United States Department of Agriculture

Natural Resources Conservation Service

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Subject: -- Geophysical Assistance --

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Purpose:
The purpose of this investigation was to further evaluate results obtained with various electromagnetic induction (EMI) tools for site-specific and high intensity soil surveys.

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Activities:
All field activities were completed during the period of 9 to 12 April 2001.

Equipment:
Seven different instruments were used in this study. These instruments included the Dualem-2 and Dualem-4 meters; EM31, EM38, and EM38DD meters; GEM300 sensor; and Veris 3100 soil EC mapping system.

Dualem Inc. manufactures the Dualem-2 and the Dualem-4 meters.[1] These meters are portable and require only one person to operate. Taylor (2000) has described the principles of operation of these meters. These meters operate at a fixed frequency (9,000 Hz) and consist of one transmitter and two receiver coils. One receiver coil and the transmitter coil provide a perpendicular geometry (P). The other receiver coil provides a horizontal co-planar geometry (HC) with the transmitter coil. This dual system permits two depths to be measured simultaneously without rotating the coils. The depth of penetration is "geometry limited" and is dependent upon the intercoil spacing, coil orientation, and frequency. The Dualem-2 has a 2-m intercoil spacing between the transmitter and the two receiver coils. It provides penetration depths of 1.3 and 3.0 m in the P and HC geometries, respectively. The Dualem-4 has a 4-m intercoil spacing between the transmitter and the two receiver coils. It provides penetration depths of 2.5 and 6.0 m in the P and HC geometries, respectively. No ground contact is required with these meters. Meters are keypad operated and measurements can either be automatically or manually triggered. The meter's processor has 1 megabyte of memory.

Geonics Limited manufacturers the EM38, EM38DD, and the EM31 meters.[1] These meters are portable and require only one person to operate. McNeill (1980) and Geonics Limited (1998 and 2000) have described principles of operation for the EM31, EM38, and EM38-DD meters, respectively. No ground contact is required with these meter. The depth of penetration is geometry limited. Lateral resolution is approximately equal to the intercoil spacing. The EM38 and the EM38-DD meters have a 1 m intercoil spacing and operate at a frequency of 14,600 Hz. They have effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). The EM38-DD meter consists of two EM38 meters bolted together and electronically coupled. One unit acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one unit acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on). The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. It has theoretical penetration depths of about 3.0 and 6.0 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980).

The Veris 3100 soil EC mapping system is a towed, multi-electrode resistivity unit manufactured by Veris Technologies.[1] Operating procedures are described by Veris Technologies (1998). The Veris 3100 implement converts measurements of apparent resistivity (ohm-m) into measurements of apparent conductivity (mS/m). In isotropic materials, conductivity is the reciprocal of resistivity. The Veris 3100 implement provides two depths of penetration: one for the upper 0 to 30 cm (shallow) and one for the upper 0 to 90 cm (deep) of the soil. The depth of penetration is "geometry limited" and is dependent upon the spacing and type of electrode array. The electrode array is a modified Wenner array with 6 unequally spaced electrodes (rotating discs). Voltage is applied to discs number 2 and 5. The wider-spaced discs (number 1 and 6) measure the current across the 0 to 90 cm depth interval; the more closely spaced discs (number 3 and 4) measure current across the 0 to 30 cm depth interval. In open fields, the Veris 3100 implement is pulled behind a pickup truck at speeds of about 5 to 10 m/hr. A Trimble 132 GPS receiver was used with this system.[1]

The GEM300 multifrequency sensor is manufactured by Geophysical Survey systems, Inc.[1] This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.6 m). Won and others (1996) have described the use and operation of this sensor. With the GEM300 sensor, the penetration depth is considered "skin depth limited" rather than "geometry limited." The skin-depth represents the maximum depth of penetration and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. Theoretical penetration depths of the GEM300 sensor are

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

dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequencies. Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

The positions of all observation points in the two detail grids were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[1] The receiver was operated in the continuous and the mixed satellite modes. Horizontal datum was the North American 1983.

After reviewing the computer simulations of each grid site, soils were described at nineteen observation points. Soils were examined to sand and gravel layers. These depths varied from about 0.55 m to 2.05 m. Brief profile descriptions recorded the depths to soil horizons and characterized their texture, colors, and carbonate contents. Additional measurements were made with each geophysical device over each of the nineteen observation points.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,[1] was used to construct two- and three-dimensional simulations. Grids were created using kriging methods with an octant search.

Recommendations:

1. Soil maps prepared by the USDA are not intended for precision agriculture. However, soil surveys do provide valuable information to precision agriculture. It is incumbent upon the Soil Survey Division to promote the use of soil information as a key component of precision agriculture and to ensure that soil surveys are used within their designed limits.

2. Confronted by increased use of EMI within the private sector, soil scientists within the Soil Survey Division need to become more familiar with this technique. Soil scientists should be aware of the maps and interpretations that can be made from apparent conductivity data.

3. Results from this study help demonstrate that EMI can be used to: direct soil sampling, construct maps of apparent conductivity in areas that have been sparsely sampled or investigated, improve soil maps, evaluate the composition of soil map units or the adequacy of existing soil lines as part of the soil survey update process, and to estimate soil properties that are too costly to comprehensively measure.

4. Results from different instruments produce similar but not identical results. Differences in measured values and spatial patterns of apparent conductivity are attributed to differences in the frequency, depth and volume of soil sounded, and depth-response functions of each instrument, as well as variations in soils and soil properties. Differences in sampling intensity and survey design also affect results.

5. Within each grid area, similar spatial patterns of apparent conductivity were obtained with most instruments. While measured values varied among instruments, these differences reflect variations in the volume and depth of materials sounded. The correlations among several instruments suggest that they are measuring similar volumes of earthen materials and provide comparable results.

6. Inconsistencies in measured values were observed between the EM38 and the EM38-DD meters. This is of great concern, as closely matching results should be obtained with these meters. Calibration errors or system noise may be responsible for the incongruous measurements obtained with the EM38-DD meter. Although subject to further evaluations, the use of EM38-DD meters within NRCS is presently not recommended.

7. To improve interpretations and to fully assess the benefits of EMI, soil, apparent conductivity, and yields maps of the surveyed fields should be compared and reviewed.

8. Geophysical interpretations are considered preliminary estimates of site conditions. The results of all geophysical investigations are interpretive and do not substitute for direct soil borings. The use of geophysical methods can reduce the number of soil observations, direct their placement, and supplement their interpretations. Interpretations should be verified by ground-truth observations.

It was my pleasure to work again in Ohio and with the Illinois "*Veris Gang*" and members of your fine staff. Special thanks are extended to Rick Taylor of Dualem Inc. (Milton, Ontario, Canada) for sharing his knowledge and participating in this study. I also wish to thank Bob Parkinson for preparing the digitized soil maps of each of the fields.

With kind regards,

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Background:
Because of emerging technologies and growing environmental concerns, the last decade has witnessed the rapid expansion of precision agriculture. Goals of precision agriculture are to produce optimal yields, maximize efficiency by varying seeding and chemical application rates, and reduce the off-site impact of chemicals.

Precision agriculture attempts to divide farmlands into management zones that have a unique combination of potential yield-limiting factors and different seeding and chemical requirements (Mulla, 1993). These within-field management zones are often difficult to accurately map because of the large number of interrelated factors that may affect crop yields. To define and delineate management zones, precision agriculture relies on soil and topographic surveys, yield maps, and soil characterization samples. Unfortunately, soil surveys prepared by the USDA do not satisfy the data requirements of precision agriculture (Bouma et al., 1999). Standard soil surveys and maps were not prepared nor intended for precision agriculture. Soil maps prepared by the USDA often do not show at an appropriate level of detail the variations in soils and soil properties needed for precision agriculture (Jaynes et al., 1995a). In addition, because of the strong taxonomic bias of soil surveys, many soil properties that influence crop yields have been overlooked in published soil survey reports (Bouma et al., 1999). As a consequence, poor correlations are often obtained between nutrient requirements or yield potentials and map units prepared by the USDA-NRCS (Carr et al., 1991).

Standard USDA soil maps are considered inappropriate for precision agriculture. The minimum delineation size that can be legibly shown on soil maps prepared at scales of 1:12,000 to 1:20,000 is too large (1.4 to 4.0 acres, respectively) and is inappropriate for precision agriculture. In addition, all delineations shown on USDA maps contain soils other than those identified in the map unit name. As a consequence, soils of contrasting physical and chemical properties but limited extent are not represented on soil maps (Jaynes et al., 1995a).

With precision agriculture, seeding and nutrient application rates are being increasingly linked to the characteristics of each soil type within fields. Precision agriculture requires a new generation of soil maps. These soil maps will be prepared at more appropriate scales (1:6000 or larger) and show in greater detail the variability of soils and soil properties across fields. The preparation of these maps will be a formidable and expensive task. Unless alternative field methods are developed, these high intensity soil maps will be prohibitively expensive, time-consuming, and labor-intensive to prepare. Alternative methods are needed to complement traditional survey techniques, provide more comprehensive coverage, and improve the characterization of soil properties. To be effective, these methods must be relatively simple, inexpensive, fast, and provide meaningful maps of soils or soil properties.

Presently, commercial seed and fertilizer dealers and soil and crop consultants are leading the way in the development of a new generation of soil maps. To accomplish this task, dealers and consultants are using a wide array of chemical, electronic, and mechanical sensors to measure and map soil and plant attributes. Continuous profiling resistivity units and electromagnetic induction (EMI) meters are two geophysical tools that are being used for high intensity soil surveys and precision agriculture. Compared with traditional soil survey methods, these tools are more rapid and provide greater detail and geo-referenced soil information (Jaynes, 1995).

Many feel that the best way to interpret an EMI map is to compare it to yield or soil survey maps (Doerge at al., 1999). While promoting the benefits of EMI to precision farming, some dealers and consultants have discouraged or even disparaged the use of USDA soil surveys. Some, promoting the use of EMI to "*fine-tune*" soil maps prepared by USDA, simply note the lack of detail or quality in these maps (Doerge 2001, Veris Technology 2001). However, others remark that EMI maps draw soil boundaries and define management zones better and are therefore "light years" ahead of the soil surveys (Olson, 2000).

Standard soil surveys and maps prepared by the USDA were not intended for precision agriculture. However, soil surveys do provide valuable information to precision agriculture. It is incumbent upon the Soil Survey Division to promote the use of soil information as a key component of precision agriculture and to ensure that soil surveys are used within their designed limits. Confronted by increased use of EMI within the private sector, soil scientists within the Soil Survey Division need to become more familiar with this technique. Soil scientists should be aware of the maps and interpretations that can be made from apparent conductivity data. Soil scientist may chose to use

EMI as a reconnaissance tool to direct subsequent soil sampling, to construct maps of apparent conductivity in areas that have been sparsely sampled or investigated, to improve soil maps or evaluate the adequacy of existing soil lines as part of the soil survey update process, or to estimate soil properties that are too costly to measure (Jaynes, 1996).

Electromagnetic Induction:
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, 1980). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976). While EMI does not measure specific ions or compounds, it can provide a measure of the bulk ionic concentration or nutrient levels in soils.

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). Kitchen and others (2000) used EMI to estimate topsoil thickness and clay content, which were associated with soil profile nutrient pools. Electromagnetic induction has been used to estimate soil water contents (Kachanoski et al., 1988; Sheets and Hendrickx, 1995), cation exchange capacity and exchangeable Ca and Mg (McBride et al., 1990), and leaching rates of solutes (Jaynes et al., 1995b). Recently, EMI has been used as a soil-mapping tool to assist precision agriculture (Jaynes, 1995; Jaynes et al., 1995b; Sudduth et al., 1995). Jaynes and others (1995a) compared EMI measurements with yield data and found that relationship between yield and EMI response varied from site to site and was not consistent from year to year.

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 studies conducted in Iowa (Jaynes et al., 1995, 1995b), variations in more than one property weakened and obscured relationships. In these studies, collective changes in the moisture, clay, and carbonate contents weakened relationships between apparent conductivity and moisture stress or drainage classes.

Study sites:
The study sites were located on Bill Richards' farm about 1 mile southwest of Circleville, Ohio. Studies were conducted in three fields that had been planted to corn (see figures 1, 2, and 3). A single mapped soil delineation dominates and was used to identify each field. The map units were Genesee silt loam, occasionally flooded (Gn), and Warsaw loam, 0 to 2 percent slopes (Wba) (Kerr and Christman, 1980). The very deep, well drained Genesee soil formed in loamy sediments on flood plains. The Genesee soil is calcareous within depths of 20 to 40 inches and may have stratified layers of sand and gravel below a depth of 50 inches. Genesee is a member of the fine-loamy, mixed, superactive, mesic Fluventic Eutrudepts family. The Warsaw series formed in loamy sediments overlying gravelly outwash on outwash plains and terraces. The well drained Warsaw soils are deep or very deep to calcareous, stratified gravelly or very gravelly coarse sands and sands. Warsaw soils have an argillic horizon that averages between 17 and 30 percent clay. Warsaw is a member of the fine-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Typic Argiudolls family.

The depth to sands and gravels varied among and across each site and affects the water-holding capacity and yields. The soil survey report describes that included with Genesee soils in mapping are narrow strips of the somewhat

poorly drained Shoals soils on lower positions on the flood plain and areas of coarser-textured Stonelick soils adjacent to streams (Kerr and Christman, 1980). Included with Warsaw soils in mapping are small areas of Eldean soils that are moderately deep to calcareous sandy and gravelly material (Kerr and Christman, 1980).

Field Procedures:
The Veris 3100 implement was towed behind a 4WD vehicle across each field. Measurements were continuously recorded and geo-referenced with a GPS receiver.

Comparative EMI studies were completed in only two fields: the field dominated by Genesee silt loam, occasionally flooded, and an irrigated field dominated by Warsaw loam, 0 to 2 percent slopes. A 150 by 150 meter grid was established in a representative area of each field (see figures 4 and 5 for the locations of these grid areas). The grid interval was 15 meters. Survey flags were inserted in the ground at each grid intersection and served as observations points. This procedure provided 121 observation points in each grid.

As measurements were obtained in both the horizontal and vertical dipole orientations and precise positioning of instruments were required, the EM31, EM38, and EM38-DD meters; Dualem-2 and Dualem-4 meters; and GEM300 sensors were operated in a station-to-station rather than a continuous mode. Measurements were taken with the EM38 and EM38-DD meters placed on the ground surface in both the horizontal and vertical dipole orientations. Measurements were taken at hip-height in both the horizontal and vertical dipole orientations with the EM31 meter and the GEM300 sensor. Measurements were taken with the Dualem-2 and Dualem-4 meters held at hip-height in both the perpendicular and horizontal co-planar geometries.

Results:
Veris Surveys:
Genesee Silt Loam, Occasionally flooded- Moving across the field at speeds of about 5 mph, the Veris 3100 implement recorded 5667 observation points in about 1.5 hours (see Figure 1 for locations of observation points). An observation (two apparent conductivity measurements with coordinates) is recorded every second. By varying the speed of advance, the number and density of observation points can be varied. Negative values were recorded at 151 observation points. Negative values are attributed to buried metallic objects, or poor ground contact of coulter-electrodes produced by very gravelly spots on the soil surface. These values were more prevalent in the "deep" data. All negative values were removed from the data set.

Figure 4 contains plots showing the spatial distribution of apparent conductivity within the upper 30 and 90 cm of the soil. In each plot, colors have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 1 mS/m. In Figure 4, the left-hand plot contains digitized soil lines from Figure 1.

