WILLOWSTICK INVESTIGATION

Of:

COMBE FILL SOUTH LANDFILL

Morris County, New Jersey

(Delineate preferential groundwater flow paths influencing the transport of contaminants away from the landfill)

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i. EXECUTIVE SUMMARY

This report presents the results of a Willowstick® geophysical investigation to characterize preferential groundwater flow paths beneath and away from the Combe Fill South Landfill. More specifically, the purpose of the investigation is to characterize groundwater flow paths that could possibly influence the transport of contaminants away from the site.

The application of the Willowstick technology, as applied to the Combe Site, is based on the principle that groundwater flowing beneath and away from the landfill increases conductivity of earthen materials through which it flows. The concentration and distribution of electric current was then interpreted and modeled to help characterize how and where groundwater preferentially flows beneath and away from the landfill to the northeast.

Six independent electrode configurations were employed for the investigation. Four of the six surveys provided quality data that helped to delineate three preferential flow paths along open fractures, which potentially contribute to the mobilization of contaminants away from the site.

Figure S1 presents a general summary of the investigation with a map of Survey #1's results.

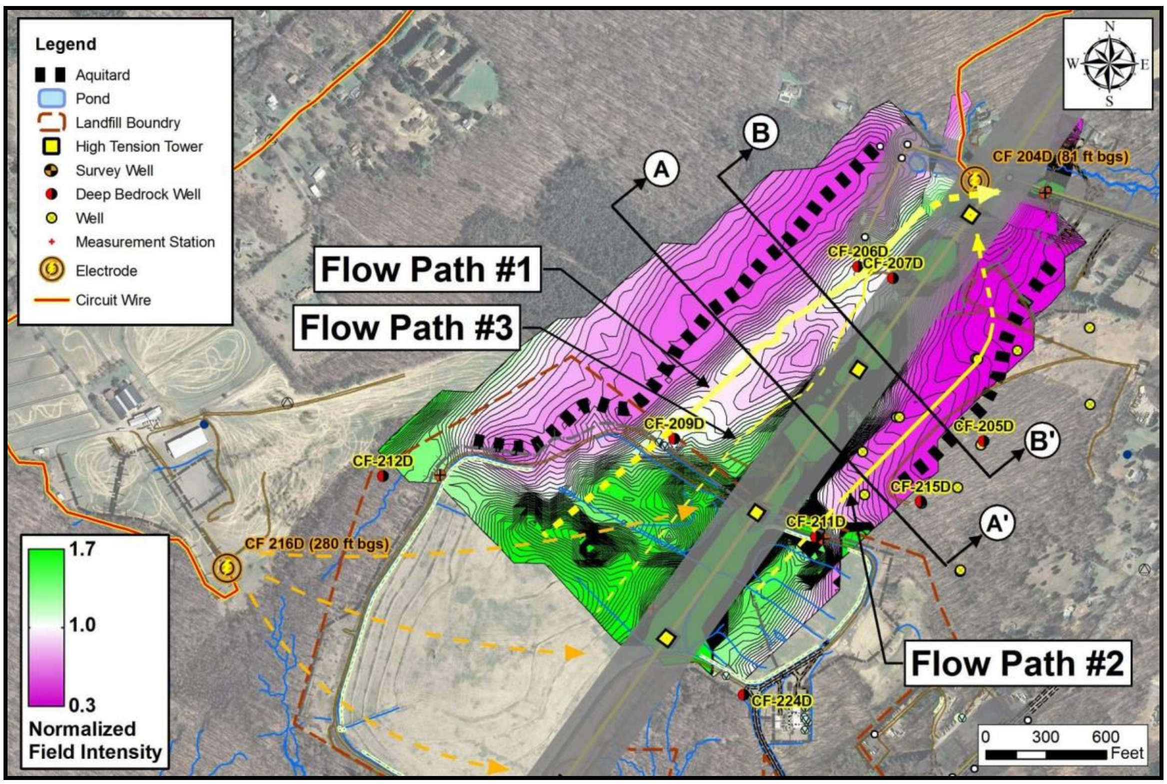

Figure S1 – General Summary of Investigation (shown with Ratio Response Map for Survey #1)

Survey #1 provides a general characterization of preferential groundwater flow beneath and away from the landfill to the northeast. The survey extends from the landfill's northeast quadrant to Schoolhouse Lane (located approximately one-half mile northeast of the landfill). Three conductive flow paths were identified which potentially convey groundwater and contaminants away from the landfill (see yellow paths labeled #1, #2 and #3). Subsequent surveys provided addition detail regarding the noted flow paths.

In Figure S1, the white shading indicates areas where the measured magnetic field is equivalent to that predicted for an electrically homogeneous subsurface model. Areas shaded purple indicate the magnetic field is less than predicted, and areas shaded green indicate the magnetic field is greater than predicted. Yellow arrows identify preferential flow paths along what are believed to be subsurface fractures—solid where clearly delineated and dotted where inferred. The thick black dashed lines represent barriers to electric current flow, keeping it mostly within these bounds. Survey #1 utilized electrodes in monitoring wells CF-216D (depth of electrode - 280 ft. bgs) and CF-204D (depth of electrode - 81 ft. bgs). As electric current flowed out and away from well CF-216D, much of it flowed across and upward through the landfill (orange dashed lines) toward the overhead electrical transmission line running through the center of the study area. Each of the transmission towers within the study area were grounded. The transmission line's grounding system allowed electric current to flow up onto the overhead power lines across the study area. This interference made it impractical to fully characterize preferential groundwater flow paths beneath the transmission line; therefore, a dark gray transparent cloud covers the transmission line corridor. Nevertheless, subsurface electric current flow was sufficient to identify three preferential flow paths potentially contributing to the mobilization of contaminants away from the site. Electric current flowing beneath the landfill is somewhat convoluted—flowing through waste materials as well as deeper preferential flow paths. Near the area where the transmission line crosses Schoolhouse Lane, the three flow paths appear to converge and then bend eastward as inferred by the yellow dashed arrows.

To further describe preferential flow paths beneath and away from the landfill, Figures S2 and S3 present cross section slices (Sections A-A′ and B-B′) of Electric Current Distribution (ECD) models targeting subsurface flow paths immediately northeast of the landfill. These ECD slices were generated from Surveys #4 and #6, each having higher density of measurement stations than did Survey #1 and better positioning electrodes to bias electric current in the noted flow paths.

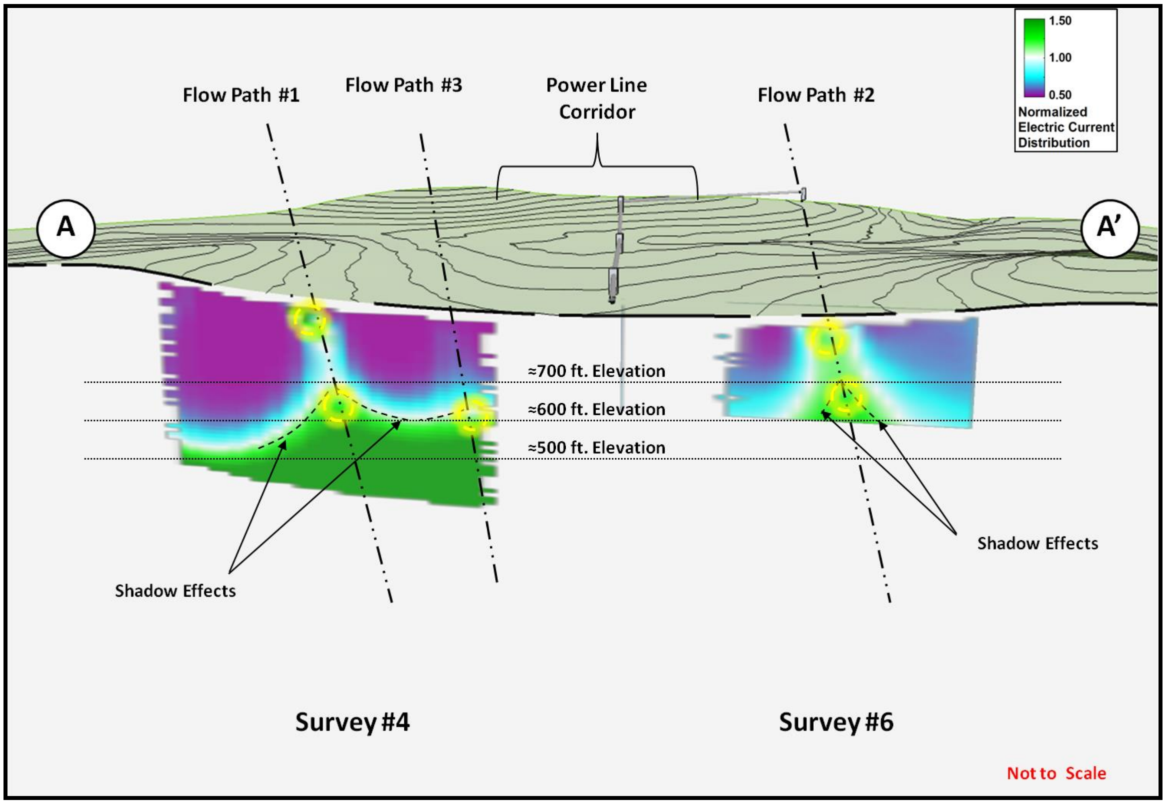

Figure S2 – Surveys #4 and #6 ECD Model Slice (Section A-A′)

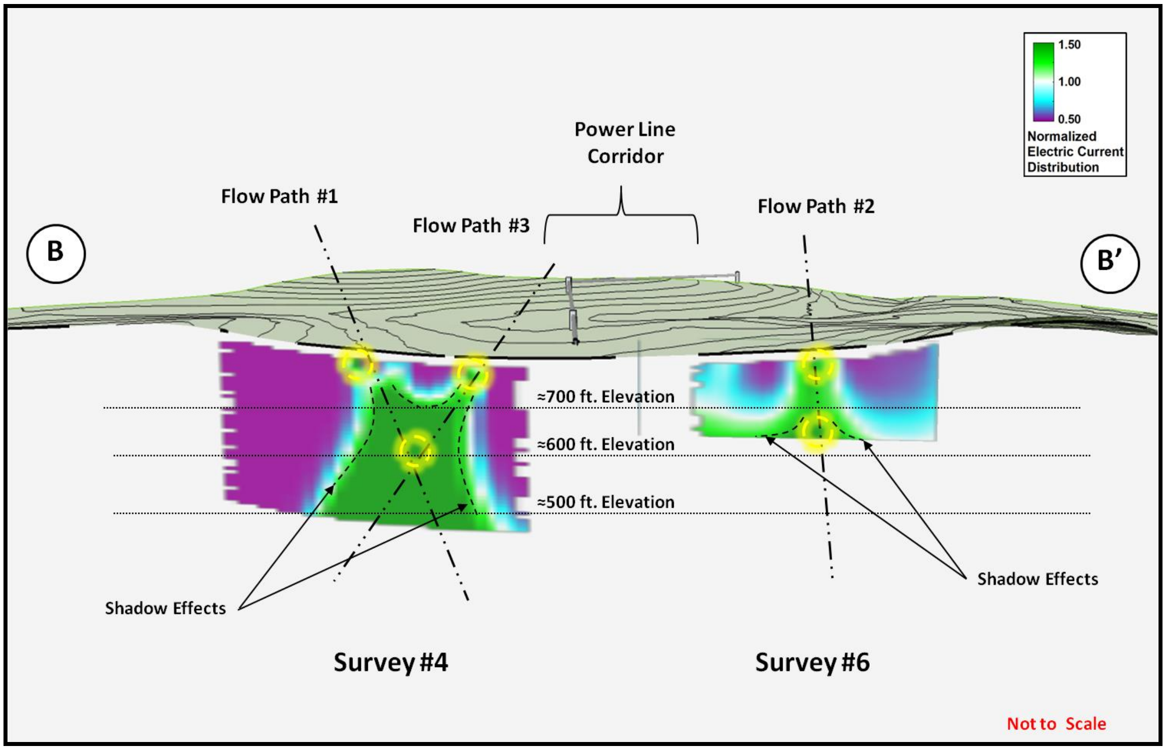

Figure S3 – Surveys #4 and #6 ECD Model Slice (Section B-B′)

These ECD model slices have been inserted into a 3D site model to show the relationship between the relevant site features and those pathways identified by the Willowstick ECD model data. The contrast between purple and green shading is interpreted as an interface between competent and more porous subsurface materials. In these figures, Flow Paths #1, #2 and #3 identify what are believed to be open fractures with a near-vertical but tilted orientation—as highlighted with dashed black “center” lines. These fractures act as open conduits to potentially conduct landfill contaminants away from the site. Section B1-B1′ is taken where the two flow paths begin to merge. The yellow circles highlight what is interpreted as zones of highest electrical concentration. Minimal information can be discerned at elevations below the deepest yellow circles due to the “shadow effects” that occur below the detected flow zones. A good analogy for explaining the shadow effect is to think of the survey data as shining a flashlight at something from above. If there is a solid object (a flow path or some conductive pathway) the top will be illuminated but a shadow will be cast below the object. Note how the green shaded areas spread out going down through the models below the most conductive zones.

In summary, the Willowstick data has provided consistent and repeatable results that delineate three preferential flow paths that potentially conduct contaminants away from the Combe Fill South Landfill to the northeast. It is recommended that this report and its accompanying information be compared with all known site information to substantiate the findings and to make the most cost-effective decisions regarding further characterization, monitoring and/or remediation.

1.0 INTRODUCTION

1.1 General

This report presents the results of a Willowstick® geophysical investigation to characterize preferential groundwater flow paths beneath and away from the Combe Fill South Landfill. More specifically, the purpose of the investigation is to help identify groundwater flow paths possibly influencing the transport of contaminants away from the site. The landfill is located in Morris County, New Jersey in Chester and Washington Townships (see Figure 1).

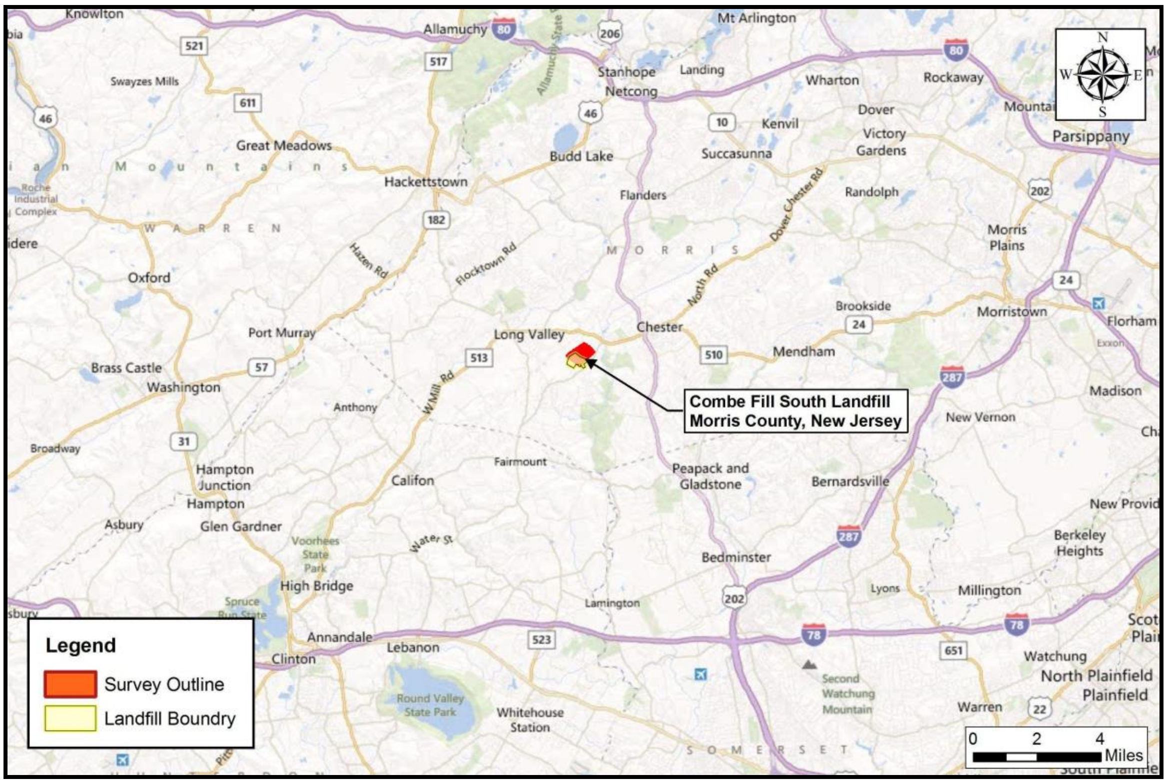

Figure 1 – Project Location Map

1.2 Background

The Combe Fill South Landfill comprises 65 acres within a 115-acre parcel of land (see Figure 2).

