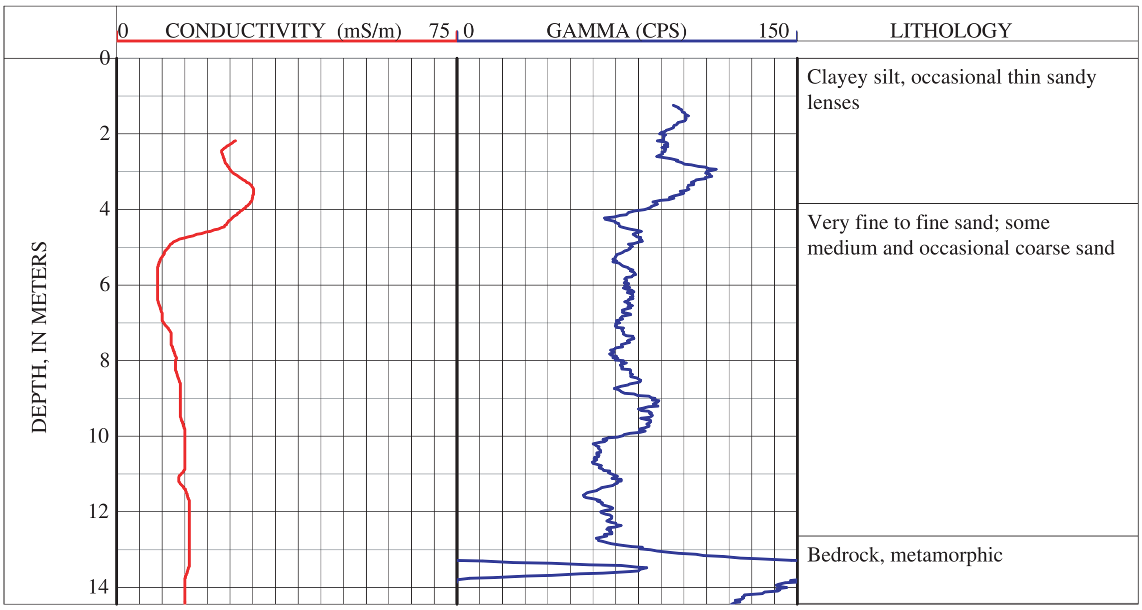

Figure 7. Borehole-geophysical logs for monitoring well 13a (MW13a), Winthrop Landfill study area, Winthrop, Maine. Left: Electromagnetic (EM) induction log, conductivity in millisiemens/meter (mS/m). Center: Natural gamma log, values in counts per second (CPS). Right: Lithology based on drillers' logs (ABB Environmental Services, 1992b).

