Use of Borehole and Surface Geophysics to Investigate Ground-Water Quality near a Road-Deicing Salt-Storage Facility, Valparaiso, Indiana

By Martin R. Risch and Bret A. Robinson

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Conversion Factors and Vertical Datum

Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per mile (ft/mi)	0.1894	meter per kilometer
acre	4,047	square meter
acre	0.004047	square kilometer
gallon (gal)	3.785	liter
foot per minute (ft/min)	0.3048	meter per minute
foot per year (ft/yr)	0.3048	meter per year
gallon per minute (gal/min)	0.06309	liter per second

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical Datum: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance in feet above sea level.

Specific conductance is given in microsiemens per centimeter (µS/cm) at 25 degrees Celsius.

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Borehole electromagnetic conductivity and **terrain electromagnetic conductivity** are given in millisiemens per meter (mS/m). A millisiemen per meter is equal to 10 microsiemens per centimeter (µS/cm).

Abbreviations used in this report:

Abbreviation	Description
m	meter
cm	centimeter
INDOT	Indiana Department of Transportation
USGS	U.S. Geological Survey
VWD	Valparaiso Water Department

Use of Borehole and Surface Geophysics to Investigate Ground-Water Quality near a Road-Deicing Salt-Storage Facility, Valparaiso, Indiana

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Abstract

Borehole and surface geophysics were used to investigate ground-water quality affected by a road-deicing salt-storage facility located near a public water-supply well field. From 1994 through 1998, borehole geophysical logs were made in an existing network of monitoring wells completed near the bottom of a thick sand aquifer. Logs of natural gamma activity indicated a uniform and negligible contribution of clay to the electromagnetic conductivity of the aquifer so that the logs of electromagnetic conductivity primarily measured the amount of dissolved solids in the ground water near the wells. Electromagnetic-conductivity data indicated the presence of a saltwater plume near the bottom of the aquifer. Increases in electromagnetic conductivity, observed from sequential logging of wells, indicated the saltwater plume had moved north about 60 to 100 feet per year between 1994 and 1998. These rates were consistent with estimates of horizontal ground-water flow based on velocity calculations made with hydrologic data from the study area.

Ratios of chloride to bromide concentrations in water samples were used to distinguish sources of chloride in the ground water— whether from road-deicing salt, domestic wastewater, or natural occurrences. Water samples identified with the chloride/bromide ratios as being affected by road-deicing salt had concentrations of dissolved solids, chloride, and sodium many times the background levels for the study area. The largest concentrations were in water from wells near the salt-storage facility—12,400 to 12,800 milligrams per liter (mg/L) dissolved solids, 6,730 to 7,230 mg/L chloride, and 3,690 to 4,400 mg/L sodium.

A conceptual, multi-layer model was developed to describe the vertical extent of the saltwater plume in the vicinity of the monitoring wells. A relation was derived between average borehole electromagnetic conductivity in the screened interval of the wells in the saltwater plume and concentrations of dissolved solids in water samples from those wells. This relation was used in the model to show borehole electromagnetic conductivity in transects of wells as a zone of saline water overlain by zones of brackish water and freshwater. The thickness and altitude of the zones of saline and brackish water decreased with increased distance from the salt-storage facility.

Two surface surveys of terrain electromagnetic conductivity were used to map the horizontal extent of the saltwater plume in areas without monitoring wells. Background values of terrain conductivity were measured in an area where water-quality and borehole geophysical data did not indicate saline or brackish water. Based on a guideline from previous case studies, the boundaries of the saltwater plume were mapped where terrain conductivity was 1.5 times background. The

extent of the saltwater plume, based on terrain conductivity, generally was consistent with the available water-quality and borehole electromagnetic-conductivity data and with directions of ground-water flow determined from water-level altitudes.

Introduction

Road-deicing salts—sodium chloride and calcium chloride—were stored, mixed with sand, and loaded at an Indiana Department of Transportation (INDOT) highway-maintenance facility adjacent to the Porter County Airport, in Valparaiso, Ind., from 1969 until the facility was closed in 1999. Prior to 1978, stockpiles of sodium chloride were not stored under a permanent roof and, for nearly 30 years, road-deicing salt and sand were mixed outside before storage or use. Vehicles used for spreading salt were washed outside. For many years, most of the runoff from the site infiltrated the ground surface and, during a period in 1982 to 1983, about 6,000 gallons of liquid calcium chloride leaked from a storage tank and seeped into the ground (Farlow Environmental Engineers, Inc., 1997).

From 1981 through 1993, the Valparaiso Water Department (VWD) monitored chloride concentrations in water from their supply wells at the Porter County Airport (fig. 1). During that time, the concentrations of chloride in one well increased from 6 mg/L to 32 mg/L (Harza Environmental Services, Inc., 1994). In 1993, the VWD began implementation of a wellhead-protection program. Several monitoring wells were installed and water samples near the highway-maintenance facility were found to contain substantial concentrations of chloride and sodium, which were assumed to be from road-deicing salt.

From 1993 through 1995, contractors for VWD and INDOT investigated ground water in the vicinity of the highway-maintenance facility and the airport, acquiring useful information installing and sampling a monitoring-well network (Farlow Environmental Engineers, Inc., 1997). From 1994 through 1998, VWD continued to monitor chloride concentrations in water from the supply wells at the airport. The largest concentration of chloride in any of the samples was 38 mg/L (Valparaiso Water Department, unpublished information, January 1999.) The nonenforceable secondary drinking-water regulation[1] for chloride is 250 mg/L (U.S. Code of Federal Regulations, 1999); the nonenforceable health advisory[2] for sodium is 20 mg/L (U.S. Environmental Protection Agency, 1996). In April 1998, INDOT, VWD, and the Indiana Department of Environmental Management (with the U.S. Environmental Protection Agency) agreed that INDOT would undertake remedial action to reduce concentrations of chloride and sodium in the ground water near the former highway-maintenance facility.

The historical analyses of the water samples collected from the monitoring-well network at the highway-maintenance facility and Porter County Airport did not provide complete information about the vertical and horizontal extent of the ground water affected by road-deicing salt. To obtain the information for planning and evaluation of remedial actions, the U.S. Geological Survey (USGS), in cooperation with INDOT, used borehole and surface geophysical techniques to investigate ground-water quality near the highway-maintenance facility. Borehole geophysical logs provided information about ground-water quality above the screened interval of the monitoring wells and beyond the well boreholes; surface geophysical surveys provided information about ground-water quality at locations where monitoring wells were not or could not be installed.

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[1]Secondary Maximum Contaminant Level from section 143.3 of part 143, National Secondary Drinking Water Regulations, U.S. Code of Federal Regulations, Title 40. From section 143.1 (Purpose) of part 143: "These regulations control contaminants in drinking water that primarily affect the aesthetic qualities relating to the public acceptance of drinking water. At considerably larger concentrations of these contaminants, health implications may also exist as well as aesthetic degradation. The regulations are not Federally enforceable but are intended as guidelines for the States."

[2]Health advisory guidance for "drinking water equivalent level," which is "a lifetime exposure concentration protective of adverse, non-cancer health effects, that assumes all of the exposure to a contaminant is from a drinking water source."

87°01'

87°00'

41°27'30"

41°27'00"

Taxiway

Runway

Public Water-Supply Well Field

8   2   3   5   6   7

City of Valparaiso

Runway

Taxiway

Porter County Airport

Airport Entrance

Murvihill Road

49

30

County Road 325 East

Former Highway-Maintenance Facility
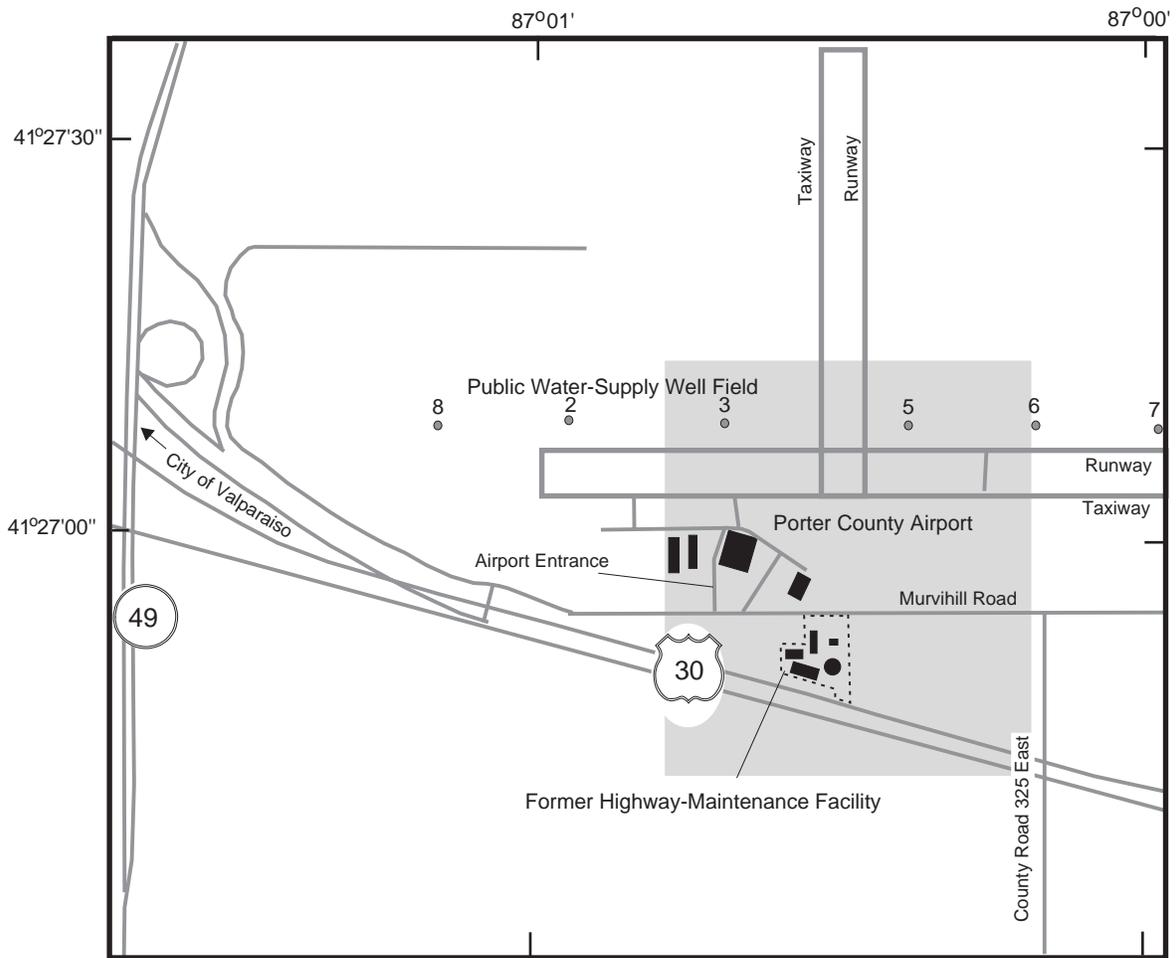
Base from U.S. Geological Survey Valparaiso 1:24,000, 1962; photo revised 1980

0   1000   2000 FEET

0   300   600 METERS

EXPLANATION

STUDY AREA

5
PUBLIC WATER-SUPPLY WELL

BUILDING

Porter County
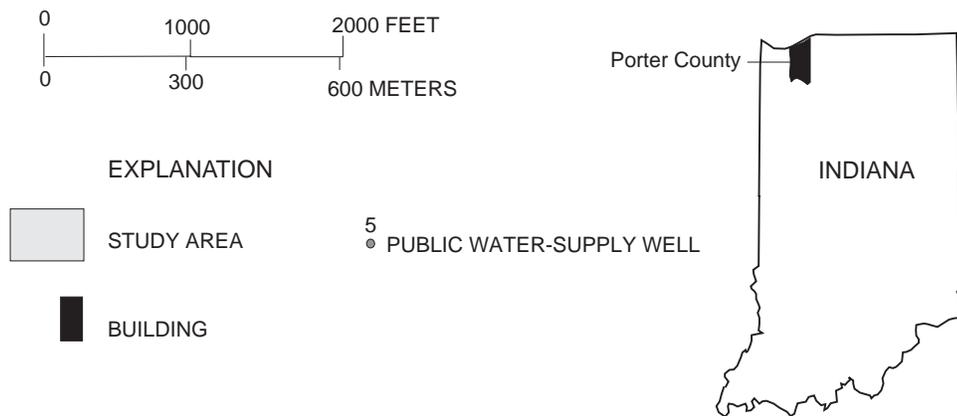
INDIANA

Figure 1. Location of the study area, Valparaiso, Indiana.

Several factors in the study area provided an opportunity to compare and integrate interpretations from the geophysical techniques with analyses of conventional water samples collected from the monitoring wells:

- a single contaminant (road-deicing salt) from a single source (a highway-maintenance facility);

- a homogeneous hydrogeologic environment that simplified interpretations of the geophysical data;

- an existing network of monitoring wells;

- availability of historical water-quality data; and

- a flat, open space (an airport) having few natural or manmade obstructions to extensive lines of surface geophysical survey stations.

Purpose and Scope

This report describes a case study for the use of borehole and surface geophysical techniques to investigate ground-water quality near a road-deicing salt-storage facility in Valparaiso, Ind. The report presents borehole geophysical data collected by the USGS in July 1994, March 1995, February 1996, and May 1998 from the monitoring-well network in the vicinity of the Porter County Airport in Valparaiso, along with surface geophysical data from surveys made by the USGS at the airport in November to December 1994 and September to October 1998. The geophysical data are compared with water-quality data collected by the USGS in March 1998 from the monitoring-well network and with historical water-quality data from 1994 and 1995. The borehole and surface geophysical data are used to interpret the vertical and horizontal extent of ground water affected by road-deicing salt.

Acknowledgments

Previous Case Studies

Results of this case study in Valparaiso, Ind., are discussed relative to previous case studies. In previous case studies, borehole and surface geophysical techniques, either alone or in combination, have been used to evaluate ground-water contamination and to delineate subsurface zones of saltwater.

Some studies relied on borehole geophysical techniques alone. Williams and others (1993) concluded that borehole logs of electromagnetic conductivity can provide a high-resolution vertical delineation of contamination in sand and gravel aquifers. In studies at five sites, Williams and others reported concentrations of dissolved solids in ground-water-contaminant plumes caused by municipal-waste disposal, septic-waste discharge, or road-deicing-salt application exceeded background levels by 10 to 20 times. The specific conductance of water samples from monitoring wells was significantly correlated with borehole electromagnetic conductivity. Mack (1993) also used borehole geophysics to vertically delineate landfill-leachate plumes in a glacial aquifer. Church and Friesz (1993) demonstrated that borehole logs of electromagnetic conductivity were effective and efficient for delineation of road-deicing salt in a sand and gravel aquifer affected

by highway runoff. In the Church and Friesz study, an extensive monitoring-well network was installed and repetitively logged to detect variations in the road-salt contamination over time. The qualitative interpretations of the geophysical data were confirmed by chemical analyses of water samples from the wells.

Some previous studies relied on surface geophysical techniques alone. Surface surveys of terrain electromagnetic conductivity have been shown to detect a contaminant plume consistently when conductivity values were elevated by a factor of 1.5 to 2.0 above average background levels because of the presence of contaminants (Grady and Haeni, 1984). Barlow and Ryan (1985) used terrain-conductivity data to delineate the areal and vertical extent of contamination in a sand and gravel aquifer. In the study by Barlow and Ryan, contours of logarithmically transformed data were found to be useful for masking background noise, thereby clarifying the areal extent of the contamination; contours of untransformed data were found to depict most clearly the vertical extent. Greenhouse and Slaine (1983) presented nine case studies in which surface geophysical techniques were used to map contaminant migration. They reported the best results were obtained in areas of unconsolidated, clay-free sediments. In those areas, the geophysical surveys defined the horizontal extent of contamination and allowed estimates of contamination levels. Greenhouse and Slaine also advocated that surface geophysical data be displayed as logarithmically transformed contours. Grady and Haeni (1984) found terrain-conductivity values to correlate with measurements of specific conductance of contaminated ground water. Chapman and Bair (1992) used surface surveys of terrain conductivity in a controlled field study to evaluate the effects on ground-water quality from oil-field brine applied for deicing roadways. In the study by Chapman and Bair, qualitative interpretations of changes in ground-water quality, based on the surface geophysical data, were found to correlate with concentrations of chloride and dissolved solids and with specific conductance in ground water.

In other studies, investigators combined borehole and surface geophysical techniques. McNew and Arav (1995) interpreted the depth of the freshwater/saltwater interface in a coastal area by combining geophysical and water-quality data. McNew and Arav used a conceptual, multilayer model of the subsurface to interpret the surface geophysical results and confirmed the interpretations with borehole geophysical and water-quality data. Paillet and others (1998) characterized the distribution of pore-water salinity in a bedrock aquifer in a coastal area by use of surface geophysical data. Paillet and others used borehole geophysical and water-quality data to calibrate the surface geophysical data in terms of pore-water salinity. Additional borehole geophysical data verified the layered inversion model used to interpret the surface geophysical data.

Monitoring-Well Network

The network of 25 monitoring wells (fig. 2) was installed in the study area during two previous investigations by VWD and INDOT (Appendix A, table A1). In the USGS study, water samples were collected from 23 of these wells and geophysical logs were made in the 16 deepest wells. Historical water-quality data from other wells installed by VWD and INDOT outside the study area did not indicate any effects from the salt-storage facility (Harza Environmental Services, Inc., 1994, and Farlow Environmental Engineers, Inc., 1997).

A contractor for VWD installed six of the network wells in 1993 and 1994—a cluster of five wells along Murvihill Road north of the salt-storage facility (TW-94A, TW-94B, TW94C, TW-94D, and TW-2) screened at intervals of increasing depth and an additional well (TW-94E) screened at the bottom of the aquifer north of the cluster of wells.

A contractor for INDOT installed the additional monitoring wells in the network in 1994 and 1995 (Farlow Environmental Engineers, Inc., 1997). Wells were installed at the salt-storage facility (MW-1, MW-2, MW-3, MW-4, MW-5, and
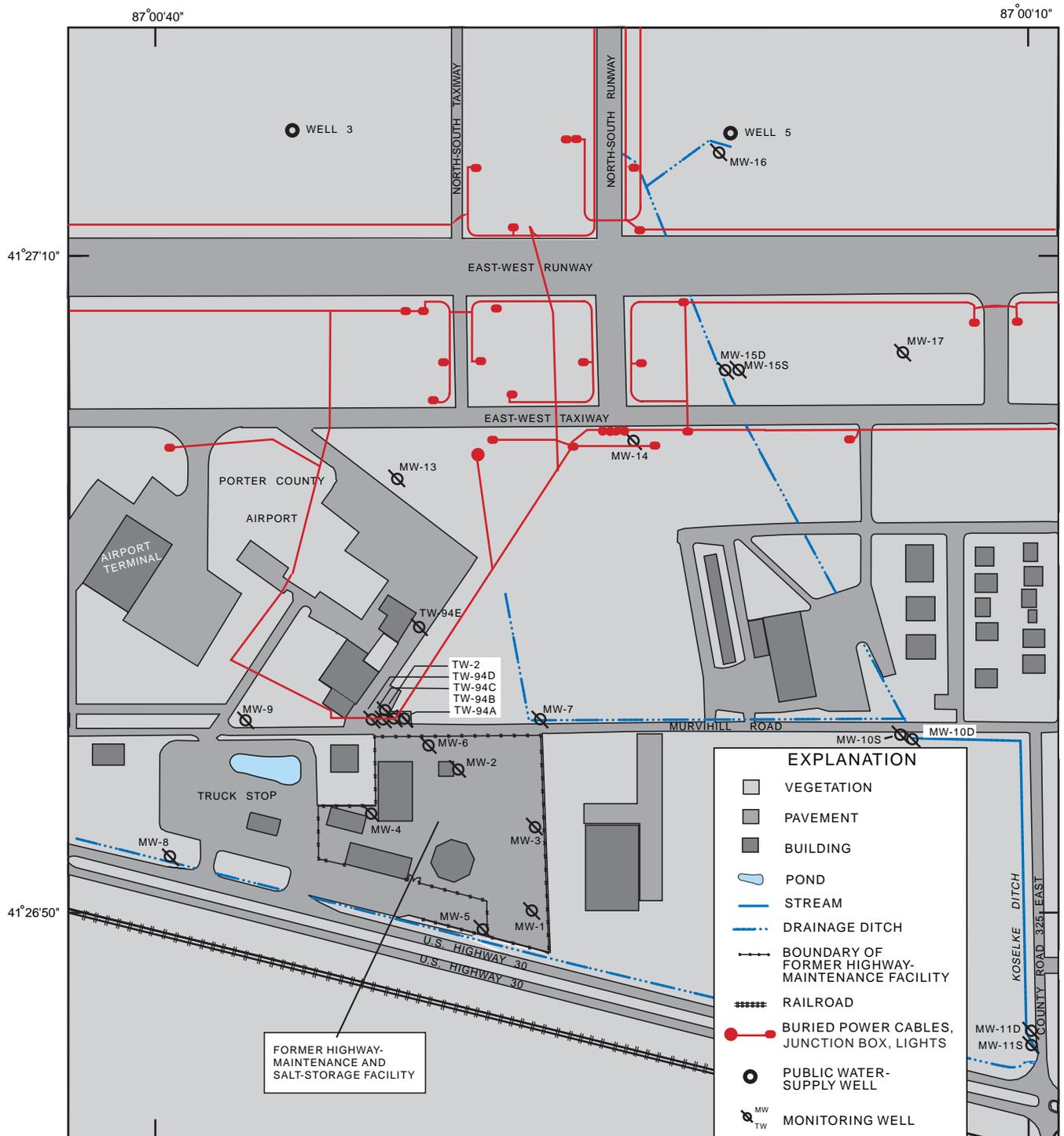
Figure 2. Study area, monitoring-well network, and buried power cables in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Base map modified from Department of Water Works, City of Valparaiso

MW-6); near the truck stop on U.S. Highway 30 (MW-8); and on Murvihill Road (MW-7 and MW-9). With the exception of MW-1 and MW-2, these wells are screened near the bottom of the aquifer. Two pairs of wells, including a well screened near the bottom of the aquifer and a well screened near the top of aquifer, were installed east of the salt-storage facility (MW-10S, MW-10D, MW-11S, and MW-11D). Wells MW-13, MW-14, MW-15S, MW-15D, MW-16, and MW-17 were installed on the Porter County Airport property. With the exception of MW-15S (screened in the middle of the aquifer), these wells were screened near the bottom of the aquifer.

Wells in the network were drilled with hollow-stem auger or mud-rotary methods. The wells were constructed of 2-in.-diameter plastic casing, with 0.01-in.-slot-size plastic screens 10 ft in length. (Well TW-2 has 4-in.-diameter casing.) The sand of the aquifer was allowed to backfill around the screen; bentonite grout was placed around the casing. Most of the wells were set in ground-level, metal well pits and have water-tight plugs at the top of the casing. After construction, the wells were developed by surging and pumping until the water was clear.

Physical and Hydrogeologic Setting

The study area covers about 190 acres in Porter County, Ind., in sections 28 and 29 of Township 35 North, Range 5 West (Valparaiso 7.5-minute quadrangle, U.S. Geological Survey, 1980 and Wanatah 7.5-minute quadrangle, U.S. Geological Survey, 1972), about 1.5 mi southeast of the City of Valparaiso. The former highway-maintenance facility is about 5.7 acres between Murvihill Road and U.S. Highway 30, about 600 ft southeast of the entrance to the Porter County Airport (fig. 1). Two VWD public water-supply wells (3 and 5) are 1,500 to 2,000 ft north of the former highway-maintenance facility and within the study area. Other VWD public water-supply wells are northwest and northeast of the study area.

A general description of the hydrogeologic setting of the study area was derived from previous studies conducted in Lake, Porter, and LaPorte Counties of Indiana (Malott, 1922; Shaver and others, 1986; Clendenon, 1990; Fraser and Bleuer, 1991a and 1991b; Bleuer and Woodfield, 1993) and from the Hydrogeologic Atlas of Aquifers in Indiana (Fenelon, Bobay, and others, 1994). Figure 3 provides a generalized diagram of the hydrogeologic setting.

Malott (1922) defined and described the physiographic regions of Indiana. The study area is in the Northern Moraine and Lake Region, which Malott divided into five sections. The study area lies within the Kankakee Lacustrine Section and very near the boundary of the Valparaiso Moraine. South of the Kankakee Lacustrine Section is the Kankakee River Flood Plain.

The Kankakee Lacustrine Section is an intermorainal lowland, trending southwest to northeast, and is composed primarily of wind- and water-deposited sand (Fraser and Bleuer, 1991b). In the vicinity of the study area, the unconsolidated deposits consist of a 120-ft-thick sand sequence underlain by fine-grained lacustrine (glacial-lake) deposits. This sequence of thick sands over lacustrine deposits is typical of the Kankakee Lacustrine Section.

The Valparaiso Moraine, immediately north of the study area, is a topographic high that curves around the southern end of Lake Michigan. This moraine forms a broad, undulating, asymmetric ridge with a north-facing slope that is slightly steeper than the south-facing slope (Fraser and Bleuer, 1991a). In most areas, the Valparaiso Moraine consists of three types of deposits. At the base, and resting directly on bedrock, are continuous and widespread lacustrine deposits. The core of the moraine is composed of thick sand, while clayey till caps the moraine. Near their common boundary, the facies of the Kankakee Lacustrine Section and the Valparaiso Moraine interfinger with each other (Fraser and Bleuer, 1991a and 1991b).

NORTH   **SOUTH**

Valparaiso Moraine Section
(Valparaiso Aquifer System)

STUDY
AREA

Kankakee Lacustrine Section
(Valparaiso Outwash Apron Aquifer System)

Kankakee River
Flood Plain
(Kankakee River
Aquifer System)

ALTITUDE, IN FEET

800

750

700

650

Regional Ground-Water Flow

TOWNSHIP 35 NORTH   TOWNSHIP 34 NORTH

(Hydrogeology modified from Clendenon, 1990, plate 2B)   Line Along 87°30′ West Longitude
(Geology modified from Fraser and Bleuer, 1991a, b)   VERTICAL SCALE GREATLY EXAGGERATED
DATUM IS SEA LEVEL

EXPLANATION

SAND SEQUENCE   FINE-GRAINED LACUSTRINE DEPOSITS

CLAYEY TILL   DEVONIAN- AND MISSISSIPPIAN-AGE
                                  ELLSWORTH SHALE BEDROCK

Figure 3. Diagrammatic hydrogeologic section in east-central Porter County, Indiana.

    In the vicinity of the study area, the thick
sand sequence (fig. 3) of the Kankakee Lacustrine
Section serves as the primary aquifer for the public
water supply. Clendenon (1990) has named this
the "Valparaiso Outwash Apron Aquifer System,"
while Fraser and Bleuer (1991b) simply refer to it
as the "eolian and fluvial sands of the Kankakee-
Valparaiso assemblage." According to Clendenon
(1990), the Valparaiso Moraine Aquifer System

is north of the study area and the Kankakee River
Aquifer System is south of the study area. Fenelon,
Bobay, and others (1994) mapped the thick surfi-
cial sand aquifer in the vicinity of the study area
as areally extensive throughout east-central Porter
County.

    A trace of the hydrogeologic section A-A′ is
shown in figure 4; the hydrogeology of the study
area is shown in the south to north hydrogeologic
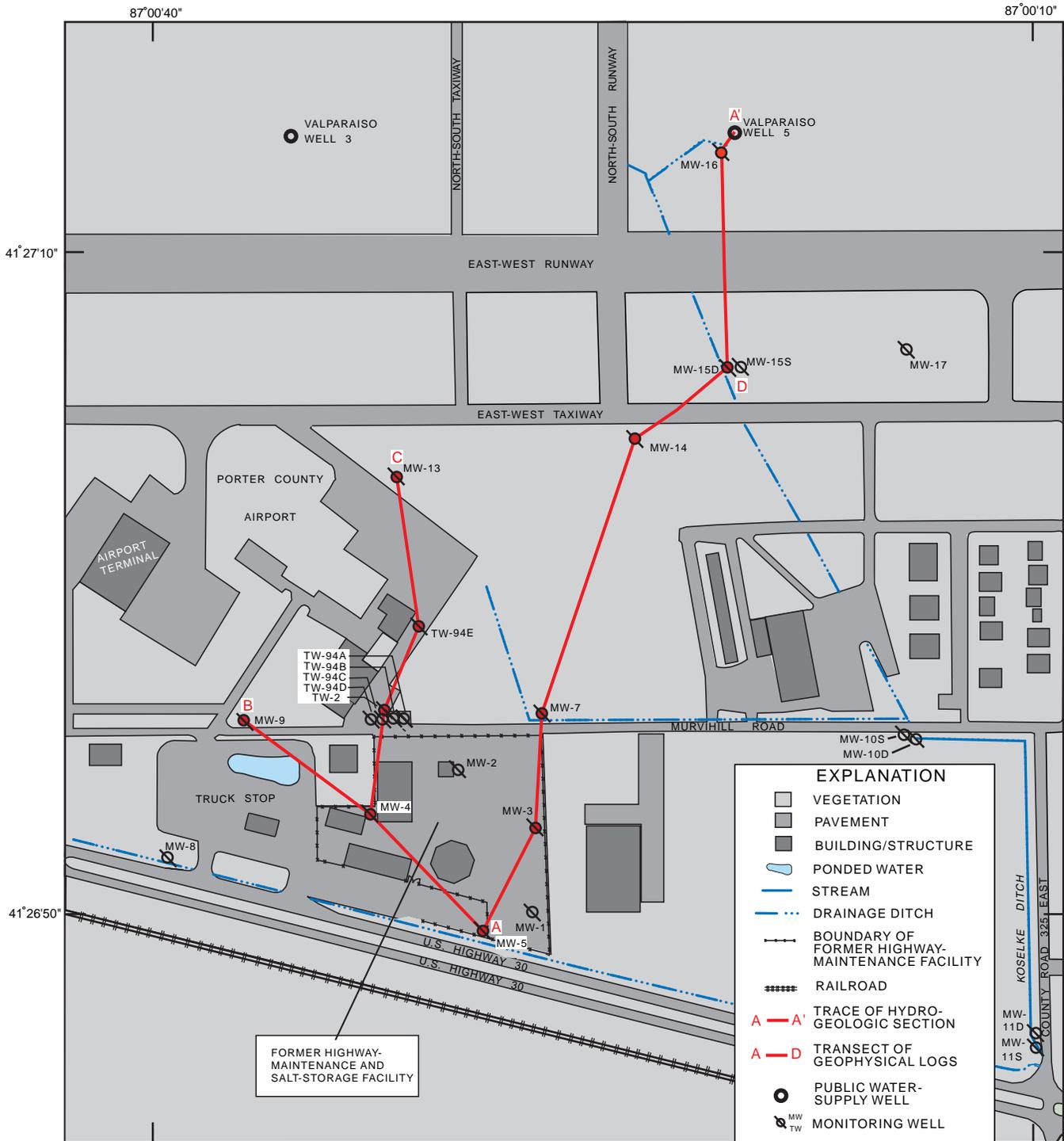
Figure 4. Trace of hydrogeologic section A-A' and transects A-B, A-C, and A-D in the vicinity of the Porter County Airport, Valparaiso, Indiana.
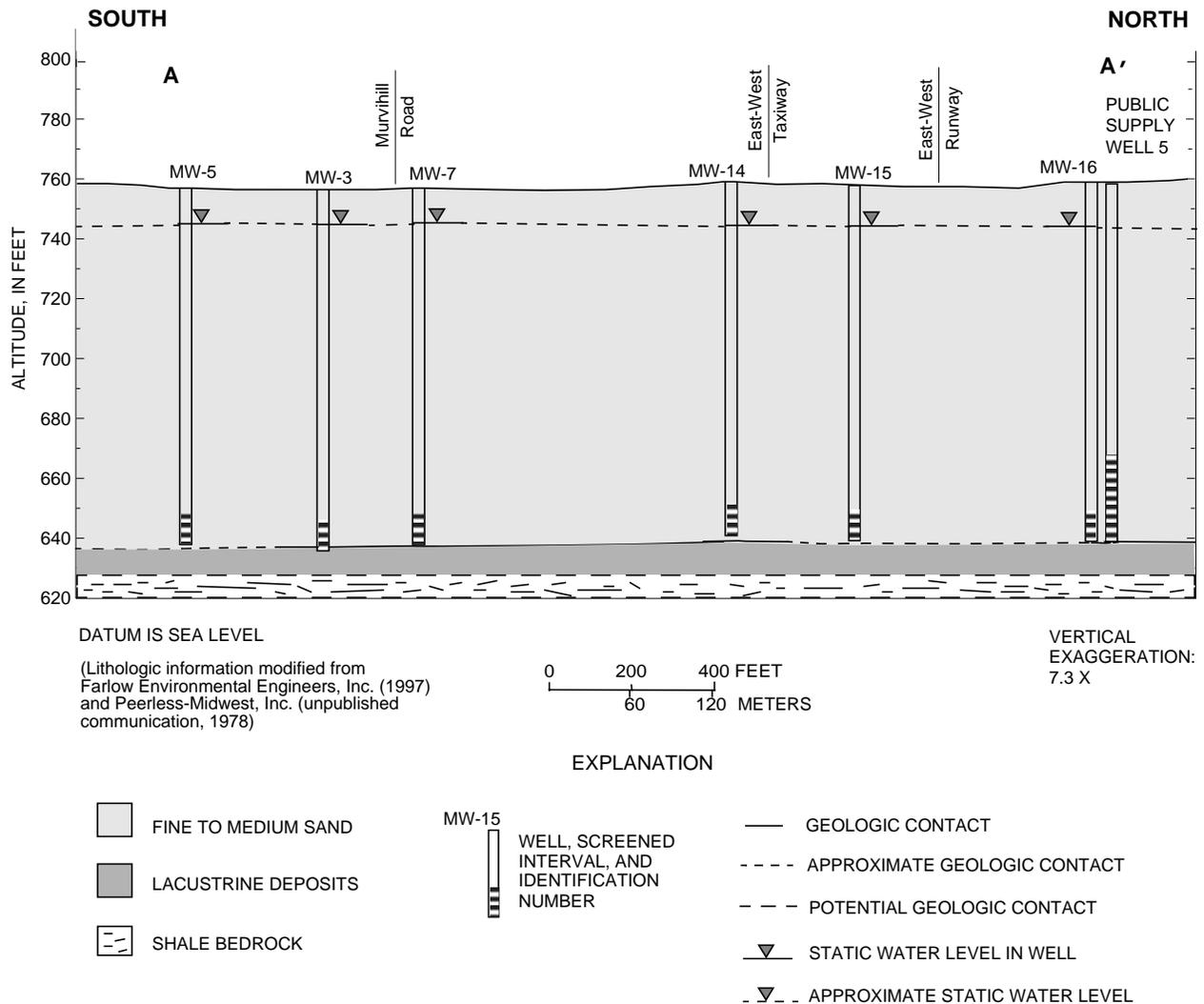
Figure 5. South to north hydrogeologic section A - A′ in the vicinity of the Porter County Airport, Valparaiso, Indiana.

section A-A′ (fig. 5). Beneath the study area is about 120 ft of homogeneous medium and fine sand above fine-grained lacustrine deposits. Geophysical logs collected from monitoring wells in the study area indicated that this thick sand sequence has a uniform texture with depth. The lacustrine deposits beneath the study area potentially have a uniform texture because of the way they were deposited in the still water of a glacial lake.