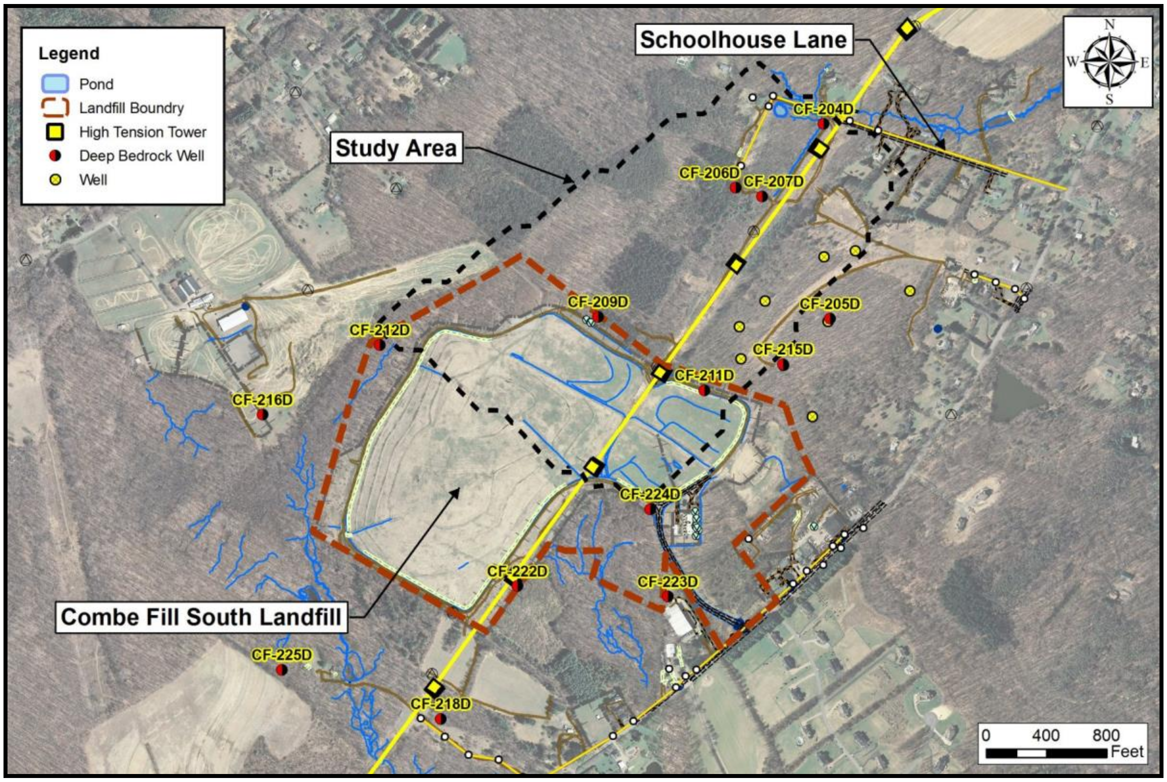

Figure 2 – Site Map

The landfill was originally operated as a municipal dump from the 1940s until 1981, accepting domestic and non-hazardous industrial wastes as well as waste sludge, septic tank waste, chemicals and waste oils. Sometime after the landfill was closed, samples of groundwater beneath and northeast of the site were found to be contaminated.

1.3 Purpose of Investigation

The purpose of performing a Willowstick geophysical investigation is to help identify groundwater flow paths that could influence the transport of contaminants beneath and away from the site to the northeast. Because saturated strata act as good subsurface electrical conductors, the geophysical technology employed for the investigation energizes the groundwater with a signature electric current. This electric current follows the water-saturated zones through the subsurface. By identifying preferential electric current flow patterns, the technology can successfully answer questions about where groundwater preferentially flows.

Although the technology can identify zones of preferential groundwater flow, it does not directly identify water volume. Therefore, groundwater flow rates should be determined by other field methods.

Willowstick believes the information provided in this report will help in the evaluation and design of monitoring well placement which can be used in conjunction with other data to better understand how and where groundwater flows beneath and away from the landfill.

2.0 WILLOWSTICK METHODOLOGY

2.1 Technology Explained

The Willowstick technology has been successfully used on many sites to identify, map and model preferential groundwater flow paths. If the reader is unfamiliar with the methodology, the reader is referred to the White Paper available at www.willowstick.com. The White Paper presents detailed information about how the technology is used to characterize zones of highest transport porosity or subsurface preferential flow paths. The White Paper can also be used as a reference to help explain certain concepts of the exploratory and diagnostic process. See "Table of Contents" at the beginning of the White Paper for a quick reference guide to find specific sections that can help clarify certain aspects of the survey and modeling process.

3.0 CONTRACT AND WORK SCHEDULE INFORMATION

3.1 Contract Information

3.2 Work Schedule

Fieldwork was initiated on Monday, June 10th, 2013. Fieldwork entailed mapping features pertinent to the investigation (including verifying power line locations and monitoring well locations, electrode locations and circuit wire route), placing electrodes in the targeted monitoring well locations, energizing the subsurface study area, and measuring and recording magnetic field intensities over the surface of the study area. The field work took approximately three weeks to complete. Data reduction, modeling, interpretation and report writing took an additional four weeks to complete. The entire investigation was completed in roughly two months.

4.0 APPROACH TO THE WORK

4.1 Survey Configurations

Originally only two survey layouts were proposed for the investigation. However, based on preliminary results, six survey configurations were eventually used as part of the overall investigation—four of which provided quality data that contributed to the overall interpretation. These four surveys utilized a horizontal dipole configuration (see Figure 3).

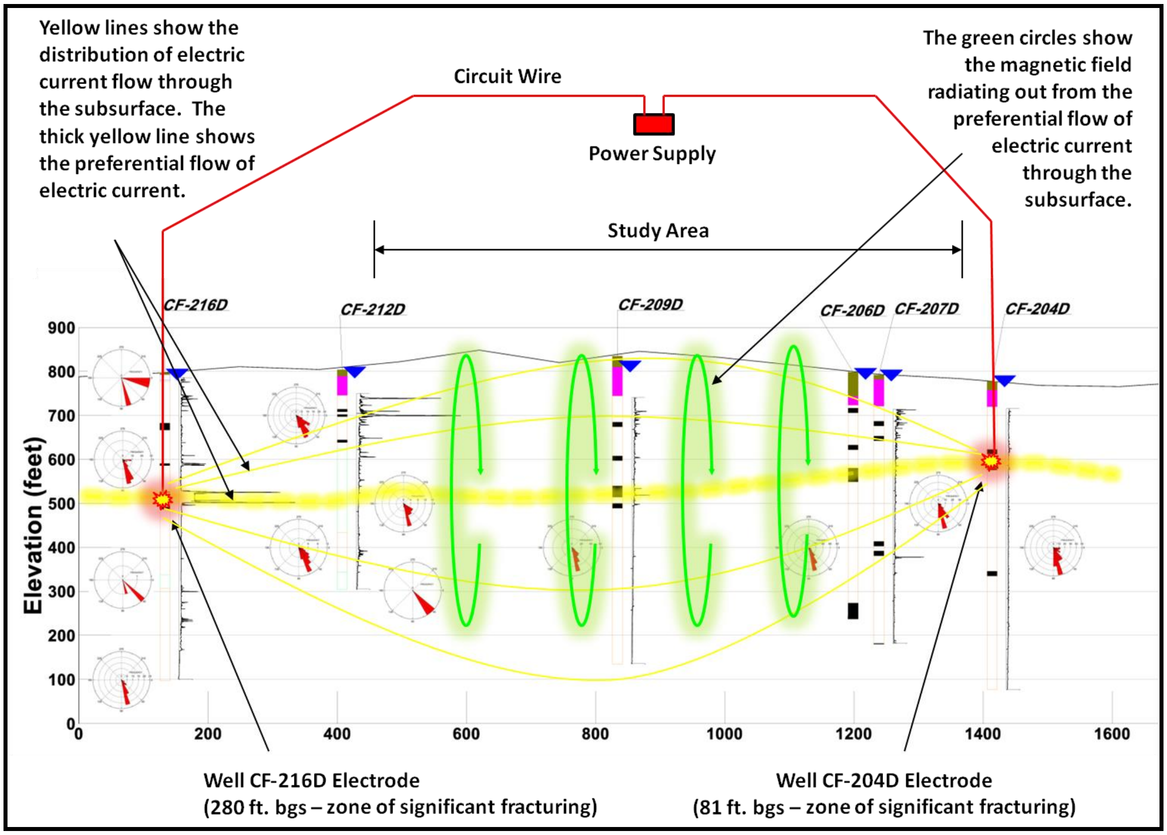

Figure 3 – Schematic of a Typical Horizontal Electrode Configuration
(Cross-section provided by)

A horizontal electrode configuration places an electrode cross-gradient of the landfill—in this case in a well completed into the groundwater of interest. A second electrode is placed down-gradient of the landfill in a well also completed in the groundwater zone of interest. The overall approach involves injecting and driving electric current between the strategically placed electrodes located on either side of the study area. An alternating electric current (AC) with a signature frequency (380 hertz) was applied to the paired electrodes. As electric current flowed between the electrodes, it generated a recognizable magnetic field that was measured from the earth's surface. The magnetic field was used to identify and model the distribution of electric current. By identifying electrically conductive flow paths and patterns between the strategically placed electrodes, questions can be addressed regarding where groundwater preferentially flows out from beneath the landfill to the northeast.

Two of the six surveys utilized a vertical dipole configuration (see Figure 4).

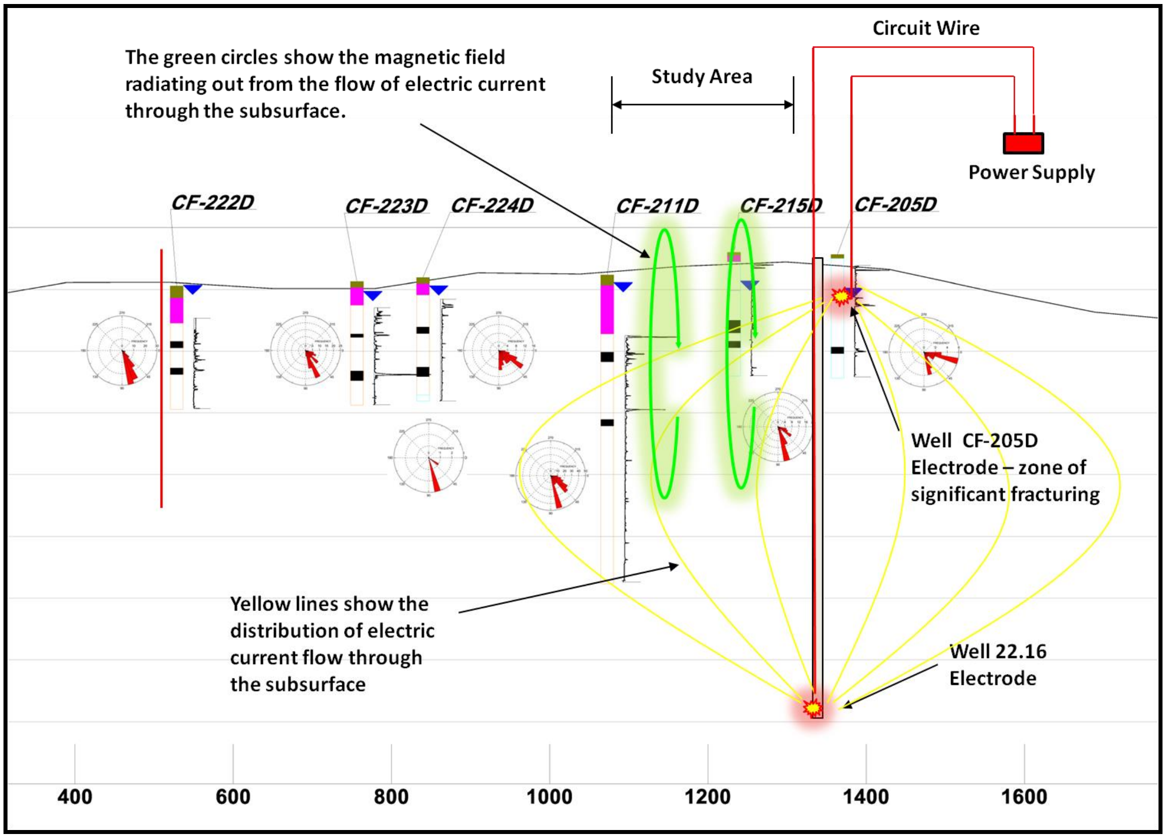

Figure 4 – Schematic of a Vertical Electrode Configuration
(Cross-section provided by)

A vertical dipole places one electrode directly above a deep electrode (one in shallow groundwater and a second deep in a well). This was done in an effort to bias electric current downward and away from surface utilities, which can help reduce interference from surface culture like that observed on the overhead transmission line. Two vertical dipoles were attempted and for the most part completed as part of the investigation, but they did not provide much information due to near-vertical bedding planes and steel cased wells, both of which had a tendency to short-circuit the electrical energy. As a result, magnetic field strength and signal-to-noise ratios were low indicating that electric current was not able to disperse outward into the subsurface.

It is sometimes difficult to know just how many or which electrode configuration will enable adequate characterization of subsurface preferential flow paths. In some cases, only one configuration is sufficient to obtain detailed information about a particular flow path; whereas, in other cases, two or more configurations may be required (depending upon the size and complexity of the site). Determining the number of energizing perspectives and which one(s) are best suited for a particular problem often requires some trial and error work—as experienced for this investigation.

4.2 Measurement Station Density

Measurement stations (small red "+" signs or crosses shown in the figures) were initially established on a 33 m or 108′ x 108′ grid. In areas that warranted additional detail, measurement stations were tightened to a 16.5 m or 54′ grid. Station spacing varied slightly depending upon terrain, vegetation and access. Many measurement stations were occupied repeatedly for quality control purposes. The position and elevation of each measurement station was recorded as part of the fieldwork. These spatial locations are critical to quality control measures, data processing, data interpretation and modeling. The measurement density or grid spacing was adequate to obtain sufficient detail and resolution for identifying preferential electric current flow paths while at the same time optimizing funds available for the investigation. Horizontal resolution of the data is ¼ to ½ the station spacing, or 28-54 foot accuracy on the larger 108′ grid, and 14-28 foot accuracy on the tighter 54′ grid.

The original 108-foot by 108-foot grid was established by Willowstick and sent to as a shapefile. used a combination of real-time kinematic (RTK) satellite navigation and differential global positioning system (DGPS) techniques to locate the measurement stations in the field prior to Willowstick mobilization to the site. Each measurement station was then physically marked with either a stake or survey nail and had its position collected with either the RTK or DGPS unit.

The measurement stations for the 54-foot by 54-foot grid were located during the respective surveys with a combination of DGPS and/or physical measurement. Each measurement station had its position collected with the DGPS unit.

5.0 DATA REDUCTION

5.1 General

A geo-referenced aerial photograph of the site was used as a base map for presenting the results of the investigation. Features critical to the investigation have been drawn on the aerial photograph to enhance their presence and to supplement the information contained on the base map. Please note that many of the figures presented here in the body of the report are also provided as full-size figures in Appendix A.

