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Application of Electromagnetic Logging to Contamination Investigations in Glacial Sand-and-Gravel Aquifers

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Abstract

Electromagnetic (EM) logging provides an efficient method for high-resolution, vertical delineation of electrically conductive contamination in glacial sand-and-gravel aquifers. EM, gamma, and lithologic logs and specific conductance data from sand-and-gravel aquifers at five sites in the northeastern United States were analyzed to define the relation of EM conductivity to aquifer lithology and water quality. Municipal waste disposal, septic waste discharge, or highway deicing salt application at these sites has caused contaminant plumes in which the dissolved solids concentration and specific conductance of ground water exceed background levels by as much as 10 to 20 times.

The major hydrogeologic factors that affected EM log response at the five sites were the dissolved solids concentration of the ground water and the silt and clay content in the aquifer. EM conductivity of sand and gravel with uncontaminated water ranged from less than 5 to about 10 millisiemens per meter (mS/m); that of silt and clay zones ranged from about 15 to 45 mS/m; and that of the more highly contaminated zones in sand and gravel ranged from about 10 to more than 80 mS/m. Specific conductance of water samples from screened intervals in sand and gravel at selected monitoring well installations was significantly correlated with EM conductivity.

EM logging can be used in glacial sand-and-gravel aquifer investigations to (1) determine optimum depths for the placement of monitoring well screens; (2) provide a nearly continuous vertical profile of specific conductance to complement depth-specific water quality samples; and (3) identify temporal changes in water quality through sequential logging. Detailed lithologic or gamma logs, preferably both, need to be collected along with the EM logs to define zones in which elevated EM conductivity is caused by the presence of silt and clay beds rather than contamination.

Introduction

Saturated deposits of glacial sand and gravel form productive aquifers and are a major source of water supply throughout much of the northeastern United States. These aquifers are highly susceptible to contamination from near-surface waste disposal and chemical storage and use. Three-dimensional flow and variations in hydraulic properties within the aquifers result in contaminant plumes that vary both areally and vertically (LeBlanc et al. 1988).

Many contaminant plumes, such as those caused by leachate from landfills and sewage disposal systems and by application of highway deicing salts, contain elevated dissolved solids concentrations and are electrically conductive. Electromagnetic (EM) geophysical methods can be used to map electrical anomalies associated with these contaminant plumes. Surface EM methods have been widely used to define the lateral extent of contamination (Benson et al. 1988). EM logging, the downhole version of the surface EM method, provides an efficient method for high-resolution, vertical delineation of electrically conductive contamination in sand-and-gravel aquifers. EM logging has been used in the petroleum industry since the late 1940s (Doll 1949). An EM probe for use in small-diameter monitoring wells, however, has been available only since the mid-1980s (McNeill 1986).

The vertical distribution of contaminant concentrations in sand-and-gravel aquifers traditionally has been defined by water quality sam-

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pling from clusters of monitoring wells, screened at successive depths. Wells with short screens provide data on specific zones, but the cost of placing enough wells at successive depths to obtain adequate vertical coverage can be prohibitive. Wells with long screens provide only composite samples and also can serve as conduits for vertical movement of contaminants (Reilly et al. 1989). EM logs from wells cased with polyvinyl chloride (PVC) provide information from which a nearly continuous profile of water quality can be derived.

This paper discusses the results of EM logging in glacial sand-and-gravel aquifers near contaminant sources at five sites in the northeastern United States and describes the effects of lithology and water quality on EM log response and the relation between EM conductivity and specific conductance. It also discusses some considerations in applying EM logging to contamination investigations.

Description of Study Sites

The study sites include municipal waste landfills near Bristol, Vermont; Farmington, Connecticut; and Albany, New York; a septic waste discharge facility near Orleans, Massachusetts; and a highway near Wareham, Massachusetts, along which deicing salts are seasonally applied (Figure 1). At all of these sites, waste disposal or deicing salt application has caused contaminant plumes that are electrically conductive because they have elevated dissolved solids concentrations. Dissolved solids concentration and specific conductance of contaminated ground water at the sites exceed background levels by as much as 10 to 20 times.

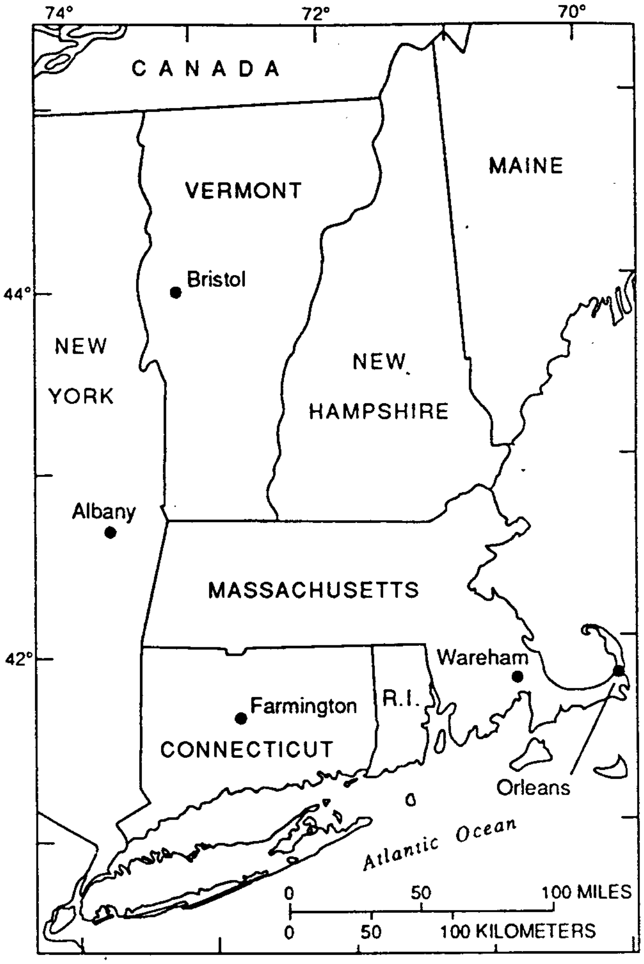

Figure 1. Location of study sites in the northeastern United States.