The sand sequence contains an unconfined aquifer with an upper boundary at the water table.

Water-level data collected in the study area indicate that the water table commonly fluctuates between an altitude of 740 and 750 ft. The lower boundary of the unconfined aquifer is the contact between the sand and the underlying lacustrine deposits at an altitude of approximately 637 ft. The contact between the sand sequence and the lacustrine deposits can be expected to be nearly constant in altitude because the lacustrine deposits were laid down in the still water of a glacial lake, which commonly produced a horizontal upper surface.

The bedrock underlying the study area is the Devonian- and Mississippian-Age Ellsworth Shale (Schneider and Keller, 1970). The bedrock surface shows a general northward regional dip and ranges from an altitude of 650 ft about 7 mi south of the study area to an altitude of 450 ft about 14 mi north of the study area near Lake Michigan (Fraser and Bleuer, 1991a). Although no wells in the vicinity of the study area have been completed to bedrock, the bedrock surface is at an altitude of approximately 630 ft (Fraser and Bleuer, 1991b) and has a smooth topography without large valleys or ridges (Gray, 1982). Fenelon, Bobay, and others (1994) report the Silurian- and Devonian-Age carbonate bedrock about 200 ft below the Devonian- and Mississippian-Age shale is another principal aquifer in the vicinity of the study area.

The Porter County Airport is near the hydrologic divide of the Kankakee River Basin and the Lake Michigan Basin. Clendenon (1990) and Beaty and others (1994) mapped the potentiometric surface associated with the unconfined sand aquifer in these basins, based on static water levels from well drillers' records. These potentiometric-surface maps indicated a regional ground-water-flow direction of south-southwest in the vicinity of the study area. A contractor for INDOT mapped a south-southwest direction of ground-water flow when all of the public water-supply wells were not pumping; when the wells were pumping, the flow direction was mapped northward toward the wells (Farlow Environmental Engineers, Inc., 1997). A contractor for VWD reported the horizontal hydraulic gradient near the salt-storage facility was 37 ft/mi north when wells 3 and 5 (fig. 1) were pumping and 12 ft/mi south when these wells were not pumping (John R. Barnhart, Peerless-Midwest, Inc., written commun., June 1994).

Methods of Investigation

This section explains the borehole geophysical techniques used for logging natural gamma activity and electromagnetic conductivity, along with a surface geophysical technique for measuring terrain conductivity. The borehole and surface geophysical techniques for measuring conductivity are termed "electromagnetic" methods because electric currents are electromagnetically induced in the ground rather than being generated with direct-contact electrodes (U.S. Environmental Protection Agency, 1993, p. 3-1). Water-sample collection and analysis also are described in this section.

Borehole Geophysical Techniques

Borehole geophysical techniques were used to make a series of measurements (called a "log") along the axis of the boreholes in which monitoring wells had been completed. Paillet and Crowder (1996, p. 884–886) described the unique attributes of geophysical logs.

(1) They are a continuous series of measurements with depth, each made in the same way with the same equipment.

(2) There is little opportunity for misplaced or missing data, unlike that possible when geologic samples are collected.

(3) The undisturbed geologic formation around the borehole is included, which is likely to be more representative of the aquifer than discontinuous samples of geologic material.

(4) More than one geophysical property can be measured independently, and the relation between the properties can be analyzed.

For this study, two types of borehole logs were made in each well—one of natural gamma activity and one of electromagnetic conductivity.

Borehole logs of natural gamma activity are used widely for identifying the lithology of aquifer materials (Keys, 1990, p. 79). Fine-grained sediments that contain abundant clay tend to contain larger amounts of naturally occurring radioisotopes that emit gamma radiation. The intensity of natural gamma radiation emitted by subsurface layers that contain more clay is larger than the intensity of radiation emitted by strata with less clay. For this study, borehole logging of

natural gamma activity was done by lowering a Mt. Sopris Instrument Co., Inc., Model 2PGA-1000 poly-gamma probe into the well with an electric winch at about 10 ft/min. The probe uses a sodium iodide crystal that emits a pulse of light when struck by a gamma ray. The pulse of light is amplified by a photo-multiplier tube that outputs a current pulse. The winch cable transmits the current pulses from the probe to the logging controller. A laptop computer and logging software recorded the counts per second of gamma radiation for each 0.1 ft of depth (Mt. Sopris Instrument Co., Inc., 1996).

Borehole logs of electromagnetic conductivity measure the ability of the aquifer materials and ground water in the vicinity of a well to conduct electricity. The electromagnetic conductivity is related directly to the concentration of dissolved solids in the ground water and the content of clay in the aquifer material (Keys, 1990, p. 66). The principles of operation for the electromagnetic-conductivity log were described by McNeill (1986) and are presented in figure 6. The electromagnetic-conductivity probe contains a transmitter coil. An alternating current is sent through the transmitter
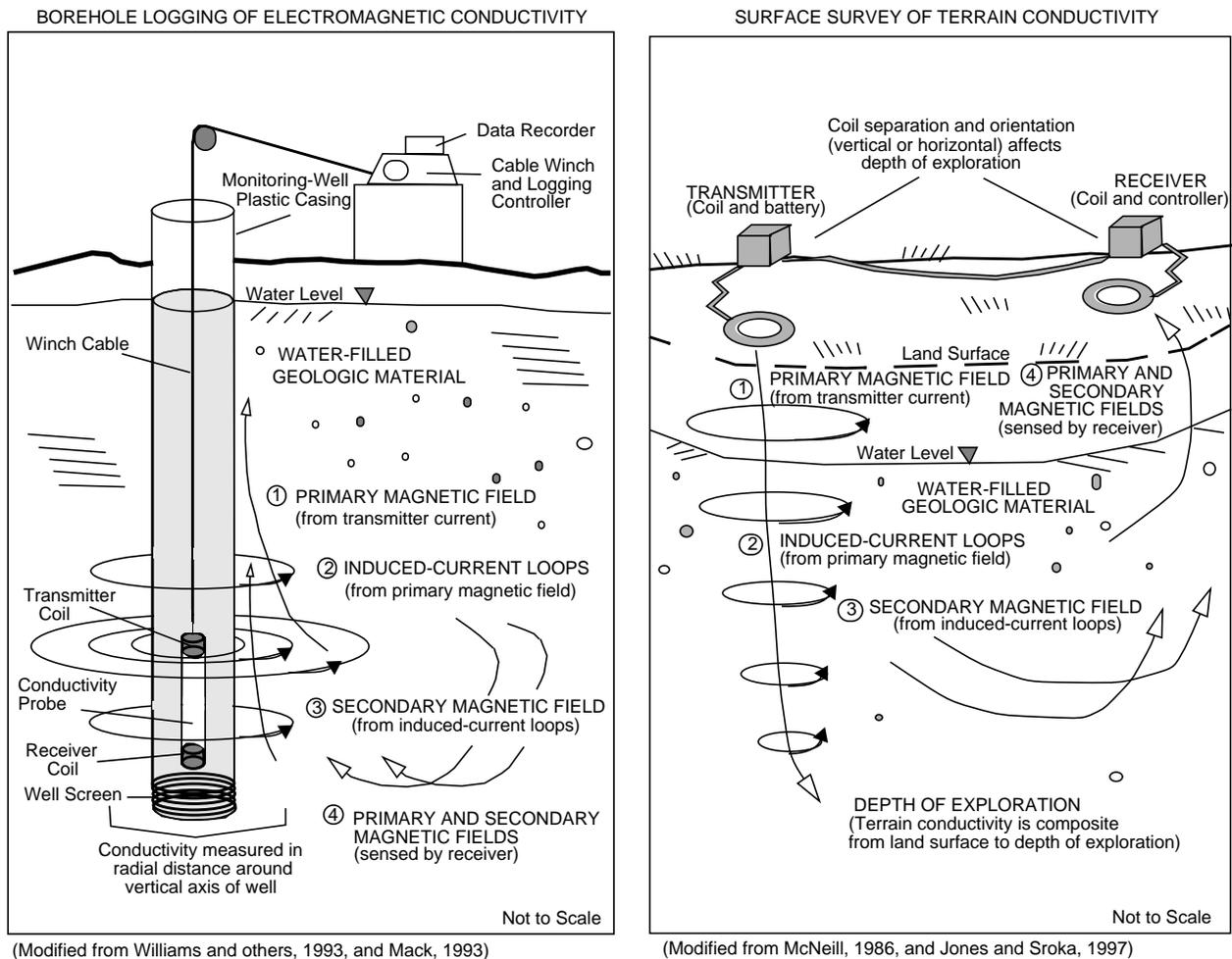
Figure 6. Principles of borehole logging of electromagnetic conductivity and a surface survey of terrain conductivity.

coil, which creates a primary magnetic field that is transmitted into the surrounding geologic formation. The primary magnetic field induces loops of eddy currents that set up a secondary magnetic field. The primary and secondary magnetic fields induce current voltage in a receiver coil in the probe. A second receiver coil in the probe helps to focus the primary magnetic field. These principles of operation explain why this type of log also is called an "electrical-induction log," an "induction log," an "electromagnetic-induction log," or an "electromagnetic log."

For this study, borehole logs of electromagnetic conductivity were obtained by lowering a Mt. Sopris Instrument Co., Inc., Model 2PIA-1000 poly-induction probe or a Geonics Limited EM-39 slimline induction tool into the well at about 10 ft/min with a logging controller and cable winch. A laptop computer and logging software recorded the electromagnetic conductivity in milisiemens per meter (mS/m) for each 0.1 ft of depth (Mt. Sopris Instrument Co., Inc., 1996). The probe measures the electromagnetic conductivity at a radial distance ranging 20 to 100 cm (approximately 8 to 39 in.) from the vertical axis of the well. The probe is most sensitive at a radial distance of 30 cm (approximately 1 ft). The measurements are not affected appreciably by water in the well or by plastic well casing (McNeill and others, 1990). The conductivity probe was calibrated according to the manufacturer's instructions before each use.

The major hydrogeologic factors that affect the log of electromagnetic conductivity are the concentration of dissolved solids in the ground water and the amount of clay in the aquifer material. Therefore, the natural gamma activity log is needed for comparison with the conductivity log; the natural gamma log identifies intervals in which an increased electromagnetic conductivity is caused by a larger amount of clay[1] in the aquifer material. In the intervals with a smaller amount of clay, large electromagnetic conductivity is caused by larger concentrations of dissolved solids in the ground water (Williams and others, 1993).

Surface Geophysical Technique

A surface geophysical technique was used to measure electromagnetic conductivity (terrain conductivity). Terrain conductivity usually is determined by one or more of the following factors in the subsurface: clay content or clay type, amount of water, salinity of the water, and the water temperature (McNeill, 1980a, p. 21). In aquifers in which the pore spaces in the granular aquifer material are saturated fully and the water temperature is constant, clay content and ground-water salinity determine the terrain conductivity. If the clay content of the aquifer material is uniform and small (as in this study area), terrain conductivity is determined primarily by salinity (that is, concentrations of dissolved solids in the ground water).

For this study, surface surveys of terrain conductivity were made with a Geonics Limited model EM34-3 system. Surface geophysical equipment for measuring terrain conductivity operates in a manner similar to the equipment for borehole logging (fig. 6). The EM34-3 system consists of a transmitter coil and battery; a receiver coil and control box; and connector cables. The transmitter coil is placed on the ground and energized with an alternating current. The primary magnetic field arising from the transmitter creates induced-current loops in the ground, which generate a secondary magnetic field. The primary and secondary magnetic fields are sensed by the receiver coil. The secondary magnetic field is a function of the intercoil spacings, the transmitter frequency, and the terrain conductivity. The receiver instrumentation directly measures values of terrain conductivity in units of millisiemens per meter (McNeill, 1980b, p. 5).

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[1]Clay-sized sediments have more surface area than an equal volume of silt or sand-sized sediments. When saturated, the larger surface area (per volume) of the clay-sized sediments will contain more electrically conductive water.

The depth of exploration in a surface survey of terrain conductivity is controlled by the coil-separation distance and the coil orientation. The EM34-3 system has fixed coil-separation distances of 10, 20, and 40 m. If the coils are coplanar and horizontal (a vertical-dipole orientation), the maximum depth of exploration is approximately 1.5 times the coil-separation distance. If the coils are coplanar and vertical (a horizontal-dipole orientation), the maximum depth of exploration is approximately 0.75 the coil-separation distance (McNeill, 1986, p. 6). Based on the three fixed coil-separation distances and the two coil orientations, six maximum depths of exploration can be obtained.

The terrain conductivity at any depth of exploration includes the conductivity of the material above that depth. As depth of exploration is increased, the terrain-conductivity value represents a thicker composite of geologic material and ground water. Also, as coil spacing is increased to obtain a greater depth of exploration, the terrain-conductivity value represents a broader composite of geologic material and ground water. For this report, the terrain conductivities from depths of exploration near the bottom of the aquifer were of greatest interest. By use of a coil-separation distance of 40 m, the maximum depths of exploration near the bottom of the aquifer were 30 m (about 100 ft) for a horizontal-dipole orientation and 60 m (about 200 ft) for a vertical-dipole orientation.

The surface survey was not intrusive; no probes, well points, or other devices were installed permanently or temporarily. The survey station for a terrain-conductivity value was mapped at the midpoint of the 40-m coil-separation distance. To reference the survey stations, field personnel measured the distance and compass bearing of stations in relation to map features such as buildings, roads, and runways. Most survey stations were 40 m apart, but some stations were closer for verification purposes or because of interference from cultural features.

Cultural features can be surface or subsurface objects that are electrically conductive, including metal pipes, wires, fences and anchors, concrete-reinforcing rods, power cables, and metal buildings. Interference from cultural features restricted measurements of terrain conductivity in areas where the data would have been useful—the salt-storage facility, the truck stop, and the paved areas near airport buildings immediately north of Murvihill Road (fig. 5).

Collection and Analysis of Water Samples

From March 3 through March 25, 1998, water samples were collected from 23 wells in the network; wells MW-6 and MW-16 could not be sampled at that time. Field procedures were consistent with the USGS Field Manual for Collection of Water-Quality Data (Wilde and others, 1998). A general description of the methods for water-sample collection and analysis follows.

A submersible, positive-displacement pump was used for purging and sampling the 23 wells. Components that contacted sample water in the devices were Teflon and stainless steel. The pump was placed in the middle of the screened interval during purging and sampling. Stagnant water was purged from the monitoring wells before sampling to obtain samples representative of water in the aquifer. At least three casing volumes were removed before sample collection, with the exception of TW-2 and MW-8. (A casing volume is the length of the water column in the well multiplied by a cross-sectional area of the well casing.)

Ground-water characteristics were monitored during well purging until the values had stabilized. The characteristics pH, specific conductance, water temperature, reduction-oxidation potential, and dissolved oxygen were measured with an electronic multimeter. Ground water from the sampling pump passed through a flow-through chamber that held the multimeter probe. Turbidity samples were measured with a portable turbidimeter. Criteria for stabilization of four ground-water characteristics was ± 0.2 standard units pH, 0.2°C water temperature, 10 µS/cm specific conductance, and less than 5 nephelometric units turbidity. Daily calibration checks of the multimeter and turbidimeter were made.

A maximum 0.2-gal/min flow rate was used for filling sample containers from the discharge hose of the pump. Most of the water samples were not filtered. The samples for dissolved solids analysis, along with three replicate samples for dissolved chloride and sodium analysis, were filtered in the field with a 0.45-micron-pore-size, disposable-cartridge filter fixed to the end of the pump-discharge hose.

The sampling pump and hose were cleaned before each well was sampled. Procedures were (a) the external surfaces of the pump and hose that were submerged during sampling were rinsed with a deionized (DI) water spray, (b) about 5 gal of a dilute solution of phosphate-free detergent and DI water were recirculated through the pump and hose for several minutes, and (c) about 10 gal of DI water were pumped through the hose. Water from well purging and equipment cleaning was collected in a portable storage tank and discharged to the sanitary sewer.

Samples for laboratory analysis were shipped by overnight carrier, and chain-of-custody documentation was maintained. The constituents for which the samples were analyzed and the analytical methods are listed in appendix A, table A2. Fifteen of the 23 samples were analyzed for 19 cations, anions, and physical properties; samples from eight wells were analyzed only for chloride and sodium. Analysis was done by the USGS Laboratory in Ocala, Fla., using methods consistent with those in Fishman and Friedman (1989), the U.S. Environmental Protection Agency (1982), and Greenberg and others (1992). Alkalinity was determined in a mobile laboratory by incremental titration (Wilde and others, 1998).

Fifteen field quality-control samples included field blanks and replicate samples (appendix A, table A3). Data from the six field blanks indicated that equipment cleaning at the start and end of sampling was effective; analytical data were unlikely to be biased by residuals from the sampling equipment. Analytical precision for the water-quality data, measured as the relative percent difference in concentrations from six pairs of replicate samples, was less than 10 percent for nearly all the constituents. (In some pairs of replicate samples, differences in concentrations of bromide were less than 0.2 mg/L and differences in concentrations of phosphate-phosphorous were less than 0.01 mg/L, but the relative percent difference was more than 10 percent.) Three pairs of filtered and unfiltered replicate samples were analyzed for sodium and chloride because some historical analyses were from filtered samples. The relative percent difference in concentrations from filtered and unfiltered samples was less than 4 percent, indicating the 1998 and historical data were comparable.

At 12 wells, a double-valved, bottom-emptying sample bailer was used to collect two water samples at discrete depths in the well screen before each well was purged. The bailer was lowered into the well on a Teflon-coated stainless-steel cable; the bailer was lowered through a mechanical device that counts the amount of cable unreeled so that the depth of the bailer intake was known. The bailer was controlled with a hand-operated winch—first, to sample near the top of the well screen and, then, near the bottom of the well screen. The purpose of the samples was to determine if a difference in chloride concentrations could be measured in the screened intervals before the wells were purged. Chloride was determined in these 24 samples with a colorimetric method involving titration with silver nitrate (Hach Company, 1980). The winch cable and disassembled sample bailer were cleaned with detergent and DI water after each use.

Ground-Water Quality

Water samples from 15 wells were analyzed for cations, anions, physical properties, and other characteristics (table 1). The water was generally neutral pH (from 7.0 to 7.5 standard units) and low in dissolved oxygen (from less than 0.01 to 0.13 mg/L), with a reduction-oxidation potential for oxidizing conditions (from 63 to 114 millivolts). Water quality from three wells (MW-10D, MW-11D, and MW-17) was different than that of the other 12 wells that had larger concentrations of sodium, calcium, iron, magnesium, chloride,

Table 1. Concentrations of cations, anions, physical properties, and other characteristics in water samples collected during March 1998 from monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana

[Concentrations are from unfiltered samples, with the exception of dissolved solids; all concentrations are milligrams per liter; SiO_2, silicon dioxide; N, nitrogen; P, phosphorous; <, less than (reporting limit); --, no data; $CaCO_3$, calcium carbonate; s.u., standard units; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mV, millivolts; °C, degrees Celsius]

Well name	Cations						
	Calcium	Iron	Magnesium	Manganese	Potassium	Silica as SiO_2	Sodium
TW-2	270	5.1	48	0.47	14	11	4,190
TW-94D	200	5.5	40	.28	6.9	12	2,560
TW-94E	270	4.1	64	.43	14	11	3,110
MW-3	230	4.0	34	.58	18	10	4,420
MW-4	260	5.0	55	.42	15	11	3,980
MW-5	470	5.6	77	.42	19	11	3,690
MW-7	210	3.1	24	.38	14	10	4,400
MW-8	160	2.5	52	.24	6.9	13	263
MW-9	390	5.5	110	.88	12	12	1,320
MW-10D	52	1.0	16	.93	2.2	15	19
MW-11D	58	.8	17	.82	2.3	14	24
MW-13	360	5.1	96	.52	13	12	1,440
MW-14	220	3.9	66	.35	8.5	12	613
MW-15D	100	3.3	34	.22	4.0	14	128
MW-17	54	1.5	17	.14	2.1	14	6.0

Well name	Anions							
	Bicar-bonate[a]	Bromide	Chloride	Fluoride	Iodide	Nitrate + Nitrite as N	Ortho-phosphate as P	Sulfate
TW-2	381	1.2	7,000	<0.1	0.038	<0.02	0.03	160
TW-94D	462	1.1	3,930	<.1	.020	<.02	.01	150
TW-94E	304	1.1	5,160	<.1	.015	<.02	.02	130
MW-3	297	.80	7,230	<.1	.014	<.02	.02	190
MW-4	377	.80	7,030	<.1	.017	<.02	.02	150
MW-5	253	.60	6,730	<.1	.017	<.02	.02	110
MW-7	255	1.3	7,200	<.1	.024	<.02	.03	170
MW-8	327	.20	572	<.1	.004	<.02	<.01	71
MW-9	209	.90	2,780	<.1	.009	<.02	<.01	44
MW-10D	270	<.05	6.0	.1	--	<.02	.01	4.0
MW-11D	211	<.05	24	.2	--	<.02	.02	69
MW-13	272	.40	3,340	<.1	.014	<.02	.01	56
MW-14	214	.10	1,350	<.1	.005	<.02	<.01	36
MW-15D	253	.20	323	<.1	.002	.02	<.01	36
MW-17	251	<.05	2.0	<.1	--	<.02	<.01	8.0

Table 1. Concentrations of cations, anions, physical properties, and other characteristics in water samples collected during March 1998 from monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana—Continued

	Physical Properties				Characteristics				
Well name	Alkalinity[a] as CaCO$_3$	Dissolved solids	Suspended solids[b]	Total solids	pH (s.u.)	Specific conduc- tance (μS/cm)	Dissolved oxygen	Reduction- oxidation potential (mV)	Water tem- perature (°C)
TW-2	312	12,400	700	13,100	7.3	20,200	<0.01	66	12.0
TW-94D	379	7,340	160	7,500	7.1	11,800	<.01	87	11.8
TW-94E	249	9,320	480	9,800	7.5	15,100	<.01	74	11.6
MW-3	244	12,800	300	13,100	7.4	20,700	<.01	85	11.4
MW-4	326	12,400	600	13,000	7.5	19,200	<.01	77	12.7
MW-5	194	12,500	500	13,000	7.6	19,400	<.01	67	11.8
MW-7	209	12,600	200	12,800	7.4	20,300	<.01	63	11.5
MW-8	216	1,520	--[c]	1,500	7.2	2,310	.13	114	11.2
MW-9	171	5,870	130	6,000	7.2	8,230	.09	112	11.0
MW-10D	220	246	14	260	7.4	431	.05	84	11.4
MW-11D	173	336	14	350	7.5	558	.09	78	11.4
MW-13	272	6,670	--[c]	6,600	7.0	10,100	.03	113	12.2
MW-14	193	2,820	180	3,000	7.2	4,510	.02	102	11.1
MW-15D	202	910	70	980	7.4	1,490	<.01	85	11.0
MW-17	220	230	20	250	7.3	428	<.01	99	11.3

[a]Determination was made by U.S. Geological Survey personnel in a mobile laboratory immediately after sample collection. Alkalinity and bicarbonate concentrations are the mean of two sequential determinations. All other analytical results are from the U.S. Geological Survey Laboratory in Ocala, Fla.

[b]Concentration was calculated as total solids minus dissolved solids.

[c]Total solids reported to be larger than dissolved solids concentration.

bicarbonate, bromide, and dissolved solids and a larger specific conductance. The largest concentrations of chloride, sodium, and dissolved solids were in water from five wells at or near the salt-storage facility (TW-2, MW-3, MW-4, MW-5, and MW-7)—6,730 to 7,230 mg/L chloride; 3,690 to 4,400 mg/L sodium; and 12,400 to 12,800 mg/L dissolved solids.

The ratios of chloride concentrations to bromide concentrations were calculated with the water-quality data from the March 1998 samples (table 2, page 18). These ratios were used as an indicator of the source of chloride in the water samples. According to Vengosh and Pankratov

(1998, p. 822), chloride/bromide ratios greater than 600 indicate dissolved road-deicing salt, and ratios approximately 300 to 600 indicate domestic wastewater. According to Davis and others (1998, p. 338), ratios between 1,000 and 10,000 indicate water affected by the dissolution of halite (sodium chloride), ratios between 300 and 600 indicate domestic wastewater, and ratios between 100 and 200 are typical of shallow ground water. On the basis of these criteria, the chloride/bromide ratios for the water samples collected in 1998 indicated the chloride in the water from wells MW-10D and MW-17 probably was typical for shallow ground water. The chloride in well MW-11D potentially originated, at least in part, from domestic

wastewater. The chloride in water from the other 12 wells came from the dissolution of road-deicing salt.

Table 2. Chloride/bromide ratios in water samples collected during March 1998 from monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana

[All concentrations in milligrams per liter; <, less than; >, greater than]

Well name	Chloride	Bromide	Chloride/ bromide ratio[a]
TW-2	7,000	1.2	5,800
TW-94D	3,930	1.1	3,600
TW-94E	5,160	1.1	4,700
MW-3	7,230	.80	9,000
MW-4	7,030	.80	8,800
MW-5	6,730	.60	11,000
MW-7	7,200	1.3	5,500
MW-8	572	.20	2,900
MW-9	2,780	.90	3,100
MW-10D	6.0	<.05	>120[b]
MW-11D	24	<.05	>480[b]
MW-13	3,340	.40	8,400
MW-14	1,350	.10	13,500
MW-15D	323	.20	1,600
MW-17	2.0	<.05	>40[b]

[a]Ratio computed as chloride concentration divided by bromide concentration, to two significant figures.

[b]Bromide concentration was less than the reporting limit. An estimate of the smallest chloride/bromide ratio was computed with a bromide concentration of 0.05 mg/L (the reporting limit). The actual ratio may be larger.

On the basis of the chloride/bromide ratios, constituent concentrations from MW-10D and MW-17 were considered to represent background water quality unaffected by road salt or other sources of chloride. Background concentrations of dissolved solids in the study area are about 230 to 246 mg/L, including about 2 to 6 mg/L chloride and 6 to 19 mg/L sodium (table 1, MW-10D and MW-17). Concentrations of dissolved

solids, chloride, and sodium in wells affected by road salt were from about 4 to 3,500 times background levels (table 1).

The concentrations of chloride and sodium in 23 water samples collected from the monitoring-well network in 1998, including the 15 wells in table 1, are shown in figure 7. The chloride and sodium data for 1998, along with data from historical water samples collected during May 1994 through October 1995, are listed in table 3 (page 20). Comparisons of the 1998 and historical water-quality data indicate that the same 14 wells have had concentrations of chloride greater than 250 mg/L since 1994 through 1995. Generally, the concentrations of chloride measured in these wells in 1998 were less than the concentrations measured in 1994 through 1995. Consistent with the chloride/bromide ratios (table 2) and other water-quality data (table 1), historical data indicated water from MW-10D, MW-11D, and MW-17 has not been affected by road salt. In addition, water from wells screened at shallower depths (MW-1, TW-94A, MW-10S, MW-11S, and MW-15S) has not been affected by road salt. An exception is TW-94B, which had 820 mg/L chloride in 1994 but 85 mg/L chloride in 1998. It is uncertain whether any differences in the historical data and the 1998 data were caused by differences in analytical or reporting methods rather than changing water quality.