MONITORING WELLS 212a AND 212b

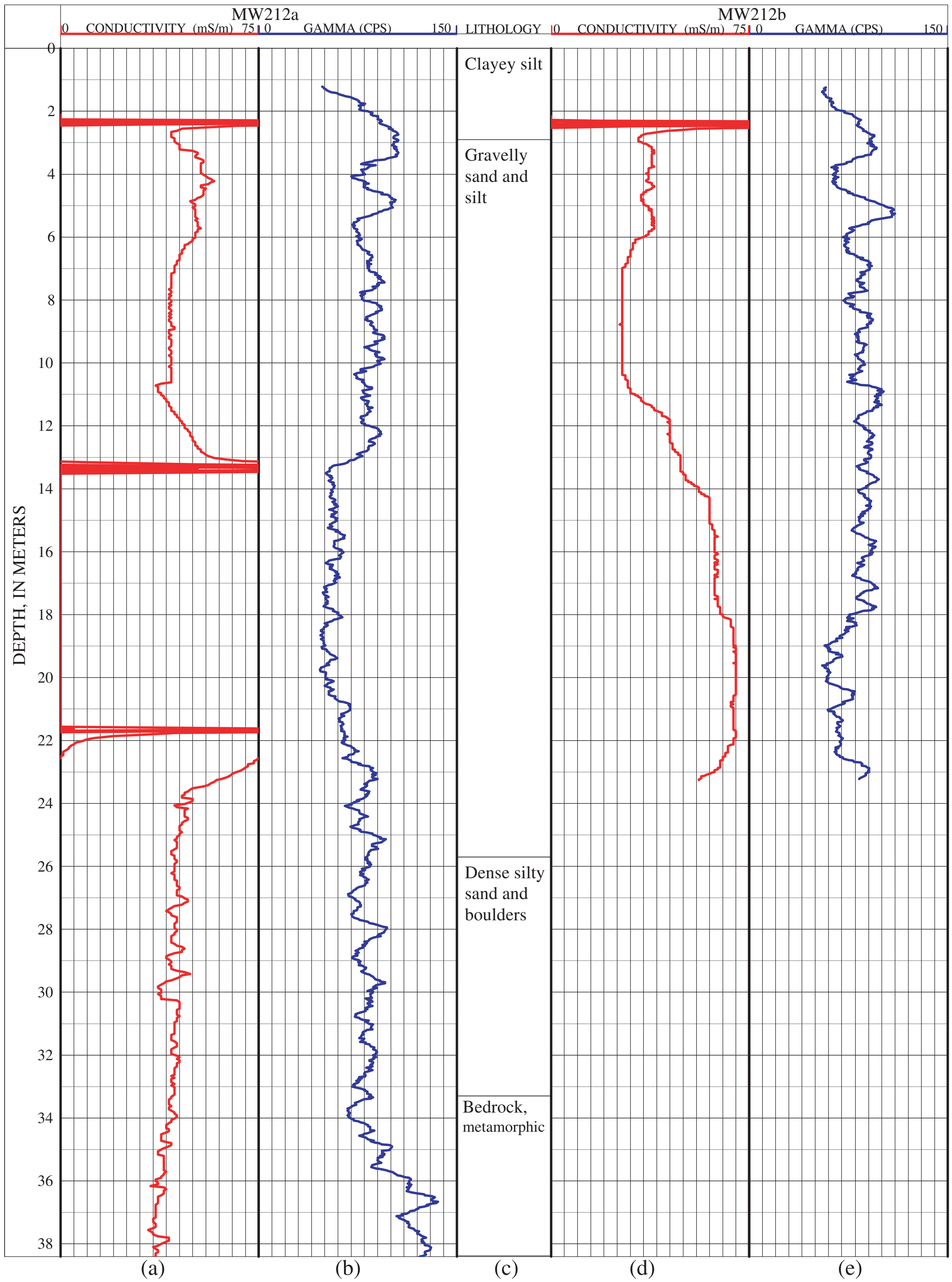

Figure 8. Borehole-geophysical logs for monitoring wells 212a (MW212a) and 212b (MW212b), Winthrop Landfill study area, Winthrop, Maine. (a) MW212a electromagnetic (EM) induction log, conductivity in millisiemens/meter (mS/m). (b) MW212a natural gamma log, values in counts per second (CPS). (c) Lithology based on drillers' logs (ABB Environmental Services, 1992b). (d) MW212b EM induction log, conductivity in mS/m. (e) MW212a natural gamma log, values in CPS.

Results of Water-Borne Geophysical Investigations

Water-borne magnetic and continuous seismic data were collected on Annabessacook Lake in October 2000 and June 2001. Differentially corrected GPS data (sub-meter accuracy) were collected in real time along with the magnetic and seismic data. Navigation was done using visual shore-based landmarks and a topographic map of the area. The survey line locations were chosen by proximity to the western shore of the lake and to areas where physical and chemical indications of seepage have been reported (E.C. Jordan Co., 1990).

Marine Magnetic Surveying

A series of magnetic surveys were conducted on Annabessacook Lake in October 2000. The survey lines were parallel to the western shore of the lake adjacent to the study area and extending north. The contoured magnetic gradiometer data are shown in Figure 9. The gradiometer data east and northeast of the landfill decrease with distance from the shore and increasing depth of water. Southeast and south of the landfill, however, a series of magnetic anomalies are apparent. These anomalies coincide with the known locations of southern flow path contamination seeps in the lake (ABB Environmental Services, 1992a). An additional anomaly also can be seen at the northeastern corner of the magnetic survey.

High Frequency Seismic Profiling

A continuous, swept-frequency, seismic-reflection profile (CSP) survey was conducted on a western portion of Annabessacook Lake, using a signal frequency range of 2-10KHz. Four north-south trending profiles were collected. Depth of water in the region ranged from less than 1.5 m to 7.5 m at the time of the survey. Distinct reflectors were not detected more than 15 m below water surface.