Landfills at Bristol, Vermont

The Bristol site is on and near a glacial-lake delta and is underlain by as much as 60 meters (m) of interbedded sand, sand and gravel, and silt and clay. The site contains two landfills, both of which are at least 20 years old and are unlined. The active landfill is on the northwestern edge of the top of the delta and receives mixed municipal waste. The other, now inactive, is at the base of the delta and southeast of the active landfill. It received mixed municipal waste and some industrial waste. The water table on top of the delta is more than 35 m below land surface; that near the lower landfill is less than 12 m below land surface. Ground water flow at the site is generally southwestward. Specific conductance of water samples from monitoring wells completed in contaminated zones downgradient of the landfills is as high as 2400 μS/cm at 25 C. Background specific conductance in uncontaminated areas ranges from 200 to 300 μS/cm at 25 C. The application of EM logging to delineate contaminant plumes at the site was presented by Mack (1993).

Landfill at Farmington, Connecticut

The Farmington site is on the western side of the Farmington River valley. The site is underlain by glacial valley-fill deposits of medium to coarse sand with some beds of silt to fine sand and very coarse sand and gravel (Grady 1989). The valley fill thickens eastward from less than 3 m under the landfill near the base of the valley wall to more than 30 m near the Farmington River in the center of the valley. Sandstone and siltstone underlie the valley fill. The landfill, which is unlined, has received mixed municipal waste for more than 30 years. The water table at the site is generally less than 6 m below land surface, and ground water flow is eastward toward the river. Specific conductance of water samples from monitoring wells completed in contaminated zones downgradient of the landfill is as high as 1350 μS/cm at 25 C. Background specific conductance ranges from 100 to 200 μS/cm at 25 C. Results of surface EM surveys and water quality sampling at the landfill site were presented by Grady and Haeni (1984) and Grady (1989).

Landfill at Albany, New York

The Albany site is on the lake plain of glacial Lake Albany. The surficial deposits at the site consist of more than 20 m of dune and deltaic sand that contain lenses of silty sand and silt and clay. The surficial sand grades into, or is in abrupt contact with, lake-bottom silt and clay that average about 15 m thick (Dineen 1982). Till locally underlies the silt and clay and directly overlies shale bedrock. Depth to bedrock at the site is probably 30 to 45 m.

The Albany landfill, which began operation in 1969, receives mixed municipal waste and refuse-boiler ash. The landfill is unlined and contains up to 30 m of fill. The water table near the boundary of the landfill ranges from about 2 to 12 m below land surface. Ground water flow in the area generally is toward the east and southeast, but ground water mounding beneath the landfill may result in radial flow away from the landfill. The specific conductance of water sampled from monitoring wells completed in contaminated zones downgradient of the landfill is as high as 4200 μS/cm at 25 C. Background specific conductance ranges from 200 to 300 μS/cm at 25 C.

Septic Waste Facility at Orleans, Massachusetts

The Orleans site is at a septic waste treatment facility in the town of Orleans on Cape Cod. Septage from septic tanks is trucked to the facility, treated, and then the treated effluent is discharged to infiltration beds. Discharge to the infiltration beds began in 1990. The site is on an extensive outwash plain. More than 100 m of outwash and lacustrine deposits underlie the site; the upper 40 m consist of sand with some silty zones.

Depth to the water table at the site ranges from 3 to 16 m. Ground water flow is westward toward a brackish marsh. Specific conductance of ground water is elevated, primarily as a result of increased chloride concentrations, and in areas downgradient of the infiltration beds is as high as 3200 μS/cm at 25 C. Background specific conductance ranges from 75 to 300 μS/cm at 25 C. The application of EM logging to delineate the contaminant plume at the site was presented by Barlow and DeSimone (1991).

Highway at Wareham, Massachusetts

The Wareham site is along a six-lane interstate highway that receives periodic applications of deicing salts during the winter months. The site is on an outwash plain; the upper deposits consist of 20 to 30 m of fine to coarse sand with some gravel, below which is a zone of silt to fine sand at least 3 m thick. Depth to the water table ranges from 5 to 10 m. Ground water flow is southward nearly perpendicular to the highway. Specific conductance of ground water is elevated, primarily as a result of increased chloride and sodium concentrations, and in areas downgradient of the highway is as high as 400 μS/cm at 25 C. Background specific conductance ranges from 40 to 70 μS/cm at 25 C. The application of EM logging to monitor the plume at this site was described by Church and Friesz (1991).

Methods

EM, gamma, and lithologic logs were collected from selected monitoring wells at the study sites, as were water level, specific conductance, and temperature data. The wells were installed by the U.S. Geological Survey or by state regulatory agencies as part of ground water contamination investigations and were constructed with 5-centimeter (cm) diameter PVC casing and screens. Many of the wells are part of well cluster installations that consist of two to five closely spaced wells screened at successive depths in the aquifer. EM, gamma, and lithologic logs were collected only from the deepest well in each cluster. Water level, specific conductance, and temperature data were collected from each well.