Water samples collected in March 1998 from 12 wells during static conditions immediately prior to purging had chloride concentrations that consistently were larger near the bottom of the well screens than near the top of the well screens (table 4, page 21). The largest differences in chloride concentrations within the 10-ft screened interval were measured in MW-7 (2,175 mg/L) and MW-13 (2,490 mg/L). These data indicated a vertical stratification in the concentrations of road salt in the aquifer. After the wells had been purged, however, concentrations of chloride in the samples pumped from the middle of the well screens generally were larger than in the samples that had been bailed. This difference highlights the potential that
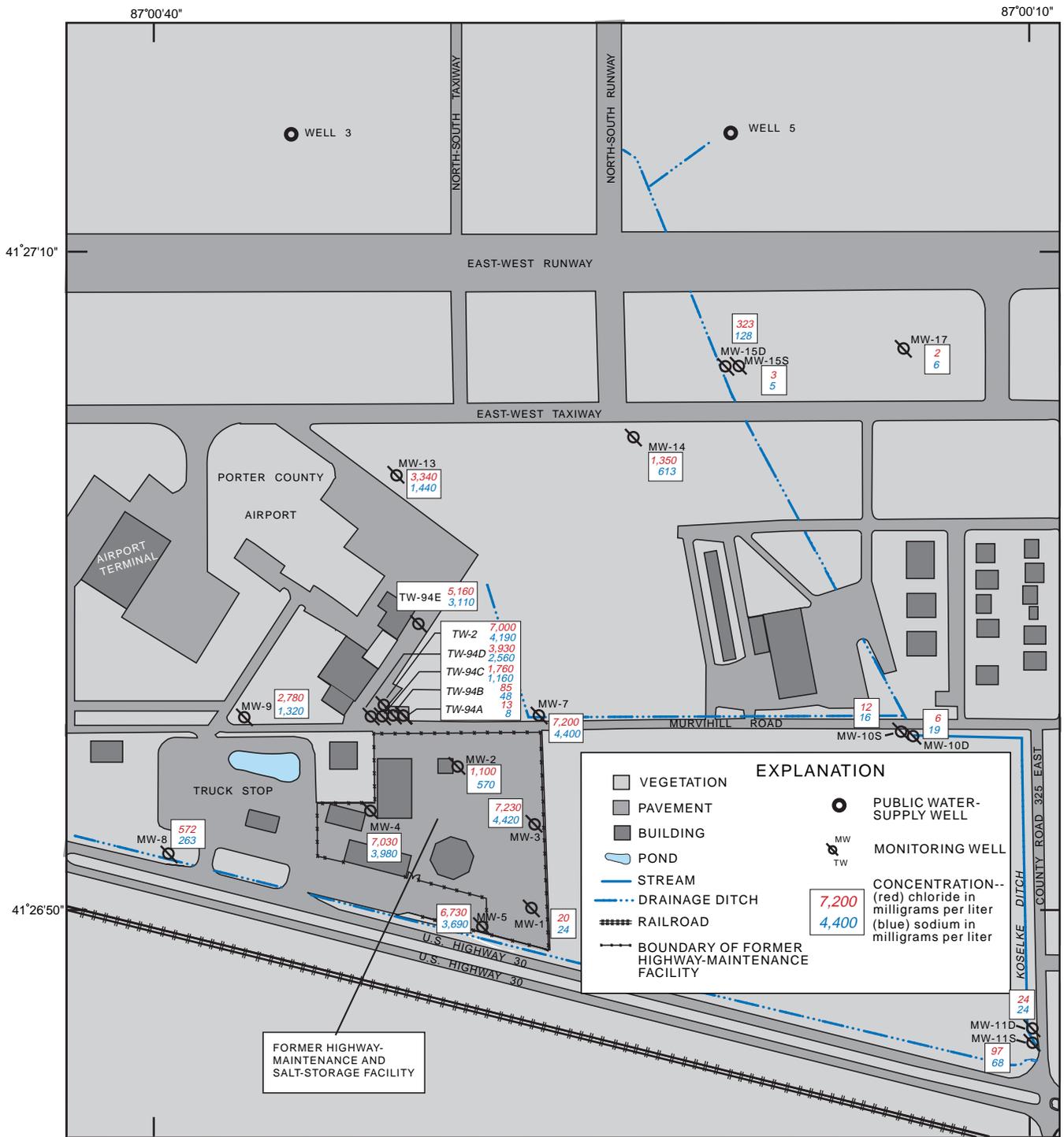
Figure 7. Concentrations of chloride and sodium in water samples collected during March 1998 from monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Base map modified from Department of Water Works, City of Valparaiso

Table 3. Chloride and sodium concentrations in water samples collected during March 1998 and in historical water samples from monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana

[All concentrations in milligrams per liter; Aug., August; Oct., October]

| Well name | March 1998 water samples[a] | | Historical water samples[b] | | |
	Chloride	Sodium	Chloride	Sodium	Date
TW-2	7,000	4,190	7,300	4,700	May 1994
TW-94A	13	8.0	13	14	May 1994
TW-94B	85	48	820	190	May 1994
TW-94C	1,760	1,160	1,800	1.200	May 1994
TW-94D	3,930	2,560	4,500	2,500	May 1994
TW-94E	5,160	3,110	5,400	3,100	June 1994
MW-1	20	24	180	70	July 1994
MW-2	1,100	570	1,800	1,100	July 1994
MW-3	7,230	4,420	7,900	5,000	Aug. 1995
MW-4	7,030	3,980	7,700	4,500	Aug. 1995
MW-5	6,730	3,690	6,000	3,800	Aug. 1995
MW-7	7,200	4,400	7,600	4,800	Aug. 1995
MW-8	572	263	590	200	Oct. 1995
MW-9	2,780	1,320	2,700	490	Oct. 1995
MW-10D	6.0	19	9.0	15	Oct. 1995
MW-10S	12	16	190	77	Oct. 1995
MW-11D	24	24	22	13	Aug. 1995
MW-11S	97	68	67	31	Aug. 1995
MW-13	3,340	1,440	2,800	1,600	Aug. 1995
MW-14	1,350	613	1,300	520	Oct. 1995
MW-15D	323	128	270	100	Aug. 1995
MW-15S	3.0	5.0	8.0	14	Oct. 1995
MW-17	2.0	6.0	4.0	11	Aug. 1995

[a]Chloride and sodium concentrations were determined by the U.S. Geological Survey Laboratory in Ocala, Fla.

[b]Historical water-sample data from Farlow Environmental Engineers, Inc. (1997) and Harza Environmental Services, Inc. (1994).

conventional water-sample collection may not have fully characterized the vertical extent of road-salt concentrations in the aquifer.

Table 4. Chloride concentrations in water samples collected during March 1998 from the screened intervals of monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana

[All concentrations in milligrams per liter]

Well name	Chloride		
	Bailed near top of well screen[a]	Bailed near bottom of well screen[a]	Pumped at middle of well screen[b]
TW-2	5,950	6,875	7,000
TW-94D	4,500	5,500	3,930
TW-94E	5,800	6,000	5,160
MW-3	6,600	7,075	7,230
MW-4	6,650	8,050	7,030
MW-5	5,625	6,500	6,730
MW-7	4,450	6,625	7,200
MW-9	1,400	1,960	2,780
MW-13	650	3,140	3,340
MW-14	17	27	1,350
MW-15D	8	225	323
MW-15S	8	11	3

[a]Chloride concentrations from samples bailed near top and bottom of well screens were determined by U.S. Geological Survey personnel in a mobile laboratory immediately after sample collection.

[b]Chloride concentrations from samples pumped at middle of well screen were determined by the U.S. Geological Survey Laboratory in Ocala, Fla.

Geophysical Investigations

Borehole geophysical logging and surface geophysical surveys were used to examine the vertical and horizontal extent of road-deicing salt in ground water of the study area. Results of the borehole logs in monitoring wells were compared with chemical analyses of water samples from those wells. Results of borehole logging and sur-face surveys were compared to rates and directions of ground-water flow calculated with water levels from wells in the study area.

Results of Borehole Geophysical Logging

The major hydrogeologic factors that affect logs of electromagnetic conductivity are the amount of clay in the aquifer and the concentration of dissolved solids in the ground water. One bore-hole log of natural gamma activity was made in 16 of the 25 monitoring wells in the network to indicate the amount of clay in the aquifer surrounding these wells. These logs, presented as plots of the raw data and as mathematically smoothed curves of the data, are in appendix B (page 49). (Data were smoothed for easier comparison with logs of electromagnetic conductivity.) For depths from approximately 15 to 115 ft, logs of the smoothed data indicated natural gamma activity ranged from approximately 10 to 60 counts per second. Natural gamma activity in that range is characteristic of geologic materials that contain less than 20 percent clay (Keys, 1990, p. 85). Natural gamma logs from wells 15 mi northwest of the study area indicate approximately 10 to 60 counts per second for coarse to fine sands and approximately 70 to 120 counts per second for silty clay and clay till (Brown, 1994, plate 2). The lithologic information from drillers' logs of moni-toring wells in the study area (for example, fig. 5) indicate fine to medium sand for the aquifer (Far-low Environmental Engineers, Inc., 1997). As a result, the natural gamma logs from the study area indicate a uniform and negligible contribution of clay to the electromagnetic conductivity of the aquifer, meaning the logs of electromagnetic con-ductivity primarily measured the amount of dis-solved solids in the ground water near the wells.
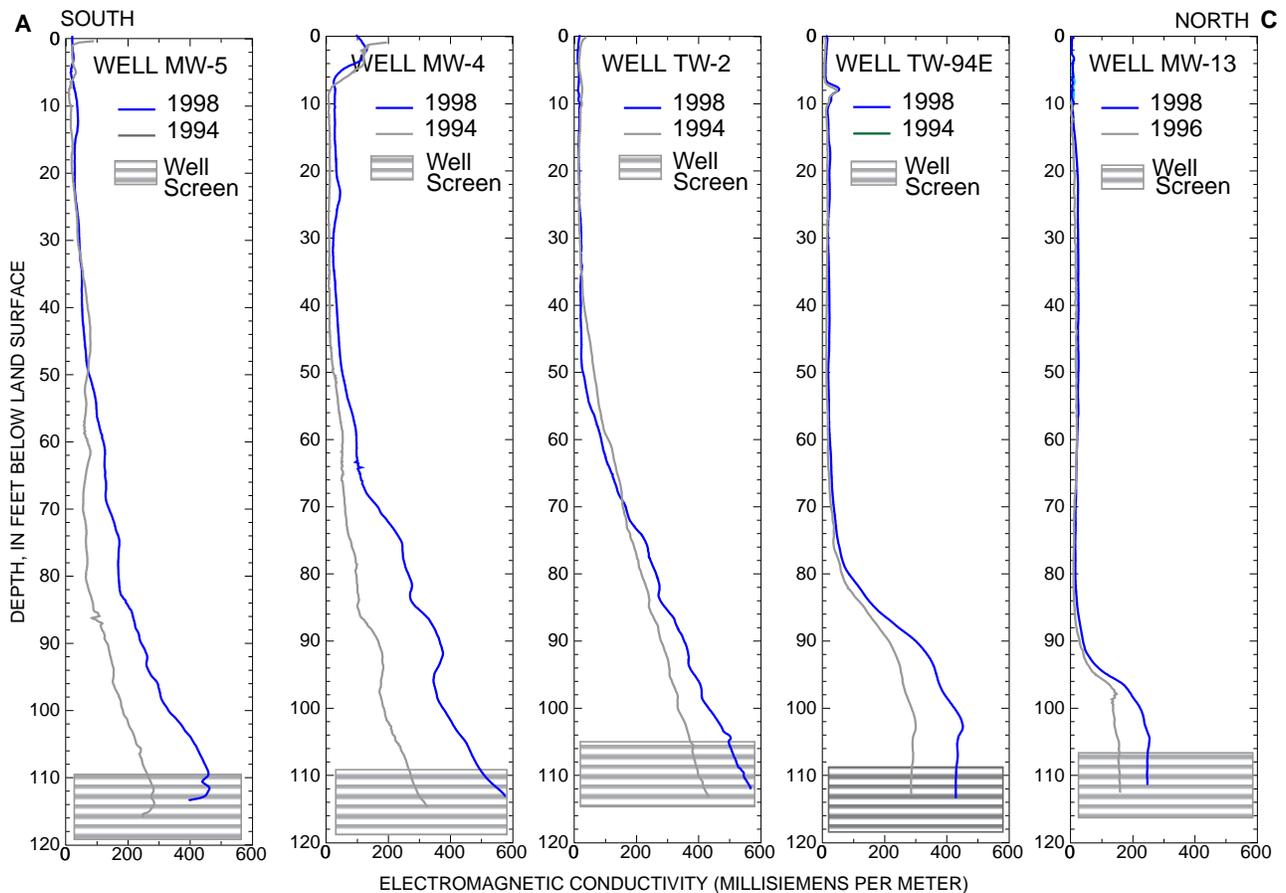
At least one log of electromagnetic conductiv-ity was made in 16 of the 25 monitoring wells in the network between July 1994 and May 1998. All 16 of the wells were logged in May 1998. These logs, presented in the form of mathemati-cally smoothed plots of the data, are in appendix B (p. 49). In 12 of the wells, two or three logs of elec-

tromagnetic conductivity made between 1994 and 1998 are plotted together. The logs from all of the wells—with the exception of MW-10D, MW-11D, MW-16, and MW-17—show a substantial increase in electromagnetic conductivity with depth. The depth at which the increase begins is shallowest (40 to 50 ft) in wells closest to the salt-storage facility; the increase begins at depths of 80 to 100 ft in wells more distant from the facility.

The vertical and horizontal extent of borehole electromagnetic conductivity in the aquifer beneath parts of the study area were examined in three transects of monitoring wells (A-B, A-C, and A-D, fig. 3) trending northwest, north, and northeast from the salt-storage facility. Figures 8, 9, and 10 show plots of borehole electromagnetic conductivity made between 1994 and 1998 in wells along these transects. Generally, the northwestern
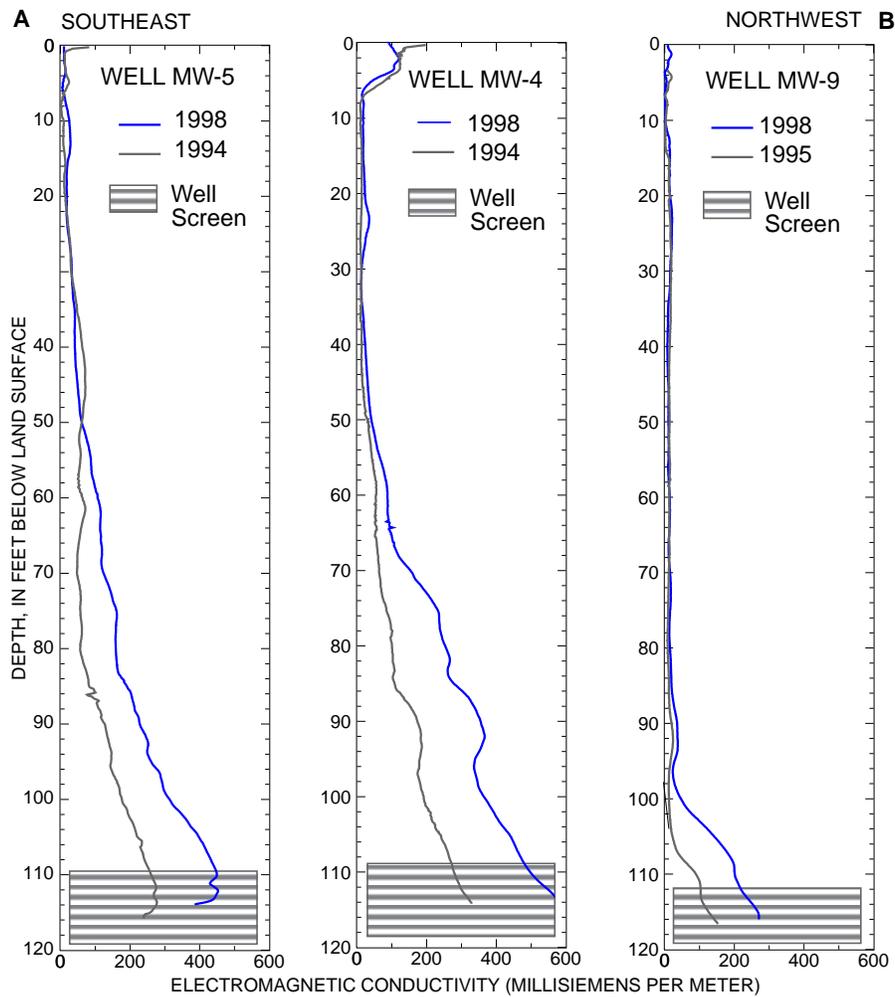
Figure 8. Borehole logs showing electromagnetic conductivity with depth in July 1994, March 1995, and May 1998, transect A-B, in the vicinity of the Porter County Airport, Valparaiso, Indiana. (Well locations are on figure 4, page 9, of this report.)
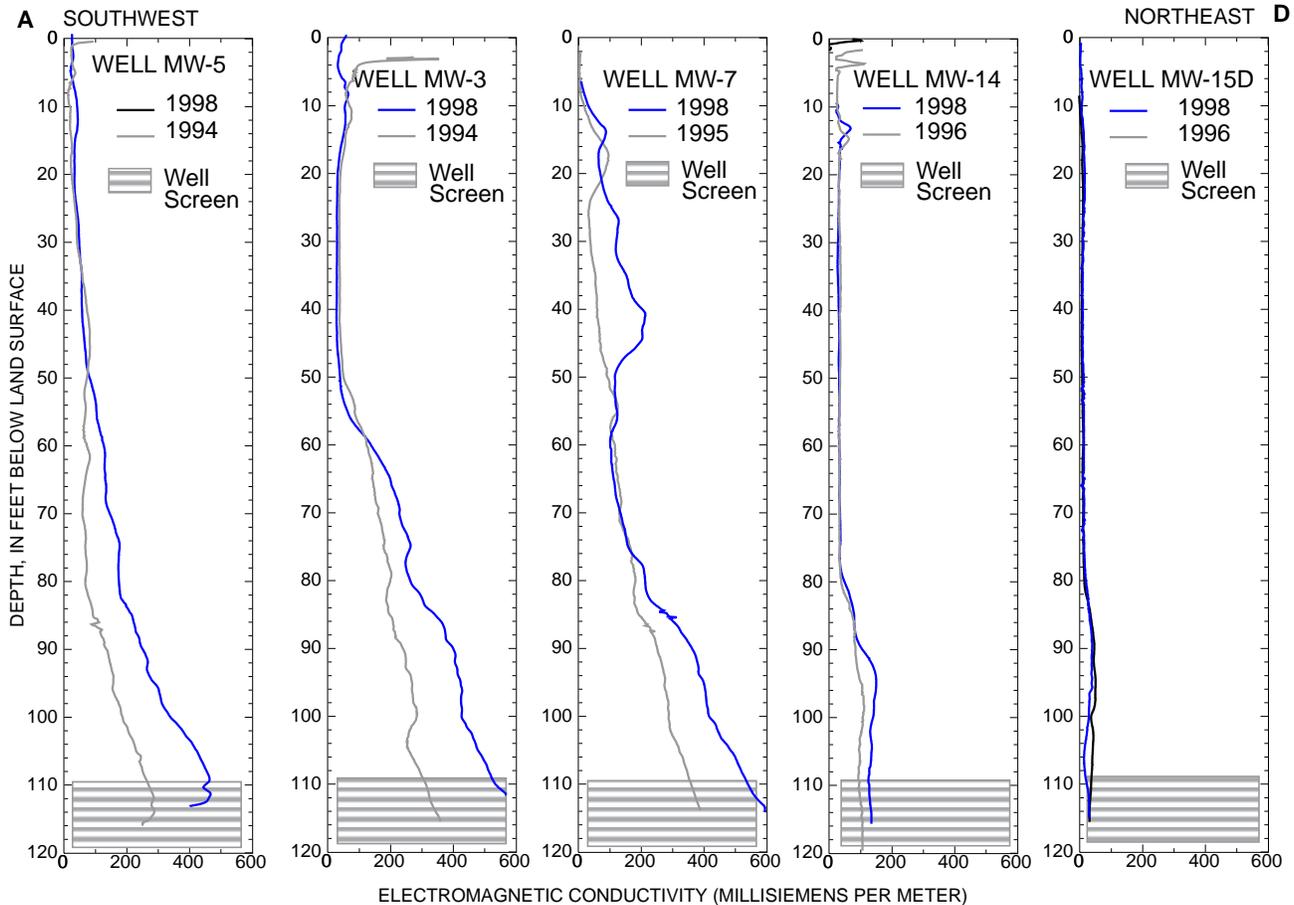
Figure 9. Borehole logs showing electromagnetic conductivity with depth in July 1994, February 1996, and May 1998, transect A-C, in the vicinity of the Porter County Airport, Valparaiso, Indiana. (Well locations are on figure 4, page 9, of this report).

and northern extent of the zone of large electromagnetic conductivity near the bottom of the aquifer cannot be illustrated because of an insufficient number of wells at the northern end of the transects farthest from the salt-storage facility (figs. 8 and 9). In contrast, the geophysical log of well MW-15D (fig. 10) appears to be near the northeastern extent of the zone of large electromagnetic conductivity.

The electromagnetic conductivity near the lower 40 to 70 ft of some wells increased 50 to 100 percent in the 3 or 4 years between 1994/1995 and 1998 (figs. 8, 9, and 10). In wells at the salt-storage facility (MW-3, MW-4, and MW-5), the increase was about 100 percent; in wells close to

the facility (TW-2, MW-7, MW-9, and TW-94E), the increase was about 50 percent. In wells farther from the facility (MW-13, and MW-14), a smaller increase occurred.

As explained earlier, borehole electromagnetic conductivity in the study area is related to the concentration of dissolved solids in ground water near the wells. The increases in electromagnetic conductivity appear to have been caused by vertical and horizontal movement of a plume of water with large concentrations of dissolved solids (called the "saltwater plume" in this report). Historical data for dissolved-solids concentrations were not available, so chloride data were examined (table 3).

Figure 10. Borehole logs showing electromagnetic conductivity with depth in July 1994, March 1995, February 1996, and May 1998, transect A-D, in the vicinity of the Porter County Airport, Valparaiso, Indiana. (Well locations are on figure 4, page 9, of this report.)

Chloride concentrations in water from wells near the salt-storage facility generally did not increase during 1994/1995 to 1998, and only a small increase occurred in some wells farther from the facility. Thus, the increases in electromagnetic conductivity over time probably were caused by movement of the saltwater plume.

Previous case studies (Williams and others, 1993; Church and Friesz, 1993) used sequential borehole geophysical logs of electromagnetic conductivity to identify changes in water quality with time. In this study, the rate of horizontal movement of the saltwater plume was estimated with the in-

creases in electromagnetic conductivity in the 4 years between July 1994 and May 1998 and with the distances between adjacent wells. The part of the plume with approximately 300 mS/m electromagnetic conductivity near the bottom of MW-4 moved 460 ft northwest to MW-9 (fig. 8). The part of the plume with approximately 400 mS/m of electromagnetic conductivity near the bottom of well TW-2 moved 240 ft north to TW-94E (fig. 9). The part of the plume with approximately 250 mS/m of electromagnetic conductivity near the bottom of TW-94E moved 400 ft north to MW-13 (fig. 9). Movement of the saltwater plume to the

northeast was not indicated by changes in electro-magnetic conductivity over time near the bottom of MW-7 and MW-14, 780 ft northeast of MW-7 (fig. 10).

The borehole geophysical data indicated the saltwater plume moved north at about 60 to 100 ft/yr and northwest at about 115 ft/yr from 1994 to 1998. The estimated horizontal groundwater-flow velocity in the study area during May 1998 was about 58 to 62 ft/yr north and 91 to 106 ft/yr northwest[2]. The rates of movement based on the borehole geophysical data are comparable to these estimated flow velocities.

Discussion of Borehole Geophysical Logs

The 1998 geophysical logs that showed an increase in borehole electromagnetic conductivity with depth corresponded to 1998 water-quality data that showed an increase in the concentration of dissolved solids with depth, particularly chloride and sodium. Figure 11 illustrates this relation with geophysical logs and water-quality data from a cluster of wells screened through different intervals (TW-94A, TW-94B, TW-94C, TW-94D, and TW-2) and from a pair of wells (MW-15S and MW-15D). Other evidence of this relation is that under static conditions, chloride concentrations were observed to be largest near the bottom of 12 wells (table 4), and borehole electromagnetic conductivity increased with depth near the bottom of these wells (appendix B, p. 49).

Previous case studies have used a conceptual, multi-layer model of saline water in the subsurface that was calibrated and verified with borehole geophysical data (McNew and Arav, 1995, and Paillet and others, 1998). In this study, a conceptual, multi-layer model was developed to describe the vertical extent of the saltwater plume, based on the borehole geophysical data from 1998. For this report, two conceptual, cross-sectional diagrams were developed to show the vertical layers (or "zones") in the saltwater plume along transects A-C and A-D. Three steps were needed to make the diagrams.

First, a relation was determined between the concentrations of dissolved solids and the average borehole electromagnetic-conductivity values from monitoring wells in the saltwater plume in 1998. Previous case studies have shown a relation between the specific conductance of water and median borehole electromagnetic conductivity from the screened intervals of wells in a sand and gravel aquifer (Williams and others, 1993). Specific conductance is related to the concentration of dissolved solids (Hem, 1992, p. 66–67); the concentration of dissolved solids was selected as the basis for the conceptual model in this study because of its use for categorizing ground water in the following step. Wells in which water contained more than 500 mg/L dissolved solids were considered to be in the saltwater plume because the nonenforceable secondary drinking-water regulation for dissolved solids is 500 mg/L (Code of

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[2]The horizontal ground-water-flow velocity in the directions of the transects of wells (A-B and A-C) was estimated with the equation for Darcy's Law and the velocity equation of hydraulics (Heath, 1989, p. 25):

$$v = \frac{Kh}{p}$$

where v is the horizontal ground-water-flow velocity in feet per year,

       K is the horizontal hydraulic conductivity in feet per year,

       h is the horizontal hydraulic gradient in feet per foot, and

       p is the porosity of the aquifer material, dimensionless.

For the estimates, the following values of $K, h,$ and p were used:

       K was 81.6 ft/day x 365 days/year near Valparaiso well 3 (Peerless Midwest, written commun., 1994);

       h was computed as the difference in water levels in May 1998 between wells in transects A-B and A-C, divided by the horizontal distance between the wells (0.0009 ft/ft northwest and 0.0005 ft/ft north, respectively); and

       p was either 0.25 or 0.30 (Heath, 1989, p. 7). The range of the estimated ground-water-flow velocity to the north and to the northwest was based on the two values for p.
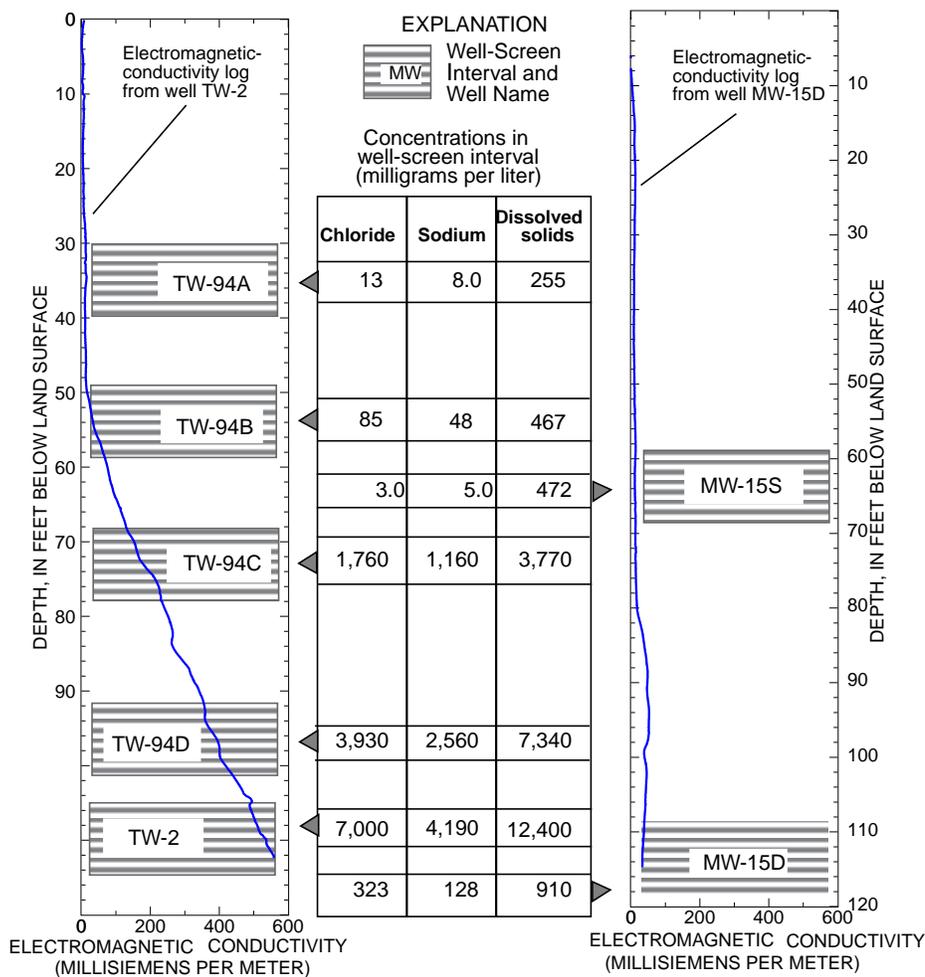
Figure 11. Comparisons of borehole logs showing electromagnetic conductivity with depth in May 1998 and concentrations of selected constituents in water samples from the screened intervals of nearby wells in March 1998, in the vicinity of the Porter County Airport, Valparaiso, Indiana. (Well locations are on figure 2, page 6, of this report.)

Electromagnetic-conductivity log from well TW-2

Electromagnetic-conductivity log from well MW-15D

EXPLANATION — Well-Screen Interval and Well Name (MW)

DEPTH, IN FEET BELOW LAND SURFACE

ELECTROMAGNETIC CONDUCTIVITY (MILLISIEMENS PER METER)

Concentrations in well-screen interval (milligrams per liter)

Well	Chloride	Sodium	Dissolved solids
TW-94A	13	8.0	255
TW-94B	85	48	467
MW-15S	3.0	5.0	472
TW-94C	1,760	1,160	3,770
TW-94D	3,930	2,560	7,340
TW-2	7,000	4,190	12,400
MW-15D	323	128	910

Federal Regulations, 1999). The concentrations of dissolved solids (the independent variable) were those detected in water samples pumped from the middle of the screened interval of 12 wells (table 1). The average[3] borehole electromagnetic-conductivity values (the dependent variable) were computed from data logged in the screened inter-vals of these 12 wells. A linear regression equation for the relation between the variables was obtained with statistical software. A log-log plot of these data and the regression line are shown in figure 12.

