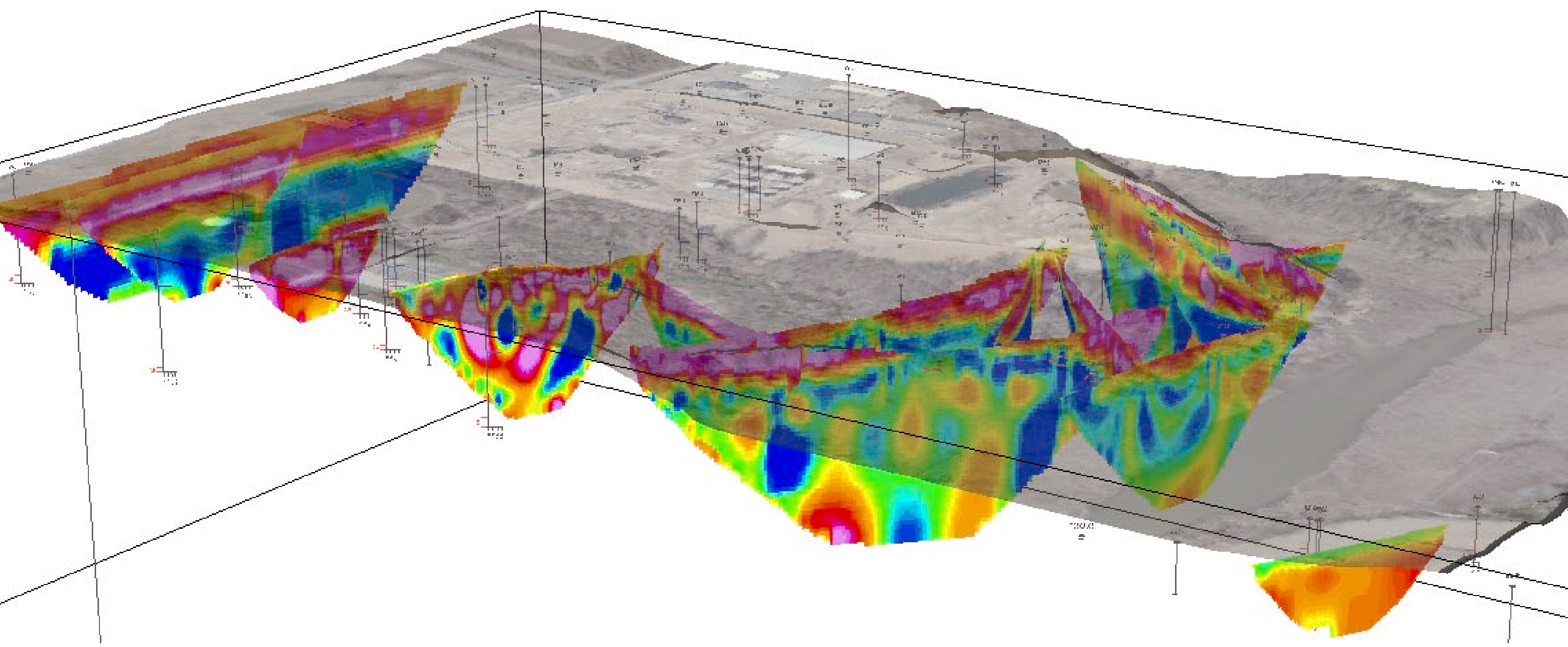
Prepared in cooperation with the U.S. Environmental Protection Agency

# Preliminary Investigation of Paleochannels and Groundwater Specific Conductance using Direct-Current Resistivity and Surface-Wave Seismic Geophysical Surveys at the Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware, 2008



Open-File Report 2010–1058

U.S. Department of the Interior
U.S. Geological Survey

**Cover.** Three-dimensional view of direct-current resistivity cross sections and wells, looking from the northeast to the southwest, Standard Chlorine of Delaware Inc., Superfund Site, Delaware City, Delaware.

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**U.S. Geological Survey**

**U.S. Department of the Interior**
KEN SALAZAR, Secretary

**U.S. Geological Survey**
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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Logistical support, data, and explanations of site history and hydrogeology from Hilary Thornton and Bernice Pasquini, U.S. Environmental Protection Agency (USEPA), Region III; Todd Keyser, Delaware Department of Natural Resources and Environmental Control (DNREC); and Chris Wolfe, HydroGeoLogic, Inc., were essential in the planning of this investigation and the analysis of the results of these surveys. Data collection would not have been possible without field assistance from Todd Keyser, John Cargill, John Barndt, and Doug Rambo, all of DNREC, and Jessica Teunis, Noel Stroik, Jeffrey Raffensperger, Luke Myers, and Brandon Fleming, all of the U.S. Geological Survey (USGS) MD-DE-DC Water Science Center. Equipment and technical advice provided by John Lane and Carole Johnson of the USGS Branch of Geophysics, and Wade Kress and Andrew Teeple of the USGS West Texas Program Office, made high-quality data collection possible. Site visits, sharing of results, and discussions of regional and neighboring site geology with Thomas E. McKenna, Delaware Geological Survey, John Jengo, Suzanne Eckel, and Bryn Welker from MWH (engineering firm), and Stephen J. Zahniser from URS Corporation (engineering firm) helped the authors conceptualize the hydrogeologic system.

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# Conversion Factors, Datums, and Acronyms

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| meter (m) | 3.281 | foot (ft) |
| meter (m) | 1.094 | yard (yd) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Flow rate | |
| meter per second (m/s) | 3.281 | foot per second (ft/s) |

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

°F=(1.8×°C)+32

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

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Altitude, as used in this report, refers to distance above the vertical datum.

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

Resistivity is given in Ohm meters.

ACRONYMS USED IN REPORT

USEPA U.S. Environmental Protection Agency

USGS U.S. Geological Survey

DNAPL Dense Non-Aqueous Phase Liquid

SCD Standard Chlorine of Delaware, Inc.

SC Specific conductance

DC Direct current

MASW Multi-channel analysis of surface waves

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## Abstract

The U.S. Geological Survey (USGS), in cooperation with Region III of the U.S. Environmental Protection Agency (USEPA) and the State of Delaware, is conducting an ongoing study of the water-quality and hydrogeologic properties of the Columbia and Potomac aquifers and the extent of cross-aquifer contamination with benzene; chlorobenzene; 1,2-dichlorobenzene; 1,4-dichlorobenzene; and hydrogen chloride (hydrochloric acid when dissolved in water) in the vicinity of the Standard Chlorine of Delaware, Inc. (SCD), Superfund Site, Delaware City, Delaware. Surface geophysical surveys and well data were used to identify and correlate low-permeability units (clays) across the site and to search for sand and gravel filled paleochannels that are potential conduits and receptors of contaminated groundwater and (or) Dense Non-Aqueous Phase Liquid (DNAPL) contaminants. The combined surveys and well data were also used to characterize areas of the site that have groundwater with elevated (greater than 1,000 microsiemens per centimeter) specific conductance (SC) as a result of contamination.

The most electrically conductive features measured with direct-current (DC) resistivity at the SCD site are relatively impermeable clays and permeable sediment that are associated with elevated SC in groundwater. Many of the resistive features include paleochannel deposits consisting of coarse-grained sediments that are unsaturated, have low (less than 200 microsiemens per centimeter) SC pore water, or are cemented. Groundwater in uncontaminated parts of the Columbia aquifer and of the Potomac aquifer has a low SC. Specific-conductance data from monitoring wells at the site were used to corroborate the DC-resistivity survey results. For comparison with DC-resistivity surveys, multi-channel analysis of surface wave (MASW) surveys were used and were able to penetrate deep enough to measure the Columbia aquifer, which is known to have elevated SC in some places. MASW survey results respond to solid material stiffness; clays and cemented sediments will have a higher velocity than silts, sands, and gravels (in order of increasing hydraulic conductivity).

Geophysical surveys detected elevated SC associated with contamination of the surficial Columbia aquifer. Groundwater with elevated SC over ambient (by an order of magnitude) produced a decrease in measured resistivity at the SCD site. Where SC data are not available from wells, it is not known if a low resistivity value measured with DC resistivity alone results from the geologic material (clay) or elevated SC in groundwater (in sand or gravel). Seismic surface waves used as part of the MASW technique are not affected by water content or quality and are used herein to distinguish between sand and clay when SC is high. Through concurrent interpretation of MASW and DC-resistivity surveys, information was gained about water quality and lithology over large areas at the SCD site.

## Introduction

The U.S. Geological Survey (USGS), in cooperation with Region III of the U.S. Environmental Protection Agency (USEPA), is involved in an ongoing study to define the hydrogeologic properties of the Columbia and Potomac aquifers in the vicinity of the former Standard Chlorine of Delaware, Inc. (SCD), Superfund Site near Delaware City, Delaware (fig. 1A). The aquifer in the Columbia Formation (also referred to herein as the Columbia aquifer) is discontinuous and infrequently used for small domestic water supplies. Parts of the Potomac Formation, however, form large continuous

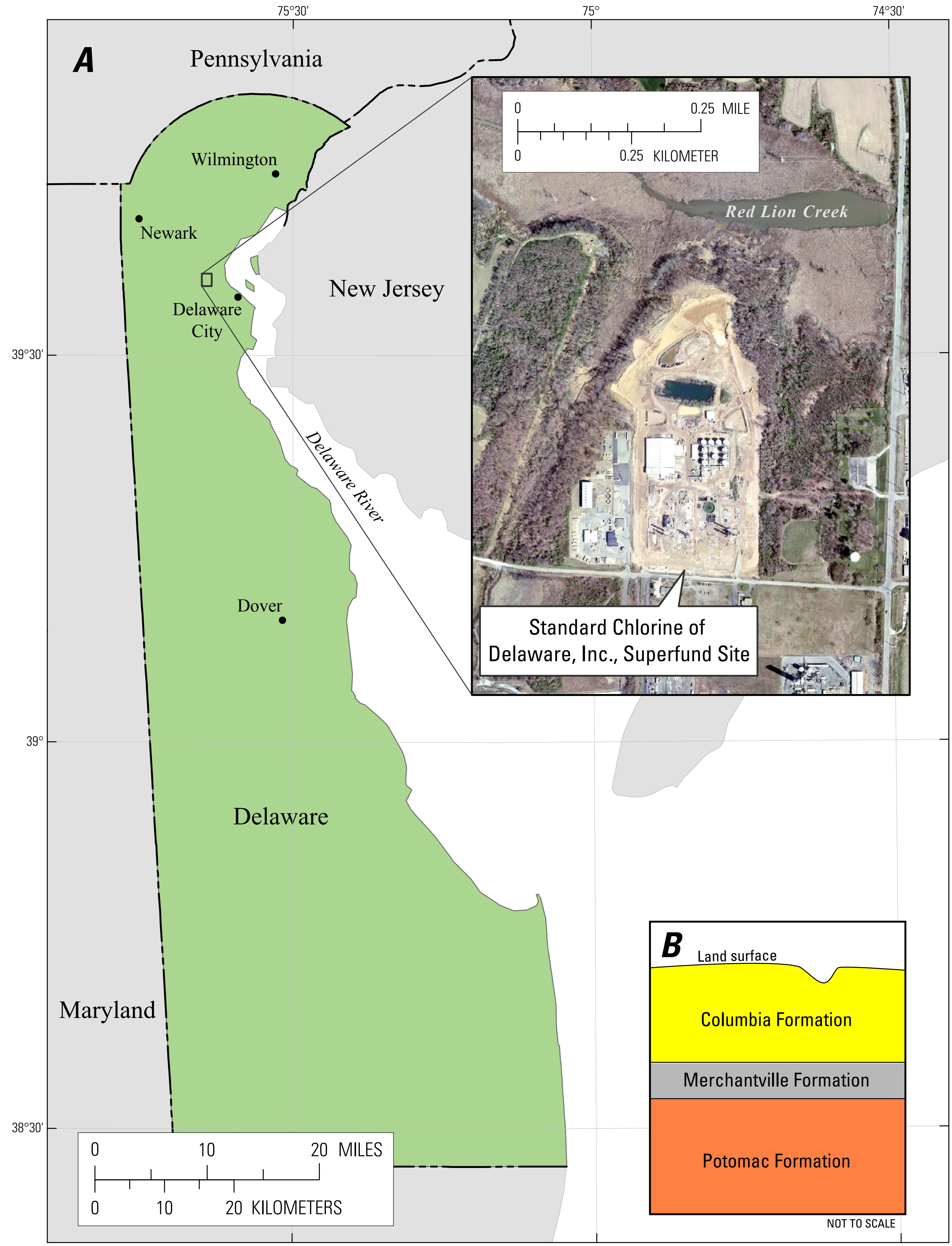


**Figure 1.** (*A*) Site location in the State of Delaware and (*B*) generalized geologic cross section, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

aquifers used as a public and industrial water supply throughout the region. The Potomac Formation (also referred to herein as the Potomac aquifer) is stratigraphically below the Columbia Formation (fig. 1B).

