United States Department of Agriculture | **Natural Resources Conservation Service** | **11 Campus Boulevard, Suite 200 Newtown Square, PA 19073**

Subject: ENG -- Electromagnetic Induction (EMI) Assistance **Date:** 6 February 2002

To: Robin E. Heard
State Conservationist
USDA-NRCS,
Suite 340, One Credit Union Place
Harrisburg, PA 17110-2993

Purpose:
An electromagnetic induction (EMI) survey was conducted to provide ancillary information to soil observations in two fields that adjoin a proposed composting pad at Pennsylvania State University, State College, Pennsylvania.

Participants:
Kent Baker, College Township Engineer, College, PA
Glen Cauffman, Farm Manager, Pennsylvania State University, State College, PA
Tim Craul, Resource Soil Scientist, USDA-NRCS, State College, PA
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Jake Eckenrode, Resource Soil Scientist, USDA-NRCS, Lamar, PA
Jim Harper, Farm Operator, Pennsylvania State University, State College, PA
Scott Heckman, Resource Conservationist, USDA-NRCS, Mill Hall, PA
Brian Mcafee, Unit Manager, Pennsylvania State University, State College, PA
Michael McDevitt, Soil Scientist, USDA-NRCS, State College, PA

Activities:
All field activities were completed on 29 January 2002.

Equipment:
The electromagnetic induction meter used in this study was the EM31, manufactured by Geonics Limited*. This meter is portable and requires only one person to operate. Principles of operation have been described by McNeill (1980a). No ground contact is required with this meter. The EM31 meter provides limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing (about 3.9 m). The EM31 meter operates at a frequency of 9,800 Hz and has theoretical observation depths of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980a). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

Locations of observation points were measured with a Trimble GPS receiver*.

To help summarize the results of this study, the SURFER for Windows, version 7.0, developed by Golden Software, Inc.,* was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

Study Sites:
Two fields located to the immediate southwest and northeast of the composting pad were surveyed with an EM31 meter

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* Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

(see Figure 1). These fields have been principally mapped as Hagerstown silty clay loam, 3 to 8 percent slopes (Braker, 1981). Also included are small areas of Hagerstown soils on 8 to 15 and from 15 to 25 percent slopes. Hagerstown soil formed in residuum weathered from limestone. The well-drained Hagerstown soil is underlain by limestone at depths of 40 to 70 inches. Included with Hagerstown soil in mapping are small areas of soils that have bedrock within depths of 20 to 40 inches. The Hagerstown soils are members of the fine, mixed, semiactive, mesic Typic Hapludults family. Hagerstown has low base status. The dominant clay mineral is illite.

