NEW JERSEY
GEOLOGICAL AND WATER SURVEY
Geological Survey Report 44

USING ELECTRICAL RESISTIVITY TO DELINEATE ACTIVE SINKHOLES AT CLINTON WILDLIFE MANAGEMENT AREA

New Jersey Department of Environmental Protection

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Cover photo: NJGWS geophysics team conducting a 3D electrical resistivity survey near an open sinkhole at Clinton Wildlife Management Area. *Photo by D. Monteverde*

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Using Electrical Resistivity to Delineate Active Sinkholes at Spruce Run Recreation Area

by

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ABSTRACT

The New Jersey Geological & Water Survey (NJGWS) conducted a subsurface investigation using electrical resistivity at the Clinton Wildlife Management Area in Union Township, Hunterdon County. Spruce Run Recreation Area is underlain by karst geology and as such may contain sinkholes. The focus of the study was to determine the location and extant of any undiscovered sinkholes on the site. The NJGWS collected 2D and 3D electrical resistivity data to delineate clay-filled sub-surface voids which may compromise infrastructure and a park visitor's safety. The profiles were located over the main access road, in the adjacent fields, and near the main well and well house as these were the important places identified by the park. Sinkholes provide a strong contrast in resistivity data and at least seven (7) were located from the geophysical study. This project shows that both 2D and 3D electrical resistivity methods are an excellent tool for locating sub-surface voids quickly and accurately.

INTRODUCTION

Sinkholes occur when acidic rainwater seeps down through surface soil and sediment, eventually reaching soluble bedrock such as chalk, salt or gypsum, or as at this site limestone and dolomite. The water gradually dissolves small parts of the rock, enlarging its natural fissures and joints thus creating cavities beneath. Unconsolidated soil and clay above are gradually washed into these openings. A similar example of a clay-filled cavity in bedrock is shown in Figure 1. Clinton Wildlife Management Area is located in Union township, Hunterdon County

Figure 1. Infilled sinkhole outcrop from Route 78, Bloomsbury Boro, Hunterdon County. *Photo by D. Monteverde*

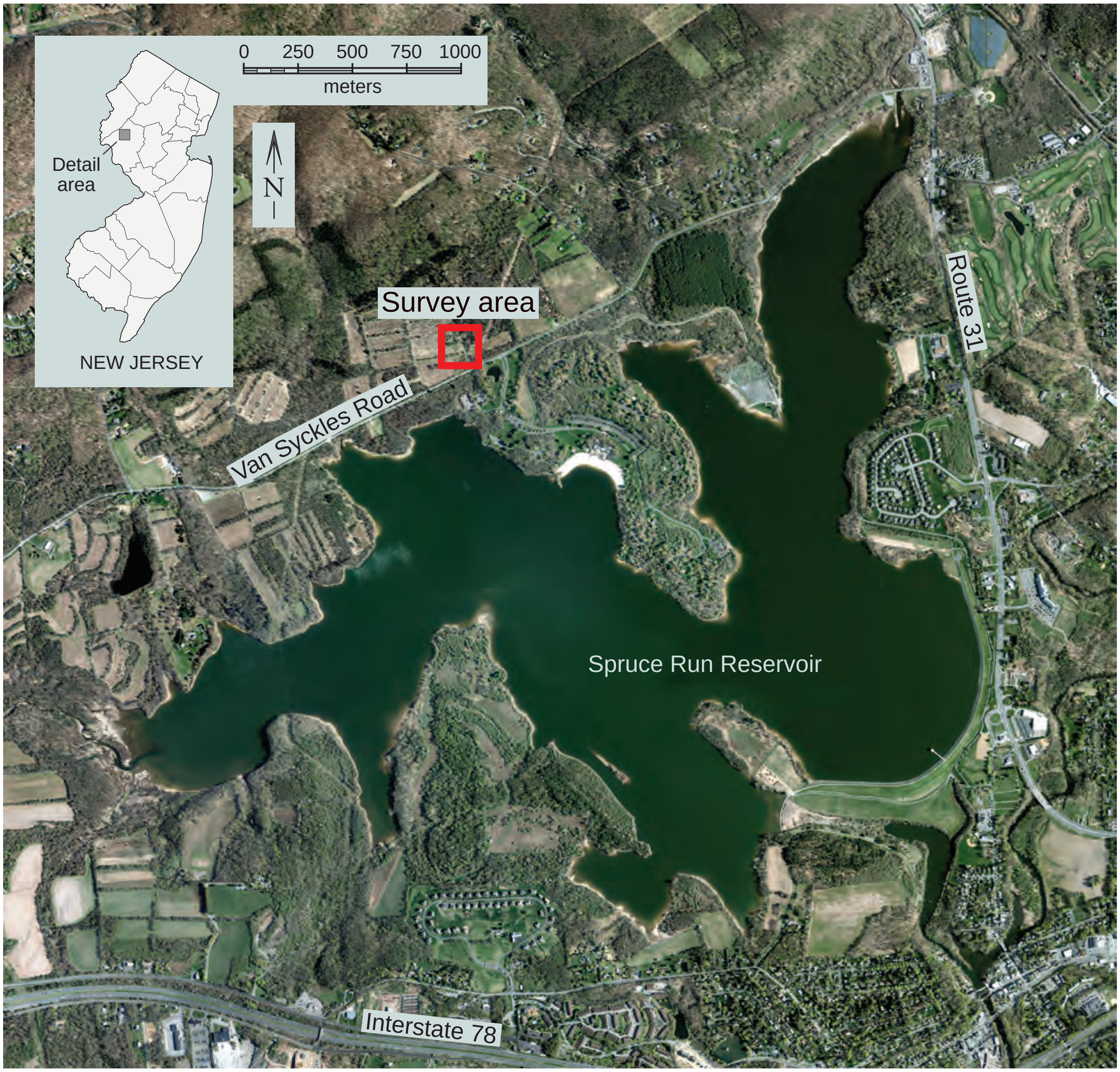


Figure 2. Satellite image of study location at Clinton Wildlife Management Area. *Aerial photo: NJ Department of Environmental Protection.*