Second, four types of water were defined on the basis of the concentration of dissolved solids and on definitions in Freeze and Cherry (1979,

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[3]Average borehole electromagnetic conductivity was computed as the arithmetic mean of the conductivity values recorded every 0.1 ft in the screened interval of each well. The top of the screened interval was computed from the well log (Farlow Environmental Engineers, Inc., 1997).
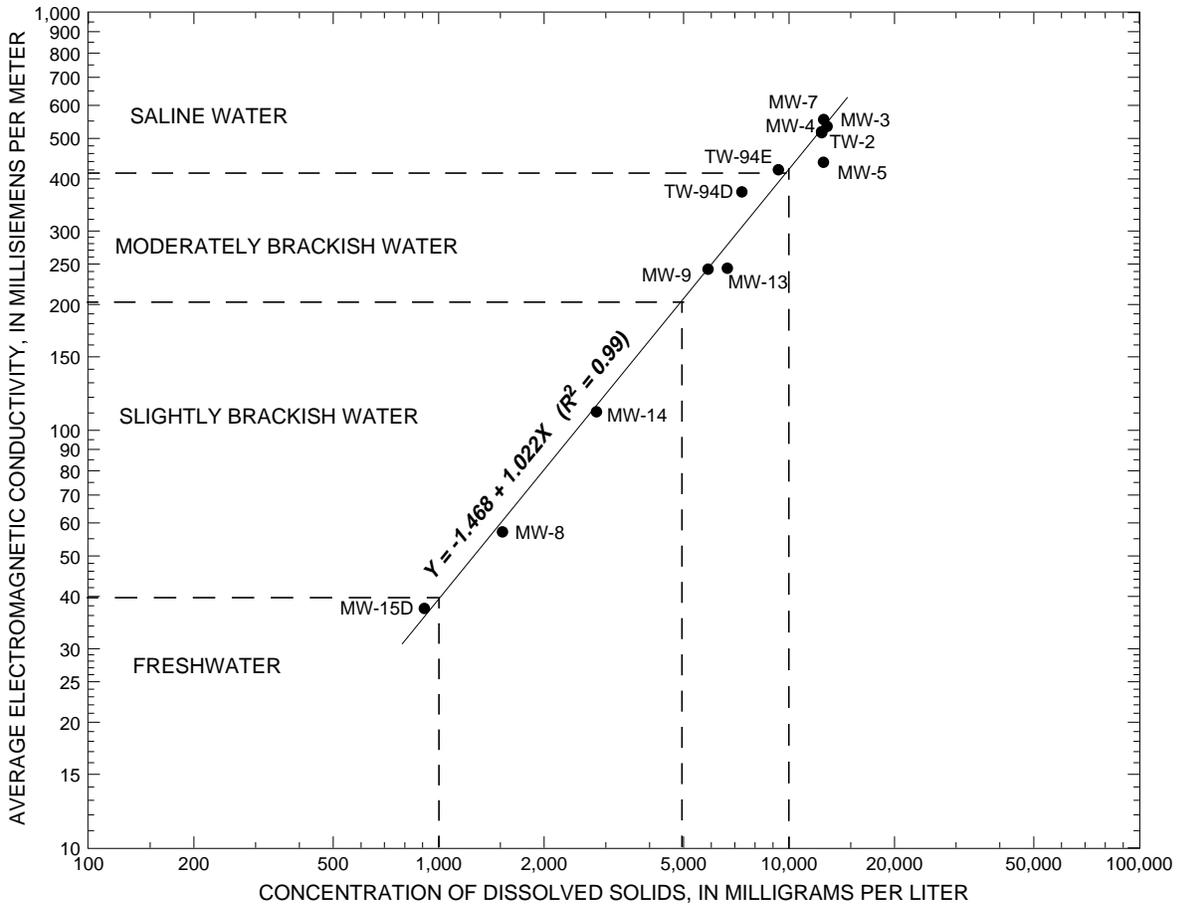
Figure 12. Log-log plot of the concentration of dissolved solids and average borehole electromagnetic conductivity in the screened interval of selected monitoring wells, March through May 1998, in the vicinity of the Porter County Airport, Valparaiso, Indiana. (Selected wells had dissolved solids concentrations greater than 500 milligrams per liter.)

p. 84) for freshwater, brackish water, and saline water. (For this report, brackish water was divided into two types.) The types of water were

- freshwater (less than 1,000 mg/L dissolved solids),
- slightly brackish water (from 1,000 to 5,000 mg/L dissolved solids),
- moderately brackish water (from 5,000 to 10,000 mg/L dissolved solids), and
- saline water (more than 10,000 mg/L dissolved solids).

The values of average borehole conductivity corresponding to concentrations of dissolved solids at the divisions between the types of water

were calculated with the regression equation ($Y = -1.468 + 1.022X$) for the line in figure 12 (table 5, page 28).

Third, the values of borehole electromagnetic conductivity for the divisions between the types of water were identified on the geophysical logs from wells in transects A-C and A-D, and these values were connected to make the diagrams (figs. 13 and 14, pages 28 and 29).

In the south to north conceptual diagram in figure 13, a 15- to 20-ft zone of saline water was below a 50- to 55-ft zone of brackish water beneath the salt-storage facility. Between TW-2 along Murvihill Road and TW-94E about 300 ft farther north, the zone of saline water remained about 20 ft thick
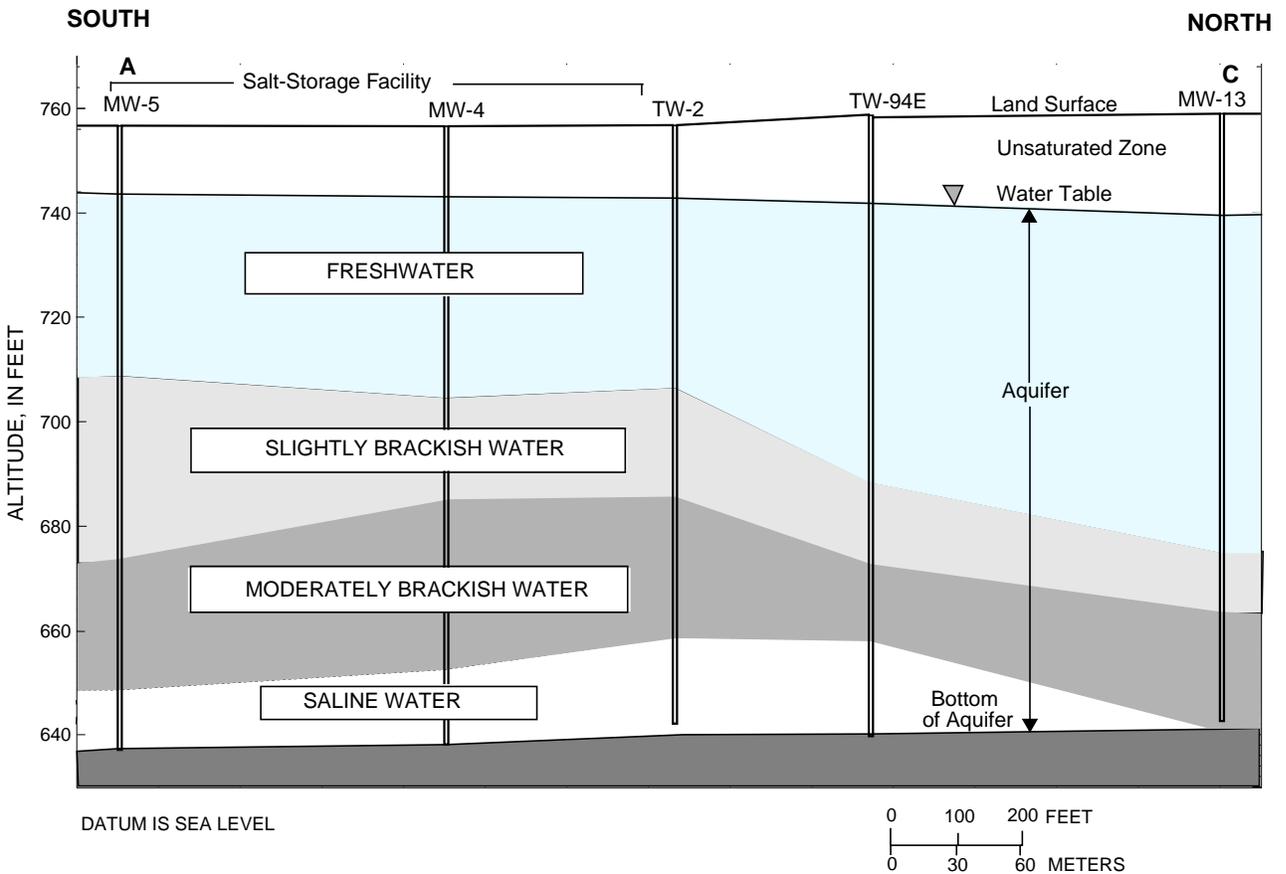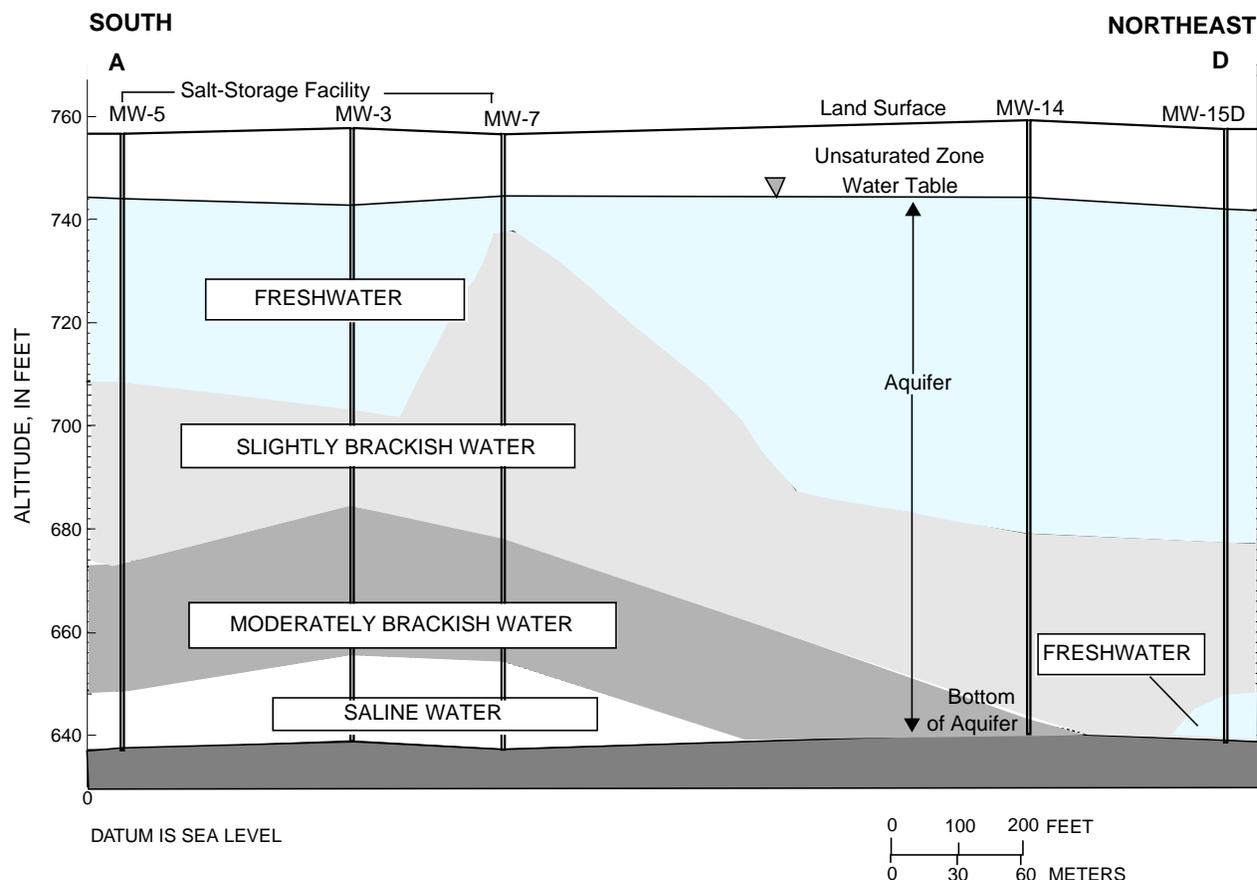
Figure 13. Types of water, based on concentrations of dissolved solids, transect A-C, in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Table 5. Types of water, concentrations of dissolved solids, and corresponding borehole electromagnetic conductivity, March through May 1998, in monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana

[mg/L, milligrams per liter; mS/m, millisiemens per meter]

Type of water[a]	Concentration of dissolved solids (mg/L)	Borehole electromagnetic conductivity (mS/m)
Freshwater	<1,000	<40
Slightly brackish water	1,000 to 5,000	40 to 204
Moderately brackish water	5,000 to 10,000	205 to 415
Saline water	>10,000	>416

[a]Definitions of freshwater, brackish water, and saline water are from Freeze and Cherry, 1979, p. 84.

Figure 14. Types of water, based on concentrations of dissolved solids, transect A-D, in the vicinity of the Porter County Airport, Valparaiso, Indiana.

and then thinned to less than 5 ft within 500 ft farther north (near MW-13 by the east-west taxi-way.) From TW-2 to MW-13, the zone of brackish water thinned from about 50 ft to about 25 ft. The northern extent of the brackish water could not be determined with the data from the wells in figure 13.

The conceptual diagram in figure 14 shows a different geometry of the saltwater plume toward the northeast. An approximately 60-ft-thick mound of slightly brackish water beneath MW-7 did not extend beneath all of the salt-storage facility. The mound tapered to 30 to 40 ft in thickness between MW-7 and MW-14, less than 800 ft farther north. It is not possible with the available data to explain the mound of slightly brackish water beneath MW-7. Near the east edge of the salt-storage facility, the 15-ft zone of saline water was below a 20- to 35-ft zone of moderately brackish water. These zones of saline water and moderately brackish water were thinner and ended in the 800 ft between the facility and MW-14. The zone of slightly brackish water, 40 ft thick at MW-14, extended through the aquifer beyond MW-15D, nearly 1,100 ft northeast of the facility. Freshwater, however, was present near the bottom of the aquifer at MW-15D.

Results of Surface Geophysical Surveys

The first set of surface geophysical data was obtained at about 100 survey stations[4] from November 30 to December 13, 1994. Terrain conductivity was measured in areas suspected to contain road-deicing salt and to delineate, if possible, the horizontal and vertical extent of the saltwater plume. In 1995, the INDOT contractor used the geophysical data to select locations for additional monitoring wells. The survey stations were located in three areas (figs. 15 and 16): at the Porter County Airport, in a field east of the salt-storage facility, and at the north end of an area about 500 ft south of the facility.

Before the surface geophysical survey in 1994, reference terrain-conductivity measurements were made at five stations about 1,500 ft north of public water-supply well 5 (fig. 1). Reference values were intended to represent an area where ground-water quality had not been affected by road-deicing salt.

In the area 500 ft south of the salt-storage facility, geophysical data were collected at three survey stations that did not have interference from cultural features. The terrain conductivity at these three stations is not included on figures 15 and 16 because of the similarity to the reference values.

Initially, the 1994 survey stations were sited close to the salt-storage facility. More stations were added to the north, west, and east until terrain-conductivity values at the 30- and 60-m depths of exploration were similar to the reference values or until decreases in conductivity values were no longer observed. If terrain-conductivity values at the 7.5- or 15-m depths of exploration were similar to the reference values or if they stayed the same as more stations were added, only measurements at the 30- and 60-m depths of exploration were continued.
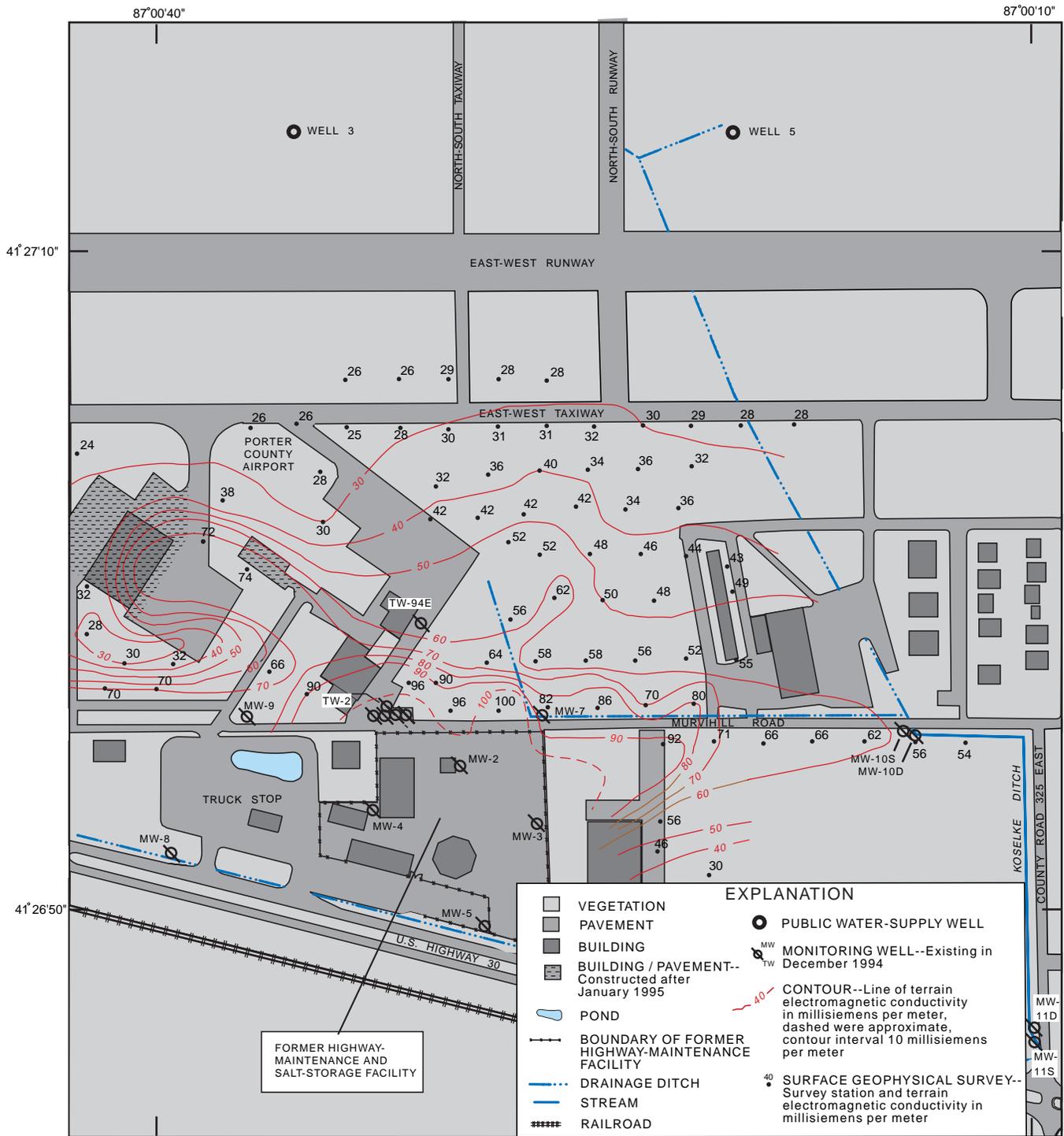
Terrain-conductivity values in the 1994 survey were largest immediately north and east of the salt-storage facility and near the bottom of the aquifer beyond the facility to the northwest, north, and east (figs. 15 and 16). At the boundary of the salt-storage facility, conductivity near the bottom of the aquifer was about 100 mS/m. A zone of large conductivity near the bottom of the aquifer (70 to 100 mS/m) extended 900 ft northwest, 200 ft north, and 650 ft east of the facility. Within those distances, terrain conductivity at the 7.5- and 15-m depths of exploration decreased to reference values.

Buried power cables were installed after 1994 for the airport runway and taxiway lighting and precision-approach instrument system (fig. 2). These buried power cables were evaluated in 1998 for their potential to affect the terrain-conductivity data collected nearby. Interference prevented a terrain-conductivity measurement if the geophysical coils were less than 10 m from the buried power cables in a line parallel or perpendicular to the cables. If a terrain-conductivity measurement was possible near a buried power cable, activation (energizing) of the runway-taxiway lighting or the precision-approach instrument system did not substantially alter the terrain conductivity measured at the 30- or 60-m depth of exploration.

In September and October 1998, a second surface geophysical survey was made at the Porter County Airport. The area for this survey was based on the borehole geophysical data from 1994, 1995, 1996, and 1998, and the water-quality data from 1998. The survey stations were north of the salt-storage facility and extended north of the east-west runway beyond public water-supply wells 3 and 5. The airport terminal building and paved areas near the terminal, along with the north-south runway and taxiway, were constructed after 1994. Survey stations from 1994, where the present airport terminal building and nearby pavement are (stippled area on figs. 15 and 16), could not be repeated in 1998.

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[4]In this report, "survey station" refers to a physical location to which a terrain electromagnetic-conductivity value is assigned from the surface geophysical survey. The physical location is the midpoint of the 40-m coil-separation distance for the surface geophysical survey equipment, as described in the section of this report, Surface Geophysical Technique.

Figure 15. Terrain electromagnetic conductivity at the 60-meter depth of exploration in November and December 1994, in the vicinity of the Porter County Airport, Valparaiso, Indiana.
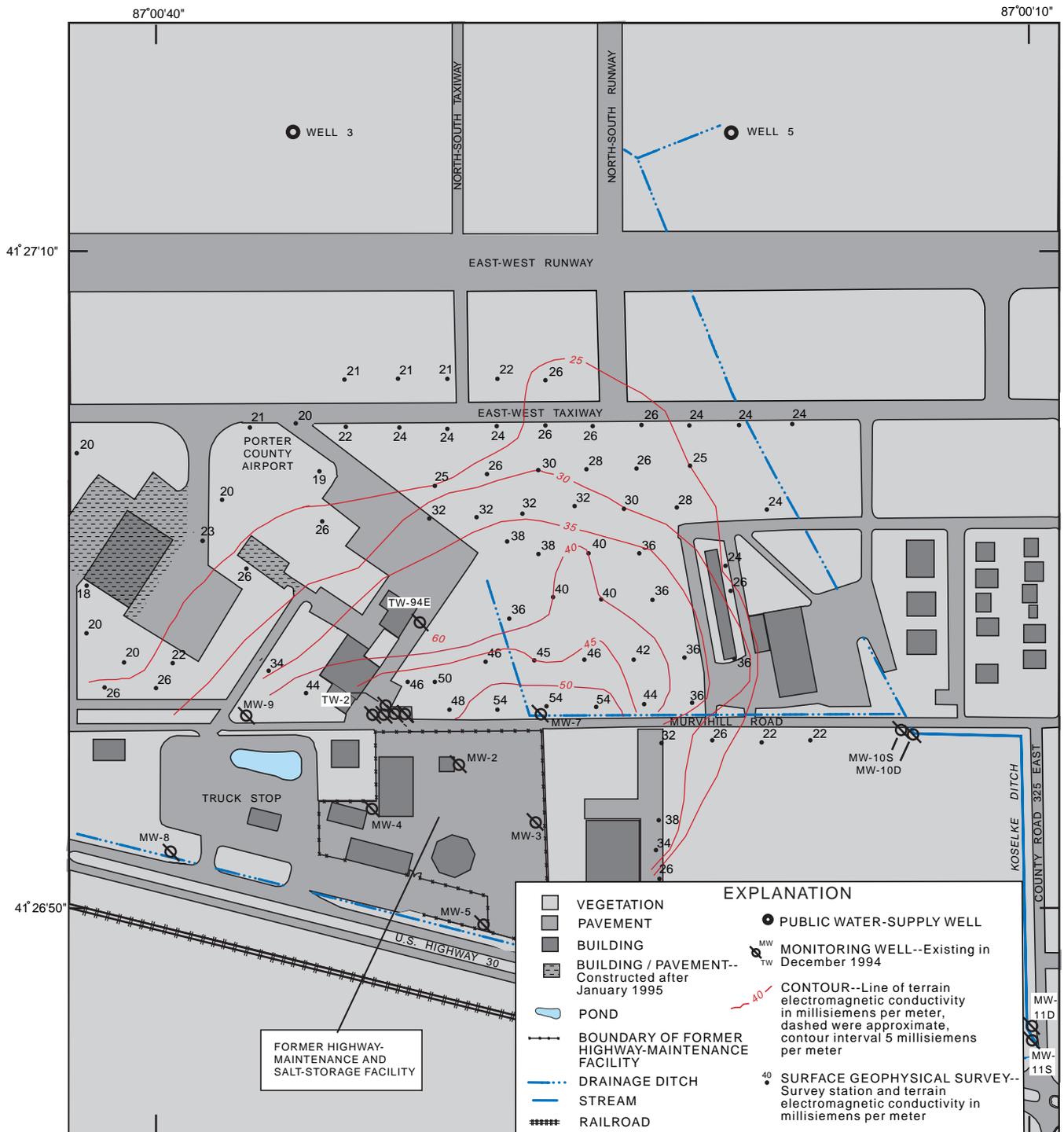
Base map modified from Department of Water Works, City of Valparaiso

Figure 16. Terrain electromagnetic conductivity at the 30-meter depth of exploration in November and December 1994, in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Terrain conductivity in the 1998 survey at the 60-m depth of exploration (fig. 17) indicated the zone with 70 to 100 mS/m in 1994 (fig. 15) was absent. Instead, a zone of conductivity greater than 60 mS/m (inside stippled area on fig. 17) was indicated immediately north of the salt-storage facility, and a zone of conductivity greater than 50 mS/m extended between and beyond public water-supply wells 3 and 5 (stippled area on fig. 17). At the 30-m depth of exploration, a zone of conductivity more than 30 mS/m also was indicated immediately north of the salt-storage facility (stippled area on fig. 18). Farther north, a zone of conductivity 14 to 18 mS/m north of the east-west taxiway and between public water-supply wells 3 and 5 generally overlaid the zone of conductivity greater than 50 mS/m mapped at the 60-m depth of exploration.

Discussion of Surface Geophysical Data

Previous case studies have found it helpful to account for background terrain conductivity when defining the horizontal extent of contaminant plumes (Barlow and Ryan, 1985, and Greenhouse and Slaine, 1983). As a guideline, terrain conductivity that is 1.5 to 2.0 times background has been used to indicate a contaminant plume (Grady and Haeni, 1984).

For this study, background terrain conductivity was based on values in 1998 in the vicinity of MW-17 (northeast section, fig. 17). Water-quality data (fig. 7, tables 1 and 2) and borehole geophysical data (appendix B) indicated MW-17 was screened in natural ground water outside the saltwater plume. Water-quality and borehole geophysical data that could provide a background value in 1994 were not available. In 1998, background was about 17 mS/m at the 60-m depth of exploration and 10 mS/m at the 30-m depth of exploration. Values for the plume boundary were computed, using 1.5 times background in 1998 (25.5 mS/m at the 60-m depth of exploration and 15 mS/m at the 30-m depth of exploration). On the basis of these values, an approximation of the plume boundary was repre-

sented by the red, thick, dashed lines on figures 17 and 18. If the background values based on 1998 measurements were applied to the 1994 data, the contours approximating plume boundaries would be 30 mS/m (figs. 15 and 16).

Generally, the zone of large terrain conductivity (70 to 100 mS/m) mapped in the 1994 survey (fig. 15) was consistent with water-quality data indicating the saltwater plume. Historical samples in 1994 from wells screened near the bottom of the aquifer in the zone of large conductivity (TW-2, MW-3, MW-4, and MW-7; table 3) had chloride concentrations from 7,300 to 7,900 mg/L. Similarly, the zone of large terrain conductivity (greater than 60 mS/m) mapped in the 1998 survey (fig. 17) was consistent with water-quality data indicating the saltwater plume. Water samples in 1998 from wells screened near the bottom of the aquifer in the zone of large conductivity (TW-2, MW-3, MW-4, and MW-7; table 3) had chloride concentrations from about 7,000 to 7,230 mg/L. Also in 1998, the eastern boundary of the salt-water plume near MW-15D indicated by the borehole geophysical data (fig. 10) and the water-quality data (fig. 7) is consistent with the boundary approximated with the surface geophysical data.

The most notable change between the 1994 and 1998 survey was the zone of terrain conductivity greater than 50 mS/m mapped near the bottom of the aquifer between and beyond public water-supply wells 3 and 5. Three explanations were proposed; however, data to verify these explanations (well borings, water-quality data, or borehole logs of natural gamma activity and electromagnetic conductivity) were not available from this investigation or from previous work in the study area. The three explanations are

(1) The zone may have been associated with the saltwater plume near the bottom of the aquifer. This explanation was consistent with several observations:

> (a) the zone appeared to originate at the salt-storage facility;
>
> (b) the zone was between monitoring wells where water-quality and borehole
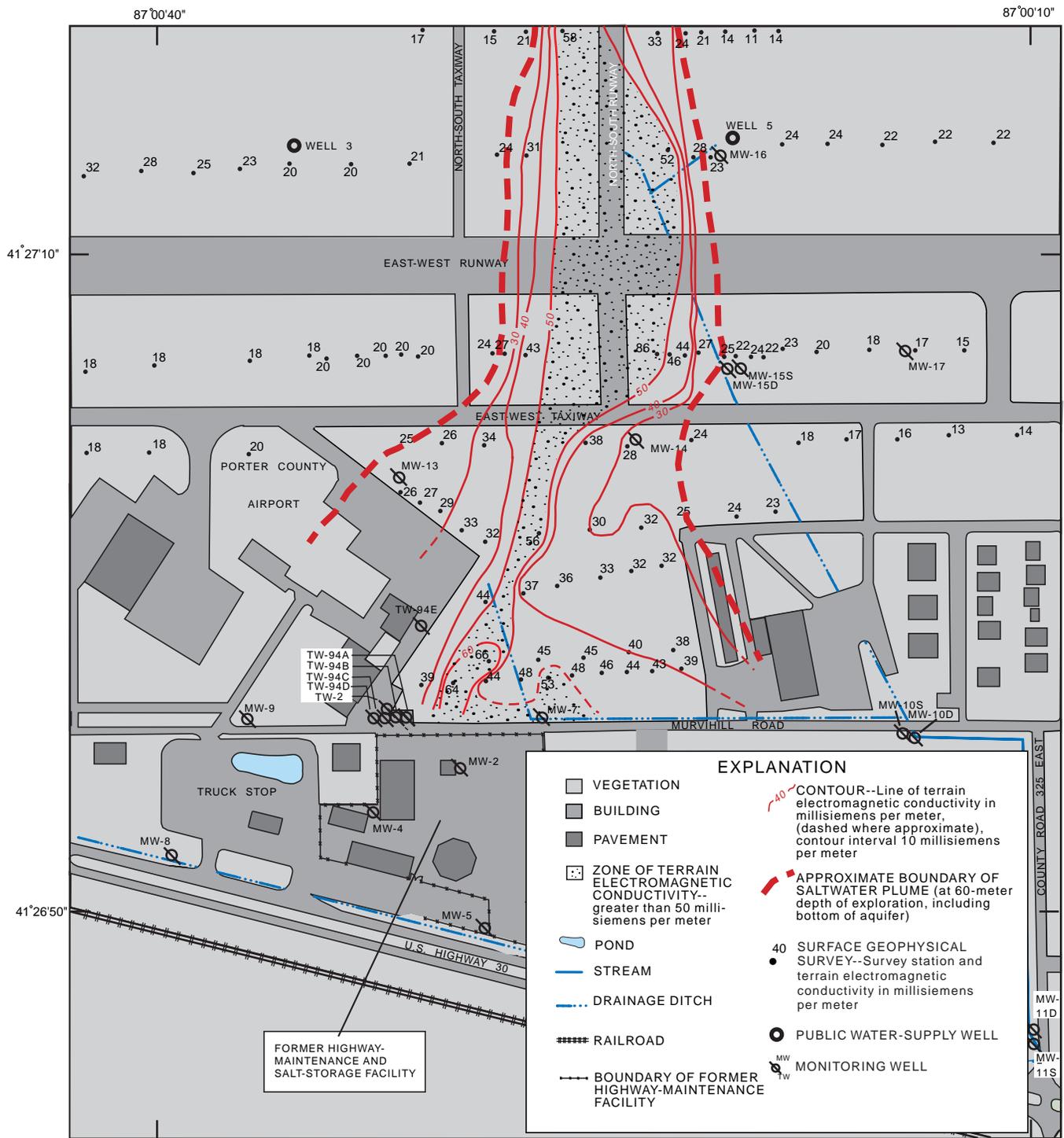
Figure 17. Terrain electromagnetic conductivity at the 60-meter depth of exploration in September and October 1998, in the vicinity of the Porter County Airport, Valparaiso, Indiana.
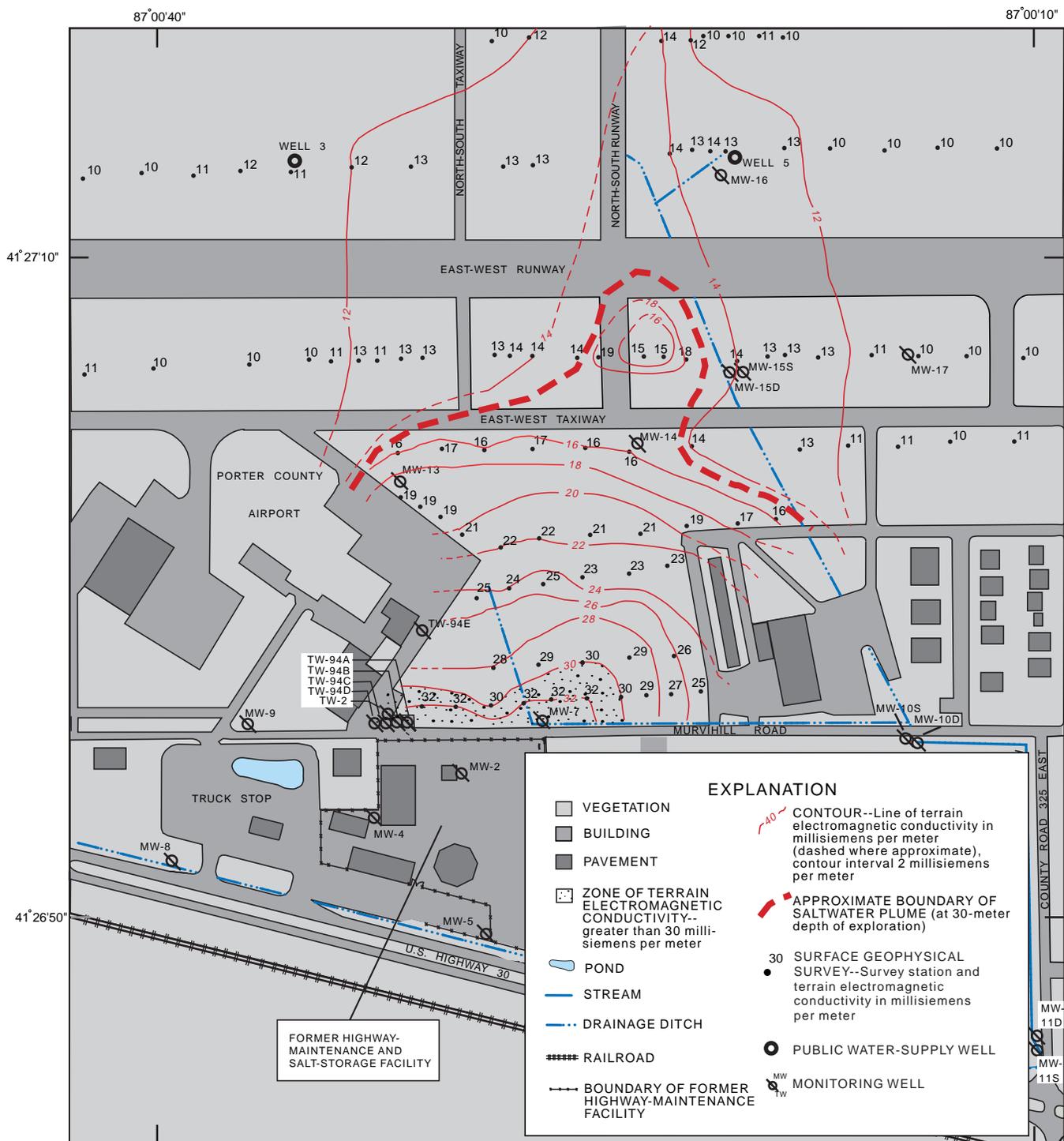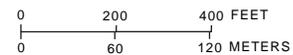
Figure 18. Terrain electromagnetic conductivity at the 30-meter depth of exploration in September and October 1998, in the vicinity of the Porter County Airport, Valparaiso, Indiana.

geophysical data indicated saltwater (TW-2, TW-94E, MW-7, MW-13, and MW-14);

(c) the horizontal extent of the zone at the 60-m depth of exploration was similar to the extent at the 30-m depth of exploration (where effects from geology below the aquifer were absent); and

(d) water-level data indicated ground-water flow to the north.

