United States Department of Agriculture	**Natural Resources Conservation Service**	**5 Radnor Corporate Center, Suite 200 Radnor, PA 19087-4585**

Subject: Geophysical Assistance **Date:** 4 September 1998

To: Nicholas Pearson
State Conservationist
USDA - NRCS
5301 Longley Lane
Building F, Suite 201
Reno, Nevada 89511

Purpose:
To provide electromagnetic induction (EMI) and ground-penetrating radar (GPR) field assistance.

Participants:
Don Breazeale, Extension Educator, Pershing County, Lovelock, NV
Joe Chiaretti, Soil Scientist, USDA-NRCS, Reno, NV
Rodney Dahl, Resource Specialist, USDA-NRCS, Fallon, NV
Jay Davison, Area Specialist, Nevada Cooperative Extension, Fallon, NV
William Dollarhide, State Soil Scientist/MLRA Office Leader, USDA-NRCS, Reno, NV
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Gail Munk, Nevada Biological Services, Lovelock, NV
Steve Herriman, Resource Soil Scientist, NRCS, Fallon, NV
Terri Pereira, Resource Conservation, Lahontan Conservation District, Fallon, NV
Tom McKay, Soil Scientist, Reno, NV

Activities:
All field activities were completed during the period of 17 to 21 August 1998.

Equipment:
The electromagnetic induction meter used was the EM38, manufactured by Geonics Limited*. This meter is portable and requires only one person to operate. Principles of operation have been described by McNeill (1986). No ground contact is required with this meter. This meter provides limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. The EM38 meter operates at a frequency of 14,600 Hz. It has theoretical observation depths of about 0.75 and 1.5 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

The radar unit used 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 models 5103 (400 mHz) and 5106 (200 mHz) antennas were used in this study. The system was powered by a 12-VDC battery. The use and

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

operation of GPR have been discussed by Morey (1974), Doolittle (1987), and Daniels and others (1988).

The position of many observation points was obtained with a Rockwell Precision Lightweight GPS Receiver (PLGR)*. The receiver was operated in the continuous mode using an external power source (portable 9 volt battery). The Universal Transverse Mercator (UTM) coordinate system was used.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,* 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.

Results:

1. In the Fallon-Fernley area, ground-penetrating radar was found to be an unsuitable geophysical tool for deep and very deep soil investigations in alluvial soils that formed on flood plains and low terraces. High rates of signal attenuation limited observation depths to less than 1.0 m in areas of Sagouspe loamy sand and less than 0.6 m in areas of East Fork clay loam. Principal factors restricting observation depths were the concentrations of soluble salts and bases, and clay content and mineralogy (smectitic). While concentrations of soluble salts and clays were low, they were sufficient to limit the use of GPR for soil investigations

2. Electromagnetic induction appears to be an effective tool for mapping saline soils. The EM38 meter appears to be suitable for assessing salinity phases and map unit composition. Although sampling was limited, an incipient predictive equation for medium textured soils has been developed. This equation can be used to relate EMI measurements directly to soil salinity classes or levels. Further sampling is encouraged to improve the accuracy of this and other equations (based on textural family and moisture content).

3. Steve Herriman received training on the use and operation of the EM38 meter. An EM38 meter (serial number 8906008) has been lent to Steve for use and evaluation. The use of this meter by other interested personnel is encouraged.

4. Steve Herriman has an obsolete version of the Surfer software program. This program can be used to create detailed two- and three-dimensional computer simulations of data collected with EMI, GPS and other methods. This software can be upgraded for nominal fee (@ $139).

5. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

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

With kind regards,

James A. Doolittle
Research Soil Scientist

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cc:
J. Culver, Director, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
J. Kimble, Supervisory Soil Scientist, USDA- NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
W. Dollarhide, State Soil Scientist/MLRA Office Leader, USDA-NRCS, Reno, NV
S. Herriman, Soil Scientist, USDA-NRCS, Agricultural Service Center, 111 Sheckler Road, Fallon, NV 89406

1. Ground-penetrating Radar

A study was conducted to evaluate the potential of using GPR to detect diagnostic soil horizons and map water table depths. The site was located along the Carson River near the Lahontan Reservoir in western part of the survey area. Radar traverses were conducted in areas that had been mapped as East Fork clay loam and Sagouspe loamy sand (Dollarhide, 1975). East Fork soil is a member of the fine-loamy, mixed, mesic Fluvaquentic Haploxerolls family. This very deep, somewhat poorly drained soil formed in mixed alluvium on flood plains and low stream terraces. Sagouspe soil is a member of the sandy, mixed, mesic Aquic Xerofluvents. This very deep, somewhat poorly drained soils formed in mixed alluvium on low stream terraces and flood plains.

Field Procedures:
Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer, water table) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (d), two-way pulse travel time (t), and velocity of propagation (v) are described in the following equation (Morey, 1974):

$$v = 2d/t$$

The velocity of propagation is principally affected by the dielectric permittivity (e) of the profiled earthen material(s) according to the equation:

$$e = (c/v)^2$$

Where c is the velocity of propagation in a vacuum (0.3 m/nanosecond). The amount and physical state of water (temperature dependent) have the greatest effect on the dielectric permittivity of earthen materials.

Calibration trials were conducted at each site. The purposes of these trials were to determine the velocity of propagation through the soil materials, establish crude depth scales, and optimize control and recording settings. At the "East Fork" site, a shovel blade was buried at a depth of 0.40 m (16 inches). The depth to this buried feature was used to estimate the velocity of propagation through the upper soil horizons. Based on the round-trip travel time to this reflector, the velocity of propagation through the upper part of the soil was estimated to be 0.0827 m/ns with the 200 mHz antenna. The dielectric permittivity was estimated to be 13.13. Observation depths were restricted by the rapid attenuation of the radar pulse in the upper part of the soil profile. In this area of East Fork soil, the maximum observation depth was only about 0.6 m.

At the "Sagouspe" site, a shovel blade was buried at a depth of 0.36 m (14 inches). Based on the round-trip travel time to the buried shovel blade, the velocity of propagation through the upper part of the soil was estimated to be 0.0862 m/ns with the 200 mHz antenna. The dielectric permittivity was estimated to be 12.11. Observation depths were restricted by rapid rates of signal attenuation. In this area of Sagouspe soil, the maximum observation depth was about 0.97 m.

Several horizons present in the upper part of the soil profile were interpretable with both the 200 and 400 mHz antennas. In general, radar reflections of soil features were interpretable at shallow (0 to 20 inches) to moderately deep (20 to 40 inches) soil depths. Below these depths radar reflections were weak, disontinous, and uninterpretable with both the 400 and 200 mHz antennas. Using a lower frequency antenna (80, 100, 120 mHz) could extend these observation depths slightly. Signal processing techniques used in the field did not increase the observation depth or interpretability of the radar profiles. Ground-penetrating radar is considered an inappropriate tool for soil or water table investigations in these alluvial soils. The use of GPR for soil investigations on upland soils may be more appropriate and should be explored.