(fig. 2). It is 2,064 acres and encompasses the Spruce Run Reservoir that is used as a backup reservoir to protect the state from prolonged droughts. It also contains the well and well-house that supplies the neighboring Spruce Run Recreation Area. NJGWS was contacted for assistance in locating and determining the extent of sinkholes recently opened at the surface. There were at least five (5) active sinkholes on or near the study area (fig. 3). The location of the sinkholes raised the possibility that the well-house, well, or the pipe supplying water to the recreational area, may be compromised. The NJGWS determined a surface geophysical method using electrical resistivity (ER) would be the best method because there is a strong contrast in resistivities between clay-filled cavities and the underlying bedrock and large areas can generally be covered in a short period of time. The NJGWS conducted several 2D and 3D electrical resistivity surveys in June 2017 and February 2018 (fig. 4).

Figure 3. Locations of active sinkholes at the study site. *Aerial photo: NJ Department of Environmental Protection.*

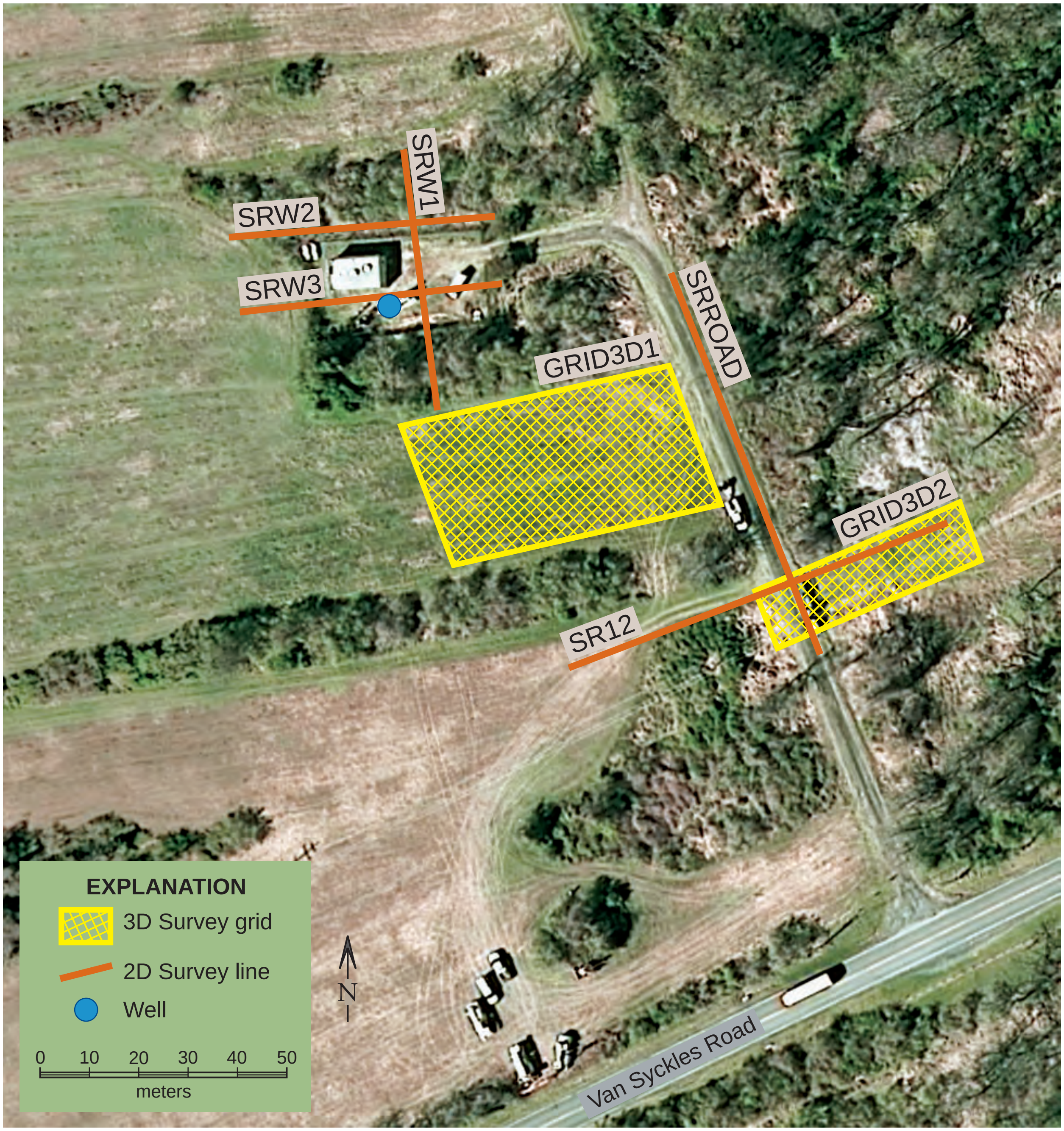
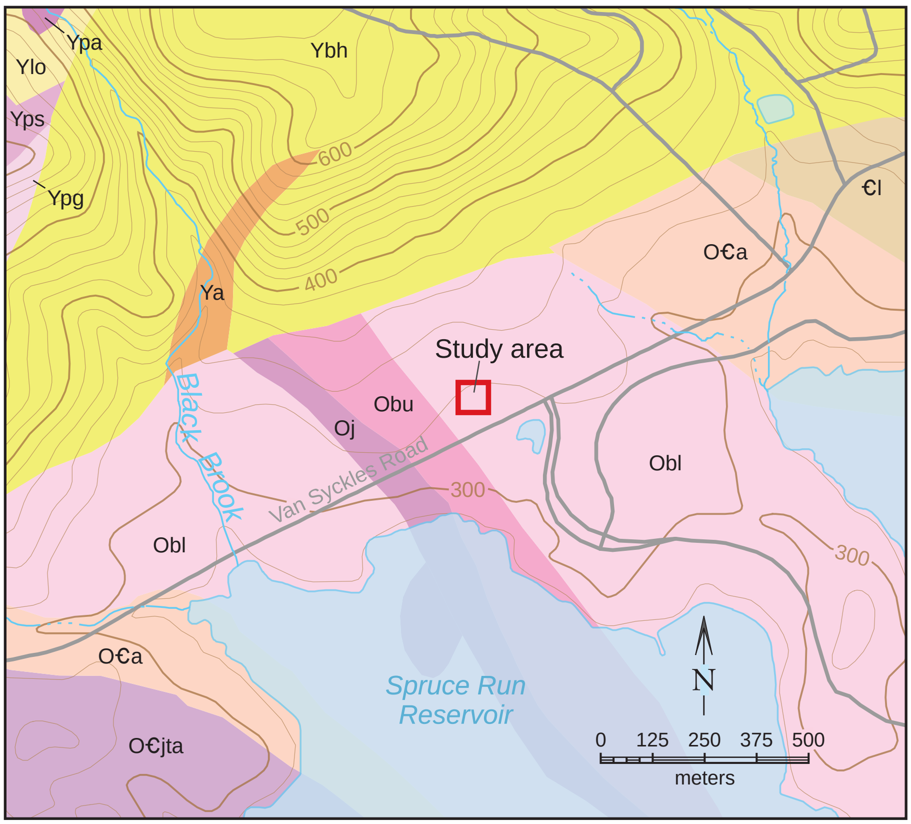