## Site Description

The SCD site is in an industrial area north of Delaware City, just south of Red Lion Creek. The SCD site was listed on the USEPA National Priorities List in 1987 and has been the subject of continuing subsurface investigations and site remediation. Investigations are designed to determine the nature and extent of contamination (U.S. Environmental Protection Agency, 2009) by chemicals released on site including benzene; hydrogen chloride (hydrochloric acid when dissolved in water); chlorobenzene; 1,2-dichlorobenzene; and 1,4-dichlorobenzene (Agency for Toxic Substances and Disease Registry, 2008). Remediation has included the removal of contaminants and industrial equipment on site and installation of a subsurface barrier wall keyed into exiting clay layers that consists of a slurry of clay, bentonite, and sand. A pump-and-treat system has been installed within the barrier wall to help prevent the spread of contamination by reversing groundwater gradients and to remove contaminants from groundwater.

Extensive groundwater contamination by over 500,000 gallons of products that were spilled at SCD was identified in the surficial (unconfined) Columbia aquifer (Roy F. Weston, Inc., 1992; Black and Veatch Special Project Corp., 2005). The Merchantville Formation clay, stratigraphically beneath the Columbia aquifer, was initially thought to be a nearly continuous impermeable layer that helped prevent contamination from migrating deeper at the site. However, recent detection of benzene; chlorobenzene; 1,2-dichlorobenzene; and 1,4-dichlorobenzene contaminants in the upper layers of the confined Potomac aquifer (U.S. Environmental Protection Agency, 2004, 2006) suggests that the clay may be discontinuous, or that holes may have been eroded through the clay by paleochannels prior to and during the deposition of the Columbia Formation. Contamination has been detected at monitoring wells screened in the upper Potomac Formation southeast of the site (fig. 2) (U.S. Environmental Protection Agency, 2004). A better understanding of subsurface features associated with paleochannels in the Columbia and Potomac aquifers would assist in defining potential groundwater-flow and transport properties of the aquifers at the SCD site. A preliminary assessment of groundwater specific conductance (SC) would help define areas of the underlying aquifers that may contain contaminants.

## Purpose and Scope

The purpose of this report is to present preliminary geophysical survey data and analyses that are being used to help define the extents of the aquifer (sand and gravel) and clay paleochannel materials, and to identify areas of the aquifers that contain SC levels above natural background conditions due to contaminant transport at the SCD site. These data and analyses can be used to help refine a conceptual model of groundwater flow at this site. Concurrent ongoing investigations to determine the directions and rate (vertically and horizontally) of groundwater flow and potentially Dense Non-Aqueous Phase Liquid (DNAPL) contaminant migration (flux) into the Potomac aquifer will utilize the information presented in this report.

## Hydrogeologic Setting

The Quaternary Columbia Formation forms the uppermost unconfined aquifer at the SCD site (Ramsey, 2005). Locally, it is 12 to 23 m thick (Roy F. Weston, Inc., 1992) and is composed of sand with some coarse sand, gravel, and stringers of silt and clay. The Cretaceous Merchantville Formation underlies the Columbia Formation and is a discontinuous layer of marine clay and silty/sandy clay forming a leaky confining unit (Woodruff, 1986). Underlying the Merchantville Formation is the Cretaceous Potomac Formation, which is composed of sand and gravel in a matrix of silt and clay nonmarine fluvial sediments. These sediments are generally deeper than 12 m below land surface and continue down to the crystalline bedrock at approximately 210 m. Individually, the aquifers in the Columbia and Potomac Formations have a complex heterogeneous set of hydraulic properties. Complexity is greatly enhanced by the discontinuous Merchantville confining layer, local pumping from multiple supply wells, and various braided and meandering fluvial system deposits within the formations.

Thicker sections of the Columbia Formation fill paleochannels that cut into the Merchantville and (or) Potomac Formations and form areas of increased groundwater flow having higher than average yields (Woodruff, 1986). Though they are separated by an erosional unconformity, clays of the Potomac and Merchantville Formations act together to form a confining layer of varying thickness (Woodruff, 1988). Roy F. Weston, Inc. (1992) found several locations where the Merchantville Formation is thin or non-existent, predominantly in the north-central portion of the site. The absence of the Merchantville Formation is a result of an increased gradient and fluvial erosion from the lowering of sea level during Pleistocene time (Phillips, 1987), which was followed by the fluvial and likely braided deposition of the Columbia Formation.

Within a meandering river system, such as that which formed the Potomac Formation, coarser material found in bed, bar, and levee deposits may form substantial groundwater-flow paths, and fine grained flood-plain material will form barriers to flow. The Delaware Geological Survey (DGS) has subdivided the Potomac Formation into five facies (environments), of which the first three, amalgamated and isolated channel sands and crevasse splay and proximal levee sands, have good to variable permeability (McKenna and others, 2004). The facies alternate with each other sequentially on the basis of

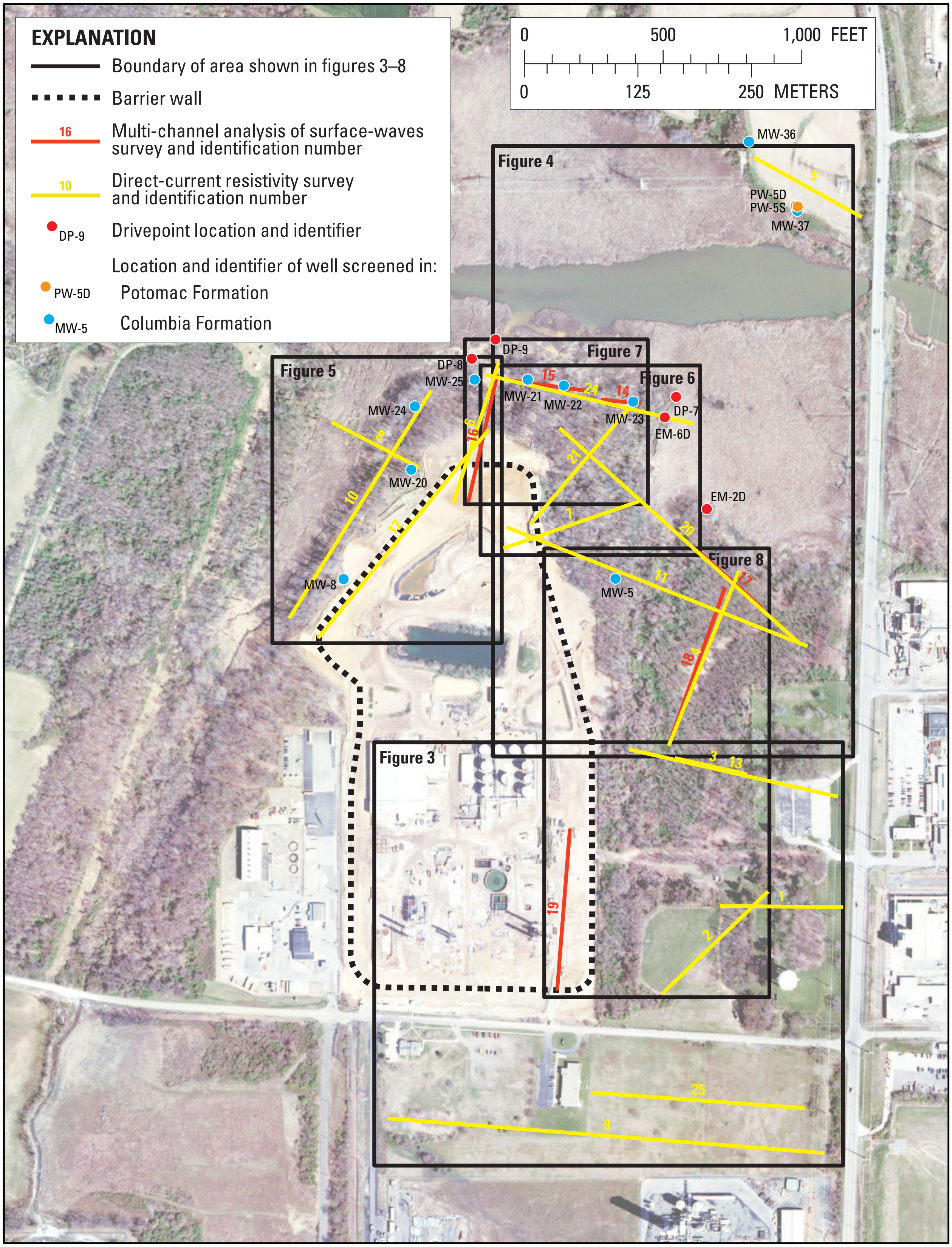


**Figure 2.** Locations of geophysical-survey lines and wells, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

the depositional environment and all potentially have some permeable sand or potential to provide aquifer leakage with limited connections. In addition to these features identified in drilling cores, other meandering river fluvial deposits may affect groundwater flow in the Potomac Formation. Clay-filled abandoned channels (oxbow lakes) can form barriers to flow, while sand and gravel bars can form flow paths, though they are difficult to correlate with borehole data (Freeze and Cheery, 1979). Benson (2006) describes the lateral variations of the different facies within the Potomac Formation that make it a heterogeneous and complex hydrogeologic system. A zone of complex faulting in the crystalline basement with offsets of 5 m or more and undetermined propagation into the Potomac Formation is located under and around the site (Woodruff, 1986; Spoljaric, 1973) and has the potential to affect groundwater flow.

In recent years, consistently downward vertical gradients from the Columbia aquifer to the Potomac aquifer at the SCD site are evident on the basis of observed water-level measurements (M.J. Brayton, U.S. Geological Survey, written commun., 2007). Groundwater flow within the Columbia aquifer is generally north towards Red Lion Creek, which is the local groundwater discharge point. In the Potomac aquifer, groundwater flow is generally from northwest to southeast towards the Delaware River, except where locally influenced by pumping (Phillips, 1987). Confining units between these two aquifers tend to limit aquifer interaction; however, some aquifer interaction has taken place on the basis of contamination detected at monitoring wells screened in the upper Potomac Formation (U.S. Environmental Protection Agency, 2004). The location and extent of gaps in confining layers between aquifers is part of an ongoing investigation to further define site hydrogeology.

# Methods of Surface Geophysical Data Collection and Analysis

Surface geophysical survey methods are useful in water-resource investigations of unconsolidated aquifers (Haeni, 1995); the use of techniques that measure different physical properties along the same survey line strengthens interpretations of hydrogeologic properties (Johnson and others, 2006). Sediment grain size, mineral content, groundwater saturation, groundwater chemistry, and surface topography affect geophysical properties. Variations in aquifer electrical properties result from different materials, pore-water chemistry, porosity, and degree of saturation. Direct-current (DC) resistivity geophysical surveys are used to measure electrical contrasts between different types of aquifer material and variations in groundwater chemistry. Water with a high SC will produce a decrease in resistivity measured by electrical geophysical methods (Urish, 1983). Contamination in the Columbia aquifer at the SCD site is commonly associated with groundwater having SC greater than 200 µS/cm, though the known Potomac aquifer contaminants are not associated with elevated SC (M.J. Brayton, U.S. Geological Survey, written commun., 2008).

Seismic methods, such as the multi-channel analysis of surface wave (MASW) technique, are complementary to electrical methods, because the chemistry of the water does not affect the propagation and velocities of the surface seismic wave. In areas of the SCD study site where SC varies over several orders of magnitude, MASW is essential to making lithologic interpretations from DC-resistivity data. Both the DC resistivity and MASW geophysical techniques were used at the SCD site. Line locations were chosen to avoid interference from metal fences and utilities and to maximize depth and detail of the survey. The DC and MASW surveys were located throughout the northern and eastern areas of the SCD site to investigate areas of the Columbia and Potomac Formations known to be contaminated (fig. 2). The western area of the site was avoided because of a lack of land access at the time of the surveys; in addition, this area is thought to be upgradient of groundwater contamination.