5.2 Data Reduction, Filtering and Quality Control

After energizing the study area from the various electrode configurations and collecting the magnetic field data, the data was reduced, normalized, and subject to appropriate filtering and quality control criteria to prepare it for interpretation and modeling.

It should be noted that circuit continuity, magnetic field strength, and signal-to-noise ratios for all four horizontal dipole configurations were strong indicating quality data. The noise floor (mean ambient field noise determined from a sampling of several frequencies in the noise spectrum) remained low and constant throughout the investigation resulting in quality data. Numerous measurements were repeated throughout the course of the fieldwork, all of which indicated clean, consistent and reliable data.

6.0 SURVEY #1

6.1 General

Survey #1 provided the best overall picture of preferential flow beneath the landfill and to the northeast. The other surveys used in the investigation were designed to confirm and detail preferential flow paths found as a result of Survey #1.

6.2 Layout

Figure 5 presents the layout used for Survey #1.

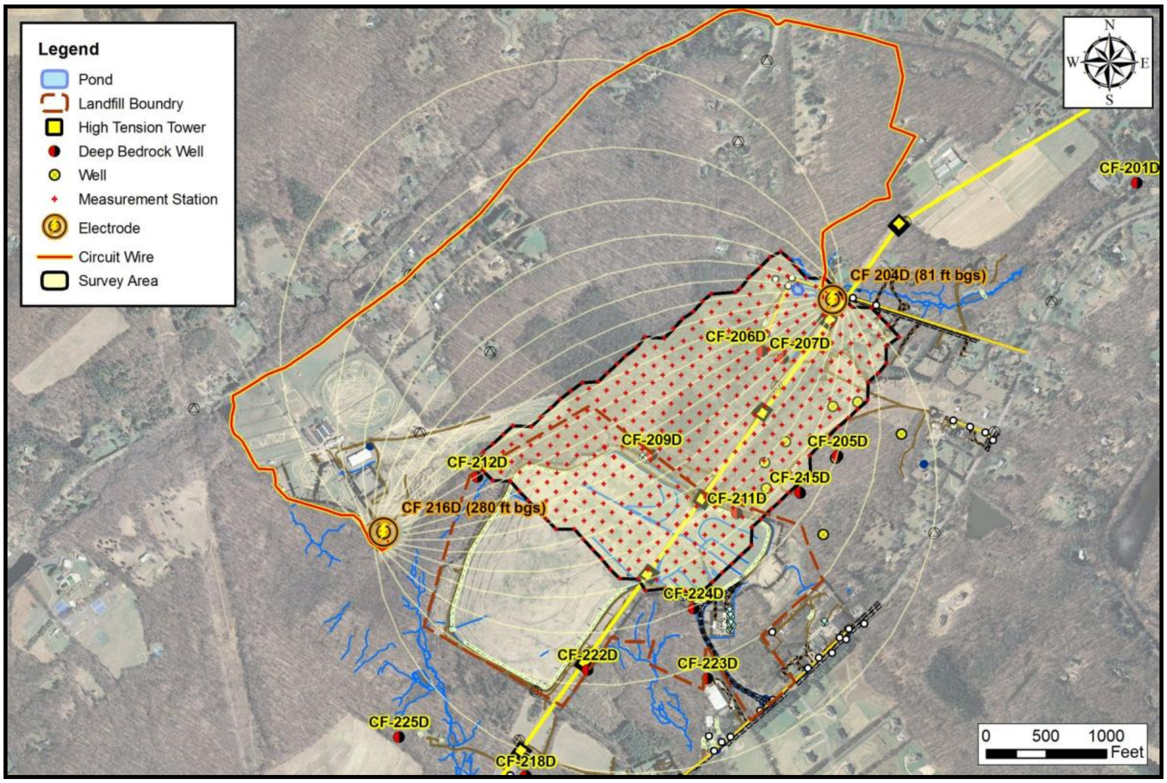

Figure 5 – Survey #1 Layout

Figure 5 shows features pertinent to the investigation. The study area covers roughly 116 acres. Electrodes (small circled lightning bolts in the figure) were strategically positioned in wells located cross-gradient and down-gradient of the study area. The cross-gradient electrode was placed in well CF-216D (280 feet bgs - elevation 517 feet). A down-gradient electrode was placed in well CF-204D (81 feet bgs - elevation 696 feet). These wells were completed in the groundwater of interest. The red/orange circuit wire connecting the strategically paired electrodes was positioned in a large loop around the study area. The electrodes and the circuit wire are located outside the study area due to the strong magnetic field influence around them. Survey #1 used the 108′x108′ grid. The locations of known conductive culture (transmission line, fences, etc.) are also drawn on the aerial photograph.

Survey #1 provides an overall characterization of how and where electric current preferentially flows out from beneath the landfill to the northeast. It should be noted that prior to performing

Survey #1, electrodes were raised up and down wells CF-216D and CF-204D—while energized—in an effort to identify common water bearing zones intercepting the two boreholes. Circuit continuity was poor at all combinations of horizons except those utilized for the survey. Originally, the investigation called for placing electrodes at multiple depths (shallow, medium and deep horizons). However, because circuit continuity was poor except where positioned, multiple surveys utilizing the same paired wells were not performed but substituted for other electrode configurations. This approach best characterized subsurface flow patterns beneath and northeast of the landfill. This will be explained later in the report.

6.3 Magnetic Field Contour Map

Figure 6 presents the magnetic field contour map created from the injected electric current for Survey #1.

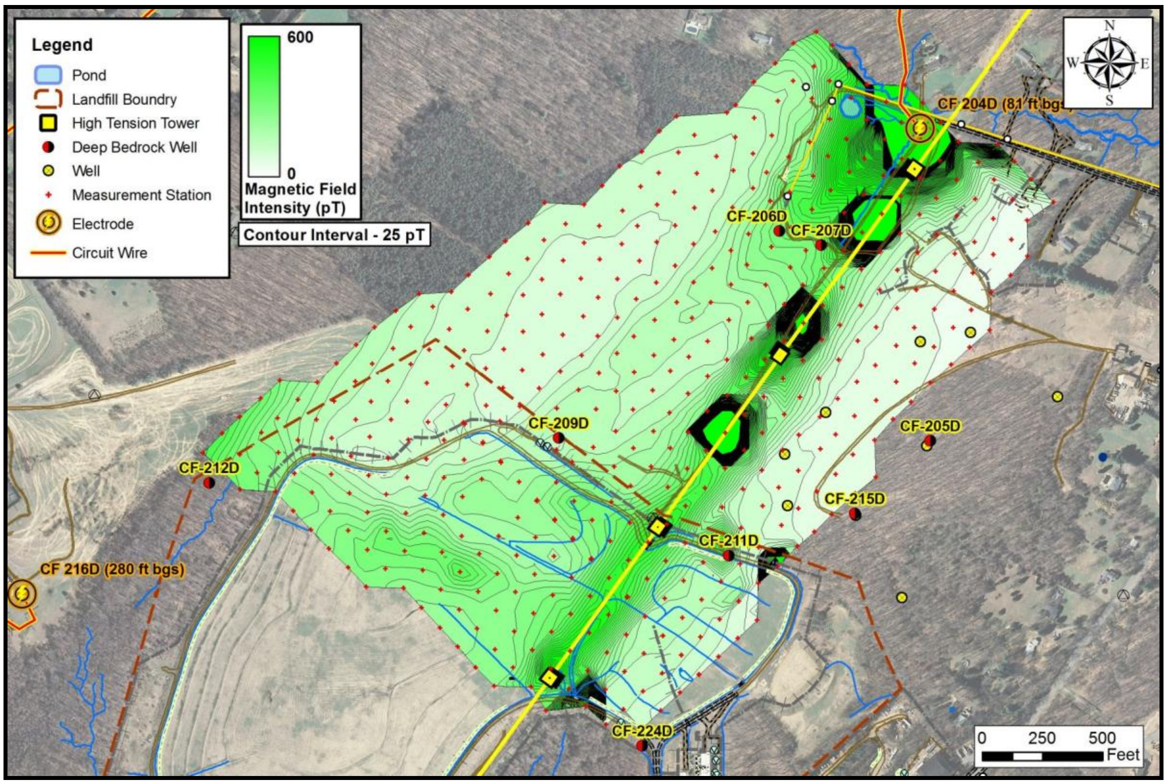

Figure 6 – Survey #1 Magnetic Field Contour Map

As shown, a significant amount of electric current flows onto near-surface conductive culture (landfill materials and transmission line). This is evident by the dark green shading beneath the landfill and along the transmission line corridor. Conductive culture is normally any man-made feature such as pipelines, power cables, steel fence lines, or other long continuous conductors. Also, landfill debris can be conductive depending on the amount and condition of sundry metals deposited in the landfill. Culture is often present and can be very problematic because it tends to be near-surface and can cause large anomalies that hide some of the magnetic signal coming from the subsurface. As electric current flowed out from well CF-216D (southwest corner of the figure), much of it flowed across and upward through the landfill debris toward the overhead transmission line running through the center of the study area. The transmission line's grounding system allowed electric current to flow onto the overhead power lines across the study area. This interference made it impractical to fully characterize preferential groundwater flow paths directly beneath the landfill and transmission line.

6.4 Predicted Magnetic Field Map

To identify areas of greater or lesser conductivity through the subsurface study area, a model was created of the site to predict the magnetic field response expected at each measurement station given the position of electrodes, circuit wire and topography. This prediction is made under the assumption of a homogenous subsurface conductivity environment (see Figure 7).

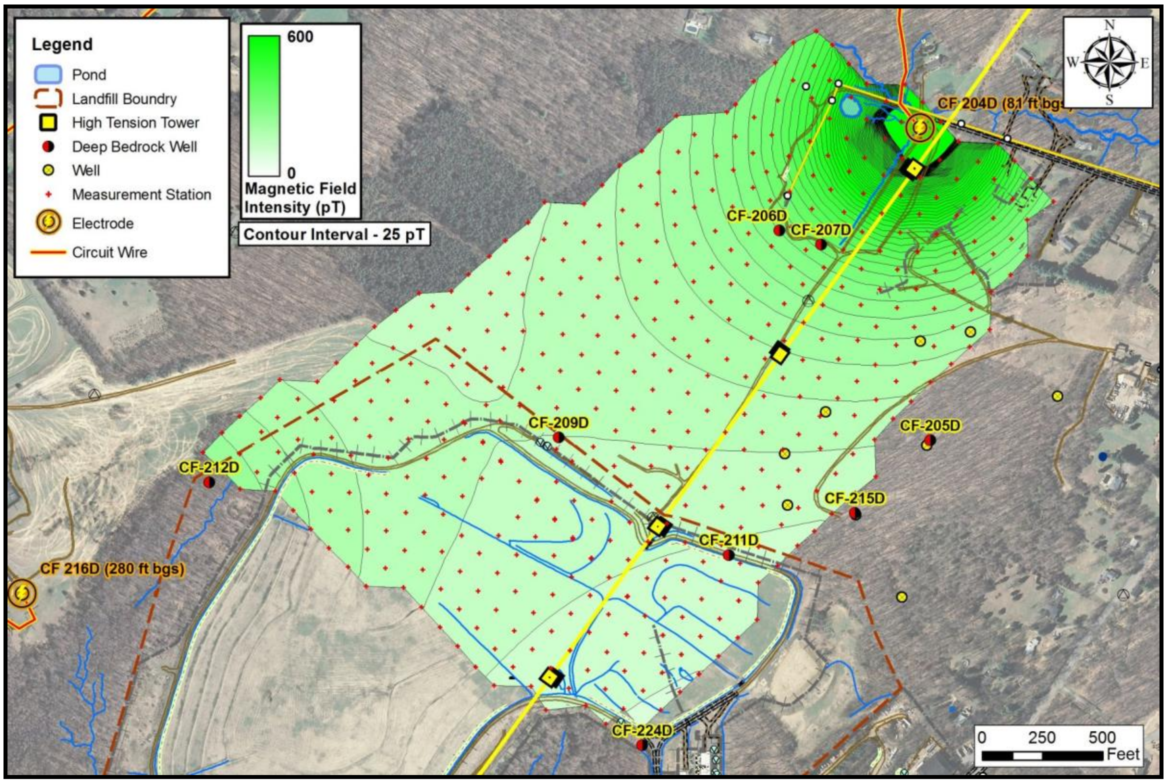

Figure 7 – Survey #1 Predicted Magnetic Field Map

Note how the predicted magnetic field map forms an hourglass shape. The model precisely predicts the effects of the electrodes, circuit wire and topography at each magnetic field measurement station.

6.5 Ratio Response Map

By dividing the magnetic field map (Figure 6) by the predicted magnetic field (Figure 7), a Ratio Response Map (see Figure 8) is created that removes electric current bias from the data set and shows areas of anomalous electric current flow (greater or lesser than predicted).

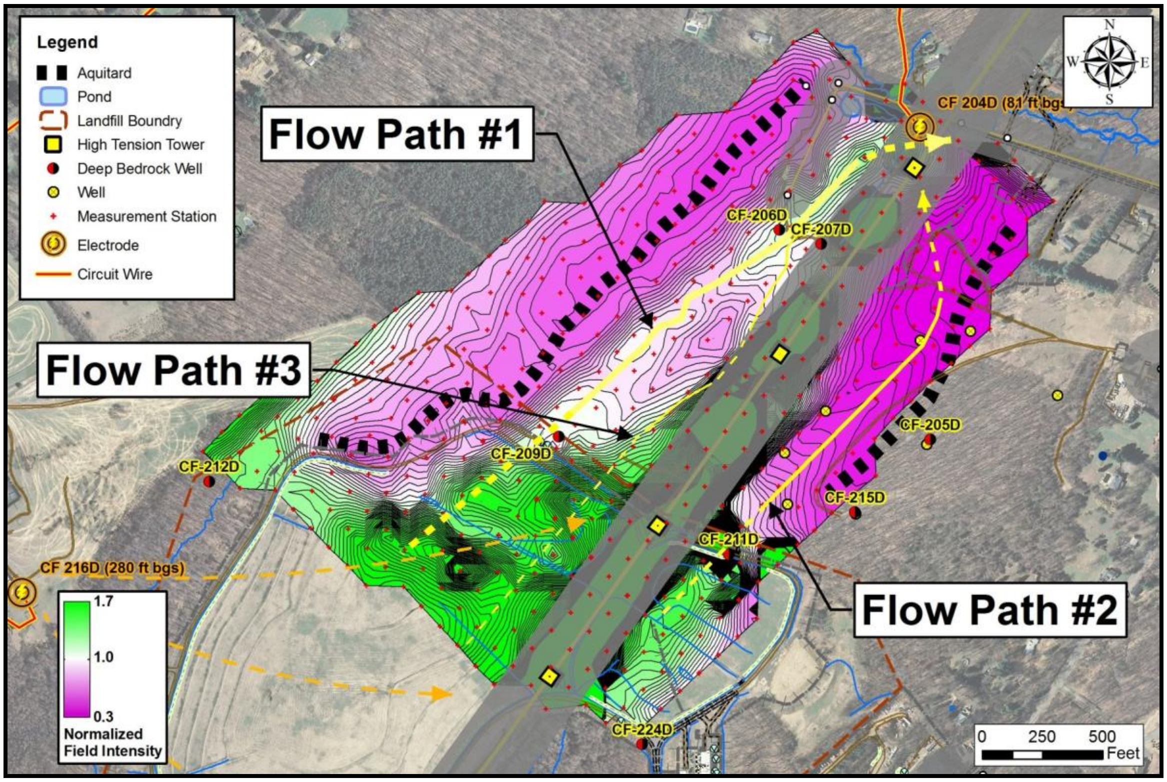

Figure 8 – Survey #1 Ratio Response Map

In Figure 8, a transparent gray cloud has been drawn across the study area where overhead power line interference made it impractical to fully characterize preferential groundwater flow paths. The white shaded contours (where the ratio is approximately 1:1) represent areas where the electric current intensity is equivalent to that predicted by the homogeneous model. Areas shaded purple indicate electric current flow is less than predicted, and areas shaded green indicate electric current flow is greater than predicted. It is important to emphasize that the purple shaded areas should not be overlooked. They can provide insightful information and can show preferential paths as revealed by the shape of contour lines, which is generally more important than color.