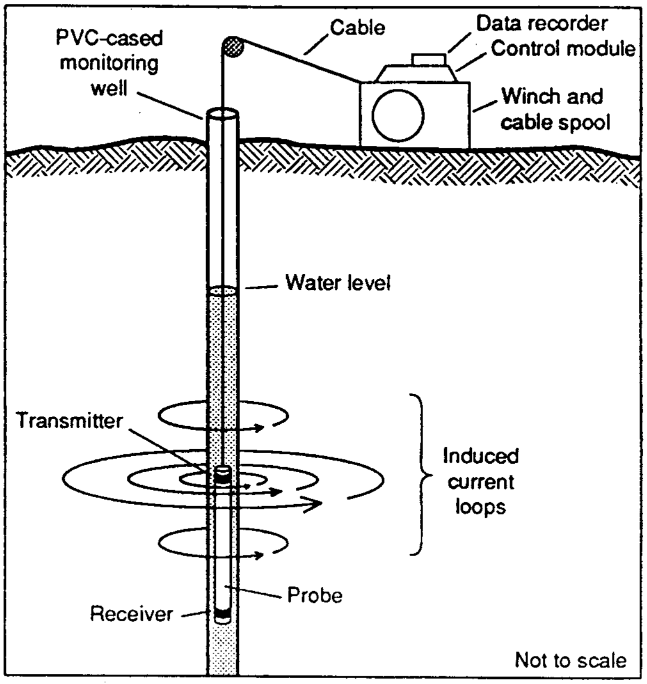

Figure 2. Electromagnetic logger. (Modified from McNeill 1986.)

A Geonics EM39 logger was used for the collection of the EM logs. EM conductivity values were recorded at 0.1-m intervals at the landfill sites and at 0.2-m intervals at the septic waste facility and highway deicing site. EM conductivity was measured at ambient ground water temperatures in the range of 9 to 16 C.

The specifications and theory of operation of the EM39 logger are described by McNeill (1986); field evaluations are presented by Taylor et al. (1989) and McNeill et al. (1990). The logging probe consists of transmitter and receiver coils (Figure 2). The transmitter coil emits an EM signal that induces eddy currents in the medium surrounding the well. These eddy currents generate an alternating secondary magnetic field that is sensed together with the primary field by the receiver coil. The strength of the secondary magnetic field is a function of the EM conductivity of the surrounding medium. Because EM conductivity is electrolytic, the current generally moves through water-filled pores within the insulating grain matrix. EM conductivity is affected mainly by the porosity, permeability, and clay and water content of the medium, and by the dissolved solids concentrations and temperature of the pore water (McNeill 1980).

The Geonics EM logging probe includes an additional receiver coil to cancel the primary field, reduce sensitivity to the wellbore fluid, and focus the horizontal response. The peak response from the instrument occurs at a radial distance of 28 cm from the probe, and half of the response is from a distance of more than 58 cm. In a well with a diameter of 15 cm or less, the effect of the specific conductance of the wellbore fluid on instrument response is negligible (McNeill 1986; Taylor et al. 1989).

Like other logging probes, the Geonics EM probe averages its response over a vertical interval. The theoretical and measured response of the instrument to an abrupt contact (Taylor et al. 1989) indicates that the measured EM conductivities of such a contact are smoothed over an interval of 1 m. McNeill et al. (1990) demonstrated that the theoretical EM log responses of abrupt and gradational contacts were essentially the same if the latter is less than 0.4 m thick. Taylor et al. (1989) showed that if a zone is less than 4 m thick, the measured EM conductivity departs from the actual values, and the EM conductivity of zones of less than 1 m thick is not well defined (Figure 3). Although the instrument does not provide good approximations of EM conductivity for zones less than 1 m thick, it is still useful in detecting the presence of such zones if the EM conductivity contrast between adjacent zones is sufficiently large.

The response of the EM logger is adversely affected by the presence of metal within a horizontal distance of about 3 m of the probe (Taylor et al. 1989). During this study, outer steel casings, coupling screws, broken-off auger teeth, and other buried metal affected instrument response at various depth intervals in many of the wells. Small metal objects caused sharp deflections, across which the EM conductivity values were readily interpolated. Larger metal objects, however, resulted in lost record for some depth intervals.

To minimize the effect of minor instrument drift, the EM logger was adjusted to read zero conductivity in a medium with negligible EM conductivity before the beginning of each field day. This adjustment was made as suggested by the manufacturer, by suspending the probe in the air away from any metal object. EM conductivity values for unsaturated sand and gravel and for sand and gravel containing water with very low dissolved solids concentrations (specific conductance of less than 150 μS/cm at 25 C) were as low as –5 mS/m, even when the instrument was zeroed immediately before logging. Negative values apparently are the result of the resolution of the instrument at very low EM conductivity.

For the landfill sites, the gamma probe and control module for the Geonics EM39 logger were used. A Mount Sopris logger with a gamma probe and module was used for the septic waste facility and highway deicing site. Gamma values were recorded at 0.1-m intervals with the Geonics logger and at 0.06- or 0.15-m intervals with the Mount Sopris logger. Gamma logs record the total gamma radiation of the medium surrounding the well (Keys 1990). The most significant naturally occurring sources of gamma radiation are potassium-40 and daughter products of the uranium- and thorium-decay series. Fine-grained beds of silt and clay generally produce higher gamma counts than sand and gravel because they include weathering products of potassium feldspar and mica and tend to concentrate uranium and thorium by ion exchange.

Water samples for specific conductance and temperature measurements were collected from single wells and from each well in well clusters. The wells were pumped or bailed until the specific conductance and temperature of the sampled water approached a constant value. The specific conductance meters were calibrated with known standards and specific conductance was reported at the standard temperature of 25 C (Hem 1985). Specific conductance measures the electrical conductivity of the water and provides a reliable estimate of the dissolved solids concentration.

