United States Department of Agriculture

Natural Resources Conservation Service

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Subject: SOI -- Geophysical Assistance --

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To: Robert L. Eddleman
State Conservationist
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Purpose:
The purpose of this investigation was to provide electromagnetic induction (EM) and ground-penetrating radar (GPR) assistance to the Wet Soil Monitoring Project in Jasper and Jennings counties.

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Activities:
All field activities were completed during the period of 22 to 25 April 1996. On 22 to 24 April, ground-penetrating radar (GPR) and electromagnetic induction (EM) field investigations were conducted at the Jasper - Pulaski State Game Preserve. The Preserve is located near the town of San Pierre in Jasper County. On 25 April, electromagnetic induction field investigations were conducted at the Muscatatuck National Wildlife Refuge. The Refuge is located near the town of Hayden in Jennings County.

Equipment:
The radar unit used in this study was the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc. The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. The model 3110 (120 mHz) antenna was used in the investigation. The system was powered by a 12-volt battery. This unit is backpack portable and

requires two people to operate. The use and operation of GPR have been discussed by Morey (1974), Doolittle (1987), and Daniels and others (1988).

The electromagnetic induction meters used in this study were the EM38 and EM31, manufactured by Geonics Limited. These meters are portable and require only one person to operate. Principles of operation have been described by McNeill (1980, 1986). No ground contact is required with these meters. Each meter provides limited vertical resolution and depth information. For each meter, lateral resolution is approximately equal to the intercoil spacing. The observation depth of an EM meter is dependent upon intercoil spacing, transmission frequency, and coil orientation relative to the ground surface.

The EM38 meter has a fixed intercoil spacing of about 1 meter. It operates at a frequency of 13.2 kHz. Theoretically, the EM38 meter has observation depths of about 75 and 150 centimeters in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter has a fixed intercoil spacing of about 3.65 meters. It operates at a frequency of 9.8 kHz. Theoretically, the EM31 meter has observation depths of about 3 and 6 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

A Rockwell Precision Lightweight GPS Receiver (PLGR) was used to obtain the coordinates of observation points. This receiver was operated using an external power source (portable 9 volt battery). During field work, the system was operated in the continuous mode. This mode uses the most power, but is able to acquire and continuously track satellites. Changes in position were continuously displayed. Positions were recorded using the Universal Transverse Mercator (UTM) coordinate system. All recorded points had a *figure of magnitude* (FOM) of 1.

Before field work, a digital elevation model (DEM) of the San Pierre Quadrangle was prepared. The DEM data was compiled in 1-degree units. Data consist of a regular array of elevations arranged using the coordinate system of the World Geodetic System 1972 Datum. Spacing among observations is 3 arc seconds. Data have an absolute horizontal accuracy of 130 meters. Data were compiled in a grid format using the Terrain Analysis Package (TAPPS) developed by Softwright (Golden, Colorado).

A DEM of the Jasper County study site was prepared from elevation data collected at 500 observation points. A theodolite was used to obtain this data. All points were tied into a geodetic survey marker. A 3-meter grid (243 rows by 260 columns) was constructed from this data set using the SURFER for Windows program, developed by Golden Software, Inc. Grids were created using kriging methods.

The SURFER for Windows program was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation. In each of the enclosed plots, colors and filled contour lines have been used. These options were selected to help emphasize spatial patterns. Other than showing trends and patterns in values of apparent conductivity (i.e., zones of higher or lower electrical conductivity) or estimated depths to water table, no significance should be attached to the colors themselves.

Discussion:

Jasper County Site:

Background

Recent interest in hydrologic modeling has increased the need for data on the depth and movement of groundwater across landscapes. Presently, much of this information is collected and monitored in wells. By recording the water levels in monitoring wells, depths to the water table are determined and potentiometric maps can be prepared. Potentiometric maps are used to estimate ground-water flow direction, flow velocities, and the location of discharge and recharge areas (Freeze and Cherry, 1979).

Typically, potentiometric maps are prepared from data collected from a few, widely spaced monitoring wells. These monitoring wells provide information concerning soil and hydrogeologic conditions at specific locations. However, hydrologic conditions for the large areas among monitoring wells must be inferred. Inferences are often based on simplified assumptions concerning soil and hydrogeologic conditions existing among monitoring wells (Koerner and others, 1979; Violette, 1987).

Toth (1963) defined three categories of groundwater flow: local, intermediate, and regional. In relatively level areas containing homogeneous soil and geologic strata, hydrologic conditions are often relatively uniform and predictable, and groundwater flow conforms to intermediate and regional models. In more sloping area, the topography creates numerous subsystems of local groundwater flow within intermediate and regional flow systems (Freeze and Cherry, 1979).

In areas of intricate and contrasting soil patterns, undulating topography, and non-homogeneous or anisotropic materials, depths to the water table and flow patterns are difficult to assess. In these areas, hydrogeologic data, models, and maps are often oversimplified and are more susceptible to errors. Improved methods are needed to understand the depth, flow, and seasonal variations of the water table across complex landscapes.

In areas of coarse-textured materials, ground-penetrating radar (GPR) techniques have been successfully used to chart water table depths among monitoring wells and into nearby areas. In areas of coarse-textured materials, GPR techniques can provide continuous records of the depths to the water table. This geophysical tool can also provide subsurface stratigraphic information useful for hydrologic modeling. In these areas, GPR techniques can be used to increase the quantity and quality of subsurface data, and reduce the need for a large number of monitoring wells.

Ground-penetrating radar techniques have been used to provided data for hydrogeologic models (Violette, 1987; Taylor and Baker, 1988); develop maps of the water table (Sellmann and others, 1983; Davis and others, 1984; Wright and others, 1984; Johnson, 1987; Bohling and others, 1989; Iivari and Doolittle, 1994); define recharge and discharge areas, or the geometry of aquifers (Johnson, 1987; Wright and others, 1984); and delineate near-surface geologic conditions (Beres and Haeni, 1991). Ground-penetrating radar profiles have been used to construct three-dimensional computer simulations showing the configuration of soil horizons and geologic strata, and to predict ground-water flow patterns in stratified, coarse-textured soils (Collins and Doolittle, 1987; Steenhuis and others, 1990; Iivari and Doolittle, 1994). In addition, GPR techniques have been used to detect wetting fronts (Vellidis and others, 1989) and contaminant plumes (Horton and others, 1981; Olhoeft, 1986; Cosgrave and others, 1987; Brune and Doolittle, 1990) in sandy soils and to estimate the moisture content of soils (Houck, 1982).

The present study in Jasper County is similar to the study conducted by Iivari and Doolittle (1994). In the study by Iivari and Doolittle, a map of the water table was developed for an area (3.2 ha.) of glacial-fluvial deposits. The site had moderate relief (about 4 m) and was in hayland. The present study was conducted on a larger (32.8 ha.), more inaccessible area of eolian deposits. The Jasper County site had greater relief (about 9.7 m) and was forested. Both studies attempted to demonstrate the feasibility of using GPR and computer processing techniques to chart the depth to the water table and assess local ground water flow in areas having intricate soil patterns, undulating topography, and non-homogeneous or anisotropic strata. The present study attempted to map water table depths across relatively large and inaccessible areas. In addition, this study attempted to integrate conventional, GPR, and GPS data collection methodologies with computer processing techniques and digital elevation models.

Study Area:
The study site was located on the San Pierre Quadrangle, Indiana (7.5 minute series). Figure 1 shows the approximate location of the quadrangle in northwestern Indiana and its relationship to the surrounding counties. The site was located on a dune-interdune landscape within the Kankakee outwash plain. The outwash plain has a nearly level topography with low sand dunes or ridges. The sand dunes and ridges have relief as great as 10 meters. The larger dune fields consist of a series of sand ridges oriented in a northeast - southwest direction. Figure 2 is a three-dimensional surface net diagram of the San Pierre Quadrangle. This figure shows the general location of the study site (enclosed by small rectangle) and its relationship to the Kankakee River, several terraces, and the dune field (hummocky areas to the South of the river). Figure 3 is a three-dimensional surface net diagram of the area surrounding the survey site (enclosed in rectangle). In Figure 3, the study area appears as a level, featureless plain. It became evident that the data points were too few and widely spaced to provide the needed resolution to define dunes and other features within the study site.

The site was located in the northern half of Section 10, T. 31 N., R. 5 W. The site was in woodland. Twenty-four monitoring wells had been installed across the site. Map units delineated within this area include Oakville fine sands, 2 to 6 percent slopes; Oakville fine sands, 6 to 15 percent slopes; Morocco loamy sands; Newton loamy fine sand, undrained; and Zadog-Maumee loamy sands (Smallwood and Osterholz, 1990). Oakville soils are members of the mixed, mesic Typic Udipsamments family. Morocco soils are members of the mixed, mesic Aquic Udipsamments family. Newton soils are members of the sandy, mixed, mesic Typic Humaquepts family. Maumee soils are members of the sandy, mixed, mesic Typic Haplaquolls family. Zadog soils are members of the coarse-loamy, mixed, mesic Typic Haplaquolls family. The Oakville soils were on higher-lying dunes. Morocco, Maumee, Newton, and Zadog soils were on lower-lying dunes and inter-dune areas.

Field Procedures:
The initial GPR survey was conducted along three north - south and three east - west trending access roads. These traverses were completed with the GPR control unit mounted in a vehicle. The 120 mHz antenna was towed behind the vehicle. Later, three additional lines were established across the southern portion of the study area. These lines were oriented in an east - west direction and spaced about 100 meters apart. As these traverses were conducted through a wooded area, radar traverses were completed with the GPR control unit carried in a backpack and the antenna pulled by hand.

Because of the unequal spacing of traverse lines and sampling, only the southern portion of the survey area will be evaluated and discussed in this report. This portion of the survey area was more intensively and uniformly sampled with GPR. A survey grid was established across this portion of the site. The grid was composed of five, parallel, west - east trending lines. Each of the these lines was about 830 meters in length and spaced about 100 meters apart. These lines extended eastwards from a north - south trending base line road. The base line and two additional lines (parallel to the base line) were established on three north - south trending access roads. Each of these lines was about 330 meters in length. Along each line (8 lines), observation flags (167) were inserted in the ground at intervals of about 30.5 meters. In addition, a diagonal line was laid out connecting fourteen monitoring wells (14 additional observation flags).

The coordinates of each observation point (190) were obtained with a GPS receiver. The locations of these points are shown in Figure 4. Most of the observation points appear properly spaced, aligned, and correctly oriented. However, slight spatial inaccuracies were presumed to occur in the data. The locations of the monitoring wells used to model water table depths and to correlate the radar imageries are also shown in Figure 4.

Before this investigation, Byron Jenkinson had completed the topographic mapping of the study area with a theodolite. In this survey, the elevations of approximately 500 points were obtained. This topographic data set was kriged using SURFER for Windows software to produce a grid of the survey area (243 rows by 260 columns) with a 3 meter interval. Figure 5 is a two-dimensional contour plot of the study site. This plot was prepared from the data collected by Byron Jenkinson. In this plot, the contour interval is 0.5 meter. The site consists of two principal dunes or ridges separated by a lower-lying inter-dune area. Relief is about 10 meters. Compared with the 1-degree unit DEM model of the site (Figure 3), the more closely spaced data points of the conventional topographic survey (Figure 5) provided improved delineation of dunes and other features within the study site. In Figure 5, the locations of the 14 monitoring wells used to model water table depths, verify the radar interpretations, and to scale the radar imageries are also shown.

The topographic, radar, and GPS data were used to construct two- and three-dimensional plots of the study site. These data sets were collected at different times and by different individuals. A concern and likely source of error were the registering of these data sets. Some information was not directly available and was interpolated. While considered slight, spatial discrepancies undoubtedly occur among the topographic and radar data collected for each observation point. These spatial discrepancies are sources of errors.