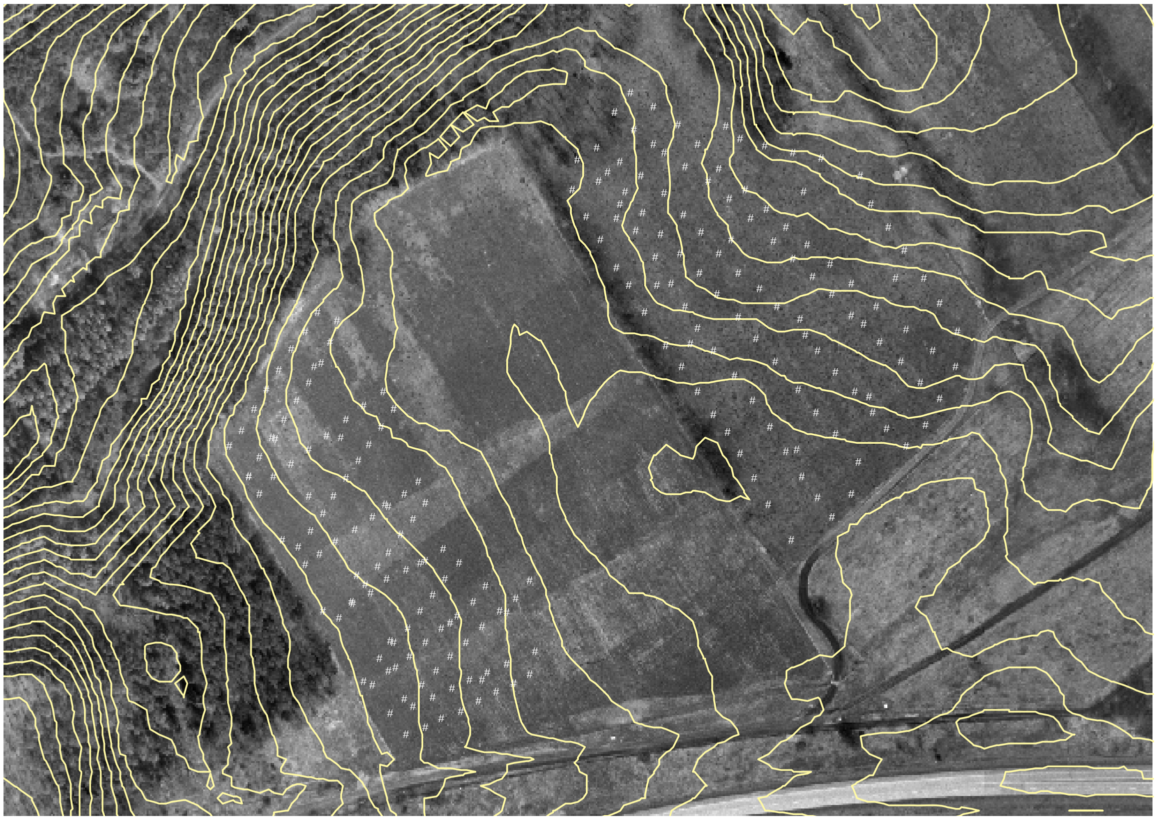

Figure 1. Aerial photograph showing contour lines and the locations of observation points in the two surveyed fields.

Field Procedures:
Random traverses were conducted in each field with the EM31 meter and a Trimble GPS system. Measurements were taken at each observation point with the EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations. The location of each observation point was determined with the Trimble GPS receiver. Figure 1 shows the locations of the observation points in each surveyed field. The composting pad will be located in the area between the two surveyed fields.

Background:
Electromagnetic induction (EMI) is a noninvasive geophysical tool that can be used for detailed site assessments. Advantages of EMI are its portability, speed of operation, flexible observation depths, moderate resolution of subsurface features, and comprehensive coverage. This geophysical method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, planning further investigations, and locating sampling or monitoring sites.

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are caused by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the type and concentration of ions in solution, the amount and type of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980b). The apparent conductivity of soils increases with increased soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction measures vertical and lateral variations in apparent electrical conductivity. Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in soils and soil properties. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations are normally used.

Electromagnetic induction is not suitable for use in all soil investigations. Generally, the use of EMI has been most successful in areas where subsurface properties are reasonably homogeneous and one property (e.g. salt, clay, or water content) exerts an overriding influence over soil electrical conductivity. In these areas, variations in apparent conductivity can be directly related to changes in the dominant property (Cook et al., 1989). In the surveyed areas of Hagerstown soil, differences moisture and salt contents were assumed to be slight and to influence EMI response less than the spatial and vertical (depth to limestone bedrock) variations in clay content. Compared with the underlying bedrock, the fine-textured Hagerstown soil is a more conductive medium.

Electromagnetic induction has been used to assess and map soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982 and 1990; Slavich and Petterson, 1990), sodium-affected soils (Ammons et al., 1989; Nettleton et al., 1994), depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993; and Sudduth et al., 1995), and edaphic properties important to forest site productivity (McBride et al., 1990). In addition, Kitchen and others (2000) used EMI to estimate topsoil thickness and clay content. Electromagnetic induction has been used to estimate soil water contents (Kachanoski et al., 1988; Sheets and Hendrickx, 1995), cation exchange capacity, exchangeable Ca and Mg, and leaching rates of solutes (McBride et al., 1990; Jaynes et al., 1995). Recently, EMI has been used as a soil-mapping tool to assist precision agriculture (Jaynes, 1995; Jaynes et al., 1993; Sudduth et al., 1995).