The direction of ground-water flow was estimated with synoptic water-level measurements made May 12 through 14, 1998, in 14 wells in the monitoring network screened near the bottom of the aquifer. An insufficient number of wells was available to represent the water table at the top of the unconfined aquifer. The water levels may not have represented the same hydraulic head near the bottom of the aquifer because some wells were filled with a taller column of saltwater or freshwater than other wells. For purposes of this study, the water-level data were converted to altitude and were contoured (fig. 19). Assuming the direction of horizontal ground-water flow was perpendicular to the contours of water-level altitude in figure 19, several directions of ground-water flow were inferred. Between Murvihill Road and the east-west taxiway, horizontal flow may have been west, northwest, or north. North of the east-west taxiway, ground-water flow was mostly north. Horizontal hydraulic gradients calculated with the water-level altitudes were 6.1 ft/mi north (between MW-7 and MW-14) and 11.4 ft/mi northwest (between MW-5 and MW-9).

Pumping records for public water-supply wells 3 and 5 indicated these wells were in use during May 1998, but information about pumping on specific days was not available (Valparaiso Water Department, unpublished information, January 1999). These wells are screened in the bottom 30 ft of the aquifer (Peerless-Midwest, Inc., un-

published information, September 1965, January 1978). It is possible that the historical pumping influence of the two public water-supply wells affected the horizontal movement of the salt-water plume at the bottom of the aquifer, drawing it to the location between public water-supply wells 3 and 5. Well 5 was taken out of service for much of 1994 and 1995; pumping of both wells was reduced by half, starting in 1997. The reduced pumping may have left some of the salt-water plume isolated from the pumping influence of wells 3 and 5, potentially indicated by the zone of terrain conductivity between these wells (fig. 17). Temporary effects on ground-water flow from pumping of the public water-supply wells could not be determined with the water-level data from May 1998.

(2) The zone may have been associated with the buried power cables (fig. 2). This explanation, however, was not consistent with other observations in the study area:

(a) buried power cables along the east-west runway and taxi-way did not cause increased terrain-conductivity values (fig. 17);

(b) an evaluation of the power cables in 1998 did not indicate terrain-conductivity values were increased when the cables were energized; and

(c) near-surface objects (less than about 13 ft in depth[1]) such as the buried power cables and geologic material have been reported to have little effect on terrain conductivity measured with equipment in the vertical-dipole orientation used for the 60-m depth of exploration (Haeni, 1995, p. A8, and McNeill, 1980b, fig. 6).

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[1]In the vertical-dipole orientation, the equipment responds mainly to geologic material between 0.1 and 1.5 times the coil-separation distance. At a 40-m coil separation, little response is reported at less than 4 m (0.1 times 40 m), which is about 13 ft.
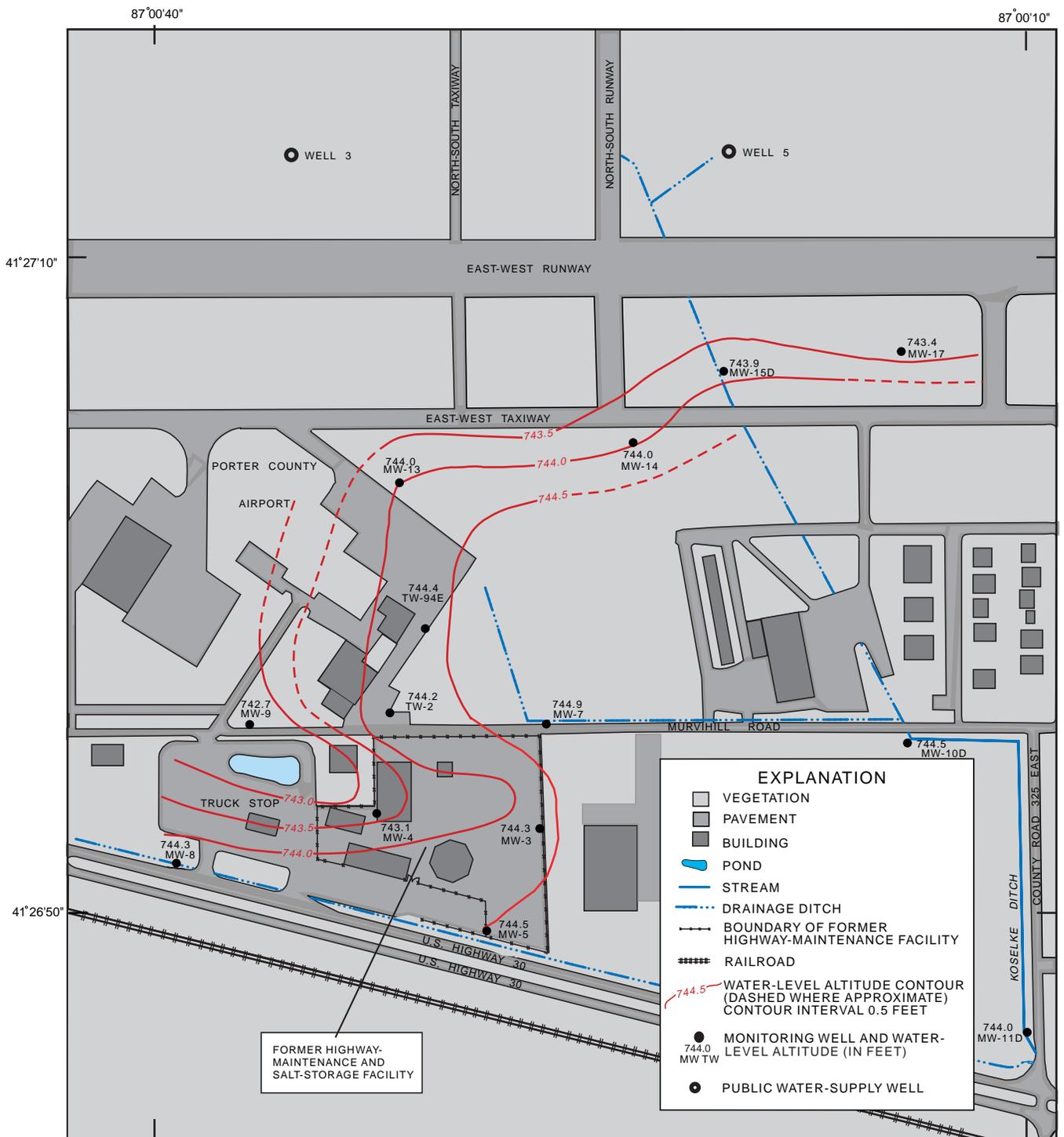
Figure 19. Water-level altitudes, May 12 through 14, 1998, in wells screened near the bottom of the glacial aquifer in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Base map modified from Department of Water Works, City of Valparaiso

(3) The zone may have been associated with a geologic feature. The 30-m depth of exploration penetrated the sand aquifer to about 100 ft below land surface. The bottom of the aquifer is about 120 ft below land surface. The 60-m depth of exploration included the bottom part of the aquifer below 100 ft, along with the lacustrine deposits and shale bedrock below the sand aquifer (to a maximum depth of about 200 ft). For the zone to be associated with a geologic feature, there would have to be a valley on the bedrock surface filled with a greater density of fine-grained sediment[1] than was present in the other lacustrine deposits on the bedrock. This explanation, however, was inconsistent with the current understanding of the hydrogeology of the study area in that the bedrock has a flat surface and the lacustrine deposits have a horizontal upper surface and uniform texture.

Summary and Conclusions

This case study demonstrated that the results of borehole logging and surface geophysical surveys could be combined with "conventional" collection and analysis of water samples to improve the understanding of effects on ground-water quality from a road-deicing salt-storage facility. Factors that simplified interpretation of the geophysical data in this study included a single contaminant and source; a homogeneous hydrogeologic environment; an existing network of monitoring wells; historical water-quality data; and a flat, open study area. Methods, concepts, and findings from a number of previous case studies that used geophysics to examine water quality were incorporated into this study. A conceptual, multi-layer model of the saltwater in the aquifer was developed for this study and used an approach that was different from those described in previous studies. This approach may be helpful in similar investigations.

The study area included a former highway-maintenance facility located near a county airport and a public water-supply well field. The area is underlain by a glacial sand aquifer about 120 ft thick above fine-grained lacustrine deposits. Previous investigations have shown that runoff and infiltration of road-deicing salts (sodium chloride and calcium chloride) stored and handled at the facility for many years had affected ground-water quality in the area. Although these earlier investigations acquired useful information through collection of water samples from a monitoring-well network, the vertical and horizontal extent of road salt in the aquifer could not be delineated fully. The study reported here provided a base line of information prior to the start of remedial action at the former salt-storage facility.

Analyses of water samples collected from the monitoring-well network provided several kinds of information about road salt in the ground water. Before monitoring wells were purged, samples were collected from discrete intervals near the top and bottom of well screens installed at the bottom of the aquifer. These samples indicated chloride concentrations were largest near the bottom of the aquifer. Ratios of chloride to bromide concentrations in water samples were used to distinguish chloride from road-deicing salt, domestic wastewater, and natural ground water. Water samples identified with the chloride/bromide ratios as affected by road-deicing salt had concentrations of dissolved solids, chloride, and sodium many times the background levels for the study area. The largest concentrations of dissolved solids, chloride, and sodium were in water from wells near the salt-storage facility.

Borehole geophysical surveys were used to obtain information about ground-water quality outside the screened intervals of monitoring wells completed near the bottom of the aquifer. Based on borehole logs of natural gamma activity that indicated a negligible contribution from clay, the borehole logs of electromagnetic conductivity primarily measured the concentration of dissolved solids in the ground water near the wells. Borehole conductivity data indicated the saltwater plume was near the bottom of the aquifer and

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[1]Terrain conductivity is increased by greater proportions of fine-grained sediments because these sediments contain more electrically conductive water molecules.

close to the salt-storage facility. The borehole conductivity data showed the vertical extent of the plume was above the screened intervals of the wells and extended beyond wells at the west, northwest, and north sides of the study area. Increases in electromagnetic conductivity in sequential borehole logs during 1994 through 1998 indicated the saltwater plume had moved north about 60 to 100 ft/yr. These rates were consistent with estimates of horizontal ground-water flow based on velocity calculations with hydrologic data from the study area.

In this study, a conceptual, multi-layer model was developed to describe the vertical extent of saltwater in the aquifer. A relation was derived between the average borehole electromagnetic conductivity in the screened interval and the concentrations of dissolved solids in water samples from wells in the saltwater plume. With this relation, borehole electromagnetic conductivity from transects of wells was used to estimate the zone of saline water beneath zones of brackish water and freshwater. The model showed the zone of saline water was as much as 20 ft thick, with a zone of brackish water above it as much as 55 ft thick.

The construction design of the pre-existing monitoring-well network limited the depth of the borehole logs of electromagnetic conductivity. The bottoms of the deepest wells in the network were near the top of the lacustrine deposits at the base of the sand aquifer. The receiver in the borehole geophysical tool is 5 ft from the end of the tool, which allowed measurements to be made within about 5 ft of the bottom of the wells. Thus, saline- or brackish-water zones less than about 5 ft thick could not be detected with the probe for electromagnetic conductivity. This limi-

tation could be overcome in similar investigations if well-construction design included a well screen at the bottom of the aquifer with a sump at least 5 ft long below the screen. Such a design would allow borehole geophysical logging of electromagnetic conductivity to be made to the bottom of the aquifer.

Surface geophysical surveys were used to obtain information about ground-water quality at locations where monitoring wells were not or could not be installed. Two surface surveys of terrain electromagnetic conductivity were used to map the horizontal extent of the saltwater plume at the beginning and end of the study period. As in previous case studies, background terrain conductivity was measured. In this study, background terrain conductivity was measured near wells unaffected by the saltwater, based on water-quality and borehole geophysical data. Using a guideline from previous case studies, the plume boundary was mapped where terrain-conductivity values were 1.5 times background. Terrain conductivity in the saltwater plume near the bottom of the aquifer generally was consistent with the available water-quality and borehole electromagnetic-conductivity data and with directions of ground-water flow based on water-level altitudes. The boundary of the plume changed between the first and second surface geophysical surveys. Near the end of the study, the plume was reduced in size near the salt-storage facility, but a narrow part of the plume extended to the northern end of the study area. This part could have been associated with horizontal movement of the salt-water plume, but water-quality and borehole electromagnetic-conductivity data could not be obtained for verification.

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Appendix A.
Supplemental Data Tables

Table A1. Selected characteristics of monitoring wells in the study area in the vicinity of the Porter County Airport, Valparaiso, Indiana

[Altitudes are in feet above sea level; -- no data]

Local well name	Year of well construction[a]	Depth to bottom of well screen[b] (feet)	Measuring-point altitude[a]	Land surface to measuring point[c] (feet)	Water-quality samples in March 1998	Year of natural gamma log	Year of borehole electromagnetic-conductivity log(s)
TW-2	1993	114.70	756.87	-0.34	yes	1994	1994, 1998
TW-94A	1993	39.74	756.77	-.34	yes	--	--
TW-94B	1993	58.75	756.77	-.34	yes	--	--
TW-94C	1993	78.45	756.62	-.34	yes	--	--
TW-94D	1993	101.50	756.76	-.34	yes	--	--
TW-94E	1993	118.60	758.35	-.34	yes	1994	1994, 1996, 1998
MW-1	--	32.70	757.96	3.0	yes	--	--
MW-2	--	32.30	756.83[d]	3.1	yes	--	--
MW-3	1994	119.90	757.84	2.5	yes	1994	1994, 1998
MW-4	1994	118.50	756.60	-.34	yes	1994	1994, 1998
MW-5	1994	119.60	756.73	-.34	yes	1994	1994, 1998
MW-6	1994	121.00[a]	758.76	--	no[e]	1994	1994
MW-7	1994	119.40	756.61	-.42	yes	1995	1995, 1998
MW-8	1994	122.00	757.39	-.67	yes	1996	1996, 1998
MW-9	1994	121.10	759.69	-.62	yes	1995	1996, 1996, 1998
MW-10D	1994	116.50	751.53	-.67	yes	1995	1995, 1998
MW-10S	1994	27.40	751.73	-.67	yes	--	--
MW-11D	1995	120.00	753.43	-.67	yes	1995	1995
MW-11S	1994	23.70	753.41	-.50	yes	--	--
MW-13	1995	116.40	758.97	-.46	yes	1996	1996, 1998
MW-14	1995	119.10	759.30	-.34	yes	1996	1996, 1998
MW-15D	1995	119.00	757.57	-.50	yes	1996	1996, 1998
MW-15S	1995	68.80	757.60	-.50	yes	--	--
MW-16	1995	121.00[a]	758.99	-.50	no[f]	1998	1998
MW-17	1995	120.00	758.29	-.50	yes	1998	1998

[a]From Farlow Environmental Engineers, Inc., 1997, appendix A.
[b]Measured in March 1998.
[c]Measured in March 1998; negative values are below land surface.
[d]One inch subtracted from altitude in Farlow Environmental Engineers, Inc., 1997, because of well repair in 1998.
[e]Permanent plumbing and electrical lines prevented access to well in March 1998.
[f]Well screened was plugged with sediment and could not be sampled in March 1998.

Table A2. Analytical constituents, methods of analysis, and reporting limits for samples collected during March 1998 from monitoring wells in the vicinity of the Porter County Airport, Valparaiso, Indiana

[mg/L, milligrams per liter; $CaCO_3$, calcium carbonate; USGS, U.S. Geological Survey Laboratory, Ocala, Fla.; IC, ion chromatography; ICP, inductively coupled plasma; ISE, ion selective electrode; N, nitrogen; P, phosphorous; AA, atomic absorption spectroscopy; std. unit, standard unit; mV, millivolt; SiO_2, silicon dioxide; μS/cm, microsiemens per centimeter; NTU, nephelometric turbidity unit; °C, degrees Celsius]

Constituent	Category	Analytical method	Laboratory	Reporting limit,	units
Alkalinity as $CaCO_3$	Physical property	titration	field, USGS	1.0	mg/L
Bicarbonate	Anion	titration	field	1.0	mg/L
Bromide	Anion	IC	USGS	.05	mg/L
Calcium	Metal	ICP	USGS	.02	mg/L
Chloride	Anion	IC	field, USGS	1.0 .1	mg/L mg/L
Dissolved oxygen	Characteristic	polarographic, membrane	field	.01	mg/L
Dissolved solids	Physical property	gravimetric	USGS	1.0	mg/L
Fluoride	Anion	ISE-automated	USGS	.1	mg/L
Iron	Metal	ICP	USGS	1.0	mg/L
Iodide	Anion	IC	USGS	.001	mg/L
Magnesium	Metal	ICP	USGS	.001	mg/L
Manganese	Metal	ICP	USGS	.2	mg/L
Nitrate+nitrite as N	Anion	colorimetric	USGS	.02	mg/L
Orthophosphate as P	Anion	colorimetric	USGS	.01	mg/L
pH	Characteristic	electrometric	field	.01	std. unit
Potassium	Metal	AA	USGS	.1	mg/L
Reduction-oxidation potential	Characteristic	electrometric	field	1.0	mV
Silica as SiO_2	Metal	ICP	USGS	.01	mg/L
Sodium	Metal	AA	USGS	.1	mg/L
Specific conductance	Characteristic	electrometric	field	1.0	μS/cm
Sulfate	Anion	IC	USGS	.2	mg/L
Total solids	Property	gravimetric	USGS	1.0	mg/L
Turbidity	Characteristic	optical	field	.1	NTU
Water temperature	Characteristic	thermistor	field	.01	°C

**Table A3.** Quality-control data for field-blanks and replicate samples collected during March 1998 in the vicinity of the Porter County Airport, Valparaiso, Indiana

[All concentrations in milligrams per liter; SiO₂, silicon dioxide; <, less than (reporting limit); N, nitrogen; P, phosphorous; RPD, relative percent difference (as percent); --, no data]

Field blank	Calcium	Iron	Magnesium	Manganese	Potassium	Silica as SiO_2	Sodium	Bromide	Chloride
Pump 1 start	0.09	0.02	0.02	0.001	<0.1	0.01	<0.1	<0.05	<0.1
Pump 1 end	.1	.03	.02	.002	<.1	.02	.1	<.05	<.1
Pump 2 start	5.8	.1	1.7	.06	<.1	1.7	<.1	<.05	1.4
Pump 2 end	.1	.06	.03	.001	<.1	.01	<.1	<.05	.1
Bailer start	.1	.01	.02	.0005	<.1	.01	<.1	<.05	<.1
Bailer end	.05	.01	.01	.0002	<.1	<.01	<.1	<.05	<.1

Field blank	Fluoride	Nitrate + nitrite - N	Orthophosphate as P	Sulfate
Pump 1 start	<0.1	<0.02	<0.01	<0.2
Pump 1 end	<.1	<.02	<.01	<.2
Pump 2 start	<.1	<.02	<.01	6.3
Pump 2 end	<.1	<.02	<.01	<.2
Bailer start	<.1	<.02	<.01	<.2
Bailer end	<.1	<.02	<.01	<.2

Replicate samples	Calcium	Calcium RPD	Iron	Iron RPD	Magnesium	Magnesium RPD	Manganese	Manganese RPD	Potassium	Potassium RPD
MW-7	210	--	3.1	--	24	--	0.38	--	14	--
replicate	210	0	3.1	0	24	0	.38	0	13	3.7
replicate	210	0	3.1	0	25	2	.39	1.3	14	0
TW-94E	270	--	4.1	--	64	--	.43	--	14	--
replicate	270	0	4.0	1.2	63	.8	.43	0	14	0
replicate	270	0	4.1	0	63	.8	.43	0	14	0
MW-5	470	--	5.6	--	77	--	.42	--	19	--
replicate	480	1	5.6	0	77	0	.37	6.3	19	0

Table A3. Quality-control data for field-blanks and replicate samples collected during March 1998 in the vicinity of the Porter County Airport, Valparaiso, Indiana—Continued

Replicate samples	Silica as SiO$_2$	Silica RPD	Sodium	Sodium RPD	Bromide	Bromide RPD	Chloride	Chloride RPD	Fluoride	Fluoride RPD
MW-7	10	--	4,400	--	1.3	--	7,200	--	<0.1	--
replicate	10	0	4,400	0	1.3	0	7,140	.5	<.1	0
replicate	10	0	4,400	0	1.3	0	7,040	1.1	<.1	0
TW-94E	11	--	3,110	--	1.1	--	5,160	--	<.1	--
replicate	11	0	3,000	1.9	1.2	4.3	5,110	.5	<.1	0
replicate	11	0	3,100	.2	1.3	8.3	5,070	1.0	<.1	0
MW-5	11	--	3,690	--	.6	--	6,730	--	<.1	--
replicate	11	0	3,700	.1	.8	14	6,830	.8	<.1	0
MW-13	12	--	1,440	--	.4	--	3,340	--	<.1	--
replicate	12	0	1,700	8.2	.4	0	3,350	.3	<.1	0

Replicate samples	Nitrate + nitrite - N	Nitrate + nitrite RPD	Ortho-phos-phate as P	Ortho-phos-phate RPD	Sulfate	Sulfate RPD	Replicate samples	Sodium	Sodium RPD	Chloride	Chloride RPD
MW-7	<0.02	--	0.03	--	160	--	TW-2	4,190	--	7,000	--
replicate	<.02	0	.02	20	170	3	filtered	4,290	1.1	6,860	1.2
replicate	<.02	0	.02	20	170	3					
TW-94E	<.02	--	.02	--	130	--	MW-3	4,420	--	7,230	--
replicate	<.02	0	.01	33	130	0	filtered	4,610	2.1	7,360	.8
replicate	<.02	0	.02	0	130	0					
MW-5	<.02	--	.02	--	110	--	MW-8	263	--	572	--
replicate	<.02	0	.02	0	110	0	filtered	244	3.7	569	.3
MW-13	<.02	--	.01	--	56	--					
replicate	<.02	0	.02	33	56	0					

Appendix B.
Borehole Geophysical Logs

Natural Gamma Activity and Electromagnetic Conductivity

July 1994 through May 1998

in the Vicinity of the Porter County Airport,

Valparaiso, Indiana

(Well locations are on figure 2.)