The ratio response map confirms that most of the electric current tends to flow up-through the landfill debris toward the transmission line from well CF-216D (see orange dashed lines). However, three conductive flow paths were identified which potentially convey groundwater and contaminants away from the landfill in the subsurface (see yellow paths labeled #1, #2 and #3). As will be shown, subsequent surveys confirm the location and depths of these preferential flow paths. The numbering or ranking of flow paths is based in part on the electric current intensity—suggesting more electric current flows through Flow Path #1 than #2, and more through #2 than #3.

Electric current flowing directly beneath the landfill is somewhat convoluted—flowing through waste materials as well as deeper preferential flow paths. Near the area where the transmission line crosses Schoolhouse Lane, the three noted flow paths appear to converge and then bend eastward as inferred by the yellow dashed arrows. The flow paths are inferred in these areas due to landfill debris and transmission line interference and are shown as dotted yellow lines.

To help interpret Survey #1's ratio response map, Surveys #4 and #6 will be presented next. Surveys #4 and #6 positioned electrodes to better direct electric current down the noted flow paths. Surveys #4 and #6 were also modeled and compared to Survey #1. Please note that Survey #2 was skipped and substituted by the other surveys due to the findings of Survey #1, which changed the approach from the way it was initially proposed. Survey #7 targeted the area where the three flow paths converge and bend eastward. Surveys #3 and #5 will be presented last. Surveys #3 and #5 were vertical dipoles that provided minimal information due to reasons mentioned (see Section 4.1).

7.0 SURVEY #4

7.1 Layout

Survey #4's electrode configuration was designed to target Flow Paths #1 and #3 between the landfill and Schoolhouse Lane (See Figure 9).

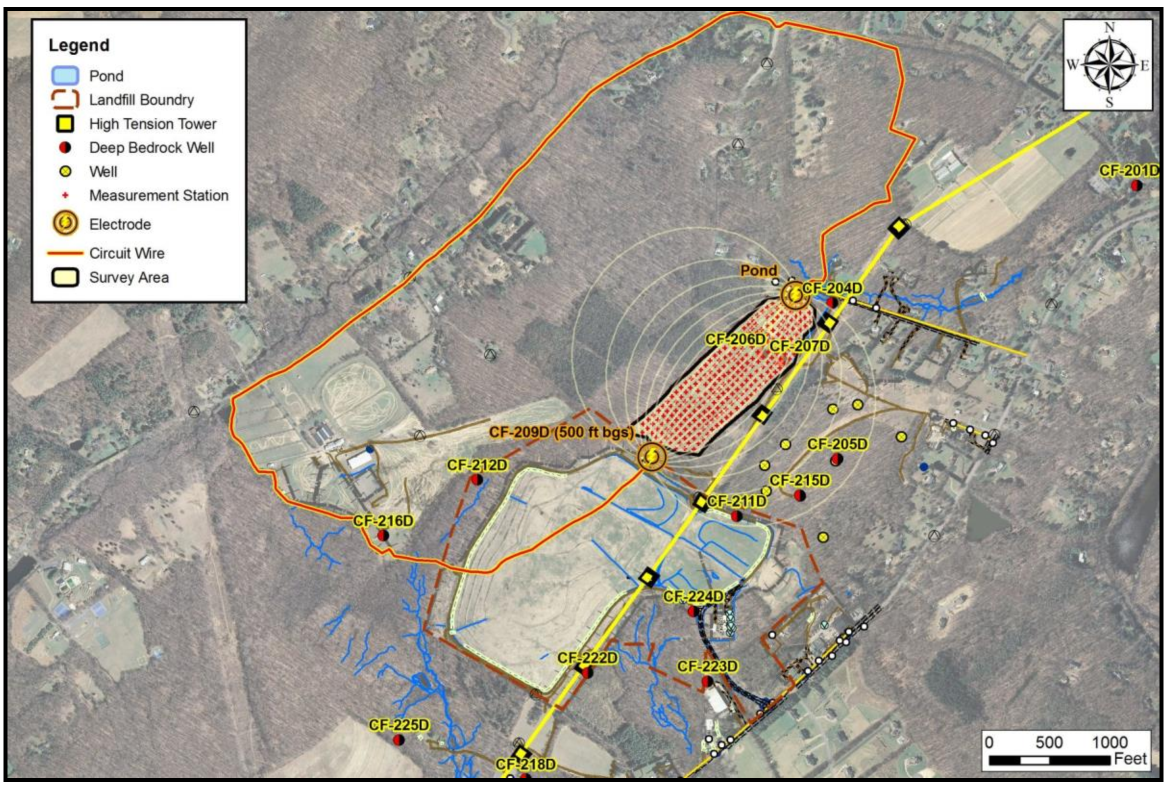

Figure 9 – Survey #4 Layout

Survey #4 placed electrodes in well CF-209D (500 feet bgs - elevation 334 feet) and a second electrode in a surface pond located southwest of Schoolhouse Lane and west of the transmission line. This configuration provided the best circuit continuity west of the power line. To delineate the fracture path with better accuracy, a tighter 54′ grid was used.

7.2 Ratio Response Map

Because Survey #4 uses the same data gathering and data reduction procedures as Survey #1, only the ratio response map will be presented for Survey #4. To view Survey #4's Magnetic Field Map and Predicted Magnetic Field Map, refer to the Figures Section in Appendix A.

Figure 10 presents the ratio response map for Survey #4.

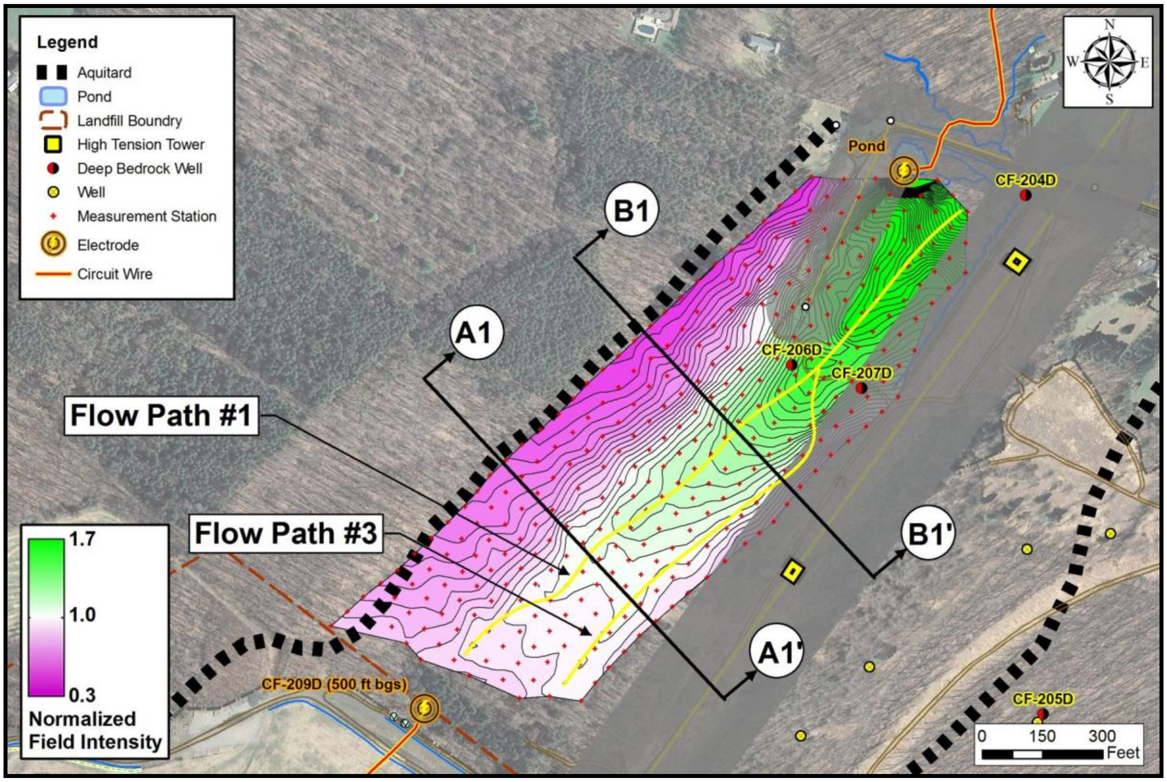

Figure 10 – Survey #4 Ratio Response Map

Survey #4 delineates two of the flow paths observed in Survey #1 (referred to as Flow Paths #1 and #3).

7.3 Electric Current Distribution Model

Because magnetic field measurements can only be obtained on the earth's surface, it is difficult to identify with any degree of certainty the vertical position or depth of preferential electric current flow without modeling. For this reason, the ratio response data was subjected to an inversion algorithm designed to predict the distribution of electric current flow in three dimensional space through the subsurface study area. Figure 11 presents a 3D view of the ECD model created for Survey #4.

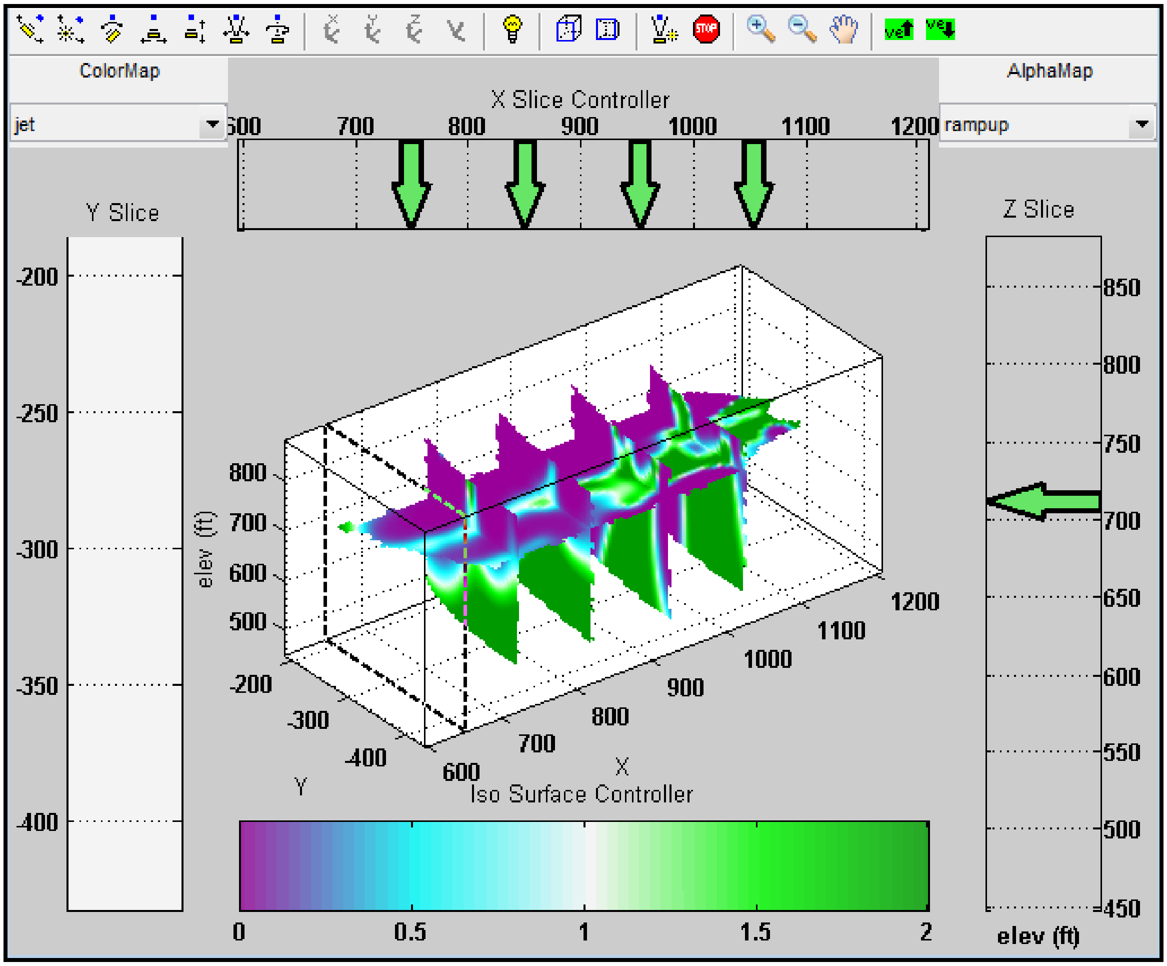

Figure 11 – Survey #4 ECD Model Slice Viewer

Willowstick uses MATLAB software to run inversion analysis and to analyze ECD inversion model volume data. The model viewer can generate slices at any elevation or cross-section position within the volume as demonstrated in the example. As part of the deliverable, Willowstick will provide the necessary MATLAB installer package and executables to run the ECD model viewer software.

In addition to ECD models generated for each survey of the investigation, a 3D *site model* was also created to show pertinent site features such as wells in relation to ECD model slices. Figure 12 presents a view of the site model, including a graphic representation of the following features:

- Surface Topography
- Landfill Boundary
- Monitoring Well Locations and Depths
- Overhead Power lines

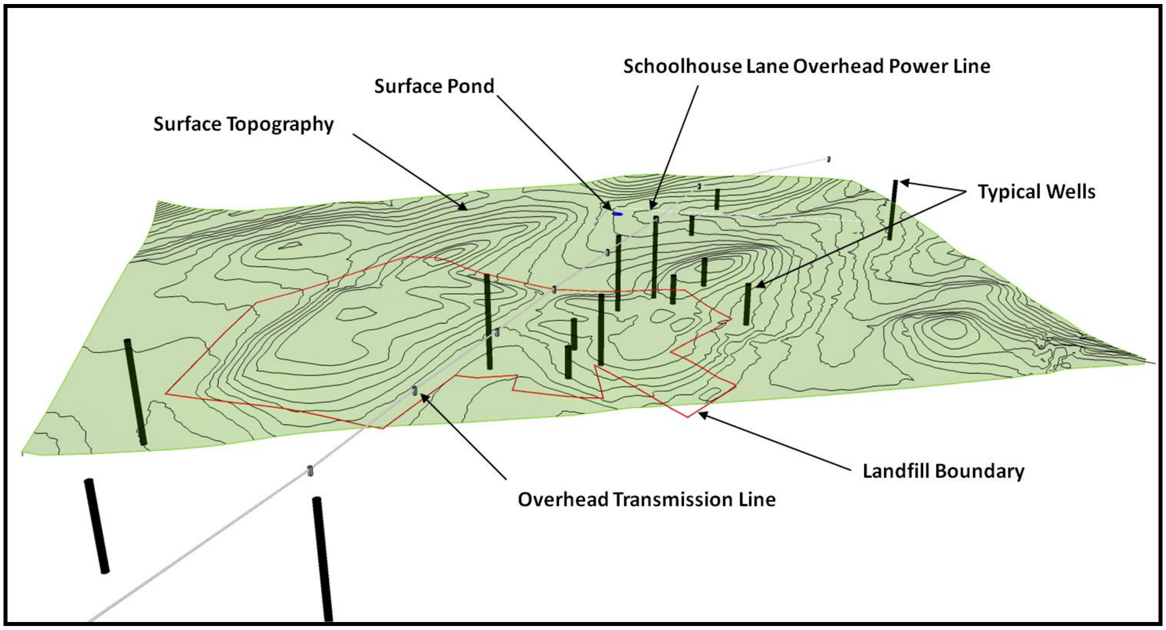

Figure 12– 3D Site Model (looking north)

Slices taken from the ECD model (cross-section, longitudinal and elevation views) will be embedded in the site model for analysis and presentation purposes.

7.4 Interpretation of ECD Model

To summarize the more notable findings of Survey #4's ECD model, Figures 13 and 14 present cross-sectional slices labeled A1-A1′ and B1-B1′ (see Figure 10 for section reference).