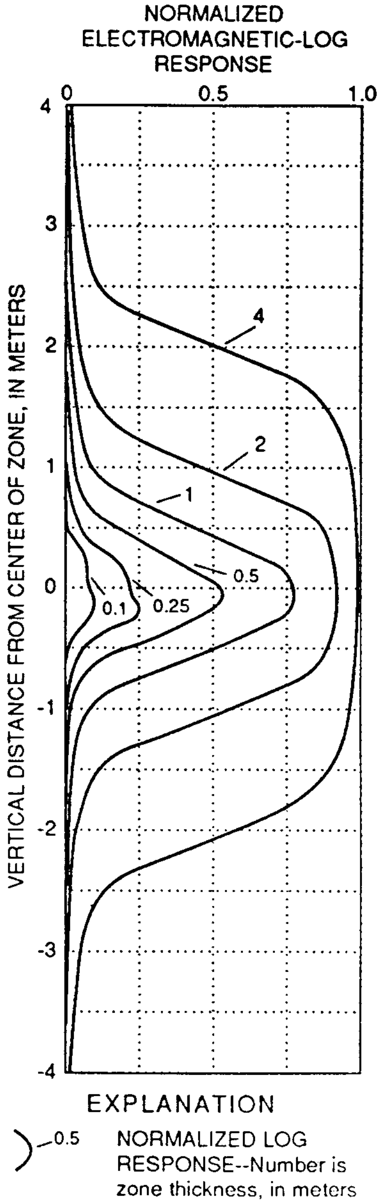

Figure 3. Normalized electromagnetic log response to geoelectric zones that range in thickness from 0.1 to 4 meters. (Modified from Taylor et al. 1989.)

Geoelectric sections at selected monitoring well sites were determined by use of a computer program developed by McNeill et al. (1990). The number of zones within each section and their thickness and EM conductivity were varied in a manner consistent with the lithologic, gamma, water level, and specific conductance data to produce an acceptable match between the measured and calculated EM conductivity logs.

Factors that Affect Electromagnetic Conductivity

The major hydrogeologic factors that affected EM log response at the study sites were the dissolved solids concentration of the ground water and the silt and clay content in the aquifer. Generalized EM, gamma, and lithologic logs that are typical of glacial sand-and-gravel aquifers are depicted in Figure 4. An idealized sand-and-gravel aquifer in which the dissolved solids concentration has not been elevated above background by contamination is represented in Figure 4A. The EM log does not show an abrupt change at the water table because the boundary between the unsaturated and saturated zones typically is poorly defined electrically in aquifers with low dissolved solids concentrations. At the study sites, EM conductivity of unsaturated sand and gravel typically was less than 5 mS/m, and that of saturated sand and gravel with low dissolved solids concentration ranged from less than 5 to only about 10 mS/m. The zone of silt and clay in the idealized aquifer (Figure 4A) is indicated by an increase in both gamma radiation and EM conductivity. EM conductivity of silt and clay zones at the study sites ranged from about 15 to 45 mS/m.

EM, gamma, and lithologic logs for an identical idealized aquifer with electrically conductive contamination are shown in Figure 4B. As a result of the high dissolved solids concentration in the water, the water table is well defined on the EM log. The contaminated sand-and-gravel zone is indicated by low gamma radiation and high EM conductivity. At the study sites, the EM conductivity of sand and gravel that contained contaminated water ranged from about 10 to more than 80 mS/m. The contact between the contaminated zone and the underlying silt and clay in the idealized aquifer (Figure 4B) is indicated by an increase in gamma radiation and a decrease in EM conductivity. The contact between the silt and clay and the underlying sand and gravel that contain uncontaminated water is indicated by a decrease in both gamma radiation and EM conductivity.

The following paragraphs describe the geophysical and hydrogeologic data from monitoring well clusters at three of the landfills to illustrate the effects of lithology and water quality on EM conductivity. Figures 5, 6, and 7 present measured EM logs, geoelectric sections and corresponding calculated EM logs, gamma and lithologic logs, and specific conductance data for the three representative sites described as follows.

Lower Landfill at Bristol, Vermont

Geophysical and hydrogeologic data collected from the cluster of wells 305, 306, 323, and 339 at the lower Bristol landfill illustrate the effects of lithology on EM log response (Figure 5). This well cluster is west of the lower landfill in an area where the ground water is uncontaminated or only slightly contaminated. The geoelectric section for this well cluster consists of seven zones. The uppermost zone is 5.5 m thick and has an EM conductivity of 10 mS/m, which is characteristic of saturated sand with minimal contamination. The next