Table 1. Basic Statistics
Veris 3100 Survey
Genesee Silt Loam, Occasionally flooded
(All values are in mS/m)

	Shallow	Deep
AVERAGE	17.4	24.7
MINIMUM	1.7	3.0
MAXIMUM	28.5	41.3
FIRST	15.1	21.3
MEDIAN	17.8	25.3
THIRD	20.1	28.8

A general comparison of the two plots reveals that apparent conductivity increased with increasing soil depth. This vertical trend is attributed to increased clay, carbonate, and moisture contents with increasing soil depths. Basic statistics for the Veris data are listed in Table 1. Within the Genesee site, for the upper 0 to 30 cm of the soil, apparent conductivity averaged 17.4 mS/m with a range of 1.7 to 28.5 mS/m. Half of the observations had values of apparent conductivity between 15.1 and 20.1 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 24.7 mS/m with a range of 3.0 to 41.3 mS/m. Half of the observations had values of apparent conductivity between 21.3 and 28.8 mS/m.

Spatial patterns evident in Figure 4 principally reflect differences in clay and moisture contents and, although soil line and patterns of apparent conductivity are often askew, correspond with soil delineations shown on the published soil survey (see Figure 1). In Figure 4, areas with higher or lower apparent conductivity form distinct, linear bands that extend largely from north to south and parallel the existing channel of the Scioto River. These bands represent soils with higher or lower clay and/or moisture contents, or abandoned channels filled with finer-textured soil materials. In both plots (Figure 4), an area of comparatively low apparent conductivity (green and light yellow colors) along the northeast border of the study site approximates a mapped delineation of Stonelick sandy loam (see "St" in figures 1and 4). The Stonelick soil is a member of the coarse-loamy, mixed, superactive, calcareous, mesic Typic Udifluvents family. Stonelick soils have lower clay content than Genesee soils. The lower apparent conductivity in this portion of the study site presumably reflects the lower clay content of Stonelick soils. In the northwest portion of both plots, differences in apparent conductivity help to define a slightly lower-lying area of Ross soil (see "Rs" in figures 1and 4). In Figure 4, this area is manifested as a narrow, elongated area of slightly higher apparent conductivity having red and orange colors. Ross is a member of the fine-loamy, mixed, superactive, mesic Cumulic Hapludolls family. This well drained soil is texturally similar to Genesee soils, but has a mollic epipedon and occupies a lower-lying position on the flood plain. The higher apparent conductivity is attributed to greater moisture, clay, and/or organic matter contents in the upper part of the Ross profile. The area of Ross soil is bordered on the west by a slightly higher lying terrace of Wea soils (see "WeB" in figures 1and 4). This area of Wea soil is evident by lower apparent conductivity values. The well drained, Wea soil is a member of the fine-loamy-mixed, active, mesic Typic Argiudolls family

Warsaw loam, 0 to 2 percent slopes (Irrigated field)- The Veris 3100 implement recorded 5469 observation points in about 1.5 hours (see Figure 2). Negative values were recorded at 13 observation points. Negative values are attributed to buried metallic objects or poor ground contact of coulter-electrodes produced by very gravelly spots on the soil surface. Once again, these values were more prevalent in the deep data. All negative values were deleted from the data set.

Figure 5 show the spatial distribution of apparent conductivity within the upper 30 and 90 cm of the soil. In each plot, colors have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 1 mS/m. In Figure 5, the left-hand plot contains digitized soil lines from Figure 2.

A general comparison of the two plots shown in Figure 5 reveals that, in most areas, apparent conductivity increased with increasing soil depth. This vertical trend is attributed to the increased clay and moisture contents of the argillic horizon. In areas of Warsaw soils, resistive sands and gravels should be deep and very deep and therefore beyond the effective penetration depth of the Veris 3100 system.

Basic statistics for the data collected with the Veris system within this area of Warsaw soils are listed in Table 2. For the upper 0 to 30 cm, apparent conductivity averaged 8.6 mS/m and ranged from 3.9 to 21.1 mS/m. Half of the observations had values of apparent conductivity between 7.1 and 9.8 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 10.9 mS/m with a range of 4.2 to 26.7 mS/m. Half of the observations had values of apparent conductivity between 9.3 and 12.2 mS/m. Compared with data collected at the Genesee site, values of apparent conductivity collected within the Warsaw site are conspicuously lower and less variable.

Table 2. Basic Statistics
Veris 3100 Survey
Warsaw loam, 0 to 2 percent slopes (Irrigated field)
(All values are in mS/m)

	Shallow	Deep
AVERAGE	8.6	10.9
MINIMUM	3.9	4.2
MAXIMUM	21.1	26.7
FIRST	7.1	9.3
MEDIAN	8.3	10.6
THIRD	9.8	12.2

Spatial patterns evident in Figure 5 principally reflect differences in clay and moisture contents. In the plot of the 0 to 90 cm data (see lower plot in Figure 5), areas of higher and lower apparent conductivity form distinct bands across this management unit. Though most bands trend in a predominantly north to south direction that parallels the existing channel of the Scioto River, some form curved or sinuous patterns. These bands may represent abandoned channels filled with finer-textured soil materials or soils with greater clay contents, shallower depths to argillic horizons, or more moist conditions. In the extreme western portion of the lower plot, areas of higher apparent conductivity (orange colors) represent lower-lying, wetter included soils.

Warsaw loam, 0 to 2 percent slopes (field across from homestead)- The Veris 3100 implement recorded 8217 observation points in about 2.25 hours (see Figure 3). No negative values were recorded in this field.

Figure 6 show the spatial distribution of apparent conductivity within this management unit for the upper 30 and 90 cm of the soil profile. In each plot, colors have been used to show the distribution of apparent conductivity. In each plot the isoline interval is 1 mS/m. In Figure 6, the left-hand plot contains digitized soil lines from Figure 3.

A general comparison of the two plots reveals that, throughout most of this field, apparent conductivity varies with increasing soil depth. Conductivity decreases with depth in lower lying, more poorly drained areas along drainageways. This vertical trend is attributed to higher clay and moisture contents in surface layers (from a recent 2" rainfall event). Conductivity decreases with increasing soil depth in areas of Warsaw (WbA) and Eldean (EnA) soils. This trend may represent the influence of the underlying stratified layers of electrically resistive sands and gravels. Warsaw soil is deep and very deep to sands and gravels, but mapped areas contain inclusions that are moderately deep to sands and gravels. Eldean soils are moderately deep to sands and gravels. Eldean is a member of the fine, mixed, superactive, mesic Typic Hapludalfs family. Eldean soils contain more clay in the upper part of its profile than Warsaw soils. However, areas that have been mapped as Eldean loam appear to have a lower conductivity than Warsaw soil. Based on EMI data, these areas of Eldean loam may have been mismapped and should be investigated by soil scientists.

Basic statistics for the Veris data collected in this field are listed in Table 3. For the upper 0 to 30 cm of the soil profile, apparent conductivity averaged 18.4 mS/m with a range of 4.8 to 37.9 mS/m. Half of the observations had values of apparent conductivity between 14.6 and 21.8 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 18.1 mS/m with a range of 3.9 to 51.1 mS/m. Half of the observations had values of apparent conductivity between 13.0 and 21.3 mS/m. Compared with data collected in the irrigated field dominated by Warsaw loam, 0 to 2 percent slopes, values are conspicuously higher and more variable in this field. This field contains a greater number of map units and contrasting soils. However, within this field, areas that have been mapped as Warsaw soil have a noticeably higher apparent conductivity than similarly mapped areas in Site 2. This probably reflects differences in the composition and depths to sands and gravels within these delineated areas.

Table 3. Basic Statistics
Veris 3100 Survey
Warsaw loam, 0 to 2 percent slopes (Field across from Homestead)
(All values are in mS/m)

	Shallow	Deep
AVERAGE	18.4	18.1
MINIMUM	4.8	3.9
MAXIMUM	37.9	51.1
FIRST	14.6	13.0
MEDIAN	18.6	17.0
THIRD	21.8	21.3

Spatial patterns evident in Figure 6 reflect differences in clay and moisture contents and depths to sands and gravels. In these plots, areas of higher and lower apparent conductivity form distinct bands. Areas of higher conductivity correspond with lower-lying areas and intermittent drainageways. In these areas, more saturated conditions, higher clay contents, and greater depths to sands and gravels explain the higher values of apparent conductivity. The field includes mapped delineations of Westland (Ws), Tippecanoe (TpA), Genesee (Gn), Ross (Rs), Stonelick (St), and Wea (WeA) soils (see Figure 3). Westland is a member of the fine-loamy, mixed, superactive, mesic Typic Argiaquolls family. Westland soils are poorly and very poorly drained, and deep or very deep to sands and gravels. Tippecanoe is a member of the fine-loamy, mixed, mesic Oxyaquic Argiudolls. The moderately well drained Tippecanoe is moderately deep to sands and gravels. Areas of more imperfectly drained and wetter Westland and Tippecanoe soils have higher apparent conductivities than areas of Warsaw soils. Ross is a member of the fine-loamy, mixed, superactive, mesic Cumulic Hapludolls family. This very deep soil has a mollic epipedon that is 24 to 40 inches thick. The area of Ross soil in the southeast portion of the field (see Figure 3) contains an area with conspicuously high apparent conductivity values. This area is suspected to represent an unreasonably large inclusion of lower-lying, wetter soils. This fairly extensive, contiguous area within the Ross delineation perhaps should have been separated during soil mapping.

Areas with lower conductivity are presumably drier, have lower clay contents, and/or shallower depths to sands and gravels than areas of higher conductivity. Areas of low apparent conductivity form curved, elongated bands that may represent abandoned point bar deposits. Though most bands trend in a predominantly north to south direction that parallels the existing channel of the Scioto River, some form curved or sinuous patterns.

EMI Surveys of Grid Sites:
The fields surveyed with the Veris 3100 soil EC mapping system consist principally of medium-textured alluvium underlain at vary depths by layers of sand and gravel. Depths to sand and gravel are greater than 1 meter in areas of Genesee and Warsaw soils. The maximum depth of penetration of the Veris system is 90 cm. The relatively shallow penetration depth of the Veris 3100 system makes this instrument inappropriate for determining the depths to sand and gravel in areas of Genesee and Warsaw soils. In open farmlands, mobile systems provide faster, less labor-intensive, and more efficient operations. All EMI instruments used in this study can be mounted on wooden trailers and towed behind a four wheel ATV (Davis et al, 1997).

Comparative studies were conducted within two grid sites using the various EMI instruments. The purpose of these studies was to determine the most appropriate EMI instrument(s) for determining the depths to sands and gravels within mapped areas of Genesee and Warsaw soils.

<u>Genesee Silt Loam, Occasionally flooded-</u>

Basic statistics for the EM38 data collected within the Genesee grid area are listed in Table 4. For the EM38 meter, the effective depths of penetration are 0 to 0. 75 and 0 to 1.5 m in the horizontal (EM38H) and vertical (EM38V) dipole orientations, respectively. Within the grid area, for the upper 0 to 75 cm of the soil, apparent conductivity averaged 21.6 mS/m with a range of 12.9 to 26.9 mS/m. Half of the observations had values of apparent conductivity between 20.1 and 23.4 mS/m. For the upper 1.5 m of the soil, apparent conductivity averaged 23.7 mS/m with a range of 15.6 to 29.5 mS/m. Half of the observations had values of apparent conductivity between 22.1 and 25.5 mS/m. In general, apparent conductivity, as measured with the EM38 meter, increased slightly with increased soil depth.

Table 4. Site 1 - Basic Statistics
Geonics Limited Meters
Genesee Grid Area
(All values are in mS/m)

	EM31H	EM31V	EM38H	EM38V	EM38-DDH	EM38-DDV
Average	18.5	24.4	21.6	23.7	29.1	16.7
Minimum	12.4	16.4	12.9	15.6	10.8	3.8
Maximum	22.8	30.2	26.9	29.5	37.8	32.6
First	16.6	22.6	20.1	22.1	27.0	13.2
Second	18.6	25.2	21.7	24.0	29.6	16.2
Third	20.2	26.8	23.4	25.5	31.7	20.3

The upper two plots in Figure 7 show the spatial distribution of apparent conductivity collected with the EM38 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each of the colored plots, the isoline interval is 1 mS/m. Values of apparent conductivity measured with the EM38 meter were moderate (13 to 30 mS/m) and spatially variable within the grid area. These characteristics suggest relatively thick layers of loamy alluvium having moderate clay and moisture contents, and deep or very deep depths to sands and gravels. Similar elongated bands of higher (red and orange colors) and lower (yellow colors) apparent conductivity are evident in each plot. These patterns are closely spaced and parallel the present course of the Scioto River. These patterns are presumed to reflect differences in alluvial deposits, and/or variations in the thickness of the overlying loamy alluvium. In this nearly level study site, areas with lower conductivity are presumed to have lower clay or moisture contents, thinner layers of loamy alluvium, and/or shallower depths to sands and gravels.

Basic statistics for the EM38-DD data are listed in Table 4. For the EM38-DD meter, the effective depths of penetration are 0 to 0. 75 and 0 to 1.5 m in the horizontal (EM38-DDH) and vertical (EM38-DDV) dipole orientations, respectively. Within grid area, for the upper 0 to 75 cm of the soil, apparent conductivity averaged 29.1 mS/m with a range of 10.8 to 37.8 mS/m. Half of the observations had values of apparent conductivity between 27.0 and 31.7 mS/m. For the upper 1.5 m of the soil, apparent conductivity averaged 16.7 mS/m with a range of 3.8 to 32.6 mS/m. Half of the observations had values of apparent conductivity between 13.2 and 20.3 mS/m.

Even though measurements were made with the EM38 and EM38-DD meters at the same observation points, data collected with these instruments were noticeably different and not strongly related. Data collected with the EM38-DD meter in the horizontal dipole orientation was moderately correlated with data collected with the EM38 meter in the horizontal ($r = 0.556$; significant at .001 level) and vertical ($r = 0.629$; significant at .001 level) dipole orientations. Data collected with the EM38-DD meter in the vertical dipole orientation were not correlated with data collected with the EM38 meter in the horizontal ($r = 0.084$) and vertical ($r = 0.073$) dipole orientations. Measurements obtained with the EM38-DD meter were more variable and significantly higher in the horizontal

dipole orientation and lower in the vertical dipole orientation than measurements obtained with the EM38 and EM31 meters. The inconsistency in measured values between the EM38 and the EM38-DD meters is of great concern, as closely matching results should be obtained with these meters. Calibration errors or system noise may be responsible for the incongruous measurements obtained with the EM38-DD meter.

The lower plots in Figure 7 show the spatial distribution of apparent conductivity collected with the EM38-DD meter. The spatial distributions of data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each of the colored plots, the isoline interval is 1 mS/m. For the EM38-DD meter, spatial patterns vaguely suggest the occurrence of linear bands of higher (red and orange colors) and lower (yellow and green colors) apparent conductivity. Data collected in the horizontal dipole orientation with both the EM38 and EM38-DD meters show similar spatial pattern. However, data collected with the EM38-DD meter in the vertical dipole orientation show spatial patterns that are strikingly dissimilar from the spatial patterns of data collected with the other instruments. Data collected with the EM38-DD meter is suspected of error.

Basic statistics for the EM31 data collected within the grid area at site 1 are listed in Table 4. For the upper 0 to 2 m of the soil (EM31 operated at a height of about 1 m above the ground), apparent conductivity averaged 18.5 mS/m with a range of 12.4 to 22.8 mS/m. Half of the observations had values of apparent conductivity between 16.6 and 20.2 mS/m. For the upper 0 to 5 m of the soil, apparent conductivity averaged 24.4 mS/m with a range of 16.4 to 30.2 mS/m. Half of the observations had values of apparent conductivity between 22.6 and 26.8 mS/m. In general, apparent conductivity measured with the EM31meter increased with increased soil depth. This vertical trend is attributed to increasing clay and moisture contents with increased depths.

