United States Department of Agriculture

Natural Resources Conservation Service

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Subject: ENG -- Electromagnetic Induction (EMI) Assistance

Date: 20 March 2000

To: Janet Oertly
State Conservationist
USDA-NRCS,
Suite 340, One Credit Union Place
Harrisburg, PA 17110-2993

Purpose:

A public water well located near Kreamer, Pennsylvania, has become contaminated. Potential seepage from a twenty-year-old agricultural waste-holding facility is suspected as a possible source of this contamination. The well is located about 2000 feet from the waste-holding facility. At the request of the Snyder County Conservation District and your Engineering Staff (USDA-NRCS), an electromagnetic induction (EMI) site investigation was conducted in the area immediately south of the waste-holding facility. The purpose of this investigation was to gather ancillary geophysical data on a portion of the area that surrounds this structure.

Participants:

Jack Clark, District Conservationist, USDA-NRCS, Middleburg, PA
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Sean LeVan, Act-6 Nutrient Management Technician, Snyder County Conservation District, Middleburg, PA
Barry Spangler, Chesapeake Bay Biosolid Technician, Snyder County Conservation District, Middleburg, PA
John Zaginaylo, Area Engineer, USDA-NRCS, Bloomsburg, PA

Activities:

All field activities were completed during on 15 March 2000.

Equipment:

The electromagnetic induction instruments used in this study were the EM31 and the EM34-3 meters and the GEM300 sensor. Geonics Limited manufactures the EM31 and EM34-3 meters.♦ Principles of operation have been described by McNeill (1980a). The EM31meter is portable and requires only one person to operate. 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). The EM34-3 meter is also portable, but requires two people to operate. The EM34-3 meter has theoretical observation depths ranging from 7.5 to 60 meters. Depth of observation depends on intercoil spacing (10, 20, or 40 m), coil orientation (horizontal or vertical) and frequency (400, 1600, and 6400 Hz). The EM31 and the EM34-3 meters provide limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. Output is calibrated to read apparent conductivity and is expressed in milliSiemens per meter (mS/m).

The GEM300 sensor is manufactured by Geophysical Survey Systems, Inc. ♦ Geophysical Survey Systems, Inc, (1998) has described the principles of operation for the GEM300 sensor. The GEM300 sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed intercoil spacing of 1.6 m. Multiple frequencies are encoded in a pseudo-random binary sequence and transmitted in a step-frequency mode. The sensor records both in-phase and quadrature measurements. Output is the mutual coupling ratio in parts per million or apparent conductivity (mS/m).

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

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

Survey area:

The site is in located immediately downslope of the waste-holding facility. The site includes an animal holding area, and strips of hayland and cropland. At the time of this survey, soils were moist throughout.

The topography of the survey area has been simulated in the two-dimensional contour plot and the three-dimensional surface net plot shown in Figure 1. In these plots, the contour interval is 2 feet. Relief is about 27 feet. The surface slopes towards the south or the upper right-hand corner of the survey area. An intermittent drainageway cross the survey area along grid line 500Y.

The survey area is located in a mapped soil delineation of Kreamer cherty silt loam, 3 to 8 percent slopes (Eckenrode, 1985). This deep, moderately well drained soil formed in colluvium weathered from cherty limestone. Depth to bedrock is greater than 5 feet. Permeability is slow. Surface runoff is slow to rapid. The Kreamer soil is a member of the clayey, illitic, mesic Aquic Hapludults family.

Field Procedures:

An irregularly shaped, 650 by 550 foot, rectangular grid was established across the site. The grid interval was 50 feet. Survey flags were inserted in the ground at each grid intersection and served as observation points. This procedure produced 128 observation points (see Figure 1, upper plot). The relative elevation of each grid intersection was determined with a laser level. Measurements were taken at each observation point with the EM31 meter held at hip height in both the horizontal and vertical dipole orientations. Measurements were taken at each observation point with the EM34-3 meter placed on the surface in the horizontal dipole orientation. A twenty-meter intercoil spacing was used. In addition, measurements were taken at 112 observation points with the GEM300 sensor held at hip-height in the vertical dipole orientation. In-phase, quadrature phase, and conductivity data were recorded with the GEM-300 sensor at four different frequencies (2010, 6030, 9810, and 14630 Hz).