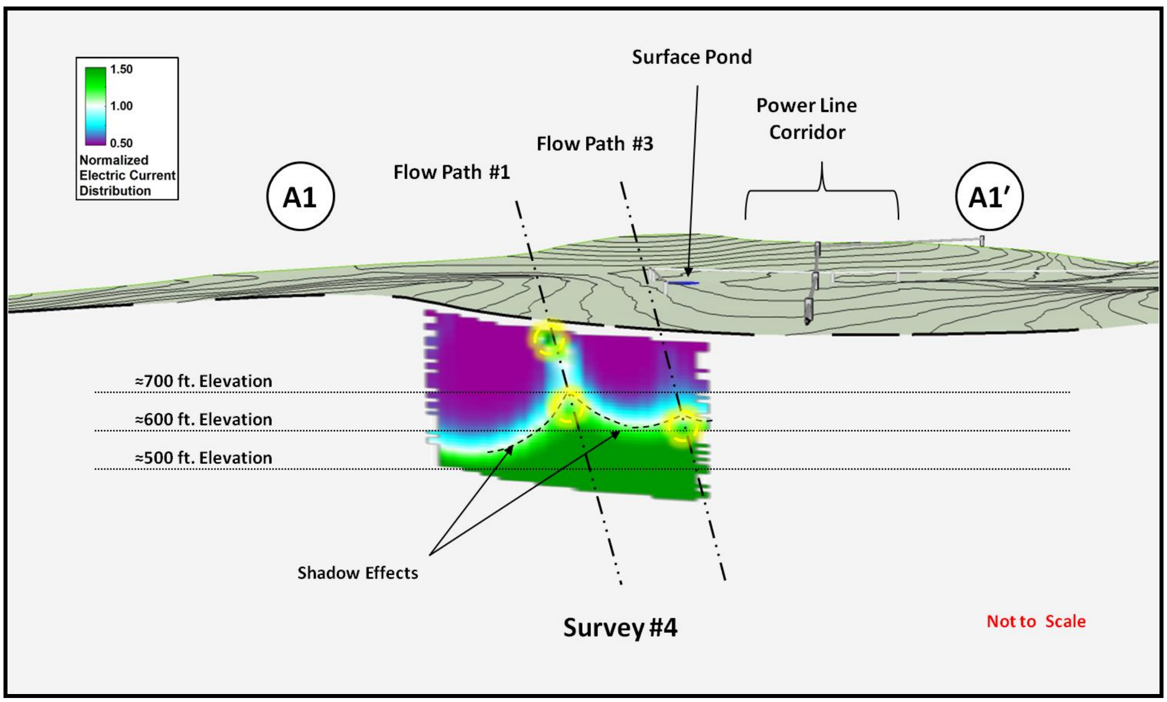

Figure 13 – Survey #4 ECD Model Slice (Section A1-A1′)

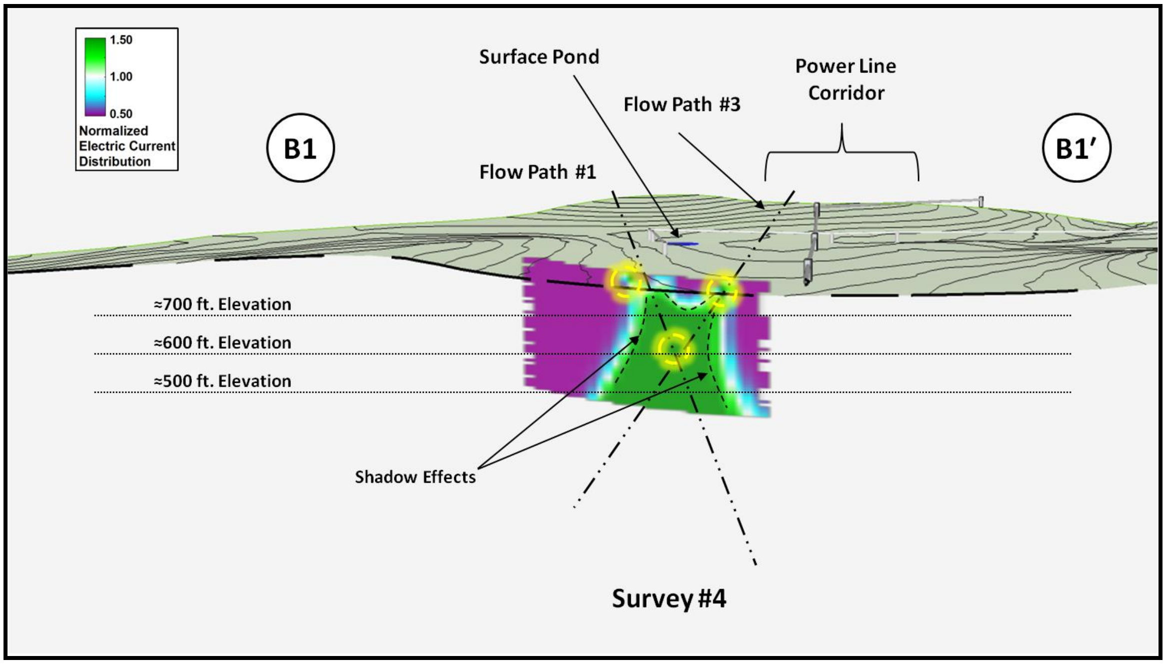

Figure 14 – Survey #4 ECD Model Slice (Section B1-B1′)

The contrast between purple and green shading is interpreted as an interface between competent and more porous subsurface materials. In these figures, Flow Paths #1 and #3 identify what are believed to be open fractures with a near-vertical but tilted orientation—as highlighted with dashed black "center" lines. These fractures act as open conduits to potentially conduct landfill contaminants away from the site. Flow Path #1 conducts more electrical energy than Flow Path #3. Section B1-B1′ is taken where the two flow paths begin to merge.

The yellow circles highlight what is interpreted as zones of highest electrical concentration. Minimal information can be discerned at elevations below the deepest yellow circles due to the "shadow effects" that occur below the detected flow zones. A good analogy for explaining the shadow effect is to think of the survey data as shining a flashlight at something from above. If there is a solid object (a flow path or some conductive pathway) the top will be illuminated but a shadow will be cast below the object. Note how the green shaded areas spread out going down through the models below the most conductive zones.

It should be noted that Survey #4's ECD model best defines subsurface flow paths between wells CF-209 and CF-207 west of the transmission line corridor (see Figure 10). This area is least affected by landfill debris and overhead power lines. As a result, flow paths are best defined in this area. Outside of this area, flow paths are less clear due to near-surface conductive culture.

To further characterize preferential Flow Paths #1 and #3 west of the transmission line corridor, Figure 15 presents a series of cross section slices.

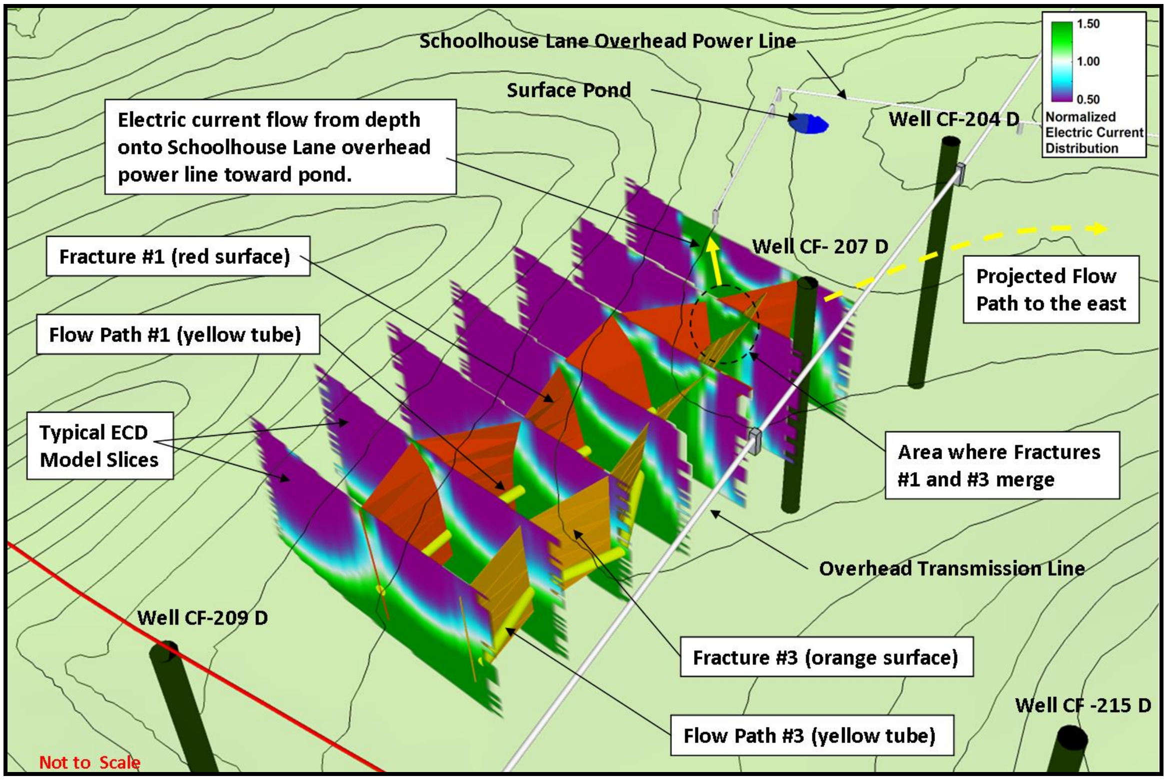

Figure 15 – Survey #4 ECD Model (Stack of Cross Sectional Slices)

The slices are taken at approximately 150-foot intervals. This view shows the connection between cross sectional slices. The red and orange shaded surfaces identify fractures #1 and #3, respectively. Yellow tubes show where electric current preferentially flows at depth along the fracture paths.

To understand the scientific accuracy of the ECD model and preferential flow paths determined by model analysis, a few considerations must be kept in mind. Horizontal error in the position of preferential flow is ¼ to ½ the spacing between data stations (maximum error). For Survey #4, a 54-foot grid spacing was used. Therefore, the horizontal error would be +/-14 to 28 feet, maximum. The ECD model provides an estimation of depth, but the accuracy of depth estimation depends on some factors that should be more carefully considered. The ability to estimate depth accurately is primarily dependent upon the degree of channelization or "focusing" of electric current. For example, Willowstick's experience with modeling shows that the depth accuracy can be as good as 5-10% (of the depth in question) where a high degree of channelization of electric current exists along well-defined flow paths. On the other hand, if electric current is distributed or dispersed evenly without any "channeling", then it has no preferential depth. Willowstick groundwater studies always fall somewhere between these two extremes. In this investigation, flow paths manifest as fairly strong heterogeneities. Therefore the expected depth accuracy is going to be comparatively good.

When comparing Survey #1's ECD model with Survey #4's, a very strong correlation exists. With tighter station spacing and more energy focused down along the flow paths, Survey #4 did a better job delineating the two paths. In Survey #1, Flow Path #3 was barely noticeable.

8.0 SURVEY #6

8.1 General

Survey #6's electrode configuration was designed to bias electric current between the landfill and Schoolhouse Lane to target Flow Path #2 east of the transmission line corridor (See Figure 16).

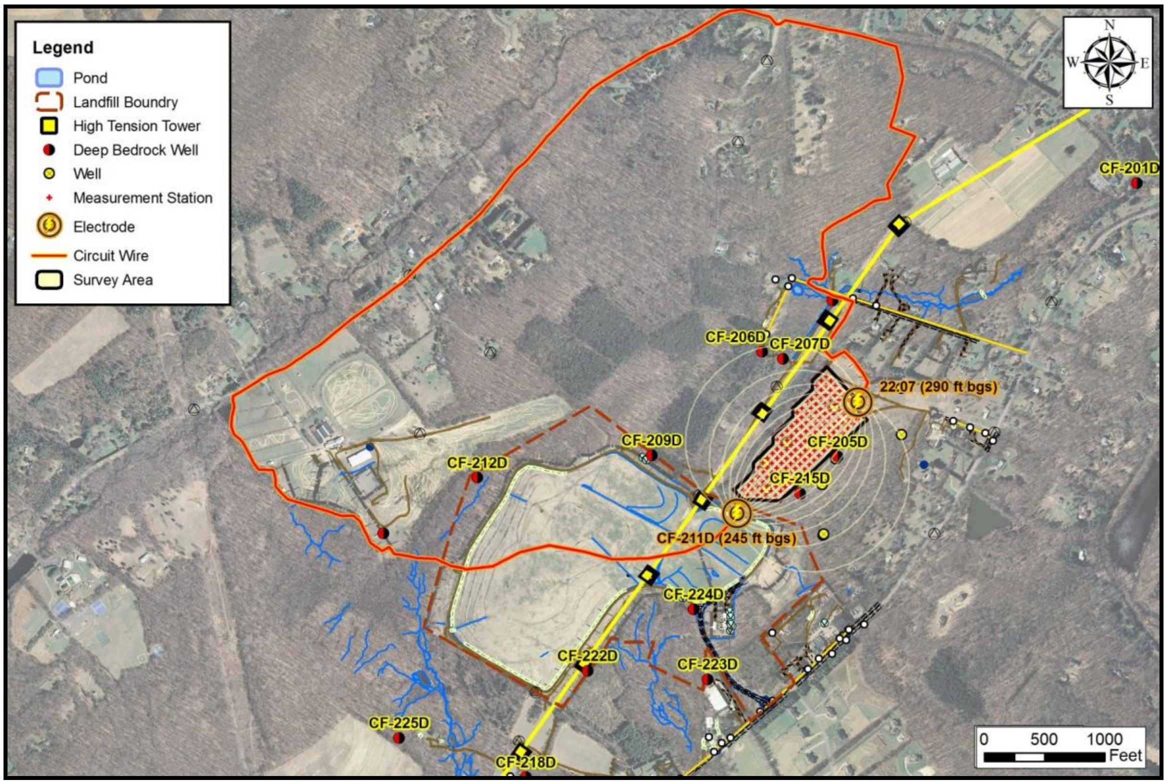

Figure 16 – Survey #6 Layout

Survey #6 targeted Flow Path #2. Several paired wells located east of the power line were tested for continuity prior to performing Survey #6. Continuity tests indicated that wells CF-211D and 22.07 were best connected electrically. Therefore, Survey #6 placed an electrode in well CF-211D (245 feet bgs - elevation 578 feet) and a second electrode in an unused potable water well 22.07 (290 feet bgs - elevation 517 feet).

Only the ratio response map and ECD model will be presented for Survey #6. To view Survey #6's Magnetic Field Map and Predicted Magnetic Field Map, refer to the Figures Section in Appendix A.

8.2 Ratio Response Map

Figure 17 presents Survey #6's ratio response map.