Figure 8 shows the spatial distribution of apparent conductivity collected with the EM31 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. The effective depths of penetration are 0 to 2 and 0 to 5 m in the horizontal and vertical dipole orientations (EM31 operated at a height of about 1 m above the ground), respectively. In each of the colored plots, the isoline interval is 1 mS/m. Values of apparent conductivity measured with the EM31 meter were moderate (12 to 30 mS/m) and variable within the grid area. These characteristics suggest relatively thick layers of loamy alluvium having moderate clay and moisture contents, and deep or very deep depths to sands and gravels. Similar elongated bands of higher (red and orange colors) and lower (yellow colors) apparent conductivity are evident in each plot. These patterns are closely spaced and parallel the present course of the Scioto River. These patterns are presumed to reflect differences in alluvial deposits, and/or variations in the thickness of the overlying loamy alluvium. In this nearly level study site, areas with lower conductivity are presumed to have lower clay or moisture contents, thinner layers of loamy alluvium, and/or shallower depths to sands and gravels.

Figures 9 shows the results of the EMI survey conducted with the GEM300 sensor within the Genesee grid area. Data collected at 19950 Hz, 14790 Hz, and 9810 Hz are shown in the upper, middle, and lower sets of plots, respectively. For each frequency, data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 1 mS/m. Frequencies of 14790 and 9810 Hz were selected as they approximate the frequencies of the EM38 and the EM31 meters, respectively. Spatial patterns shown in these plots resemble the spatial patterns of apparent conductivity as measured with the EM38 and EM31 meters. However, with the GEM300 sensor, signal amplitudes are higher and contrasts between areas of higher and lower conductivities are greater.

Table 5 summarizes the GEM300 data collected within the Genesee grid area. As measured with this sensor, apparent conductivity was moderate and quite variable across the grid area. Measurements obtained in the horizontal dipole orientation are more sensitive to changes in apparent conductivity that occur at or near the soil surface. Measurements obtained in the vertical dipole orientation are more sensitive to changes in apparent conductivity that occurred at greater soil depths. Strong ($r = 0.910$ to 0.979) and significant (0.001 level) correlations existed between data collected at different frequencies but similar dipole orientations. Data collected

in the horizontal dipole orientation and at a frequency of 19950 Hz were the most strongly correlated with the data collected with the EM31 meter in either the horizontal (r = 0.738) or vertical (r = 0.737) dipole orientations.

Table 5. Basic Statistics
GEM300 Sensor
Genesee Grid Area
(All values are in mS/m)
(Frequency (Hz) and Coil Orientation (H or V))

	9810H	**9810V**	**14790H**	**14790V**	**19950H**	**19950V**
Average	17.4	25.5	20.7	29.7	24.7	34.0
Minimum	5.8	4.1	11.1	9.9	15.3	15.7
Maximum	33.8	38.8	36.7	55.7	41.4	45.8
First	14.8	17.8	18.1	23.7	22.1	28.5
Second	18.0	28.6	21.5	32.0	25.8	35.8
Third	20.0	33.5	23.0	36.3	27.2	40.6

With each frequency, measurements obtained with the GEM300 sensor in the vertical dipole orientation were higher and more variable than those obtained in the horizontal dipole orientation. This trend suggests the presence of more conductive materials in the subsurface. The more conductive materials may be layers of calcium carbonate enrichment or finer-textured materials in the upper part of the substratum, and/or the water table.

Apparent conductivity decreased with increasing penetration depths (lower frequency). However, this trend may be related to the reduction in signal amplitudes with decreasing frequency rather than the presence of more resistive soil materials at greater depths. With a frequency of 9810 Hz, apparent conductivity ranged from 5.8 to 33.8 mS/m in the horizontal dipole orientation and from 4.1 to 38.8 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 14.8 and 20.0 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 17.8 and 33.5 mS/m. With a frequency of 14790 Hz, apparent conductivity ranged from 11.1 to 36.7 mS/m in the horizontal dipole orientation and from 9.9 to 55.7 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 18.1 and 23.0 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 23.7 and 36.3 mS/m. With a frequency of 19950 Hz, apparent conductivity ranged from 15.3 to 41.4 mS/m in the horizontal dipole orientation and from 15.7 to 45.8 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 22.1 and 27.2 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 28.5 and 40.6 mS/m.

Figure 10 shows the results of the survey conducted with the Dualem meters. Data collected with the Dualem-2 and the Dualem-4 meters are shown in the upper and lower sets of plots, respectively. In Figure 10, data collected in the perpendicular and horizontal coplanar geometries are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 1 mS/m. Spatial patterns shown in these plots resemble the spatial patterns obtained with the EM38 and EM31 meters, and the GEM300 sensor.

Table 6 summarizes the apparent conductivity measurements collected with the Dualem-2 and the Dualem-4 meters within the Genesee grid area. Values of apparent conductivity increased and became more variable with increased depth of penetration. For each meter, measurements of apparent conductivity were lower and less variable in the shallower-sensing perpendicular geometry (P). The higher values of apparent conductivity measured in the horizontal coplanar geometry (HC) reflect increased calcium carbonate, clay, and/or moisture contents with increased depths of observation. The apparent conductivity of the upper 1.3 meters (measured with the Dualem-2

meter in the perpendicular geometry (P-2)) averaged 7.5 mS/m with a range of 5.9 to 9.7 mS/m. Half of the observations had values of apparent conductivity between 6.8 and 8.0 mS/m. These values are remarkably low for this grid area. The apparent conductivity of the upper 2.5 meters (measured with the Dualem-4 meter in the perpendicular geometry (P-4)) averaged 19.5 mS/m with a range of 12.6 to 24.3 mS/m. Half of the observations had values of apparent conductivity between 18.1 and 21.3 mS/m. The apparent conductivity of the upper 3.0 meters (measured with the Dualem-2 meter in the horizontal coplanar geometry (HC-2)) averaged 15.5 mS/m with a range of 10.8 to 20.1 mS/m. Half of the observations had values of apparent conductivity between 14.5 and 16.7 mS/m. The apparent conductivity of the upper 6.0 meters (measured with the Dualem-4 meter in the horizontal coplanar geometry (HC-4)) averaged 20.1 mS/m with a range of 13.2 to 25.1 mS/m. Half of the observations had values of apparent conductivity between 18.4 and 22.5 mS/m.

Table 6. Basic Statistics
DUALEM -2 & DUALEM-4 Meters
Genesee Grid Area
(All values are in mS/m)

	HC-2	P-2	HC-4	P-4
Average	15.5	7.5	20.1	19.5
Minimum	10.8	5.9	13.2	12.6
Maximum	20.1	9.7	25.1	24.3
First	14.5	6.8	18.4	18.1
Second	15.8	7.4	20.9	19.8
Third	16.7	8.0	22.5	21.3

As measured with the Dualem-2 and the Dualem-4 meters, apparent conductivity was low to moderate and relatively invariable across the site. Measurements obtained with the Dualem-2 meter in the horizontal coplanar orientation were strongly correlated with measurements obtained with the EM31 meter in the horizontal ($r = 0.814$) and vertical ($r = 0.912$) dipole orientations. The conspicuous low measurements obtained with the Dualem-2 meter in the perpendicular orientation were not related to measurements obtained with any other meters or sensors. Measurements obtained with the Dualem-4 meter in the horizontal coplanar and perpendicular geometries were strongly related to measurements obtained with the EM31 meter in the vertical dipole orientation ($r = 0.932$ and 0.897, respectively).

Warsaw Loam, 0 to 2 % slopes-

At each of the 121 observation points (grid intersection) measurements were obtained with the Veris 3100 EC soil mapping system. Basic statistics for the Veris 3100 system data collected within the Warsaw grid area are listed in Table 7. For the shallow measurements (0 to 0.30 m), apparent conductivity averaged 8.4 mS/m with a range of 3.2 to 13.3 mS/m. Half of the observations had values of apparent conductivity between 7.3 and 9.5 mS/m. For the deep measurements (0 to 0.90 m), apparent conductivity averaged 10.9 mS/m with a range of 7.2 to 14.9 mS/m. Half of the observations had values of apparent conductivity between 9.7 and 12.0 mS/m. In general, measurements of apparent conductivity collected with the Veris 3100 system in this area of Warsaw loam were exceedingly low, invariable, and increased very slightly with increased soil depth. Compared with data from the Genesee grid area, soils at this site were noticeably drier and contained more sands in the upper part of soil profiles. The conspicuously lower apparent conductivity values reflect the lower clay and moisture contents found within the upper part of the Warsaw soil profile.

Table 7. Basic Statistics
Veris 3100 Soil EC Mapping System
Warsaw Grid Area
(All values are in mS/m)

	Shallow	Deep
Average	8.4	10.9
Minimum	3.2	7.2
Maximum	13.3	14.9
First	7.3	9.7
Second	8.2	10.8
Third	9.5	12.0

Figure 11 shows the spatial distribution of apparent conductivity collected with the Veris 3100 system within the Warsaw grid area. The spatial distributions of apparent conductivity collected for the shallow (0 to 30 cm) and deep (0 to 90 cm) depths are shown in the left-hand and right-hand plots, respectively. In each of these colored plots, the isoline interval is 1 mS/m. Compared with the plots for the larger management unit (see Figure 2), values of apparent conductivity are similarly low and invariable within the Warsaw grid area (see Figure 11). The slightly higher apparent conductivity in the deep plot may reflect the higher clay content of the argillic horizon, which ranges in thickness from about 25 to 65 cm and whose upper boundary varies in depth from 23 to 66 cm. Faint, linear patterns are evident in each plot. These patterns principally trend in a north-northeast to south-southwest direction that closely parallels the present flood plain of the Scioto River and presumably approximates the course of former outwash channels. These closely spaced patterns are presumed to reflect differences in clay content and/or variations in the thickness of the overlying loamy alluvium.

Table 8. Basic Statistics
Geonics Limited Meters
Warsaw Grid Area
(All values are in mS/m)

	EM31H	EM31V	EM38H	EM38V	EM38DD-H	EM38DD-V
Average	8.7	11.2	4.7	10.8	15.8	17.0
Minimum	7.4	9.8	1.0	7.0	9.8	0.2
Maximum	10.6	14.0	16.0	20.0	23.0	53.7
First	8.2	10.4	4.0	9.0	14.2	8.6
Second	8.6	11.0	5.0	11.0	15.9	13.0
Third	9.2	11.8	6.0	12.0	17.5	20.5

Basic statistics for the EM38 data collected with the Warsaw grid area are listed in Table 8. For the shallower-sensing, horizontal dipole orientation (EM38H), apparent conductivity averaged 4.7 mS/m with a range of 1.0 to 16.0 mS/m. Half of the observations had values of apparent conductivity between 4.0 and 6.0 mS/m. For the deeper-sensing, vertical dipole orientation (EM38V), apparent conductivity averaged 10.8 mS/m with a range of 7.0 to 20.0 mS/m. Half of the observations had values of apparent conductivity between 9.0 and 12.0 mS/m. Similar to measurements collected with the Veris 3100 system, measurements collected with the EM38 meter in this area of Warsaw loam were exceedingly low, invariable, and increased slightly with increased soil depth. Although sounding a greater depth than the Veris 3100 system, the depth weighting function of the EM38 meter makes it sensitive to changes in soil properties within the upper part of the soil profile. A moderate ($r = 0.650$) and significant (0.001 level) correlation was found between the deep measurements of the Veris system and measurements obtained with the EM38 meter in the horizontal dipole orientation. A weaker ($r = 0.438$), but

significant correlation (0.001 level) was found between the shallow measurements of the Veris system and measurements obtained with the EM38 meter in the horizontal dipole orientation.

The upper plots in Figure 12 show the spatial distribution of apparent conductivity collected with the EM38 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each of the colored plots, the isoline interval is 1 mS/m.

Values of apparent conductivity measured with the EM38 meter were low (1 to 20 mS/m) within the grid area. These measurements suggest relatively thin layers of loamy alluvium having low to moderate clay and moisture contents. The plots of EM38 data (see Figure 12) show faint, linear bands of slightly higher (yellow and light orange colors) and lower (green colors) apparent conductivity that trend in a north-northeast to south-southwest direction. These patterns are similar to those obtained with the Veris 3100 system (see Figure 11) and suggest depositional sequences related to former outwash channels.

Basic statistics for the EM38-DD data collected within the Warsaw grid area are listed in Table 8. For the shallower-sensing, horizontal dipole orientation (EM38DD-H), apparent conductivity averaged 15.8 mS/m with a range of 9.8 to 23.0 mS/m. Half of the observations had values of apparent conductivity between 14.2 and 17.5 mS/m. For the upper deeper-sensing, vertical dipole orientation (EM38DD-V), apparent conductivity averaged 17.0 mS/m with a range of 0.2 to 53.7 mS/m. Half of the observations had values of apparent conductivity between 8.6 and 20.5 mS/m.

Data collected with the EM38-DD meter were conspicuously higher and more variable than data collected with the EM38 meter. Even though measurements were made at the same observation points, data collected with the EM38-DD and EM38 meters in the horizontal dipole orientation were only moderately correlated ($r = 0.507$; significant at .001 level). Data collected with the EM38-DD and EM38 meters in the vertical dipole orientation were also moderately correlated. However, the relationship was negative ($r = -0.401$). Results should be positive and more strongly correlated with these two devices. While calibration errors or system noise may be responsible for the incongruous measurements, results obtained with the EM38-DD meter suggest serious design or operational flaws.

The lower plots in Figure 12 show the spatial distribution of apparent conductivity collected with the EM38-DD meter. The spatial distributions of data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each of the colored plots, the isoline interval is 1 mS/m. For the EM38-DD meter operating in the horizontal dipole orientation, spatial patterns vaguely suggest the occurrence of linear bands of higher (orange colors) and lower (yellow colors) apparent conductivity. These patterns are similar to those collected with the EM38 meter. The exceptionally high values of apparent conductivity obtained with the EM38-DD meter in the southeast portion of the grid is anomalous and incongruent with measurements obtained with the other EMI devices.

Basic statistics for the EM31 data collected within the Warsaw grid area are listed in Table 8. For the upper 0 to 2 m of the soil (EM31 operated at a height of about 1 m above the ground), apparent conductivity averaged 8.7 mS/m with a range of 7.4 to 10.6 mS/m. Half of the observations had values of apparent conductivity between 8.2 and 9.2 mS/m. For the upper 0 to 5 m of the soil, apparent conductivity averaged 11.2 with a range of 9.8 to 14.0. Half of the observations had values of apparent conductivity between 10.4 and 11.8 mS/m. Measurements obtained with the EM31 meter in the horizontal dipole orientation were moderately correlated ($r = 0.523$) with measurements obtained with the EM38 meter in the vertical dipole orientations.

Figure 13 shows the spatial distribution of apparent conductivity collected with the EM31 meter in the horizontal and vertical dipole orientations (left-hand and right-hand plots, respectively). In each of the colored plots, the isoline interval is 1 mS/m. Linear patterns evident in each plot trend in a north-northeast to south-southwest

direction and are similar to those obtained with the EM38 meter. These faint, linear patterns presumably reflect differences in clay content and/or variations in the thickness of the overlying loamy alluvium.

Values of apparent conductivity measured with the EM31 meter were low (7.4 to 14.0 mS/m) and invariable within the Warsaw grid area. These characteristics suggest comparatively thin layers of loamy alluvium having low clay and moisture contents, and relatively shallow depths to sands and gravels. A general comparison of the two plots shown in Figure 8 reveals that apparent conductivity increases with increased soil depths. This trend may reflect the higher clay content of the argillic horizon or the presence of a lower-lying layer of calcium carbonate enrichment.