Background:

Electromagnetic induction (EMI) is a noninvasive geophysical tool that is used for site assessments. Advantages of EMI are its portability, speed of operation, flexible observation depths, moderate resolution of subsurface features, and comprehensive coverage. Results of EMI surveys are interpretable in the field. 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 produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the volumetric water content, type and concentration of ions in solution, temperature and phase of the soil water, and amount and type of clays in the soil matrix (McNeill, 1980b). The apparent conductivity of soils increases with increases in 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 has been successfully used to investigate the migration of contaminants from waste sites (Brune and Doolittle, 1990; Drommerhausen, et al., 1995; Eigenberg et al., 1998; Radcliffe et al., 1994; Ranjan and Karthigesu, 1995; Siegrist and Hargett, 1989; and Stierman and Ruedisili, 1988). Soils affected by animal wastes have higher conductivity than soils that are unaffected by these contaminants. Electromagnetic induction has been used to infer the relative concentration, extent, and movement of contaminants from waste-holding facilities. Electromagnetic induction does not provide a direct measurement of specific ions or compounds. However, measurements of apparent conductivity have

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been correlated with concentrations of chloride, ammonia, and nitrate nitrogen in the soil (Brune and Doolittle, 1990; Ranjan and Karthigesu, 1995; Eigenberg et al., 1998).

Theories of Operation:

The depth of observation and measured EMI response are influenced by the instrument's coil orientation, coil separation, and frequency, as well as the conductivity of the profiled material(s). For all EMI instruments, response is not uniform with depth; surface and shallow layers contribute more to the overall response than deeper layers. The orientation (either vertical or horizontal) of the transmitter and receiver coil axis with respect to the ground surface affects the response from materials at different depths (McNeill, 1985). In the horizontal dipole orientation, these instruments are more sensitive to near surface materials. In the vertical dipole orientation, these instruments are more sensitive to deeper materials.

For meters developed by Geonics Limited, the depth of observation is considered to be "*geometry limited*" rather than "*skin depth limited*" (McNeill, 1980a). With these meters, increasing the intercoil spacing and decreasing the frequency will theoretically result in greater depths of observation.

The theoretical observation depth of the GEM300 sensor is dependent upon the apparent conductivity of the profiled material(s) and the operating frequency. With the GEM300 sensor, the depth of observation is considered "*skin depth limited*" rather than "*geometry limited*" (Won, 1980 and 1983, Won et al., 1998). Skin depth represents the maximum depth of observation for an EMI instrument operating at a specific frequency and sounding a medium of known conductivity. The skin depth (D) can be estimated using the following equation (McNeill, 1996):

$$D = 500/(s*f)^{-2} \qquad [1]$$

Where s is the ground conductivity (mS/m) and f is the frequency (kHz).

According to equation [1], skin depth is inversely proportional to frequency; greater depths of observation can be achieved by decreasing the frequency. Low frequency signals have longer periods of oscillation and loose energy less rapidly than high frequency signals. As a consequence, low frequency signals travel farther through conductive mediums than high frequency signals. Won and others (1996) noted, that at a given frequency, the depth of observation is greater in low conductivity than in high conductivity soils. With the GEM300 sensor, changing the transmitter frequency will change the depth of observation. Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor (Won et al., 1996).

Results:

EM31 Meter

Table 1 summarizes basic statistics for the surveys conducted with the EM31 and the EM34-3 meters. With the EM31 meter, apparent conductivity increased with increasing depth of observation (shallow-sensing horizontal dipole orientation (0 to 3 m) measurement were less than those of the deeper-sensing vertical dipole orientation (0 to 6 m)).

Table 1

Basic Statistics
EM Meters
(All values are in mS/m)

				Quartiles			
Meter	**Orientation**	**Minimum**	**Maximum**	**1st**	**Median**	**3rd**	**Average**
EM31	Horizontal	6.4	21.2	8.0	9.0	9.9	9.7
EM31	Vertical	8.4	26.2	11.0	12.2	13.6	13.1
EM34-3	Horizontal	7.0	19.0	9.0	10.0	11.0	10.5

Values of apparent conductivity were relatively low, but variable across the site. Apparent conductivity averaged 9.7 mS/m and 13.1 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 9.9 mS/m. In the deeper-sensing, vertical dipole orientation, one-half the observations had values of apparent conductivity between 11.0 and 13.6 mS/m.

Because of higher clay and moisture contents, the soil was assumed to have a higher conductivity than the underlying limestone bedrock. As a consequence, conductivity should decrease with increasing depth of observation as a greater volume of the underlying, more resistive bedrock is averaged into the EMI response. However, the opposite effect was observed with the EM31 meter. As the meter was held at hip-height, when operated in the horizontal dipole orientation, the instrument is more sensitive to the one-meter column of air directly beneath the coils than the underlying soil. The lower readings in the horizontal dipole orientation may reflect the disproportionate weighing of this column of air into the meter's response.

Figure 2 contains two-dimension plots of apparent conductivity obtained within the EM31 meter in the horizontal and vertical dipole orientations. In each plot the isoline interval is 2 mS/m. In each plot, a conspicuous area of high apparent conductivity is evident in the southeast (lower left hand) corner of the study area. As the highest values of apparent conductivity are adjacent to the waste-holding facility and decrease in a down slope direction away from the waste-holding facility, this pattern is believed to represent a plume of contaminants seeping from the structure. In the vertical dipole orientation (0 to 6 m) a conspicuous plume of higher conductivity (> 14 mS/m) is evident at a distance of 325 feet from the waste-holding facility.