The characteristics of the water-bottom reflections indicate that the lake bottom materials range from soft-bottom, which returned a low-amplitude reflection, to hard-bottom, which returned a high-amplitude reflection and a reduced depth of penetration. Based on visual observation of the lake bottom in areas where the survey was conducted, the low-amplitude, water-bottom reflections correlate with a soft, muddy lake bottom, whereas the high-amplitude reflections correlate with a high density of cobble and small-boulder size rocks on the lake bottom.

Three distinct sub-bottom units can be observed in the seismic sections (Figure 10). Based on prior seismic studies and research (Morrissey and others, 1985; Haeni, 1988; Haeni, 1996), site-specific geological characterization (E.C. Jordan Co., 1990), and regional surficial-geology maps (Prescott, 1969), layer 1 is interpreted as lacustrine deposits of fine sands or a combination of clayey silts and fine sands, layer 2 as medium sands and (or) silty, gravelly sands and layer 2 as bedrock.

Layer 1 starts at the water bottom and ranges from less than 0.5 to 1.5 m thick. It displays distinct parallel and subhorizontal depositional features. In areas with a hard bottom, layer 1 is absent, which may be the result of reduced penetration or differences in sediment deposition in these areas.

An erosional surface is visible on the seismic profile in many areas between layer 1 and layer 2. This unconformity is most distinct in cut-and-fill features visible on the seismic profile. Layer 2 varies in thickness from less than 1 m to over 5 m and displays dipping bedding. The boundary between layers 2 and 3 is difficult to identify; this difficulty may be a result of the limited signal energy at this depth or the result of increased scattering.

Comparison of parallel profiles indicates similar stratigraphic structures and continuation of many subsurface features such as those seen in Figure 10. Seismic profiles along Annabessacook Lake adjacent to the study area suggest the presence of sediment-infilled topographic lows that could act as preferential conduits for contaminant migration in the study area.