Figures 14 shows the results of the EMI survey conducted with the GEM300 sensor within the Warsaw grid area. Data collected at 19950 Hz, 14790 Hz, and 9810 Hz are shown in the upper, middle, and lower sets of plots, respectively. For each frequency, data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 1 mS/m. Linear patterns evident in each plot trend in a north-northeast to south-southwest direction and are similar to those obtained with the EM38 and EM31 meters. These linear patterns are presumed to reflect differences in clay content and/or variations in the thickness of the overlying loamy alluvium.

Table 9. Basic Statistics
GEM300 Sensor
Warsaw Grid Area
(All values are in mS/m)
(Frequency (Hz) and Coil Orientation (H or V))

	9810H	9810V	14790H	14790V	19950H	19950V
Average	6.5	4.0	11.7	8.6	14.0	10.6
Minimum	3.2	0.7	8.5	6.0	11.1	-0.9
Maximum	10.2	7.9	15.5	11.2	18.4	13.6
First	5.3	3.2	10.6	8.0	12.8	9.9
Second	6.1	4.1	11.4	8.6	13.8	10.7
Third	7.6	4.7	12.6	9.3	15.0	11.5

Table 5 summarizes the data collected with the GEM300 sensor within the Warsaw grid area. For each frequency, measurements obtained with the GEM300 sensor in the deeper-sensing, vertical dipole orientation were lower than those obtained in the shallower-sensing, horizontal dipole orientation. Values of apparent conductivity also decreased with decreasing frequency (increasing penetration depths). These trends suggest the presence of less conductive materials in the subsurface. The less conductive material is the underlying sands and gravels. With a frequency of 9810 Hz, apparent conductivity ranged from 3.2 to 10.2 mS/m in the horizontal dipole orientation and from 0.7 to 7.9 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 5.3 and 7.6 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 3.2 and 4.7 mS/m. With a frequency of 14790 Hz, apparent conductivity ranged from 8.5 to 15.5 mS/m in the horizontal dipole orientation and from 6.0 to 11.2 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 10.6 and 12.6 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 8.0 and 9.3 mS/m. With a frequency of 19950 Hz, apparent conductivity ranged from 11.1 to 18.4 mS/m in the horizontal dipole orientation and from -0.9 to 13.6 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity

between 12.8 and 15.0 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 9.9 and 11.5 mS/m.

As measured with the GEM300 sensor, apparent conductivity was low and invariable across the site. Moderate to strong (r = 0.635 to 0.977), significant (0.001 level) correlations exist between data collected with the GEM300 sensor in the same dipole orientation but at different frequencies. Correlations were lower for data collected with the GEM300 at the same frequencies but operating in different dipole orientations. Data collected at a frequency of 19950 Hz in the horizontal dipole orientation were the most strongly correlated with the data collected with the EM31 meter in either the horizontal (r = 0.738) or vertical (r = 0.737) dipole orientations.

Figure 15 shows the results of the surveys conducted with the Dualem meters. Data collected with the Dualem-2 and the Dualem-4 meters are shown in the upper and lower sets of plots, respectively. In Figure 15, data collected in the perpendicular and horizontal coplanar geometries are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 1 mS/m. Linear patterns evident in each plot trend in a north-northeast to south-southwest direction and are similar to those obtained with the EM38 and EM31 meters and the GEM300 sensor. These linear patterns are presumed to reflect differences in clay content and/or variations in the thickness of the overlying loamy alluvium.

Table 10 summarizes the apparent conductivity measurements collected with the Dualem-2 and the Dualem-4 meters within the Warsaw grid area. For each meter, measurements of apparent conductivity were lower in the shallower-sensing perpendicular geometry (P). The higher values of apparent conductivity measured in the horizontal coplanar geometry (HC) may reflect increased calcium carbonate, clay, and/or moisture contents with increased depths of observation. The apparent conductivity of the upper 1.3 meters (measured with the Dualem-2 meter in the perpendicular geometry) averaged 3.5 mS/m with a range of 2.5 to 5.5 mS/m. Half of the observations had values of apparent conductivity between 3.2 and 3.8 mS/m. The apparent conductivity of the upper 2.5 meters (measured with the Dualem-4 meter in the perpendicular geometry) averaged 6.9 mS/m with a range of 5.2 to 10.0 mS/m. Half of the observations had values of apparent conductivity between 6.3 and 7.4 mS/m. The apparent conductivity of the upper 3.0 meters (measured with the Dualem-2 meter in the horizontal coplanar geometry) averaged 5.6 mS/m with a range of 3.9 to 8.4 mS/m. Half of the observations had values of apparent conductivity between 5.0 and 6.0 mS/m. The apparent conductivity of the upper 6.0 meters (measured with the Dualem-4 meter in the horizontal coplanar geometry) averaged 8.7 mS/m with a range of 7.2 to 10.9 mS/m. Half of the observations had values of apparent conductivity between 8.1 and 9.3 mS/m.

Table 10. Basic Statistics
DUALEM-2 & DUALEM-4 Meters
Warsaw Grid Area
(All values are in mS/m)

	HC-2	P-2	HC-4	P-4
Average	5.6	3.5	8.7	6.9
Minimum	3.9	2.5	7.2	5.2
Maximum	8.4	5.5	10.9	10.0
First	5.0	3.2	8.1	6.3
Second	5.5	3.5	8.7	6.7
Third	6.0	3.8	9.3	7.4

As measured with the Dualem-2 and the Dualem-4 meters, apparent conductivity was low and invariable within the Warsaw grid area. Measurements obtained with the Dualem-4 meter in the horizontal coplanar orientation were strongly correlated with measurements obtained with the EM31 meter in the vertical (r = 0.947) and horizontal (r =

0.785) dipole orientations. Measurements obtained with the Dualem-2 meter in the perpendicular orientation were not related to measurements obtained with any other meters or sensors. Measurements obtained with the Dualem-4 meter in the horizontal coplanar geometry were strongly related to measurements obtained with the EM31 meter in both the horizontal and vertical dipole orientations (r = 0.765 and 0.767, respectively).

Summary:
Within each grid area, similar spatial patterns of apparent conductivity were obtained with most instruments. While measured values varied among instruments, these differences reflect variations in the volume and depth of materials sounded. The correlations among several instruments suggest that they are measuring similar volumes of earthen materials and provide comparable results. In general stronger correlations can be found in the data collected with the same instruments but at different frequencies or receiver orientations than with different instruments. The strongest correlations were obtained between data collected with the Dualem-2 and Dualem-4 meters and the EM31 meter; and data collected with the EM38 meter operated in the vertical dipole orientation and data obtained with the Dualem-2 meter in the horizontal coplanar geometry (r = 0.860). Compared with studies conducted in Iowa and Missouri, correlations among the various instruments were noticeably lower within both grid areas. The lack of correlation between data collected with the EM38-DD meter and the Dualem-2 in the perpendicular geometry, and other devices suggest possible equipment malfunctions or errors.

Estimating the Depth to Sands and Gravels:
The depth to sands and gravels varied among and within each of the surveyed map units and affects water-holding capacity and yields. Estimates of the depths to sands and gravels can be obtained from measurements of apparent conductivity. Areas with greater depths to sands and gravel have thicker caps of loamy alluvium and therefore greater clay and moisture contents than areas with lesser depths to sands and gravels. Other factors equal or constant, areas with greater depths to the more electrically resistive sands and gravels have greater EMI responses. In areas of Genesee and Warsaw soils the depths to sands and gravels are deep and very deep. These depths are outside the effective penetration depth of the Veris 3100 soil EC mapping system and the EM38 and EM38-DD meters when operated in the horizontal dipole orientations.

When estimating soil properties with EMI, samples should be collected in each field and compared with EMI data. In the Genesee field, at eight sample points, the measured depths to sands and gravels averaged 1.57 m and ranged from 0.56 to 2.29 m. In the Warsaw (irrigated) field, at eleven sample points, the measured depths to sands and gravels averaged 0.96 m and ranged from 0.33 to 1.85 m. At the time of this survey, the Genesee field was noticeably wetter than the Warsaw fields and water ponded on the surface in some areas.

Data collected with the different EMI devices at nineteen sampling points were used to develop predictive regression equations. Regression coefficients varied with each instrument and differed considerably between the fields. Based on eight samples points within the Genesee field, depths to sands and gravel were most strongly correlated with measurements obtained with the EM31 meter in the vertical dipole (r = 0.755, 0.020 level) and horizontal (r = 0.733, 0.033 level) orientation, and the Dualem-2 meter operated in the horizontal coplanar geometry (r = 0.791, 0.016 level).

Based on eleven samples points within the Warsaw field, depths to sands and gravel were most strongly correlated with measurements obtained with the EM31meter in the horizontal dipole (r = 0.777, 0.004 level) and vertical dipole (r = 0.811, 0.002 level) orientations, and the Dualem-2 meter in the horizontal coplanar geometry (r = 0.773, 0.004 level), and the Dualem-4 meter in the perpendicular (r = 0.751, 0.007 level) and horizontal coplanar (r = 0.765, 0.005 level) geometries.

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 contents). In addition, measurement error was introduced into the data sets because of differences in the area profiled with the various

EMI instruments versus the point of soil observed with the soil probe. Acknowledging these deficiencies, data collected with the Dualem-2 meter in the horizontal coplanar geometry in the field dominated by Genesee soils and data collected with the EM31meter in the vertical dipole orientation in the field dominated by Warsaw soils were used to develop the following equations to predict the depth to sands and gravels:

$$\text{Genesee Field: } D = -1.78 + (0.175 * \text{Dualem-2 (HCP)} \quad [1]$$

$$\text{Warsaw Field: } D = -7.23 + (0.716 * \text{EM31V}) \quad [2]$$

where "D" is depth to sands and gravels (m) and "Dualem-2 HCP" and "EM31V" are the apparent conductivity (mS/m) measured with the Dualem-2 meter operating in the horizontal coplanar geometry and the EM31 meter operating in the vertical dipole orientation, respectively.

Using equation [1], the average difference between predicted and measured depths to sands and gravel at the eight sample points within the Genesee grid area was 0.23 m with a range of 0.05 to 0.85 m. The interpretations were less than the soil measurements obtained in the same field at the eight sampling points. However, at one half of the sample points, the difference between measured and predicted depths to sands and gravels was between 0.07 and 0.23m.

Based on 121 EMI measurements and predictive Equation [1], the average depth to sands and gravels within the Genesee silt loam, occasionally flooded, grid area was 0.94 m with a range of 0.10 to 1.74 m. One-half of the observations had depths to sands and gravels between 0.76 and 1.14 m. Depths to sands and gravel were shallow at 9 percent, moderately deep at 43 percent, deep at 45 percent, and very deep at 3 percent of the observation points. Based on EMI interpretations soils within the Genesee grid area were mostly shallower to sands and gravels than mapped.

Figure 16 contains two-dimensional plots of apparent conductivity and predicted depths to sands and gravels that have been overlain on a three-dimensional surface net diagram of the Genesee silt loam, occasionally flooded, grid area. The spatial patterns evident in Figure 16 indicate that the depth to sands and gravels is relatively invariable over short distances. Areas shallower to sands and gravels appear to be more common on higher-lying, more sloping areas.

Using equation [2], the average difference between predicted and measured depths to sands and gravel at the eleven sample points within the Warsaw grid area was 0.24 m with a range of 0.01 to 0.49 m. At one half of the sample points, the difference between measured and predicted depths to sands and gravels was between 0.16 and 0.32 m.

Based on 121 EMI measurements and predictive Equation [2], the average depth to sands and gravels within the Warsaw loam, 0 to 2 percent slopes, grid area was 0.82 m with a range of about 0.10 to 2.8 m. One-half of the observations had depths to sands and gravels between 0.22 and 1.21 m. These values are comparable to measurements obtained in the same field at the eleven sampling points. Depths to sands and gravel were shallow at 36 percent, moderately deep at 31 percent, deep at 13 percent, and very deep at 20 percent of the observation points. The preponderance of shallow and moderately deep to sands and gravels soils is not in accord with the dominant soil that had been mapped in this area.

Figure 17 contains two-dimensional plots of apparent conductivity and predicted depths to sands and gravels that have been overlain on a three-dimensional surface net diagram of the Warsaw loam, 0 to 2 percent slopes, grid area. The spatial patterns evident in Figure 17 indicate that the depth to sands and gravels are overwhelmingly shallow and moderately deep, but highly variable within the grid area. Areas deeper to sands and gravels appear to be

associated with the ephemeral drainage channel and on lower-lying concave surfaces. As soils were wetter along the drainage channel and on concave surfaces, the greater interpreted depths to sands and gravels may be associated with the increased soil moisture contents and be in error.

Discussion:

Interpretations of EMI or resistivity data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity have been used to infer changes in soils and soil properties. Electrical resistivity and EMI integrate the bulk physical and chemical properties for a defined observation depth into a single value. As a consequence, measurements can be associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993; Doolittle et al., 1996). For each soil, intrinsic physical and chemical properties, as well as temporal variations in soil water and temperature, establish a unique or characteristic range of apparent conductivity values.

Electromagnetic induction is useful to precision agriculture when apparent conductivity can be associated with soil properties that are related to crop productivity and where spatial patterns of apparent conductivity correspond to patterns of crop yield variation. Patterns of apparent conductivity do not tend to vary significantly over time. Doerge and others (1999) noted that once an apparent conductivity map is prepared, it remains relatively accurate unless some significant soil modification occurs (e.g. accelerated erosion, land leveling, terrace construction, flood deposition or erosion). However, temporal variations in apparent conductivity do occur as a consequence of changes in soil moisture content and temperature. Values of apparent conductivity increase with increased soil moisture content and/or temperature (about 2 % per degree Centigrade) (McNeill, 1980).

In open farmlands of the mid-west, EMI field mapping is facilitated and expedited by mounting the EMI instruments on a non-metallic sled and towing the unit behind a suitable field vehicle that is equipped with GPS. Mobile systems, such as the Veris 3100 soil EC mapping system, provide faster, less labor-intensive and more efficient operations. However, all of the electromagnetic induction meters used in this study can be mounted on wooden trailers and towed behind a four wheel ATV (Davis et al, 1997).

The production of apparent conductivity maps from EMI measurements does not require advance knowledge of soils and soil survey techniques (Jaynes, 1995). As a consequence, highly trained soil scientists are not required to collect the data. However, knowledgeable soil scientists are required to interpret the data and must visit field sites to confirm their interpretations.