EM34-3 Meter

Table 1 summarizes basic statistics for the survey conducted with the EM34-3 meter and a 20-m intercoil spacing. Apparent conductivity averaged 10.5 mS/m in the horizontal dipole orientation. One-half the observations had values of apparent conductivity between 9.0 and 11.0 mS/m. These values are slightly lower than those obtained with the EM31 meter in the vertical dipole orientation. A greater column of earthen materials was measured with the EM34-3 meter (20 m intercoil spacing by 15 m observation depth) than with the EM31 meter (3.8 m intercoil spacing by 6 m observation depth). As a consequence, the resolution of the EM34-3 meter is considerably less. Because a greater volume of earthen materials is averaged into the EMI response, the presence of a contaminant plume will be less noticeable and even indistinct when greater depths are profiled.

Figure 3 contains a two-dimension plot of apparent conductivity obtained within the EM34-3 meter in the horizontal dipole orientation. The isoline interval is 2 mS/m. Once again, a conspicuous area of high apparent conductivity is evident in the southeast (lower left hand) corner of the study area. A conspicuous plume of higher conductivity (> 12 mS/m) is evident at distances of about 200 to 300 feet from the waste-holding facility. However, compared with the plots shown in Figure 2, the most conductive portion (>16 mS/m) of the plume appears to have moved about 50 ft to the west. This section is located within an animal holding area.

GEM-300 Multifrequency Electromagnetic Profiler:

Table 2 summarizes the basic statistics for the survey conducted with the GEM300 sensor. With this sensor, measured responses decreased with decreasing frequency and increasing depth of observation. This relationship most likely reflects the increased response from the underlying limestone bedrock with increasing observation depth. Because of its lower clay and moisture contents, the limestone bedrock is presumed to be more resistive than the overlying soil materials.

Table 2

Basic Statistics
GEM300 Survey
(All values are in mS/m)

Frequency	Minimum	Maximum	Quartiles 1st	Quartiles Median	Quartiles 3rd	Average
2010	0.0	26.5	4.7	7.1	11.9	8.8
6030	10.5	36.2	15.5	17.0	20.4	18.6
9810	11.6	37.5	16.9	18.2	21.4	19.8
14610	13.1	39.9	18.7	19.9	22.7	21.5

With the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 8.8, 18.6, and 19.8, and 21.5 mS/m at frequencies of 2010, 6030, 9810, and 14610 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths (observation depths) were about 11.9 m at 2010 Hz, 4.7 m at 6030 Hz, and 3.6 m at 9810 Hz and 0.9 m at 14610 Hz.

At 2010 Hz, apparent conductivity averaged 8.8 mS/m in the vertical dipole orientation. One-half the observations had values of apparent conductivity between 4.7 and 11.9 mS/m. At 6030 Hz, apparent conductivity averaged 18.6 mS/m in the vertical dipole orientation. One-half the observations had values of apparent conductivity between 15.5 and 20.4 mS/m. At 9810 Hz, apparent conductivity averaged 19.8 mS/m in the vertical dipole orientation. One-half the observations had values of apparent conductivity between 16.9 and 21.4 mS/m. The close similarity between data collected at 6030 and 9810 Hz may reflect their comparable skin depths (4.7 and 3.6 m, respectively). At 14610 Hz, apparent conductivity averaged 21.5 mS/m in the vertical dipole orientation. One-half the observations had values of apparent conductivity between 18.7 and 22.7 mS/m.

Measurements of apparent conductivity collected with the GEM300 sensor, though comparable, were higher and more variable than those collected with the EM31and EM34-3 meters. Differences in equipment calibration by the manufacturers are believed to explain the higher values of apparent conductivity recorded by the GEM300 sensor than by the EM31 and EM34-3 meters. In addition, differences in the depth of observation, volume of soil material measured, and resolution of each tool will affect measurements.

Apparent conductivity data collected with the GEM300 sensor are shown in figures 4 and 5. In each plot the isoline interval is 3 mS/m. The frequency at which data were collected is shown above each plot. The depth of observation is assumed to increase as the frequency decreases. Although values and spatial patterns vary among these plots, the conspicuous zone of higher apparent conductivity observed in the plots of the EM31 and EM34-3 meters data is apparent in each of these plots. In each plot, the highest values of apparent conductivity are near the waste-holding facility and decrease in a down slope direction away from the structure, this pattern is believed to represent a plume of contaminants seeping from the structure. Data collected at 14610 Hz (0 to 0.9 m) show a broad and highly conductive (>20 mS/m) area evident at a distance of over 400 feet from the waste-holding facility. Data collected at 2010 Hz (0 to 11.9 m) show a more restricted and less conductive (> 12 mS/m) area that is still apparent at a distance of over 300 feet from the waste-holding facility.