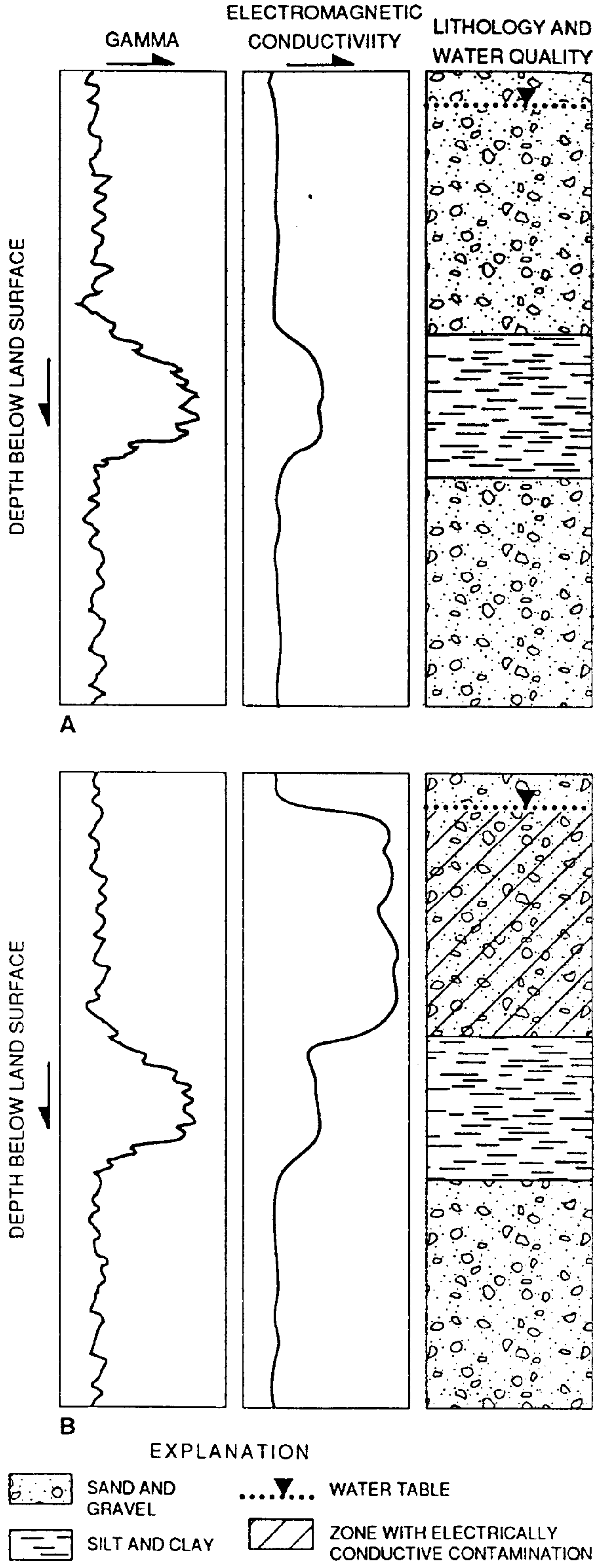

Figure 4. Electromagnetic log response in idealized glacial sand-and-gravel aquifers: (a) uncontaminated aquifer, (b) contaminated aquifer.

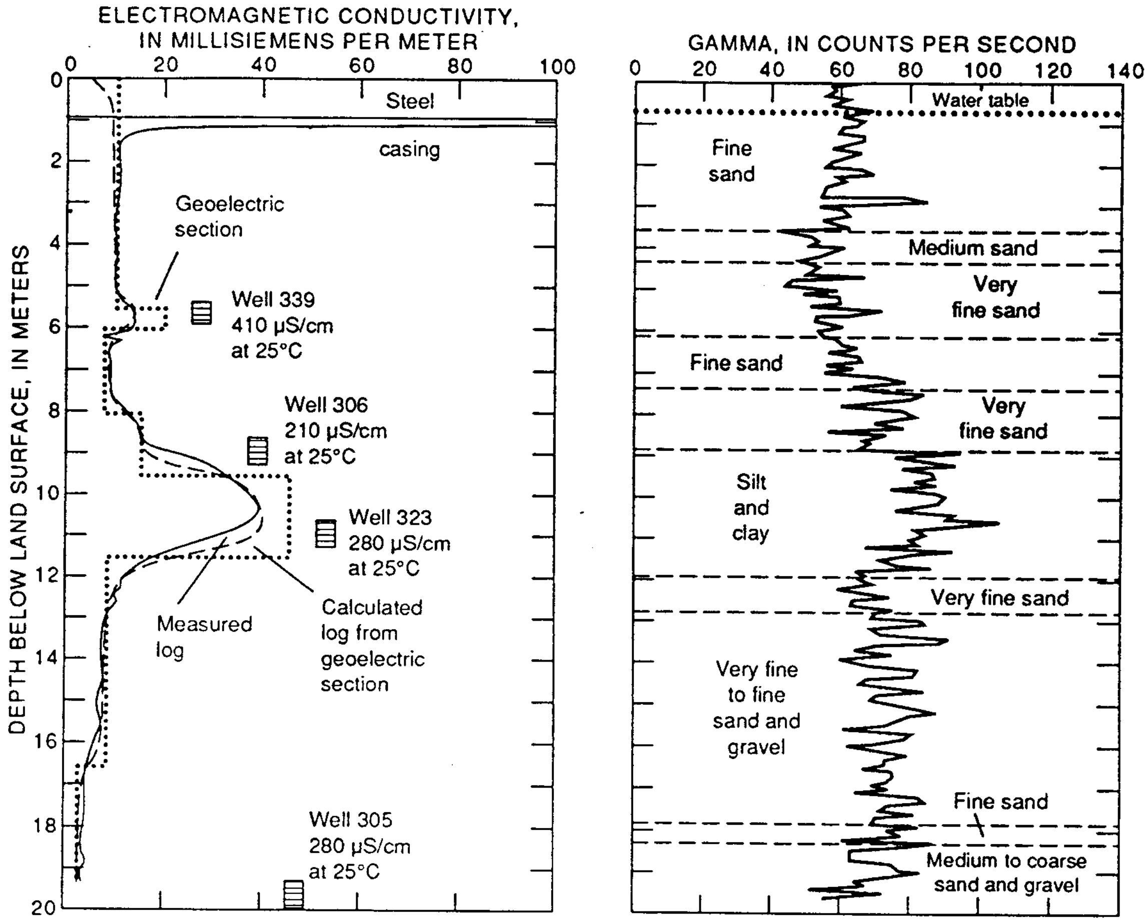

Figure 5. Electromagnetic, gamma, and lithologic logs; specific conductance data; and geoelectric section for the cluster of wells 305, 306, 323, and 339 at the lower Bristol landfill site.