Electromagnetic induction methods can provide a relatively inexpensive, fast, and comprehensive means for mapping the depths to bedrock (Bork et al., 1998; Doolittle et al., 1998; Palacky and Stephens, 1990; Zalasiewicz et al., 1985). This technique has also been used to locate water-bearing fault or fracture zones in bedrock (Beeson and Jones, 1988; Edet, 1990; Hazell et al., 1988; Olayinka, 1990). In areas of karst, EMI techniques have been used to detect anomalous subsurface patterns indicative of solution features (Canace and Dalton, 1984; Pazuniak, 1989; Robinson-Poteet, 1989; Rumbens, 1990). These studies have documented that EMI can provide large quantities of data for site characterization and assessments, and can be applied over broad areas and soils.

Results:

Table 1 summarizes basic statistics for the EMI survey. A total of 110 and 117 observations were recorded in the fields that were located to the southwest and northeast of the proposed compost pad, respectively. At most observation points, apparent conductivity decreased with increasing depth of observation (shallow-sensing horizontal dipole orientation (0 to 3 m) measurement were greater than those of the deeper-sensing vertical dipole orientation (0 to 6 m)). This relationship is associated with the higher water and clay contents of soils. The underlying limestone bedrock is more resistive (less conductive) than the overlying soil materials.

Values of apparent conductivity were relatively low and invariable across both fields. In the southwestern field, apparent conductivity averaged 8.6 mS/m and 6.5 mS/m in the horizontal and vertical dipole orientations, respectively. In the shallower-sensing, horizontal dipole orientation, one-half the observations had values of apparent conductivity between 8.0 and 9.2 mS/m. In the deeper-sensing, vertical dipole orientation, one-half the observations had values of apparent conductivity between 5.6 and 7.2 mS/m. In the northeastern field, apparent conductivity averaged 8.3 mS/m and 6.2

mS/m in the horizontal and vertical dipole orientations, respectively.   In the shallower-sensing, horizontal dipole orientation, one-half the observations had values of apparent conductivity between 7.4 and 9.2 mS/m. In the deeper-sensing, vertical dipole orientation, one-half the observations had values of apparent conductivity between 5.0 and 7.4 mS/m.

Table 1. Basic Statistics for EMI Survey
(All values are in mS/m)

	Southwest Field		**Northeast Field**	
	EM31H	***EM31V***	**EM31H**	**EM31V**
Average	8.6	*6.5*	8.3	6.2
Minimum	4.2	*2.8*	4.0	2.4
Maximum	13.2	*10.2*	12.0	9.8
First Quartile	8.0	*5.6*	7.4	5.0
Third Quartile	9.2	7.2	9.2	7.4