## Direct-Current Resistivity

DC-resistivity surveys measure the electrical resistivity of the subsurface materials and can be a valuable tool to help characterize lithologic materials, including paleochannel features, and water quality of contaminated sites. For example, under ambient groundwater-quality conditions at the SCD site, clay will have a much lower resistivity response than sand, which will be less resistive than gravel. Saturated sand or gravel will be less resistive than unsaturated sand or gravel (Zohdy and others, 1974; Kearey and Brooks, 1991). If the pore water of a sand or gravel is altered by contaminated, conductive groundwater, gravel may appear less resistive than clay because of elevated SC of the water.

Direct current is induced in the ground using two current electrodes, while the voltage is measured across two potential electrodes; larger surveys use up to 10 electrode pairs at once to improve survey efficiency. Apparent resistivity is calculated from the resistance value measured and geometric factors, which are based on electrode spacing and array type (arrangement of current and potential electrodes in relation to each other). Dipole-dipole and Schlumberger array (Zohdy and others, 1974) survey configurations were used, and reverse dipole-dipole and reciprocal Schlumberger surveys served as quality-check surveys for this study. Results of the Dipole-dipole array have the greatest lateral resolution and are interpreted and presented in this report. DC-resistivity data were processed using RES2DINV version 3.55 (Loke, 1999) to produce inverted resistivity sections from the apparent resistivity data. Data are inverted to convert apparent values that are averages corresponding to a half-sphere depth into estimates of values at a specific depth; however, results are slightly less reliable at the ends of survey lines.

The quality-check survey inversion results were compared to ensure that the same general interpretations could be made.

Cultural features such as buried pipes, well casings, and fences can interfere with the DC-resistivity surveys, and were avoided, where possible, in this study. Several metal chain-link fences and a large buried metal waste pipe on the southeast side of the site outside the barrier wall (fig. 2) limited data collection in this area. Survey line locations were chosen to maximize length, which corresponds to depth of DC-resistivity investigations.

## Multi-Channel Analysis of Surface Waves

MASW surveys take advantage of the strongest part of the seismic signal, the surface (S) wave, which is also known as ground roll. Data collection using a towable land streamer with 24 skid-mounted geophones receiving data at each measuring point (center of land streamer) allows for a dispersion curve analysis (Park and others, 1998, 2001). A higher-energy sound seismic source helps to create a low-frequency signal; a hitch-mounted 40 km accelerated weight drop was used in this study. Though data collection through coupling to the ground with spikes is ideal, reliable results can be obtained with skid-mounted geophones because the method utilizes the lower frequency portion of the seismic signal (J. Ivanov, Kansas Geological Survey, written commun., 2006). Near-continuous data collection is possible with a towable land streamer (Lane and others, 2008) equipped with skid-plate mounted geophones.

Dispersion-curve results are inverted (Xia and others, 1999) to interpolate S-wave velocity with depth in SurfSeis2 (Park, 2006). S-wave velocities are roughly equivalent to shear-wave velocities. Unlike compression-wave velocities used in seismic reflection and refraction (Zohdy and others, 1974), S-wave velocities are unaffected by water content. MASW velocity results indicate rigidity of solid material; therefore, waves traveling through clay, cemented sediment, and bedrock will have a higher velocity than those traveling through unconsolidated silt, sand, and gravel. Because the surface-wave propagation velocity is not affected by water content or water conductivity, MASW is especially useful in contaminated-site settings. In these settings, the conductivity of the pore water may be higher in some areas because of contaminants. Use of only DC resistivity would make it difficult to distinguish between conductive pore-water and a conductive geologic material.

Interpretations of surface geophysical surveys are made in the context of water-level and SC data from monitoring wells at the SCD site. Because of the depth limit of MASW signal penetration (21 m maximum at this site), it is best suited for imaging the Columbia and Merchantville Formations, though in lower-elevation parts of the site, the upper Potomac Formation silts and clays are shallow enough to be imaged.

## Paleochannels and Groundwater Specific Conductance

In areas where SC is low and constant, DC resistivity alone can be used to identify electrically resistive, hydraulically conductive paleochannel features within electrically conductive silts and clays. In places at the site where SC varies or is elevated (greater than 1,000 µS/cm), different and complementary physical properties measured with DC resistivity and MASW (electrical versus seismic) are needed for interpretations. A more detailed and accurate interpretation of paleochannel features and elevated groundwater SC is made when the surveys cover the same area and are plotted at the same scale. Slight differences in the line locations (fig. 2) occur because of the physical layout of each tool. Combined interpretations in this study are facilitated by sketching an interpreted layer on MASW results and overlaying the sketched layer on resistivity cross sections at the same depth and location. A velocity of approximately 250 m/s was chosen as a value to guide the sketching of a layer and aid in interpretations because it is approximately the halfway point in the range of velocities measured. This helped to delineate major differences in lithology. This sketched pattern was projected from the MASW cross sections onto the resistivity cross sections to aid in interpretations.

One range of resistivity values can represent one or more types of material, degrees of saturation, and groundwater SC. Because the data from MASW surveys are not affected by the presence of water or its electrical properties, results can be used to narrow the range of materials that can be interpreted from a resistivity survey (table 1). Sand interpretations in MASW (slow velocity) that correspond with low resistivity indicate areas of increased SC in the pore water. Low velocity in MASW results and high-resistivity values are likely unconsolidated sand or gravel and may indicate incised areas in low-resistivity, high-velocity clay layers.

A three-dimensional data set was constructed to facilitate an analysis of DC-resistivity results and nearby groundwater SC values from wells at the site. Field SC values with sample dates as close as possible to the DC-resistivity survey dates were chosen (J. Cannon, HydroGeoLogic, and M.J. Brayton, U.S. Geological Survey, written commun., 2009) Field measurements were made when parameters stabilized in a flow-through cell under low-flow pumping conditions.

**Table 1.** Relative response of direct-current resistivity and multi-channel analysis of surface waves to material, unsaturated sand, and specific conductance of groundwater.

[SC, specific conductance; DC, direct current; MASW, multi-channel analysis of surface waves]

| Material | Relative response | | | |
|---|---|---|---|---|
| | DC Resistivity | | MASW | |
| | Low | High | Slow | Fast |
| Unsaturated sand | | X | X | |
| Cemented sand | | X | | X |
| Sand with high SC groundwater | X | | X | |
| Sand with low SC groundwater | | X | X | |
| Clay | X | | | X |

# Results of Geophysical Surveys, Paleochannels and Relation to Groundwater Specific Conductance

In general, the low-velocity layers identified with MASW correspond to hydraulically conductive silts, sands, and possibly gravels (in order of increasing hydraulic conductivity); the more rigid, stiffest, highest-velocity layers represent clays, sandy silty clays, or cemented layers of coarser sediments. DC-resistivity results provide thickness and extent information on these near-surface materials in addition to deeper hydraulically conductive sand or gravel within the Potomac Formation. The most electrically conductive features at the site are impermeable clays and sediment with high SC groundwater. Resistive features include unsaturated sediments, sands, and gravels with low SC pore water and cemented sediments. Sands and gravels are more likely associated with paleochannel, or near channel features, where silts and clays would be a part of a paleo-flood plain, cut-off oxbow infilling, or marine deposit.

## Direct-Current Resistivity

Unsaturated gravels, sands, and silts of the Columbia Formation and saturated sands and gravels with low SC (less than 200 µS/cm) groundwater in sands of the Columbia and Potomac Formations have relatively high resistivity values (resistive), in contrast to clays of the Merchantville and Potomac Formations. High SC (over 1,000 µS/cm) groundwater in the Columbia Formation has relatively lower resistivity values (conductive).

Results from lines 1 and 2 show a thick (about 20 m) resistive sequence on top of a more conductive feature at about -10 m elevation (figs. 3A and B). Wells near lines 13 and 3 (figs. 3C and D) contain water with high SC in the Columbia Formation. This, in addition to close proximity to metal well casings and metal fence posts, make results from these lines difficult to interpret. There is a thick conductive layer in lines 9 and 25 from approximately -3 to -23 m elevation. The conductive feature is thinner and discontinuous from 220 to 275 m along line 9. There is a highly resistive zone at depth from 100 to 150 m along line 9 and around 100 m along line 25 (figs. 3E and F).

Results from lines 4, 20, and 11 (figs. 4A, C, and D) show a very thin and inconsistent conductive layer below -4 m elevation with a thin resistive layer on top. The edge of a conductive layer is identified on the bottom east edge of line 5 (fig. 4B) at -20 m elevation, and there is a thin (3 m thick), slightly conductive layer at the surface. A deep very resistive feature is identified centered at -50 m elevation from 200 to 250 m along line 20. Moderately resistive features of different sizes are identified in lines 20 and 11 (figs. 4C and D) beneath the conductive layer. The barrier wall within the SCD site is imaged as a vertical conductive feature at 27 m along line 11.

A thin, moderately conductive layer extends from 0 to around 50 m at -1 m elevation along line 8 (fig. 5A); most of the rest of the material along this line is resistive. The thick conductive layer in lines 6 (fig. 5B) and 12 thins to the north and west in lines 8 and 10. Results from line 10 indicate large and small resistive features beneath a thin discontinuous conductive layer (fig. 5C). There is a resistive feature below the thick conductive layer (described above) from -40 m elevation through the bottom of the section extending from 100 to 155 m along line 12.

Conductive features are thin and discontinuous along line 24 (fig. 6A). The conductive anomaly at the surface on the east end of line 24 is because of high SC groundwater, and there are some resistive features beneath the conductive layers on the west end of the line. Along line 21, a thick conductive feature extends from 0 to 105 m, and a similar conductive feature extends from about 40 m to the east end along line 7 (figs. 6B and C).

## Multi-Channel Analysis of Surface Waves

MASW surveys provided results from just below the surface to a depth of 13 to 21 m below the ground surface. The higher-quality data with clear dispersion curve images provided more reliable lateral resolution, and when lower-frequency signals could be generated, they allowed for the deeper investigations. Higher-velocity materials are rigid and likely correspond to semi-permeable or impermeable silts, clays, or cemented layers at the SCD site. A high-velocity layer appears

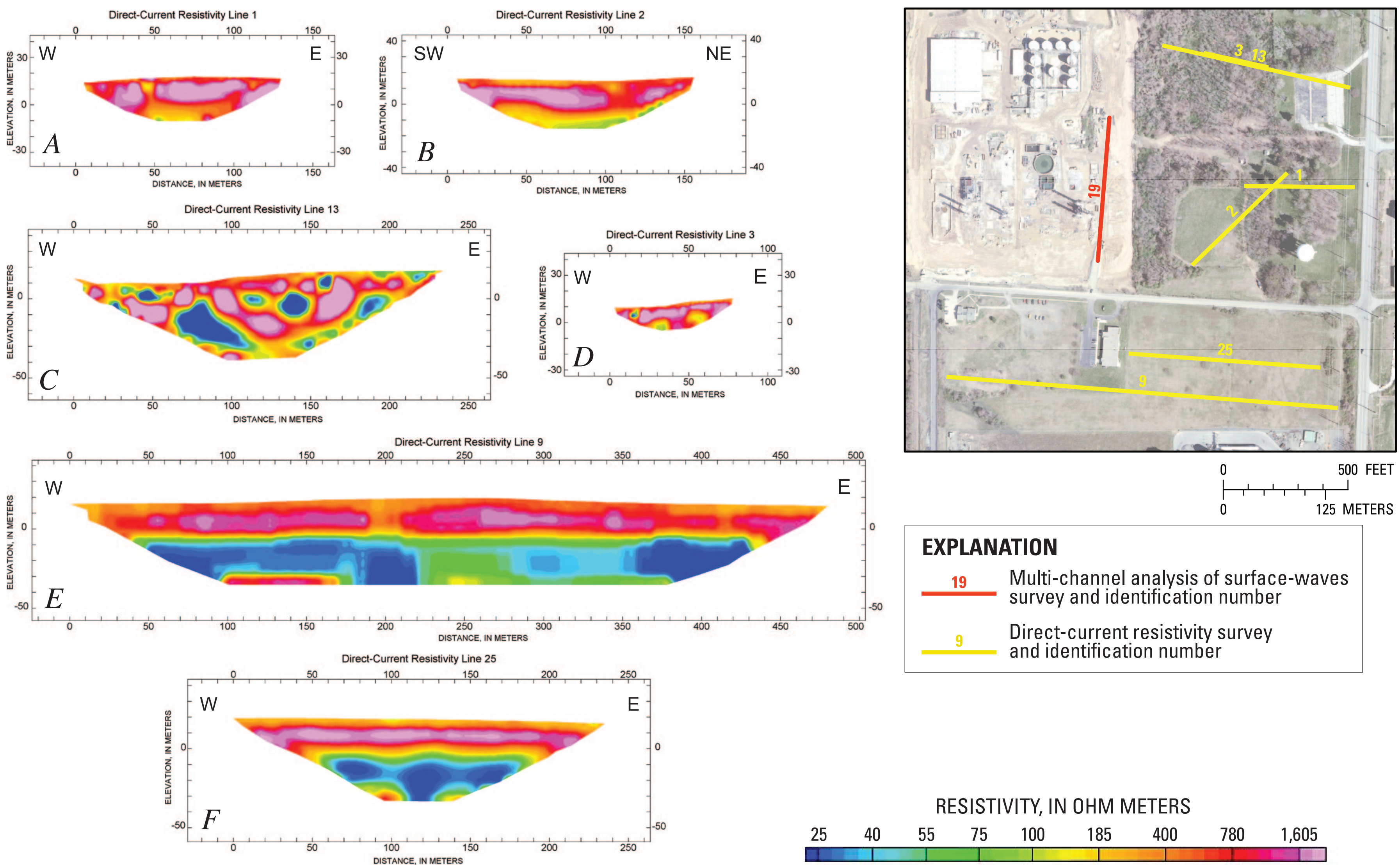


**Figure 3.** Direct-current resistivity results from (*A*) line 1, (*B*) line 2, (*C*) line 13, (*D*) line 3, (*E*) line 9, and (*F*) line 25, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