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Site 1
Genesee silt loam, occasionally flooded

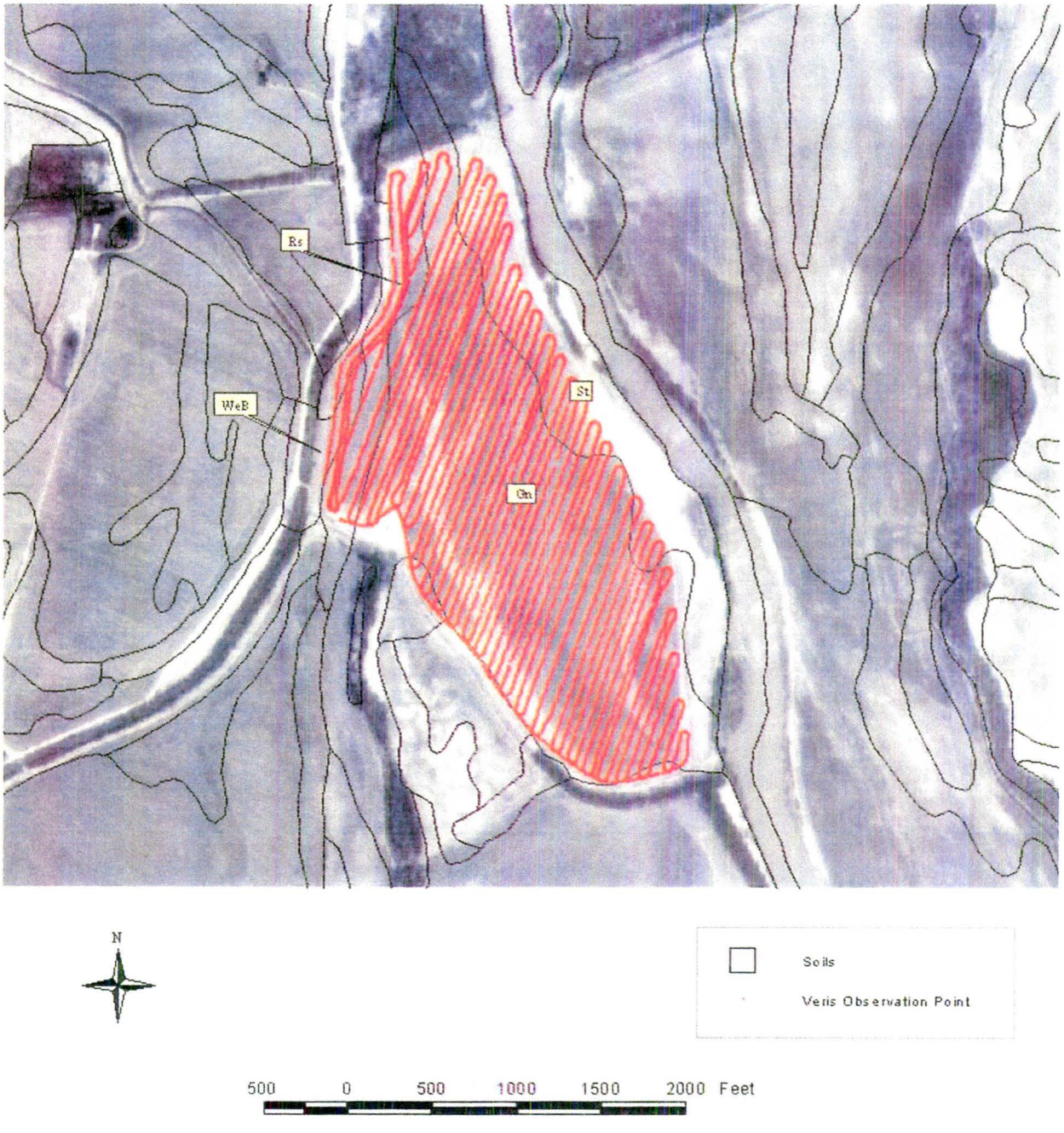
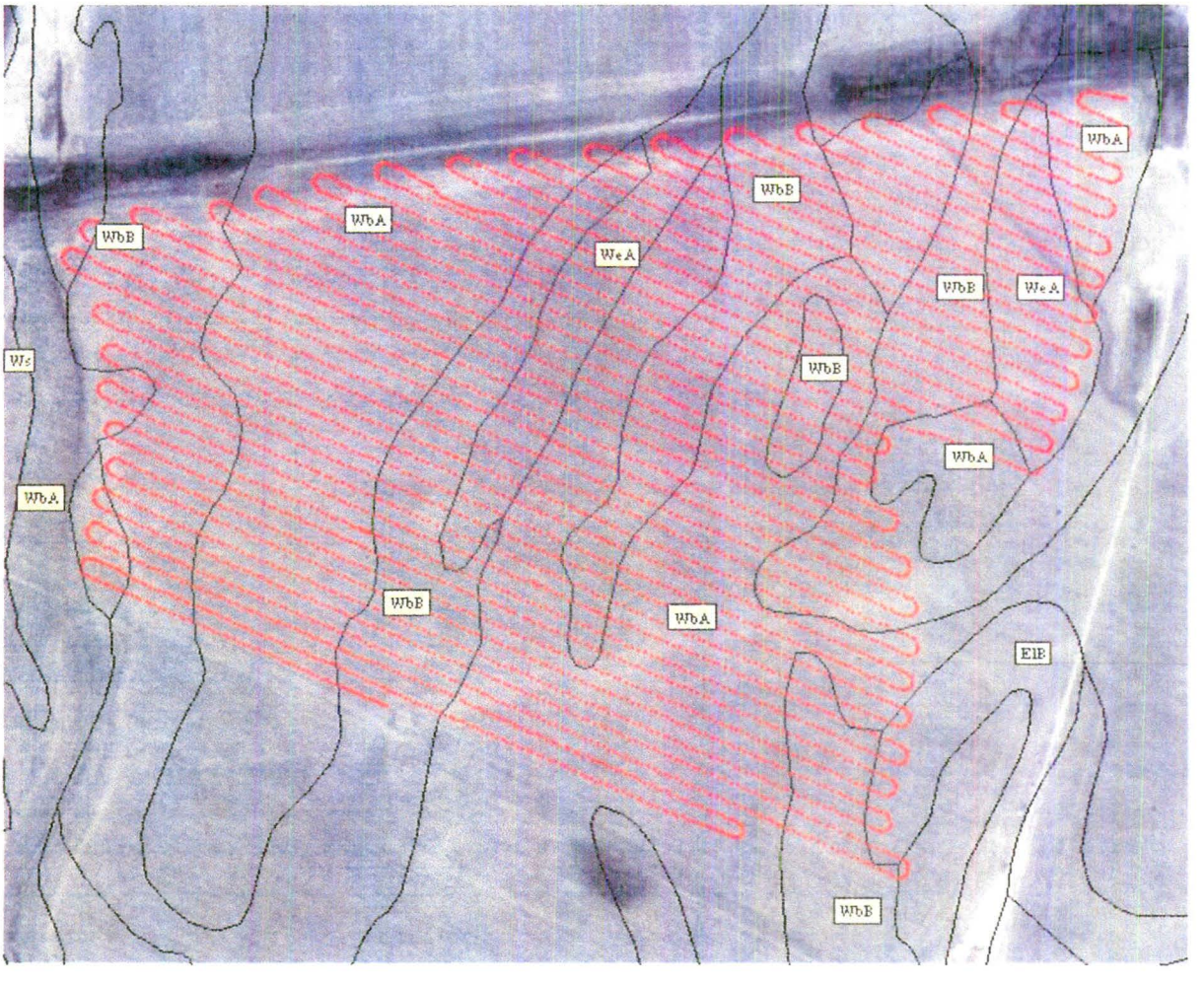
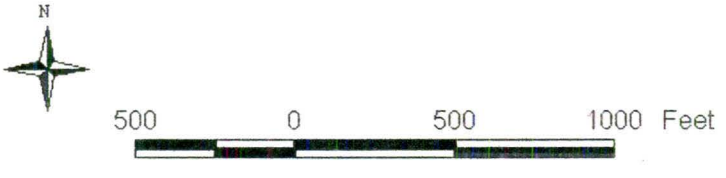


Figure 1

Site 2
Warsaw loam, 0 to 2 percent slopes





Soils

Veris Observation Point

Figure 2

Site 3
Warsaw loam, 0 to 2 percent slopes

Figure 3

EMI SURVEY
GENESEE SILT LOAM, OCCASIONALLY FLOODED
VERIS 3100 SOIL EC MAPPING SYSTEM

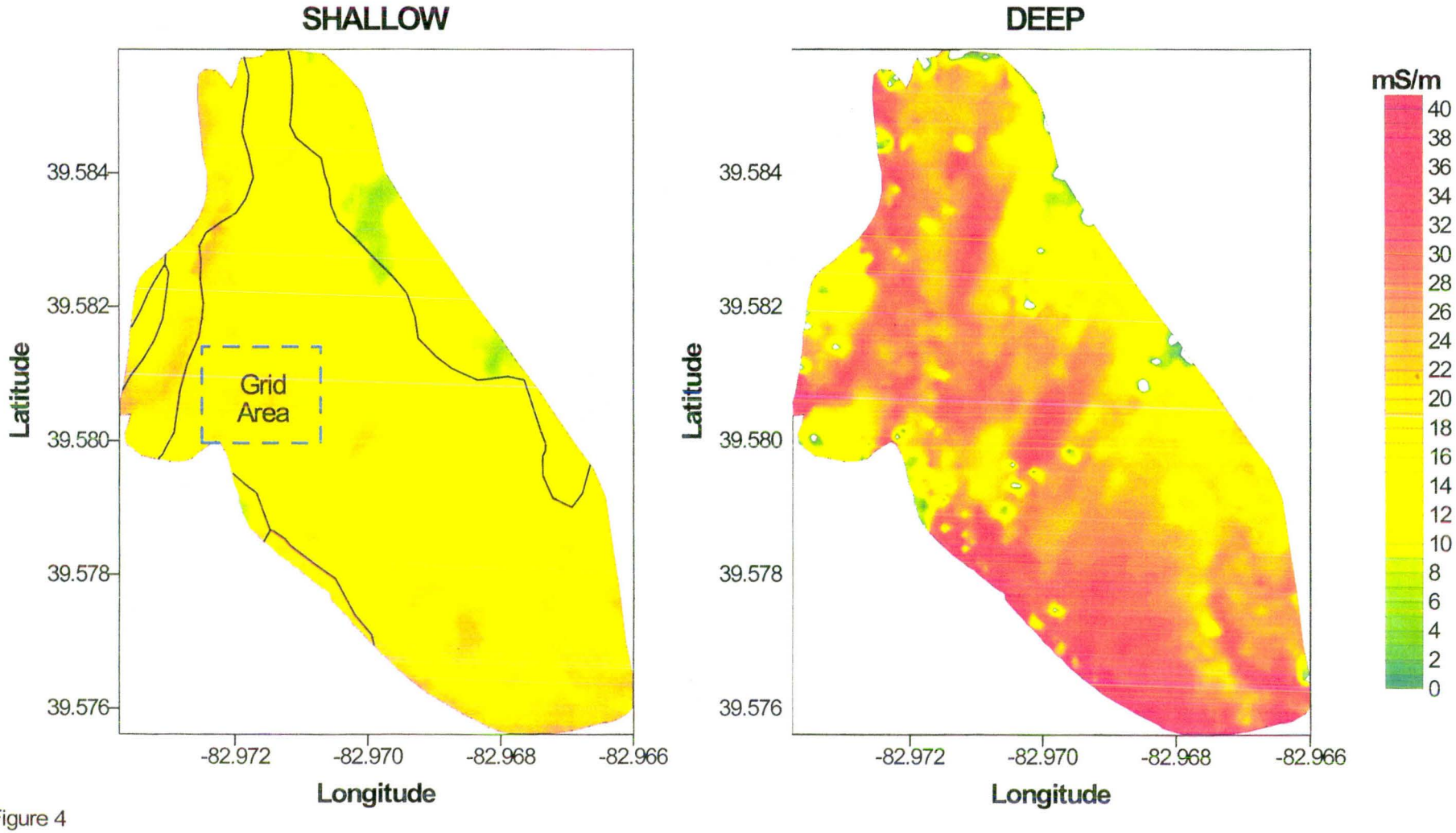
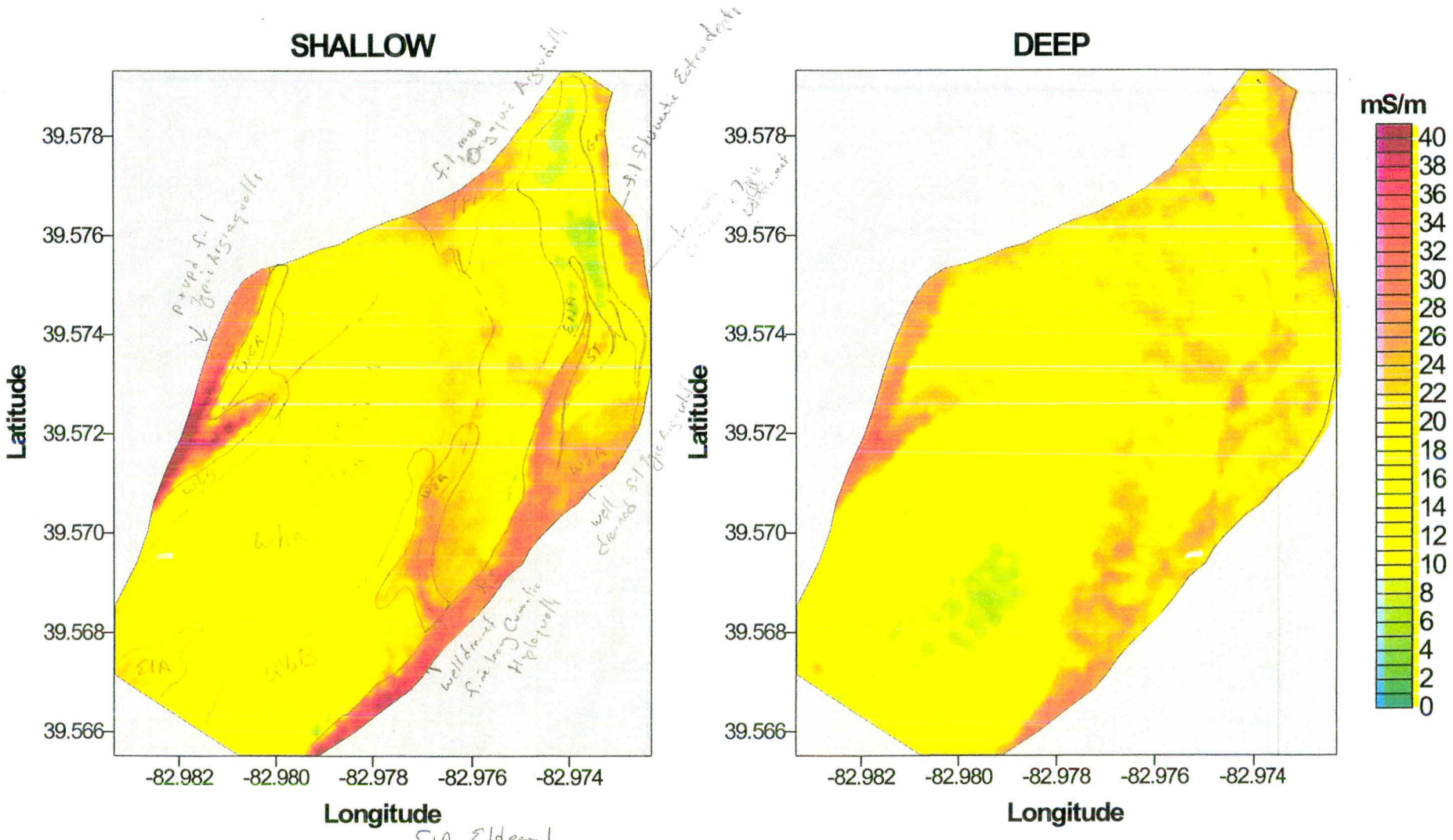