The radar survey was completed by pulling the 120 mHz antenna along nine survey lines. This procedure provided about 5840 meters of continuous radar imagery. However, interpretations were restricted to the 190 observation points.

Fourteen monitoring wells (see Figure 4) had been previously installed within the study site to determine depths to the water table and the directions of ground-water flow. Water levels in the fourteen monitoring wells were measured at the time of the radar survey. These data were used to scale the radar profiles and to construct two-dimensional plots of the water table. Following the scaling of the radar profiles, the depth to the water table at each observation point (190) was determined. The elevation of the water table was determined at each observation point by subtracting the interpreted depth to the water table from the interpolated elevation of the ground surface.

Calibration:
The suitability of using GPR techniques was assessed during field trials. These trials established the approximate depth of observation and the suitability of the 120 mHz antenna for charting water table depths. A scanning time of 160 nanoseconds (ns) and a scan rate of 32.0 scan/second were used in these trials and in all subsequent field work. During these trials, control and recording settings were optimized.

Following calibration, a radar traverse was conducted along a line of fourteen monitoring wells. As the antenna was pulled passed each monitoring well or between each well set, the operator impressed a vertical line on the radar profile (see Figure 6). The GPR is a time scaled system and measures the time that it takes electromagnetic energy to travel from the antenna to an interface (e.g., water table) and back. To convert travel time into a depth scale, the depth to the water table at each observation well was measured and these depths were used to scale the radar imagery. These data were used to determine the dielectric constant and velocity of propagation of electromagnetic energy through the coarse-textured materials. This information was used to construct a depth scale for the radar profiles.

The measured depths to the water table and the interpreted pulse travel times to the water table interface at the fourteen monitoring wells were compared. At these wells, depths to the water table ranged from 1.04 to 9.7 meters. The coefficient of determination (r^2) between the measured depth and interpreted depth (depth = speed * time) to this interface was 0.9989. This correlation is exceptional and exceeds those obtained by Johnson (1987) and Iivari and Doolittle (1994). At the fourteen observation sites, differences between measured and interpreted depths to the water table ranged from -0.149 to 0.211 m. Seventy-one percent of the observations had differences less than 0.1 m.

The dielectric constant was estimated to be 5.73. Based on the averaged round-trip travel time to the water table, the velocity of propagation through the unsaturated, coarse-textured materials was estimated to be 0.1254 m/ns. The maximum depth of observation was estimated by the equation:

$$D = VT/2$$

Where D is the depth of observation, V is the velocity of propagation, and T is the two-way travel time of a radar pulse. According to this equation and with a scanning time of 160 ns, the maximum observation depth was about 10 meters.

Interpretation of radar profiles:
The study site provided an ideal setting for data acquisition with GPR. Figure 6 is a representative radar profile from the study area. The horizontal scale represents units of distance traveled along a traverse line. The vertical scale is a time or depth scale, which is based on the estimated velocity of propagation (0.1254 m/ns). In this figure, the depth of investigation is about 10 meters (see scale along left-hand margin). The vertical lines at the top of this figure represent the locations of the monitoring wells. Letters and numbers have been used to identify the monitoring wells. The locations of the monitoring wells identified in this profile are indicate by small circles in Figure 5.

The radar profile appearing in Figure 6 has been processed through RADAN software. Processing was limited to signal stacking, customizing color transforms and tables, and annotations. Arcone (1982) observed that signal stacking reduces incoherent background noise while enhancing the image of the water table. Often, because of noise suppression, stacked traces have considerably more discernible features especially at greater depths.

Processing was limited to this profile. As the image of the water table was generally clear and identifiable on most radar profiles, all depth interpretations were made on unprocessed data. Computer processing of radar imagery is relatively expensive, time consuming, and not justified for all radar surveys (Violette, 1987). However, in some studies, computer processing of radar imagery has enhanced the resolution of subsurface features and reduced interpretation errors and biases.

In Figure 6, the soil surface is represented by the series of dark, closely spaced, horizontal lines that extend across the upper part of the profile. Subsurface reflectors apparent in this figure included the water table, stratification within the eolian deposits (B), and a lower-lying, highly contrasting layer (C). Because of high-amplitude reflections from the lower-lying layer, this layer is believed to represent a conspicuous change in texture and a lithologic discontinuity.

In Figure 6, the water table is represented by strong, nearly continuous reflections. The upper boundary of the water table has been highlighted with a dark line. In coarse-textured materials, the electromagnetic gradient is abrupt and dielectric properties are strongly contrasting between saturated and unsaturated soil materials. Because of these properties, the upper boundary of the water table produces strong reflections and distinct images on most radar profiles (Shih and others, 1986). These authors observed a decrease in the amplitude and resolution of this interface on radar profiles as the amount of fines in the soil increased and the capillary fringe became more diffuse.

In most portions of this profile (Figure 6), the image of the water table consists of three distinct bands. Because of variations in surface elevations, it ranges in depth from about 1 to 10 meters. In areas where the water table is close to the soil surface, its reflection is difficult to identify and trace on radar profiles. In some areas, the image of the water table is obscured by near-surface soil horizons or strata within the eolian deposits.

Figure 7 represents a *terrain corrected* version of Figure 6. Terrain correction is a process whereby the surface of the radar profile is adjusted to conform with the ground topography. At each monitoring well, the radar profile has been adjusted to the elevation of the ground surface. The radar profile appearing in Figure 7 has been compressed (vertically). In Figure 7, the water table appears to occur at relatively shallow depths in the lower-lying inter-dune area and plunges to greater depths beneath the higher-lying dunes.

Based on Figure 7, the apparent direction of groundwater flow appears to be from the inter-dune areas towards the dunes. This would suggest that, at this time of the year, interdune areas represent recharge areas. However, this relationship must be tempered by possible observation and interpretation errors. As mentioned earlier, the topographic, radar, and GPS data sets were collected at different times and by different individuals. A source of error was the registering of these data sets. Some information was not directly available and was interpolated. Slight spatial discrepancies exist among these data sets.

Errors also occurred in the interpretation of the radar imagery. Errors in radar depth interpretation were considered small (considering the strong correlation between observed and interpreted depths at the fourteen wells). Errors in the estimation of the depths to the water table can be attributed to (i) variations in the velocity of propagation of the radar signal through the vadose zone, slight spatial discrepancies among the sites of elevation, GPS, and radar measurement, and (iii) indistinct or obscured images of the water table on some portions of radar profiles (most notably where it occurred within 1 meter of the soil surface).

Within the study site, based on interpretations of the radar profiles at the 190 observation points, the average depth to the water table was 2.54 meters with a range of 0.65 to 9.79 meters. One-half of the observations had depths to water table between 1.08 and 3.08 meters. Within the study site, based on measurements taken at 14 monitoring wells, the average depth to the water table was 3.1 meters with a range of 1.04 to 9.70 meters. One-half of the observations had depths to water table between 1.18 and 2.72 meters. The similarity between these two data sets was most remarkable and unexpected. The significance of these data sets may lie with the placement of the monitoring wells and their representation of the larger area.

Computer simulated plots:
Figure 8 is a two-dimensional plot simulating the depth to the water table within the survey site. This simulation is based upon radar interpretations made at 190 observation points. Depths to the water table appear to mimic the topography (see Figure 5) of the survey site. In Figure 8, the locations of the 14 monitoring wells are also shown.

The elevation and relative subsurface topography of the water table have been simulated in Figure 9 and 10. Figure 9 is based on observations made at the fourteen monitoring wells. In this plot, the water table appears fairly level across the site. The topography of the water table varies about 1.2 meters. In Figure 9, the general direction of ground-water flow is towards the left-hand margin. Ground water appears to flow from the eastern dune towards the western dune (see Figure 5). The two wells in the extreme upper left-hand corner of Figure 9 are located on the western dune. The surface elevations of these wells averaged about 3.94 meters higher than the average surface elevation of the fourteen wells. A slight, but noticeable rise in the water table occurs in the lower right-hand corner of this figure. This rise occurred at well site 8B. This well was located on eastern dune and the highest recorded elevation along the traverse line (224.11 meters). This well was about 7.04 meters higher than the average surface elevation of the fourteen wells.

Figure 10 is based on observations made at the 190 observation points. The larger data base used in this plot has resulted in a more intricate pattern of local ground-water relief and flow. In this plot, the topography of the water table has a range of about 9.14 meters. In this plot, the water table appears fairly level only in the inter-dune areas. Conspicuous depressions in the topography of the water table appear beneath portions of the two higher-lying dunes (compare with Figure 5). The locations of these depressions in the water table appear to correspond with troughs in the crests of the dunes. The depressions in the water table are about 1 to 2 meters deep. They appear to be elongated about an axis. A majority of the depressions appear to be aligned and oriented in a northwest to southeast direction. This orientation is orthogonal to the orientation of the sand dunes and ridge lines.

Figure 11 contains a three-dimensional surface net of the surface (upper plot) and the water table (lower plot) within the study site. At first glance, the topography of the water table conforms with the general form of the land surface. However, several subdued, northwest to southeast trending troughs are evident in the subsurface topography of water table. The reason for these troughs is unclear. These features are enigmatic. As they do not conform with any simple model, it must be questioned whether these features are real or are artifacts of the survey design. If real, do these relationships and forms endure throughout the year.

Jennings County Site:

EM Interpretations:

The purpose of this exploratory study was to assess the potential of using EM techniques in southern Indiana. Electromagnetic induction techniques use 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 observation depth. Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the (i) volumetric water content, (ii) type and concentration of ions in solution, (iii) temperature and phase of the soil water, and (iv) amount and type of clays in the soil matrix, (McNeill, 1980). The apparent conductivity of soils increases with increases in the exchange capacity, water content, and clay content.

Electromagnetic inductive methods measure vertical and lateral variations in the apparent electrical conductivity of earthen materials. 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 earthen materials. Interpretations of the EM data are based on the identification of spatial patterns within data sets.

Advantages of EM methods include speed of operation, flexible observation depths (with commercially available systems from about 0.75 to 60 meters), and moderate resolution of subsurface features. Results of EM surveys are interpretable in the field. This technique can provide in a relatively short time the large number of observations needed for site characterization and assessments. Maps prepared from correctly interpreted EM data provide the basis for assessing site conditions and for planning further investigations.

Electromagnetic induction techniques are not suitable for use in all investigations. Generally, the use of EM techniques has been most successful in areas where subsurface properties are reasonably homogeneous and the effects of one property (e.g. clay, water, or salt content) dominates over the other properties. In these areas, variations in EM response can be related to changes in the dominant property or feature (Cook and others, 1989).

Study Area:

Study site was located in the Muscatatuck National Wildlife Refuge. The site was located principally in the northwest quarter of Section 19, T. 6 N., R. 7 E. The site was in woodland. Map units delineated within this area include Avonburg silt loam, 0 to 2 percent slopes; Cincinnati-Rossmoyne silt loams, 4 to 10 percent slopes, eroded; Clermont silt loam; and Wakeland silt loam (Nickell, 1976). Avonburg soils are members of the fine-silty, mixed, mesic Aeric Fragiaqualfs family. Cincinnati soils are members of the fine-silty, mixed, mesic Typic Fragiudalfs family. Clermont soils are members of the fine-silty, mixed, mesic Typic Ochraqualfs family. Rossmoyne soils are members of the fine-silty, mixed, mesic Aquic Fragiudalfs family. Wakeland soils are members of the coarse-silty, mixed, nonacid, mesic Aeric Fluvaquents family.