Figure 4. Locations of the electrical resistivity survey lines and grids. *Aerial photo: NJ Department of Environmental Protection.*

SITE DESCRIPTION

The study area is an approximately two-acre portion north of Van Syckles Road at the base of Musconetcong Mountain in the Clinton Wildlife Management Area. The area is generally flat with grass fields divided by trees and shrubs. The neighboring Spruce Run Recreation Area is supplied by groundwater from a well located in the study area. This well and well-house were also compromised by the sinkholes and were included as part of the study.

The bedrock geology (fig. 5) in the study area is the middle sequence of the lower part of the Beekmantown Group of Ordovician age. It is contained between southwest dipping stacked thrust sheets to the west and east. It consists of about 600 feet of medium to dark grey, aphanitic to medium grained, thin bedded dolomite and overlies the Allentown Dolomite of Ordovician



Description of Units

O€jta	Jutland Kilppe Sequence, Unit A	Ybh	Hornblende Granite
Oj	Jacksonburg Limestone	Ypg	Pyroxene Granite
Obu	Beekmantown Group, Upper Part	Ypa	Pyroxene Alaskite
Obl	Beekmantown Group, Lower Part	Yps	Pyroxene Syenite
O€a	Allentown Dolomite	Ylo	Quartz-Oliogoclase Gneiss
€l	Leithsville Formation	Ya	Amphibolite

Figure 5. Bedrock map of study area, geology from Monteverde and others, 2015.

and Cambrian age (Monteverde and others, 2015). There are no bedrock exposures within the study area, but Monteverde and others (2015) show the bedrock to be dipping west-southwest at about 45 degrees. The surficial geology consists of pre-Illinoian age glacial till and Holocene and Late Wisconsinan age stream terrace deposits (Stone and others, 2002).

GEOPHYSICAL FIELD METHODS

Theory of Resistivity

The basic operating principle for an ER survey involves generating a direct current between two stainless steel electrodes implanted in the ground, while measuring the ground voltage between two other implanted electrodes. Given the current flow and voltage drop between the electrodes, differences in subsurface electrical resistivity can be determined and mapped. Resistivity profiles illustrate vertical and lateral variations in subsurface resistivity. The presence of water or water-saturated soil or bedrock will strongly affect the results of a resistivity survey. Air-filled caves or air-filled pore space in the vadose zone are easy to detect using the ER method, since air has near-infinite resistivity, in contrast with more conductive surrounding bedrock. By contrast, subsurface voids filled with water or clay would be indicated by zones of very low resistivity (< 15 ohm-m).

The depth of investigation for an ER survey is directly related to the length of the array of electrodes – the longer the array, the greater the penetration that can be obtained. For the Spruce Run survey, electrode spacing was 2 m or 3 m, and the full array length for each survey line was 56 m or 84 m. A standard dipole-dipole array configuration used to survey each ER line attained depths of between 13 m and 20 m. Stainless steel stakes, 45 cm long, were used as electrodes.

Data Acquisition

Resistivity survey lines were deployed using an AGI SuperSting R8/IP™ resistivity meter. It is an 8-channel earth resistivity meter with an internal switchbox system that can take up to 8 measurements at one time and is powered by a single 12 volt deep-cycle battery (Figure 6). A Trimble Geo 7X handheld GNSS System with external antennae and TerraSync software GPS unit was used to collect coordinates of each survey line.

Both 2D and 3D electrical resistivity data

Figure 6. The AGI SuperSting R8/IP™ resistivity meter connected to a 12 V battery and a 28-electrode multi-core cable collecting a 2D resistivity profile. The cable is connected to stainless steel electrodes pushed into the sub-surface. The Trimble Geo 7X GPS unit shown on the left side of the figure. *Photo by M. Gagliano*.

were acquired at the study site. A 2D survey uses electrodes placed in a parallel line. For the data collection at this site a 28-electrode multicore cable was used. The dipole-dipole (Reynolds, 2011) array was used for all surveys as it is very efficient to use with a multi-electrode system. This array also useful for mapping shallow lateral variation (Peake, 2005). With this system, measurements are taken sequentially using different sets of four electrodes controlled by the switchbox to combine the vertical sounding minimal (Loke, 1997; Chambers and others, 2002; Nyquist and Roth, 2005). In this study GRID3D1 was a combined series of parallel lines and GRID3D2 was standard 3D survey (fig. 4).