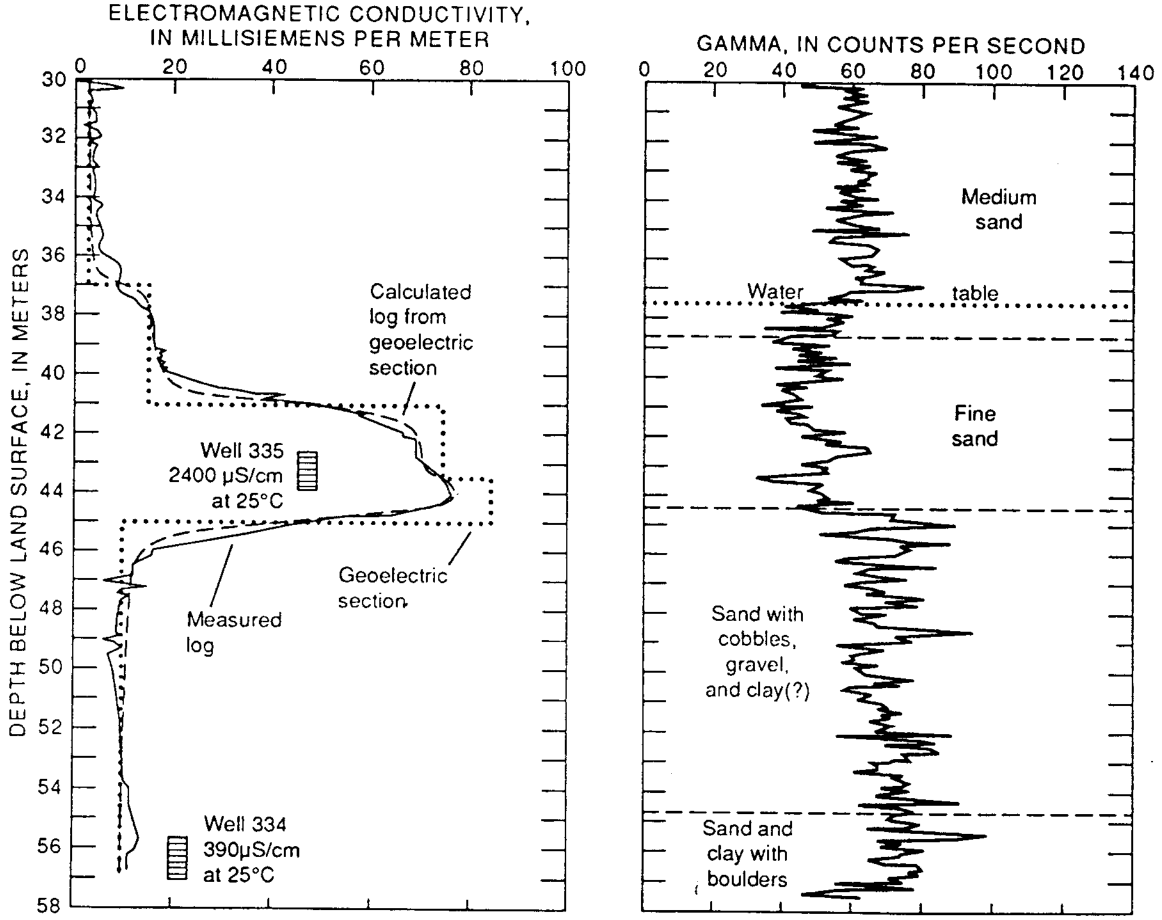

Figure 6. Electromagnetic, gamma, and lithologic logs; specific conductance data; and geoelectric section for the pair of wells 334 and 335 at the upper Bristol landfill site.

zone, at a depth of 5.5 to 6 m, has an EM conductivity of 20 mS/m, which suggests an increase in contamination or in the silt and clay content of the saturated sand. The gamma log does not indicate an increase in the silt and clay content, but water from well 339, which is screened at a depth of 5.2 to 5.8 m, had a specific conductance of 410 μS/cm at 25 C, which is slightly above background levels.

EM conductivity of the third zone, at a depth of 6 to 8 m, is 7.5 mS/m, which is characteristic of saturated sand with little or no contamination. The EM conductivity of the fourth zone, at a depth of 8 to 9.5 m, is 15 mS/m, and water from well 306, which is screened at a depth of 8.5 to 9.1 m, had a specific conductance of 210 μS/cm at 25 C. This indicates that the slightly elevated EM conductivity in this 1.5-m thick zone probably is related to an increase in silt and clay content rather than an increase in specific conductance.

EM conductivity of the fifth zone, at a depth of 9.5 to 11.5 m, increases to 45 mS/m. This zone correlates with a 3-m thick zone of silt and clay indicated by the gamma log and recorded on the lithologic log. Water from well 323, which is screened at a depth of 10.7 to 11.3 m in the silt and clay zone, had a specific conductance of 280 μS/cm at 25 C; thus, the elevated EM conductivity in this zone apparently is caused by silt and clay and not contamination.

EM conductivity of the sixth zone, at a depth of 11.5 to 16.5 m, is 7.5 mS/m, and that of the seventh zone below a depth of 16.5 m is 2.5 mS/m, which indicates little or no contamination. Water sampled from well 305, screened at a depth of 19.2 to 20.4 m, had a specific conductance of 280 μS/cm at 25 C.

Upper Landfill at Bristol, Vermont

Geophysical and hydrogeologic data from the paired wells 334 and 335 at the upper Bristol landfill illustrate the effects of water quality on EM log response (Figure 6). This well pair is southwest of the upper landfill in an area where the water in part of the aquifer is contaminated. The geoelectric section at the wells consists of five zones. The upper zone has an EM conductivity of 2.5 mS/m and correlates with the unsaturated sand deposits above the water table. The second zone, which extends from below the water table at a depth of 37 to 41 m, has an EM conductivity of 15 mS/m and correlates with a zone of saturated fine sand with a minor amount of contamination. The third zone, whose top is defined by the sharp increase in EM conductivity at a depth of 41 m, extends to a depth of 43.5 m, and the fourth zone extends from a depth of 43.5 to 45 m. The third and fourth zones, which have EM conductivities of 75 and 85 mS/m, respectively, represent the main plume of contamination in the aquifer. Water from well 335, screened at a depth of 42.4 to 43.9 m, had a specific conductance of 2400 μS/cm at 25 C, an order of magnitude above background levels. The fifth zone, below a depth of 45 m, has an EM conductivity of 10 mS/m, indicating