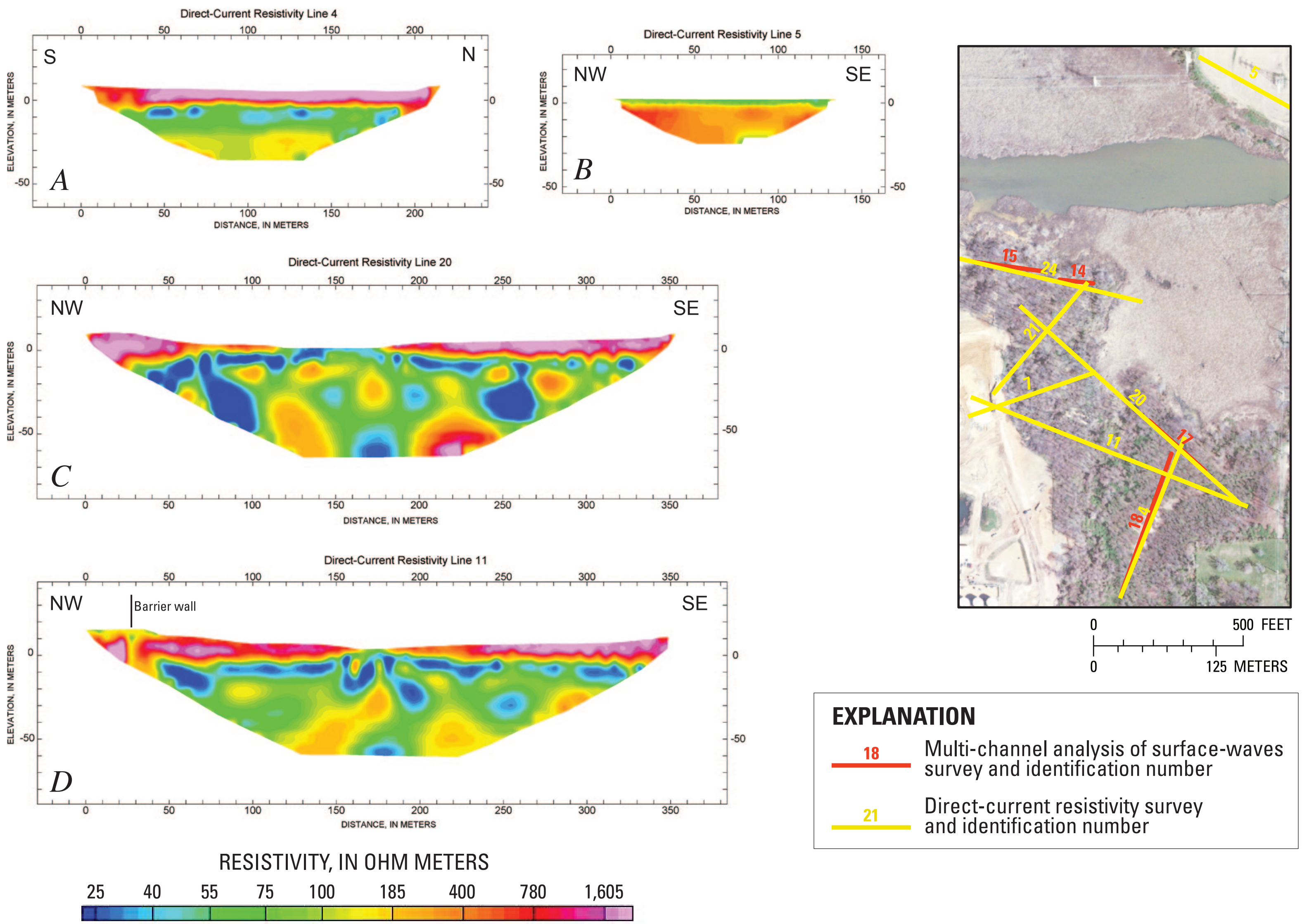


**Figure 4.** Direct-current resistivity results from (*A*) line 4, (*B*) line 5, (*C*) line 20, and (*D*) line 11, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

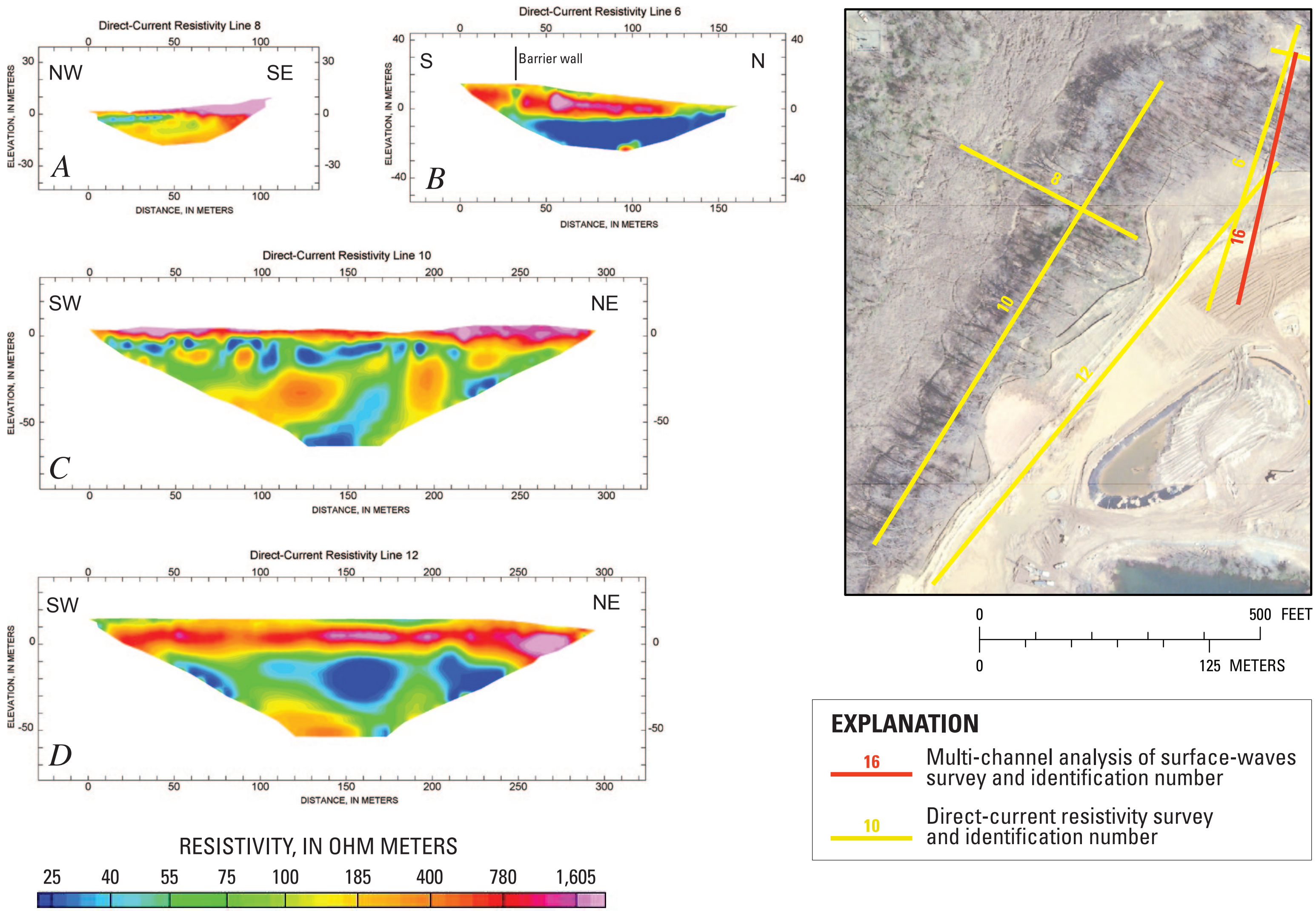


**Figure 5.** Direct-current resistivity results from (*A*) line 8, (*B*) line 6, (*C*) line 10, and (*D*) line 12, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

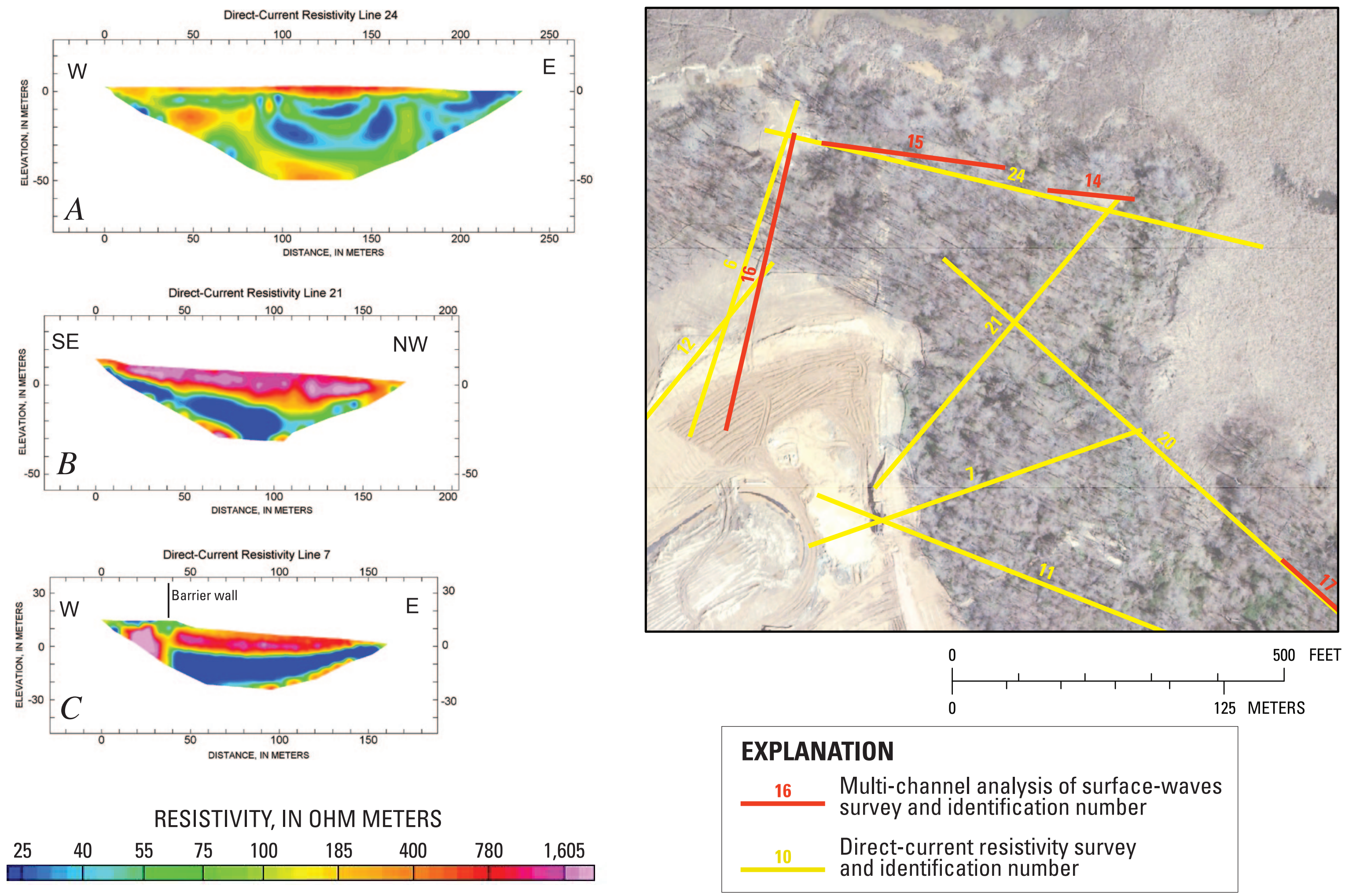


**Figure 6.** Direct-current resistivity results from (*A*) line 24, (*B*) line 21, and (*C*) line 7, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

to be continuous below about -18 m in elevation along line 14 (fig. 7A). Results from line 15 indicate areas where holes or thin spots in the clay may be present in the vicinity of 5, 40, and 80 m along the line. There is also a thin layer of higher-velocity material that is discontinuous along line 15 from 0 to -5 m in elevation (fig. 7B).