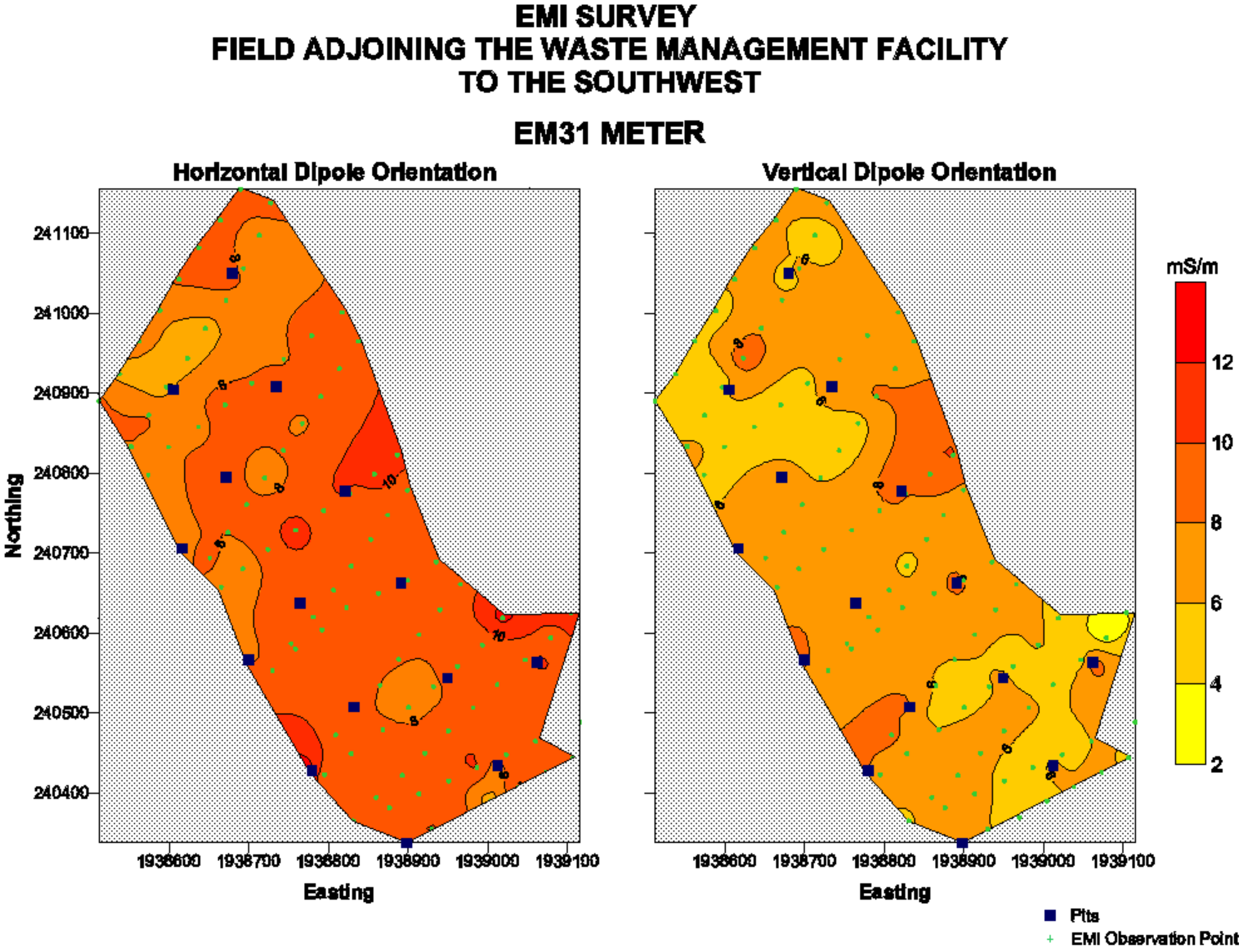

Figure 2 – Two-dimensional plots of apparent conductivity in the field located to the southwest of the proposed compost pad. Data collected with the EM31 meter in the shallower-sensing (0 to 3 m) horizontal and deeper–sensing (0 to 6 m) vertical dipole orientations.

Figure 2 contains two-dimension plots of apparent conductivity obtained with an EM31 meter in the field that is located to the southwest of the proposed compost pad. In each plot the isoline interval is 2.0 mS/m. This interval is less than the recognized range in observation errors (2 to 4 mS/m). However, because of the relatively invariable apparent conductivity measured with the EM31 meter in this area of Hagerstown soil, use of a larger interval would provide little or no spatial information. The locations of the 15 soil pits and the 110 EMI observations are shown in each plot.

A comparison of the two plots in Figure 2 shows that apparent conductivity decreases with increased soil depth across the site (apparent conductivity measurements are higher in the shallower-sensing horizontal dipole orientation (0 to 3 m) than in the deeper-sensing vertical dipole orientation (0 to 6 m)). In the horizontal dipole orientation, apparent conductivity is higher because the more conductive, fine-textured soil material makes up a greater proportion of the profiled column than the underlying, more resistive limestone bedrock. Apparent conductivity measured in the vertical dipole orientation is lower because a greater portion of the 0 to 6 m column is composed of more resistive limestone bedrock. Areas of low conductivity correspond to areas where the bedrock was observed to be shallower in soil pits.