Field Procedures:

Each study site was about 13 hectares. Four traverses were conducted across the site with an EM38 and an EM31 meter. These traverses were abbreviated by several stream channels and areas of ponded water. At varying intervals along each traverse line, measurements were obtained with the

EM meters and the coordinates of these observation points were obtained from the GPS receiver. The distance between observations and traverse lines were varied by the GPS operator to accommodate breaks in topographic slopes. Intervals between observation points ranged from about 10 to 100 meters. A total of 41 observation points was recorded on the site. The locations of these points and the traverse lines within the study site are shown in Figure 12.

At each observation point, measurements were taken with the EM38 and EM31 meters in both the horizontal and vertical dipole orientations. For each measurement, the meter was placed on the ground surface. The coordinates of each observation point (41) were recorded with a Rockwell Precision Lightweight GPS receiver.

Discussion:
Basic statistics for the EM data collected within the Muscatatuck site are displayed in Table 1. In general, values of apparent conductivity increased and became more variable with increasing observation depths. Values of apparent conductivity increased with increasing observation depths. For the shallower sensing EM38 meter, measurements averaged 7.4 mS/m and 11.2 mS/m in the horizontal and vertical dipole orientations, respectively. One-half of the observations had values of apparent conductivity between 6.0 and 8.3 mS/m in the horizontal (0 to 75 centimeters), and between 10.2 and 12.7 mS/m in the vertical (0 to 150 centimeters) dipole orientation. For the deeper sensing EM31 meter, measurements averaged 20.4 mS/m and 27.8 mS/m in the horizontal and vertical dipole orientations, respectively. One-half of the observations had values of apparent conductivity between 16.4 and 23.3 mS/m in the horizontal (0 to 3 meters), and between 21.6 and 32.4 mS/m in the vertical (0 to 6 meters) dipole orientations. As water was ponded in many areas and the soils were saturated to the surface, moisture content was not considered the principal property influencing EM responses. The increased conductivity with increasing soil depth was attributed to higher clay contents and the occurrence of pinnacles of shale bedrock (relatively conductive materials).

Table 1

Basic Statistics
EM Survey
Muscatatuck Site
(All values are in mS/m)

Meter	Orientation	Minimum	Maximum	Quartiles 1st	Median	3rd	Average
EM38	Horizontal	3.6	13.2	6.0	7.4	8.3	7.4
EM38	Vertical	4.9	21.2	10.2	11.6	12.7	11.2
EM31	Horizontal	9.5	33.1	16.4	21.6	23.3	20.4
EM31	Vertical	12.4	45.3	21.6	29.2	32.4	27.8

Figures 13 and 14 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 15 and 16 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 2 mS/m. In each figure, patterns reflect changes in soil type, drainage, and parent materials. In figures 13 and 14, areas of lower conductivity are believed to represent soils which are better drained and/or with lower clay contents. The circular pattern of higher apparent conductivity appearing in figures 15 and 16, is believed to represent a pinnacle of shale.

Recommendations:

1. The results of the studies in Jasper and Jennings counties were most encouraging. Geophysical techniques can be used to support soil and hydrogeologic investigations. While propitious, these studies have produce more questions than answers. Further investigations are recommended to improve the use of the techniques discussed in this paper, verify interpretations, refine soil and hydrogeologic models, and better understand temporal variations in the depths and movement of ground water in these settings.

2. The radar survey in Jasper County revealed an intricate pattern of local ground-water relief and flow. The topography of the water table appears to mimic the general form of the land surface. However, several subdued, northwest to southeast trending troughs were evident in the subsurface topography of water table. The reason for these troughs is unclear. As these features do not conform with preconceived notions and simple models of the site, they are suspected. If possible, the presence of these features should be verified.

3. In Jasper County, the topographic, radar, and GPS data were collected at different times and by different individuals. A concern and source of error were the registering of these data sets. Some information was not directly available and was interpolated. While considered slight, spatial discrepancies occur among the data sets. Further studies are needed to improve techniques and reduce these spatial discrepancies.

4. All radar profiles will be returned to Byron Jenkinson under a separate cover letter. Disc of the data is available upon request.

5. It was my pleasure to work with the staff of Purdue University and NRCS in Indiana.

With kind regards,

James A. Doolittle
Research Soil Scientist

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References

Arcone, S. 1982. Radar detection of ground water. p. 68-76. *IN:* Dardeau, E. A. (ed.) Proceedings of the Ground-Water Detection Workshop. 12-14 January 1982. Vicksburg, Mississippi. Department of the Army. Waterways Experiment Station.

Beres, M. and F. P. Haeni. 1991. Application of ground-penetrating radar methods in hydrogeologic studies. Ground Water 29(3):375-386.

Bohling, G. C., M. P. Anderson, C. R. Bentley. 1989. Use of ground penetrating radar to define recharge areas in the Central Sand Plain. Technical Completion Report G1458-03. Geology and Geophysics Department, University of Wisconsin-Madison. 62 pp.

Brune, D. E., and J. Doolittle 1990. Locating lagoon seepage with radar and electromagnetic survey. Environ. Geol. Water Sci. 16(3):195-207.

Collins, M. E. and J. A. Doolittle. 1987. Using ground-penetrating radar to study soil microvariability. Soil Science Society of America J. 51: 491-493.

Cook, P. G., M. W. Hughes, G. R. Walker, and G. B. Allison. 1989. The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. Journal of Hydrology 107:251-265.

Cosgrave, T. M., J. P. Greenhouse, and J. F. Barker. 1987. Shallow stratigraphic reflections from ground-penetrating radar. p. 555-569. *IN*: Proceeding of First National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. May 18-21, 1987. Las Vegas, Nevada. National Water Well Association, Dublin, Ohio.

Davis, J. L., R. W. D. Killey, A. P. Annan, and C. Vaughan. 1984. Surface and borehole ground-penetrating radar surveys for mapping geologic structures. p. 681-712. *IN:* Proceedings of the National Water Well Association/Environmental Protection Agency Conference on Surface and Borehole Geophysical Methods in Ground Water Investigations. Feb. 7-9, 1984. San Antonio, Texas..

Daniels, D. J., D. J. Gunton, and H. F. Scott. 1988. Introduction to subsurface radar. IEE Proceedings 135F(4):278-320.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. *IN:* Soil Survey Techniques, Soil Science Society of America Special Publ. No 20. p. 11-32.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Inc. Englewood Cliffs, New Jersey. 604 pp.

Houck, R. T. 1982. Measuring moisture content profiles using ground-probing radar. Technical Report, XADAR Corporation, Springfield, Virginia. 10 pp.

Horton, K. A., R. Morey, R. H. Beers, V. Jordan, S. S. Sandler, and L. Isaacson. 1981. An evaluation of ground-penetrating radar for assessment of low level nuclear waste disposal sites. Office of Nuclear Regulatory Research. Nuclear Regulatory Commission, Report Number NUREG/CR2212.

Iivari, T. A. and J. A. Doolittle. 1994. Computer simulations of depths to water table using ground-penetrating radar in topographically diverse terrains. p. 11-20. *IN:* Kovar, K. and J. Soveri (eds.). Groundwater Quality Management (Proceedings of GQM 93, International Association of Hydrological Sciences. Conference held at Tallinn, Estonia. September 1993. 485 pp.

Johnson, D. G. 1987. Use of ground-penetrating radar for determining depth to the water table on Cape Cod, Massachusetts. p. 541-554. *IN*: Proceeding of First National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods. May 18-21, 1987. Las Vegas, Nevada. National Water Well Association, Dublin, Ohio.

Koerner, R. M., J. S. Reif, M. J. Burlingame. 1979. Detection methods for location of subsurface water and seepage. Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT11. p. 1301-1316.

McNeill, J. D. 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6. Geonics Limited, Mississauga, Ontario. 15 pp.

McNeill, J. D. 1986. Geonics EM38 ground conductivity meter operating instructions and survey interpretation techniques. Technical Note TN-21. Geonics Ltd., Mississauga, Ontario. 16 pp.

Morey, R. M. 1974. Continuous subsurface profiling by impulse radar. p. 212-232. *IN*: Proceedings, ASCE Engineering Foundation Conference on Subsurface Exploration for Underground Excavations and Heavy Construction, held at Henniker, New Hampshire. Aug. 11-16, 1974.

Nickell, A. E. 1976. Soil Survey of Jennings County, Indiana. USDA-Soil Conservation Service. U. S. Government Printing Office. Washington, D. C. 91 pp.

Olhoeft, G. R. 1986. Direct detection of hydrocarbon and organic chemicals with ground-penetrating radar and complex resistivity. p. 1-22. *IN*: Proceedings of the National Water Well Association Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater. Houston, Texas.

Sellmann, P. V., S. A. Arcone, A. J. Delaney. 1983. Radar profiling of buried reflectors and the groundwater table. Cold Region Research and Engineering Laboratory Report 83-11. Hanover, New Hampshire. 10 pp.

Shih, S. F., J. A. Doolittle, D. L. Myhre, and G. W. Schellentrager. 1986. Using radar for ground water investigation. Journal of Irrigation and Drainage Engineering 112(2):110-118.

Smallwood, B. F. and L. C. Osterholz. 1990. Soil Survey of Jasper County, Indiana. USDA-Soil Conservation Service. U. S. Government Printing Office. Washington, D. C. 205 pp.

Steenhuis, T. S., K.-J. S. Kung, and L. M. Cathles III. 1990. Finding layers in the soil. Ground-penetrating radar as a tool in studies of groundwater contamination. Engineering Cornell Quarterly (Autumn) p. 15-19.

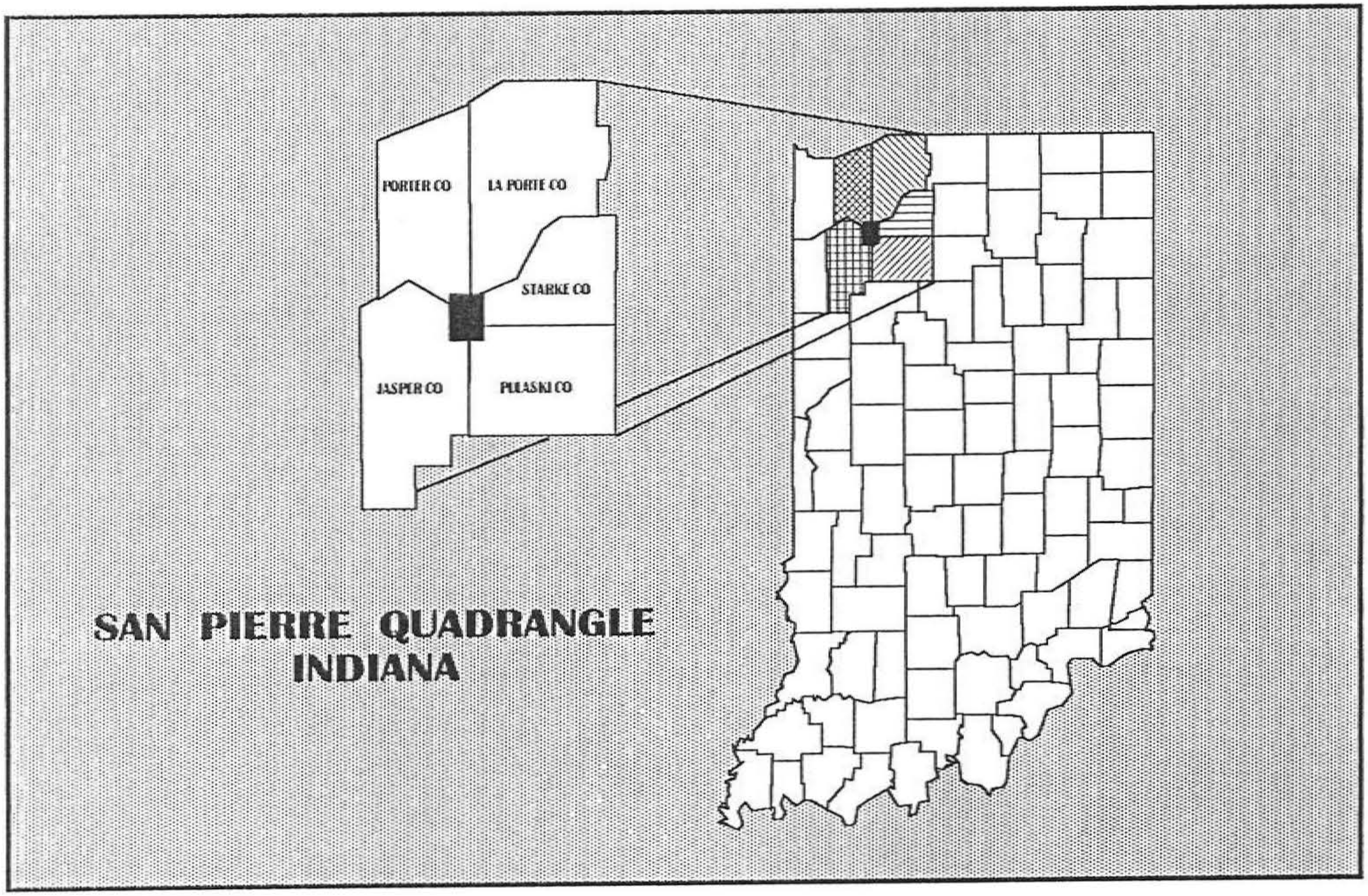
Taylor, K. R. and M. E. Baker. 1988. Use of ground-penetrating radar in defining glacial outwash aquifers. p. 70-98. *IN*: Proceeding of the FOCUS Conference on Eastern Regional Ground Water Issues, Stamford, Connecticut. September 27-29, 1988. National Water Well Association, Dublin, Ohio.