2. Electromagnetic Induction

Background

Electromagnetic induction is a noninvasive geophysical tool that has been used in high intensity surveys, salinity evaluations, and for detailed site assessments. Electromagnetic induction uses electromagnetic energy to measure the bulk soil electrical conductivity of soil below the transmitter and receiver coils. This apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983).

Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the types and concentration of ions in solution, the amount and types of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980). Apparent conductivity is principally affected by changes in the electrolyte concentration of the soil water and the soil water content (Johnston, 1997). However, at low soil moisture contents, EMI is less sensitive to changes in soil-water content. At high soil moisture contents, EMI is more sensitive to changes in soil-water content (Hanson, 1997). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction methods map spatial variations in apparent electrical conductivity. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity have been used to infer changes in soils and soil properties. Electromagnetic induction has been extensively used by soil scientists to identify, map, and monitor soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982 and 1990; Rhoades and Corwin, 1981; Rhoades et al., 1989a and 1989b; Slavich and Peterson, 1990; and Wollenhaupt et al., 1986). This technology has also been used to assess and map 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), regional differences in soil mineralogy (Doolittle et al., 1995), and edaphic properties important to forest site productivity (McBride et al., 1990). In addition, electromagnetic induction has been used to measure soil water contents (Kachanoski et al., 1988), cation exchange capacity (McBride et al., 1990), and leaching rates of solutes (Jaynes et al., 1995b).

Apparent conductivity can be used to assess the within-field variability of soils and soil properties. Apparent conductivity can be associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993, Doolittle et al., 1996). Electromagnetic induction integrates the bulk physical and chemical properties of soils into a single value for a defined observation depth. The inherent physical and chemical properties of each soil, as well as temporal variations in soil water and temperature, establish a unique and characteristic range of apparent conductivity values. This range can be influenced by differences in use or management practices (Sudduth and Kitchen, 1993, Sudduth et al., 1995).

Electromagnetic induction is ideally suited to high intensity soil surveys. Apparent conductivity has been used as a surrogate for soil and soil properties. Spatial patterns of apparent conductivity have been used to prepare soil attribute maps (Doolittle et al., 1996). Results from EMI surveys have been used to map soils and soil properties, guide sampling, and facilitate site assessments. Recently, EMI has been used in the Midwest to map soil attributes for precision farming (Jaynes, 1995; Jaynes et al., 1995a; Sudduth et al., 1995). This technique is relatively fast, inexpensive, and provides the comprehensive coverage needed for precision farming.

Generally, the use of EMI has been most successful in areas where soils and subsurface properties are reasonably homogeneous. This technique has been most effective in areas where the effects of one property (e.g., clay, water, or salt content) dominate over the other properties. In these areas, variations in EMI response can be directly related to changes in the dominant property (Cook et al., 1989). In areas of saline soils, it has been estimated that 65 percent of the variance in apparent conductivity can be explained by changes in salinity alone (Williams and Baker, 1982).

Electromagnetic induction is not suitable for use in all soils. The use of EMI is often inappropriate in areas having varied soils with complex and highly variable properties and spatial distributions. In these areas, relationships are weakened and results are more ambiguous. Predictive models constructed from EMI data are more accurate in areas having a minimal sequence of dissimilar horizontal layers. The predictive accuracy of EMI data decreases with increasing numbers of subsurface layers. In addition, an EMI meter must be sensitive to the differences existing between soil layers. In other words, a meter must be able to detect differences in electromagnetic properties between the layers.

Some dissimilar materials have similar values of apparent conductivity and therefore produce non-unique (equivalent) solutions. This occurs where differences in apparent conductivity caused by changes in one property (e.g., layer thickness; soluble salt, clay, or water contents) are offset by variations in another property. Many soils have subsurface layers that vary in thickness and in chemical and physical properties, but have closely similar conductivity values. Where these dissimilar layers occur in the same landscape, they can produce equivalent solutions or measurements. Equivalent solutions are caused by the simultaneous change in two or more properties (e.g., layer thickness; soluble salt, clay or water contents). Equivalent solutions obscured results and limited the effectiveness of EMI. In studies conducted by Jaynes and others (1995, 1995b) in Iowa, coexistent changes in the moisture, clay, and carbonate contents weakened relationships between apparent conductivity and moisture stress or drainage classes.

EMI surveys in the Fallon-Fernley Area

Multiple fields and soil map units were traversed or gridded with EMI during the week of August 17 to 21, 1998. Traverse and grid surveys were conducted in delineated areas of selected map units. The names of these map units are shown in Table 1. Table 2 contains the taxonomic classification of the soils sampled. Surveys were conducted in areas that had been mapped with sandy to fine textural classes and non-saline to strongly saline salinity classes. During field work, thirteen sites were sampled for determination of soil salinity. Measurements of soil salinity are compare with measurements apparent conductivity taken at the same observation point. The strength of the relationships between soil salinity and apparent conductivity will be used to assess the suitability of EMI techniques for salinity appraisals within Fallon-Fernley soil survey area.

Table 1

Soil Map Units traversed with EMI techniques

Symbol	Map Unit Name
Ar	Appian-Tipperary complex
Ca	Carcity clay
Ea	East Fork clay loam
Hh	Humboldt silt loam, moderately coarse substratum, strongly saline
Ht	Humboldt silty clay, slightly saline
Pa	Parran silty clay
Ra	Ragtown sandy clay loam
Sa	Sagouspe loamy sand
Sb	Sagouspe loamy sand, saline
So	Sonoma silt loam, slightly saline-alkaline
Sn	Stillwater clay loam, strongly saline

Table 2

Taxonomic Classification

Soil	Classification
Appian	Fine-loamy over sandy or sandy-skeletal, mixed, mesic Typic Natrargids
Carcity	Clayey over sandy or sandy-skeletal, smectitic, mesic Cumulic Endoaquolls
East Fork	Fine-loamy, mixed, mesic Fluvaquentic Haploxerolls
Fernley	Mixed, mesic Aquic Xeropsamments
Humboldt	Fine, smectitic, calcareous, mesic Fluvaquentic Endoaquolls
Parran	Fine, smectitic, mesic Typic Aquisalids
Ragtown	Fine, smectitic, calcareous, mesic Typic Torriorthents
Sagouspe	Sandy, mixed, mesic Aquic Xerofluvents
Sonoma	Fine-silty, mixed, calcareous, mesic Aeric Fluvaquents
Stillwater	Fine, smectitic, calcareous, mesic Fluvaquentic Endoaquolls
Tipperary	Mixed, mesic Typic Torripsamments

Basic statistics for the sampled map units are presented in Table 3. The number of observations varied with each map unit and surveying methods (grid or traverse). Each soil and soil map unit has a distinct range of apparent conductivity. This range may vary slightly because of the properties of a given soil, variations in map unit composition, management or moisture contents. In a given soil survey area, this range can be used as distinguishing characteristic of soils and soil map units. For soils, the unique combination of chemical and physical properties, and the arrangements of soil horizons, produce a distinct and identifiable range in apparent conductivity. For map units, apparent conductivity will vary with changes in map unit composition and phases. In general, coarser textured soils have lower conductivity than finer textured soils. Saline phases of a soil have higher conductivity than non-saline phases.