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 sampling). 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. Comparable spatial patterns of apparent conductivity were obtained with the EM31and EM34-3 meters, and the GEM300 sensor. Each identified a conspicuous area having higher values of apparent conductivity than surrounding soils and earthen materials. This area is believed to reflect the affects of contaminants seeping from the waste-holding facility. Compared with other similar investigations conducted on waste-holding facilities in Pennsylvania, the extend of this zone is considered remarkably large (detectable at distances greater than 200 to 400 feet from the structure).

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:
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Relative Topography

(contour interval = 2 ft)

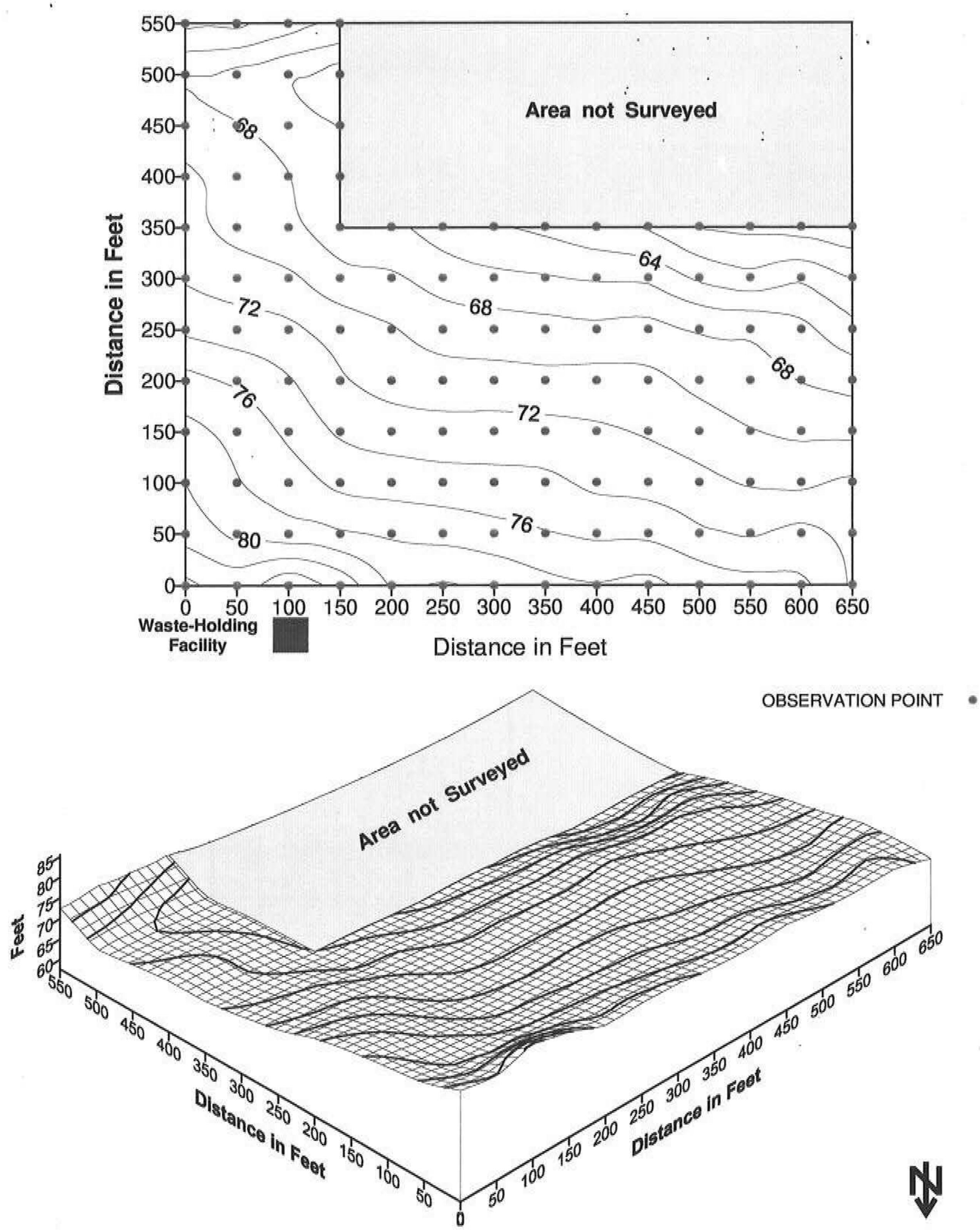


Figure 1

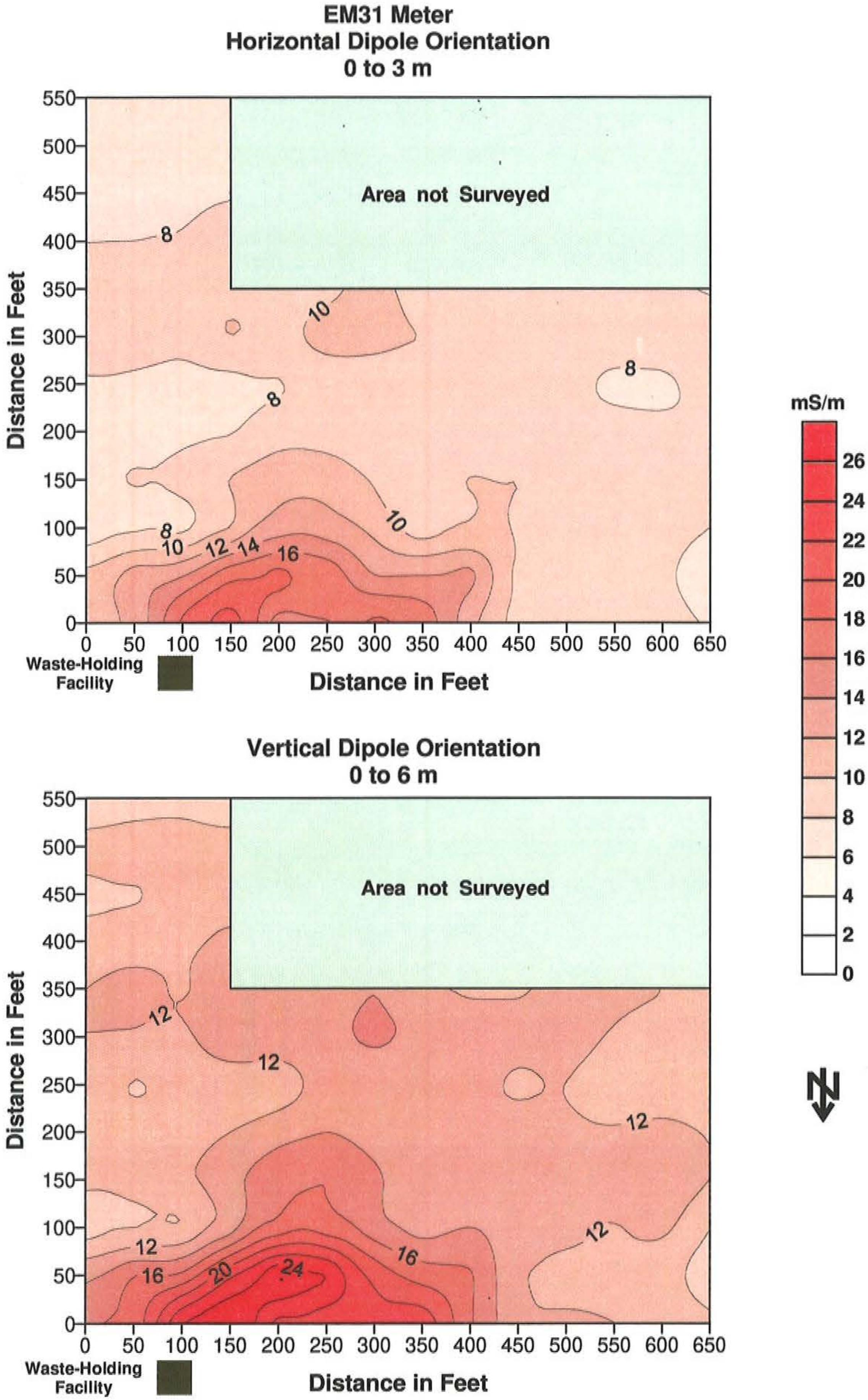

EM31 Meter
Horizontal Dipole Orientation
0 to 3 m
Area not Surveyed
Distance in Feet
Distance in Feet
Waste-Holding Facility
Vertical Dipole Orientation
0 to 6 m
Area not Surveyed
Distance in Feet
Distance in Feet
Waste-Holding Facility
mS/m
0
2
4
6
8
10
12
14
16
18
20
22
24
26
N