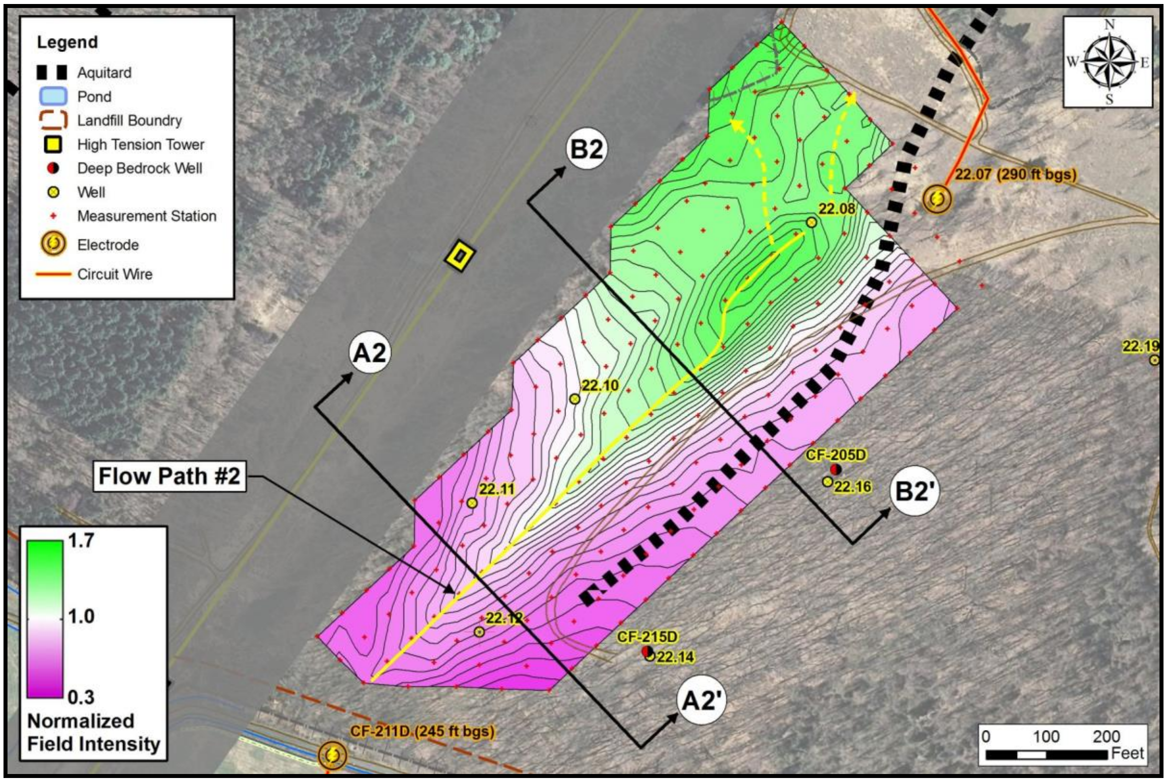

Figure 17 – Survey #6 Ratio Response Map

As highlighted by a yellow line, Flow Path #2 (noted from Survey #1) is delineated very well in Survey #6's ratio response map.

8.3 Electric Current Distribution Model

As with Survey #4, Survey #6's ratio response data was subjected to an inversion algorithm designed to predict the distribution of electric current flow in three dimensional space through the subsurface. To summarize the more notable findings of Survey #6's ECD model, Figures 18 and 19 present cross section slices A2-A2′ and B2-B2′.

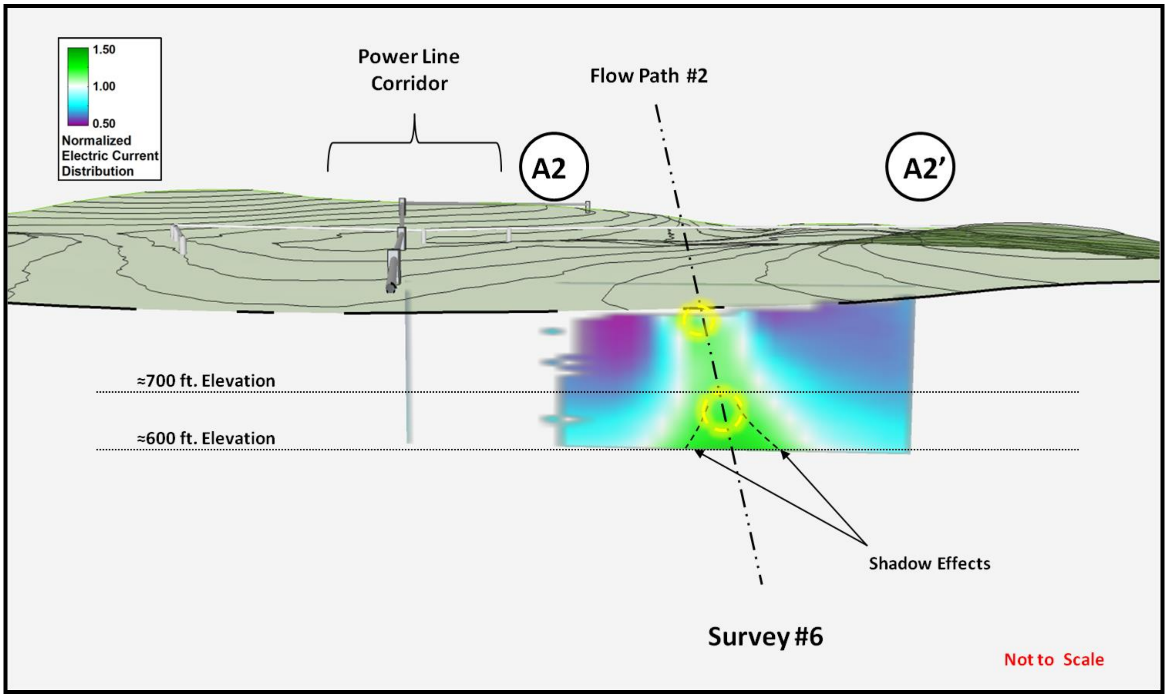

Figure 18 – Survey #6 ECD Model Slice (Section A2-A2′)

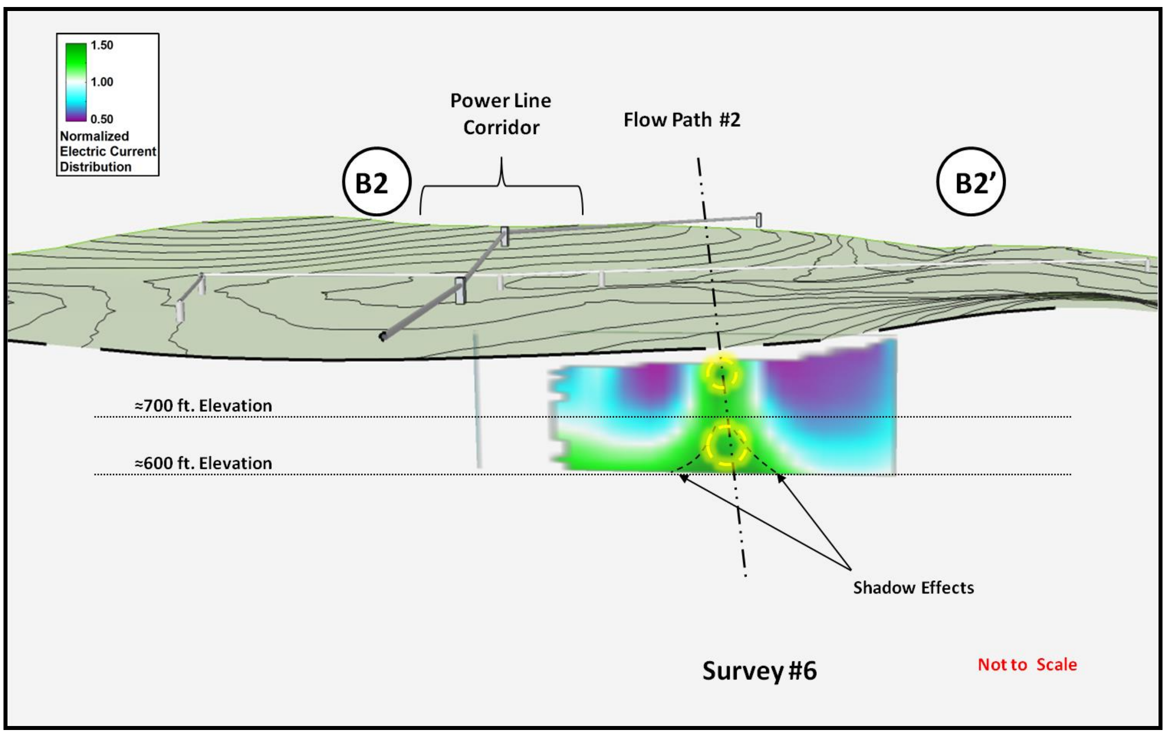

Figure 19 – Survey #6 ECD Model Slice (Section B2-B2′)

As mentioned, the contrast between purple and green shading is interpreted as an interface between competent and more porous subsurface materials. In these figures, Flow Path #2 is believed to be following an open fracture. The yellow circles highlight what is interpreted as zones of highest electrical concentration. By comparison, Flow path #2 appears slightly more conductive than Flow Path #3 but not as conductive as Flow Path #1.

To further characterize preferential flow paths east of the transmission line corridor, Figure 20 presents a series of cross section slices stacked one in front of the other.

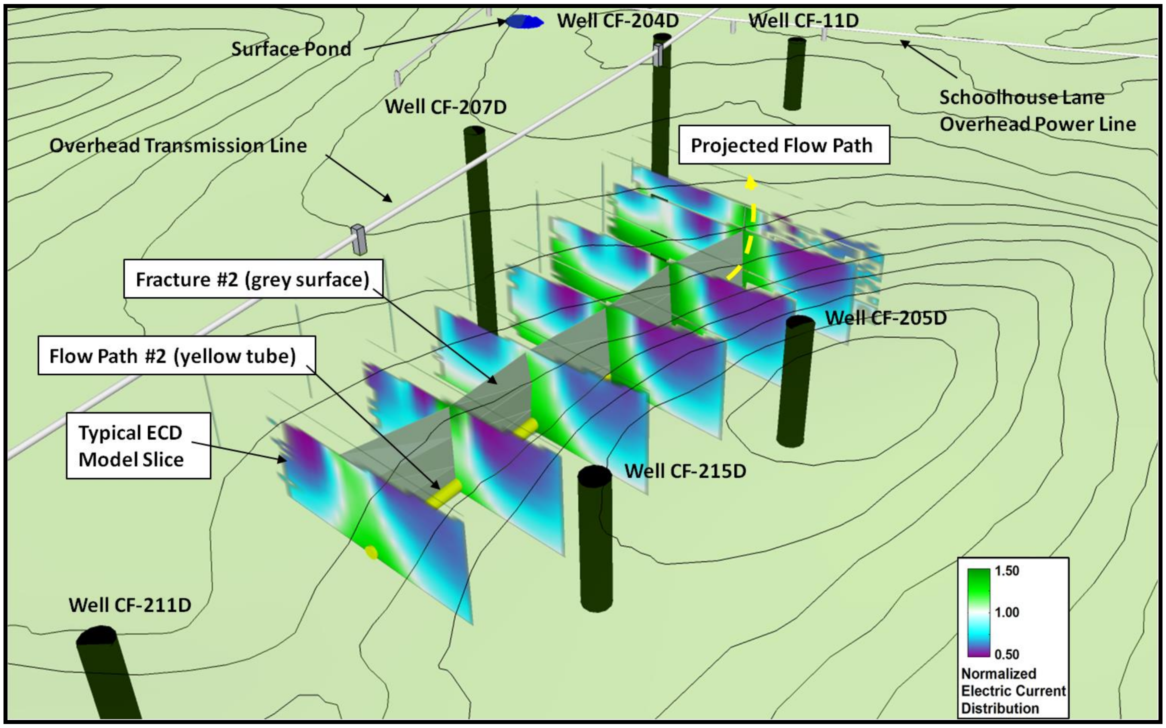

Figure 20 – Survey #6 ECD Model (Stack of Cross Sectional Slices)

These slices are taken at approximately 150-foot intervals. This view shows the connection between cross sectional slices. The gray shaded surface identifies fracture #2. A yellow tube identifies the location where electric current preferentially flows at depth along the fracture (Flow Path #2). At the north end of the survey area, the flow path bends toward Flow Paths #1 and #3 where they possibly converge.

Because it is difficult to present 3D models in the 2D format (within a written report), Willowstick has selected representative slices through the ECD models in an attempt to provide sufficient overview of the results and to present the interpretation of the data. By analyzing the ECD model carefully with the MATLAB slice viewer, the center of preferential flow paths can be determined in an effort to optimize vertical and horizontal well placement. Again, the MATLAB model, site model, and associated ArcGIS shapefiles will be included with the delivery of this report.

9.0 SURVEY #7

9.1 Layout

Survey #7 placed an electrode in a pond southwest of Schoolhouse Lane. A second electrode was placed in well CF-12D northeast of Schoolhouse Lane. The electrode in well CF-12D was placed at 85 feet bgs (elevation 715 feet). Figure 21 presents the layout for Survey #7.

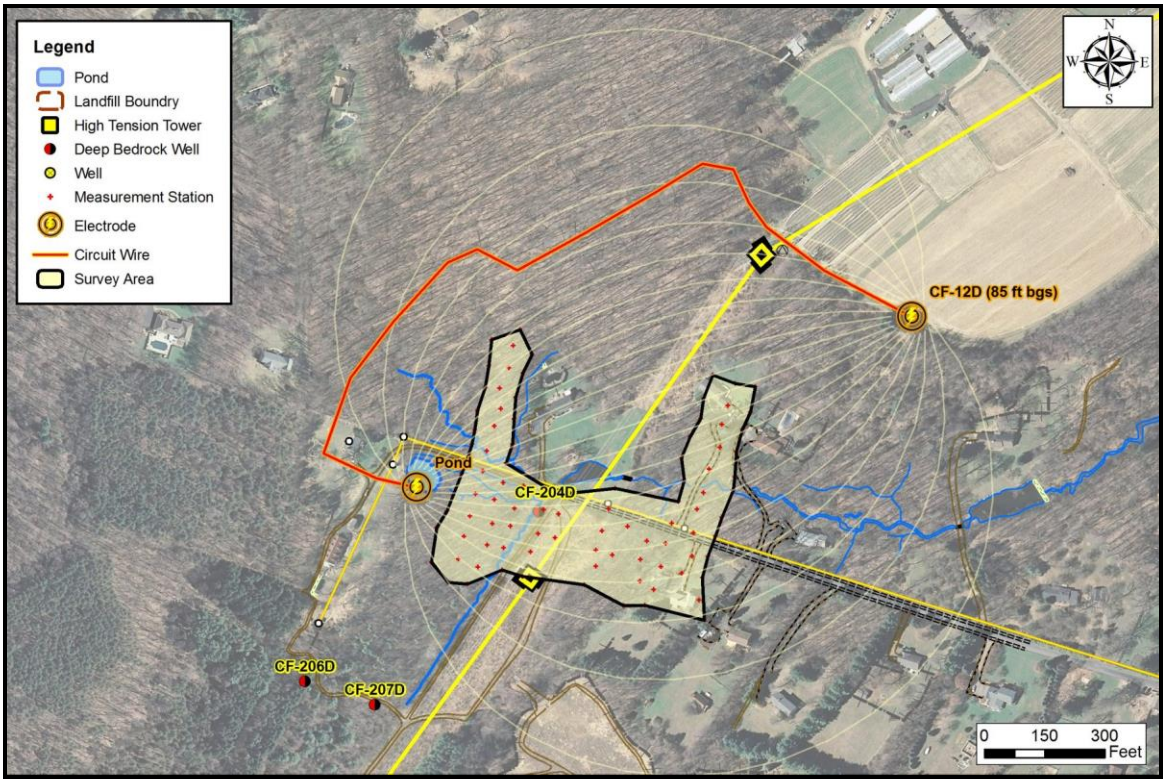

Figure 21 – Survey #7 Layout

The purpose of Survey #7 was to determine if the converging flow paths continued in a northeast direction or if they turned eastward. Survey #1 hinted to this, however, due to overhead power lines crisscrossing the area, it was unclear if the flow paths turned eastward. Regardless of the potential interference from the overhead power lines, an attempt was made to bias electric current beneath this area of interest. It should be noted that the study area is shaped like the letter “U”. The center of the “U” consists of private property which could not be accessed during the investigation.

9.2 Ratio Response Map

Figure 22 presents Survey #7’s ratio response map.