Table 3
Basic Statistics
EMI Transects
Fallon-Fernley Soil Survey Area

(All values are in mS/m)

					Quartiles		
Map Unit	**Meter**	**Orientation**	**Minimum**	**Maximum**	**1st**	**3rd**	**Average**
East Fork clay loam	EM38	Horizontal	11.0	88.0	29.5	43.5	37.8
(N = 54)	EM38	Vertical	9.0	92.0	37.0	49.8	43.9
Parran silty clay	EM38	Horizontal	37.0	161.0	68.5	122.2	98.6
(N = 15)	EM38	Vertical	43.0	172.0	87.2	123.0	109.7
Ragtown sandy clay loam	EM38	Horizontal	48.0	79.0	49.0	56.0	57.0
(N = 54)	EM38	Vertical	63.0	118.0	66. 0	77.0	76.1
Sagouspe loamy sand	EM38	Horizontal	11.0	47.0	15.8	37.2	27.6
(N = 13)	EM38	Vertical	17.0	70.0	20.2	48.6	41.5
Sagouspe loamy sand, saline	EM38	Horizontal	23.0	35.0	23.2	68.5	51.2
(N = 5)	EM38	Vertical	35.0	85.0	64.4	38.5	76.0
Stillwater clay loam, saline	EM38	Horizontal	45.0	183.0	76.0	134.0	107.9
(N = 16)	EM38	Vertical	49.0	183.0	86.0	160.0	117.3
Carcity clay	EM38	Horizontal	42.0	72.0	54.0	54.0	60.0
(N = 6)	EM38	Vertical	52.0	79.0	64.0	74.0	66.6
Sagouspe loamy sand	EM38	Horizontal	7.0	16.0	8.0	12.0	10.4
(N = 32)	EM38	Vertical	5.0	19.0	8.0	15.0	12.1
Sonoma silt loam	EM38	Horizontal	40.0	106.0	56.8	74.2	66.4
(N = 71)	EM38	Vertical	57.0	133.0	74.0	89.0	83.2
Humboldt silt loam, saline	EM38	Horizontal	61.0	178.0	96.0	129.8	120.1
(N = 57)	EM38	Vertical	79.0	178.0	130.0	165.8	146.9

Systematic EMI Surveys
The purpose of systematic EMI surveys is to identify the distribution and extent of soil and salinity patterns and to assess the relative level of salinity or other soil properties within these patterns.

1. East Fork Clay Loam
A rectangular grid was established across an area (about 2.3 acres) of East Fork clay loam. The grid interval was 50 feet. At each grid intersection a survey flag was inserted in the ground. This procedure provided 54 observation sites. At each observation point, measurements were taken with the EM38 meter, placed on the ground surface, in both the horizontal and vertical dipole orientations.

Figure 1 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (left-hand plot) and vertical (right-hand plot) dipole orientations. In Figure 1, the left-hand plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The right-hand plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 10 mS/m. Areas of high conductivity (> 50.0 mS/m) are believed to represent included areas of very slightly saline soils. In the southeast corner of each plot, areas of low conductivity (< 30.0 mS/m) are believed to represent a *stringer* of coarser textured Fernley soils.

2. Sagouspe Loamy sand
The study site was located in a field of alfalfa. Random traverses were conducted across the site. At a paced interval of about 50 feet along each traverse line, measurements were obtained with the EM38 meter. The coordinates of these observation points were obtained with a Rockwell Precision Lightweight GPS receiver. At each observation point, measurements were taken with the EM38 meter in both the horizontal and vertical dipole orientations. For each measurement, the meter was placed on the ground surface.

Figure 2 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (upper plot) and vertical (lower plot) dipole orientations. In Figure 2, the upper plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The lower plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 4 mS/m.

Compare with the delineated area of East Fork clay loam (Figure 1), the mapped area of Sagouspe loamy sand has markedly lower apparent conductivity. For East Fork soils, the apparent conductivity of the upper 30 inches (measured with the EM38 meter in the horizontal dipole orientation) averaged 37.8 mS/m. One-half of the observations had an apparent conductivity between 29.5 and 43.5 mS/m. The apparent conductivity of the upper 60 inches (measured with the EM38 meter in the vertical dipole orientation) averaged 43.9 mS/m. One-half of the observations had an apparent conductivity between 37.0 and 49.8 mS/m. The increased conductivity with depth was attributed to greater moisture and salt contents at greater soil depths.

In contrast, for Sagouspe soils, the apparent conductivity of the upper 30 inches (measured with the EM38 meter in the horizontal dipole orientation) averaged 10.4 mS/m. One-half of the observations had an apparent conductivity between 8.0 and 12.0 mS/m. The apparent conductivity of the upper 60 inches (measured with the EM38 meter in the vertical dipole orientation) averaged 12.1 mS/m. One-half of the observations had an apparent conductivity between 8.0 and 15.0 mS/m. As with East Fork soils, the increased conductivity with depth observed in this area of Sagouspe loamy sand was attributed to increased moisture and salt contents with increasing soil depths.

3. Lovelock Sub-Surface Drip Irrigation Demonstration Site
The demonstration site was located in an alfalfa field. The site was in mapped delineations of Sonoma silt loam, drained, and Sonoma silt loam, slightly saline - alkaline. Four traverses were conducted across the site. At a paced interval of about 50 feet along each traverse line, measurements were obtained with the EM38 meter. The coordinates of these observation points were obtained with a Rockwell Precision Lightweight GPS receiver. At each observation point, measurements were taken with the EM38 meter in both the horizontal and vertical dipole orientations. For each measurement, the meter was placed on the ground surface.

Figure 3 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (upper plot) and vertical (lower plot) dipole orientations. In Figure 2, the upper plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The lower plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 5 mS/m. In Figure 3, lines have been drawn separating the management plots. The six, rectangular plots have dripperlines installed at different depths (either 12 or 18 inches) and have different irrigation regimes (75, 100, and 125 percent of evapotranspiration). These plots are sub-irrigated. The eastern most triangular plot is flood-irrigated and is not a part of the demonstration project. The triangular plot has noticeably higher values of apparent conductivity. The higher values of apparent conductivity are believed to result from increased concentrations of soluble salts in the soil profile. This plot is located at the end of flooding runs, and is believed to be inadequately flooded. As a consequence, soluble salts are not removed from the soil profile.