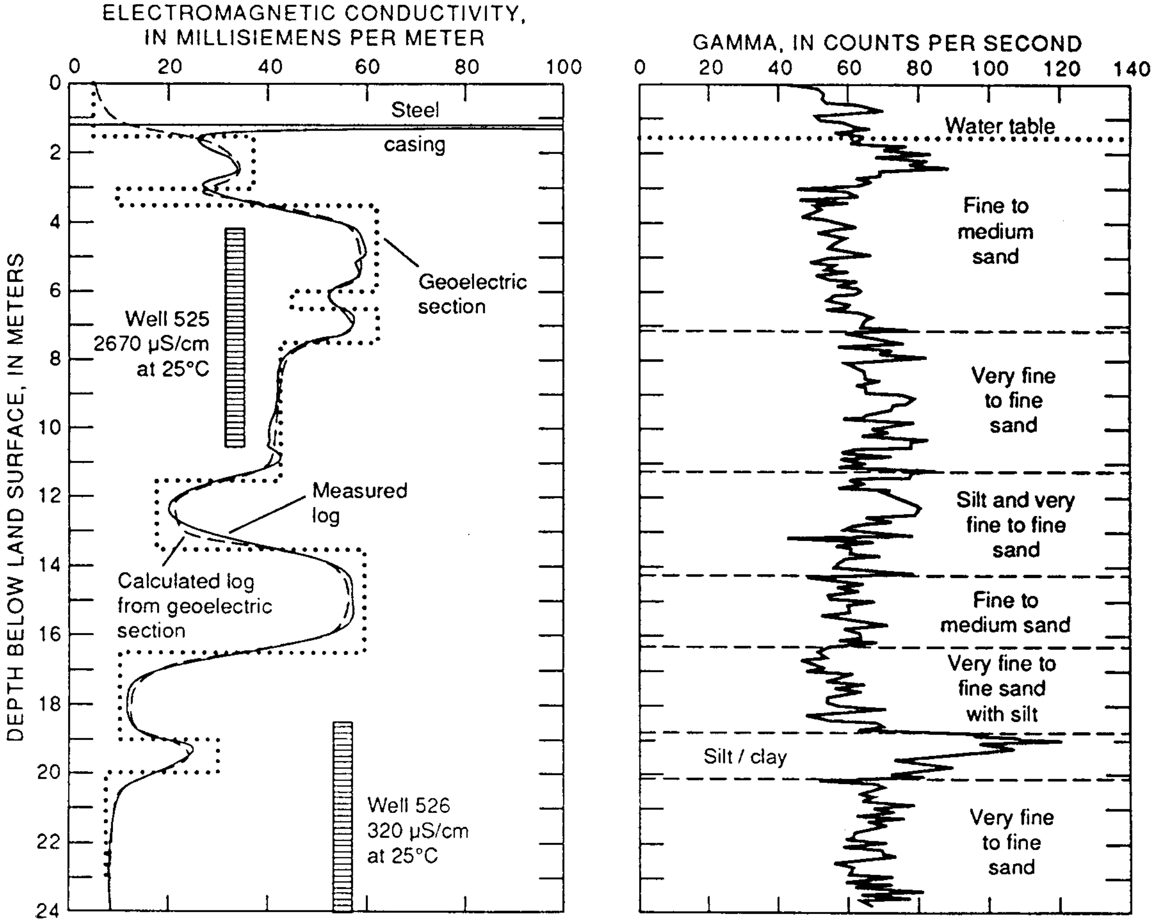

Figure 7. Electromagnetic, gamma, and lithologic logs; specific conductance data; and geoelectric section for the pair of wells 525 and 526 at the Albany landfill site.

little or no contamination. Gamma radiation is elevated in this zone, suggesting an increase in the silt and clay content of the aquifer. Water from well 334, screened at a depth 55.5 to 57 m, had a specific conductance of 390 μS/cm at 25 C — a value only slightly higher than background levels.

Landfill at Albany, New York

Geophysical and hydrogeologic data from the pair of wells 525 and 526 at the Albany landfill site illustrate the effects of both water quality and lithology on EM log response (Figure 7). The well pair is at the eastern edge of the landfill in an area where part of the aquifer is contaminated. The geoelectric section at the well pair consists of 12 zones. The uppermost zone is 1.5 m thick and has an EM conductivity of 5 mS/m, representative of an unsaturated sand. From a depth of 1.5 to 3 m, the EM conductivity of the section increases to 37.5 mS/m and correlates with a zone of increased silt and clay content indicated by the gamma log. No fine-grained deposits are recorded in the lithologic log, however, probably because drilling samples from this interval were incomplete.

From a depth of 3 to 3.5 m, EM conductivity decreases to 10 mS/m, which is characteristic of saturated sand with minimal contamination. At a depth of 3.5 m, the EM conductivity increases to 62.5 mS/m, which indicates significant contamination in the fine to medium sand. Near the contact between fine to medium sand and very fine to fine sand at a depth of 7 m, EM conductivity decreases to 42.5 mS/m. Water from well 525, screened at a depth of 4.3 to 10.4 m, had a specific conductance of 2670 μS/cm at 25 C — a value an order of magnitude above background levels. Near the contact with a silt-rich zone at a depth of 11 m, EM conductivity decreases to 17.5 mS/m.

From a depth of 13.5 to 16.5 m, EM conductivity increases to 60 mS/m. As in the previous case, this zone of contamination correlates with a zone of fine to medium sand. From a depth of 16.5 to 19 m, EM conductivity decreases to 10 mS/m in a zone of silty sand, but from a depth of 19 to 20 m it increases to 30 mS/m, which correlates with a zone of silt and clay as indicated by the gamma log and recorded on the lithologic log. This increase in EM conductivity apparently is related to lithology and not to water quality. At a depth of 20 m, near the contact with very fine to fine sand, EM conductivity decreases to 7.5 mS/m, indicating little or no contamination in this zone. Water from well 526, screened from a depth of 18.6 to 24.7 m, had a specific conductance of 320 μS/cm at 25 C — a value only slightly above background levels.