Data quality from the line 16 survey is poor, lacking consistency and low-frequency returns (resulting in a shallower investigation depth of 14 m), likely because of inconsistent and poorly compacted fill material beneath the road and (or) poor coupling of the skid plates on the rough surface. Results show some high-velocity material at the start of the line but are unreliable past 30 m distance (fig. 7C). Lines 17 and 18 indicate thin spots and holes in high-velocity layers (figs. 8A and B). Though data from line 19 did not have many low-frequency returns, which resulted in a shallow penetration depth, the returns were of good quality, enabling an interpretation of a thin, high-velocity zone near the surface from 70 to 140 m. A discontinuous high-velocity layer around 0 m elevation is also seen in the results from line 19 (fig. 8C), which was surveyed through pavement.

## Paleochannels and Groundwater Specific Conductance

Electrically resistive paleochannel features were interpreted with DC-resistivity data alone where SC was low; where SC was high, MASW was needed to help interpret paleochannels. Paleochannels in the Columbia Formation have been interpreted that incise through the Merchantville Formation and into the Potomac Formation. Paleochannels in the Potomac Formation are often found in a matrix of more conductive material, likely clay or silt. Potomac Formation paleochannel features that contain abundant sand and are electrically resistive could be part of facies identified by McKenna and others (2004), including amalgamated and isolated channels (and bars) and crevasse splay and proximal levee sands.

Resistive features identified in DC-resistivity lines 5, 8, and 9 (figs. 4B, 5A, and 3E) are interpreted as Columbia Formation material in paleochannels that have eroded through the Merchantville or Potomac Formation clay. A similar

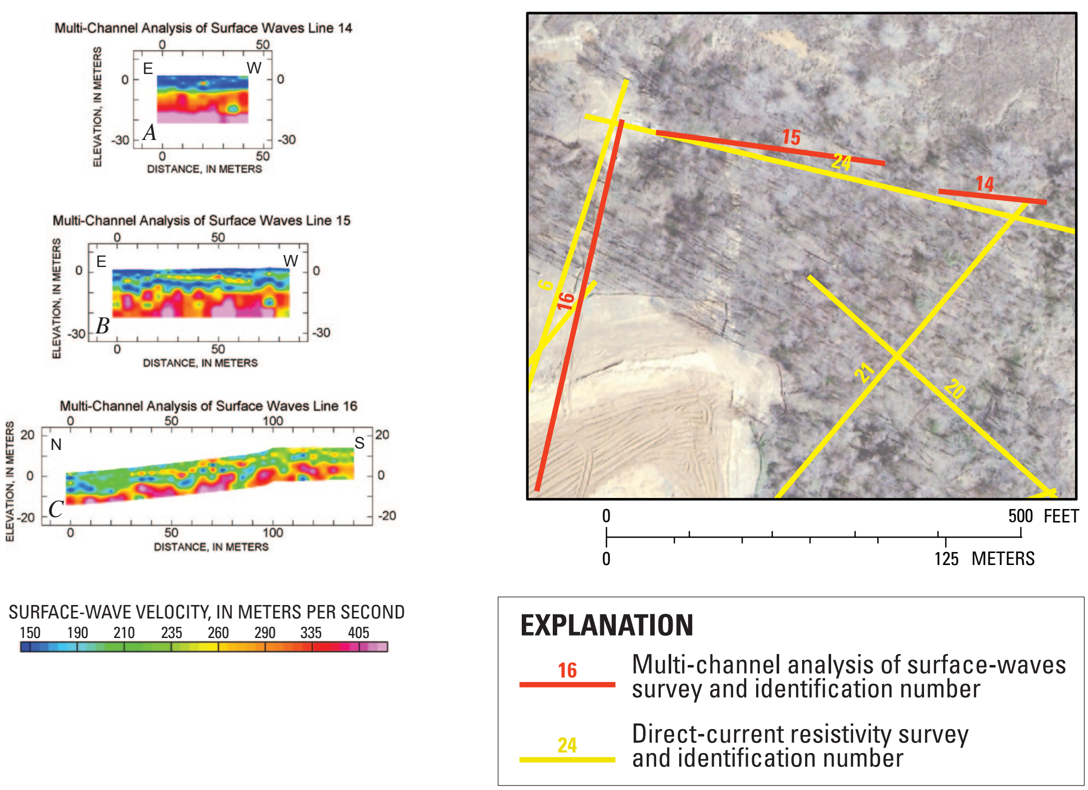


**Figure 7.** Multi-channel analysis of surface waves (MASW) results from (*A*) line 15, (*B*) line 14, and (*C*) line 16, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

deep-cutting feature is seen in line 13 (fig. 3C), though it is not known if the low-resistivity features are clay or high SC water. Deeper paleochannel features formed during the deposition of the Potomac Formation consist of resistive (greater than 150 ohm m) material at -10 m elevation or deeper that is within a matrix of silt and clay are seen in lines 4, 5, 6, 9, 10, 11, 12, 13, 20, 24, and 25 (figs. 3C, 3E, 3F, 4A, 4C, 4D, 5A, 5C, 5D, and 6A). Ongoing DC-resistivity measurements of core and SC measurements at wells will help further define these features.

Combined DC-resistivity and MASW results from lines 17 and 20 indicate continuous thin clays around -8 m elevation with sand having elevated SC pore water on top from 200 to 250 m along the line. Shallower, discontinuous, cemented layers are indicated throughout the combined section as well (figs. 9A and B). Results from lines 4 and 18 indicate thin spots, discontinuous clay, and potentially elevated SC at the northern end (figs. 10A and B). Outcroppings of cemented sediment and loose sand along the south and center areas of these lines provided evidence for interpretations. Results from lines 14, 15, and 24 indicate small amounts of thin clay, cemented sediments, and sand with slightly higher SC in the pore water on the east side (figs. 11A and B).

Information on well water SC and MASW results are used to determine where groundwater SC is elevated (above 1,000 µS/cm). Wells, the potentiometric surface, and screened intervals plotted on resistivity sections for analysis are shown in appendix 1. Resistivity values measured during DC-resistivity surveys nearest to screen intervals where groundwater SC was measured have been selected from these views. In general, when SC was higher, resistivity values were lower. When SC was lower, resistivity was higher and had a wider range of values because it is controlled more by varying geologic materials (fig. 12). Because SC likely changes with time, groundwater levels and flow, dates of the measurements, and DC-resistivity data collection are listed in the figure captions in appendix 1.

SC was low (below 200 µS/cm) and resistivity was high at wells near line 5 where there were not any site-related contaminants (appendix 1, fig. 1–1). Groundwater SC was considered ambient here. Groundwater with elevated specific conductance SC over ambient levels (by an order of magnitude) produced a decrease in measured resistivity. SC was very high (3,800 µS/cm) at EM-2D and resistivity was low (appendix 1, fig. 1–2). Along line 24, SC increased to the east and resistivity dropped (appendix 1, fig. 1–6).

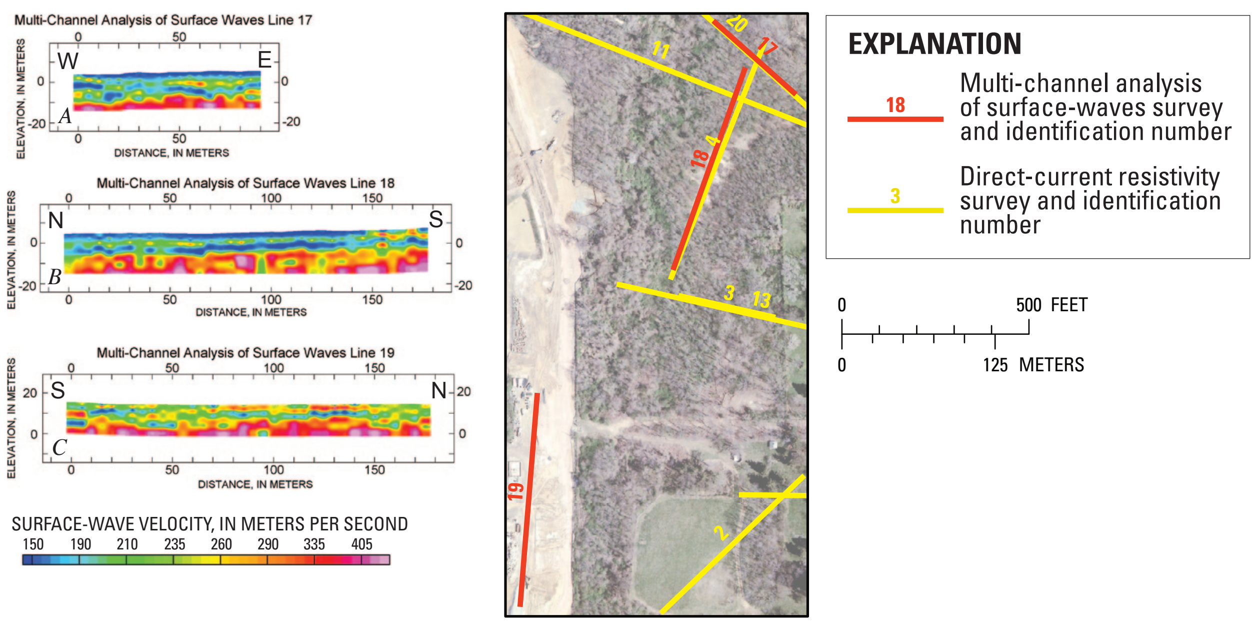


**Figure 8.** Multi-channel analysis of surface waves (MASW) results from (*A*) line 17, (*B*) line 18, and (*C*) line 19, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