4. Humboldt Soils
The site was located in a field of alfalfa. The site was in mapped delineations of Humboldt silty clay, slightly saline and Humboldt silt loam, moderately coarse substrata, strongly saline. Four traverses were conducted across the site. At a paced interval of about 50 feet along each traverse line, measurements were obtained with the EM38 meter.. The coordinates of these observation points were obtained with a Rockwell Precision Lightweight GPS receiver. At each observation point, measurements were taken with the EM38 meter in both the horizontal and vertical dipole orientations. For each measurement, the meter was placed on the ground surface.

Figure 4 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (upper plot) and vertical (lower plot) dipole orientations. In Figure 4, the upper plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The lower plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 10 mS/m.

Plant growth was noticeably affected by salts in the eastern (right-hand) portion of the survey area. Observed values of apparent conductivity were highest in this area. In other areas, the alfalfa was less stunted though irregular growth patterns testified to the influence of salts. Patterns of apparent conductivity in these portions of the survey area were generally lower and more intricate.

These interpretative plots show how EMI can be used to help assess variations in soils and soil properties, evaluate "modal" soil conditions, locate and characterize soil boundaries, and identify sites for more detailed observations. Computer simulations of EMI data offer alternative methods of displaying soil information. These simulations can help describe the magnitude and rates of change in soils and/or soil properties within selected map units.

Interpreting Soil Salinity from EMI Measurements

Electromagnetic induction methods are used to rapidly identify and map soil salinity. To predict soil salinity, EMI methods require a minimum amount of soil sampling and analysis. Predictive models are often sufficiently accurate to establish trends in soil salinity. However, because of the non-uniform response distribution with depth, the conversion of EMI measurements into meaningful measures of soil salinity has been difficult (Johnston et al., 1997).

A goal of this investigation has been to relate apparent conductivity (EC_a) measured with the EM38 meter directly to the electrical conductivity of the saturated paste extracts (Ec_e) using simple linear regression equations. This approach has been used by several investigators (Wollenhaupt et al., 1986; McKenzie et al., 1989; Johnston et al., 1996).

The Fallon-Fernley area is considered a less than favorable environment for the use of EMI. The surveyed sites included a wide range in soils, soil texture, salinity level, and water contents. The examined soils formed principally in alluvium on flood plains, deltas, and paleo-terraces. The predecessor of the Carson River deposited thick beds of alluvial deposits in Churchill County. These alluvial deposits often have complex and abrupt, vertical and horizontal changes in texture, and are derived from mixed rock sources.

Soil materials are highly stratified and vary in clay, soluble salt, and moisture contents. Soil horizons and subsurface layers are often segmented, and are varied in arrangement and thickness. Soils have varying concentrations of soluble salts and calcium carbonates. The number, composition, arrangement, and lack of continuity of these layers weakened predictive relationships and fostered vague or inconclusive interpretations. In most soils, diversion, drainage, and irrigation cause the water table and soil moisture content to fluctuate. In the Fallon-Fernley area simultaneous changes in clay, moisture, and soluble salt contents can produce equivalent solutions that obscured interpretations and results.

At each site, measurements were made with the EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations. At thirteen observation sites, soil samples were taken at 0 to 10 and 10 to 20 inches' depth intervals. Only one core sample was collected at each site. As the EM38 meter measures a much larger volume of soil than that represented in the core sample, slight discrepancies between the measurement exist. As soil temperatures were not recorded, no corrections were made in the EMI data.

Soil samples were grouped into textural, salinity, and depth categories. Soil texture has an affect on the relationship between apparent conductivity and saturated paste extract conductivity (Halvorson et al., 1977). The three broad groups of textural classes used were sandy, loamy, and clayey. The salinity classes were: non-saline (<2 mmhos/cm), very slightly saline (2 to < 4 mmhos/cm), slightly saline (4 to < 8 mmhos/cm), and moderately saline (8 to < 16 mmhos/cm).

Results were initially disappointing. Relationships between apparent conductivity with the electrical conductivity of the saturated extract were weaken by the small sample population as well as the large variations in soils and soil properties. Based on all observations (thirteen sample sites), the strongest relationship was between EC_a measured with the EM38 meter in the vertical dipole orientation and EC_e. However, the coefficient of determination (r^2) was very low (0.2387) and indicated no or a very weak relationship between these two factors.

Next, the data set was grouped according to soil depth. The two depths sampled were 0 to 10 inches (13 observations) and 10 to 20 inches (12 observations). For the shallower depth interval, the strongest relationship was between EC_a measured with the EM38 meter in the horizontal dipole orientation and EC_e. The coefficient of determination (r^2) was extremely low (0.2283) and indicated no to a very weak relationship between these two factors. For the deeper depth interval, the strongest relationship was between EC_a measured with the EM38 meter in the vertical dipole orientation and EC_e. The coefficient of determination (r^2) was 0.4470 and indicated a weak, positive (correlation coefficient (r) = 0.669) relationship between these two components.

Next, the deeper (10 to 20 inches) data set was grouped according to soil textural classes (sandy, loamy, and clayey). Because of the small sample population (n = 2), no regression analysis could be performed on data grouped within the sandy textural class. For the medium textural class (5 observations), the strongest relationship was between EC_a measured with the EM38 meter in the vertical dipole orientation and EC_e. The coefficient of determination (r^2) was 0.6162 and indicated a moderate relationship between these two factors.

A comparison of salinity classes with EC_a resulted in stronger relationships. The salinity classes were assigned arbitrary values of: 0, non-saline; 1, very slightly saline: 2, slightly saline; and 3, moderately saline. The strongest relationship was between salinity class and EC_a measured with the EM38 meter in the vertical dipole orientation. The coefficient of determination (r^2) was 0.8028 and indicated a strong, positive (r = 0.896) relationship between these two components.

For the fine textural class (5 observations), the strongest relationship was between EC_a measured with the EM38 meter in the horizontal dipole orientation and EC_e. The coefficient of determination (r^2) was 0.7709 and indicated a moderate relationship between these two factors. The correlation coefficient was 0.878 and indicated a strong, positive relationship between these two components.

Though premature at this time, predictive equations can be developed. For medium textured soils, the highest correlation was found between salinity classes and data collected with the EM38 meter in the vertical dipole orientation. The coefficient of determination, r^2, between salinity class and apparent conductivity was 0.8028 (significant at the 0.05 level). Data collected with the EM38 meter in the vertical dipole orientation were used to develop a predictive regression equation:

$$SC = -1.8894 + (0.0384 * EM38V) \qquad [1]$$

Where "SC" is salinity class and "EM38V" is the apparent conductivity (mS/m) measured with the EM38 meter in the vertical dipole orientation. Based on this predictive equation, Table 4 has been developed. In Table 4, the electrical conductivity of the saturated extract is expressed in mmhos/cm; the apparent conductivity is expressed in mS/m and was measured with the EM38 meter in the vertical dipole orientation.