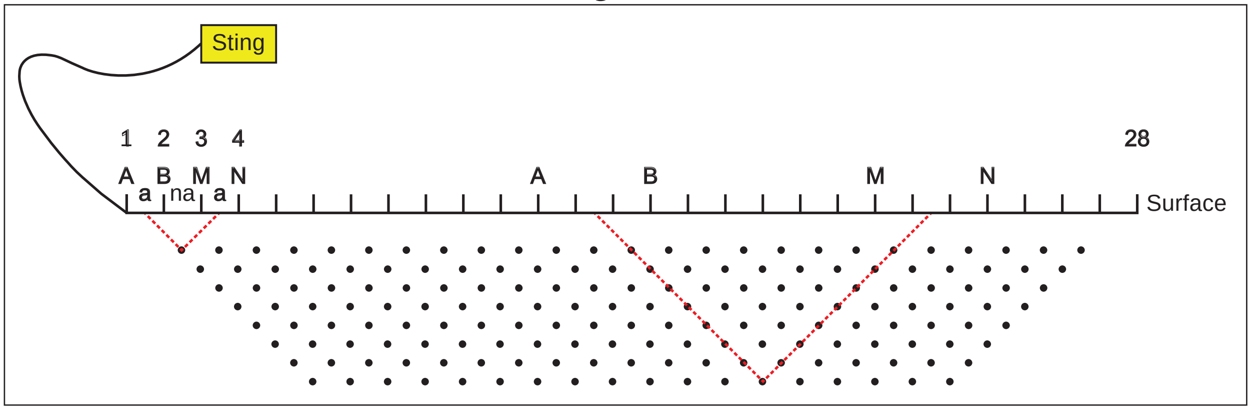


Figure 7. The building of an electrical resistivity tomogram using a multi-electrode cable. The sequence will begin with the electrodes 1, 2, 3 and 4 at the location shown at the left of the diagram. As the spacing between the electrodes is small the potential electrodes will measure apparent resistivities at a shallow depth. The electrodes will then be moved to various places along the line and at varying spaces collecting data points both horizontally and vertically. The further the potential electrodes are from each other the deeper the measurement will be. This is illustrated on the right, where the A, B, M, N electrodes are spaced further apart, resulting in a deeper sounding. The dots are where the apparent resistivity measurements are taken.

and horizontal profiling (fig. 7).

A 3D resistivity tomograph can be produced in two possible ways. The standard way to deploy a multielectrode cable to collect 3D data is to snake it back and forth in a serpentine pattern (fig. 8a). If placed in a rectangular pattern, the potentials will measure in the x direction, y direction, and diagonally, thereby the current passes through every space in the grid (fig. 8b). This is time consuming and requires a very long multi-core cable. For example, the 28-meter cable would only cover a grid of 5 m by 5 m. The survey time can be decreased if instead of using the setup illustrated in Figure 8a, we combine parallel 2D lines (fig. 8c) because potentials are only measured in the y-direction (fig. 8d), and all 28 electrodes can be used for each segment. In theory, method 1 should produce more accurate results since data is collected across plane, however in practice several studies have shown the difference in the final data set to be

Data Processing

EarthImager-2D™ and EarthImager-3D™ software was used to process the resistivity data. The software uses a forward and inverse modeling procedure to create a synthetic data set based on measured apparent resistivity. This is an iterative process; a root-mean-square (RMS) error is calculated for each new iteration. Noisy data points are progressively removed over the course of several iterations until the RMS error is reduced to an acceptable level. Every iteration requires the removal of a certain number of data points to attain smoother model output, and ideally the iterative process will terminate before too much useful data is filtered out. The number of data points collected in the field is a function of array configuration and number of electrodes.