WATER-BORNE MAGNETIC GRADIOMETER DATA

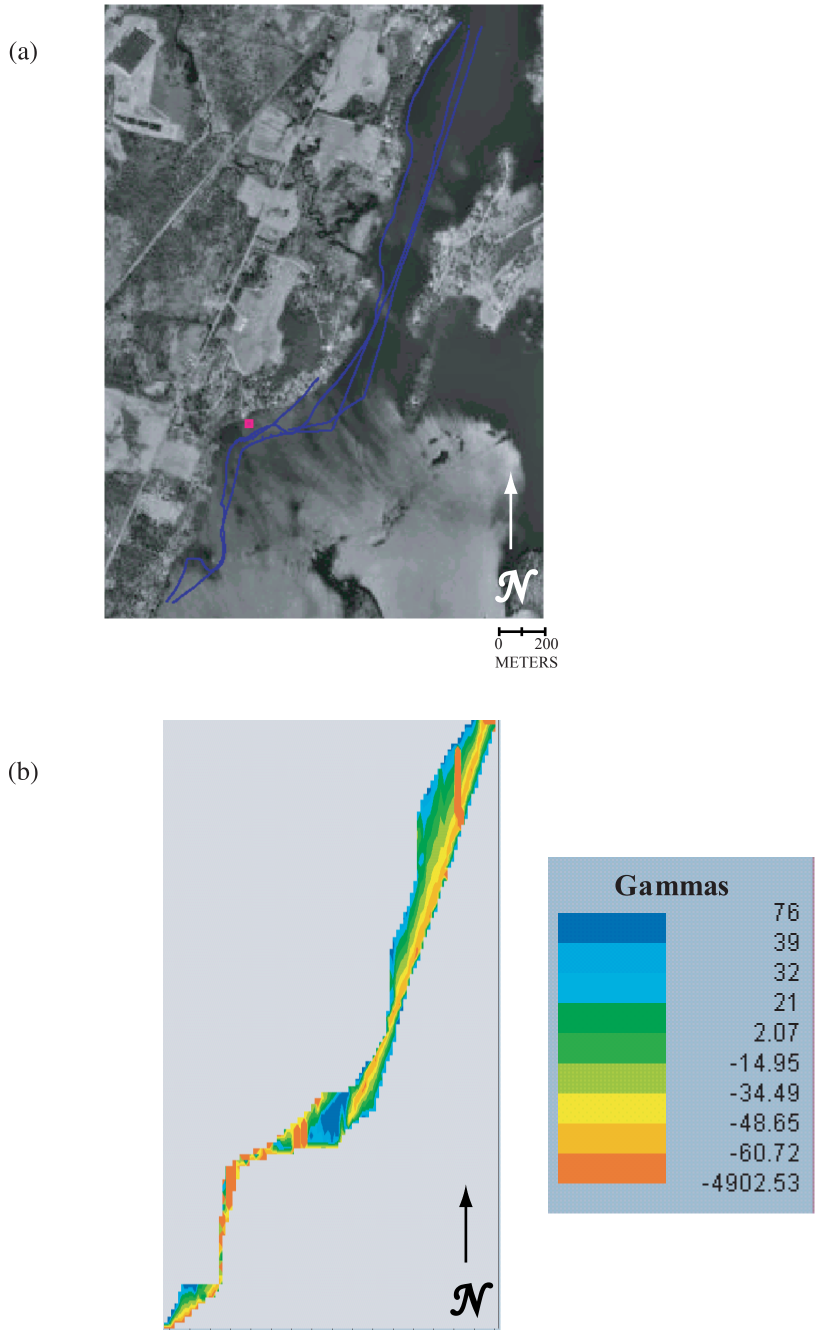

Figure 9. Water-borne magnetic survey locations and data on Lake Annabessacook, Winthrop Landfill study area, Winthrop, Maine. (a) USGS orthophoto of the study area and Lake Annabessacook. Approximate location of water-borne magnetic survey transects is shown in blue. Approximate location of iron-rich seep is shown in pink (ABB Environmental Services, 1992a). (b) Contoured magnetic gradiometer data, in gamma.