Figure 3 contains two-dimension plots of apparent conductivity obtained with an EM31 meter in the horizontal and vertical dipole orientations in the field located to the northeast of the proposed compost pad. In each plot the isoline interval is 2.0 mS/m. The locations of the 12 soil pits and the 117 EMI observations are shown in each plot. Once again, spatial patterns are believed to reflect differences in clay content and/or depth to more resistive bedrock.

Values of apparent conductivity are believed to principally reflect variations in soil depth. Areas with lower apparent conductivity are assumed to have shallower depths to bedrock than areas with higher apparent conductivity. A moderate ($r = 0.721$) and significant (0.001 level) correlation was found between measured depths to bedrock at the 27 pits and measurements obtained with the EM31 meter in the horizontal dipole orientation. A weaker ($r = 0.593$), but significant correlation (0.001 level) was found between the measured depths to bedrock and measurements obtained with the EM31 meter in the vertical dipole orientation.

The lack of stronger relationships within the two fields is attributed to variations in soil properties (e.g., moisture, texture, thickness and depth to the subsoil; amount of coarse fragments; and moisture content). In addition, measurement error was introduced into the data sets because of differences in the area profiled with the EM31 meter versus the point where depth measurement was made in each pit. Acknowledging these deficiencies, data collected with the EM31meter in the horizontal dipole were used to develop the following equations to predict the depth to bedrock:

$$D = -0.964 + (0.2429 * EM31H) \quad [1]$$

where "D" is depth to bedrock (m) and “EM31H” is the apparent conductivity (mS/m) measured with the EM31 meter operating in the horizontal dipole orientation.

Using equation [1], at the 27 pits, the average difference between predicted and measured depths to bedrock was 0.29 m with a range of 0.03 to 0.80 m. At one half of the pits, the difference between measured and predicted depths to bedrock was between 0.08 and 0.45 m.