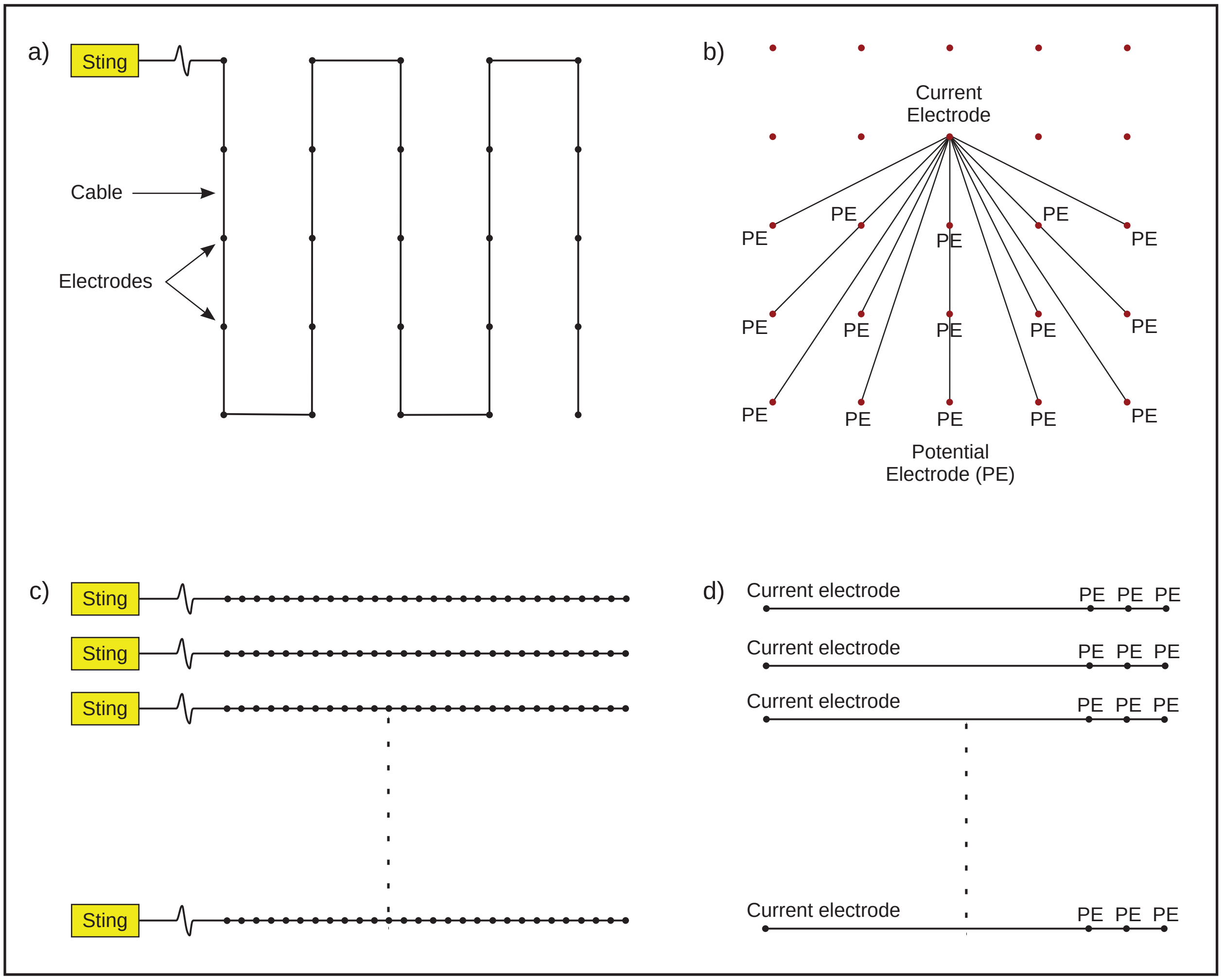


Figure 8. Plan view of possible layouts for a 3D survey. a) Setup for a "true" 3D survey with a single cable deployed in a rectangular pattern. b) In this case, potential electrodes will measure in the x, y and diagonal directions obtaining a complete set of data. c) Setup for a true 3D survey using a single cable that is moved in increments. d) The potential electrodes only measure in the y direction (along the cable), so there are a limited number of electrode pairs which reduces the total dataset. Figure c) is the same setup that is used for the "pseudo" 3D. However, for the "pseudo" 3D, each individual line is inverted as a 2D section, and the resistivities in between are interpolated.

GEOPHYSICAL DATA INTERPRETATION

The ER had an effective depth resolution of approximately 13 m for the 2 m spacing electrode cable and 20 m for the 3 m electrode spacing cable. Units with resistivities greater than 400 ohm-m were mapped as dolomite; units with resistivities less than 100 ohm-m were mapped as moist soil or clay; units with resistivities greater than 100 ohm-m but less than 400 ohm-m were interpreted as transitional zones probably consisting of moderately to intensely fractured and/or weathered dolomite with clay in-fill. A review of the geophysical data showed depth to bedrock in the area varies between 4 m to 15 m. Bedrock is interpreted as overlain by soil or clay. The hummocky aspect of the karst bedrock topography is apparent both in the 2-D lines and in-depth slices through the 3D grids. The soil valleys appear as transitional zones and the limestone ridges as resistive zones. In many cases the low resistivity anomalies are likely to be clay and water filled cavities in fractures and openings in the pinnacled bedrock. In many cases these are close to or connected to an existing sinkhole. See Appendix 1 for locations of the active sinkholes and geophysical anomalies (indicating a possible sinkhole) at the site.

Five 2D surveys and two 3D surveys were completed during the study (Figure 4). The results are discussed below.

2D Interpretations

- Line SR12 runs west-east directly adjacent to the existing sinkhole (Figure 9). The top of bedrock can be seen in the west side of the profile at a depth of approximately 6m. On the east side of the profile is a low resistivity anomaly which is likely to be connected to the existing sinkhole.
- Line SRW1 runs north-south near the well-house enclosure. It indicates a low resistivity anomaly at the 27 m mark, but no determination can be made because this spot is directly adjacent to the sludge tank on the property (Figure 10).
- Line SRW2 is located north of the well-house. The data indicates a possible soil void, and this was confirmed by the opening of a sinkhole directly over this spot. There is also an exposed pipe here as well (Figure 11).

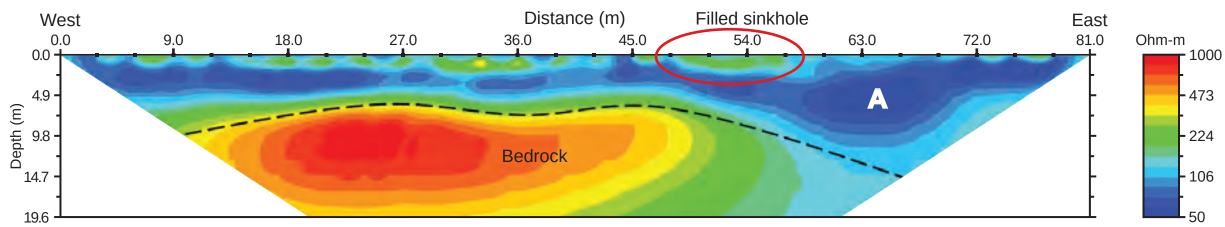


Figure 9. Line SR12. This 2D resistivity profile is crossing the driveway and a recently filled in sinkhole. The length was 81 m and the electrode spacing was 1 m. The profile shows bedrock (dolomite), *bottom*, the filled sinkhole, *top middle*, circled in red, and a large area of conductive material, *right* (A).