Table 4
Prediction of Saturation Extract Electrical Conductivity (EC_e) from EMI Measurements (EC_a) for Medium-Textured Soils

Salinity Class	Code	EC_e	EC_a
Non-Saline	0	<2	<53
Very Slightly Saline	1	2 to <4	53 to <106
Slightly Saline	2	4 to <8	106 to <210
Moderately Saline	3	8 to <16.	210 to < 418
Strongly Saline	4	>16	>418

With adequate sampling, the accuracy of equation [1} and the values appearing in Table 4 can be improved. Similar predictive equations and values can be developed for other soil textural classes.

Although the sample population was small several conclusions have emerged from this brief study. Results of this study confirm the feasibility of relating apparent conductivity measured with the EM38 meter directly to the electrical conductivity of the saturated paste extracts using simple linear regression equations. However, to assess salinity, soils should be grouped and evaluated by textural classes. The impact of varying soil moisture should also be assessed. In addition, relationships and predictive equations can be improved by using broad salinity classes rather than absolute values of EC_e.

References

Ammons, J. T., M. E. Timpson, and D. L. Newton. 1989. Application of aboveground electromagnetic conductivity meter to separate Natraqualfs and Ochraqualfs in Gibson County, Tennessee. Soil Survey Horizons 30(3):66-70.

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.

Cook, P. G., and G. R. Walker. 1992. Depth profiles of electrical conductivity from linear combinations of electromagnetic induction measurements. Soil Sci. Soc. Am. J. 56:1015-1022.

Corwin, D. L., and J. D. Rhoades. 1982. An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46:517-520.

Corwin, D. L., and J. D. Rhoades. 1990. Establishing soil electrical conductivity - depth relations from electromagnetic induction measurements. Communications in Soil Sci. Plant Anal. 21(11&12):861-901.

Daniels, D. J., D. J. Gunton, and H. F. Scott. 1988. Introduction to subsurface radar. IEE Proceedings 135:(F4) 278-320.

Dollarhide, W. E. 1975. Soil Survey of Fallon-Fernley Area, Nevada. USDA -Soil Conservation Service, University of Nevada Agricultural Experiment Station, and USDI - Bureau of Indian Affairs. Washington, DC. p. 112.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. pp. 11-32. In: Reybold, W. U. and G. W. Peterson (eds.) Soil Survey Techniques, Soil Science Society of America. Special Publication No. 20. p. 98

Doolittle, J., E. Ealy, G. Secrist, D. Rector, and M. Crouch. 1995. Reconnaissance soil mapping of a small watershed using EM and GPS techniques. Soil Survey Horizons 36:86-94.

Doolittle, J., R. Murphy, G. Parks, and J. Warner. 1996. Electromagnetic induction investigations of a soil delineation in Reno County, Kansas. Soil Survey Horizons 37:11-20.

Doolittle, J. A., K. A. Sudduth, N. R. Kitchen, and S. J. Indorante. 1994. Estimating depth to claypans using electromagnetic inductive methods. J. Soil and Water Conservation 49(6):552-555.

Greenhouse, J. P., and D. D. Slaine. 1983. The use of reconnaissance electromagnetic methods to map contaminant migration. Ground Water Monitoring Review 3(2):47-59.

Halvorson, A. D., J. D. Rhoades, and C. A. Reule. 1977. Soil salinity four-electrode conductivity relationships for soils of the Northern Great Plains. Soil Sci. Soc. Am. J. 41:961-971.

Hanson, B. R. 1997. Response of electromagnetic conductivity meter to soil salinity and soil-water content. Journal of Irrigation and Drainage Engineering 123:141-143.

Hoekstra, P., R. Lahti. J. Hild, R. Bates, and D. Phillips. 1992. Case histories of shallow time domain electromagnetics in environmental site assessments. Ground Water Monitoring Review. 12(4):110-117.

Jaynes, D. B. 1995. Electromagnetic induction as a mapping aid for precision farming. pp. 153-156. IN: Clean Water, Clean Environment, 21st Century: Team Agriculture. Working to Protect Water Resources. Kansas City, Missouri. 5 to 8 March 1995.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1993. Soil type and crop yield determination from ground conductivity surveys. 1993 International Meeting of American Society of Agricultural Engineers. Paper No. 933552. ASAE, St. Joseph, MI. 6 p.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1995a. Yield mapping by electromagnetic induction. pp. 383-394. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Site-Specific Management for Agricultural Systems. Minneapolis, Minnesota. March 27-30, 1994. American Society of Agronomy, Madison, Wisconsin.

Jaynes, D. B., J. M. Novak, T. B. Moorman, and C. A. Cambardella. 1995b. Estimating herbicide partition coefficients from electromagnetic induction measurements. J. Environmental Quality. 24:36-41.

Johnston, M. A., M. J. Savage, J. H. Moolman, and H. M. du Plessis. 1996. Calibration models for interpreting soil salinity measurements using an electromagnetic induction technique. S. African. J. Plant Soil 13:110-114.

Johnston, M. A., M. J. Savage, J. H. Moolman, and H. M. du Plessis. 1997. Evaluation of calibration methods for interpreting soil salinity from electromagnetic induction measurements. Soil Sci. Soc. Am. J., 61:1627-1633.

Kachanoski, R. G., E. G. Gregorich, and I. J. Van Wesenbeeck. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68:715-722.

McBride, R. A., A. M. Gordon, and S. C. Shrive. 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. Soil Sci. Soc. Am. J., 54:290-293.

McKenzie, R. C., W. Chomistek, and N. F. Clark. 1989. Conversion of electromagnetic inductance readings to saturated paste extract values in soils for different temperature, texture, and moisture conditions. Can. J. Soil Sci. 69:25-32.

Easting	Northing	Em38h	Em38v	Map unit
349106	4370818	37	43	Parran sic
349089	4370817	126	129	Parran sic
349072	4370814	70	88	Parran sic
349056	4370813	161	172	Parran sic
349038	4370812	89	119	Parran sic
349022	4370812	106	91	Parran sic
349006	4370812	121	121	Parran sic
348991	4370810	121	150	Parran sic
348974	4370810	78	102	Parran sic
348958	4370809	137	140	Parran sic
348941	4370809	82	111	Parran sic
348924	4370808	76	85	Parran sic
348908	4370807	157	143	Parran sic
348889	4370812	54	64	Parran sic
349066	4370808	64	88	Parran sic
348957	4370783	66	82	Ragtown scl
348939	4370783	48	63	Ragtown scl
348924	4370779	79	118	Ragtown scl
348909	4370773	48	65	Ragtown scl
348897	4370766	56	70	Ragtown scl
348881	4370762	56	74	Ragtown scl
348862	4370758	55	77	Ragtown scl
348844	4370751	56	67	Ragtown scl
348829	4370745	56	77	Ragtown scl
348813	4370741	50	68	Ragtown scl
366642	4357537	171	180	Stillwater cl, saline
346313	4362495	163	179	Stillwater cl, saline
346309	4362478	134	167	Stillwater cl, saline
346316	4362464	83	108	Stillwater cl, saline
346315	4362446	45	49	Stillwater cl, saline
346317	4362429	105	102	Stillwater cl, saline
346331	4362417	106	120	Stillwater cl, saline
346332	4362401	99	96	Stillwater cl, saline
346332	4362383	90	95	Stillwater cl, saline
346333	4362365	76	75	Stillwater cl, saline
346325	4362345	65	85	Stillwater cl, saline
346319	4362327	100	95	Stillwater cl, saline
346320	4362308	64	86	Stillwater cl, saline
346320	4362293	158	160	Stillwater cl, saline
346320	4362259	183	183	Stillwater cl, saline
346320	4362243	84	97	Stillwater cl, saline
346238	4361750	65	74	Carcity c
346238	4361769	64	79	Carcity c
346239	4361786	59	68	Carcity c
346240	4361802	62	74	Carcity c
346240	4361817	54	54	Carcity c
346240	4361833	62	72	Carcity c
346242	4361851	72	61	Carcity c
346240	4361869	42	52	Carcity c
341913	4368304	15	18	Sagouspe ls
341932	4368304	10	12	Sagouspe ls
341947	4368303	7	11	Sagouspe ls
341963	4368303	10	14	Sagouspe ls