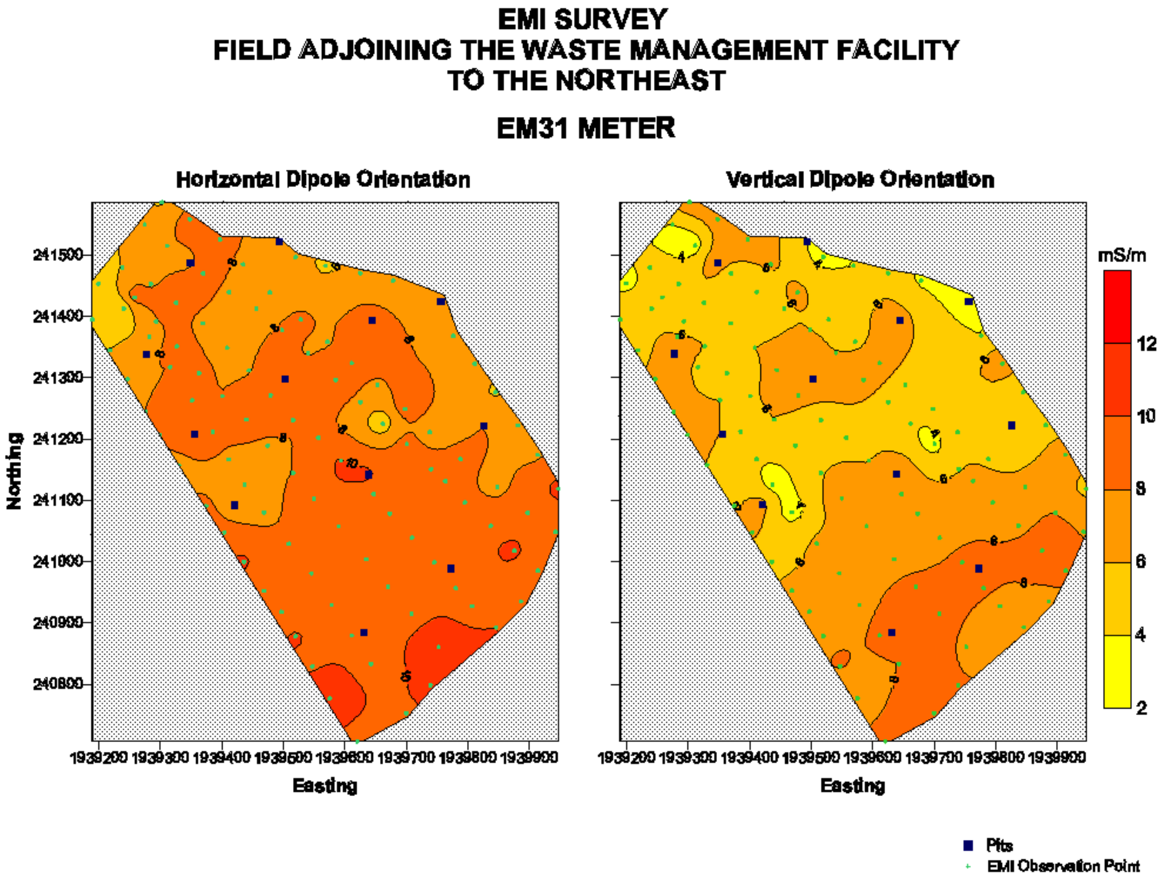

Figure 3 – Two-dimensional plots of apparent conductivity in the field located to the northeast of the proposed compost pad. Data collected with the EM31 meter in the shallower-sensing (0 to 3 m) horizontal and deeper–sensing (0 to 6 m) vertical dipole orientations.

Based on 110 EMI measurements and predictive Equation [1], the average depth to bedrock within the field that is located to the southwest of the proposed compost pad is 1.11 m with a range of 0.06 to 2.24 m. One-half of the observations had depths to bedrock between 0.98 and 1.27 m. Depths to bedrock are shallow (0 to 0.5 m) at 5 percent, moderately deep (0.5 to 1.0 m) at 22 percent, deep (1.0 to 1.5 m) at 62 percent, and very deep (>1.5 m) at 11 percent of the observation points.

Based on 117 EMI measurements and predictive Equation [1], the average depth to bedrock within the field that is located to the northeast of the proposed compost pad is 1.04 m with a range of 0.01 to 1.95 m. One-half of the observations had depths to bedrock between 0.83 and 1.27 m. Depths to bedrock are shallow at 8 percent, moderately deep at 37 percent, deep at 48 percent, and very deep at 7 percent of the observation points.

Figure 4 contains two-dimensional plots of the interpreted depths to bedrock within each of the surveyed fields. The spatial patterns evident in Figure 4 suggest that the depth to bedrock is relatively invariable over short distances. Areas that are shallower to bedrock appear to be more common on higher-lying, more sloping areas. The shape of several small, isolated areas of very deep (>1.5 m) soils suggest the possibility of solution features. However this interpretation is based on a modest number of observations and was not confirmed by ground-truth observations. In addition, other factors (variation in moist or soil texture) could influence the observed spatial patterns.