Figure 4

EMI SURVEY
ROSS LOAM, OCCASIONALLY FLOODED
VERIS 3100 SOIL EC MAPPING SYSTEM



EIA Eldean l

Ena Eldean sl 0-2% f.loamy mixed typic Hapludalfs

Gn · Genesee sil f-l Typic Udifluvent

Rs Ross loam occasionally flooded f-l cumulic Hapludolls

Wbatb Warsaw loam 0-2,2-6% f.loamy sands Typic Argiudoll

Wea Wea sil 0-2 f-l Typic Argiudoll,

Ws Westland sicl f-l Typic Argiaquolls

EMI SURVEY
GENESEE SILT LOAM, OCCASIONALLY FLOODED
EM38 & EM38-DD METERS

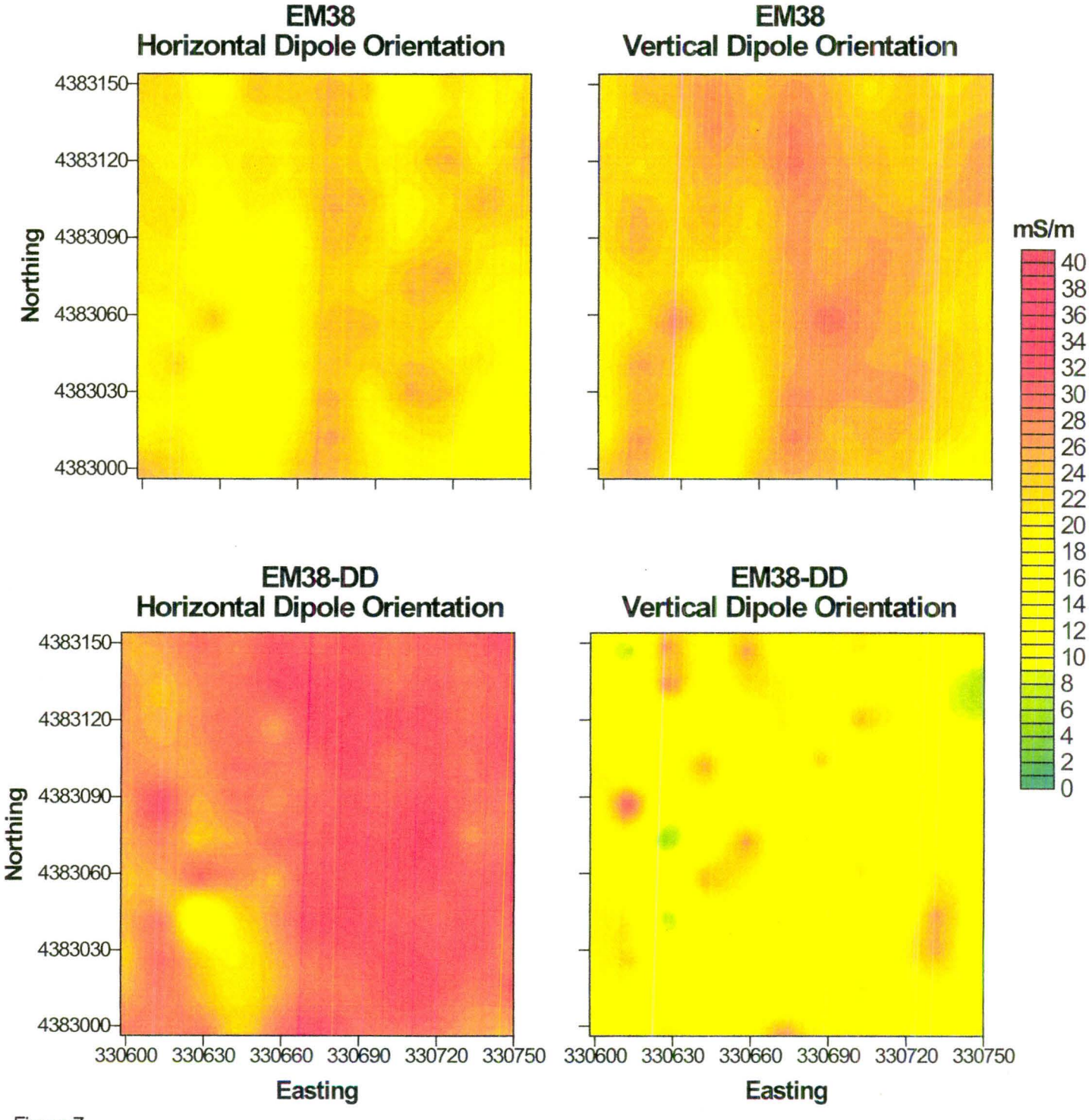


Figure 7

EMI SURVEY
GENESEE SILT LOAM, OCCASIONALLY FLOODED
EM31 METER

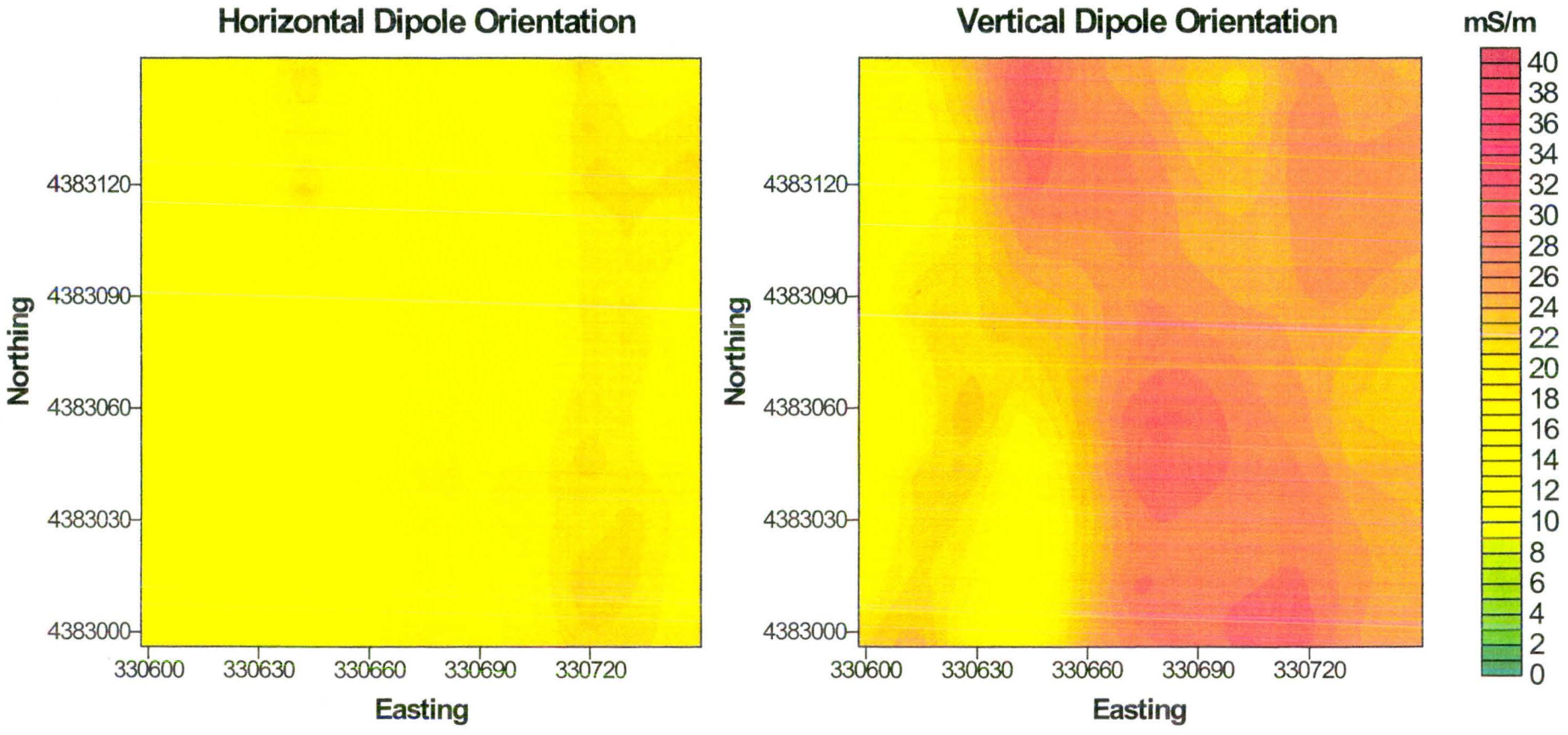


Figure 8

EMI SURVEY