Toth, J. 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of Geophysical Research, 68:4795-4812.

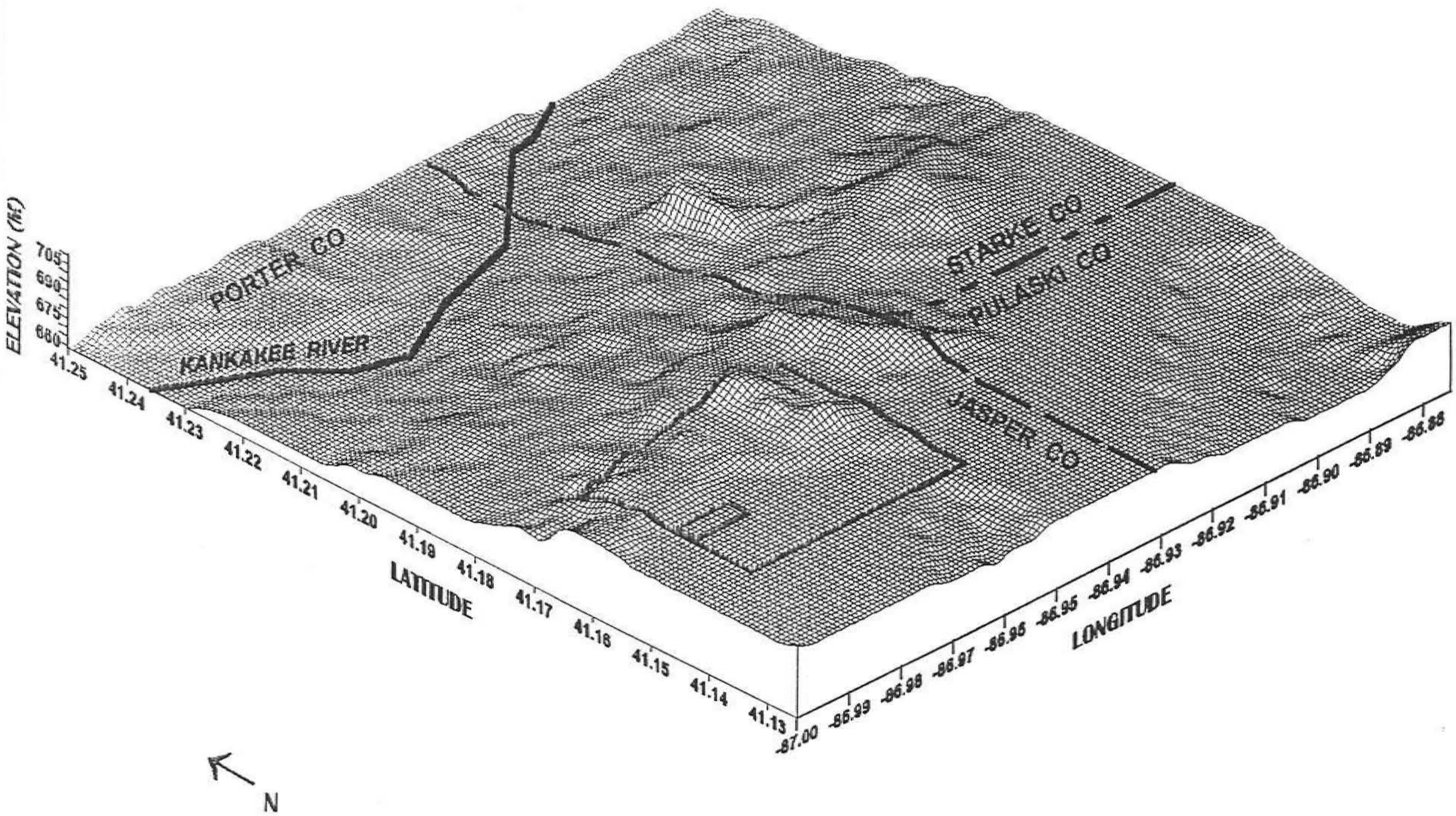
Vellidis, G., M. C. Smith, D. L. Thomas, M. A. Breve, and C. D. Perry. 1989. Using ground-penetrating radar (GPR) to detect soil water movement in sandy soil. American Society of Agricultural Engineers Paper No. 89-2520. St., Joseph, Michigan: ASAE. 13 pp.

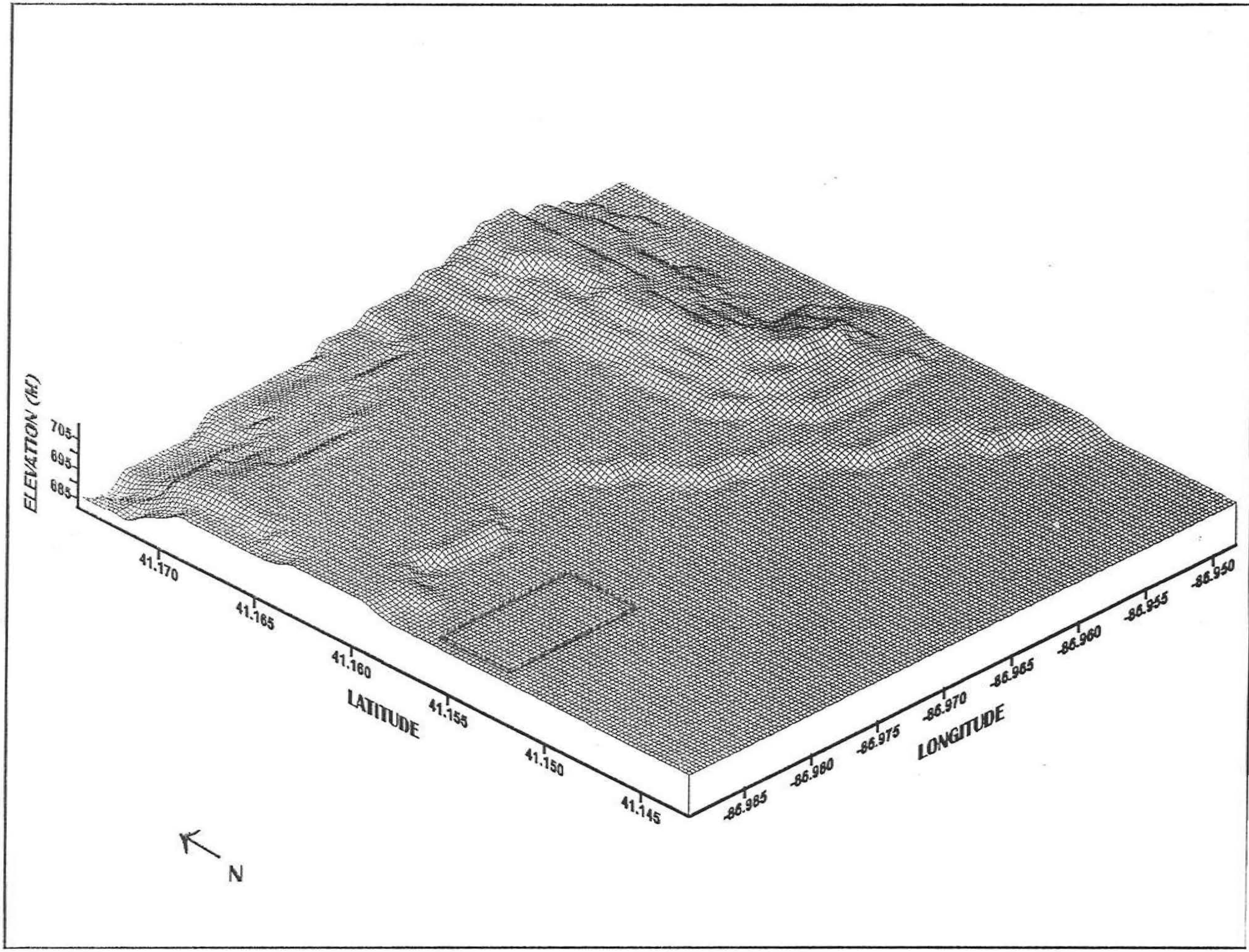
Violette, P. 1987. Surface geophysical techniques for aquifers and wellhead protection area delineation. Environmental Protection Agency, Office of Ground Water Protection, Washington, D.C., 49 pp.

Wright, D. L., G. R. Olhoeft, and R. D. Watt. 1984. Ground-penetrating radar studies on Cape Cod. p. 666-680. *IN:* D. M. Neilsen (ed.) Surface and Borehole Geophysical Methods in Ground Water Investigations. National Water Well Association, Worthington, Ohio.