(Note: Horizontal scales have been adjusted
to the data for each well. The horizontal scales
will vary from well to well.)
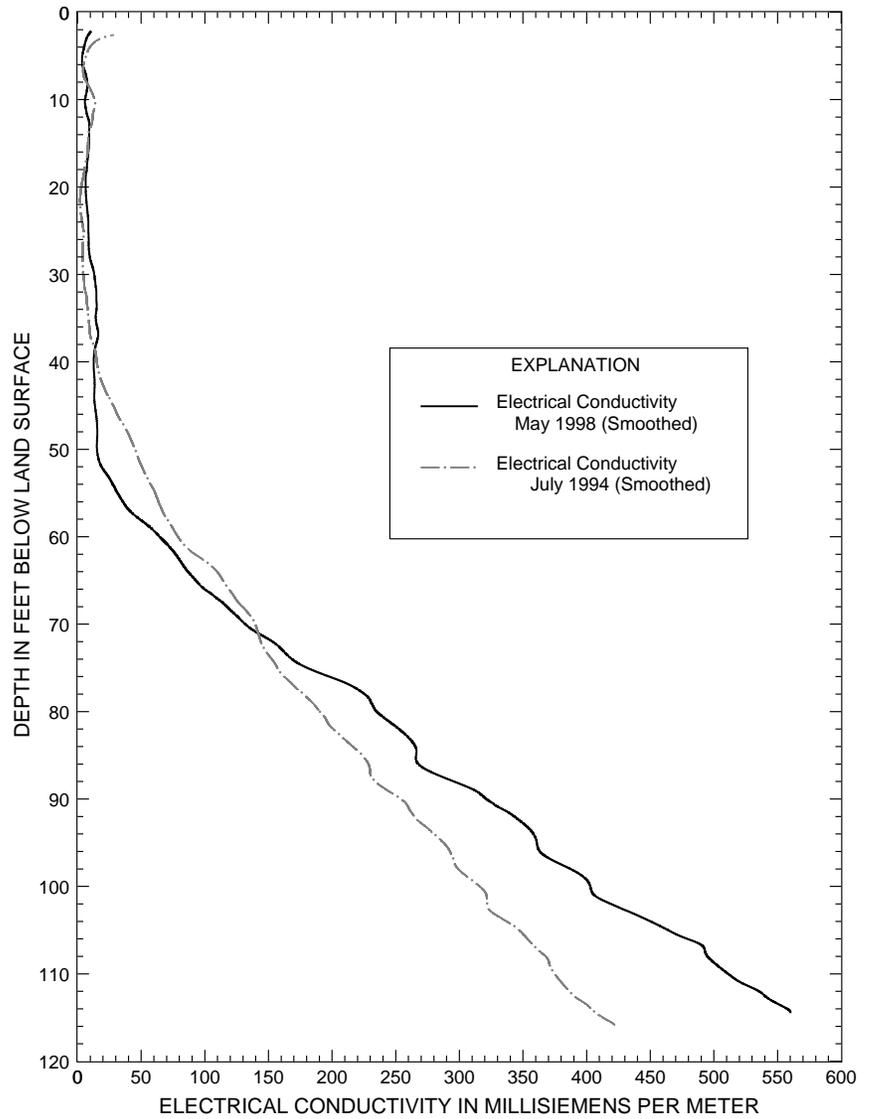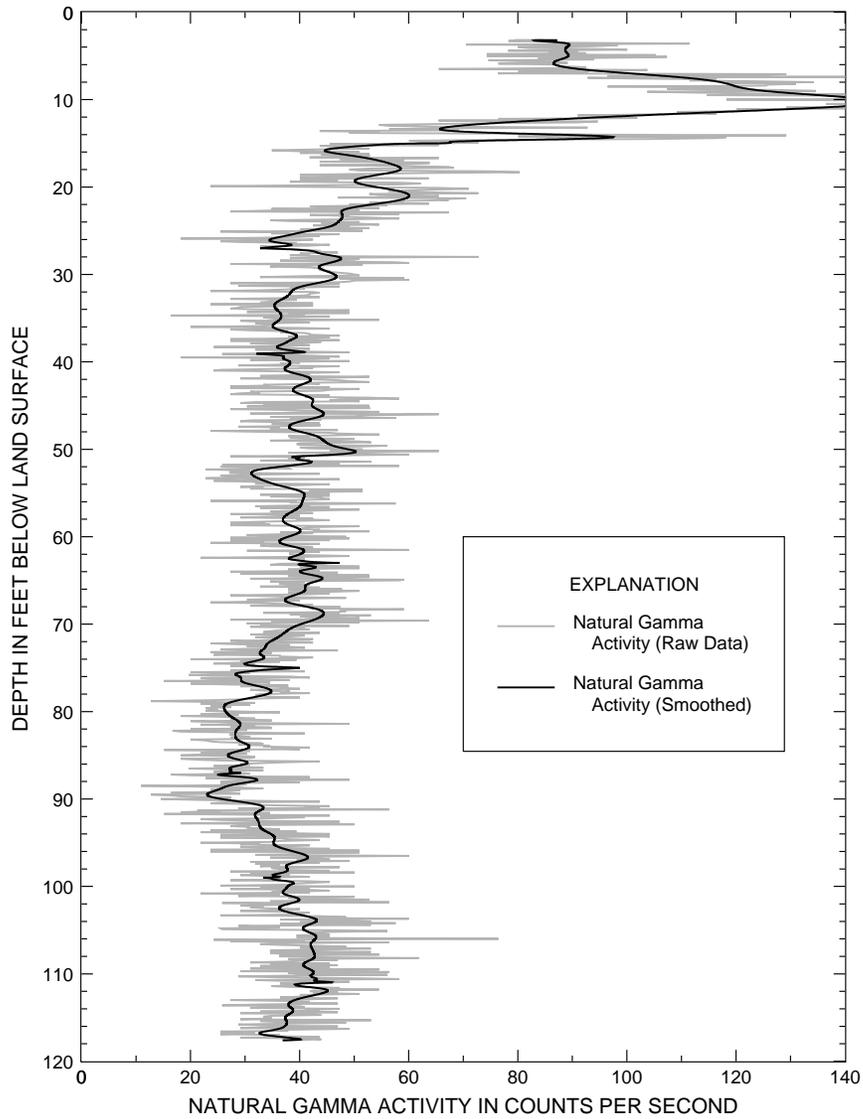
Borehole geophysical logs of natural gamma activity, July 1994, and electrical conductivity in July 1994 and May 1998, in monitoring well **TW-2** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
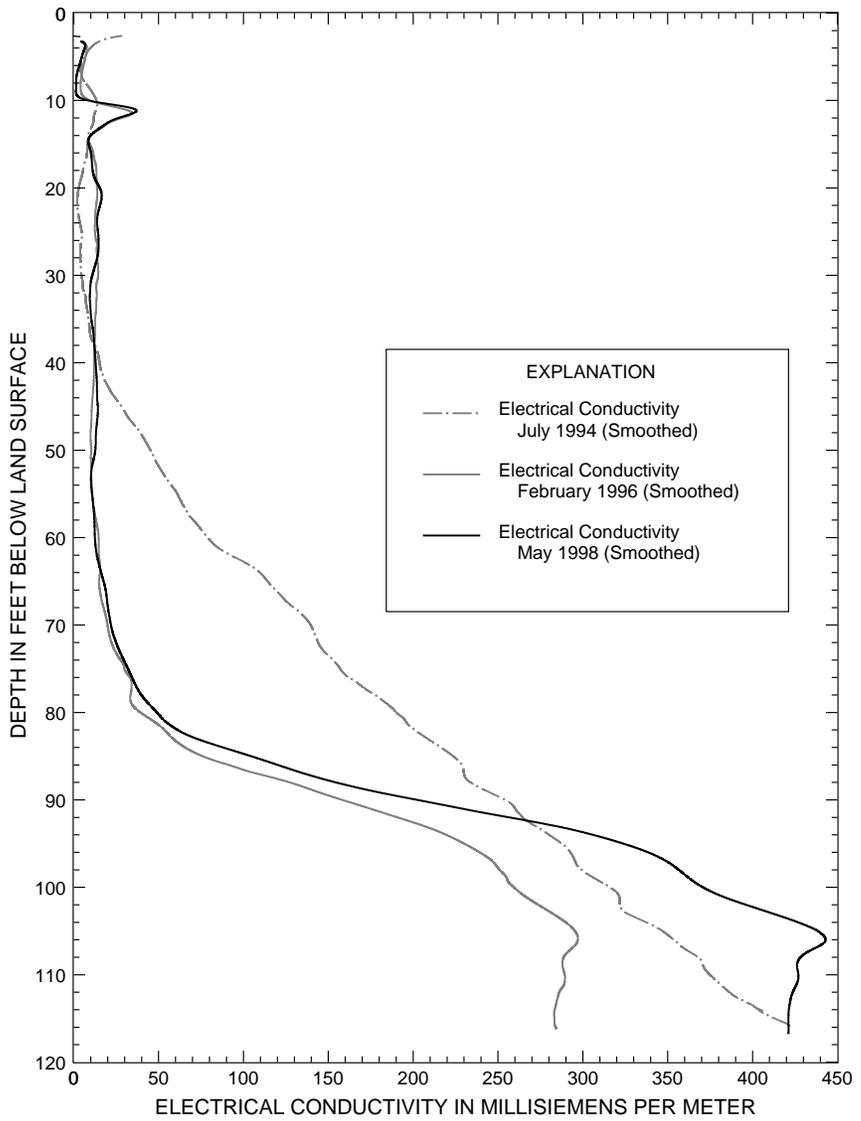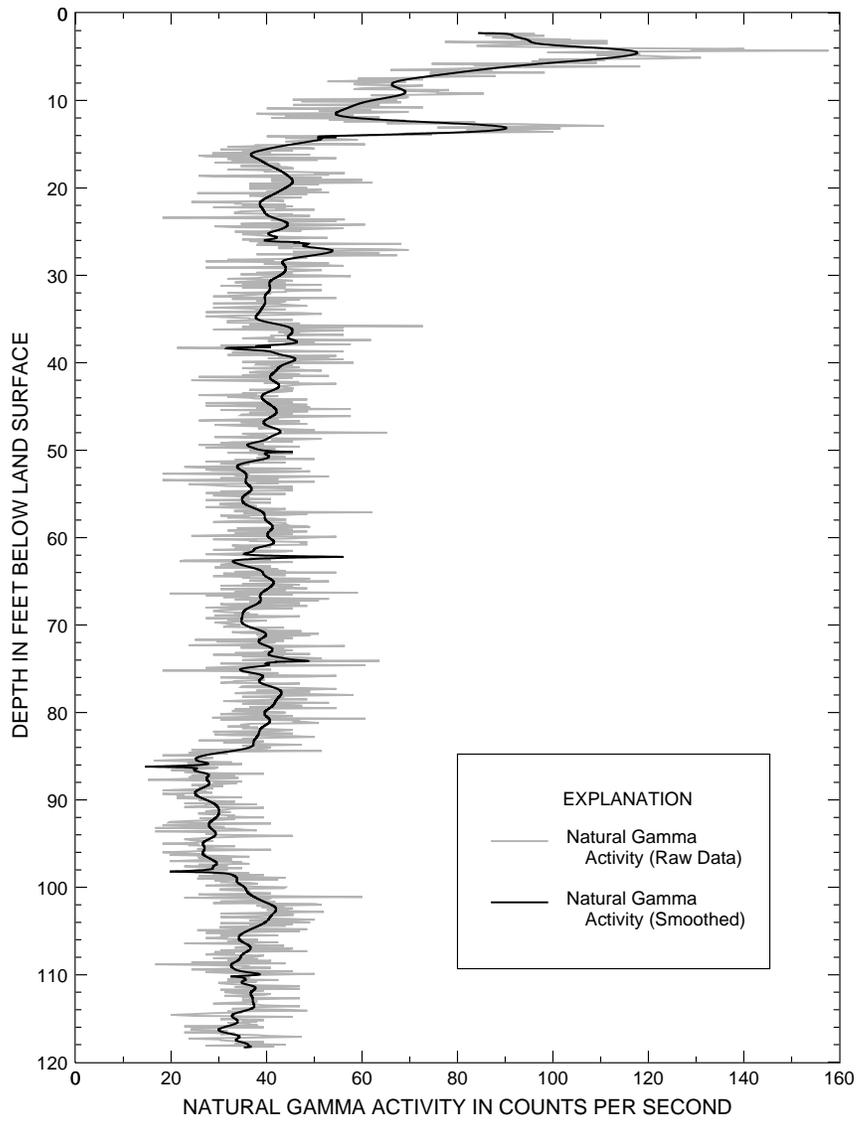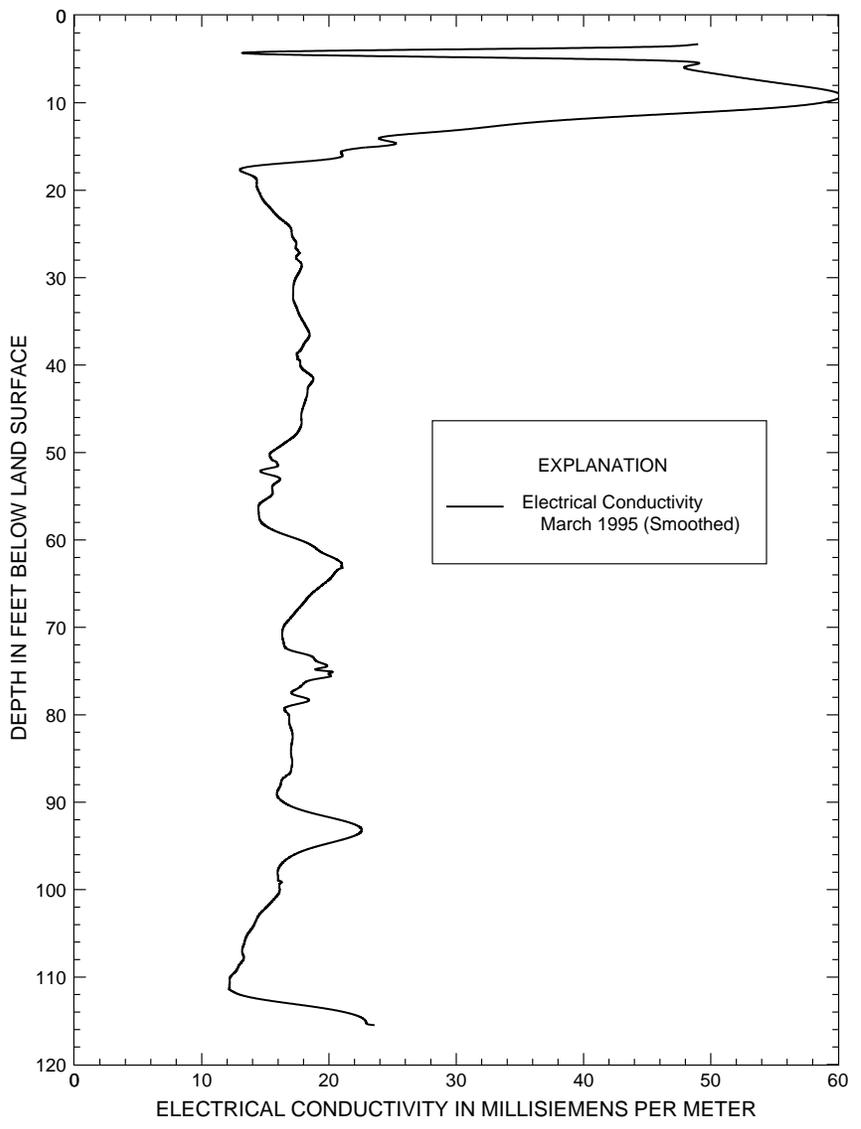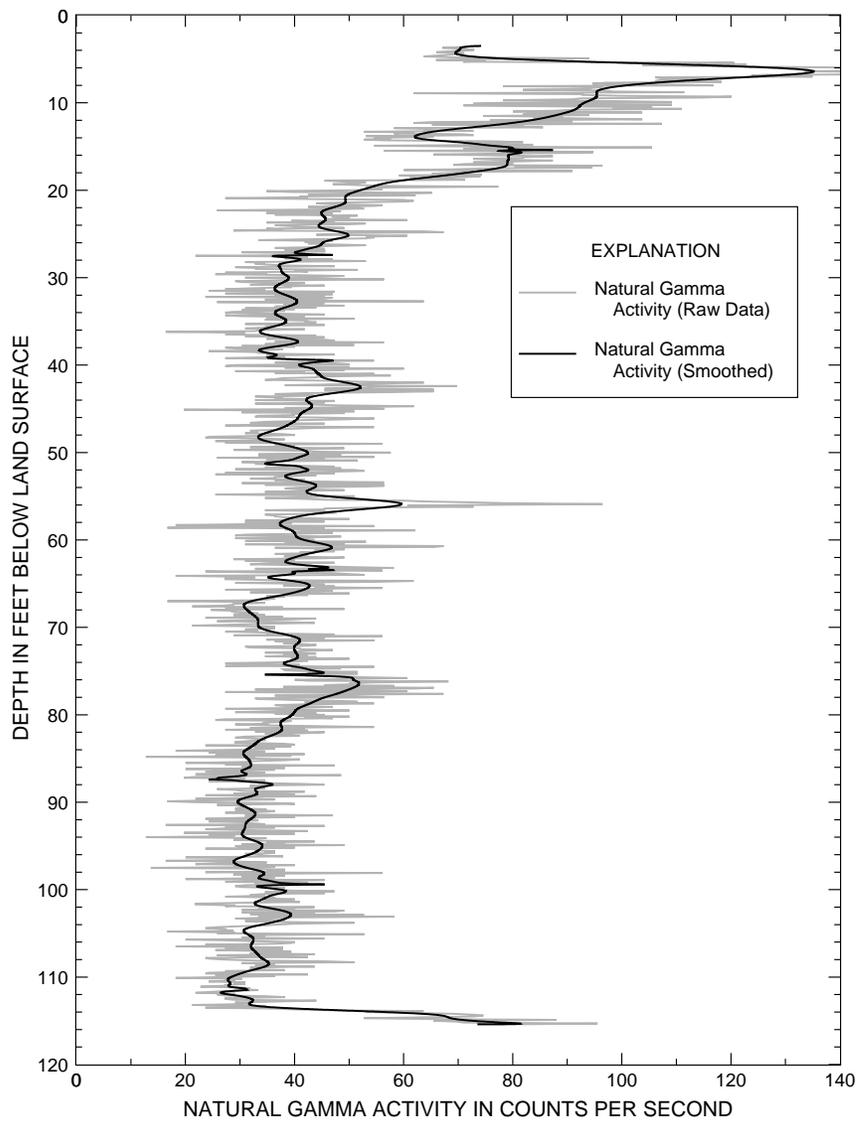
Borehole geophysical logs of natural gamma activity, July 1994, and electrical conductivity, July 1994, February 1996, and May 1998, in monitoring well **TW-94E** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
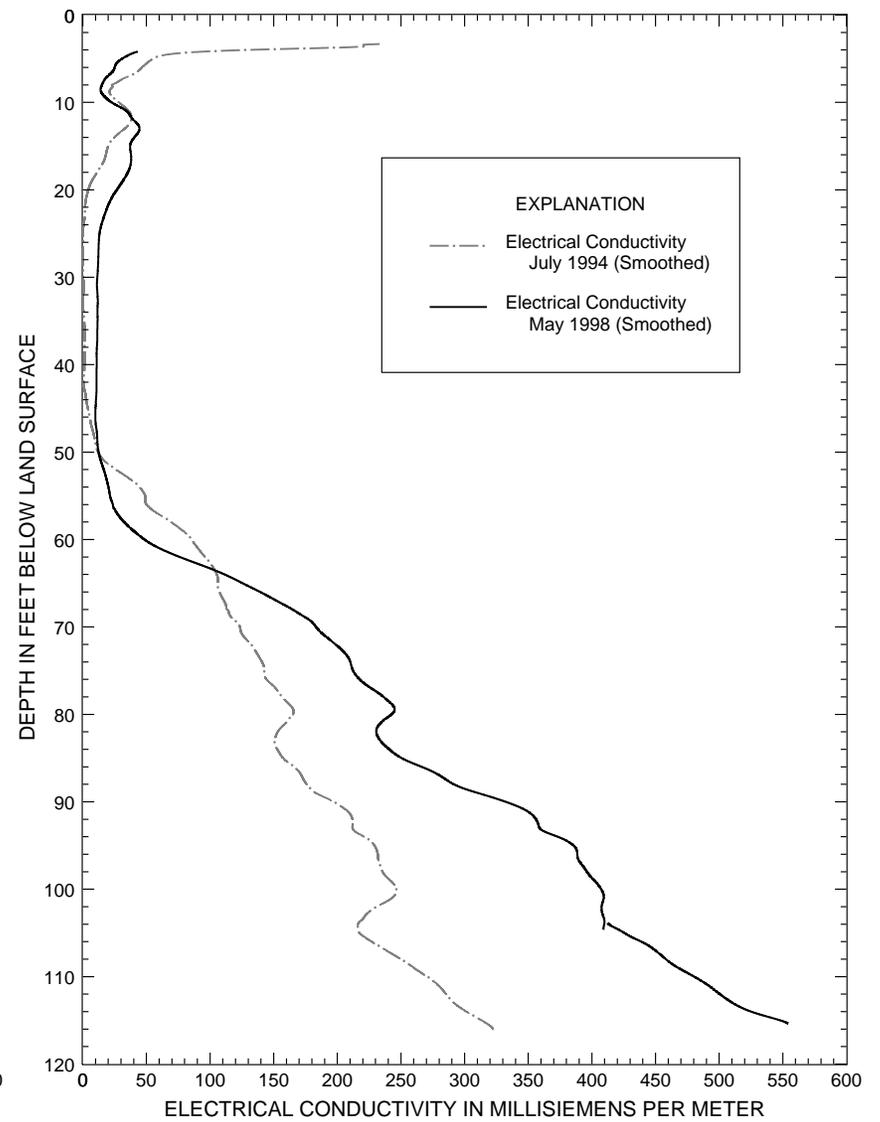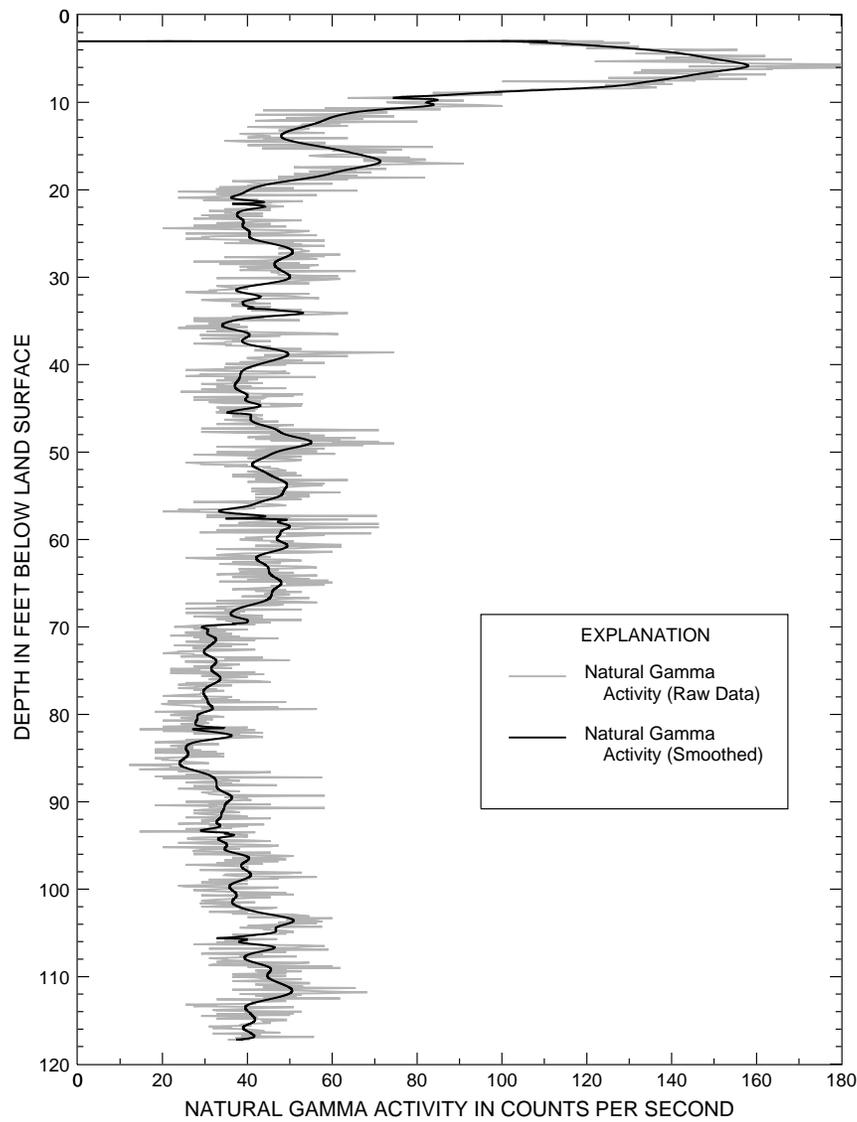
Borehole geophysical logs of natural gamma activity, July 1994, and electrical conductivity, July 1994 and May 1998, in monitoring well **MW-3** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
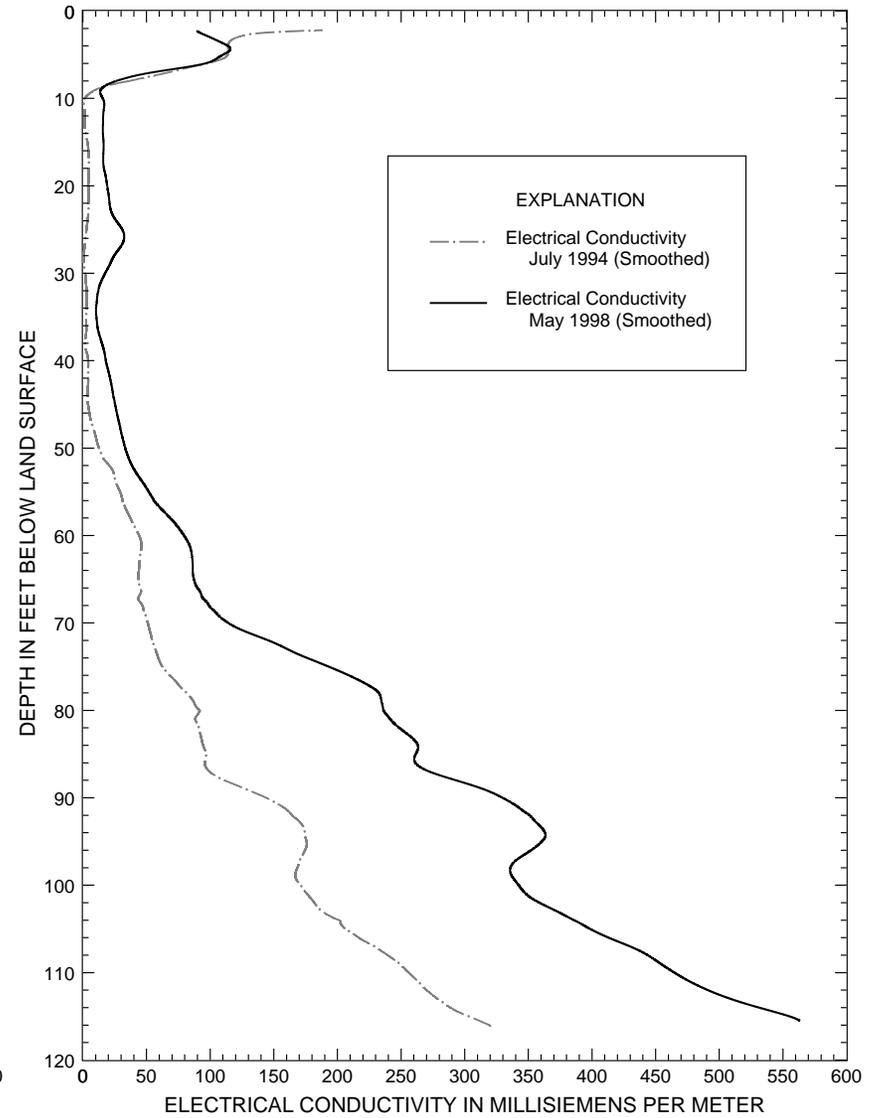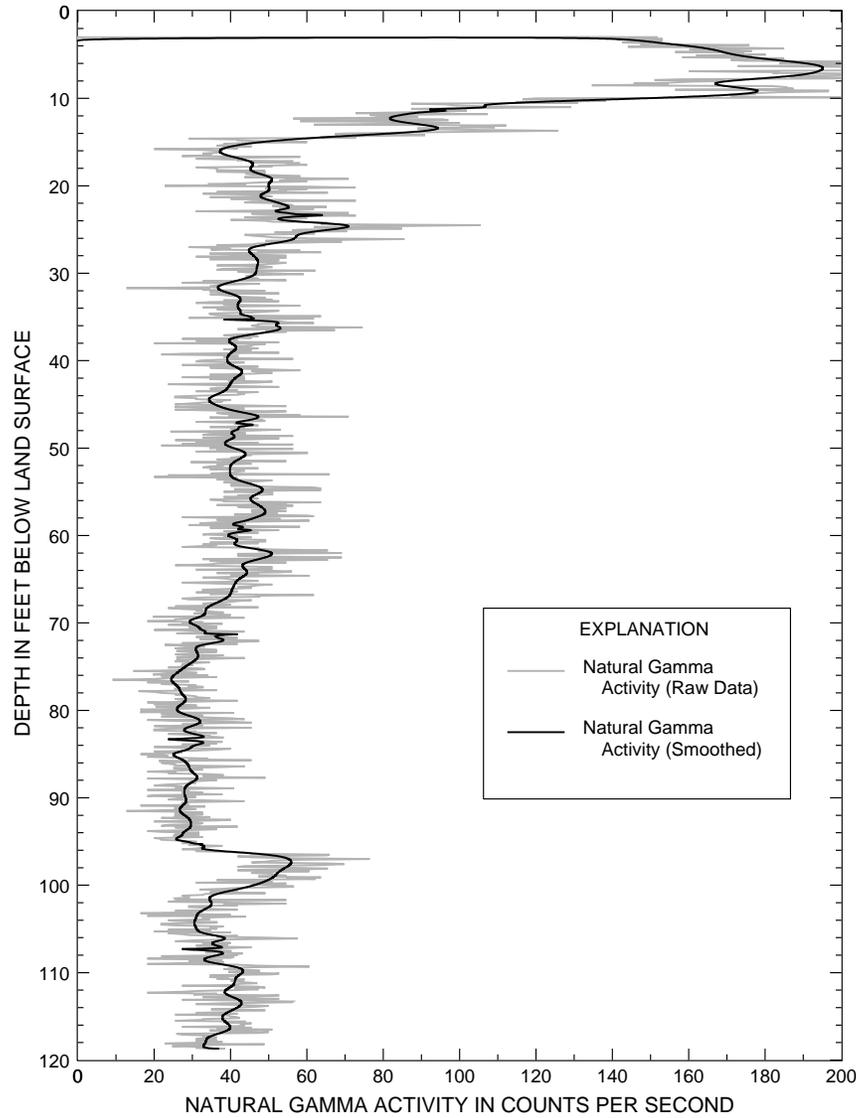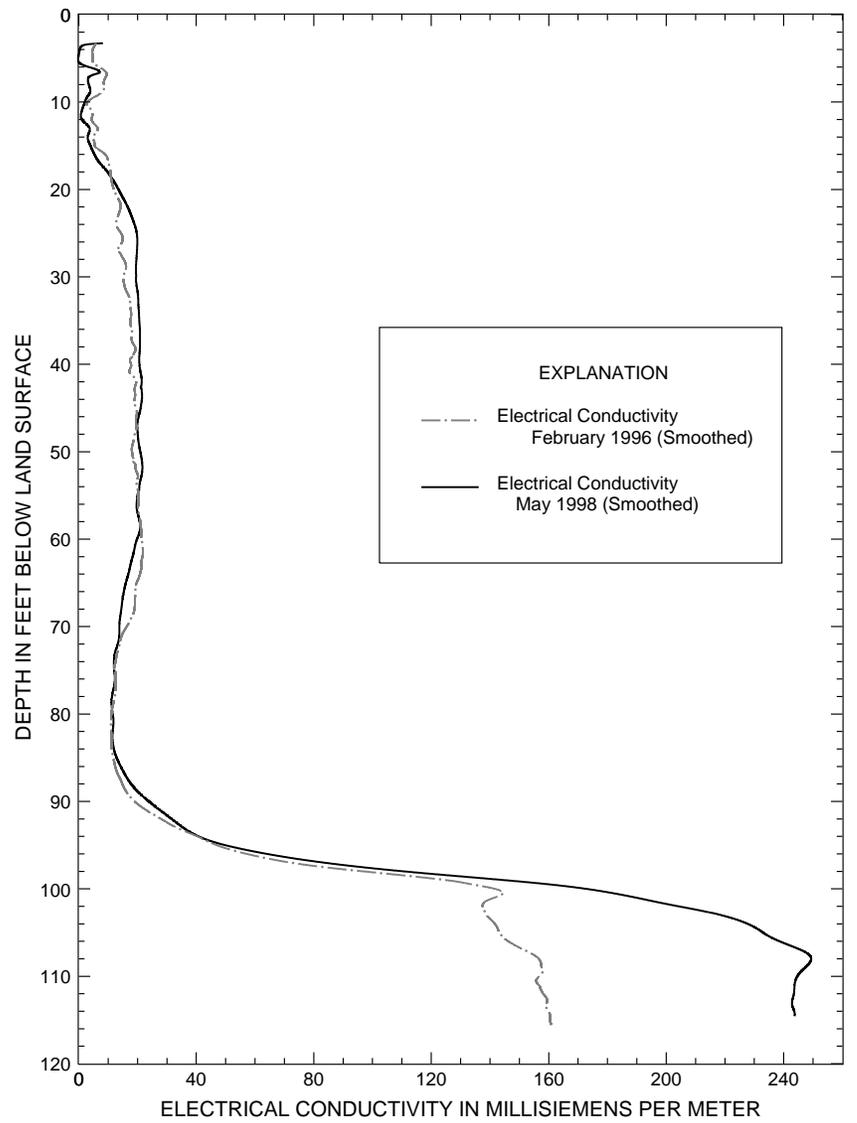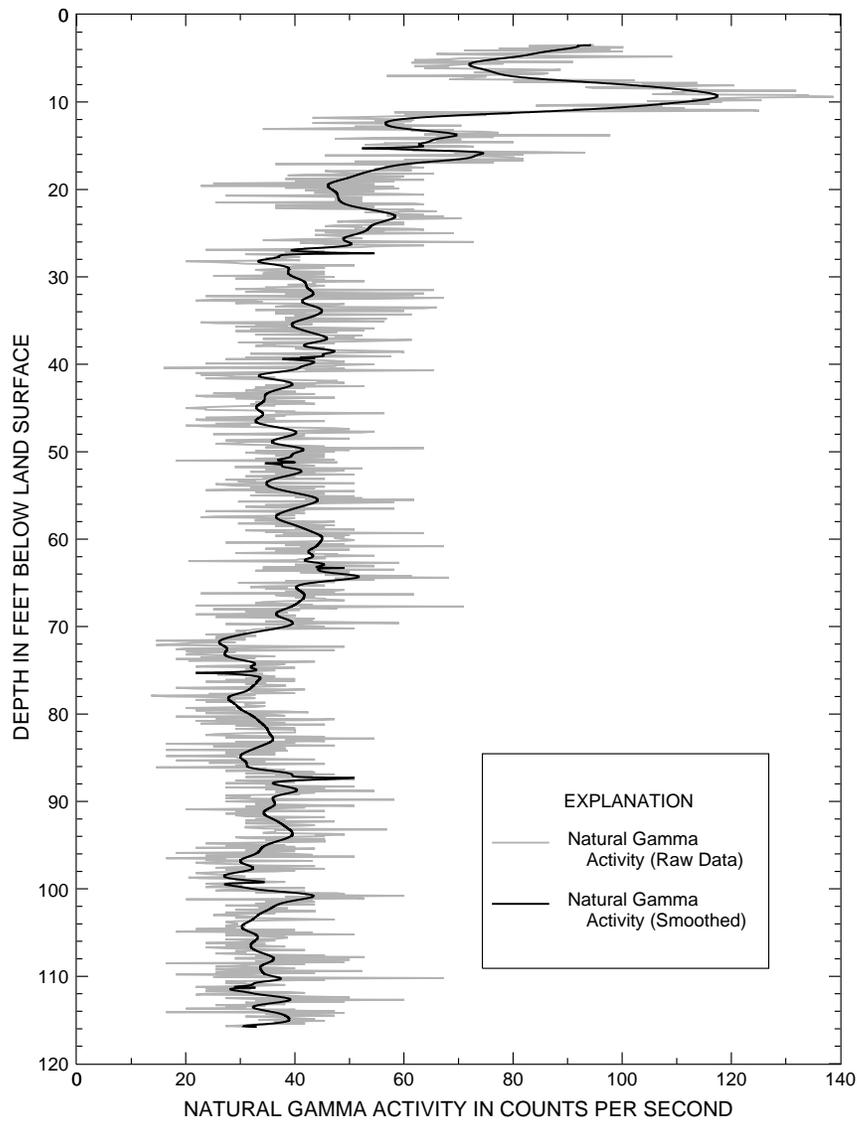
Borehole geophysical logs of natural gamma activity, July 1994, and electrical conductivity, July 1994 and May 1998, in monitoring well **MW-4** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
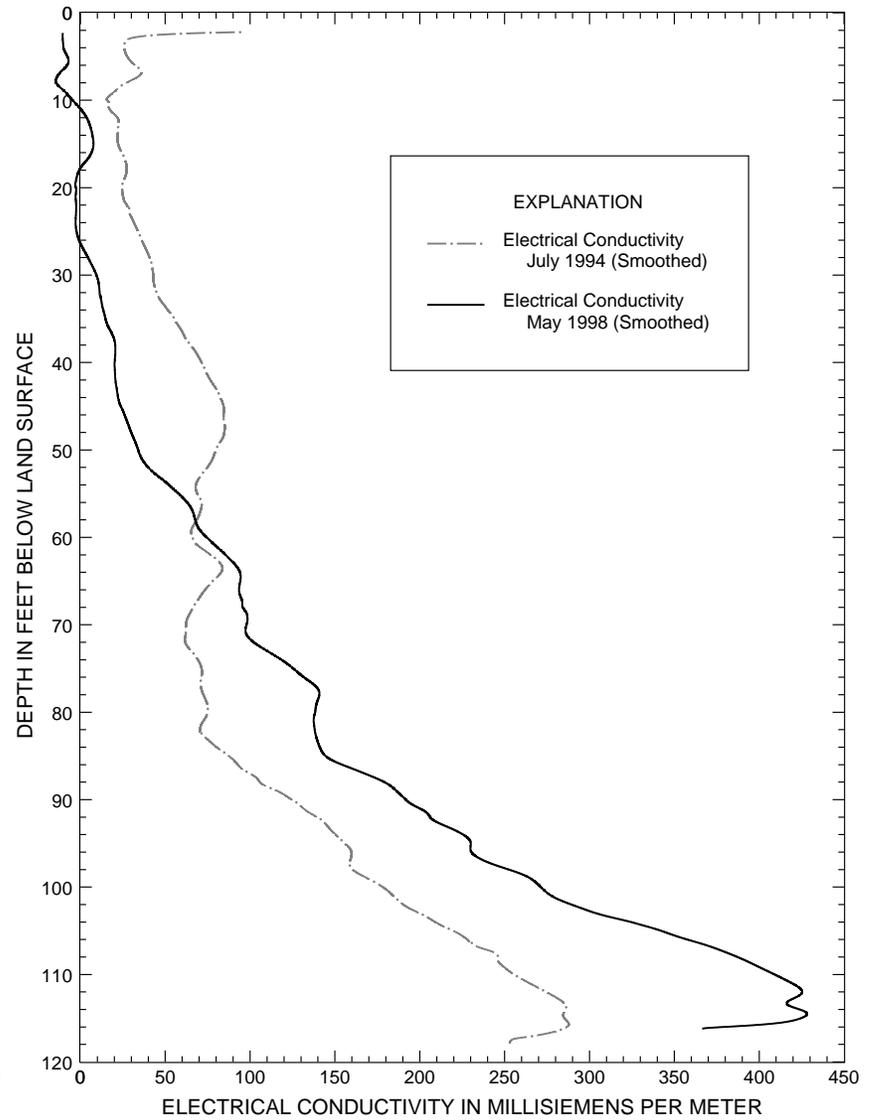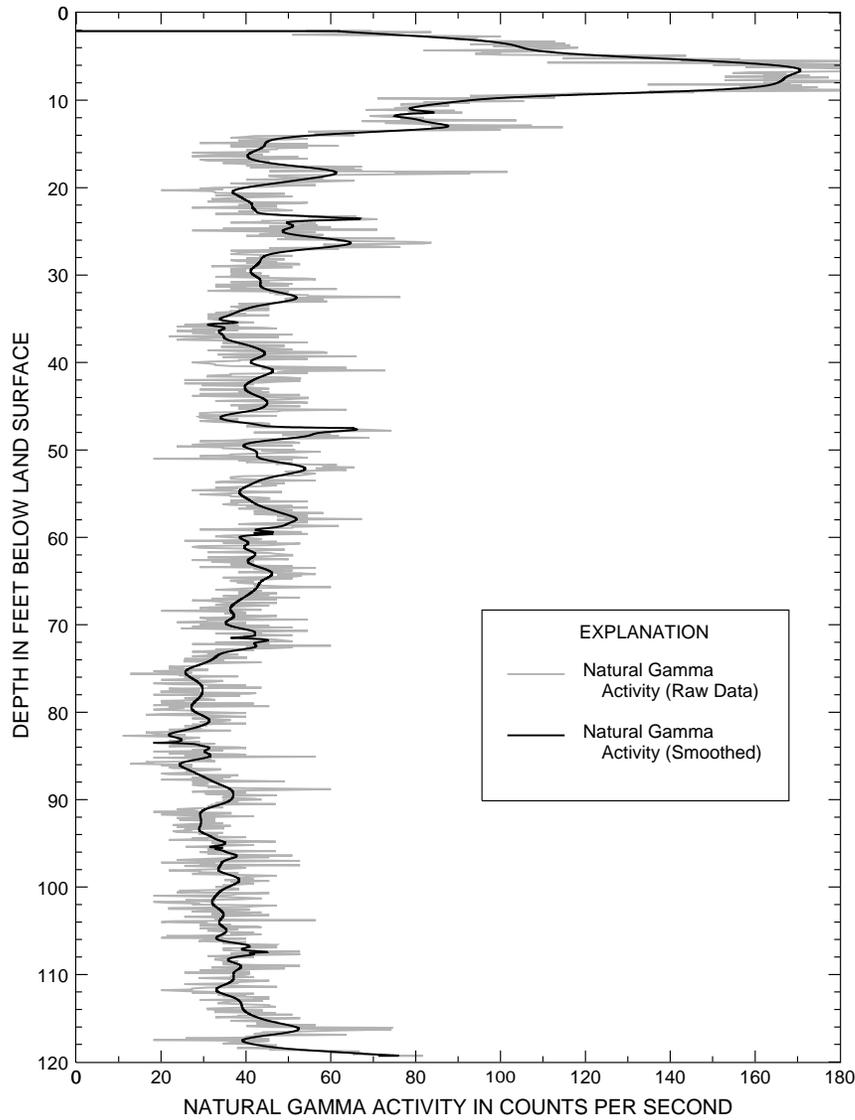