Figure 2

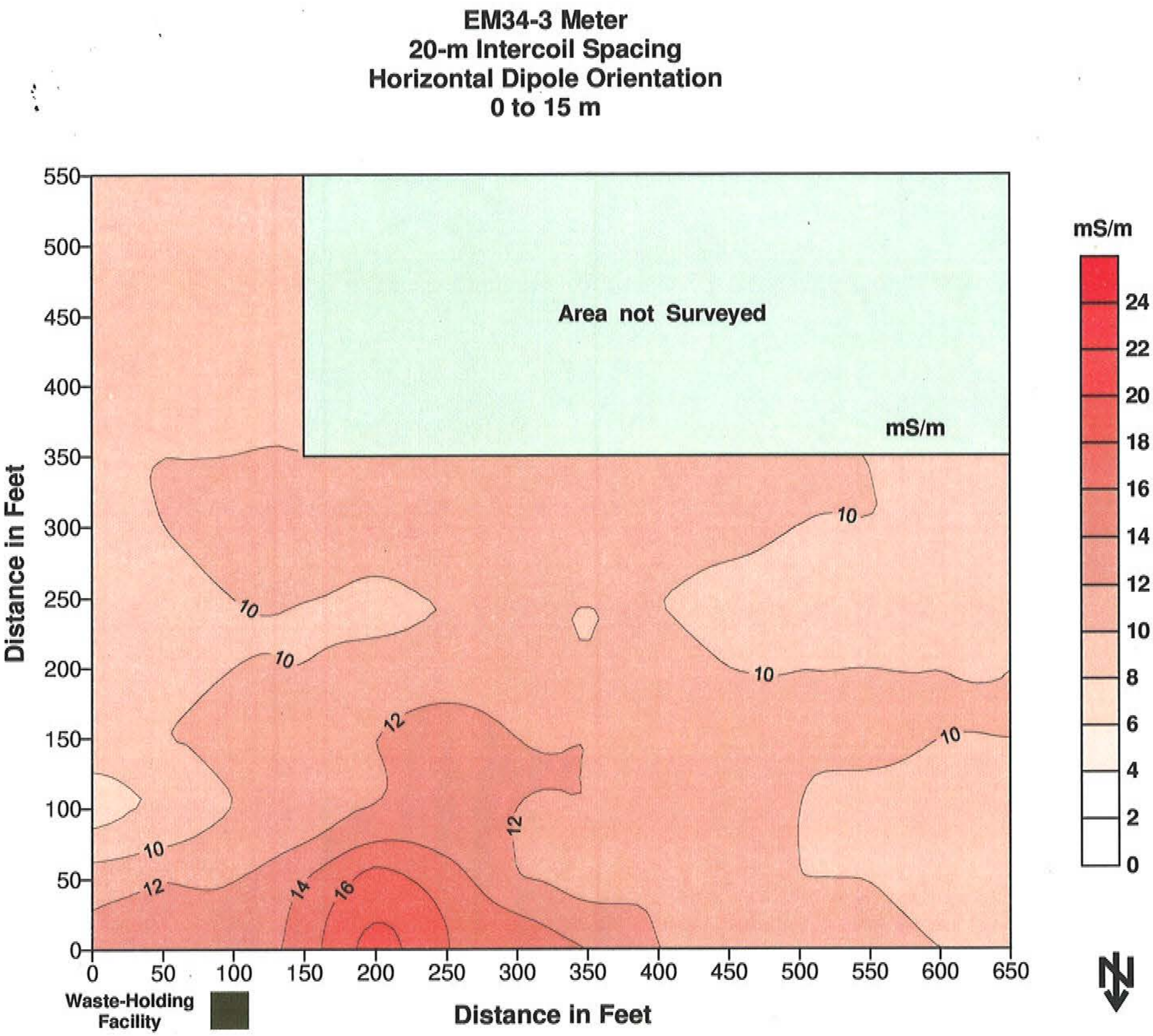

EM34-3 Meter
20-m Intercoil Spacing
Horizontal Dipole Orientation
0 to 15 m
Area not Surveyed
mS/m
Distance in Feet
Distance in Feet
Waste-Holding Facility
mS/m
0
2
4
6
8
10
12
14
16
18
20
22
24
0
50
100
150
200
250
300
350
400
450
500
550
600
650
10
12
14
16
N