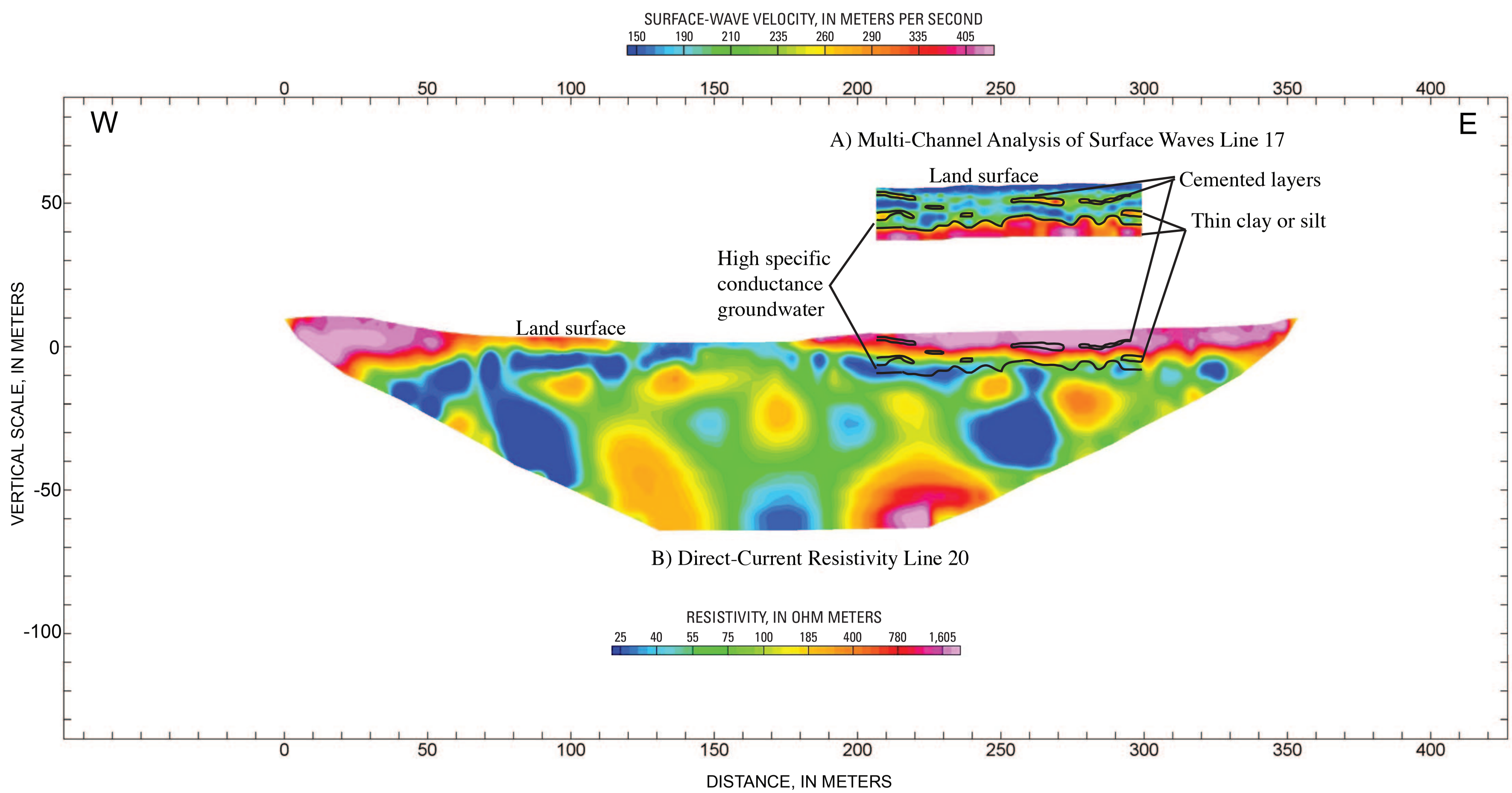


**Figure 9.** Co-located surface geophysical results from (*A*) line 17 multi-channel analysis of surface waves (MASW) with stiff layer interpretation in black and (*B*) line 20 direct-current resistivity with MASW projected interpretation, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

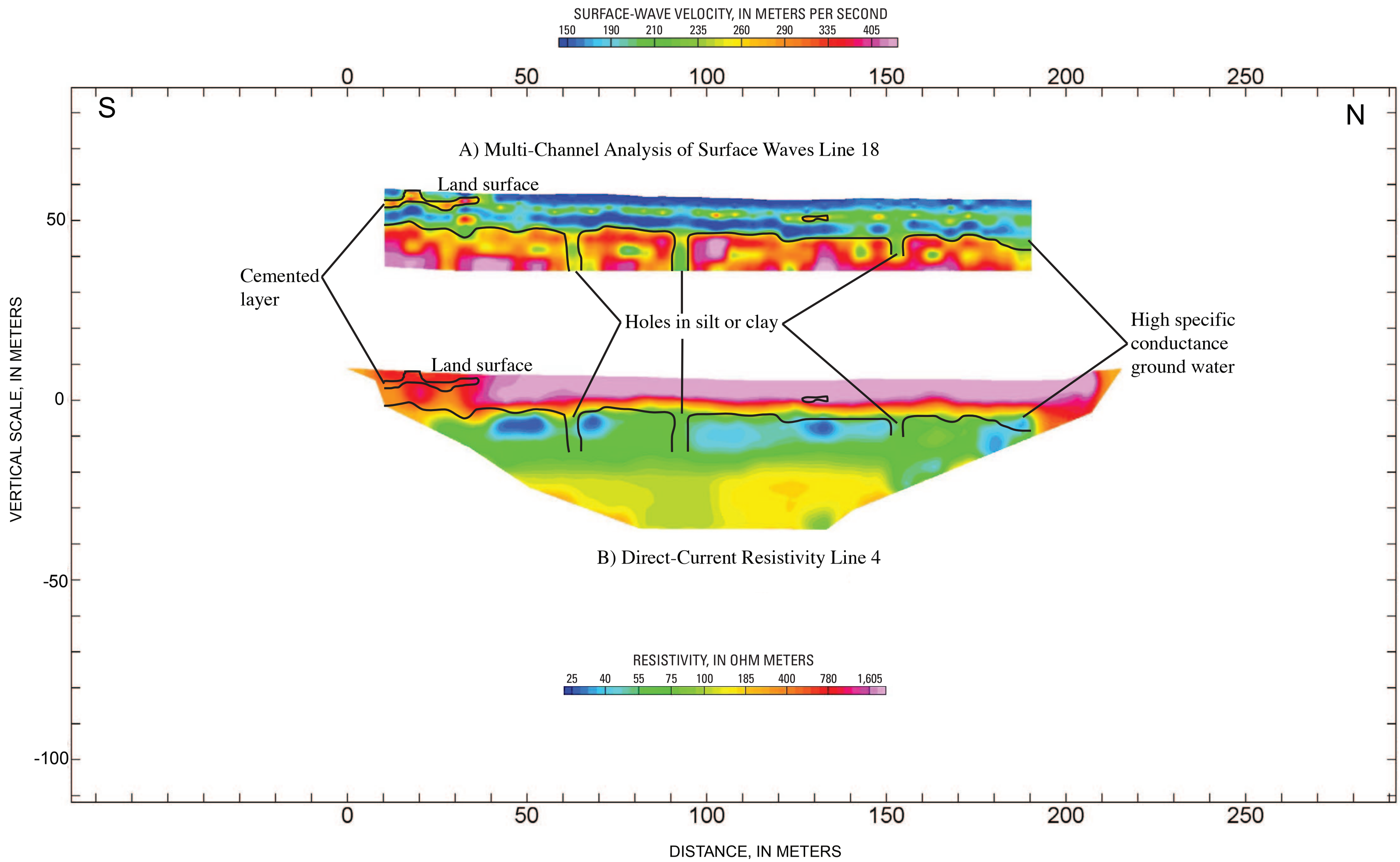


**Figure 10.** Co-located surface geophysical results from (*A*) line 18 multi-channel analysis of surface waves (MASW) with stiff layer interpretation in black, and (*B*) line 4 direct-current resistivity with MASW projected interpretation, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

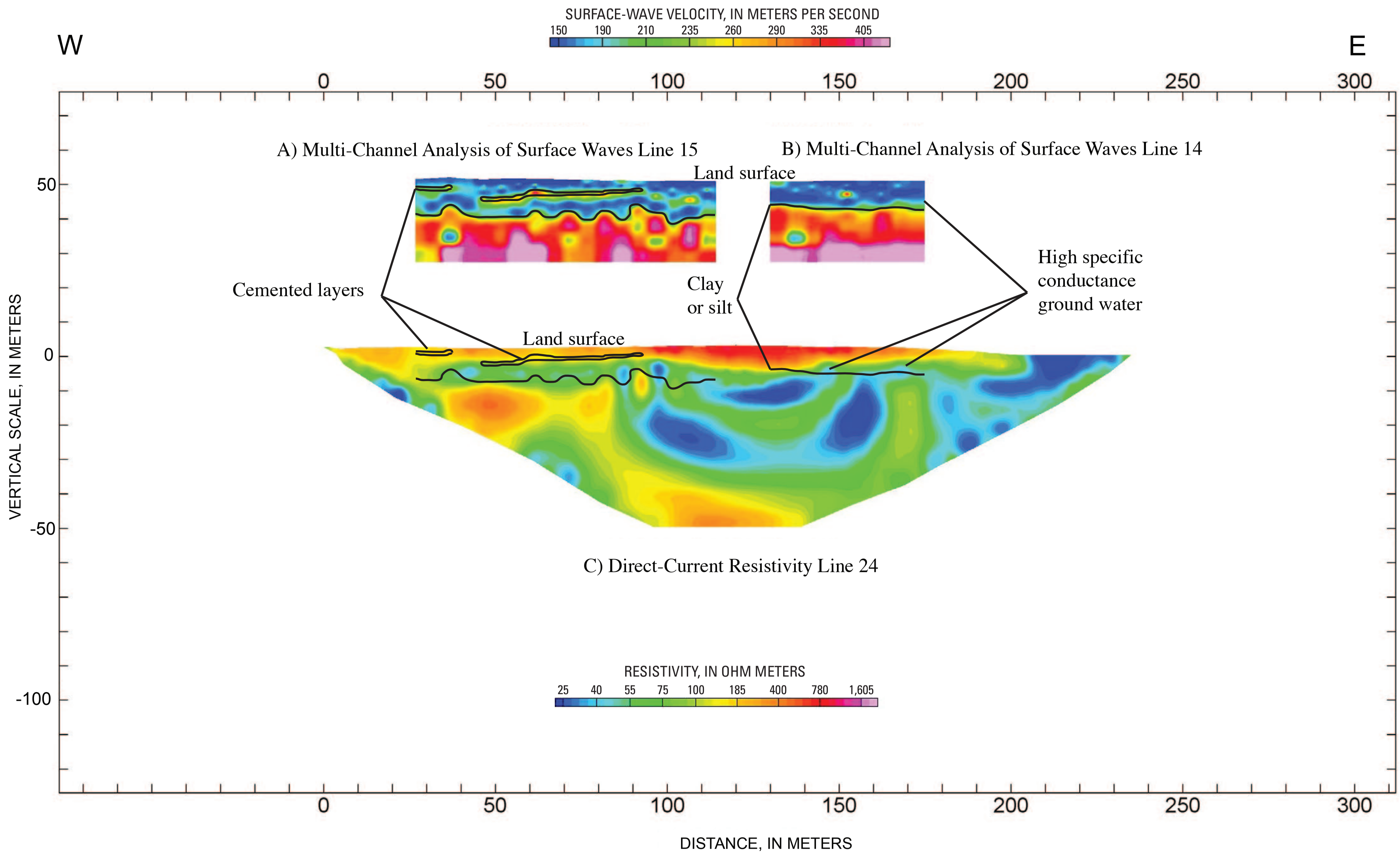


**Figure 11.** Co-located surface geophysical results from (*A*) lines 14 (left) and 15 (right) multi-channel analysis of surface waves (MASW) with stiff layer interpretation in black, and (*B*) line 24 direct-current resistivity with MASW projected interpretation, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

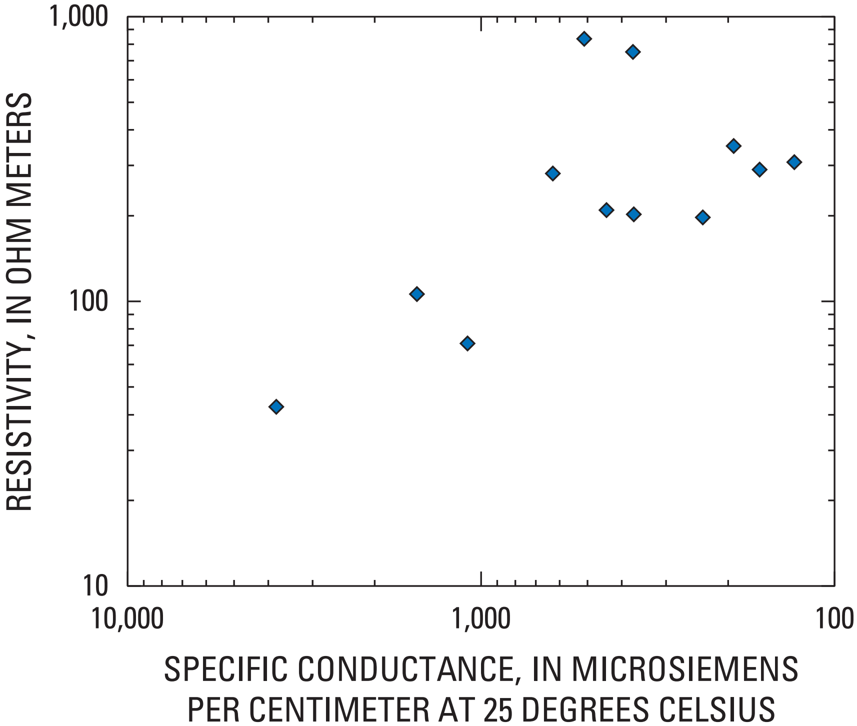


**Figure 12.** Relation between specific-conductance measurements from wells and resistivity values at screened-interval depths from adjacent cross sections, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

## Summary

The USGS is cooperating with Region III of the USEPA in an ongoing study to define the hydrogeologic properties of the Columbia and Potomac aquifers in the vicinity of the Standard Chlorine of Delaware, Inc. (SCD), Superfund Site near Delaware City, Delaware. The SCD site was listed on the USEPA National Priorities List in 1987 and has been the subject of continuing investigations to determine the nature and extent of dissolved phase and DNAPL contamination. Results from this preliminary investigation on the occurrence of paleochannels and areas of elevated groundwater specific conductance at the SCD site may be useful for remedial planning and operations.