CONTINUOUS SEISMIC-REFLECTION PROFILE

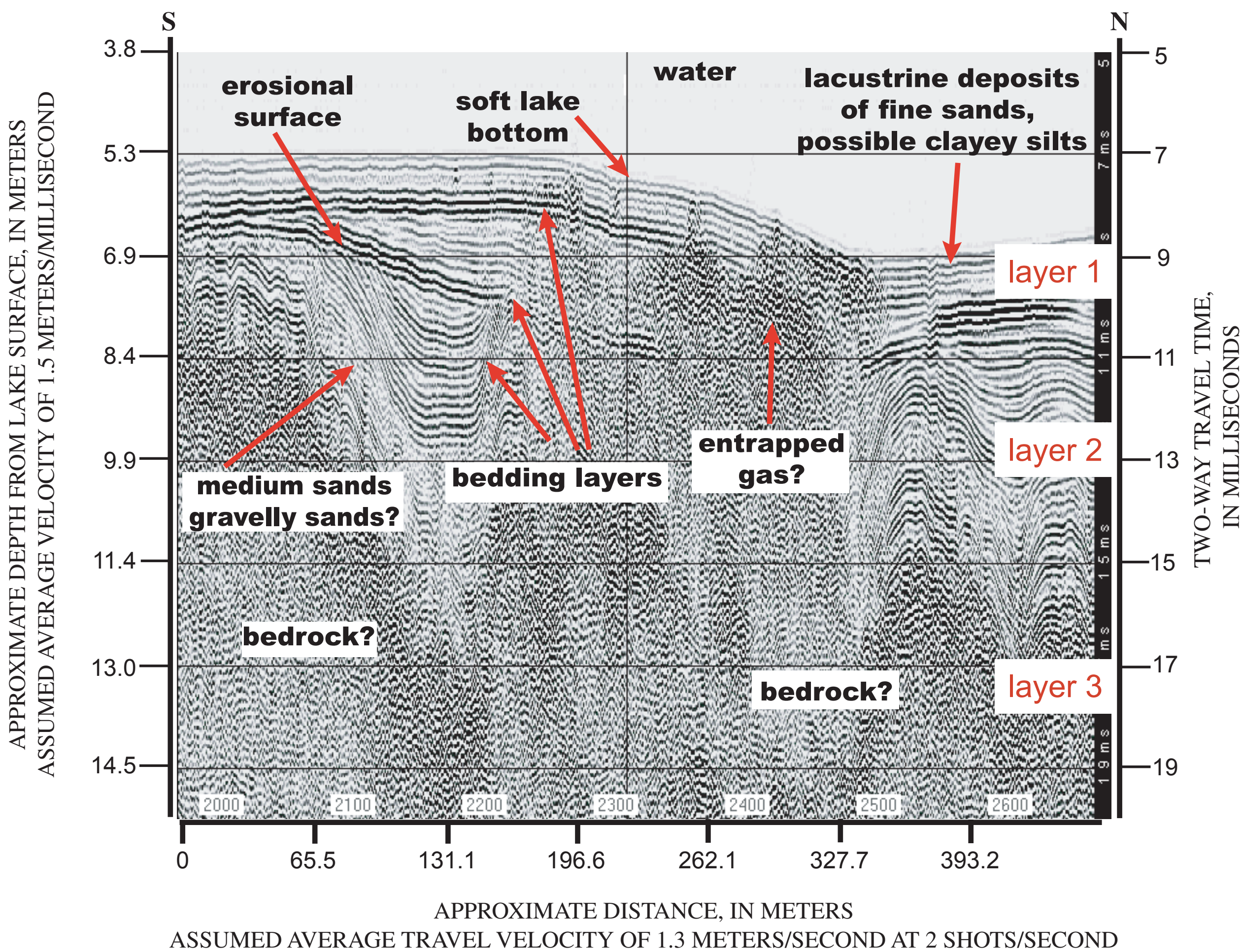

Figure 10. South to North section of continuous seismic reflection profile, Annabessacook Lake, Winthrop, Maine. Real data channel displayed after application of AGC with a Time Varying Gain and High Pass Filter of 2500Hz and a Low Pass Filter of 6250 Hz.

Integrated Interpretation

Based on the integrated interpretation of the surface, borehole, and water-borne geophysical surveys, a conceptual model is proposed that describes the movement of landfill leachate from the site of the former landfill south to the lake (Figure 11).

Analysis of surface and borehole dc-resistivity and EM data identifies discrete, low-resistivity zones in the subsurface of the study area. Assuming the low-resistivity anomalies are induced by increases in ground-water specific conductance (Mack, 1993), these low-resistivity zones are interpreted to indicate the presence of landfill leachate. On line SF4, the leachate plume appears to emerge from the toe of the southeastern edge of the landfill. On lines SF1 and SF2, two low-resistivity anomalies are observed at depth farther from the landfill, and borehole EM logs from MW8a and the MW212 series contain conductive anomalies that increase in depth closer to the lake. These data are interpreted to indicate that the plume increases in depth as it migrates from the landfill south toward the lake.

Seismic profiles along Annabessacook Lake adjacent to the study area suggest well-stratified sediment-infilled bedrock topographic lows that could act as preferential conduits for contaminant migration between the landfill and lake. The bullet-like low-resistivity anomalies in surface resistivity surveys and the high-conductivity zones in EM logs support the interpretation of the plume migration through preferential flow zones in the overburden.

Anomalies seen in the water-borne magnetic data collected along the shoreline correlate with known locations of iron-rich ground water seeping into the lake south of the landfill. This correlation is interpreted to confirm the presence of iron-rich ground water from the landfill upwelling into the lake along the lakeshore south of the MW212 series.

Summary

The USGS, in cooperation with UTC, used an integrated suite of borehole, surface, and water-borne geophysical methods near the site of the former Winthrop Landfill, Winthrop, Maine, to investigate the hydrogeology affecting the transport of leachate from the landfill to nearby Annabessacook Lake. The USGS used a multi-faceted, integrated approach to data collection and interpretation. The objective of this integrated geophysical study was to provide constraints on the location and extent of the southern flow path(s) of contamination from the landfill to the lake; identify shoreline seep geophysical signatures; identify potentially hidden seeps in the lake; and determine depth to bedrock below Annabessacook Lake in the study area.