PORTER CO
LA PORTE CO
STARKE CO
JASPER CO
PULASKI CO
SAN PIERRE QUADRANGLE
INDIANA

SAN PIERRE QUADRANGLE
INDIANA




ELEVATION (M)
705
695
685
41.170
41.165
41.160
41.155
41.150
41.145
LATITUDE
-86.985
-86.980
-86.975
-86.970
-86.965
-86.960
-86.955
-86.950
LONGITUDE
N

WET SOIL MONITORING PROJECT
JASPER PULASKI STATE GAME PRESERVE
JASPER COUNTY, INDIANA

LOCATION OF OBSERVATION AND MONITORY WELL SITES

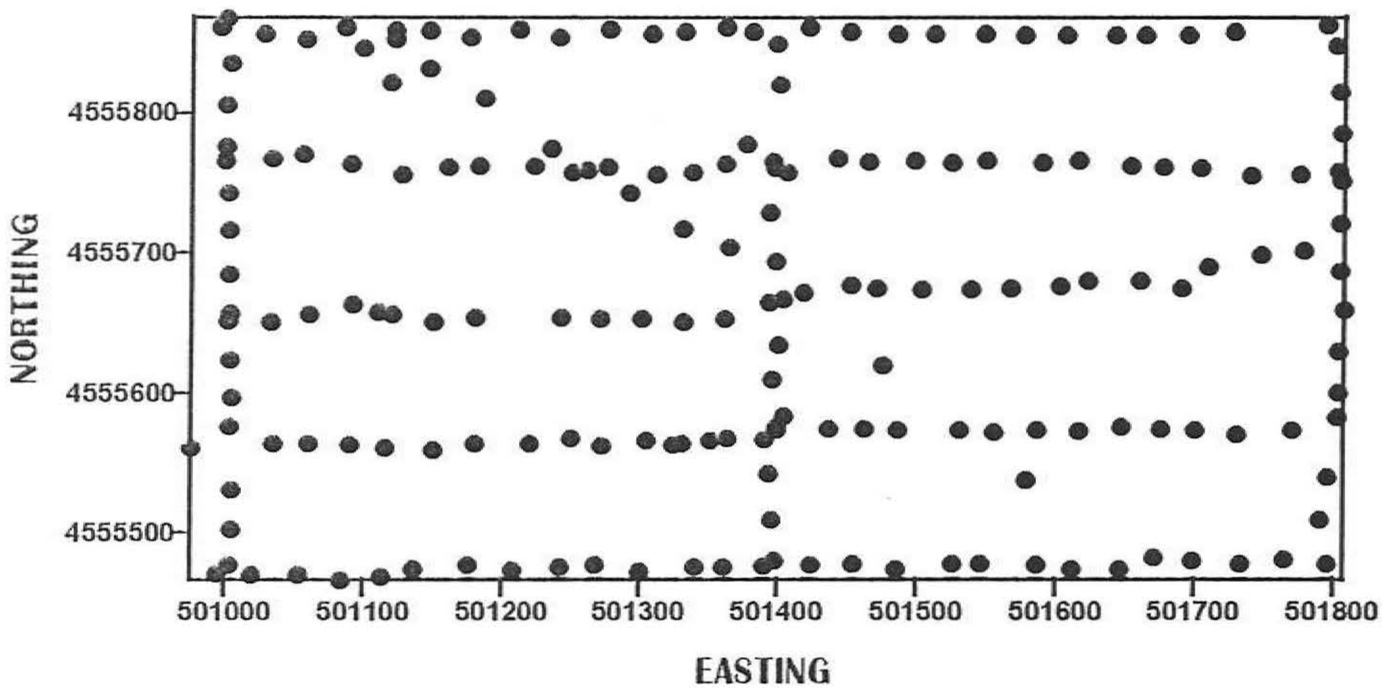


FIGURE 4

● OBSERVATION SITE

WET SOIL MONITORING PROJECT
JASPER PULASKI STATE GAME PRESERVE
JASPER COUNTY, INDIANA

RELATIVE TOPOGRAPHY

CONTOUR INTERVAL = 0.5 M

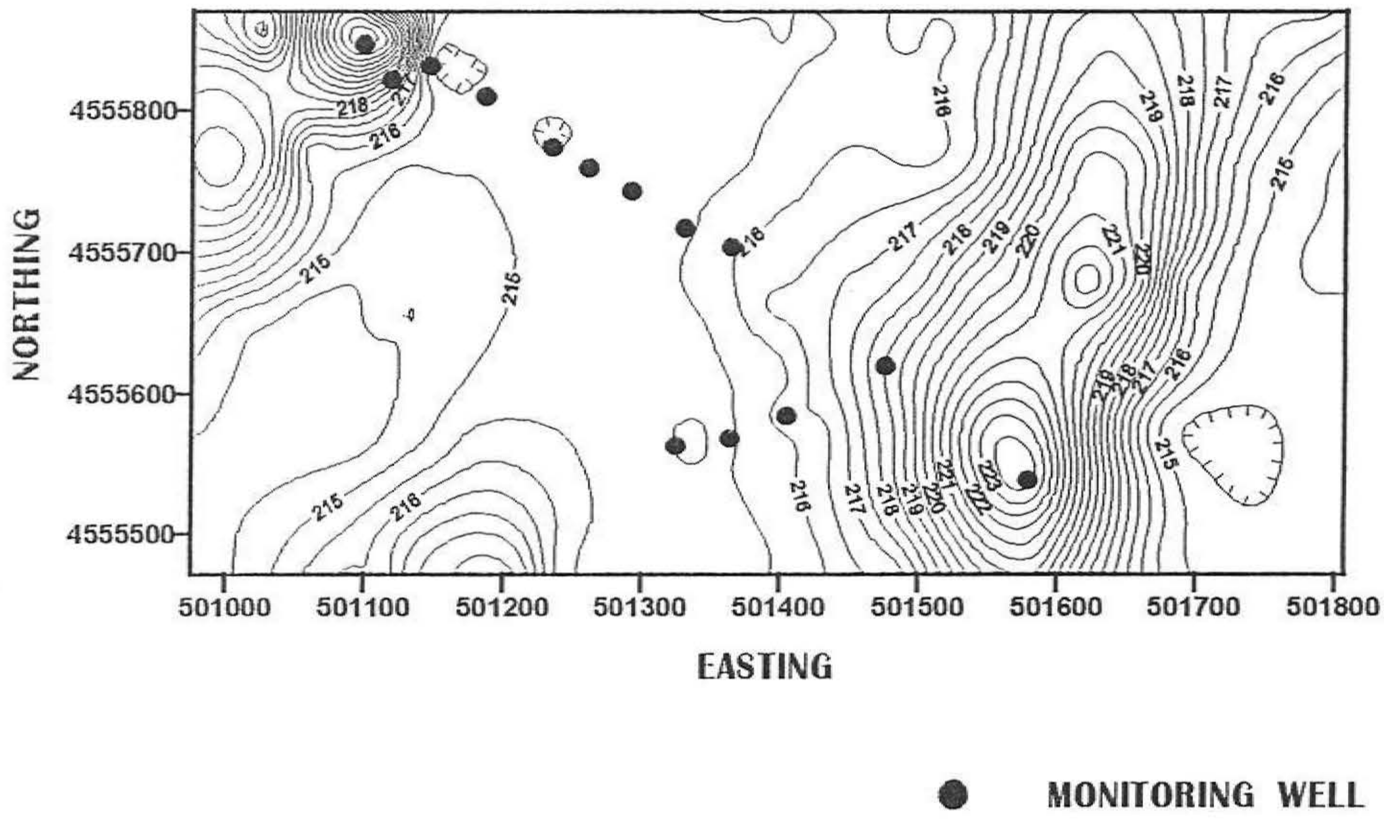
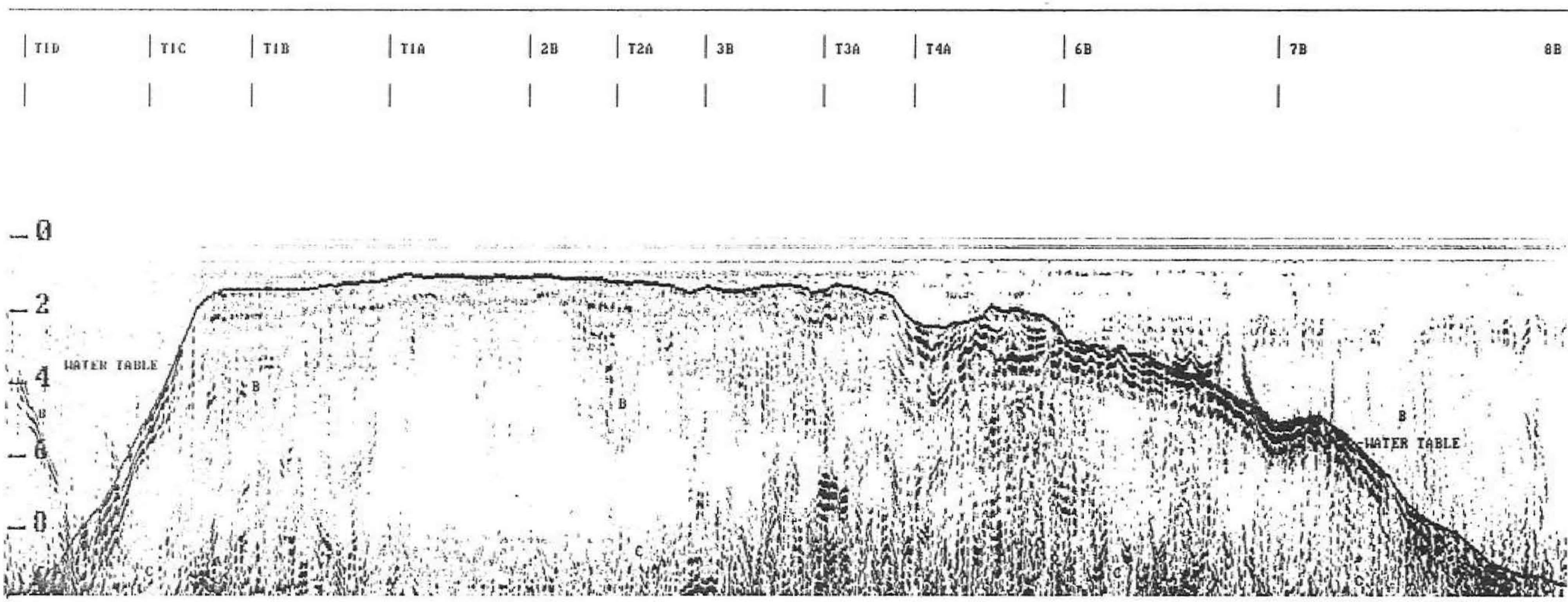