Easting	Northing	Em38h	Em38v	Map unit
341979	4368302	7	10	Sagouspe ls
341995	4368301	7	7	Sagouspe ls
342012	4368299	8	8	Sagouspe ls
342029	4368300	9	9	Sagouspe ls
342028	4368284	8	8	Sagouspe ls
342010	4368282	8	7	Sagouspe ls
341996	4368283	8	7	Sagouspe ls
341979	4368281	10	10	Sagouspe ls
341963	4368281	16	19	Sagouspe ls
341945	4368280	11	13	Sagouspe ls
341930	4368280	10	14	Sagouspe ls
341914	4368280	8	15	Sagouspe ls
341914	4368263	10	14	Sagouspe ls
341929	4368264	11	14	Sagouspe ls
341946	4368263	13	14	Sagouspe ls
341962	4368263	14	18	Sagouspe ls
341978	4368263	9	10	Sagouspe ls
341994	4368262	8	7	Sagouspe ls
342008	4368262	9	5	Sagouspe ls
342026	4368262	11	8	Sagouspe ls
342031	4368323	11	15	Sagouspe ls
342015	4368326	10	10	Sagouspe ls
341999	4368326	10	13	Sagouspe ls
341981	4368326	12	11	Sagouspe ls
341965	4368327	14	16	Sagouspe ls
341950	4368328	14	17	Sagouspe ls
341931	4368330	14	17	Sagouspe ls
341915	4368331	12	16	Sagouspe ls
336951	4369543	33	33	Appian-Tipperary
336954	4369546	25	28	Appian-Tipperary
336946	4369553	17	30	Appian-Tipperary

Sampling Sites

MAP UNIT	Depth inches	Textural Class	EM38h mS/m	EM38v mS/m	Salinity mmhos/cm	Salinity class
Sagouspe Ls	0-10	1	18	26	0.30	0
	10-20	1	18	26	0.30	0
Fallon FS saline	0-10	2	74	110	1.00	0
	10-20	2	74	110	13.00	3
Fallon FS saline	0-10	2	29	40	3.00	1
	10-20	2	29	40	1.50	0
Parran SIC	0-10	3	37	43	0.50	0
	10-20	3	37	43	0.50	0
Parran SIC	0-10	3	89	119	1.00	0
	10-20	3	89	119	1.50	0
Parran SIC	0-10	3	137	140	1.50	0
East Fork CL	0-10	2	41	44	0.50	0
	10-20	2	41	44	1.00	0
East Fork CL	0-10	2	54	64	0.30	0
	10-20	2	54	64	0.50	0
Fernley L	0-10	1	11	9	0.30	0
	10-20	1	11	9	0.50	0
East Fork CL	0-10	2	88	92	0.50	0
	10-20	2	88	92	2.50	2
Stillwater CL, saline	0-10	3	90	95	4.00	2
	10-20	3	90	95	3.00	1
Stillwater CL, saline	0-10	3	183	183	3.00	1
	10-20	3	183	183	9.00	3
Carcity CL	0-10	3	72	61	1.00	0
	10-20	3	72	61	5.00	2

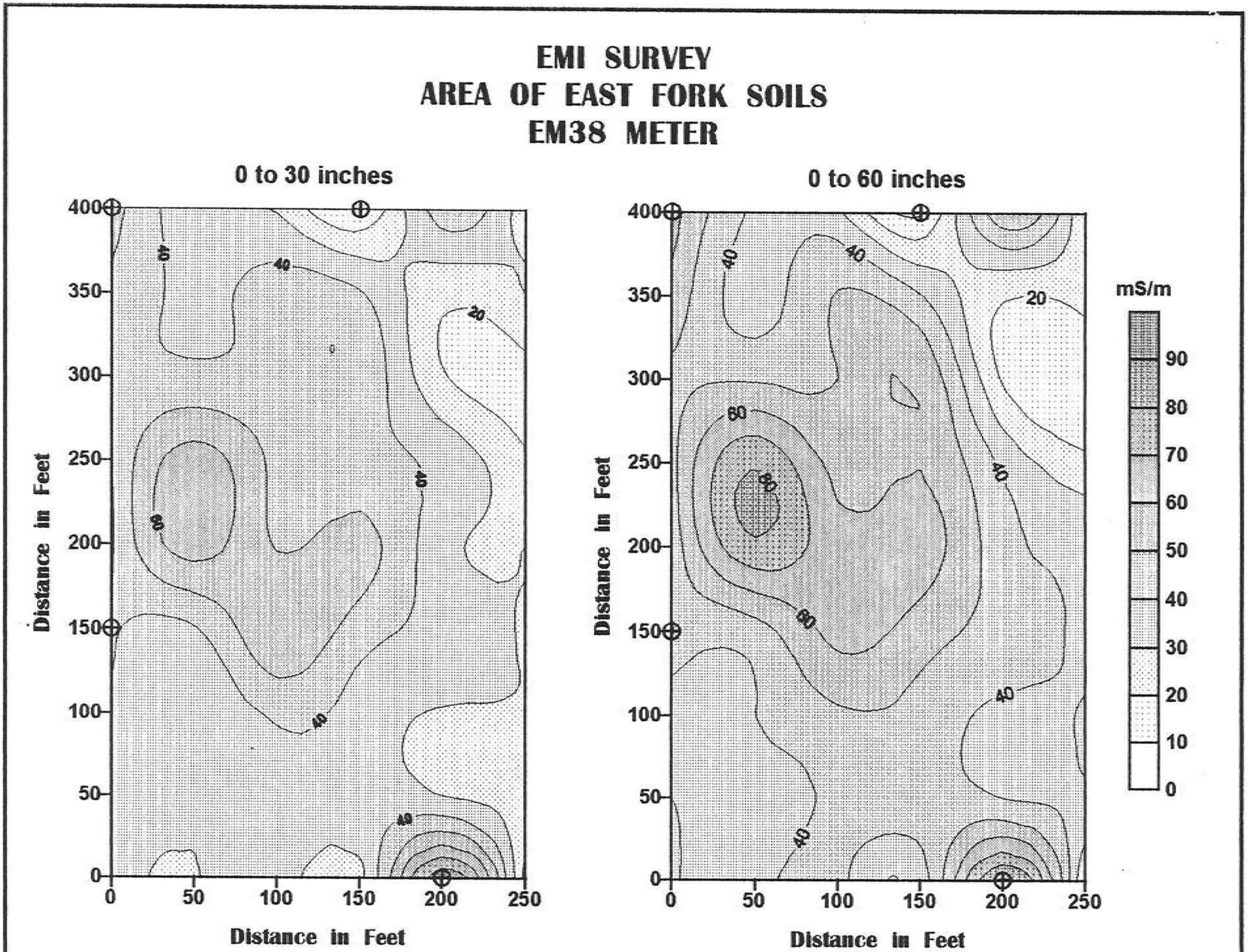
EMI SURVEY
AREA OF EAST FORK SOILS
EM38 METER
0 to 30 inches
0 to 60 inches
Distance in Feet
Distance in Feet
Distance in Feet
Distance in Feet
0
50
100
150
200
250
300
350
400
40
20
60
80
mS/m
0
10
20
30
40
50
60
70
80
90
N ←
⊕ sample site