Figure 3

GEM300 Sensor
Vertical Dipole Orientation

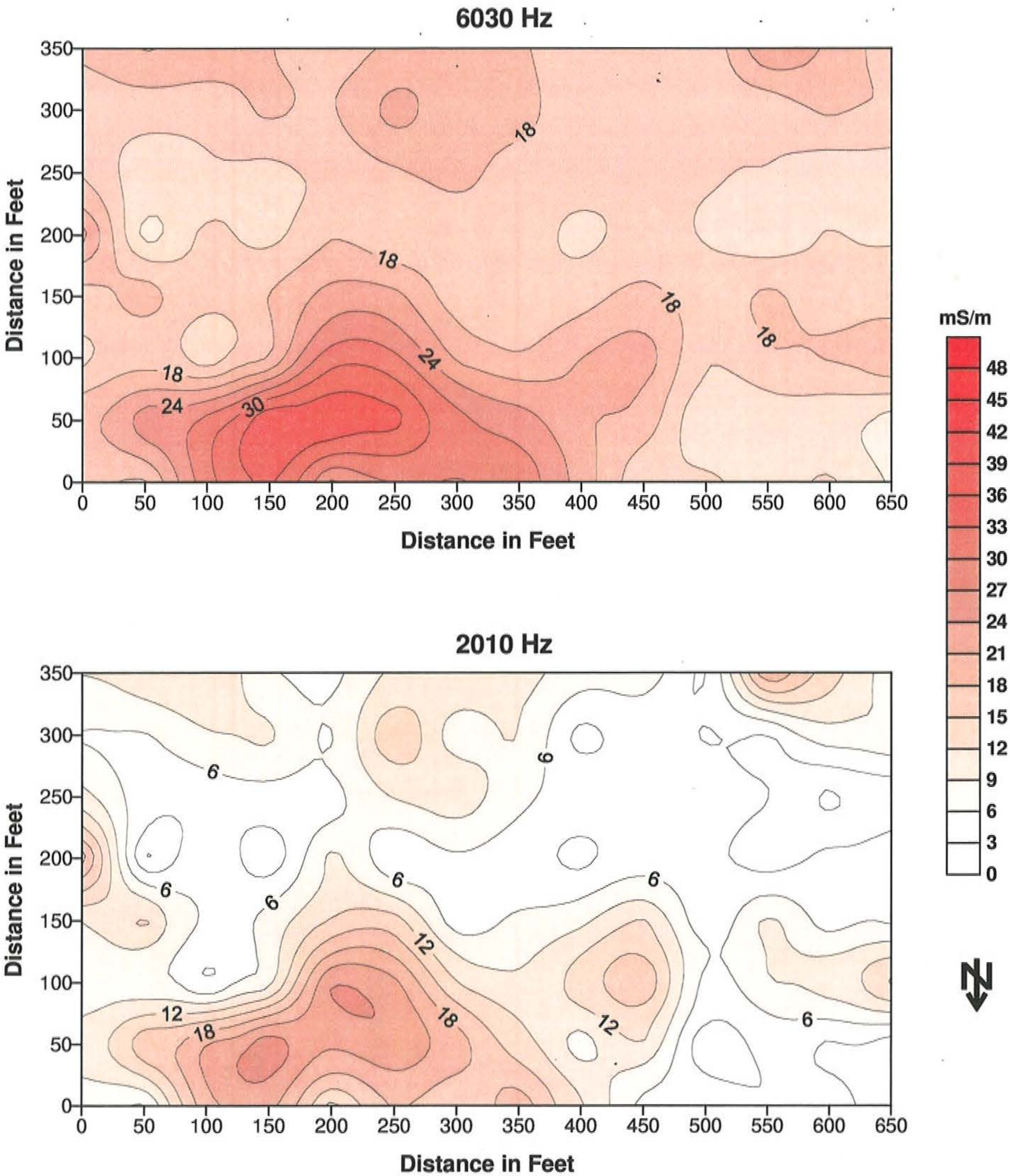
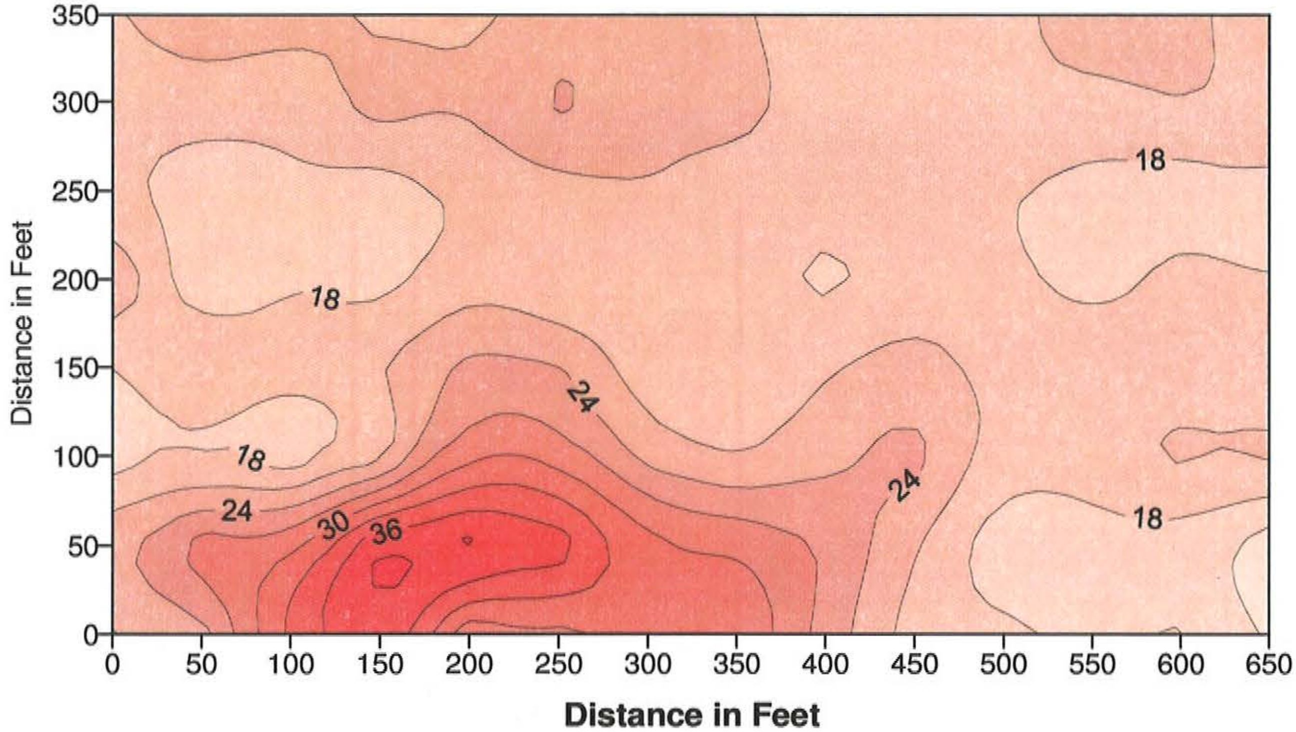
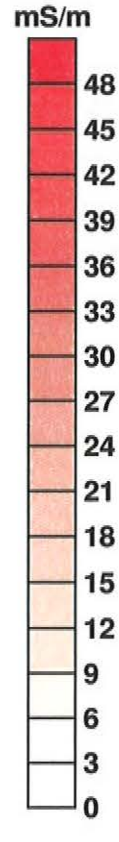