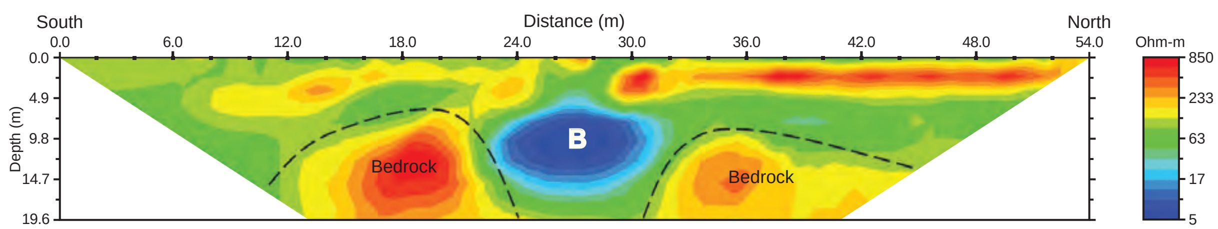


Figure 10. Line SRW1 is a 2D profile directly to the east of the well-house enclosure. The length was 54 m and the electrode spacing was 2 m. It indicates a low resistivity anomaly (B) at the 27 m mark, which is indicative of a soil void, but no determination can be made because this spot is directly adjacent to the sludge tank on the property (fig. 4). If the sludge tank were filled with water or contained any metal, it would also show up as low resistivity.

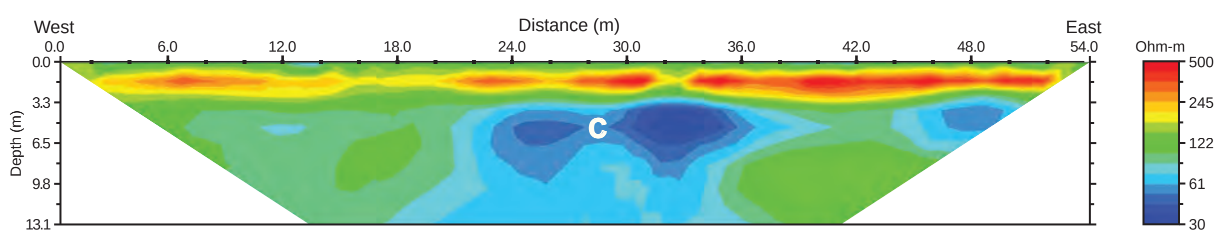


Figure 11. Line SRW2 is a 2D profile directly to the north of the well-house enclosure. The length was 54 m and electrode spacing was 2 m. A low resistivity anomaly (C) can be seen between the 22 m and 36 m mark and indicates a possible soil void. This was confirmed by the opening of a sinkhole directly over this spot. There is also an exposed pipe here as well.

- Line SRW3 is located south of the well-house. It shows low resistivity, but the results are likely affected by metal and electrical equipment near the survey line. The anomaly at 31 m is close to the well casing, which would also be conductive because it is steel. The anomaly between the 20 m and 24 m mark is close to the generator onsite. While equipment on the surface doesn't usually affect resistivity values, in this case there may be wires and conduit underground which may impact results. There does appear to be an anomaly at the 9 m mark indicating a possible soil void here (Figure 12).

- Line SRROAD runs north south along the access road adjacent to the existing sinkhole. There is a large anomaly between the 25 m and 50 m marks with a similar signature as other sinkholes in the vicinity (Figure 13).

3D Interpretations

- Grid 3D1 is in the field south of the well house (Figure 14). Resistivity values of 50 to 90 Ohm-m appear to connect and correlate to known sinkholes on the property. The subsurface immediately to the east of the sinkhole is characterized by a similar pattern of resistivity values. More specifically, a large zone consisting of low resistivity values (50-90 Ohm-m) is observed immediately to the east of the sinkhole on profile SR12 (Figure 9). These features are interpreted as clay-filled solution-widened joint or zone of intensely fractured rock with clay-infill and extend across the entire survey area. Figure 14a and Figure 14b also illustrates the hummocky and pinnacled nature of the dolomite bedrock as the size of the pinnacle increases with depth.

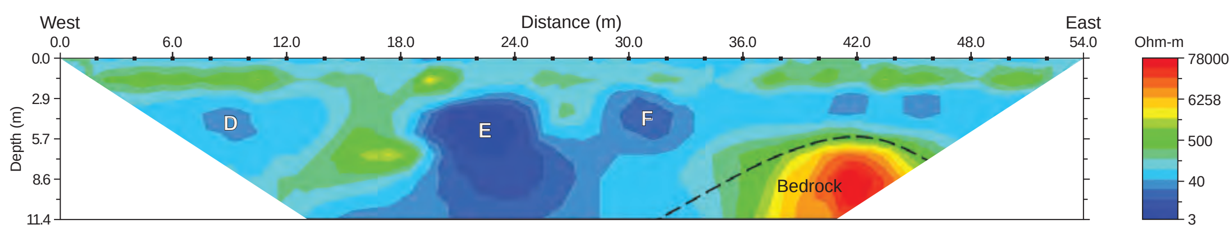


Figure 12. Line SRW3 is a 2D profile directly to the south of the well-house enclosure. The length was 54 m and the electrode spacing was 2 m. This line has 3 low resistivity anomalies, but they are difficult to interpret due to the infrastructure adjacent to the line. The anomaly at 31 m (D) is close to the well casing, which would also be conductive since it is steel. The anomaly between the 20 m and 24 m (E) mark is close to the generator onsite. While equipment on the surface doesn't usually affect resistivity values, in this case, there may be wires and conduit underground which may impact results. There does appear to be an anomaly at the 9 m (F) mark indicating a possible soil void here.