Figure 1

EMI SURVEY
AREA OF SAGOUSPE LOAMY SAND
EM38 METER

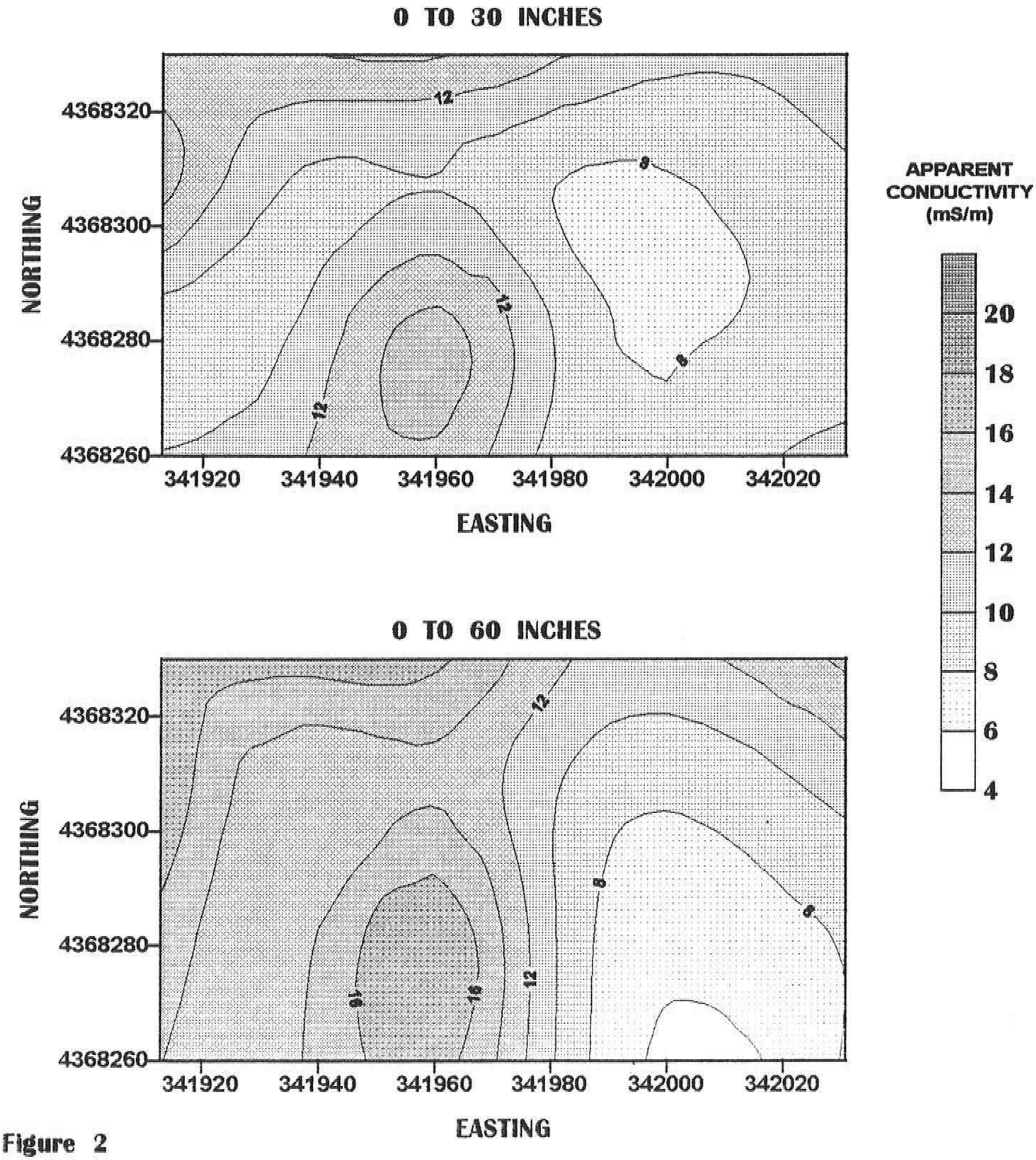

Figure 2

LOVELOCK SUB-SURFACE DRIP IRRIGATION PLOT
ELECTROMAGNETIC INDUCTION SURVEY
EM38 METER

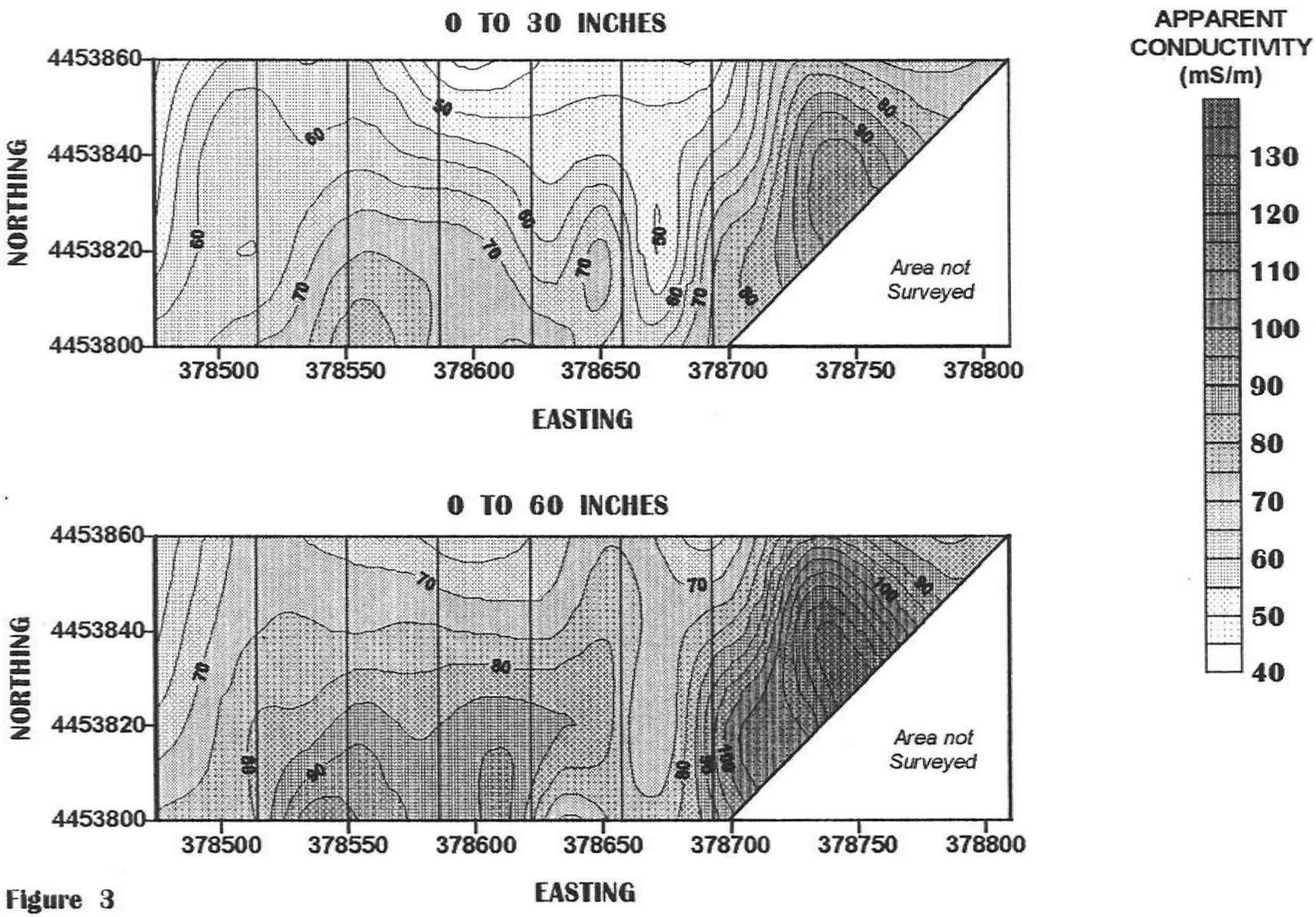