GENESEE SILT LOAM, OCCASIONALLY FLOODED
GEM300 SENSOR

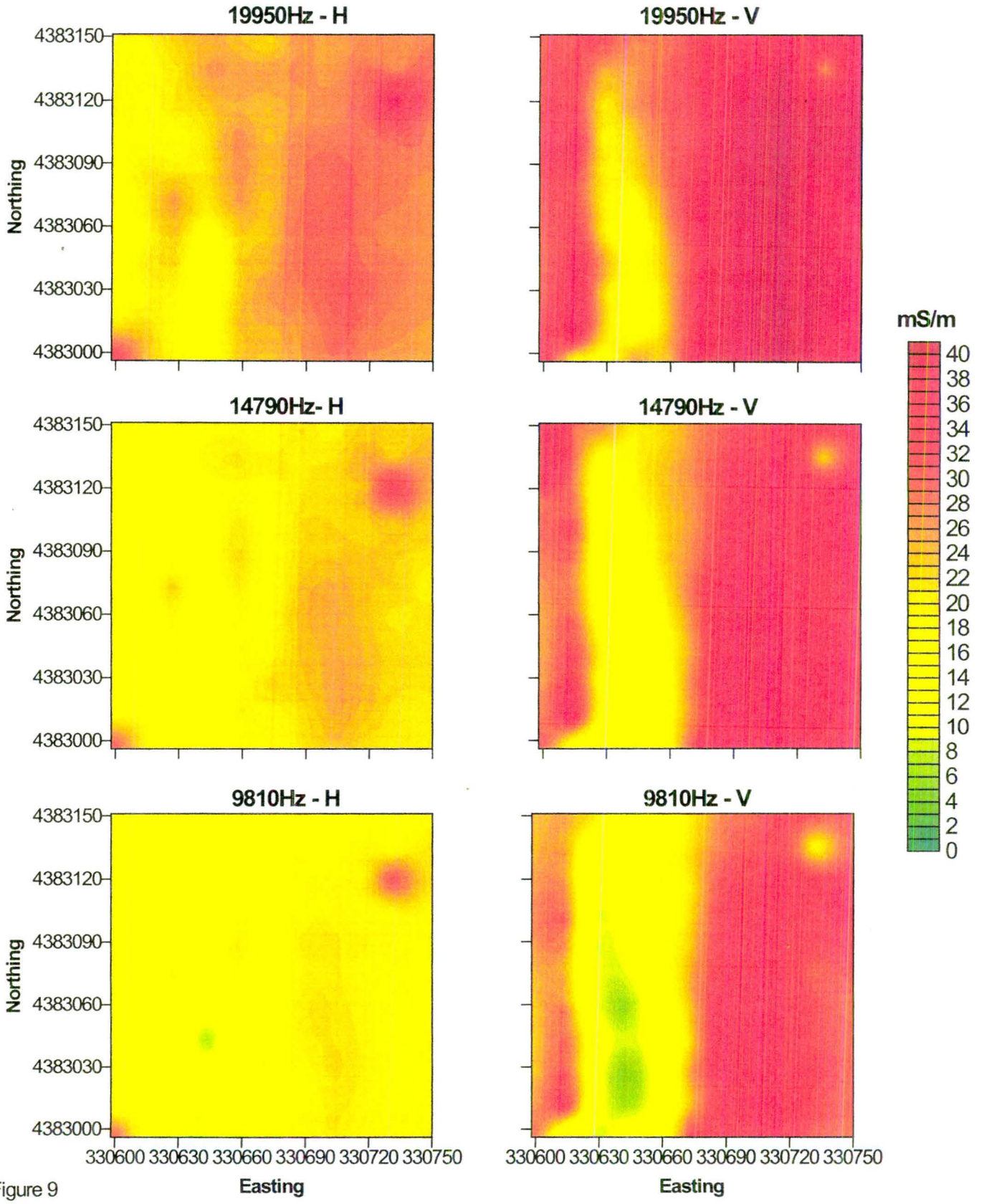


Figure 9

EMI SURVEY
GENESEE SILT LOAM, OCCASIONALLY FLOODED
DUALEM2/4 METERS

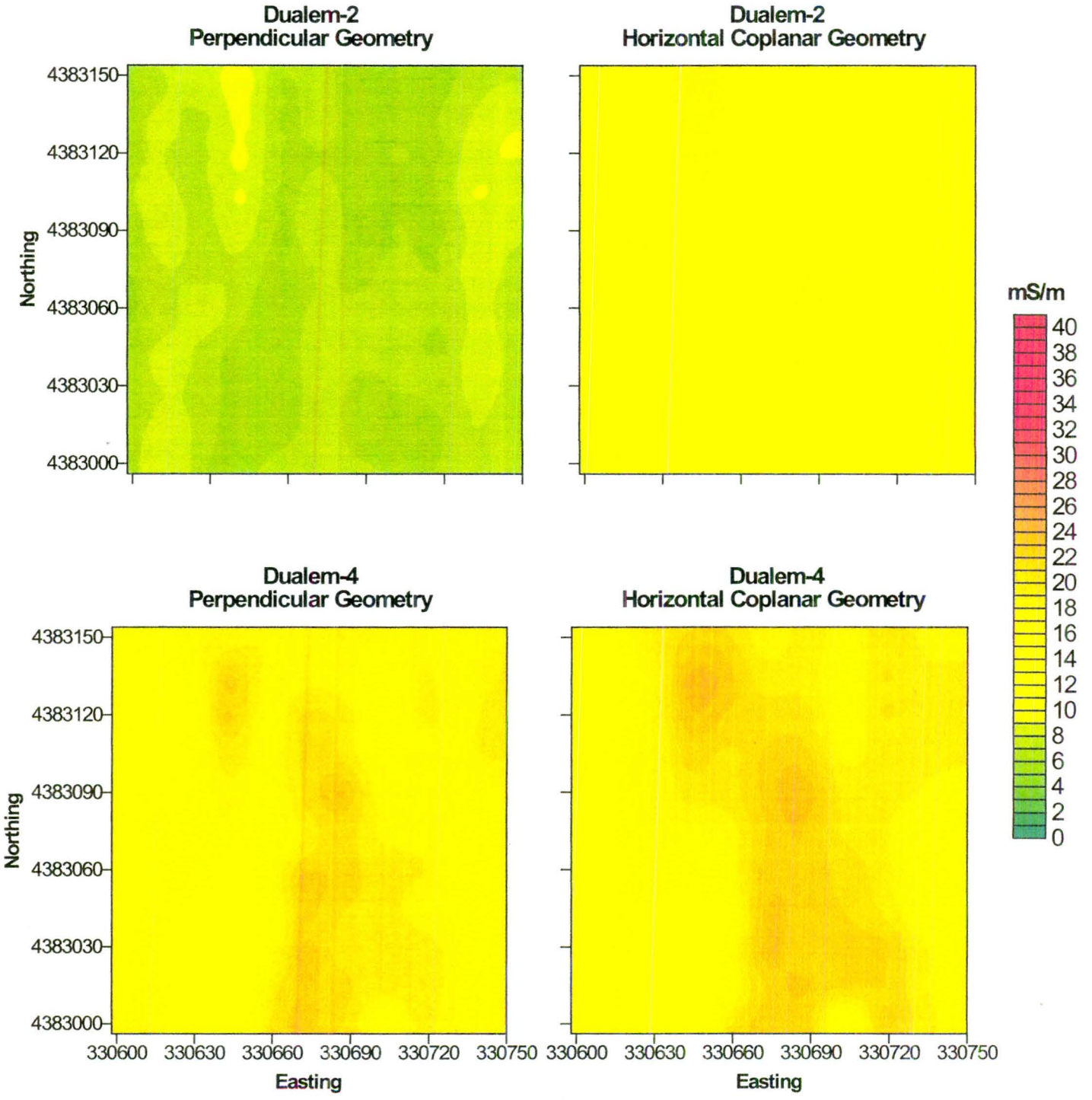


Figure 10

EMI SURVEY
AREA OF WARSAW LOAM, 0 TO 2 PERCENT SLOPES
VERIS 3100 SOIL EC MAPPING SYSTEM

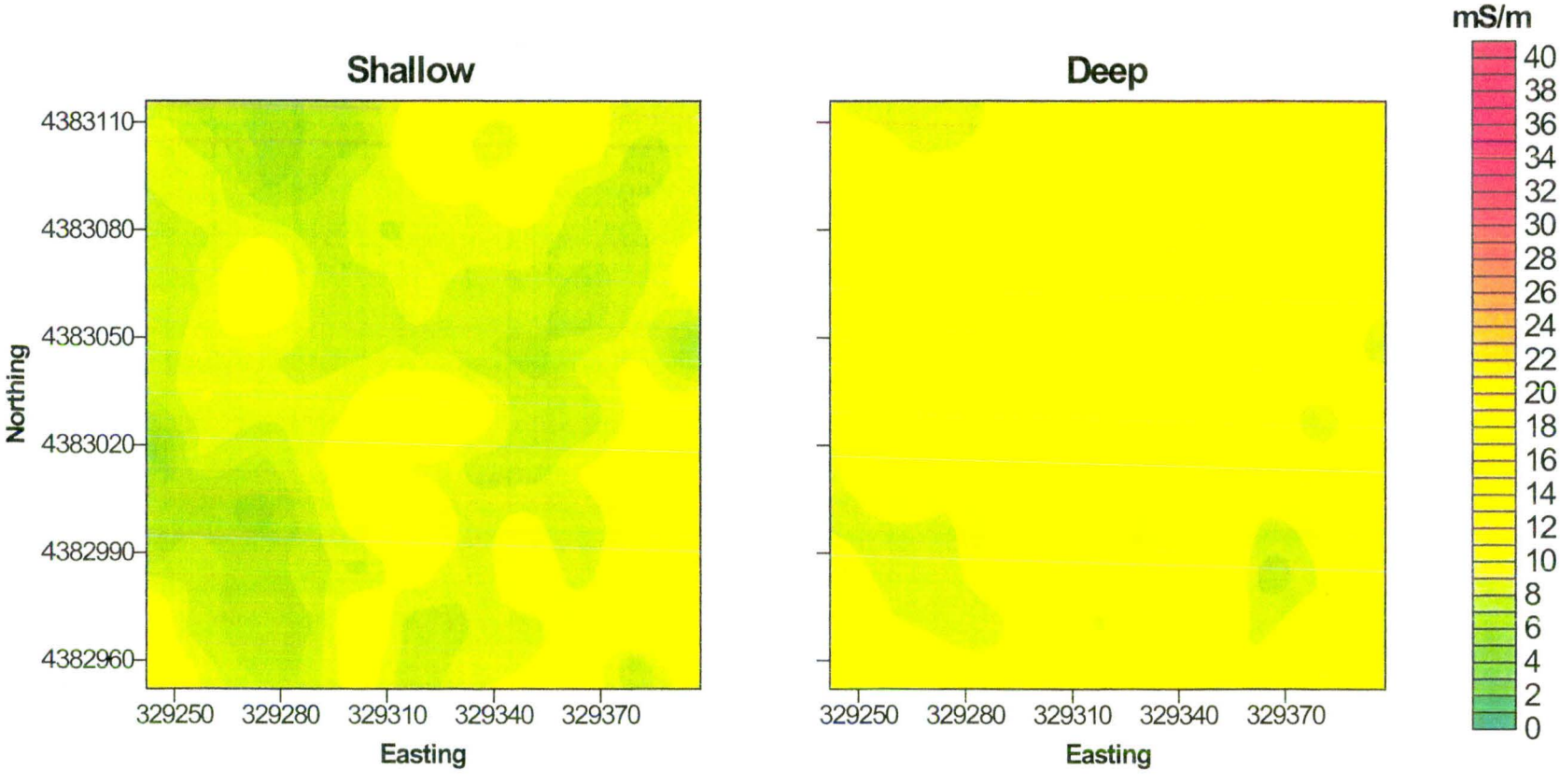


Figure 11

EMI SURVEY
AREA OF WARSAW LOAM, 0 TO 2 PERCENT SLOPES

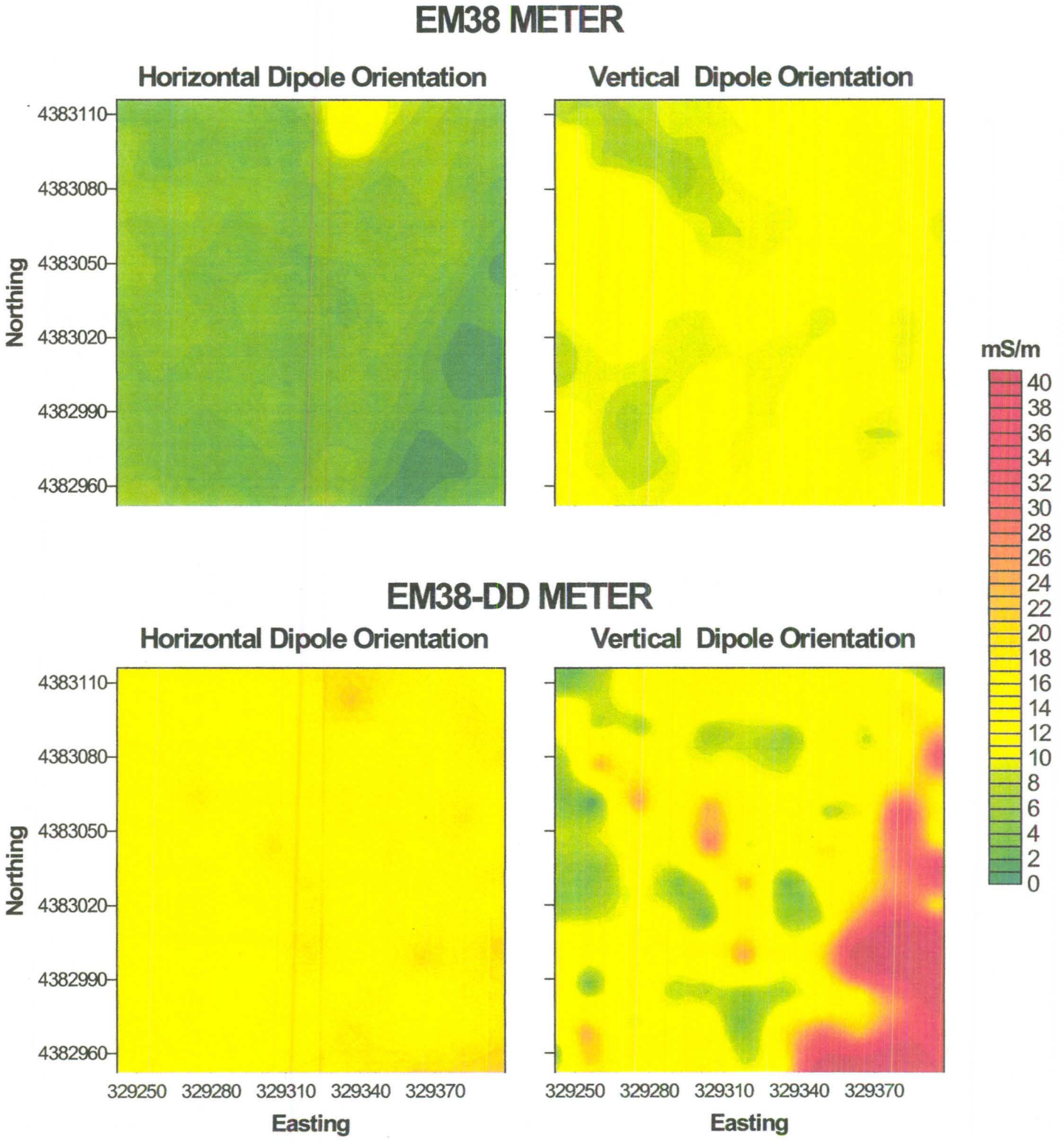


Figure 12

EMI SURVEY
AREA OF WARSAW LOAM, 0 TO 2 PERCENT SLOPES
EM31 METER

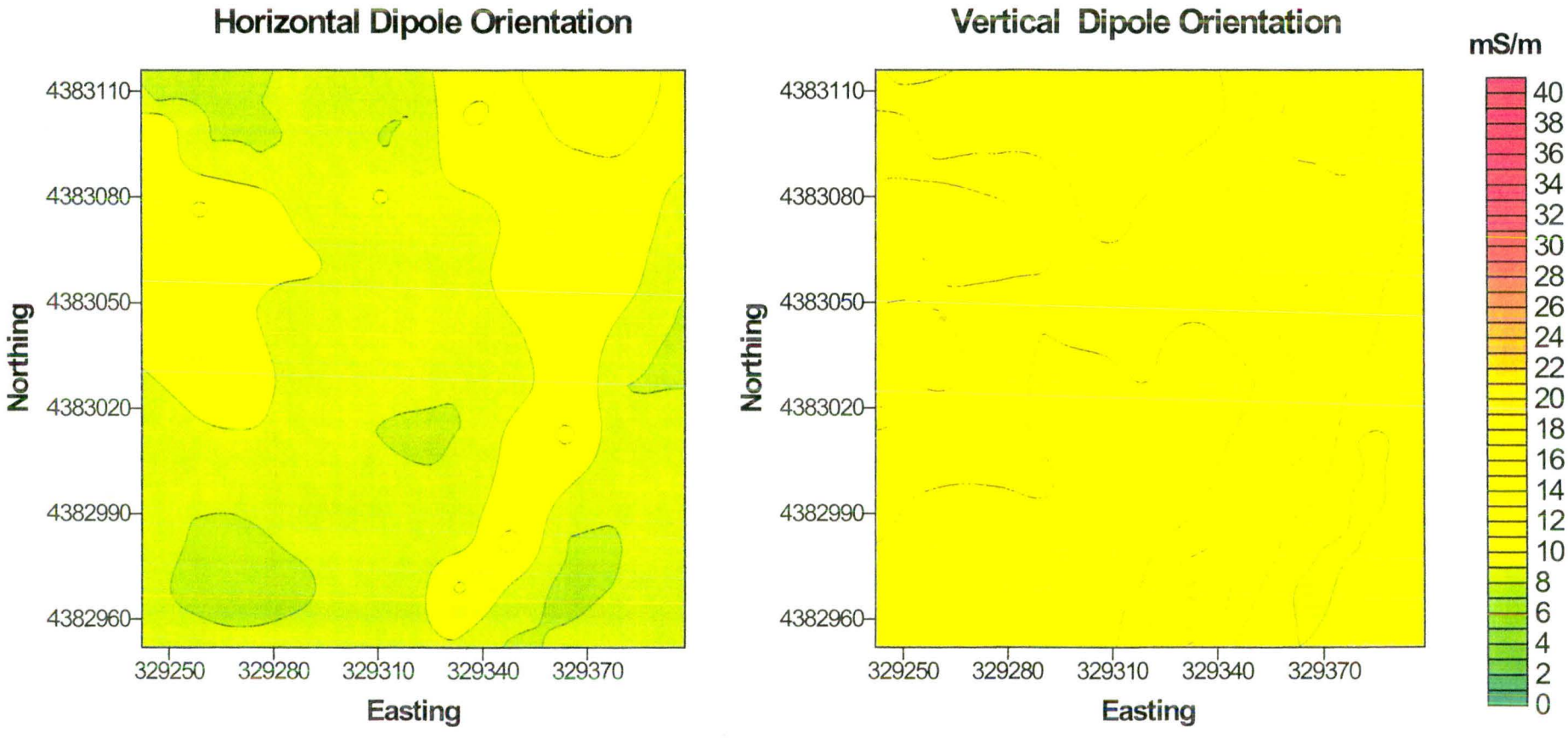


Figure 13

EMI SURVEY
AREA OF WARSAW LOAM, 0 TO 2 PERCENT SLOPES
GEM300 SENSOR