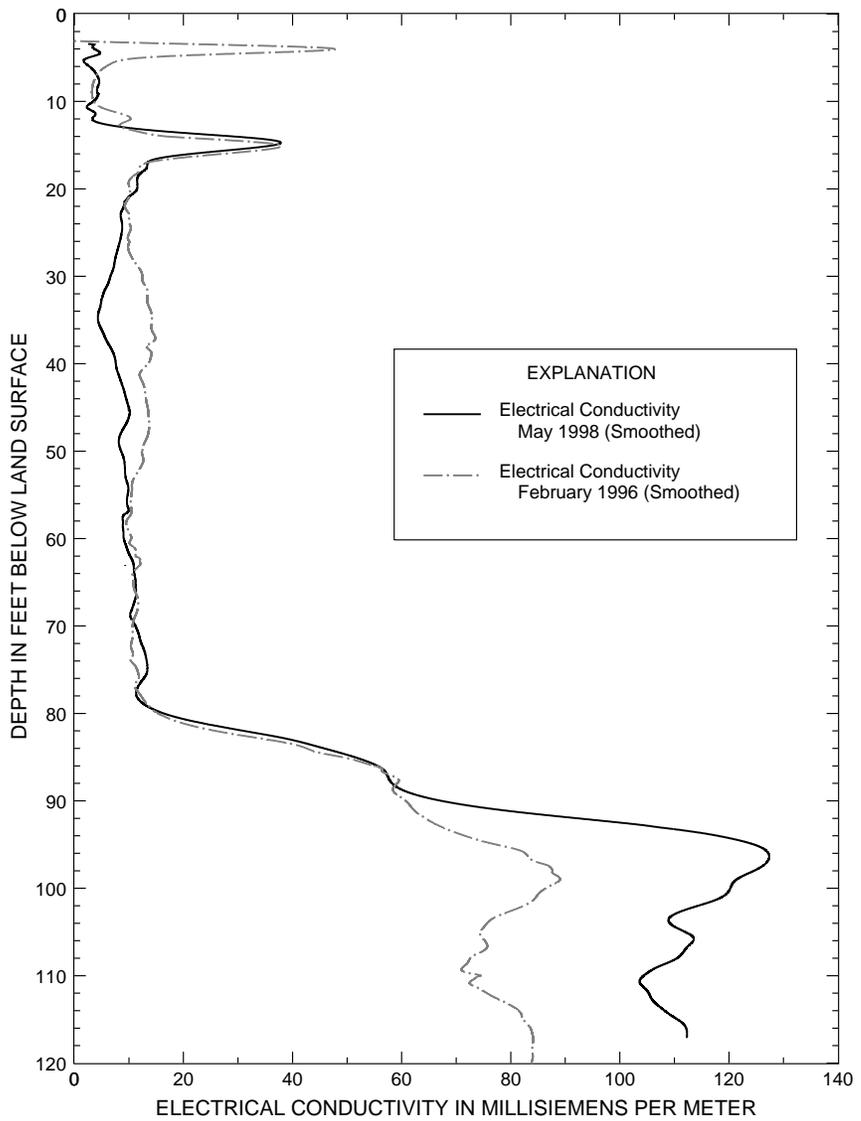Borehole geophysical logs of natural gamma activity, July 1994, and electrical conductivity, July 1994 and May 1998, in monitoring well **MW-5** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
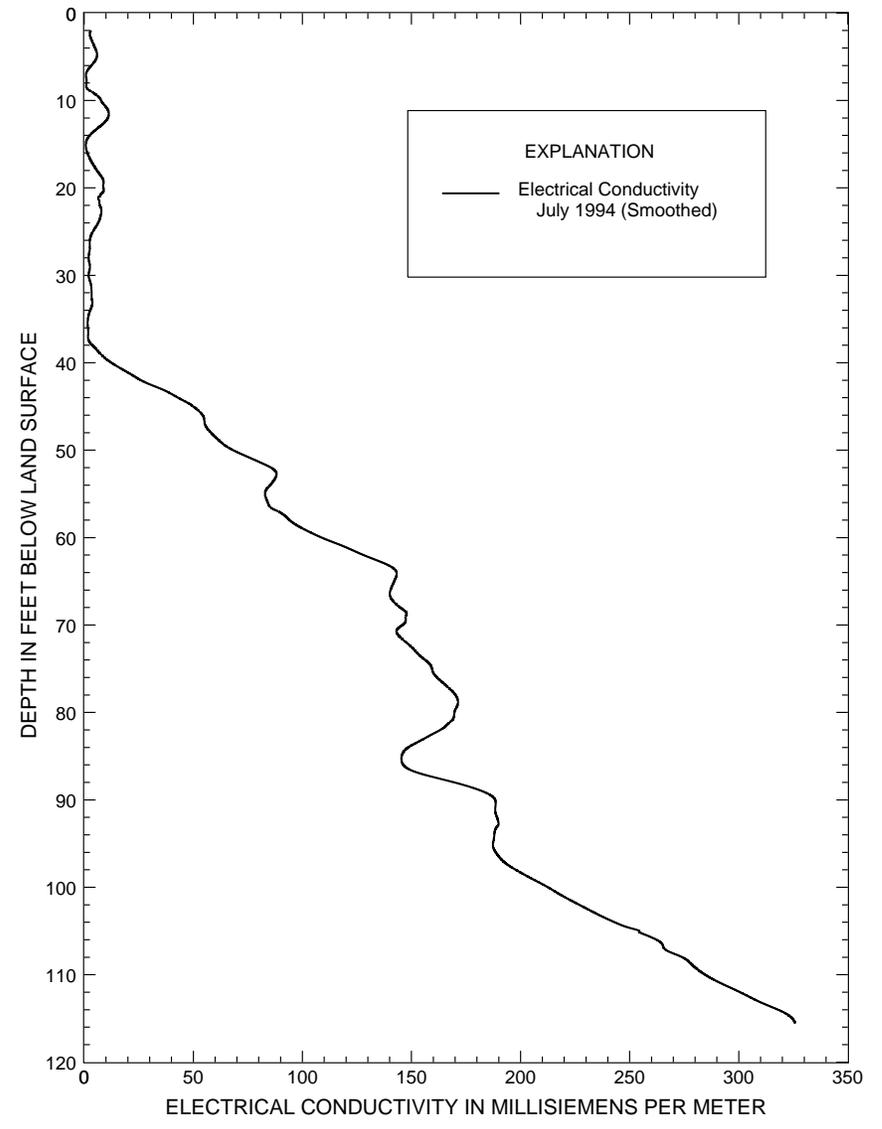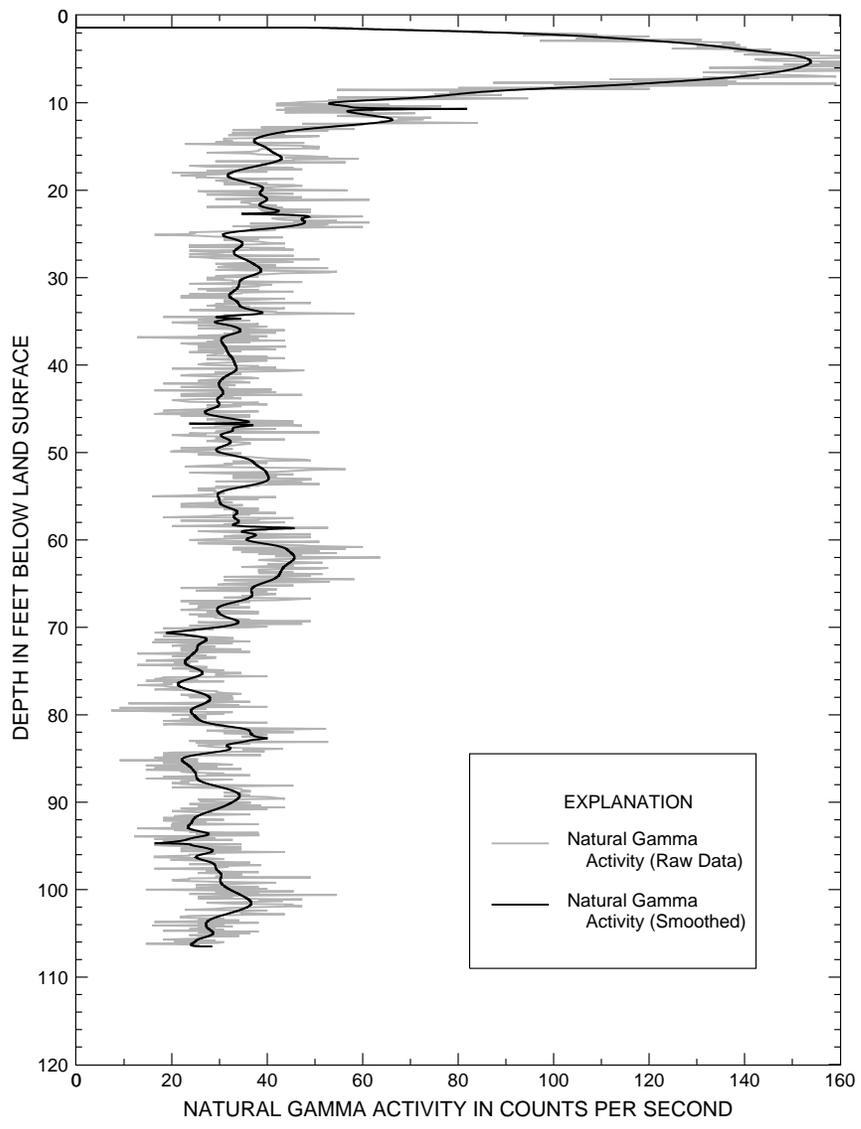
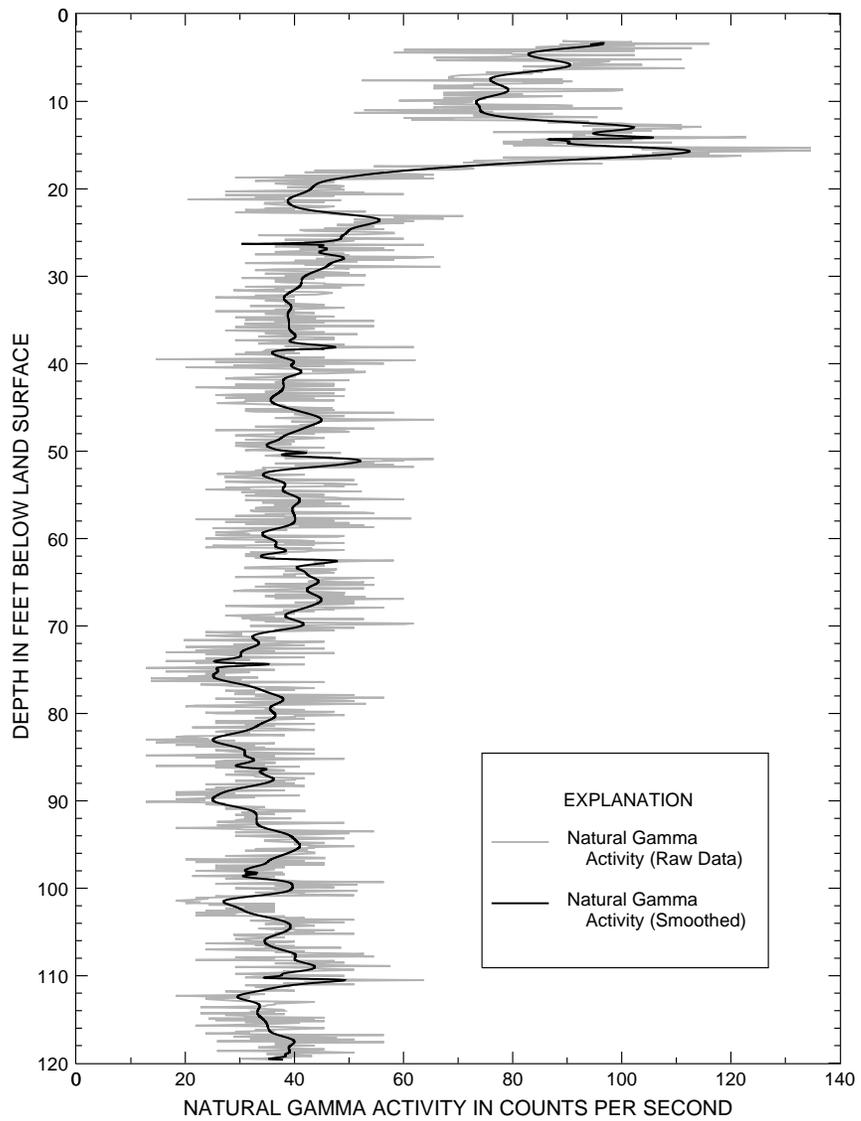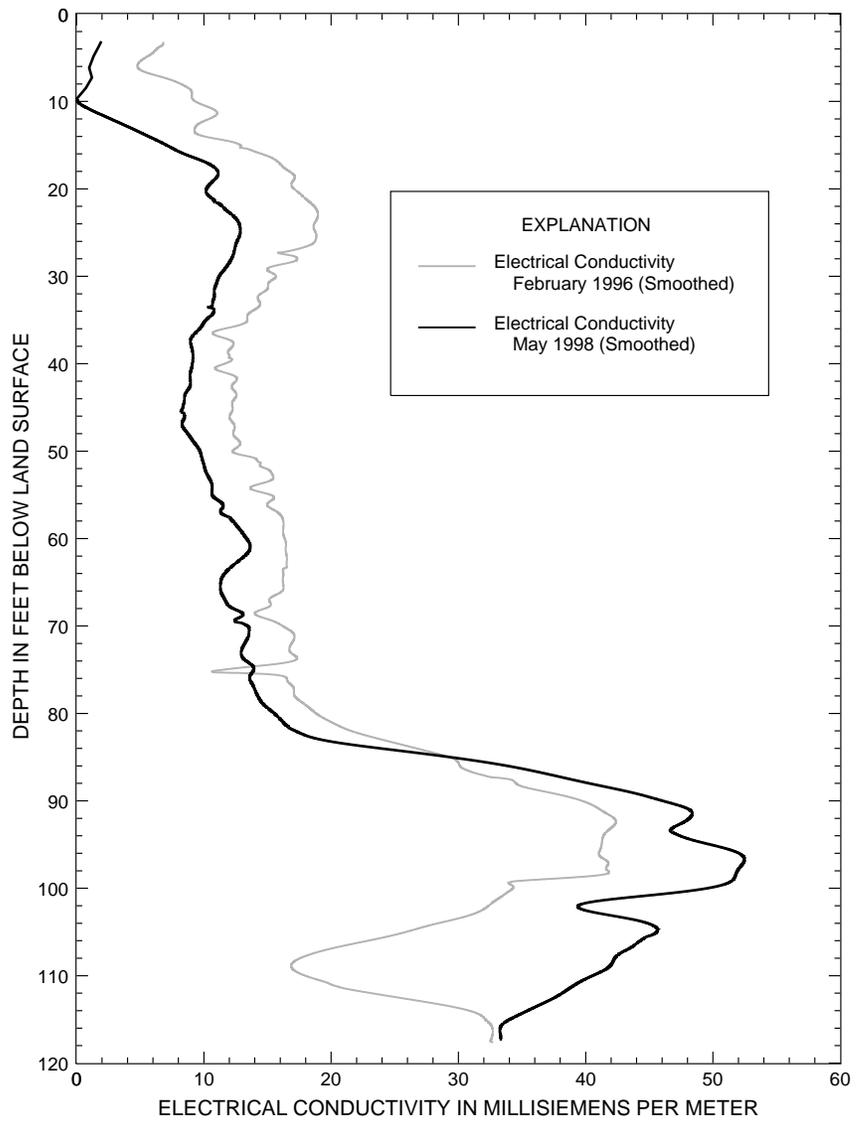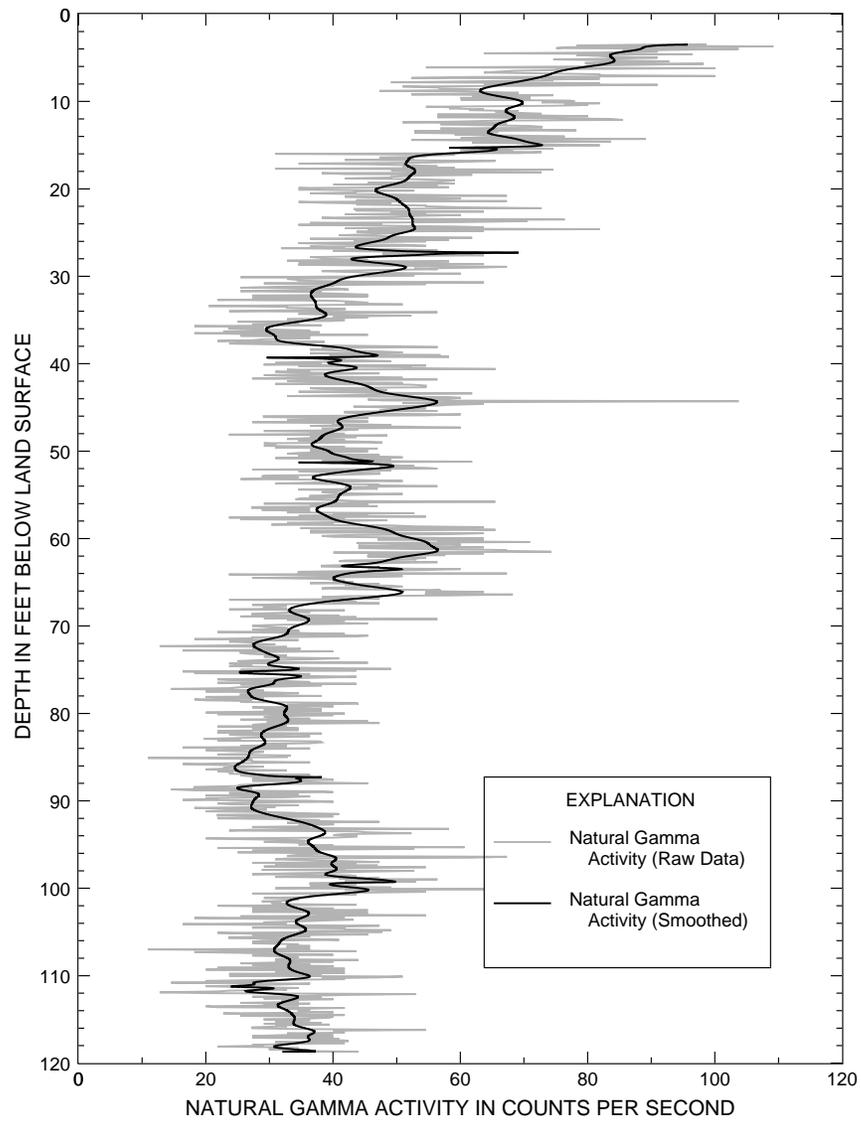Borehole geophysical logs of natural gamma activity and electrical conductivity, July 1994, in monitoring well **MW-6** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
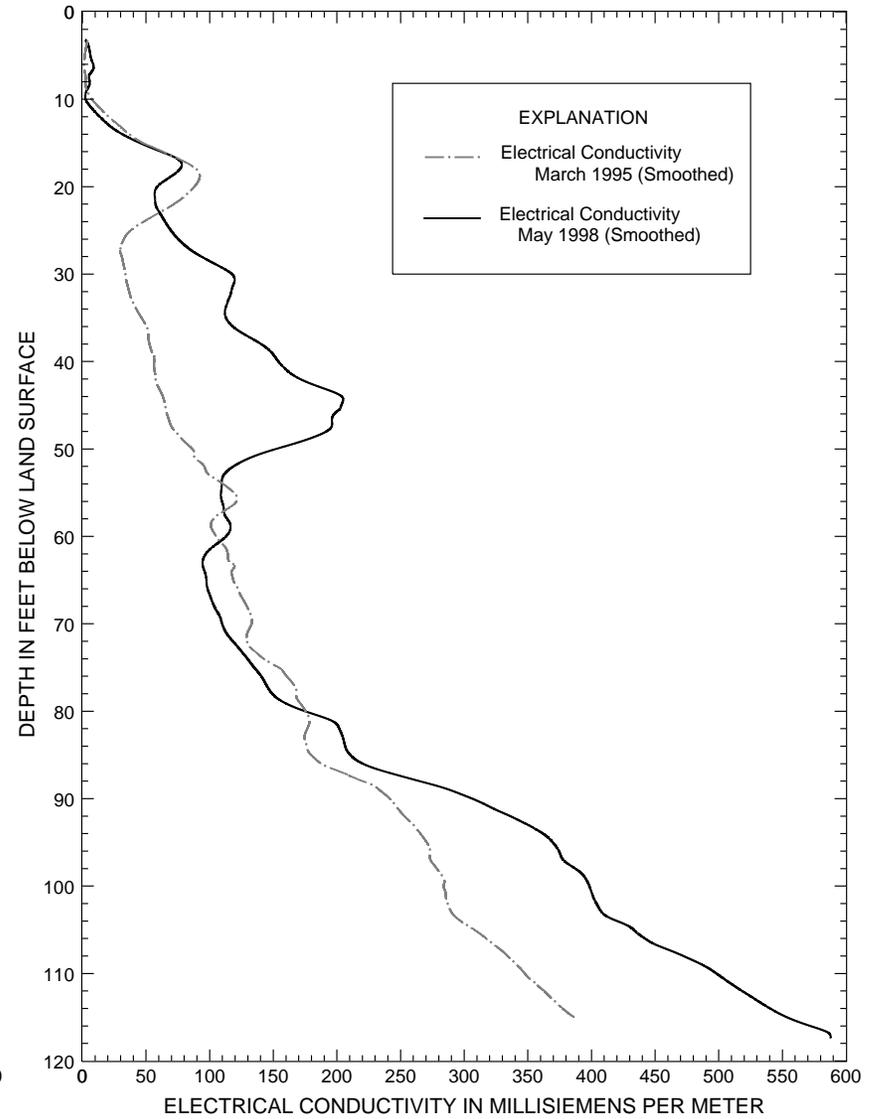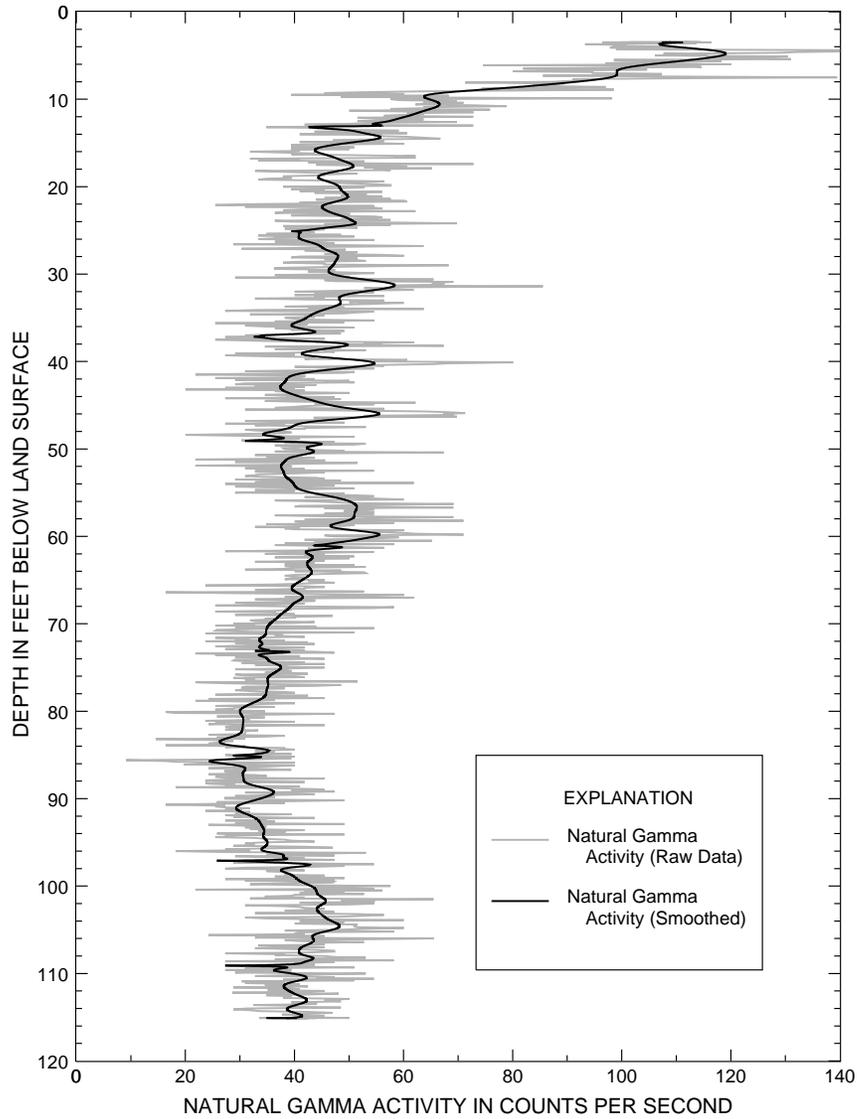
Borehole geophysical logs of natural gamma activity, March 1995, and electrical conductivity in March 1995 and May 1998, in monitoring well **MW-7** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
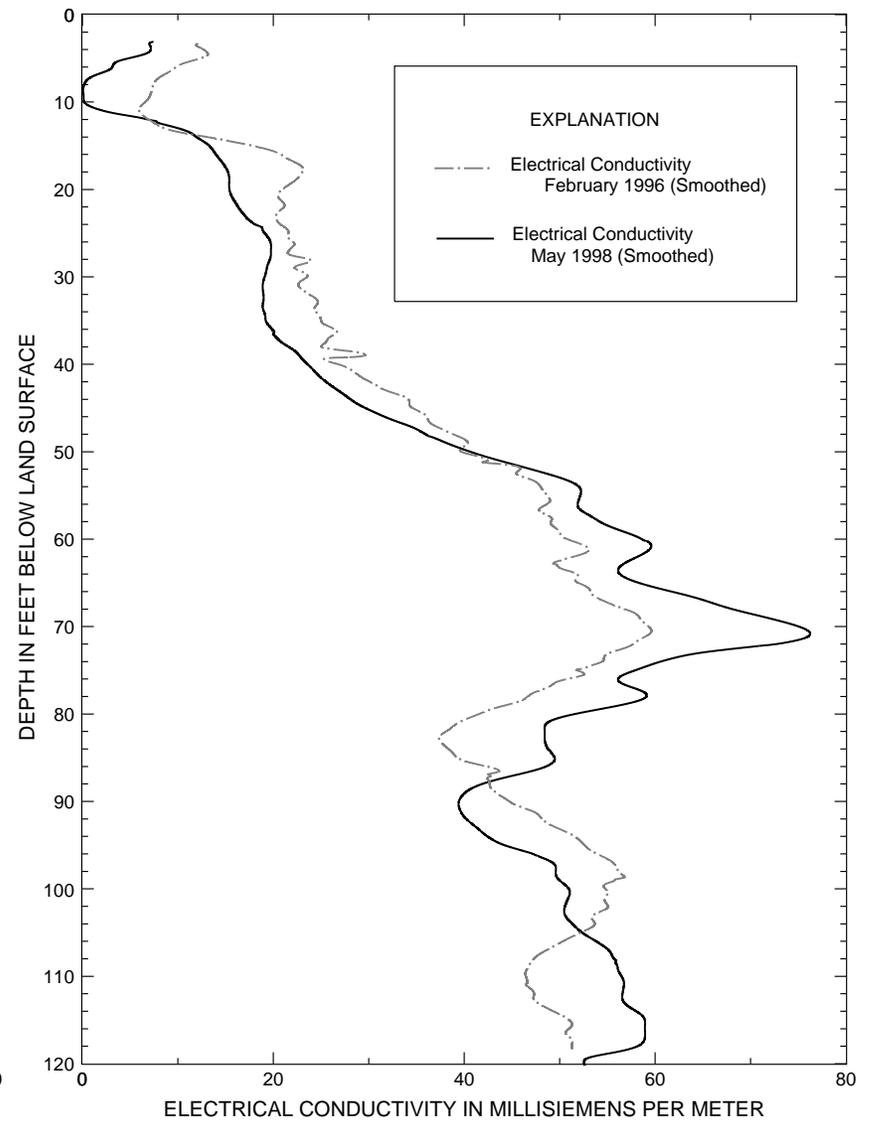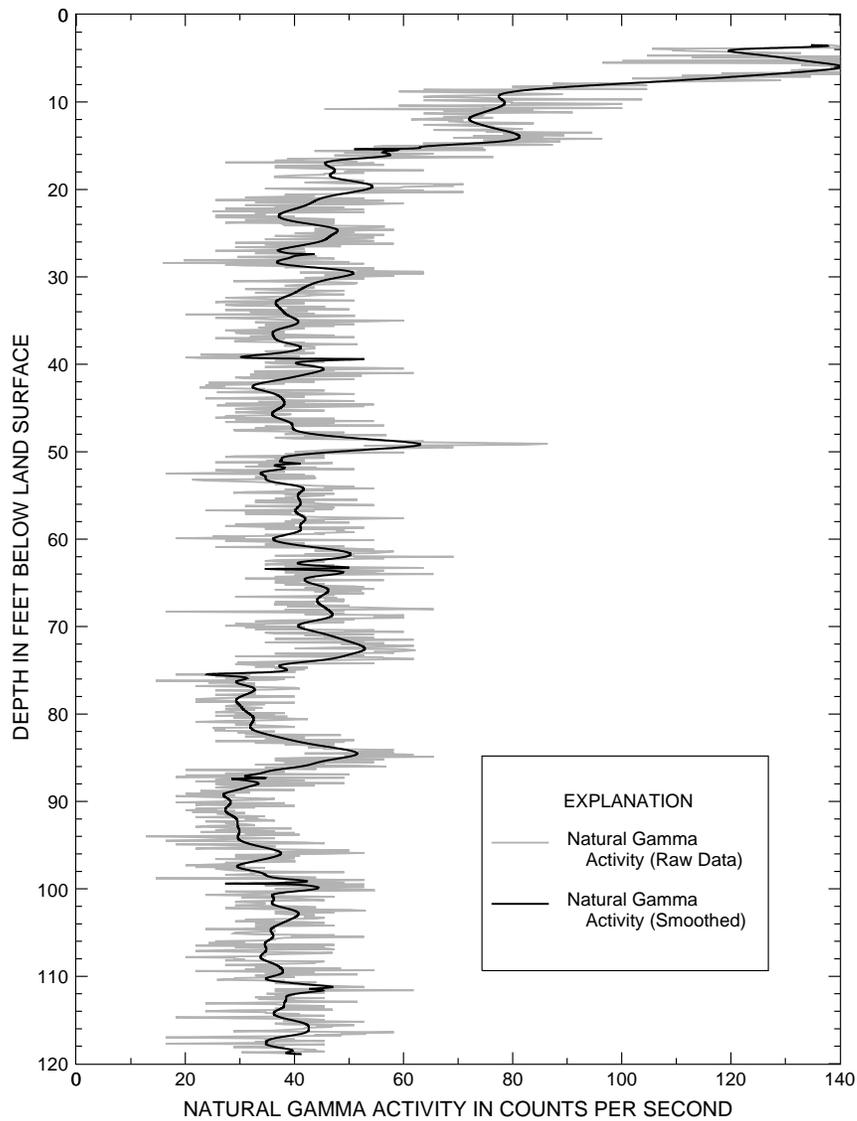
Borehole geophysical logs of natural gamma activity, February 1996, and electrical conductivity in February 1996 and May 1998, in monitoring well **MW-8** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
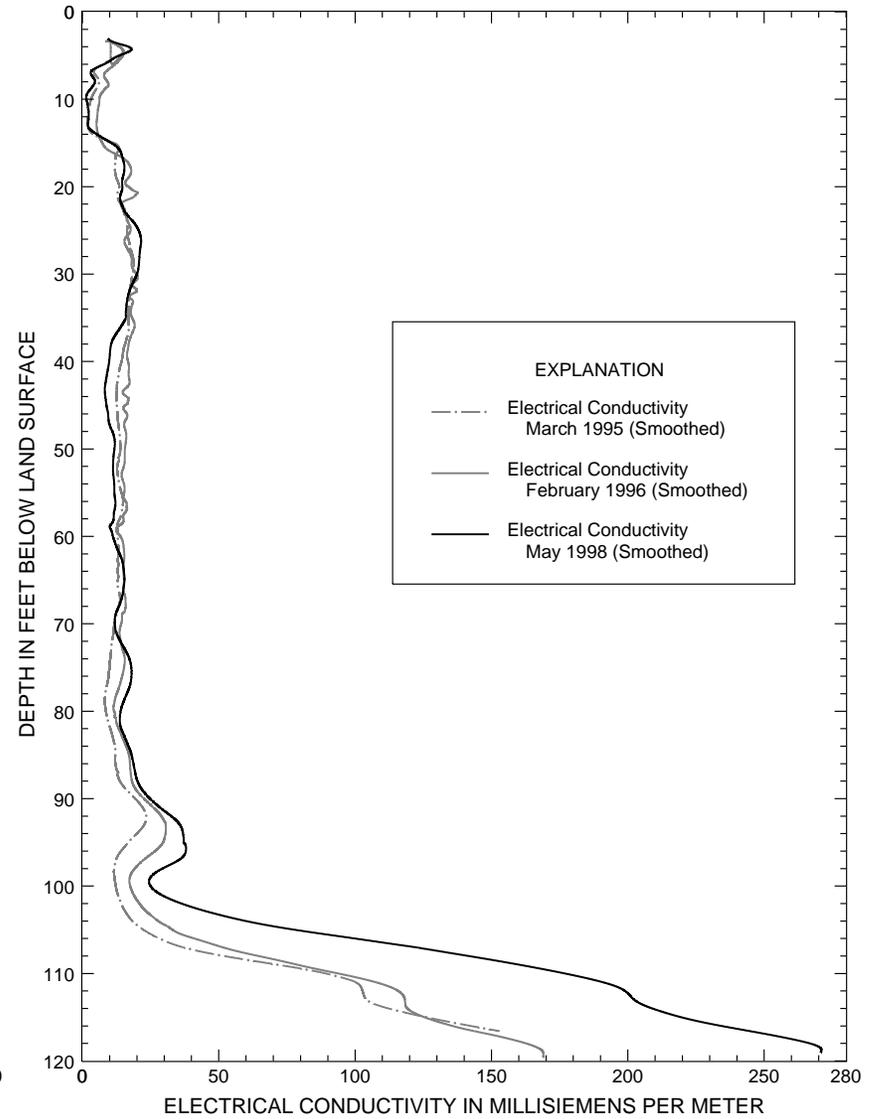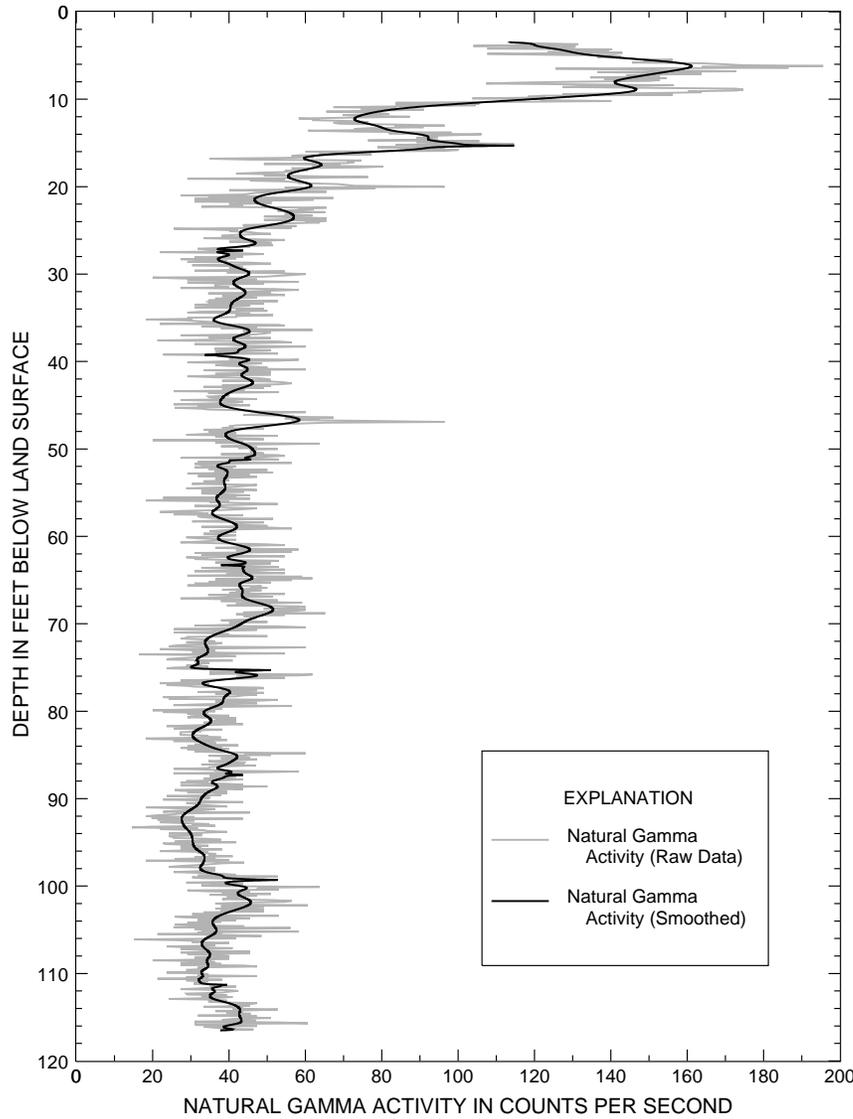
Borehole geophysical logs of natural gamma activity, March 1995, and electrical conductivity, March 1995, February 1996, and May 1998, in monitoring well **MW-9** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
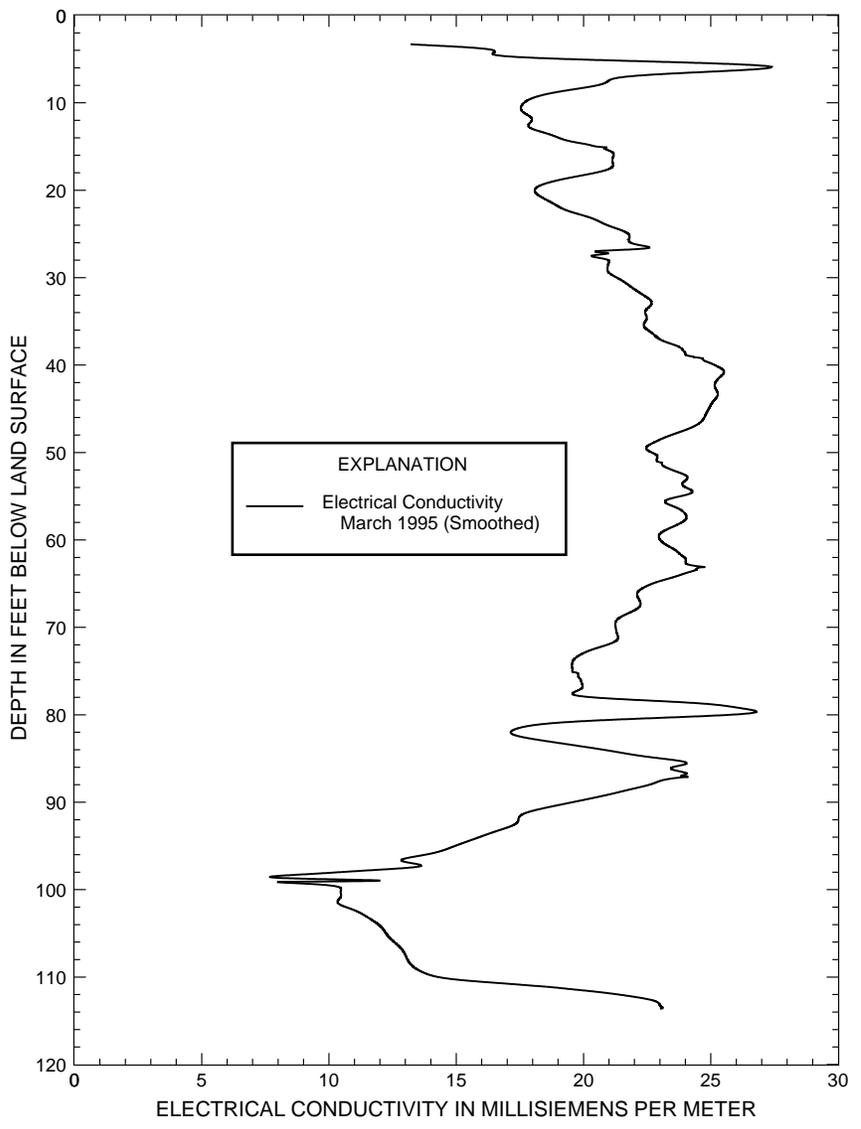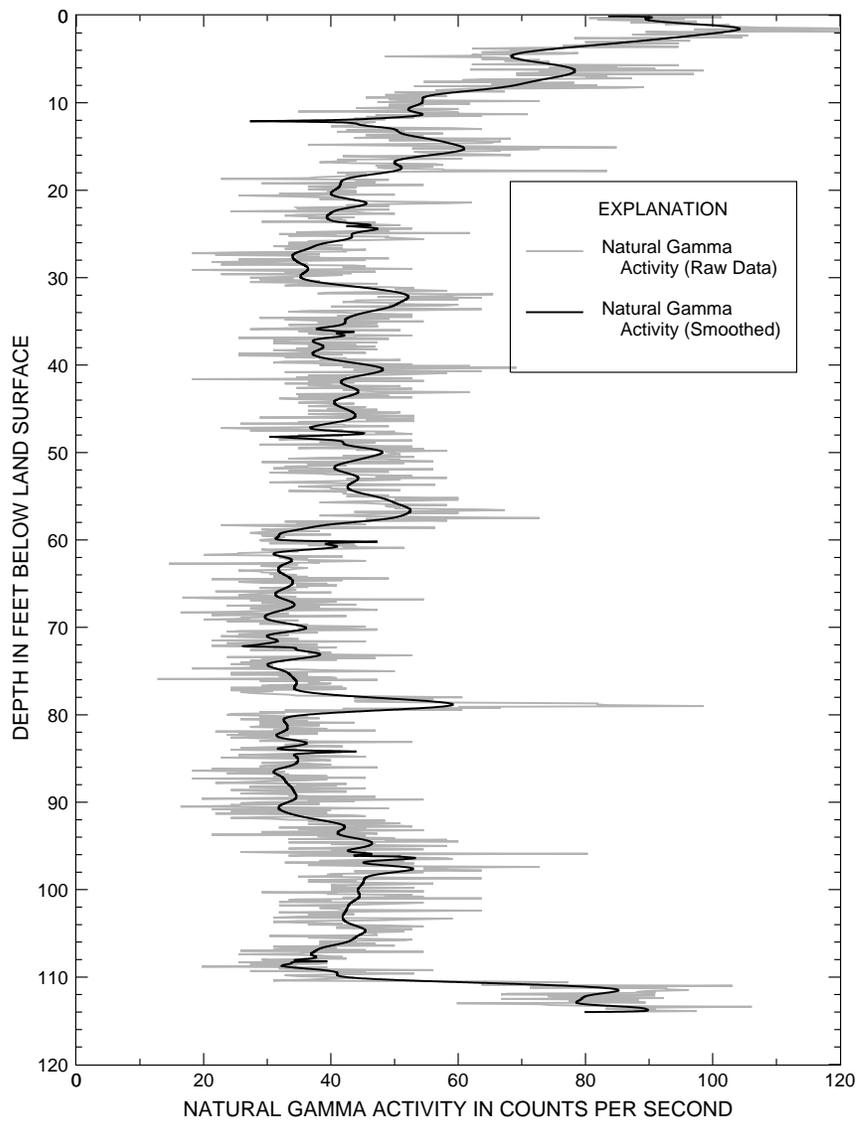