Interpretation of surface 2D resistivity, magnetic, and inductive terrain-conductivity data and EM borehole logs delineates an electrically conductive anomaly consistent with a leachate plume moving from the current landfill boundary southward through the overburden to the shores of Annabessacook Lake. Surface and borehole geophysical data collected south and southeast of the landfill indicate the presence of a discrete, shallow conductive anomaly at the toe of the southeastern edge of the landfill and near the lake shore. The conductive anomalies appear at increasing depths closer to the lake. Magnetic anomalies off-shore confirm the presence of iron-rich landfill leachate discharging into the lake south of the landfill. High-resolution swept-frequency seismic data were used to map sediment and grain size distribution in the lake sub-bottom along the shoreline, identifying sediment-infilled bedrock lows which may act as conduits for contaminant migration.

LOCATION AND INTERPRETATION OF GEOPHYSICAL ANOMALIES

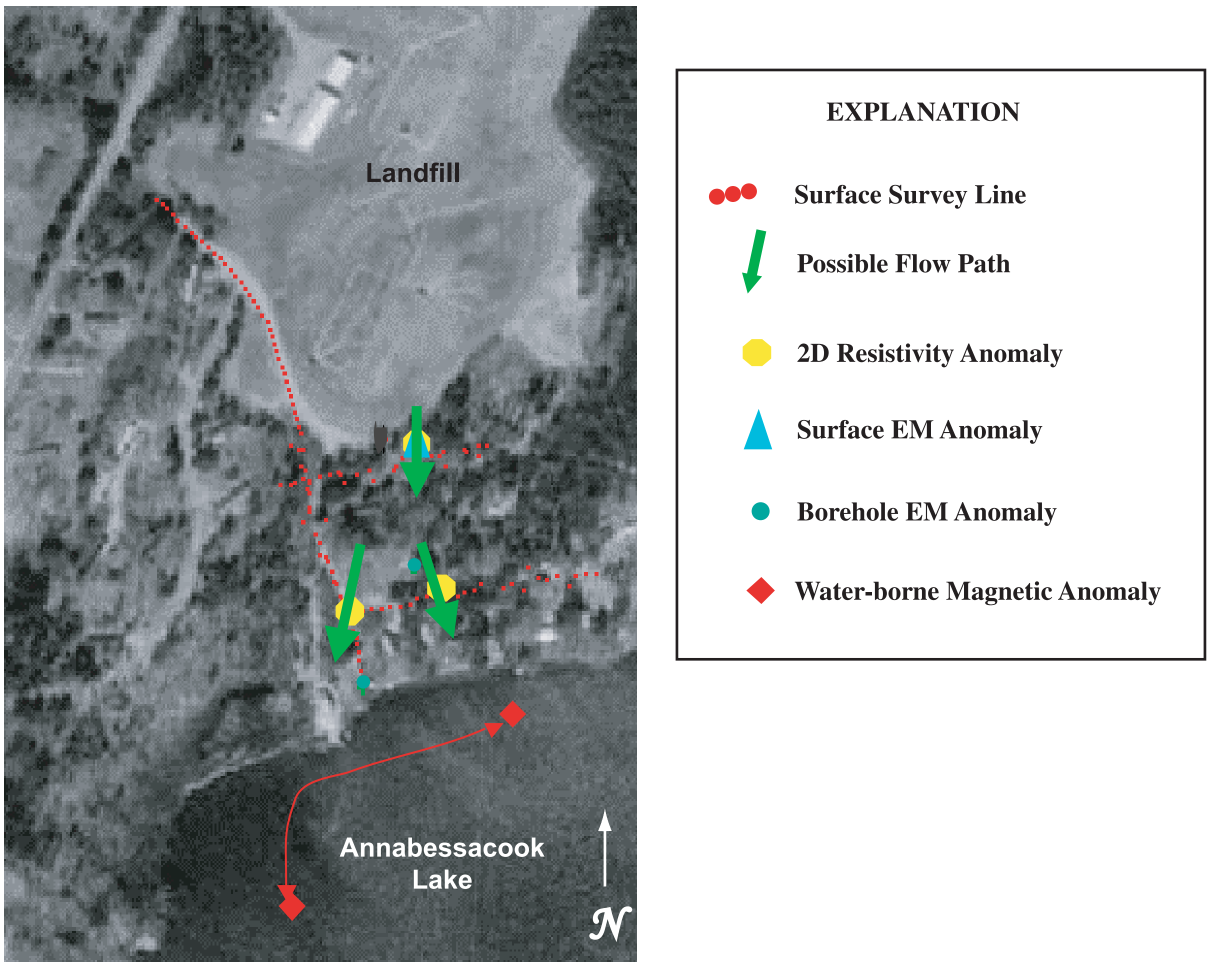

Figure 11. Locations of geophysical anomalies and interpretation of possible southern flow path, Winthrop Landfill study area, Winthrop, Maine.