Relation Between Electromagnetic Conductivity and Specific Conductance

The relation between the measured EM conductivity of the glacial sand-and-gravel aquifers and the specific conductance of the water sampled from the monitoring wells was analyzed by regression methods. Specific conductance values and the median of the measured EM conductivity for 49 screened intervals in sand and gravel were determined at 27 well cluster and single well installations. Excluded from the analysis were EM conductivity and specific conductance data from well screen intervals that were entirely within silt and clay zones, such as in well 323 (Figure 5). Screened intervals that were partly completed in silt and clay zones, such as well 526 (Figure 7), were included, but EM conductivity values corresponding to a silt and clay zone were excluded from the calculation of the median values on the assumption that these zones contributed little sample water. Also excluded were data from well screen intervals in which the median value for EM conductivity was negative.

The median EM conductivity values were converted from mS/m to μS/cm and adjusted to the standard temperature of 25 C according to the temperature of the ground water sampled from the screened interval and the following relation (McNeill 1980):

$$EM_s = \frac{10\ EM_a}{1 + 0.022\ (T_a - 25\ C)} \qquad (1)$$

where:

EM_s = EM conductivity, in μS/cm at 25 C

EM_a = EM conductivity, in mS/m at the ambient ground water temperature

T_a = ambient ground water temperature, in C.

For those screened intervals in which temperature measurements were not available, the median temperature of ground water samples at the site was used.

The frequency distributions of the EM conductivity and specific conductance data both showed strong right skews. Therefore, these data were logarithmically transformed to improve normality. The correlations of the transformed data with their normal scores (Ryan et al. 1985) were 0.993 for the log of the EM conductivity data and 0.991 for the log of the specific conductance data. Both are significant at the 0.05 level.

The relation between the log of EM conductivity and the log of specific conductance was determined by regression statistics. The correlation of the log of EM conductivity and the log of specific conductance is significant at the 0.05 level with a correlation coefficient of 0.844. The fitted relation is:

$$\text{Log } SC_s = 0.65 + 0.94 \text{ Log } EM_s \qquad (2)$$

where:

SC_s = specific conductance of water sampled from screened interval, in μS/cm at 25 C

EM_s = median of the EM conductivity of the screened interval, in μS/cm at 25 C.

The median EM conductivity and specific conductance data are plotted with the fitted regression line in

Figure 8. Scatter in the relation is caused in part by variability in the silt and clay content in the aquifers; departure of measured EM conductivity from actual values in transition zones and in zones less than 4 m thick; and measurement errors in the EM conductivity, specific conductance, and temperature data.

Considerations for Use of Electromagnetic Logging

EM logging can be applied to investigations of contamination in glacial sand-and-gravel aquifers to

1. Determine optimum screened intervals for monitoring wells.
2. Provide a nearly continuous vertical profile of specific conductance to complement depth-specific water quality samples from monitoring wells.
3. Identify temporal changes in water quality through sequential logging of monitoring wells.

In glacial sand-and-gravel aquifers, flow system hydraulics and subtle changes in lithology can greatly affect contaminant transport and, thus, make proper selection of screened intervals in monitoring wells difficult. The use of EM logging during well construction can significantly increase the efficiency and effectiveness of monitoring programs. EM logging of PVC-cased wells or mud-filled holes that penetrate the investigated aquifer can provide the information needed for optimum vertical placement of well screens. Detailed lithologic or gamma logs, preferably both, are needed to define zones in which elevated EM conductivity is related to silt and clay beds rather than contamination. Gamma logs provide continuous data that are not biased by individual interpretation.

Water samples from monitoring wells with short-screen intervals provide limited vertical coverage of water quality in the aquifer. On the other hand, water samples from long-screen intervals provide only a composite view of water quality within the sampled depth intervals. To complement depth-specific samples, a nearly continuous profile of specific conductance of ground water in sand and gravel can be estimated from EM logs by use of the regression equation presented in this paper. The regression equation cannot be used to estimate the specific conductance of ground water in silt and clay zones. Where specific conductance is correlated with the contaminants of interest, EM logs provide the data needed for vertical profiling of water quality. Continuous water quality profiles enable detailed three-dimensional mapping of complex contaminant plumes.

Sequential EM logging of wells provides an efficient method for monitoring water quality over time. EM logging provides a method for monitoring water quality through the entire vertical section of the aquifer, not just screened intervals, and thereby maximizes the chance of detecting changes in the contaminant plume.

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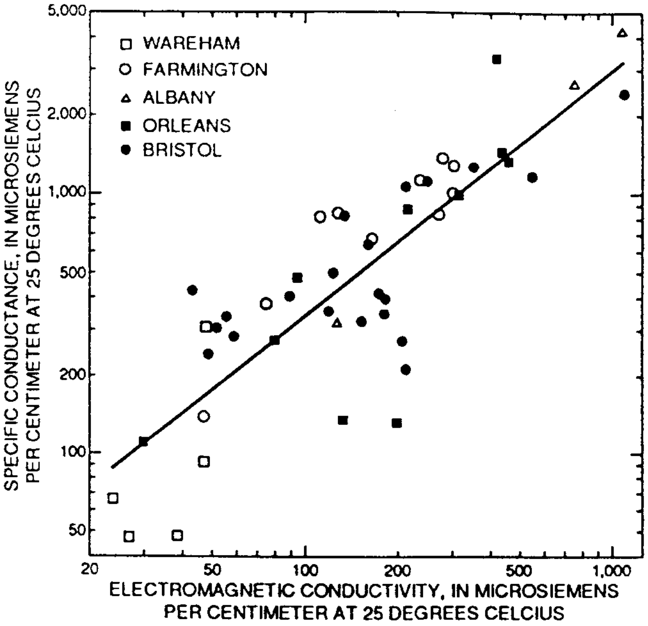

Figure 8. Relation between electromagnetic conductivity and specific conductance of the water from selected well screen intervals in glacial sand-and-gravel aquifers.

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