FIGURE 5



T1D
T1C
T1B
T1A
2B
T2A
3B
T3A
T4A
6B
7B
8B
0
2
4
6
8
WATER TABLE
WATER TABLE
B
B
B
B
C
C
C
C

FIGURE 6

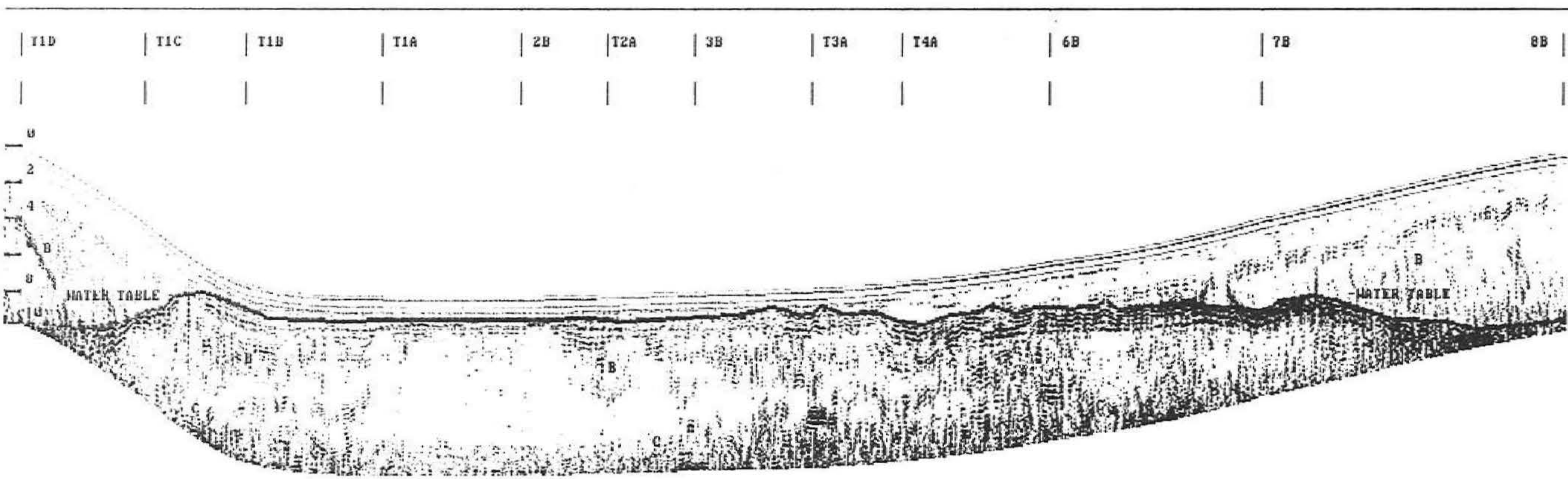

T1D
T1C
T1B
T1A
2B
T2A
3B
T3A
T4A
6B
7B
8B
0
2
4
8
WATER TABLE
B
C
WATER TABLE

FIGURE 7

WET SOIL MONITORING PROJECT
JASPER PULASKI STATE GAME PRESERVE
JASPER COUNTY, INDIANA

DEPTH TO WATER TABLE

INTERVAL = 0.5 M

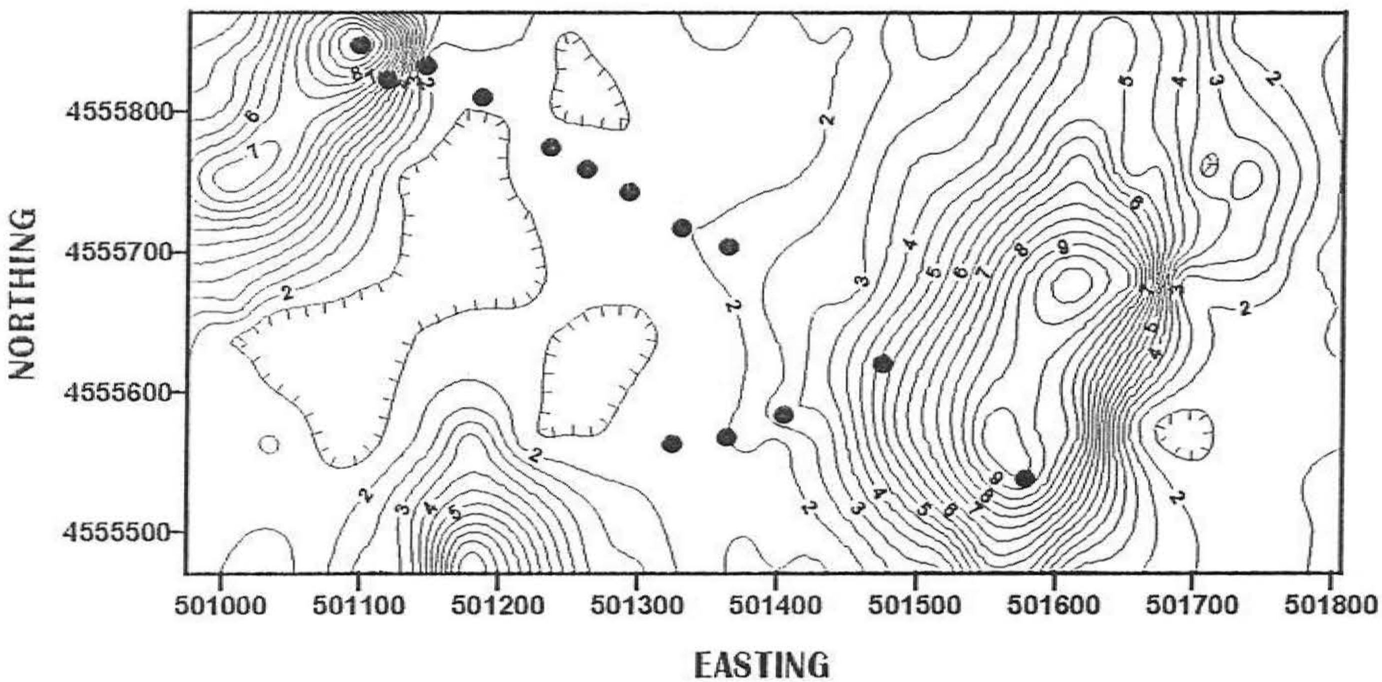


FIGURE 8

● MONITORING WELL

WET SOIL MONITORING PROJECT
JASPER PULASKI STATE GAME PRESERVE
JASPER COUNTY, INDIANA

RELATIVE TOPOGRAPHY OF WATER TABLE

CONTOUR INTERVAL = 0.25 M