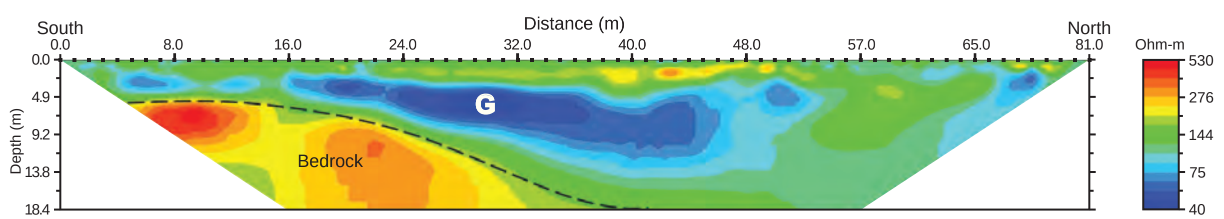


Figure 13. Line SRROAD is a 2D resistivity profile that runs north-south along the access road adjacent to the existing sinkhole. The length was 84 m and the electrode spacing was 1 m. There is a large low resistivity anomaly between the 25 m and 50 m mark (G) indicating a possible soil void.

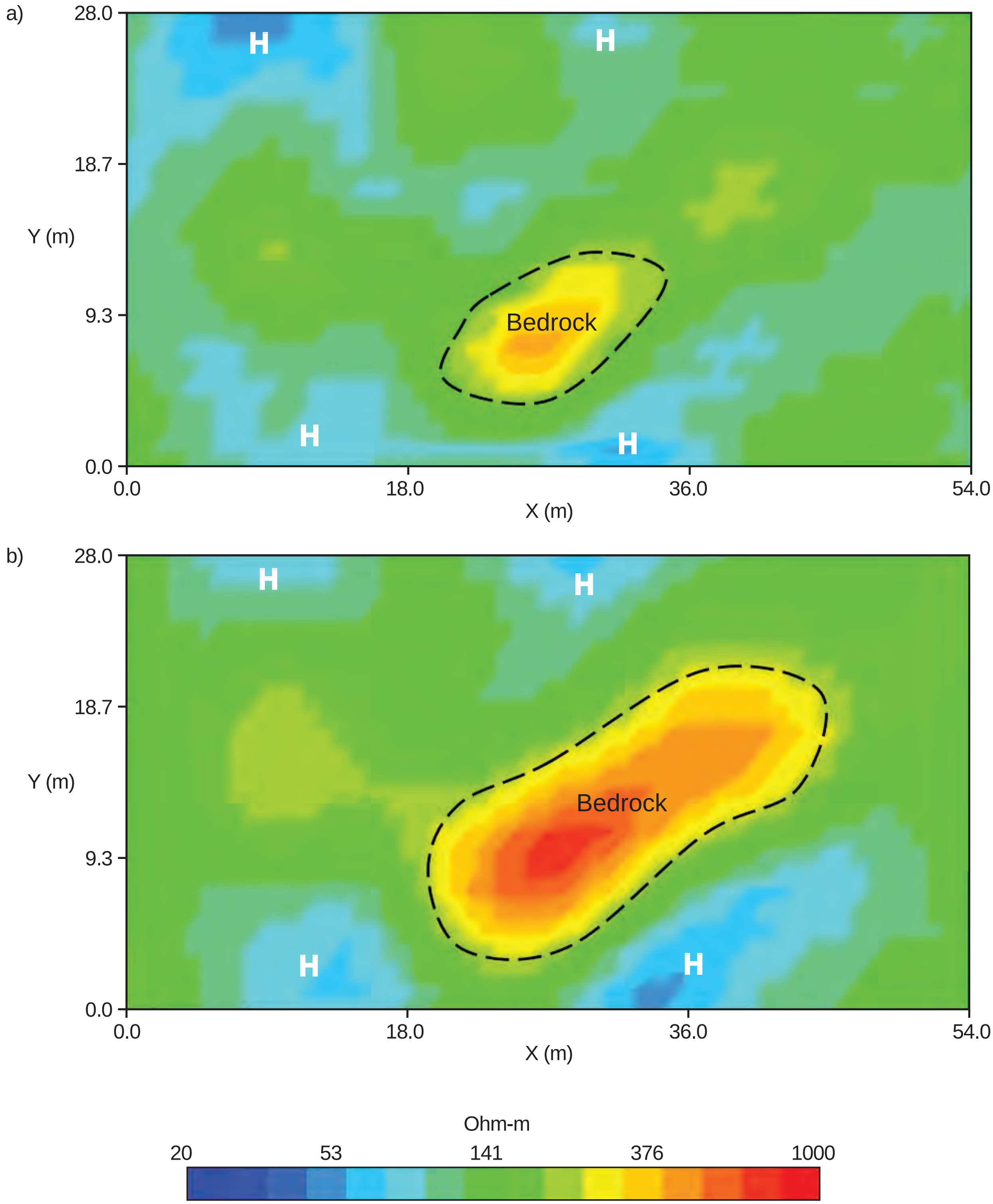


Figure 14. GRID3D1. a) Resistivity slice in the horizontal plane at a depth of 3 m. b) Resistivity slice in the horizontal plane at a depth of 6 m. The low resistivity zones (H) are interpreted as clay-filled solution-widened joints or zones of intensely fractured rock with clay-infill. These all are close to or connect with known sinkholes in the study area. These figures also illustrate the hummocky and pinnacled nature of the high resistivity dolomite bedrock (dashed black line) as the size of the pinnacle increases with depth.