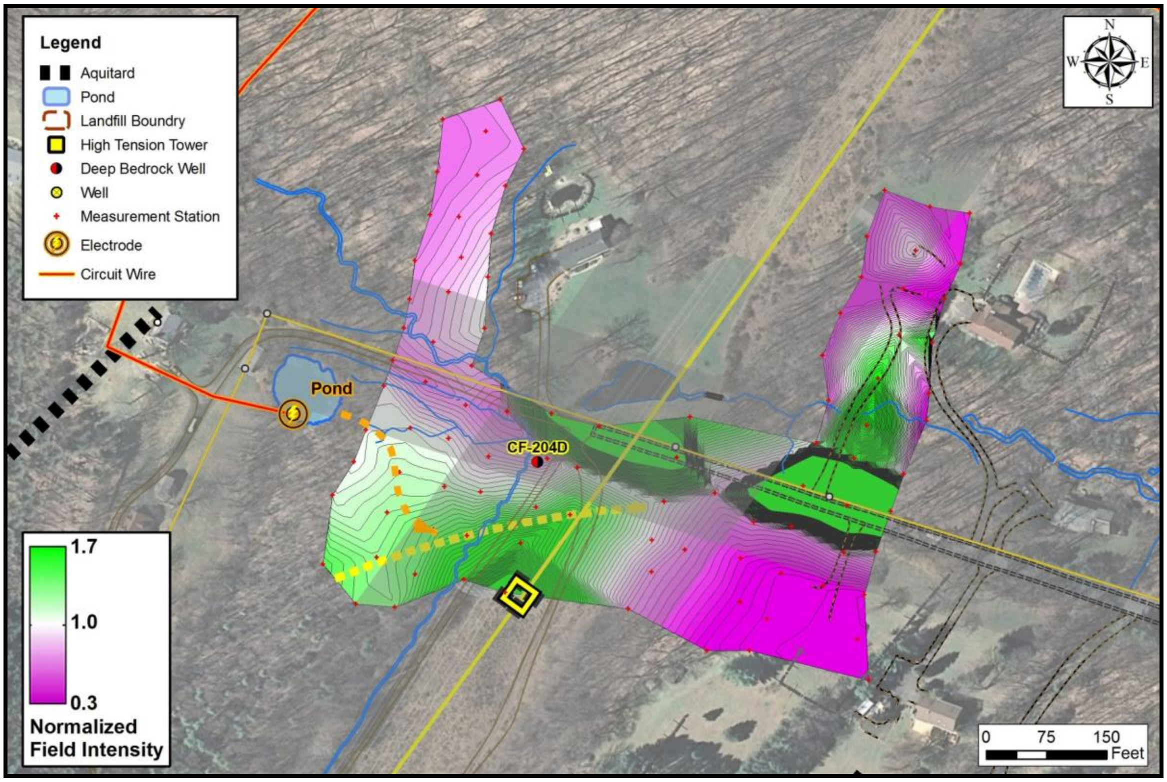

Figure 22 – Survey #7 Ratio Response Map

Based on a pre-modeling interpretation of Survey #7's ratio response map, electric current preferentially flows out from the pond (see orange dashed arrow) toward the yellow dashed line which represents the inferred flow path from Survey #1. There is no evidence in Survey #7's ratio response map suggesting that the flow path continues northward; it appears much more likely that it bends eastward.

9.3 ECD Model

Figure 23 presents a horizontal slice taken through Survey #7's ECD model at elevation 750 feet—roughly 50 feet below ground surface.

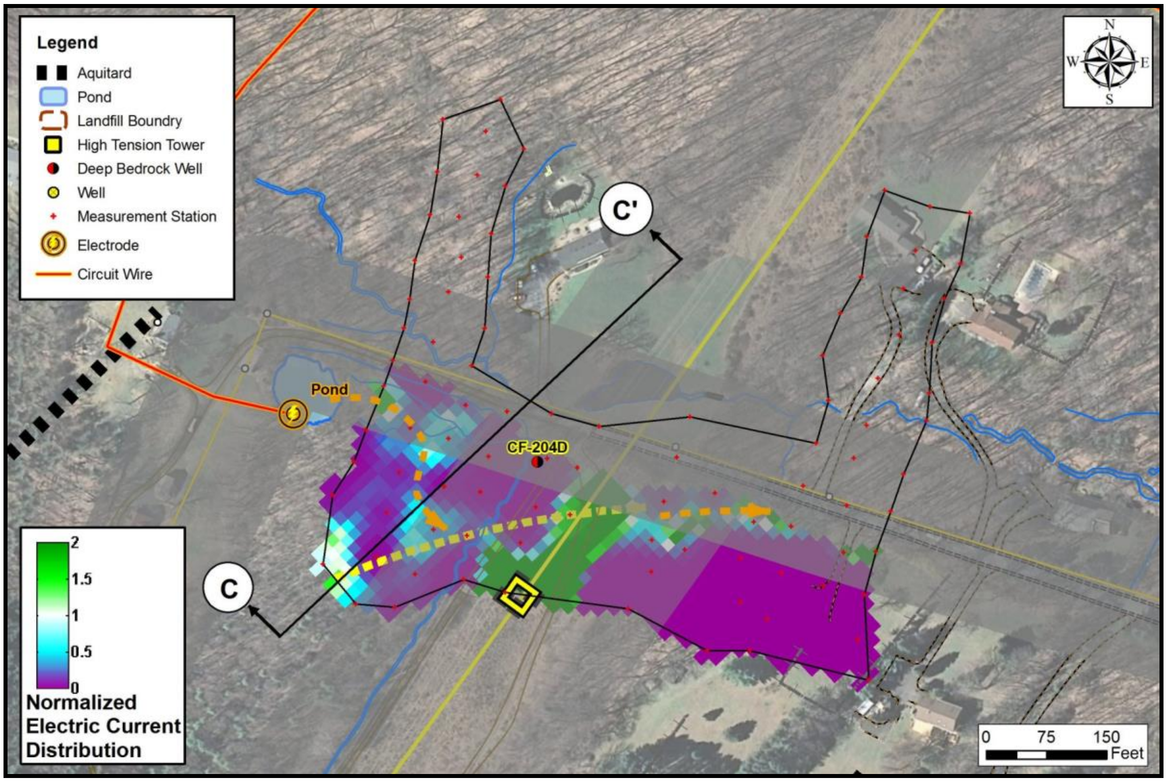

Figure 23 – Survey #7 ECD Model Slice (Elevation 750 feet)

This elevation slice shows dark green shading beneath the transmission line. This was expected due to the close proximity of the transmission line. The yellow dashed arrow represents the inferred flow path as observed in Survey #1. It is inferred because this portion of Survey #1 was unclear in defining the flow path due to the power line interference. On either side of the transmission line, however, electric current flow paths are noted by orange dashed lines. The orange dashed line on the west side of the transmission line denotes the path electric current follows from the pond down to depth in what is believed to the converging flow paths. The orange dashed line on the east side denotes a flow path to the east beneath Schoolhouse Lane. Survey #7 correlates well with Survey #1. Figure 24 presents cross-section slice C-C′.

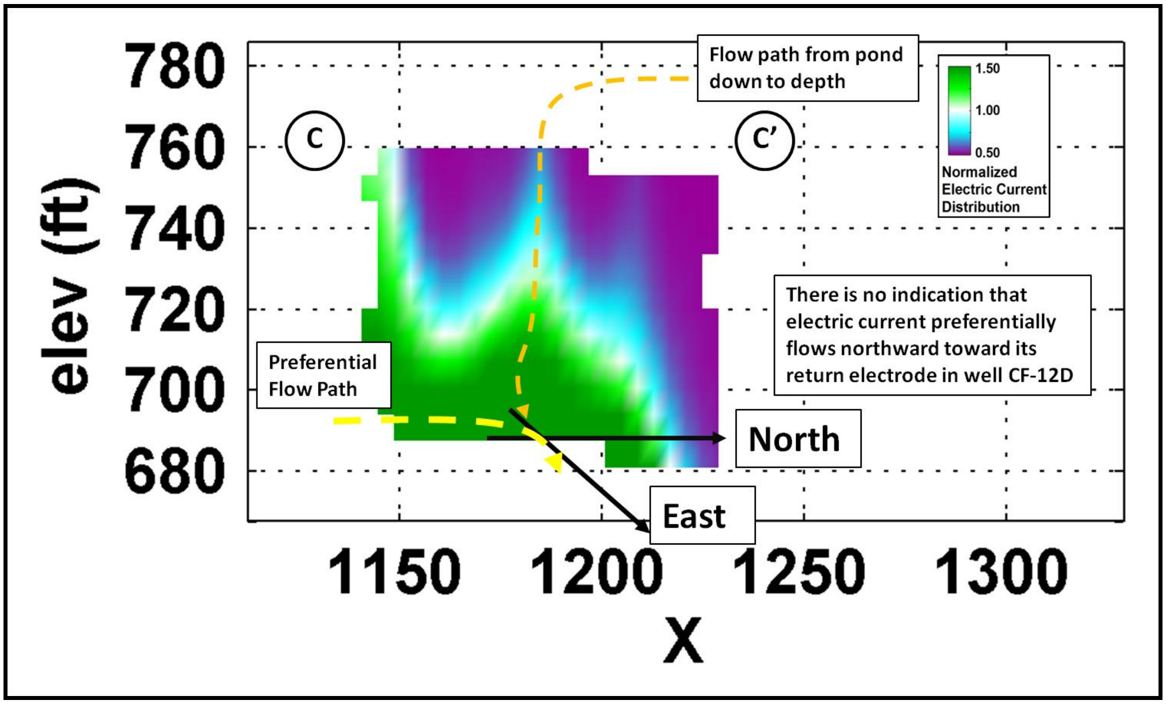

Figure 24 – Survey #7 ECD Model (Section C-C')

Again, there is no evidence that suggests the converging flow paths continue northward. Both Surveys #1 and #7 suggest that the flow paths bend eastward. Please note how the green shading in Figure 24 drops off along the north or right edge of Section C-C′.

To further describe preferential flow in the vicinity of Schoolhouse Lane, Figure 25 places Survey #7's ratio response map directly on top of Survey #1's ratio response map for comparison.

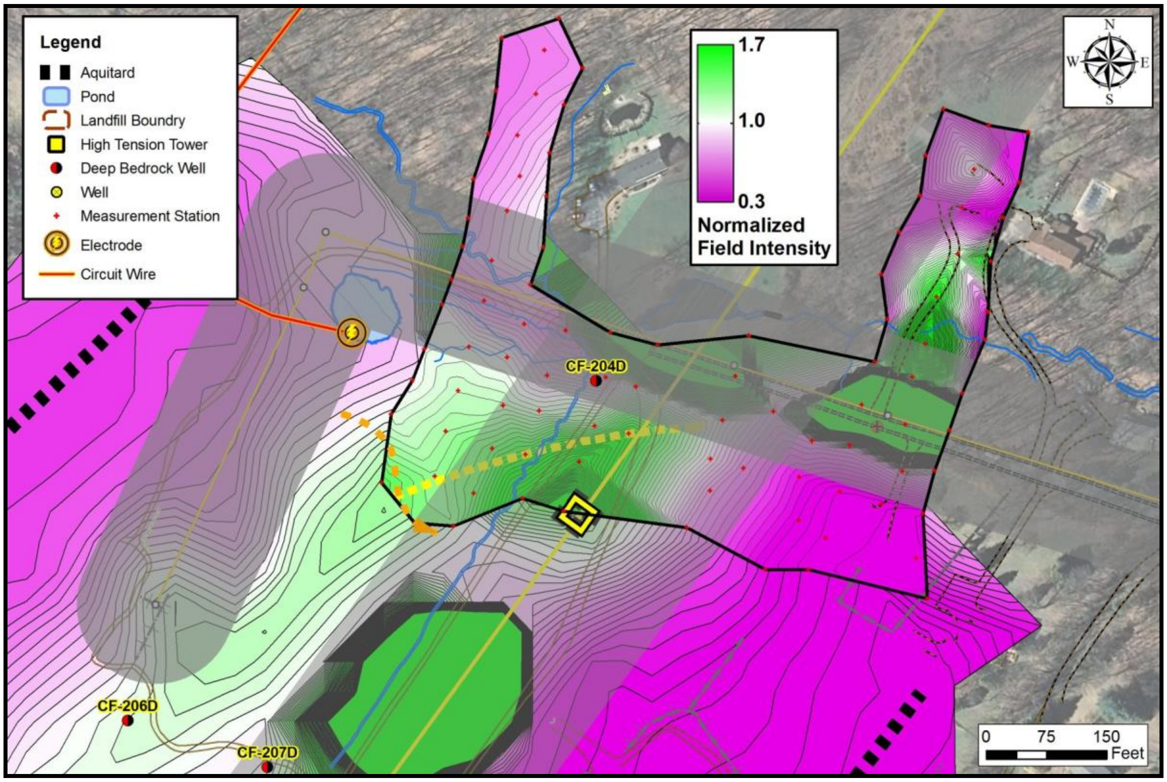

Figure 25 – Surveys #1 and #7 Ratio Response Map Comparison

These maps show a strong correlation. Keep in mind, both surveys energized the subsurface from very different perspectives—nevertheless, they both support the supposition that the open fractures that converged south of Schoolhouse Lane bend eastward in this area.

10.0 SURVEYS #3 AND #5 – VERTICAL ELECTRODE CONFIGURATIONS

10.1 Survey #3

As mentioned, vertical dipoles place one electrode directly above another (one in shallow groundwater and a second at depth). This was done in an effort to bias electric current downward and away from the surface, thereby minimizing interference from near-surface culture such as the landfill and the overhead power lines. Survey #3 was designed to bias electric current downward and away from the transmission line in the vicinity of Flow Path #2. A relatively shallow electrode was placed in well CF-205D (155 feet bgs). A deeper electrode was placed in an unused potable water well 22.07 (690 feet bgs)—creating a separation of roughly 535 feet. Although conditions for a vertical dipole were not ideal—given near-vertical bedding planes and steel cased wells—the vertical dipoles were tried and tested as part of the investigation. Figure 26 presents the signal-to-noise map created for Survey #3.

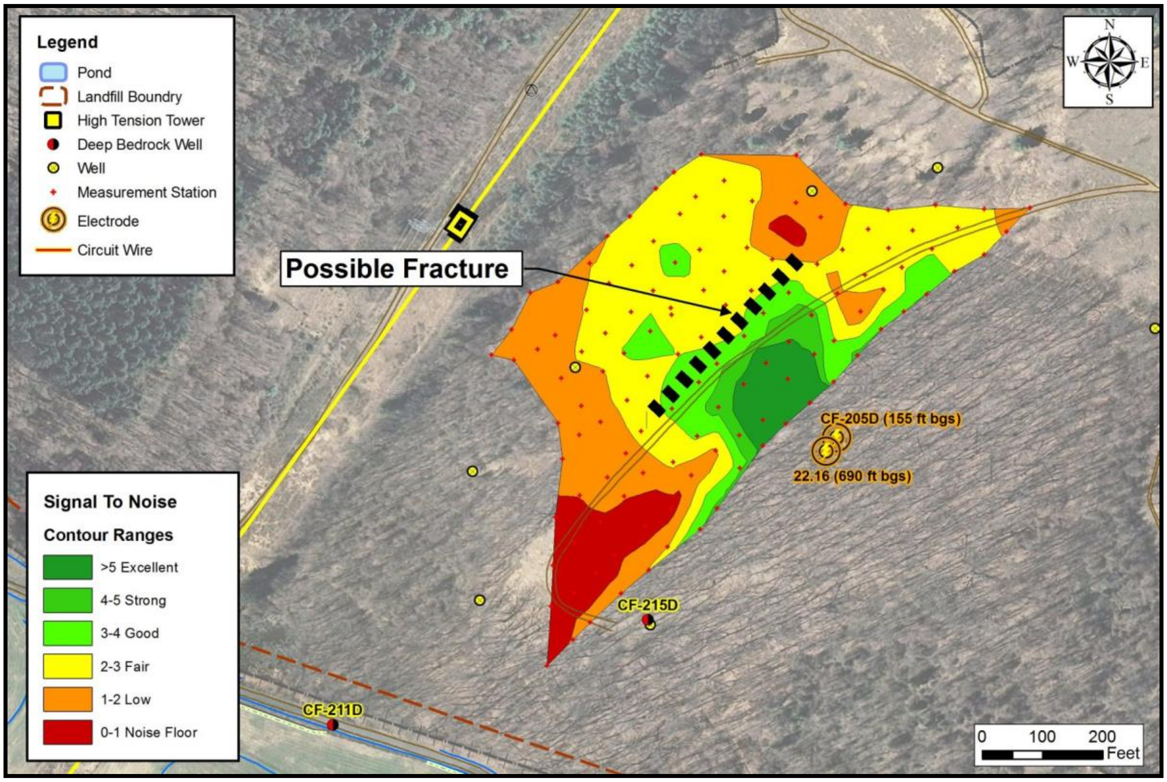

Figure 26 – Survey #3 Signal-to-Noise Map

Signal strength and signal-to-noise ratios are determined for every measurement station and are monitored to ensure that the signal is at least two to three times stronger than the average background noise in the frequency spectrum. If the signal-to-noise ratios fall below two, the data is unreliable. As evident from the red, orange and yellow shading in Figure 26, Survey #3 had poor signal-to-noise. Because Survey #3's measurements were weak—down around the noise floor, the survey was cut short and not completed. As a result, the survey is considered unreliable. The survey, however, did show evidence of a potential fracture as noted by a thick dashed black line. As electric current radiated out from the upper electrode, a strong signal was recorded as evidenced by the dark green shading. However, signal strength died quickly as it dived downward along fracture #2 to its return electrode at depth. There was no additional information gained from performing Survey #3.