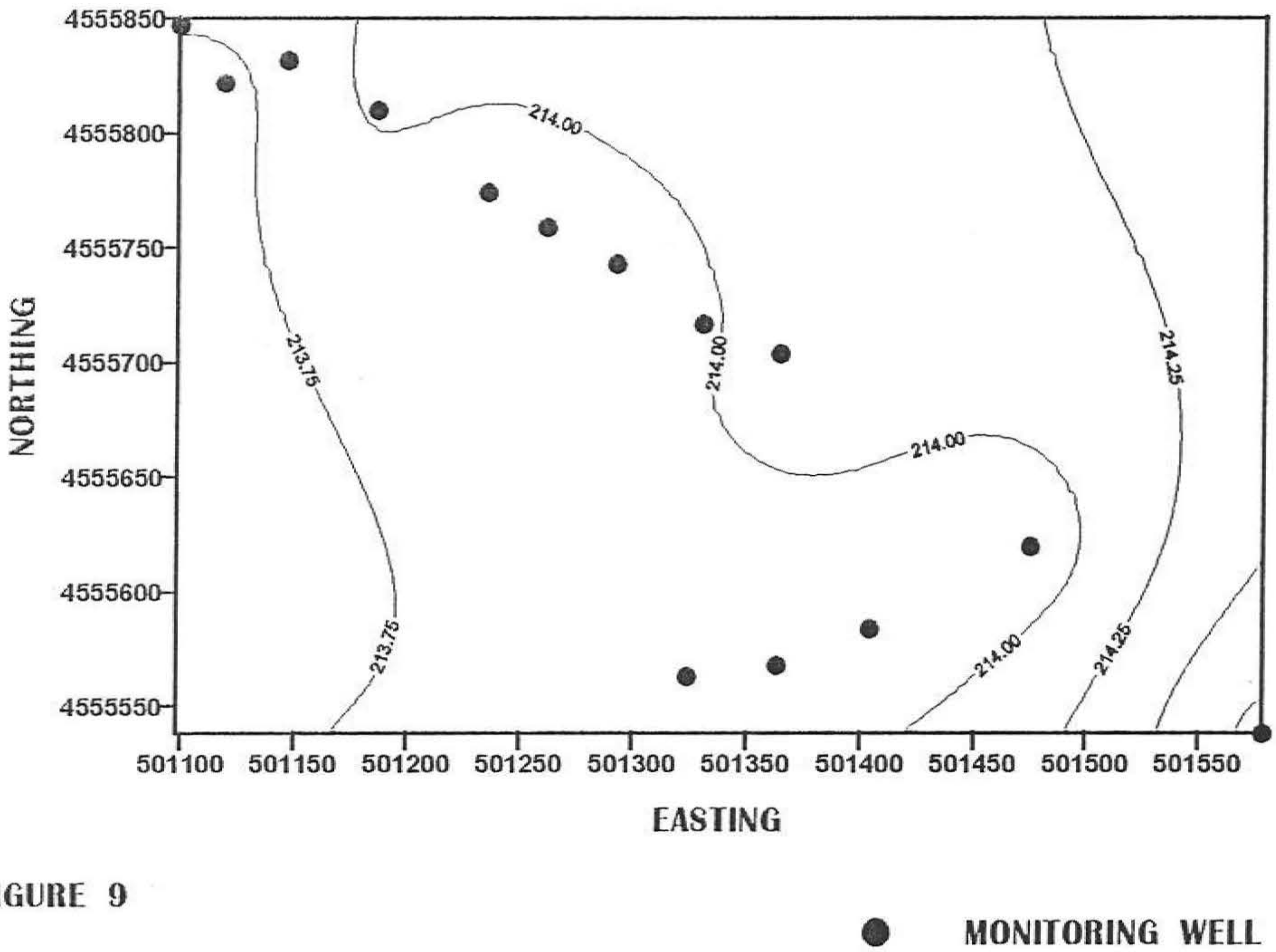


FIGURE 9

WET SOIL MONITORING PROJECT
JASPER PULASKI STATE GAME PRESERVE
JASPER COUNTY, INDIANA

RELATIVE TOPOGRAPHY OF THE WATER TABLE

INTERVAL = 0.5 M

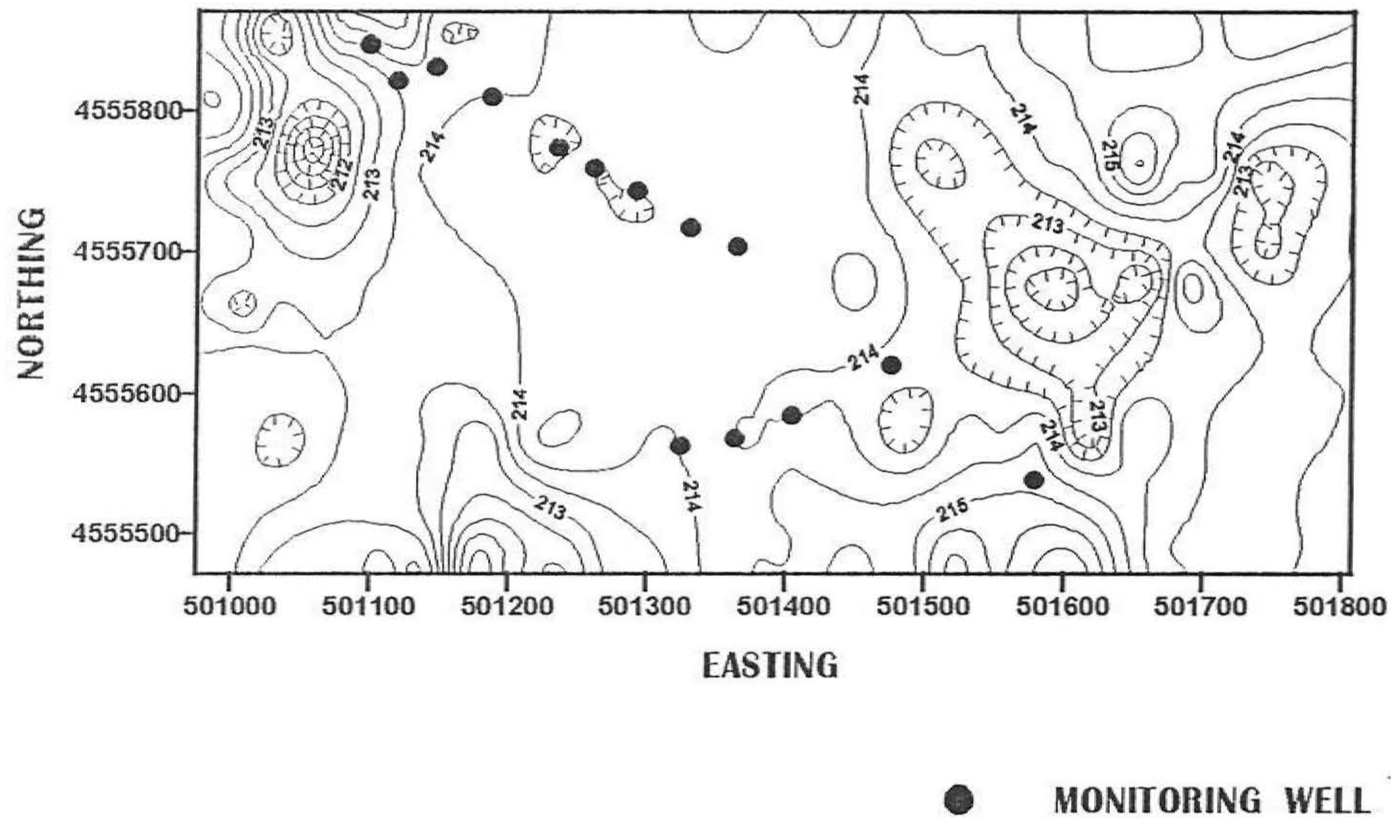


FIGURE 10

WET SOIL MONITORING PROJECT
JASPER PULASKI STATE GAME PRESERVE
JASPER COUNTY, INDIANA

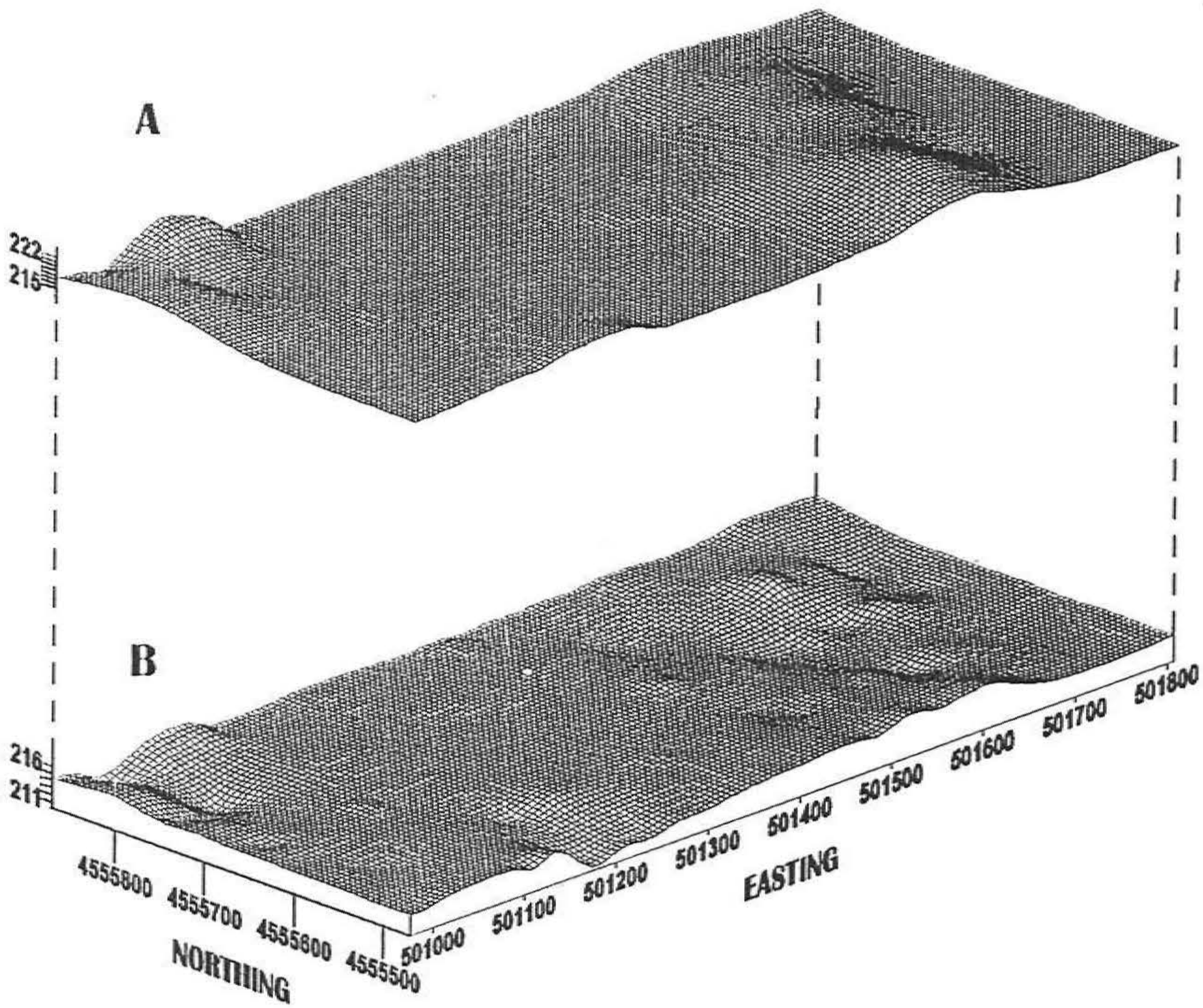


FIGURE 11

MUSCATATUCK
NATIONAL WILDLIFE REFUGE
JENNINGS COUNTY, INDIANA

EM SURVEY
LOCATION OF OBSERVATION POINTS

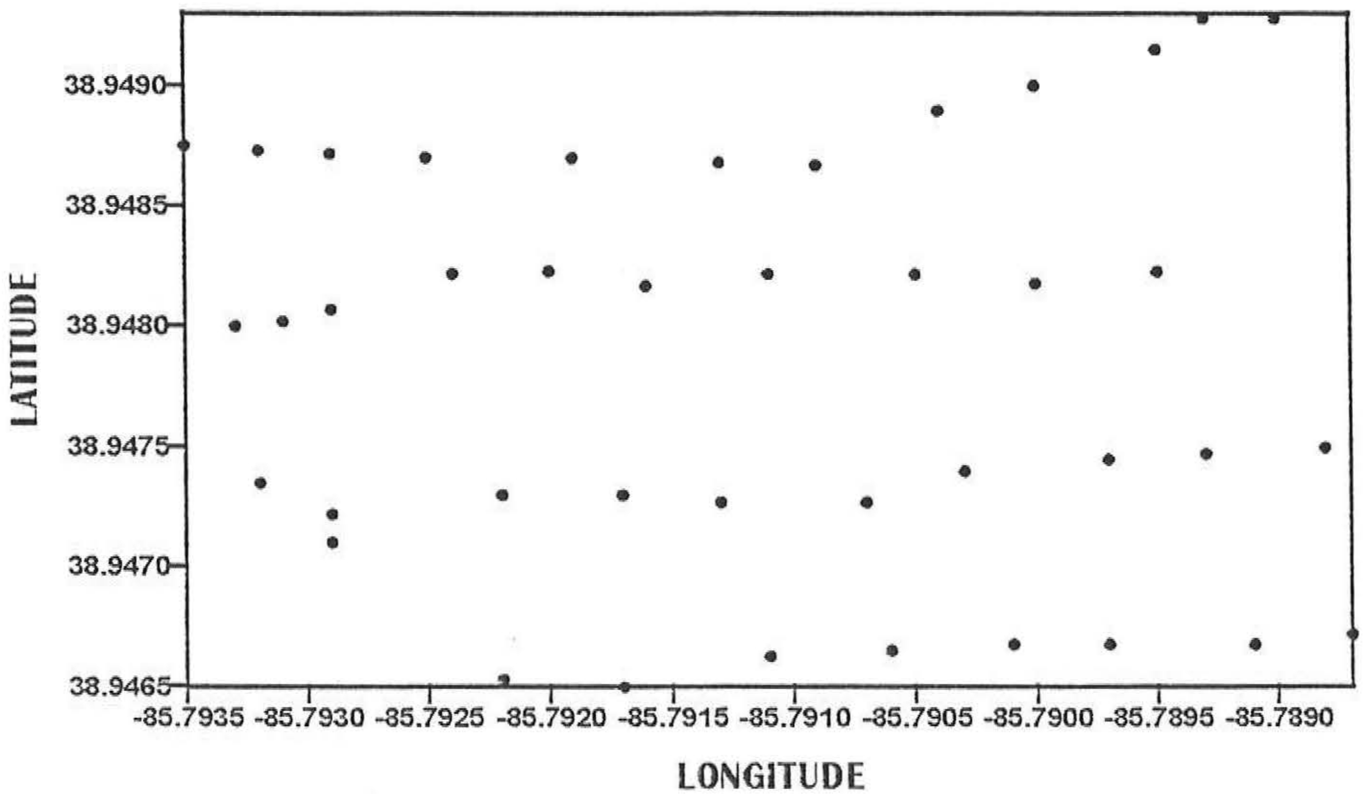


FIGURE 12

MUSCATATUCK
NATIONAL WILDLIFE REFUGE
JENNINGS COUNTY, INDIANA