Figure 4

GEM300 Sensor
Vertical Dipole Orientation

14610 Hz





9810 Hz

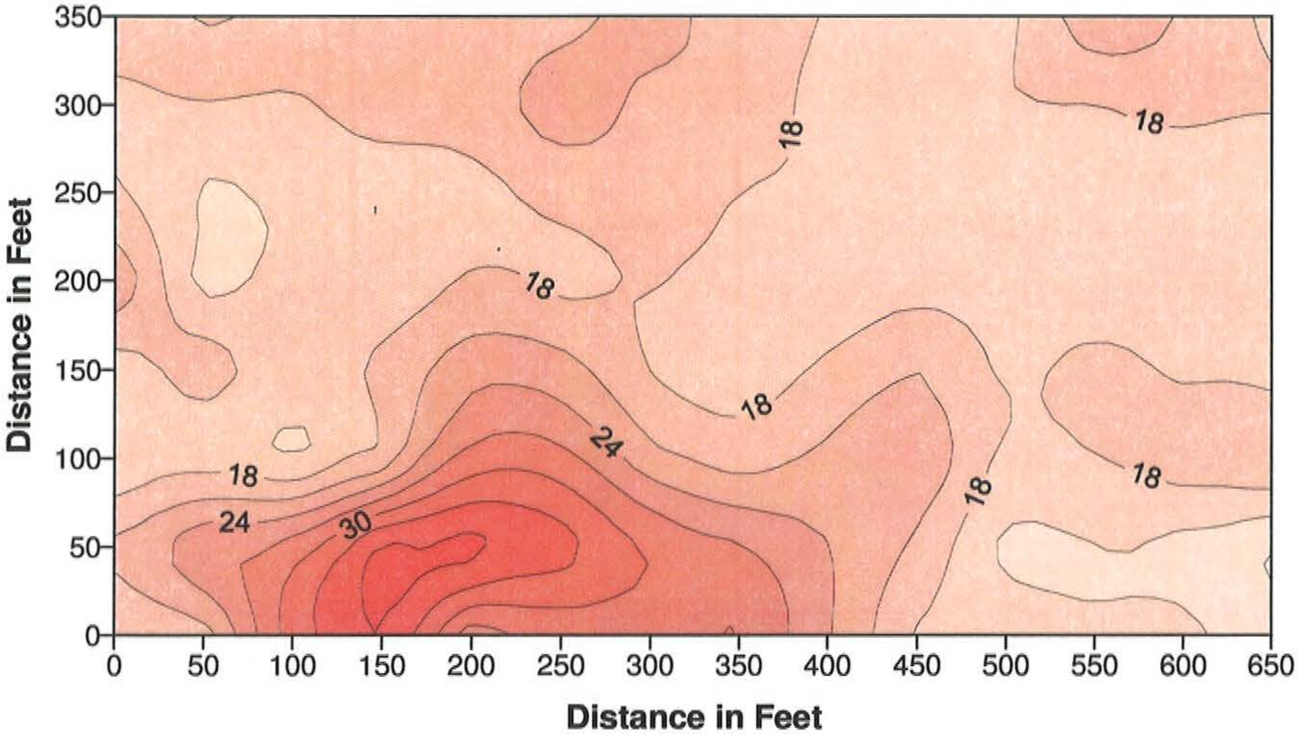


Figure 5