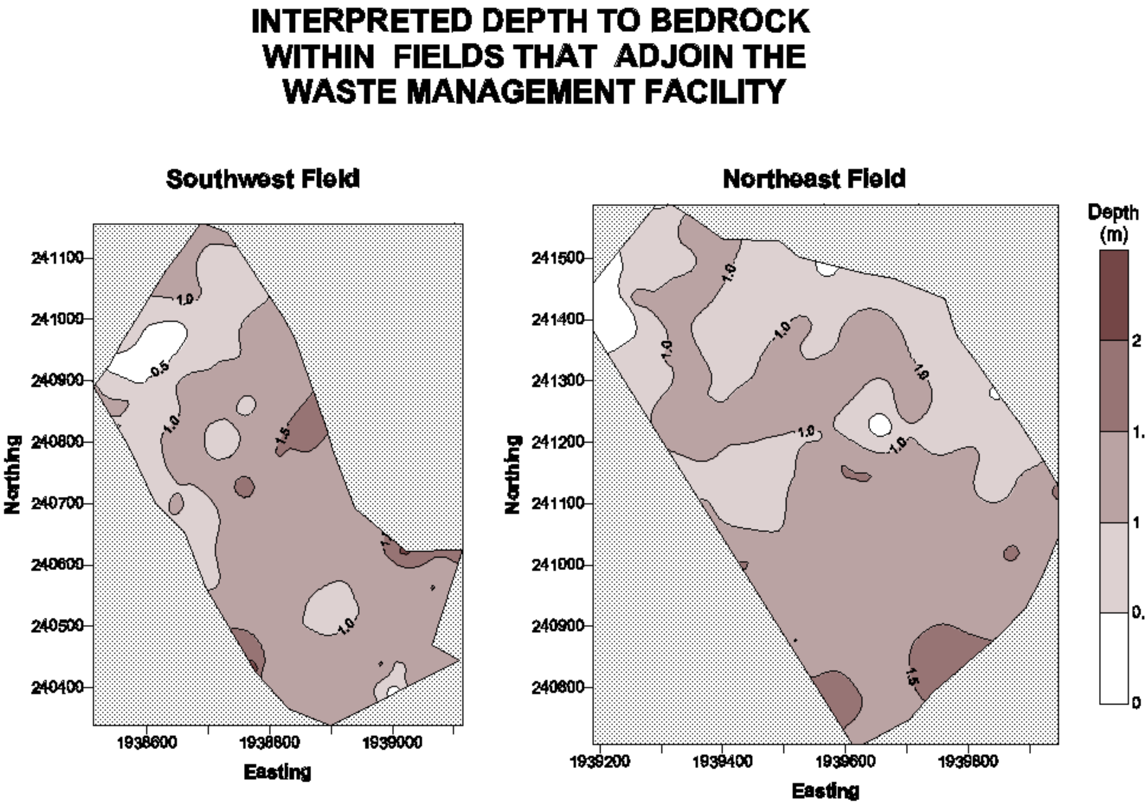

Figure 4 – Two-dimensional plots of the interpreted depths to bedrock in the fields located to the southwest and northeast of the proposed compost pad. Depths are in m.

Conclusions:

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations are interpretive and do not substitute for direct ground-truth observations (soil borings and pits). The use of geophysical methods can reduce the number of coring observations, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

2. Simulations prepared from correctly interpreted EMI data provide the basis for assessing site conditions. Values of apparent conductivity were low (2.4 to 13.2 mS/m) within the two surveyed fields. Spatial patterns evident in the enclosed plots appear to principally reflect variations in the thickness of the soil mantle and depth to bedrock. A moderate (r = 0.721) and significant (0.001 level) correlation was found between the measured depth to bedrock at the 27 pits and measurements obtained with the EM31 meter in the horizontal dipole orientation. Interpreted patterns suggest comparatively shallow (< 1.5 m) and uniform depths to bedrock (see Figure 4). Isolated patterns of shallower or deeper depths to bedrock patterns suggest the possible occurrence of minor solution feature and pinnacles within the fields that adjoin the proposed site of the composting-pad.

3. Additional, time-lapsed and more comprehensive EMI surveys of the site are recommended. An EM38 meter would provide shallower observation depths (<1.5 m) and greater resolution of soil features (1 m intercoil spacing). This meter is suited to the assessment of soil properties and the delineation of potential overland flow patterns emanating from the compost pad.

It was my pleasure to work in Pennsylvania and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
B. Ahrens, Director, USDA-USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
W. Bowers, State Conservation Engineer, USDA-NRCS, Suite 340, One Credit Union Place, Harrisburg, PA 17110-2993
G. Cauffman. Manager Farm Operations, Pennsylvania State University, Farm Services Building, University Park, PA 16802-1126
B. Hudson, Director of Soils Survey Division, USDA-NRCS, Room 4250 South Building, 14th & Independence Ave. SW, Washington, DC 20250
C. Olson, National Leader for Soil Investigations, USDA-USDA, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866

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