Acknowledgments

The authors thank United Technologies Corporation for its support and for permission to access monitoring wells. The authors gratefully acknowledge Brian Butler of Harding ESE and Dave Witham, the Winthrop Landfill site manager, of Woodward and Curran, for continued logistical support. We thank the private homeowners on Annabessacook Lake who allowed access to the lake from their private docks. We also thank Robert Dudley, Bruce Hansen, and Jim Degnan of the USGS for assistance with the data collection in this investigation. Reviews by John Williams, Fred Paillet, and Carole Johnson of the USGS resulted in scientific and editorial improvements in the manuscript.

References

1. ABB Environmental Services (1992a), "Remedial Action Work Plan Winthrop Landfill Task II-7B iii Hydrogeologic Investigation Phases I and II – Field Investigation and Modeling Activities, Volume I - Text", Portland, Maine, April 1992.
2. ABB Environmental Services (1992b), "Remedial Action Work Plan Winthrop Landfill Task II-7B iii Hydrogeologic Investigation Phases I and II – Field Investigation and Modeling Activities, Volume IVA, Appendices D-2 and D-3", Portland, Maine, April 1992.
3. Breiner, S. (1999), *Applications Manual for Portable Magnetometers*, Sunnyvale, California, Geometrics, Inc., 58 p.
4. deGroot-Hedlin, C. and Constable, S. (1990), "Occam's Inversion to Generate Smooth, Two-Dimensional Models from Magnetotelluric Data", *Geophysics*, **55**, pp. 1613-1624.
5. E.C. Jordan Co. (1990), "Remedial Action Work Plan Winthrop Landfill Task II-7B iii Hydrogeologic Investigation Executive Summary", Portland, Maine, July 1990.
6. Frischknecht, Frank C., Labson, Victor F., Spies, Brian R., and Anderson, Walter L. (1991) "Profiling Methods Using Small Sources", *in* Nabighian, Misac N. and Corbett, John D., eds., *Electromagnetic Methods in Applied Geophysics – Applications Part A*: Tulsa, Oklahoma, Society of Exploration Geophysicists, pp. 105-270.
7. Geometrics, Inc. (1996), G-856 *Memory-Mag Proton Precession Magnetometer Instruction Manual*, Sunnyvale, California, Geometrics, Inc., 65 p.
8. 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* Nielsen, David M. and Curl, Mary, eds., *NWWA/EPA Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations, February 7-9, 1984, San Antonio, Texas*. Nation Water Well Association (publisher), pp. 338-367.
9. Haeni, F.P. (1986), "Application of Continuous Seismic Reflection Methods to Hydrologic Studies", in *Groundwater* Vol. 24, No.1, January-February 1986, pp. 23- 31.
10. Haeni, F.P. (1988), "Evaluation of the Continuous Seismic-Reflection Method for Determining the Thickness and Lithology of Stratified Drift in the Glaciated Northeast", *in* Randall, A.D. and Johnson, I.A., eds. *Regional Aquifer Systems of the United States – the northeast glacial aquifers*. American Water Resources Association Monograph Series 11, pp. 63-82.
11. Haeni, F.P. (1996), "Use of Ground-Penetrating Radar and Continuous Seismic-Reflection Profiling on Surface-Water Bodies in Environmental and Engineering Studies", *JEEG*, Volume 1, Issue 1, April 1996, pp. 27-35.
12. Keys, W. Scott (1997), *A Practical Guide to Borehole Geophysics in Environmental Investigations*, USA, CRC Press, Inc., 176 p.