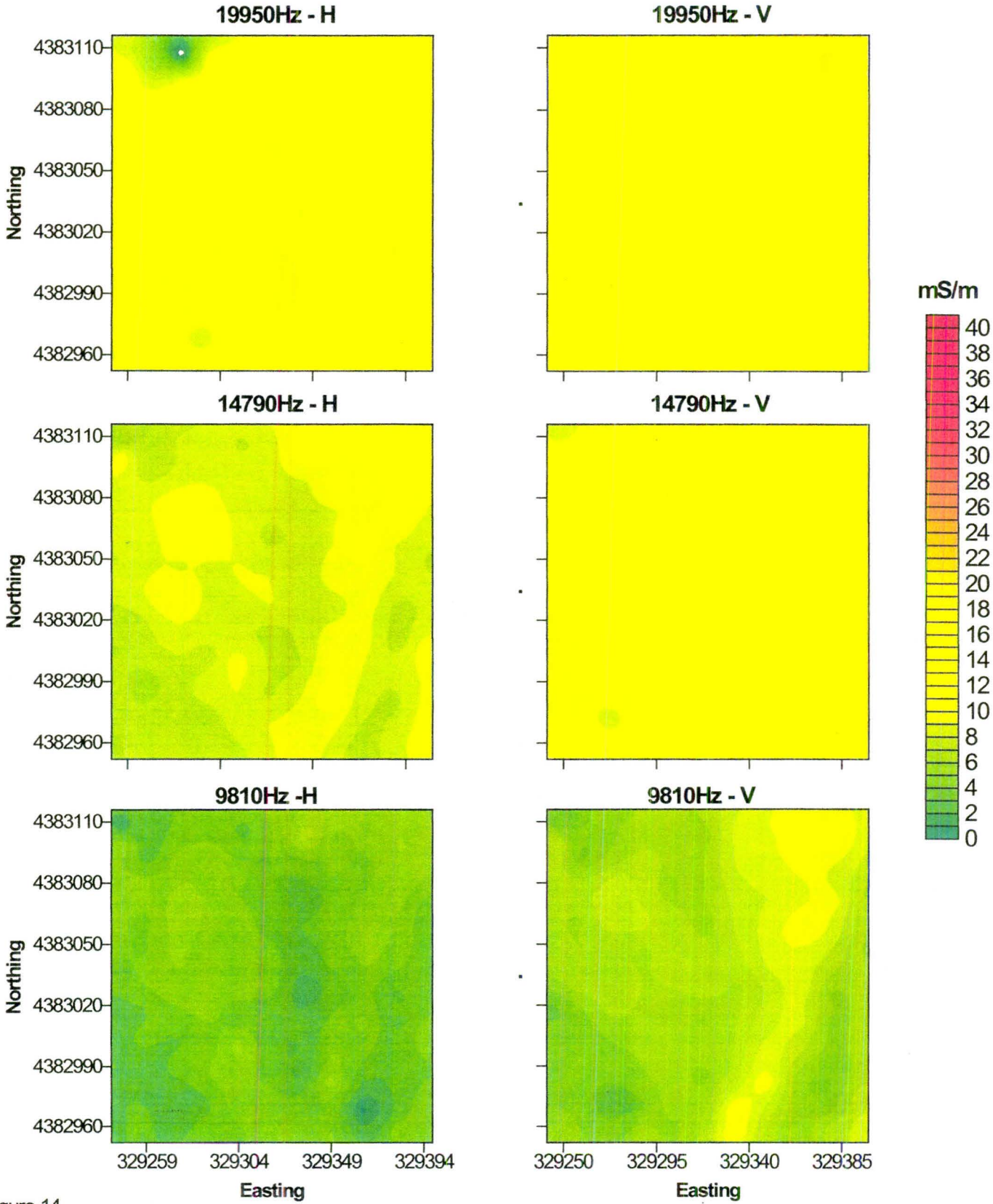


Figure 14

EMI SURVEY
AREA OF WARSAW LOAM, 0 TO 2 PERCENT SLOPES
DUALEM2/4 METERS

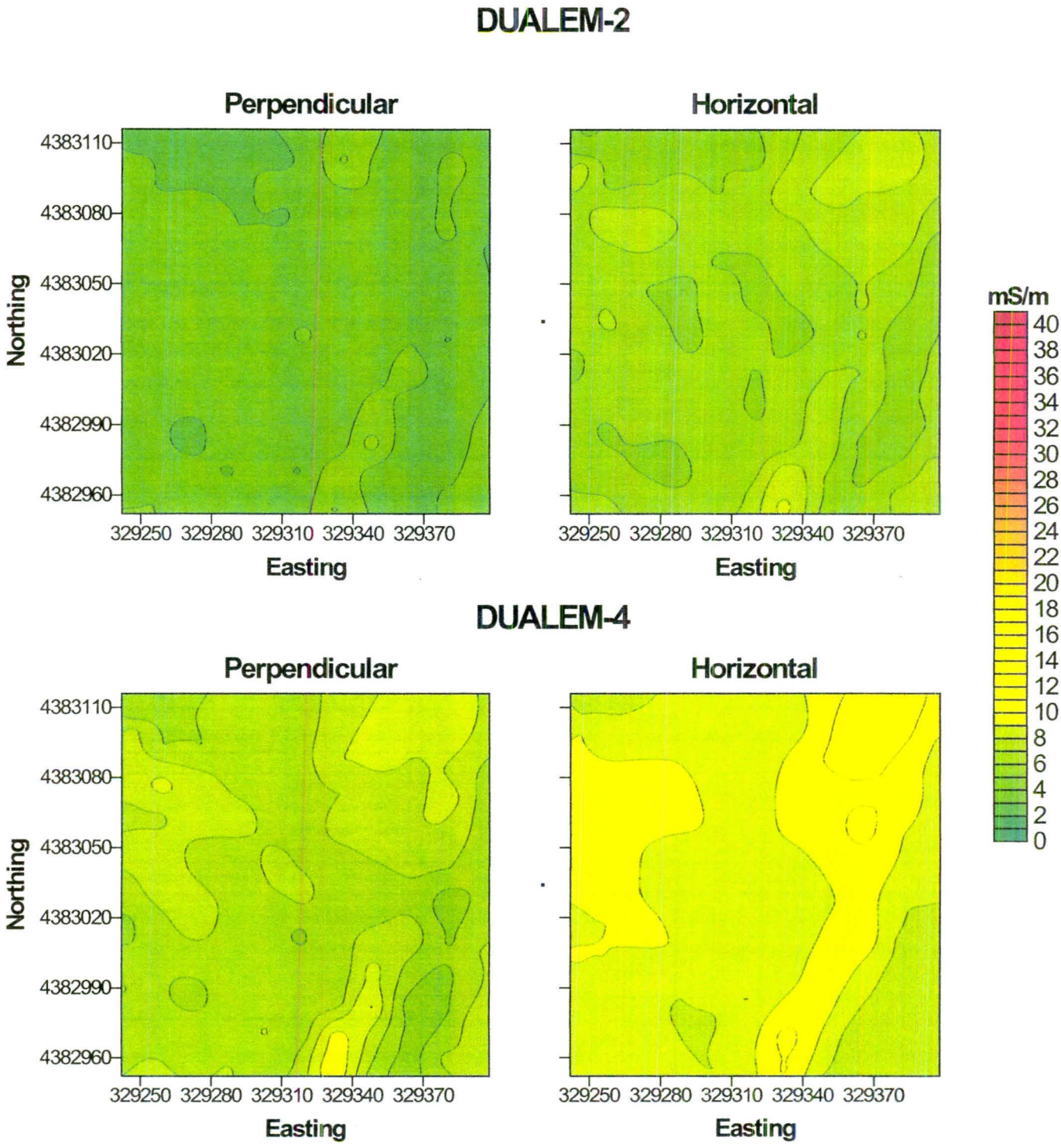
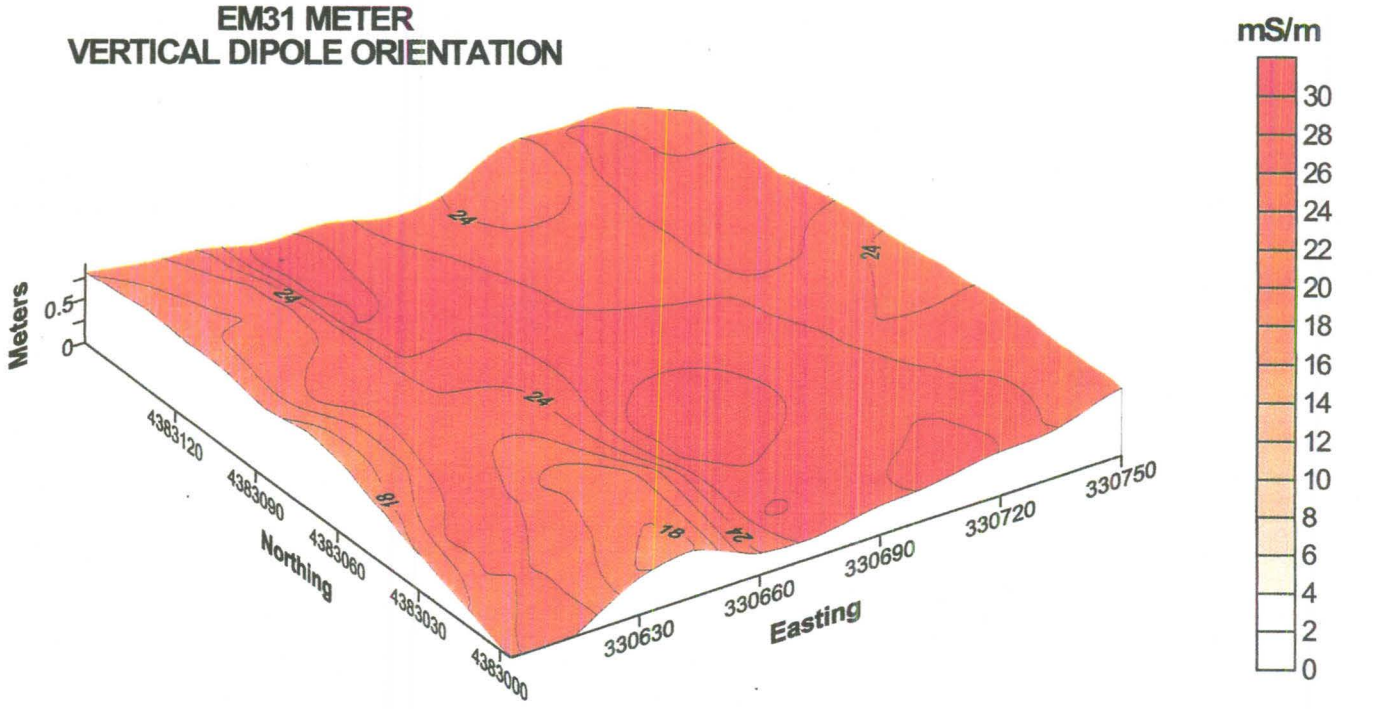
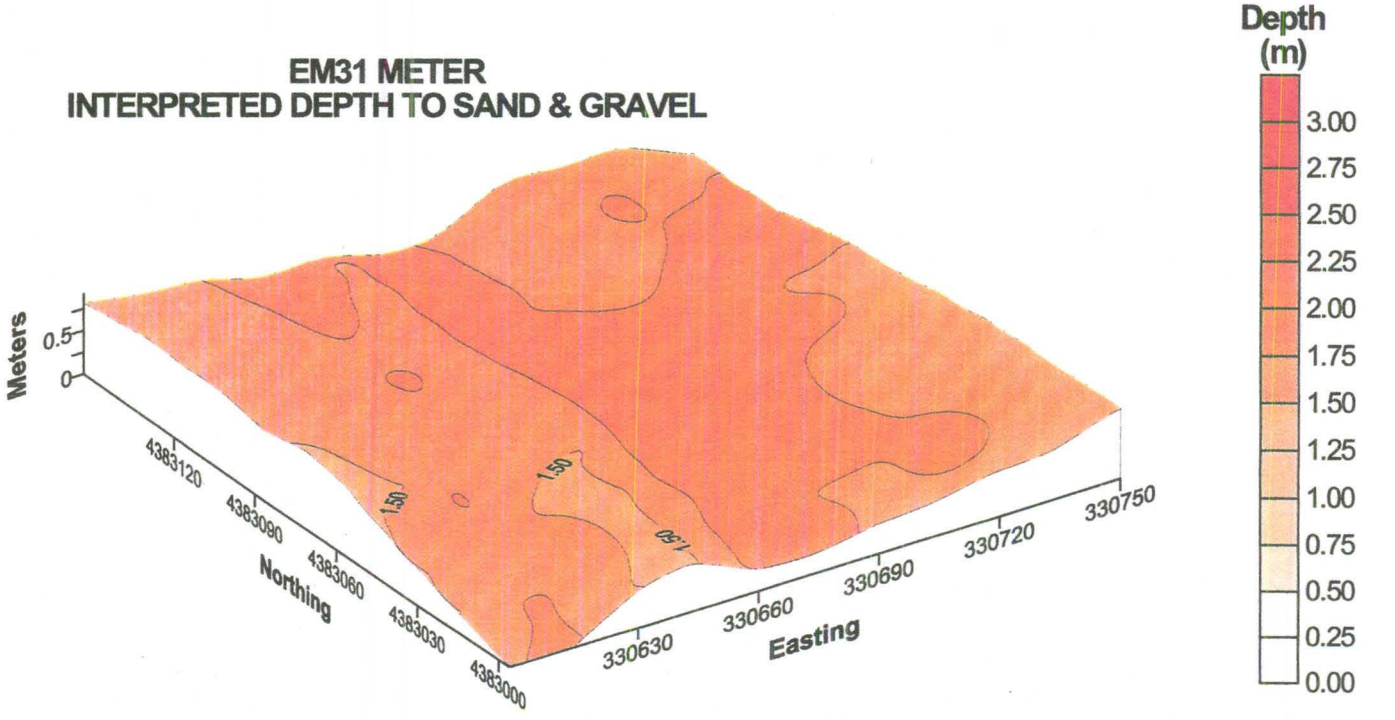


Figure 15

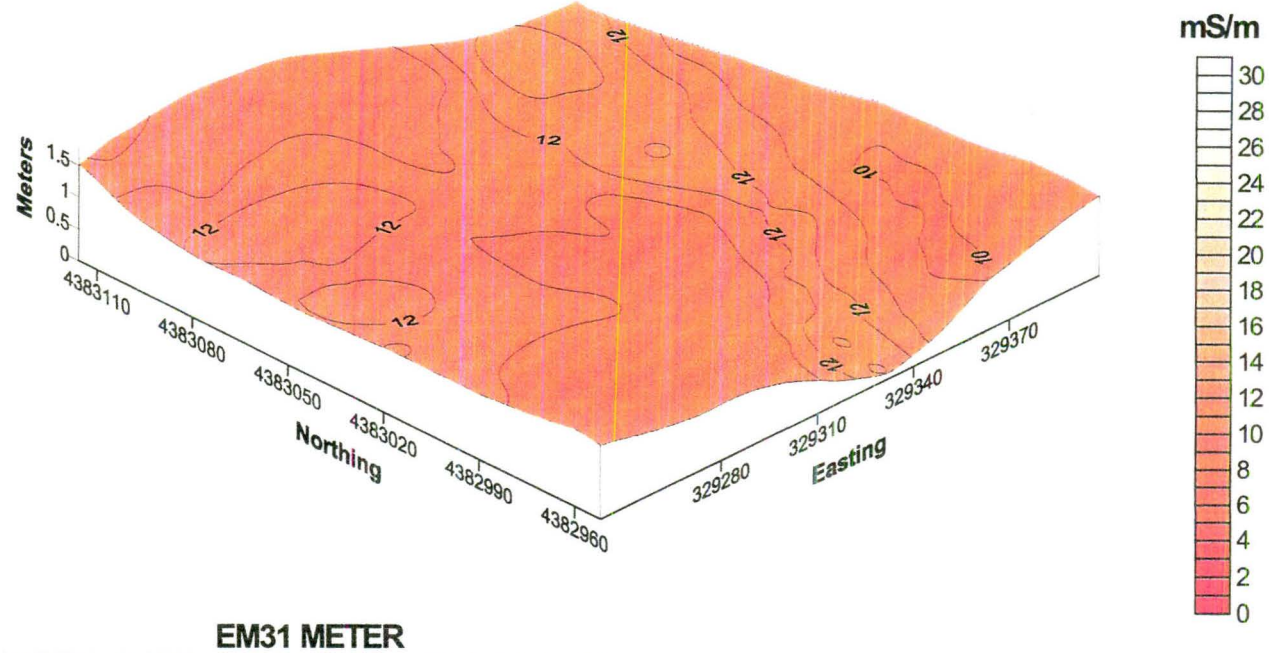
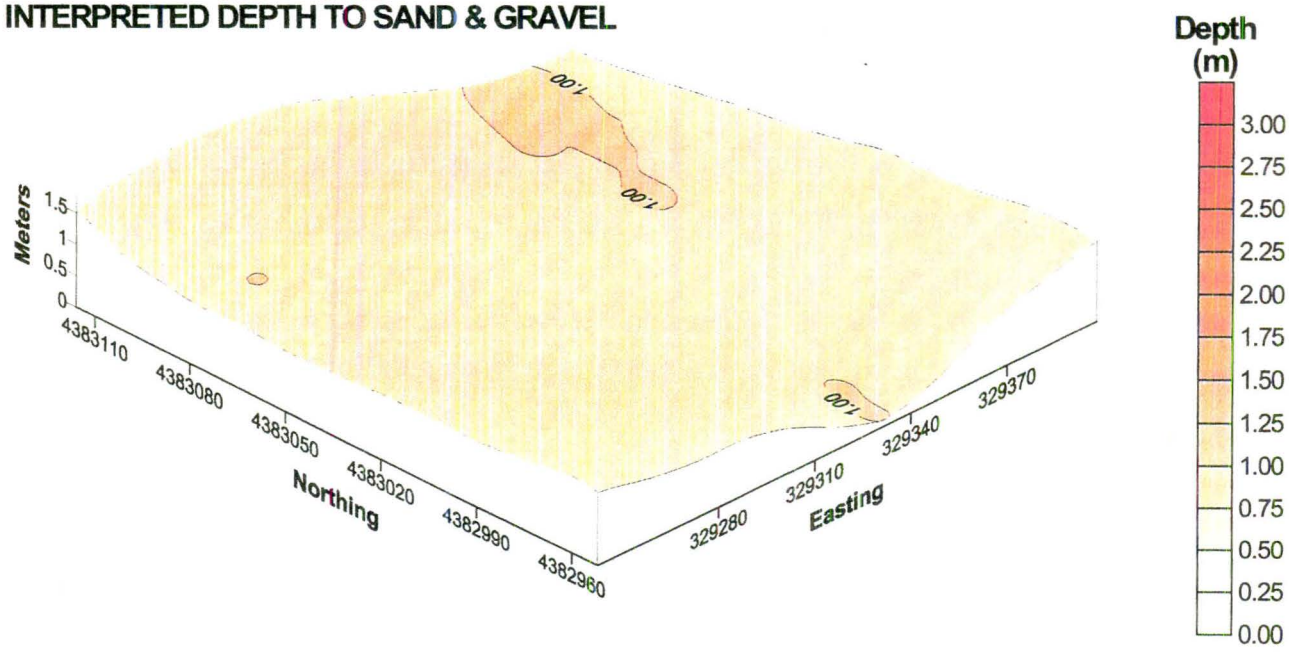
EMI SURVEY
AREA OF GENESEE SILT LOAM, OCCASIONALLY FLOODED
APPARENT CONDUCTIVITY & INTERPRETED DEPTH TO SAND & GRAVEL





EMI SURVEY
AREA OF WARSAW AND ELDEAN SOILS
APPARENT CONDUCTIVITY & INTERPRETED DEPTH TO SAND & GRAVEL

EM31 METER
VERTICAL DIPOLE ORIENTATION



EM31 METER
INTERPRETED DEPTH TO SAND & GRAVEL