Figure 3

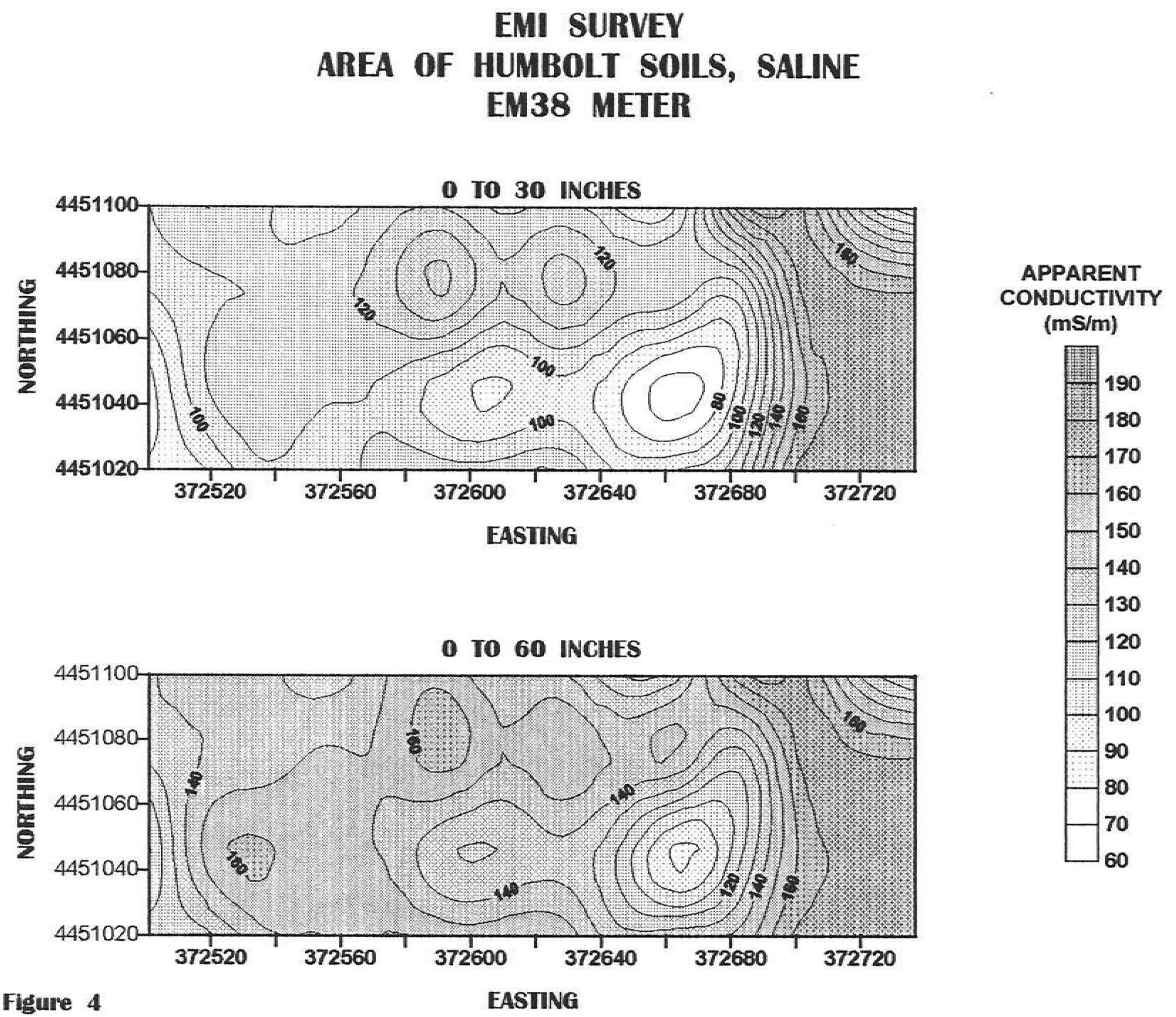
EMI SURVEY
AREA OF HUMBOLT SOILS, SALINE
EM38 METER
0 TO 30 INCHES
NORTHING
EASTING
0 TO 60 INCHES
APPARENT CONDUCTIVITY (mS/m)
190
180
170
160
150
140
130
120
110
100
90
80
70
60

Figure 4