13. Loke, M.H. (2001), Tutorial: 2-D and 3-D electrical imaging surveys. http://www.geoelectrical.com (accessed 13 Mar. 2001).
14. Mack, Thomas J. (1993), "Detection of Contaminant Plumes by Borehole Geophysical Logging", *Ground Water Monitoring and Remediation Review*, v. 13, no. 1, pp. 107-144.
15. McNeill, J.D. (1980), "Electromagnetic Terrain Conductivity Measurements at Low Induction Numbers", Mississauga, Ontario, Canada, Geonics, Ltd., Technical Note TN-6, 7 p.
16. McNeill, J.D. (1986), "Geonics EM39 Borehole Conductivity Meter Theory of Operation", Mississauga, Ontario, Canada, Geonics, Ltd., Technical Note TN-20.
17. McNeill, J.D. (1990), "Use of Electromagnetic Methods for Groundwater Studies", *in* Ward, Stanley H., ed., *Geotechnical and Environmental Geophysics Volume 1: Review and Tutorial*: Tulsa, Okalahoma, Society of Exploration Geophysicists, pp. 191-218.
18. McNeill, J.D., Bosnar, M., and Snelgrove, F.B. (1990), "Resolution of an Electromagnetic Borehole Conductivity Logger for Geotechnical and Ground Water Applications", Mississauga, Ontario, Canada, Geonics, Ltd., Technical Note TN-25, 28 p.
19. Morrissey, D.J., Haeni, F.P., and Tepper, D.H. (1985), "Continuous Seismic-Reflection Profiling of a Glacial-Drift Deposit on the Saco River, Maine and New Hampshire", in *Proceedings of the Association of Ground Water Scientists and Engineers Eastern Regional Ground Water Conference, July 16-18, 1985, Portland, Maine*, pp. 277-296.
20. Nell, Craig D. and Locke, Daniel, B. (1999), "Winthrop Quadrangle, Maine – Significant Sand and Gravel Aquifers", Open File No. 99-32, Maine Geological Survey, Augusta, Maine, scale 1:24,000.
21. Oldenburg, Douglas W. and Li, Yaoguo (1999), "Estimating Depth of Investigation in DC Resistivity and IP Surveys", *Geophysics*, **64**, pp. 403-416.
22. Powers, C.J., Wilson, Joanna, Haeni, F.P., and Johnson, C.D. (1999), *Surface-geophysical Investigation of the University of Connecticut Landfill, Storrs, Connecticut*: U.S. Geological Survey Water-Resources Investigations Report 99-4211, 34 p.
23. Prescott, Glen C. Jr. (1969), "Ground-Water Favorability Areas and Surficial Geology of the Lower Kennebec River Basin, Maine", Hydrologic Investigations Atlas HA-337. USGS, Washington, D.C.
24. Reynolds, John M. (1997), *An Introduction to Applied Environmental Geophysics*, West Sussex, England, John Wiley & Sons Ltd., 796 p.
25. Sylwester, Richard E. (1983), "Single-Channel, High-Resolution, Seismic Reflection Profiling: A Review of the Fundamentals and Instrumentation", *in* Geyer, Richard A., and Moore, J. Robert, eds. *CRC Handbook of Geophysical Exploration at Sea*. CRC Press: Florida, pp. 77-122.
26. Thompson, Woodrow B. (1977), "Reconnaissance Surficial Geology of the Augusta Quadrangle, Maine", Open File No. 77-23, Maine Geological Survey, Augusta, Maine.
27. Tsourlos, Panagiotis I., Szymanski, John E., and Tsokas, Gregory N. (1999), "The Effect of Terrain Topography on Commonly Used Resistivity Arrays", *Geophysics*, **64**, pp. 1357-1363.
28. United States Environmental Protection Agency (2001), EPA Region 1 National Priorities List Publication Assistance Database, http://yosemite1.epa.gov/r1/npl_pad.nsf (accessed 13 Oct. 2001).
29. United States Environmental Protection Agency (1983). NPL Site Narrative at Listing: Winthrop Landfill, http://www.epa.gov/superfund/sites/npl/nar36.htm (accessed 13 Oct. 2001).
30. Williams, J.H., Lapham, W.W., and Barringer, T.H. (1993), "Application of Electromagnetic Logging to Contamination Investigations in Glacial Sand-and-Gravel Aquifers", *Ground Water Monitoring and Remediation Review*, v. 13, no. 3, pp. 129-138.

31. Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R. (1974), *Application of Surface Geophysics to Ground-water Investigations*, Techniques of Water-Resources Investigations of the United States Geological Survey, book 2, chap. D1, 116 p.