Electrically resistive units measured with DC-resistivity surveys correspond to unsaturated gravel and sand of the Columbia Formation or saturated sand and gravel with low SC groundwater in the Columbia and Potomac Formations. Electrically conductive clays of the Merchantville and Potomac Formations and high SC groundwater in the Columbia Formation were identified with DC-resistivity surveys. MASW surveys detected higher velocity, rigid materials that are interpreted as semi-permeable or impermeable silts, clays, or cemented layers; lower-velocity materials correspond to unconsolidated sand or gravel. MASW surveys are not affected by groundwater or its electrical properties, and DC-resistivity results are not strongly affected by the degree of cementation of sediment.

Through combining interpretations from the MASW and DC-resistivity surveys, more detailed and specific materials were identified. Lower-velocity MASW results associated with sand that corresponds with areas of low resistivity indicate areas of increased SC groundwater. Low-velocity MASW results in conjunction with high resistivity values represent unconsolidated sand or gravel and can indicate gaps or paleochannel incision in the low-resistivity, high-velocity clay layers. Sand-filled paleochannels identified in the Columbia Formation have incised through the Merchantville and into the Potomac Formation. Sand-filled paleochannels were also identified within the Potomac Formation at the SCD site, as part of a more conductive clay or silt matrix.

Variations in groundwater SC affect the results of DC-resistivity surveys at this site. For example, when SC values were lower, resistivity survey result values were controlled more by differences in geologic material than groundwater quality on the west side of the site and on the north side of Red Lion Creek. When pore water had a low SC, lower resistivity values indicated silt and clay; higher resistivity values correspond with higher hydraulic conductivity sands or gravels. Elevated SC, confirmed by well data and the combination of DC-resistivity and MASW, was detected along the northern edge of the SCD site (southern edge of Red Lion Creek) in the Columbia Formation.

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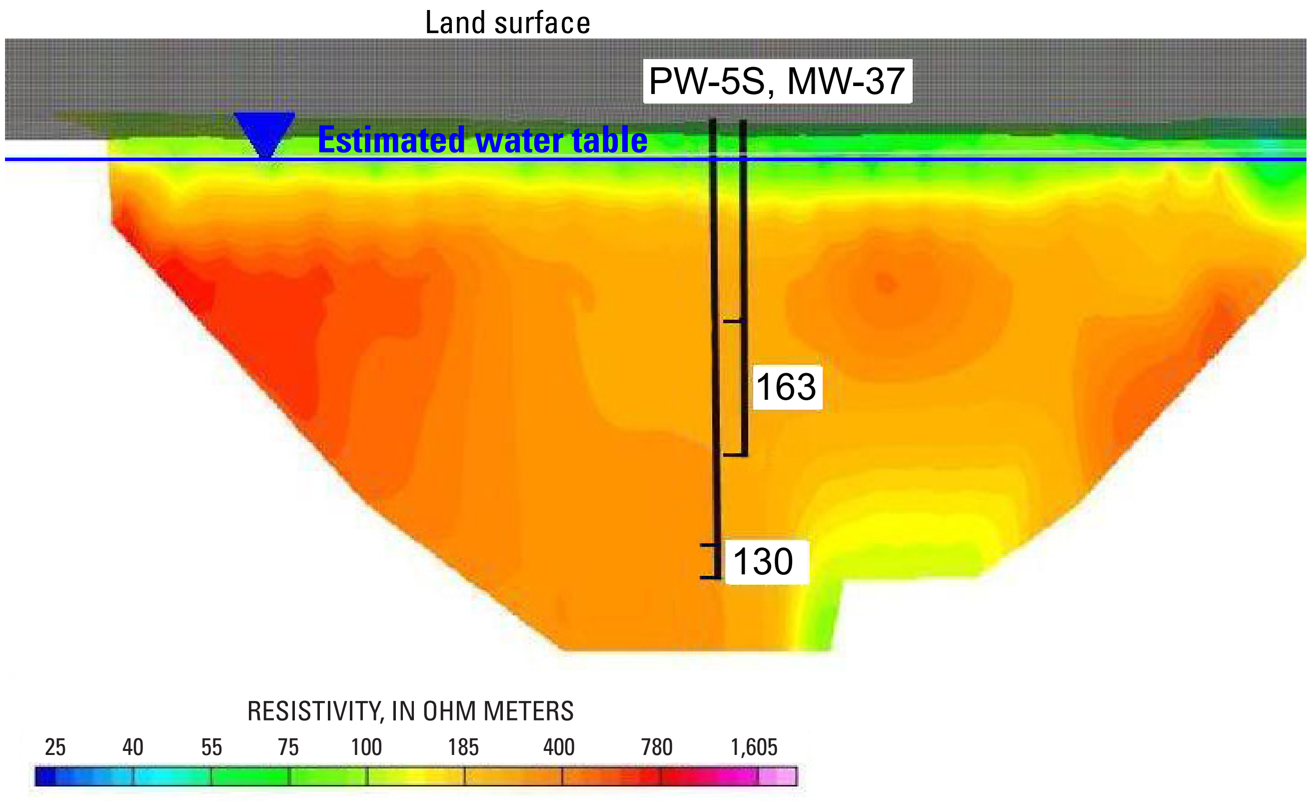
# Appendix 1. Direct-Current Resistivity Cross Sections with nearby Well Water Levels, Screened Intervals, and Specific Conductance Values

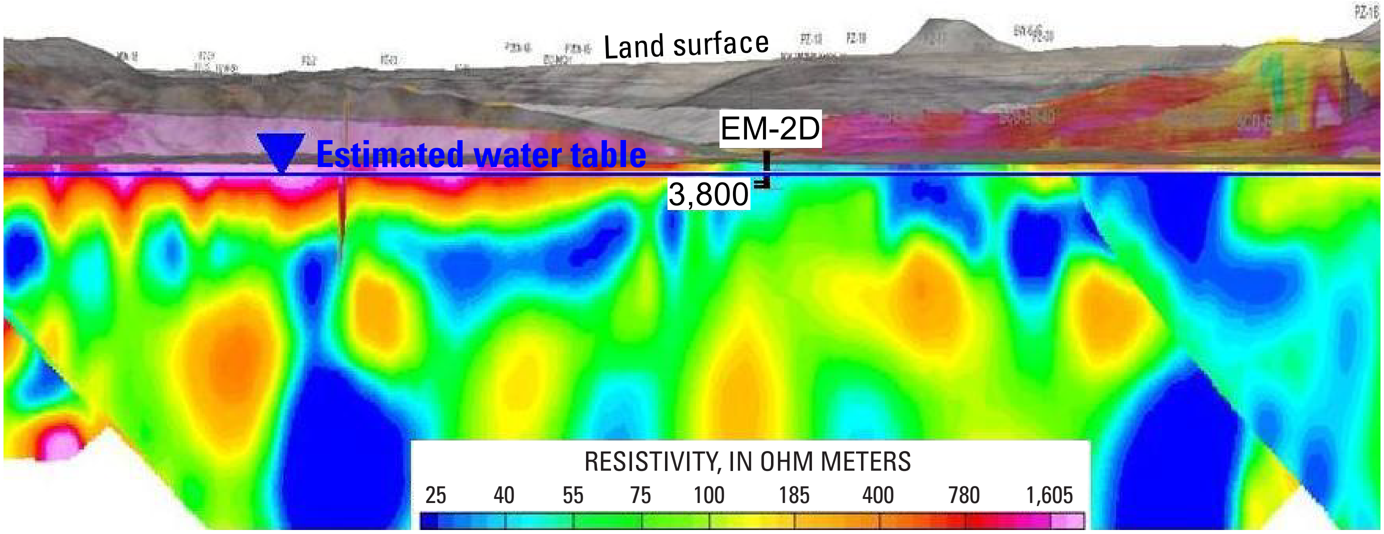



**EXPLANATION**

MW-37 Well location and identifier

163 Screened interval and specific conductance at screened interval, in microsiemens per centimeter at 25 degrees Celsius

**Figure 1–1.** Direct-current resistivity cross section with nearby wells (MW-37 and PW-5S) projected showing screened intervals, water levels, and specific conductance values (measured August 29 and 30, 2007). Results from line 5 (collected November 13, 2007) viewed looking to the north from the south with a 2X vertical exaggeration. For locations, distance, and depth scales refer to figures 2 and 6, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

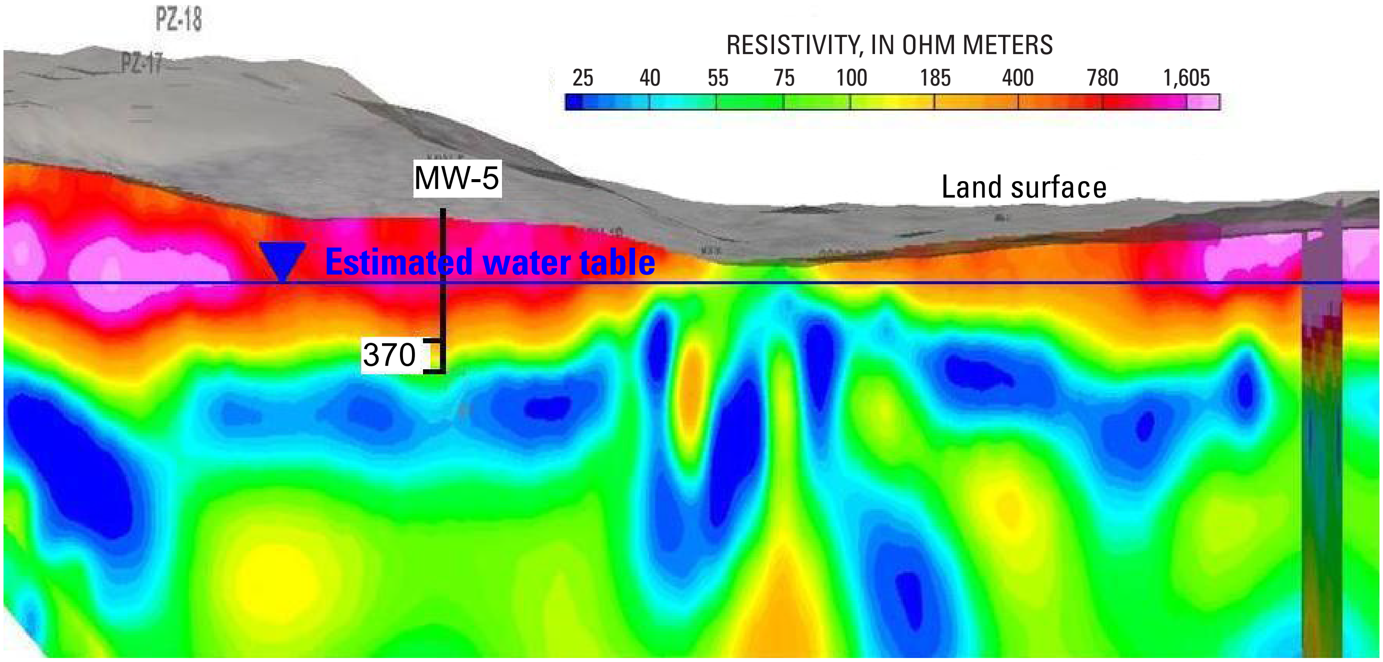



**EXPLANATION**

EM-2D — Well location and identifier

3,800 — Screened interval and specific conductance at screened interval, in microsiemens per centimeter at 25 degrees Celsius