- Grid 3D2 (Figure 15) was completed over the existing sinkhole east of the access road to determine the extent and direction of the remaining cavity. The area at the surface of the sinkhole is characterized by a high resistivity (> 400 ohm-m) region which is due to the presence of gravel, stone, and airspace due to the filling of the sinkhole. This was an expected result. The subsurface immediately to the east and northeast of the

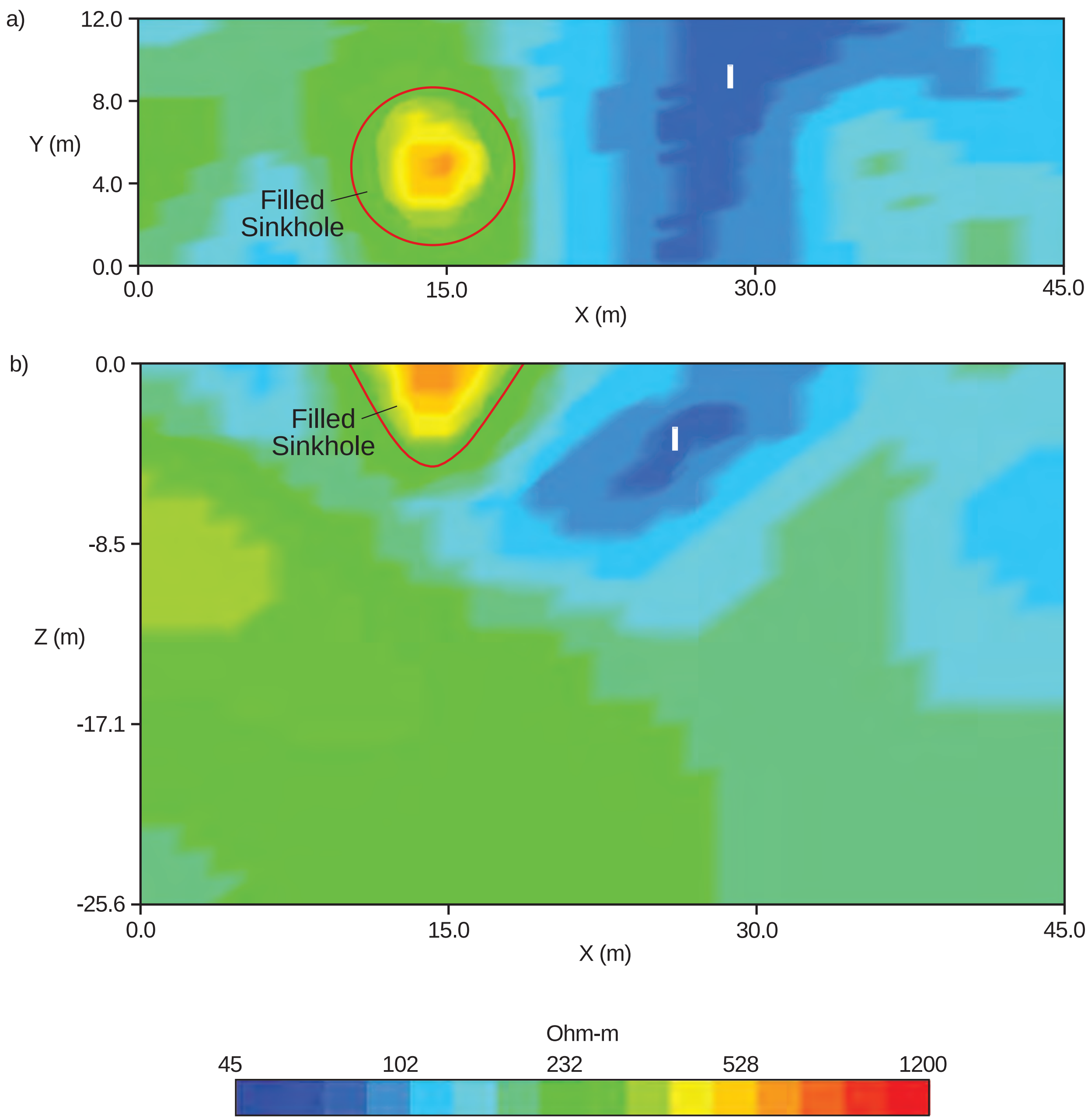


Figure 15. GRID3D2. a) Resistivity slice in the horizontal plane from GRID3D2 at a depth of 4 m. The resistive region (above 400 ohm-m) is the location of the existing sinkhole. b) Resistivity slice in the vertical plane at the midpoint of GRID3D2. The resistive region (above 400 ohm-m) is the location of the existing sinkhole. Please note Z = depth. The circled red resistive region is the location of the existing sinkhole. In this case, the opening at the top of the sinkhole where it has started to cave in is filled with gravel, stone, cement, and airspace which are all resistive materials. The blue low resistivity region (I) to the northeast of the existing sinkhole indicates a possible clay-filled soil void and is likely the direction the current sinkhole may continue to open.

sinkhole is characterized by a pattern of low resistivity values (50-100 Ohm-m), which as previously described is an indicator of a possible cavity at this site. This anomaly extends at least 15 m beyond the existing sinkhole (Figure 15a). In cross section view the anomaly is 15 meters deep (Figure 15b). The rest of the survey is characterized by intermediate resistivity values which are indicative of the soil and overburden.

CONCLUSION

Electrical resistivity is an effective tool for locating sinkholes. It is quick to set up and execute and can be used to distinguish clay, water-filled, and air-filled voids due to the strong contrast of resistivity between these materials and the underlying bedrock. The presence of low resistivity anomalies near known sinkholes and throughout the survey area indicates possible clay-filled solution-widened openings in the dolomite. NJGWS found evidence of at least seven (7) new sinkholes and evidence of existing sinkholes on site that may become larger.

NJGWS recommended additional investigatory work, such as borings, that would target the anomalies to confirm the interpretation and determine if these are indeed possible sinkholes and whether there may be any open cavities at depth in the rock. If they are clay-filled cavities then the clay may wash away causing further sinkholes at the surface, which could further compromise the well or pipe running to the recreational area.

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APPENDIX 1

Appendix 1. Locations of active sinkholes (yellow) geophysical anomalies (red) found during this study that may indicate possible future sinkhole development on the property. Please note that these points are approximate centers of each location but represent a much larger area. *Aerial photo: NJ Department of Environmental Protection.*