10.2 Survey #5

Survey #5 was performed to characterize preferential flow paths in Flow Path #1 located near the north edge of the landfill. Survey #5 placed an upper electrode in well PZ-21R (91 feet bgs) and a lower electrode in adjacent well CF-209D (500 feet bgs)—creating a separation of about 409 feet. Again, this vertical dipole had similar difficulties as did Survey #3 and did not provide any additional information about Flow Path #1 below or northeast of the landfill.

11.0 SUMMARY OF INVESTIGATION

11.1 Summary of Results

The objective of the Willowstick geophysical investigation was to help characterize groundwater flow paths that could influence the transport of contaminants beneath and away from the Combe Fill South Landfill to the northeast. This objective has been met with very strong correlations among multiple surveys. To summarize the results, there are six important observations and findings that were derived from the reduced and modeled data. These observations and findings are:

1. Groundwater flowing beneath and away from the landfill increased the conductivity of earthen materials through which it flowed. As a result, the concentration and distribution of electric current was interpreted and modeled to help characterize how and where groundwater preferentially flows beneath and away from the landfill to the northeast.

2. Six independent electrode configurations were employed for the investigation. Four of the six surveys provided quality data that helped to delineate three preferential flow paths along open fractures, which potentially contribute to the mobilization of contaminants away from the site.

3. Conductive utility lines did cause some anomalies that interfered with the magnetic field coming from the subsurface in some areas. Fortunately, the locations of near-surface conductive features are known and their influence on the magnetic field was identified and taken into account while interpreting the data.

4. In order to enhance areas of greater or lesser conductivity through the subsurface study areas, the magnetic field data was compared to models of predicted magnetic field to create ratio response maps for easier interpretation. The ratio response maps remove electric current bias from the data and show areas of greater or lesser conductivity than that which is predicted under electrically-homogeneous circumstances.

5. Each survey's ratio response data was subjected to an inversion algorithm designed to predict the distribution of electric current flow in three dimensional space beneath the area covered by the measurement stations.

6. The ECD models show elongated near-vertical electric current flow paths which strongly suggest that groundwater is following open fractures that potentially conduct contaminants away from the landfill.

Figure 27 presents a general summary of the investigation with a map of Survey #1's results.

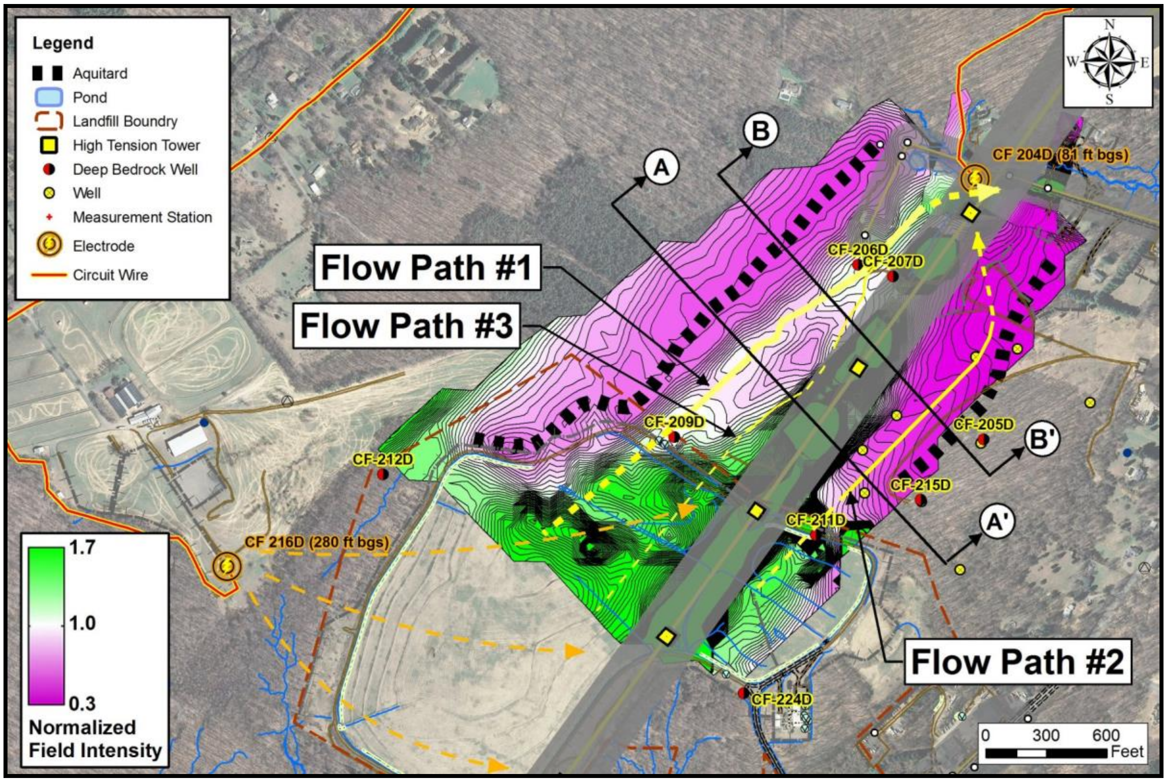

Figure 27 – Summary of Investigation (shown with Ratio Response Map for Survey #1)

Survey #1 provides a general characterization of preferential groundwater flow between the landfill and Schoolhouse Lane. Three conductive flow paths were identified which potentially convey groundwater and contaminants away from the landfill. These are labeled #1, #2 and #3. Subsequent Surveys #4, #6 and #7 provided addition detail regarding the noted flow paths. Survey #4 best delineated Flow Paths #1 and #3 located west of the transmission line. Survey #6 best delineated Flow Path #2 located east of the transmission line and Survey #7 best delineated preferential flow beneath Schoolhouse Lane where the flow paths converge and turn eastward.

To describe preferential flow paths beneath and away from the landfill, Figures 28 and 29 present cross section slices (Sections A-A′ and B-B′) of the ECD models from Surveys #4 and #6.

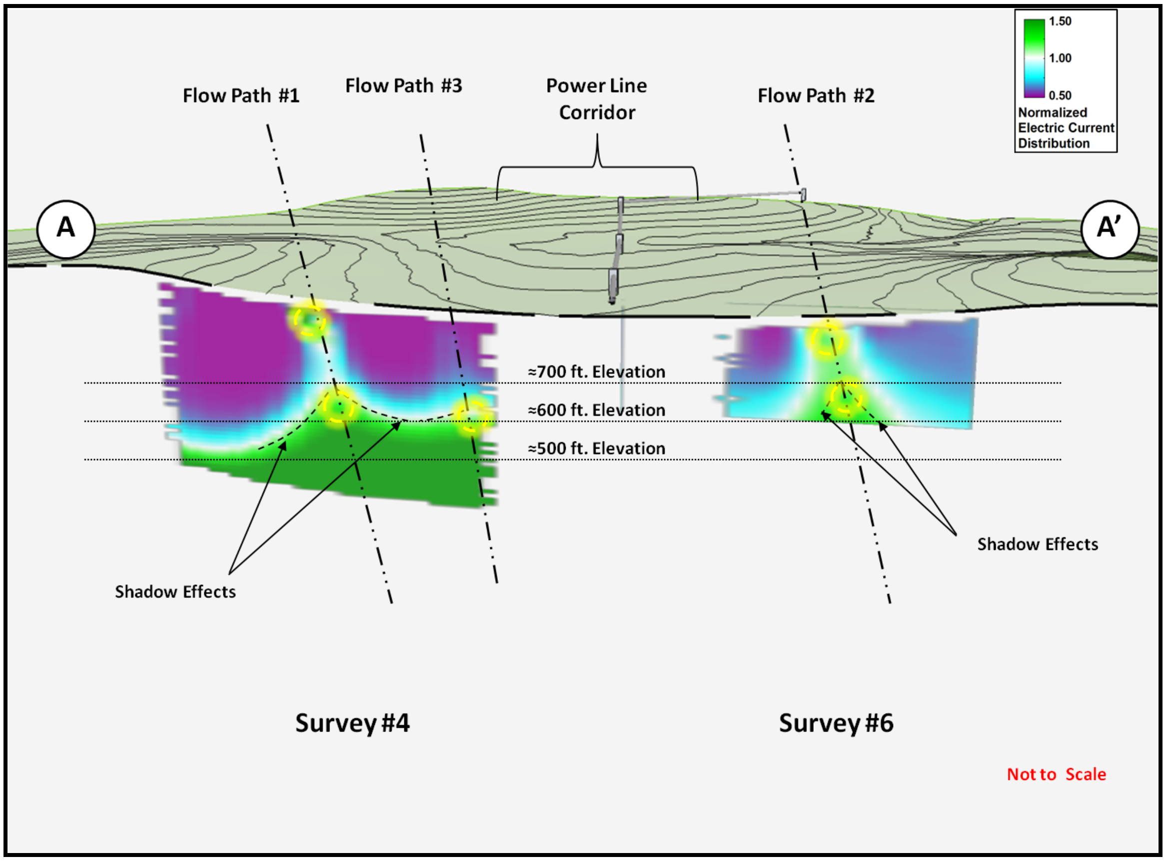

Figure 28 – Surveys #4 and #6 ECD Model Slice (Section A-A′)

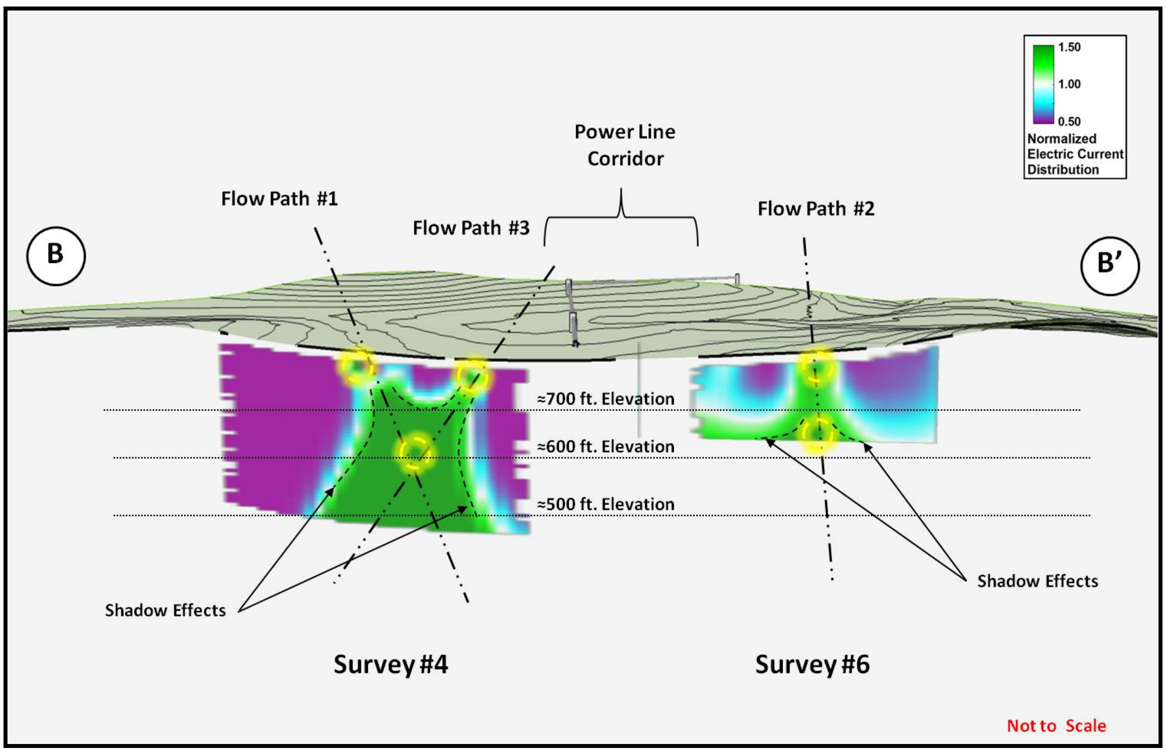

Figure 29 – Surveys #4 and #6 ECD Model Slice (Section B-B′)

The ECD model slices were inserted into a 3D site model to show the relationship between the relevant site features and those pathways identified by the Willowstick ECD model data. The contrast between purple and green shading is interpreted as an interface between competent and more porous subsurface materials. In these figures, Flow Paths #1, #2 and #3 identify what are believed to be fractures that electric current preferentially follows out from the landfill to the northeast. The yellow dashed circles highlight what is interpreted as zones of highest electrical concentration (also interpreted as preferential groundwater flow paths).

The survey results indicate that the electrode configurations and the measurement station spacing were appropriately designed and applied to the site. The principal challenge of every investigation is to establish electric current flow through the subsurface study areas that will help define and characterize changes in electrical properties. In any given survey configuration, it should be recognized that the technology's success is largely dependent upon the ability to establish electrical current flow that will follow and stay focused in the targeted medium that it is intended to follow. Although some of the electric current flowed onto overhead power lines, the surveys were very successful because enough electric current flowed through the targeted subsurface study area to identify and model preferential flow paths.

It should be noted that although the technology delineated preferential electric current flow paths in 3D space, it does not directly identify the amount of groundwater flowing along a particular pathway. The numbering or ranking of flow paths is based on electric current intensity—suggesting more electric current flows through Flow Path #1 than #2, and more through #2 than Flow Path #3.

12.0 RECOMMENDATIONS

12.1 General

The ECD model results can be used by and the EPA to provide a guided and cost effective approach in helping make informed decisions concerning the placement of additional groundwater monitoring wells if deemed necessary. This information can also be used to evaluate an appropriate remedial design if deemed necessary. Rather than recommend well locations, Willowstick will provide the maps, ECD models, and shapefiles to be used as a guide.

12.2 Other Recommendations

It is recommended that the maps and models provided in this report be carefully understood and utilized as a planning tool. There are no other recommendations made or implied as a result of this investigation. Willowstick does not specialize in groundwater remediation, engineering consulting or construction. Willowstick simply focuses its expertise on groundwater characterization by mapping, modeling and monitoring electric current flow distribution through the subsurface area of interest.

The information contained herein should be compared with known information of the site to further characterize and substantiate subsurface conditions impacting groundwater flow beneath and northeast of the landfill.

13.0 DISCLAIMER

13.1 Disclaimer

It should be recognized that the Willowstick geophysical survey methodology and inversion model are new and emerging technologies. The data, interpretations and recommendations obtained from the survey and modeling methodology is based upon sound applied physics and Willowstick's experience in working with and developing the technology. By definition, the evaluation of geologic, hydro-geologic and/or geophysical conditions is a difficult and an inexact science. However, Willowstick feels strongly that the technology has yielded information that can greatly help characterize groundwater flow beneath the Combe Fill South Landfill.

APPENDIX A – FIGURES