Borehole geophysical logs of natural gamma activity, May 1998, and electrical conductivity, March 1995, in monitoring well **MW-10D** in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Borehole geophysical logs of natural gamma activity and electrical conductivity, March 1995, in monitoring well **MW-11D** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
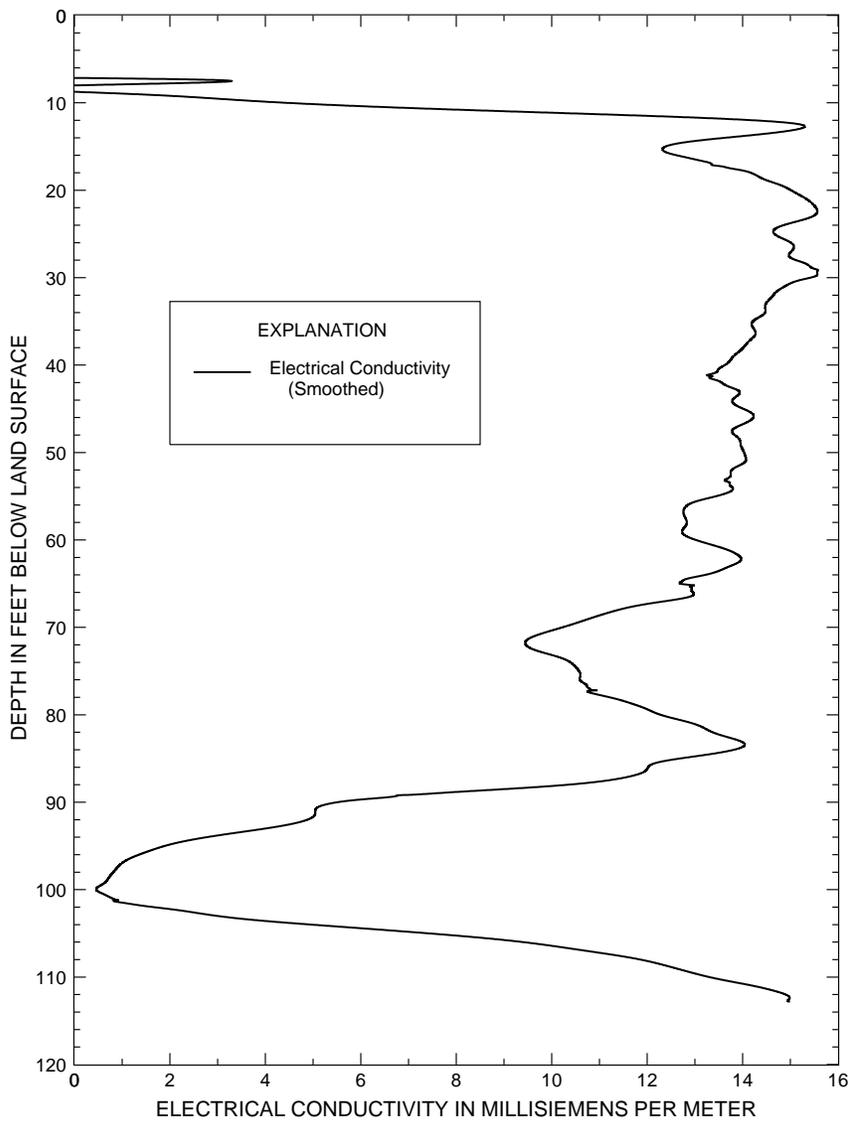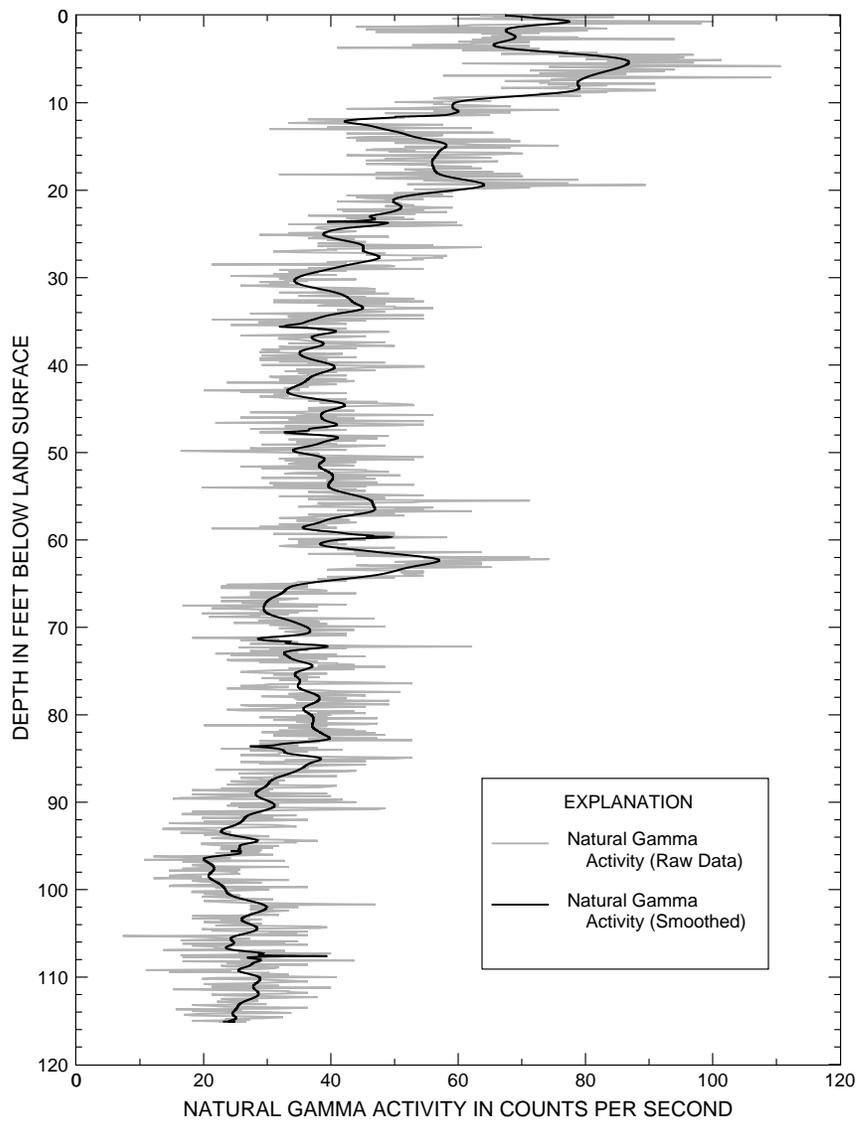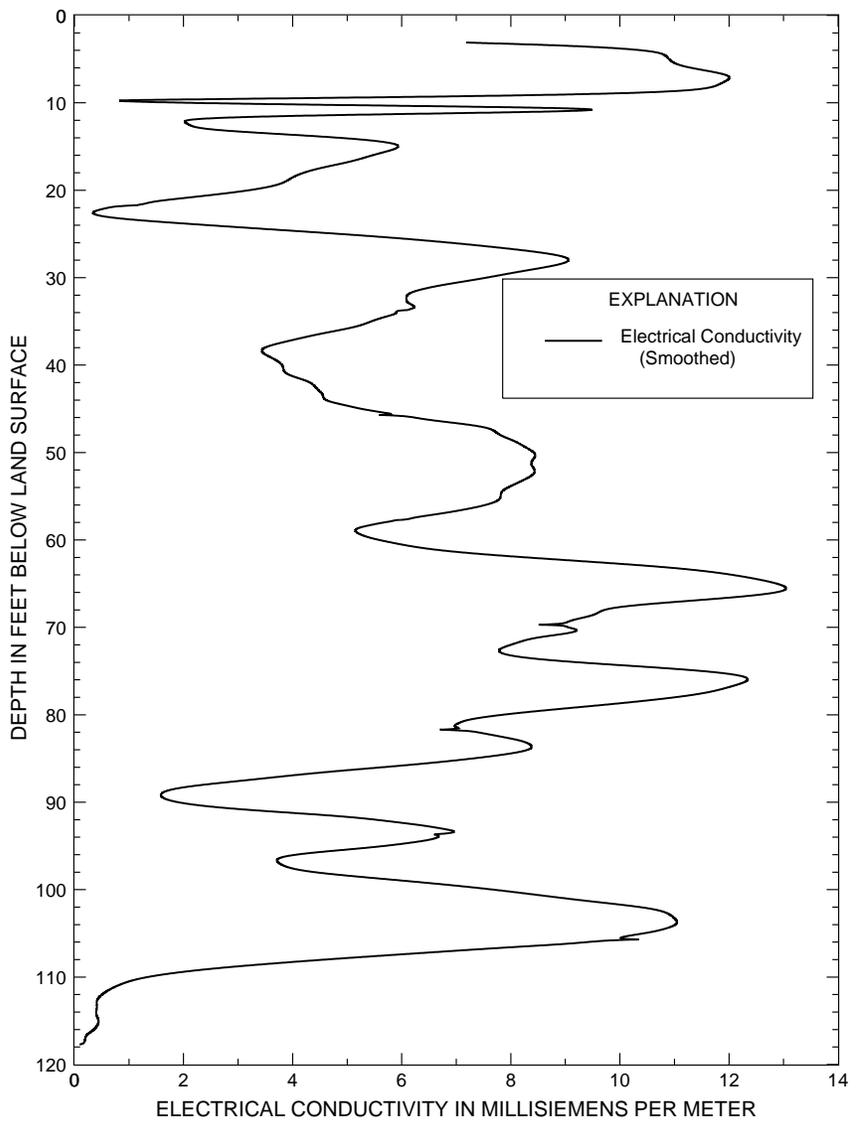
Borehole geophysical logs of natural gamma activity, February 1996, and electrical conductivity, February 1996 and May 1998, in monitoring well **MW-13** in the vicinity of the Porter County Airport, Valparaiso, Indiana.
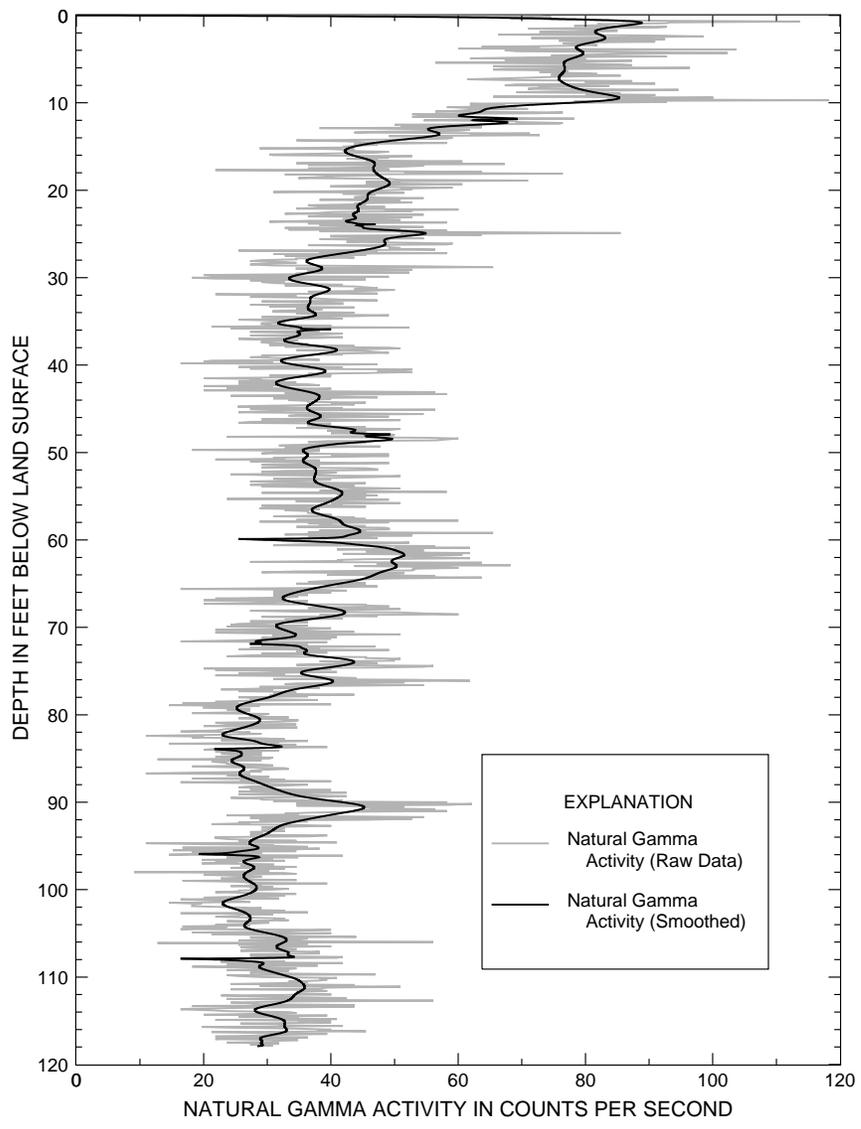
Borehole geophysical logs of natural gamma activity, February 1996, and electrical conductivity, February 1996 and May 1998, in monitoring well **MW-14** in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Borehole geophysical logs of natural gamma activity, February 1996, and electrical conductivity, February 1996 and May 1998, in monitoring well **MW-15D** in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Borehole geophysical logs of natural gamma activity and electrical conductivity in monitoring well **MW-16**, May 1998, in the vicinity of the Porter County Airport, Valparaiso, Indiana.

Borehole geophysical logs of natural gamma activity and electrical conductivity in monitoring well **MW-17,** May 1998, in the vicinity of the Porter County Airport, Valparaiso, Indiana.