EM SURVEY
EM38 METER
HORIZONTAL DIPOLE ORIENTATION

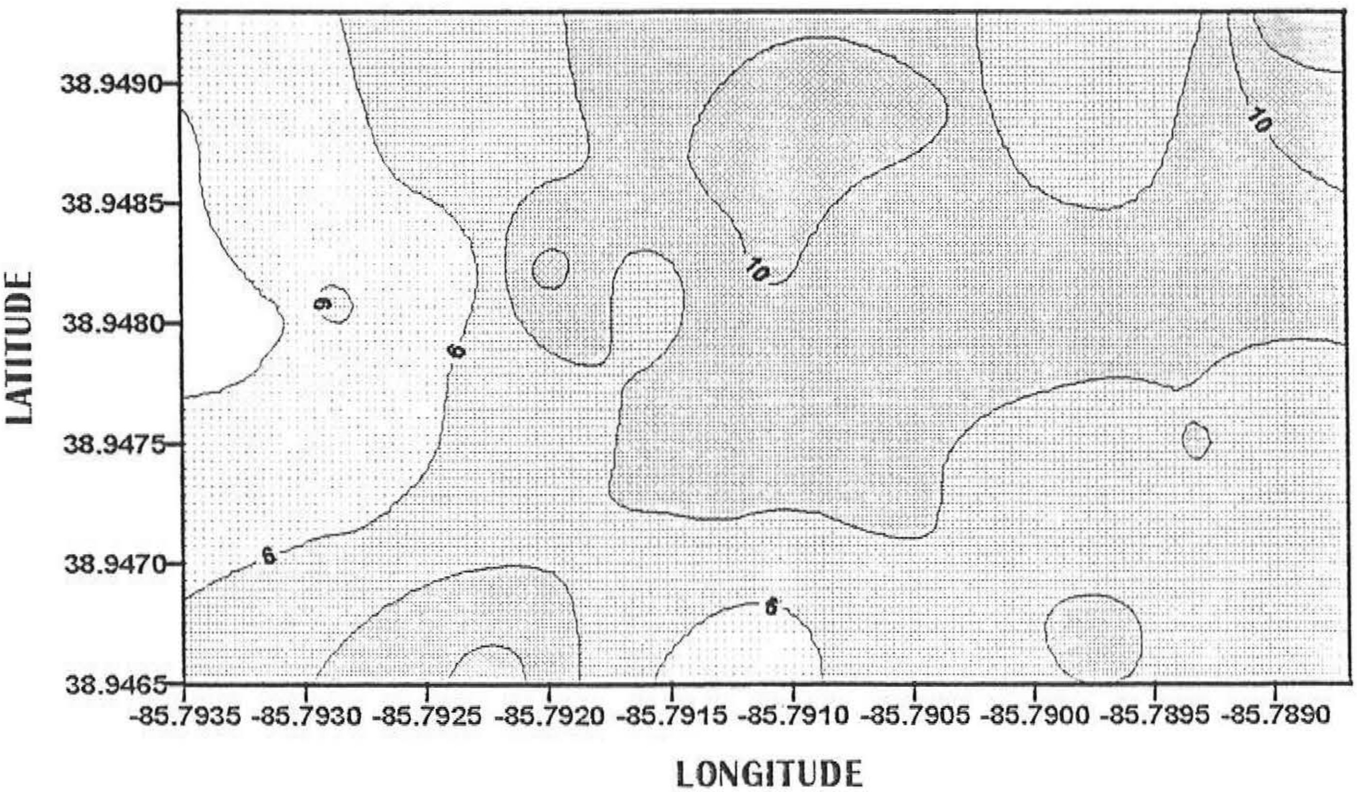


FIGURE 13

MUSCATATUCK
NATIONAL WILDLIFE REFUGE
JENNINGS COUNTY, INDIANA

EM SURVEY
EM38 METER
VERTICAL DIPOLE ORIENTATION

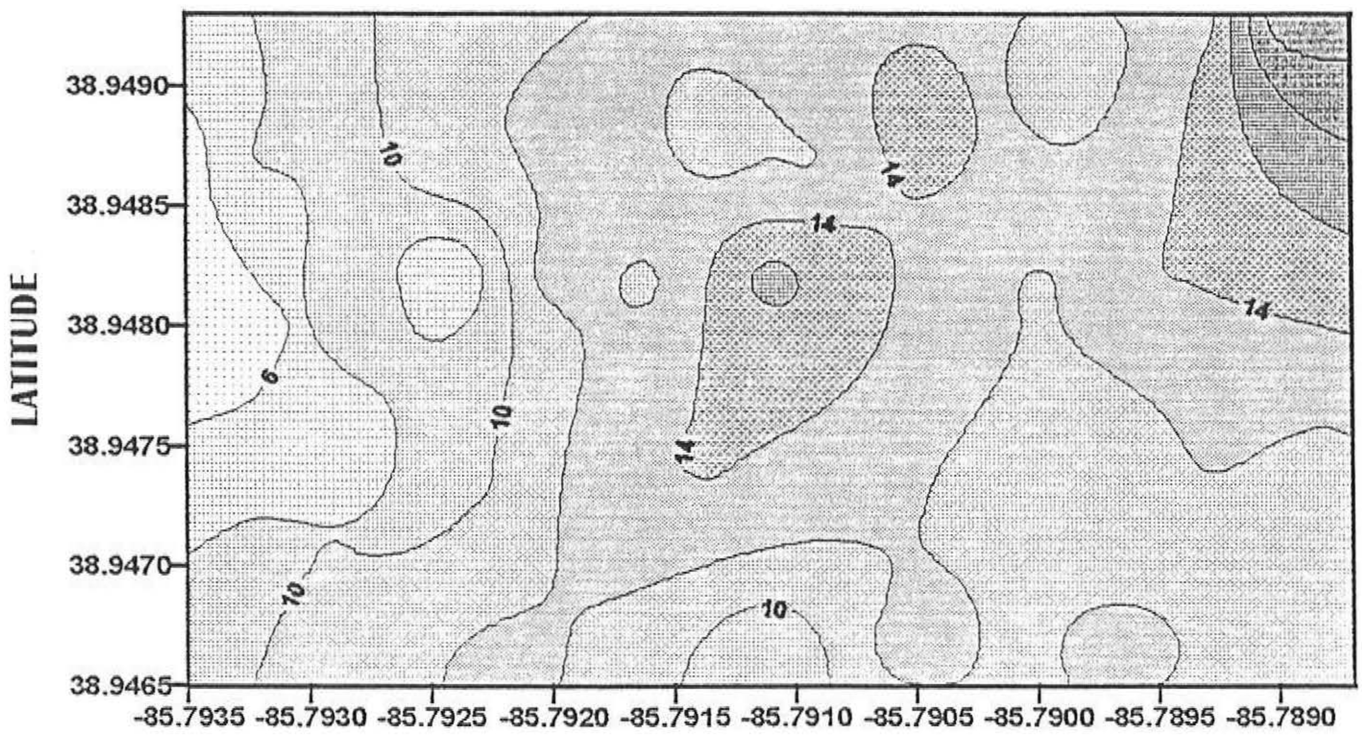


FIGURE 14

MUSCATATUCK
NATIONAL WILDLIFE REFUGE
JENNINGS COUNTY, INDIANA

EM SURVEY
EM31 METER
HORIZONTAL DIPOLE ORIENTATION

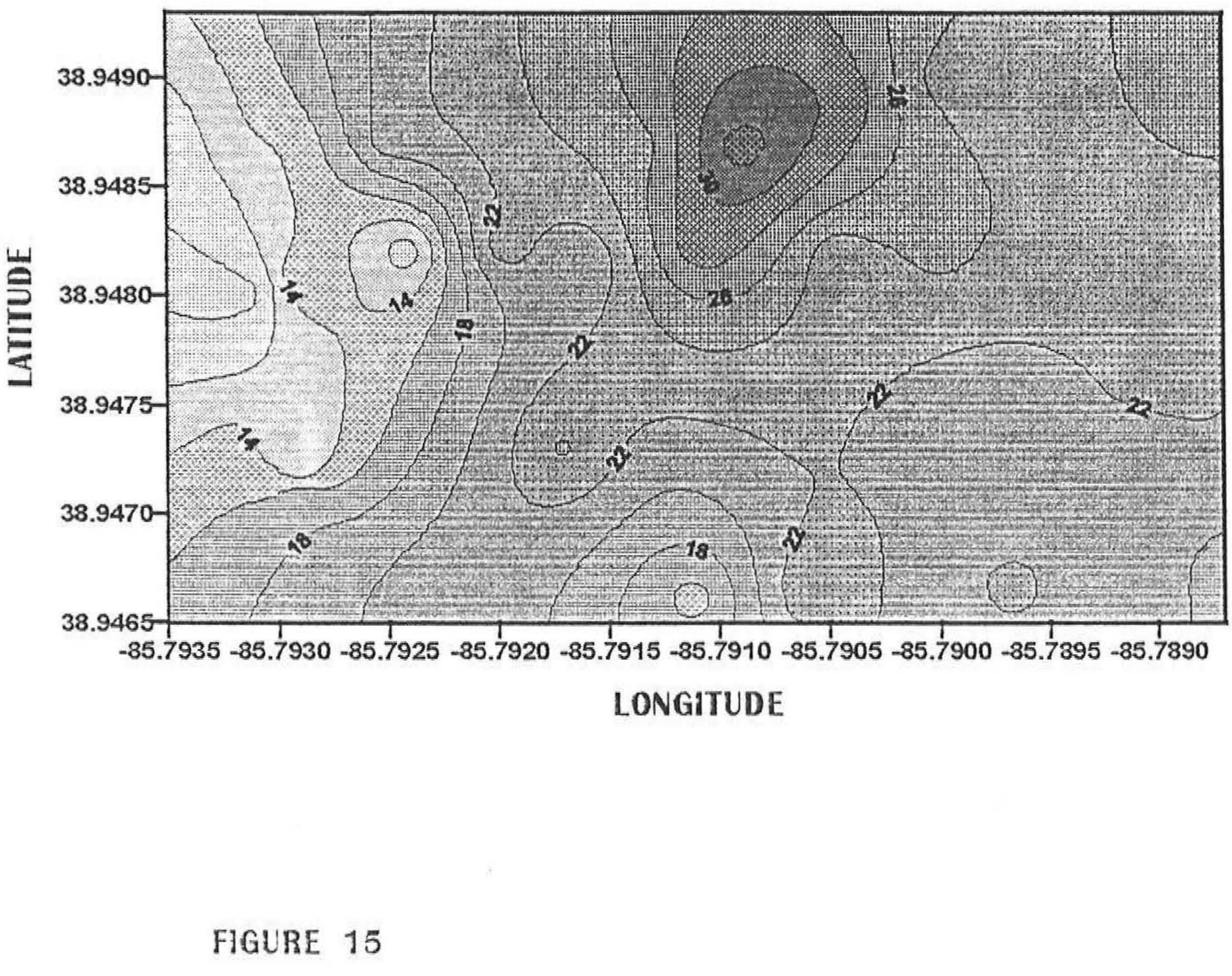


FIGURE 15

MUSCATATUCK
NATIONAL WILDLIFE REFUGE
JENNINGS COUNTY, INDIANA

EM SURVEY
EM31 METER
VERTICAL DIPOLE ORIENTATION

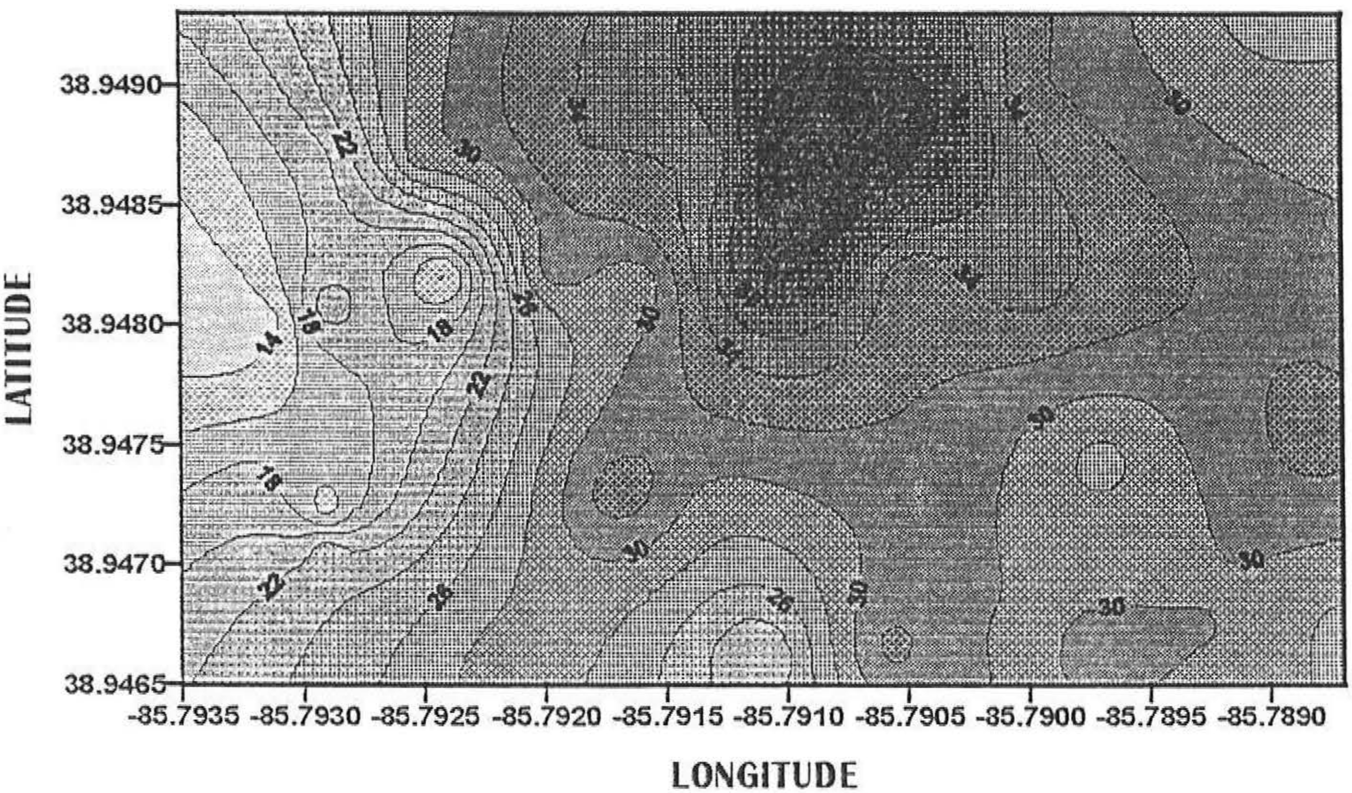


FIGURE 16