**Figure 1–2.** Direct-current resistivity cross section with nearby well (EM-2D) projected showing screened intervals, water levels, and specific conductance values (measured June 12, 2008). Results from line 20 (collected July 9, 2008) viewed looking to the south from the north with a 2X vertical exaggeration. For locations, distance, and depth scales refer to figures 2 and 6, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

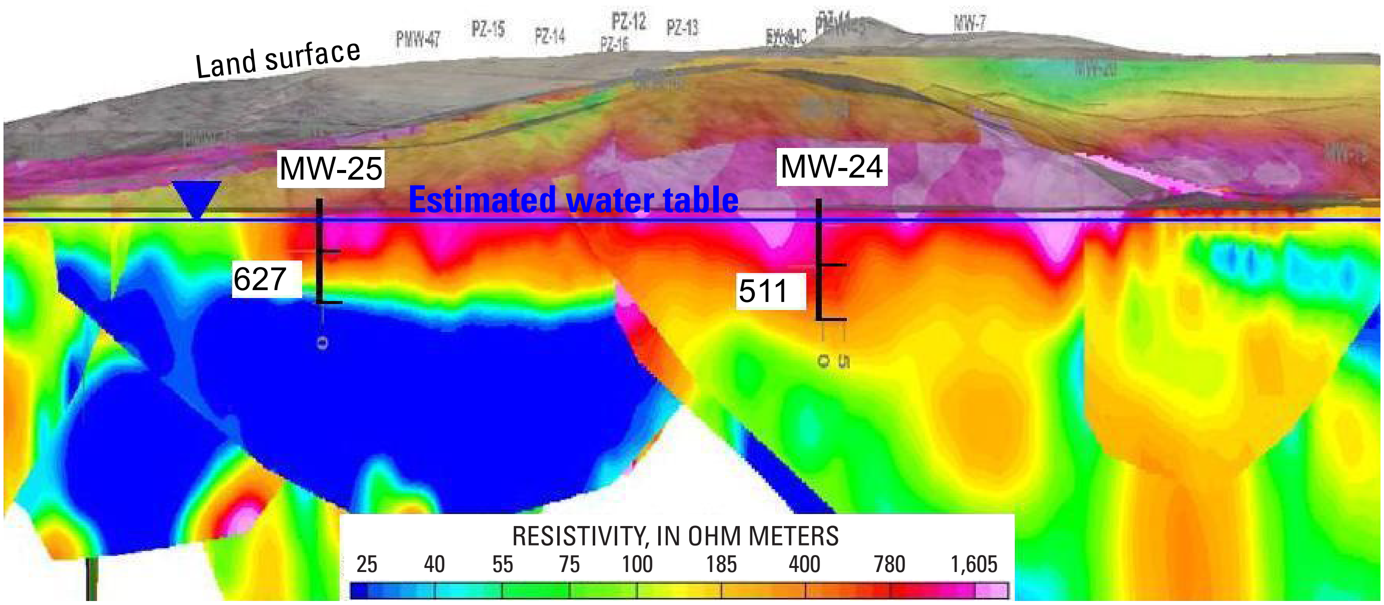



**EXPLANATION**

MW-5 — Well location and identifier

370 — Screened interval and specific conductance, in microsiemens per centimeter at 25 degrees Celsius

**Figure 1–3.** Direct-current resistivity cross section with nearby well (MW-5) projected showing screened interval, water level, and specific conductance value (measured December 15, 2008). Results from line 11 (April 23, 2008) are viewed looking to the north from the south with a 2X vertical exaggeration. For locations, distance, and depth scales refer to figures 2 and 6, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

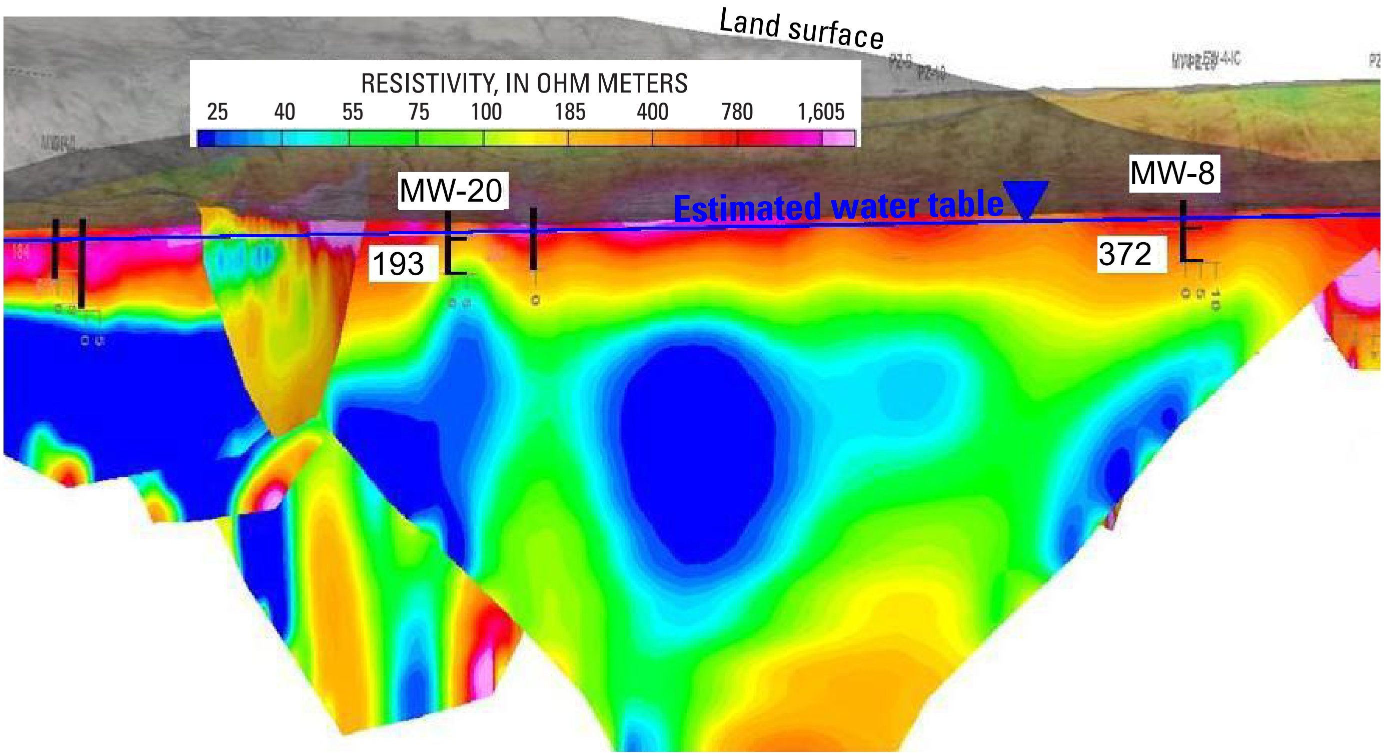



**EXPLANATION**

MW-24 Well location and identifier

511 Screened interval and specific conductance at screened interval, in microsiemens per centimeter at 25 degrees Celsius

**Figure 1–4.** Direct-current resistivity cross section with nearby wells (MW-25 and MW-24) projected showing screened intervals, water levels, and specific conductance values (measured December 12 and 15, 2008). Results from lines 6, 10 (sections with wells, collected January 25, 2008, and April, 22, 2008), and 8 (on right side, coming out of page) are viewed looking to the east from the west with a 2X vertical exaggeration. For locations, distance, and depth scales refer to figures 2 and 7, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.




**EXPLANATION**

MW-8 Well location and identifier

372 Screened interval and specific conductance at screened interval, in microsiemens per centimeter at 25 degrees Celsius

**Figure 1–5.** Direct-current resistivity cross section with nearby wells (MW-37 and PW-5S) projected showing screened intervals, water levels, and specific conductance values (measured August 29 and 30, 2007). Results from lines 6, 8 (coming out of page, left side), and 12 (section with wells, collected April, 23, 2008) viewed looking to the east from the west with a 2X vertical exaggeration. For locations, distance, and depth scales refer to figures 2 and 7, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

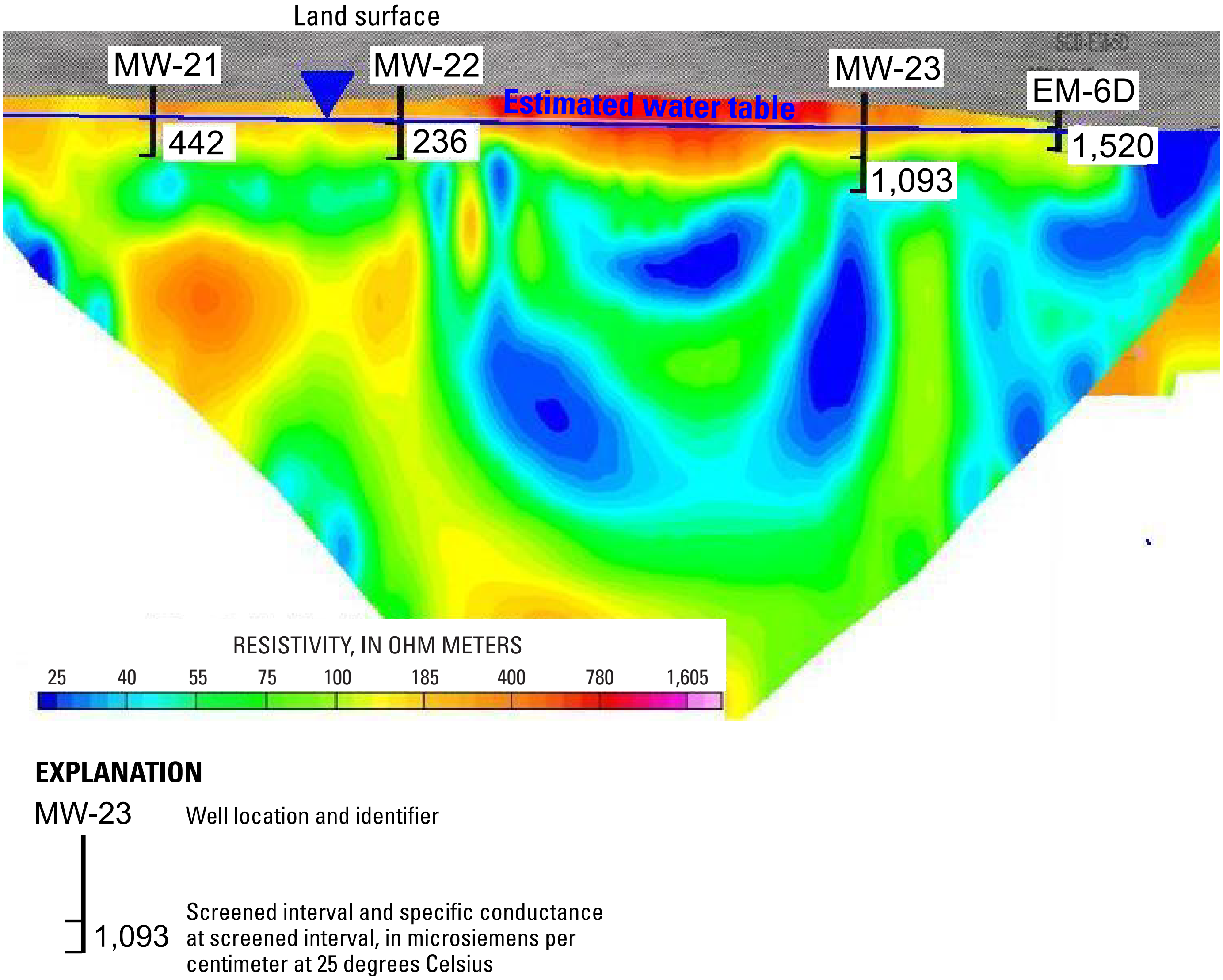



**Figure 1–6.** Direct-current resistivity cross section with nearby wells (MW-22, MW-23, MW-21, and EM-6D) projected showing screened intervals, water levels, and specific conductance values (measured December 12, 12, and 15, 2008, and September 16, 2008). Results from line 24 (collected July 10, 2008) viewed looking to the north from the south with a 2X vertical exaggeration. For locations, distance, and depth scales refer to figures 2 and 8, Standard Chlorine of Delaware, Inc., Superfund Site, Delaware City, Delaware.

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