United States Department of Agriculture

Natural Resources Conservation Service

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Subject: Geophysical Assistance

Date: 31 August 1999

To: Stephen F. Black
State Conservationist
USDA - NRCS
655 Parfet Street
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Purpose:
To provide electromagnetic induction (EMI) and ground-penetrating radar (GPR) field assistance.

Participants:
Jim Borchert, Soil Survey Project Leader, USDA-NRCS, Ft. Morgan, CO
Shana Carpenter, Student Trainee, USDA-NRCS, Sterling, CO
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Dawn Jackson, District Conservationist, USDA-NRCS, Sterling, CO
Lori Jazwick, Soil Conservationist, USDA-NRCS, Sterling, CO
Michael Petersen, Area Resource Soil Scientist, USDA-NRCS, Greeley, CO
Carolyn Rogers, Conservation Technician, , USDA-NRCS, Brighton, CO
Norman Wells, District Conservationist, USDA-NRCS, Brighton, CO
Tim Wheeler, Soil Scientist (TSS), USDA-NRCS, Lakewood, CO

Activities:
All field activities were completed during the period of 26 to 29 July 1999.

Equipment:
The radar unit used was the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.[1] The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A model 5106 (200 mHz) antenna was used in this study. A 12-VDC battery powered the system. Morey (1974), Doolittle (1987), and Daniels and others (1988) have discussed the use and operation of GPR.

The electromagnetic induction meter used in this study was the EM38 manufactured by Geonics Limited.[1] This meter is portable and requires only one person to operate. Geonics Limited (1998) has described principles of operation. No ground contact is required with this meter. The EM38 meter operates at a frequency of 14,800 Hz. This meter provides limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. It has theoretical observation depths of about 0.75 and 1.5 meters in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

A GEM300 multifrequency sensor, developed by Geophysical Survey systems, Inc.,[1] was also used in this study. The GEM300 sensor is a newly developed EMI meter. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.3 m). Won and others (1996) have described the use and operation of this sensor.

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[1] Trade names have been used in this report to provide specific information. Their use does not constitute endorsement.

The position of many observation points was obtained with a Rockwell Precision Lightweight GPS Receiver (PLGR)[2]. 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.,[2] was used to construct two- and three-dimensional simulations. Grids were created using kriging methods with an octant search. .

Results:

1. Ground-penetrating radar appears to be an appropriate tool for mapping the depths to paleosols and determining the taxonomic composition of non-saline, coarse-textured soils in northeastern Colorado. However, GPR signals were rapidly attenuated by the paleosol, which limited the depth of observation. In an area of coarse-textured soils, GPR charted the depth to a medium textured paleosol. Within the study area, the depth to paleosol averaged 60.54 inches and ranged from 23.8 to 113.6 inches.

2. The use of GPR in mountainous areas of Colorado should be explored. This technology has not been used by NRCS in upland areas of the Rocky Mountains. The suitability of GPR as a quality control tool for soil mapping and bedrock determinations is unknown in these areas.

3. Electromagnetic induction is an effective tool for mapping saline soils. The EM38 meter is suitable for assessing salinity phases and map unit composition. The use of the multiple linear regression equations developed by the USDA-ARS Salinity Laboratory and the EM38 meter provides a reasonably accurate, practical, and cost-effective method to map spatial salinity patterns at the field scale within the South Platte River Valley.

4. In the study that was conducted on an area of saline soils in Logan County, EMI measurements were obtained with two instruments. Results were found to be similar, but not identical. The results of this and other ongoing research projects will benefit users of EMI. Information obtained from these studies will provide a better understanding of the advantages and limitations of both tools. The results will also benefit soil scientists, conservationists, and agronomist, who may need to understand the differences between these tools for research or demonstration purposes.

5. Samples have been collected and sent to the National Soil Laboratory for analysis. Results from various chemical and physical analyses will help to determine the suitability of both the EM38 meter and the GEM300 sensor for salinity mapping.

6. Shana Carpenter, Dawn Jackson, Lori Jazwick, Tim Wheeler and Jim Borchert received training on the use and operation of the EM38 meter. Mike Peterson, Tim Wheeler, and Jim Borchert received training on the use and operation of the GEM300 sensor.

7. 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.

8. The field study was well organized by Mike Petersen. Mike is commended for his efforts.

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

With kind regards,

James A. Doolittle
Research Soil Scientist

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[2] Trade names have been used in this report to provide specific information. Their use does not constitute endorsement.

cc:

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1. Ground-Penetrating Radar

Background:

The suitability of GPR for soil investigations is highly site-specific. Ground-penetrating radar works well in coarse and moderately coarse textured, non-calcareous and non-saline soils. In areas of coarse-textured soils, GPR has been used to monitor water table depths. As part of the Wet-Soils Monitoring Project, this study attempted to profile the depths to the water table in an area of coarse-textured eolian deposits on a dune and interdunal landscape in northeastern Colorado.

Study Site:

The study site is located in southern Weld County about 3.8 miles northeast of Roggen, Colorado. It is in the northeast quarter of Section 21, T. 3 N., R. 62 W. The site was in rangeland. Figure 1 is a three-dimension surface net of the study site. Relief is about 8 ft. Several low dunes occur in the western part of the study site. An intermittent stream crosses the eastern part of the site in primarily a south to north direction. The study site has been mapped as Loup-Boel loamy sands, 0 to 3 percent slopes and Valent sand 3 to 9 percent slopes (Crabb, 1980). The very deep, very poorly drained and poorly drained Loup and the somewhat poorly drained Boel soils formed in loamy and sandy alluvium on flood plains and interdunal areas. Loup soil is a member of the sandy, mixed, mesic Fluvaquentic Haplustolls family. Boel soil is a member of the sandy, mixed, mesic Typic Endoaquolls family. The very deep, excessively drained Valent soil formed in mixed eolian deposits on dunes. Valent soil is a member of the mixed, mesic Ustic Torripsamments family.

Field Procedures:

Random traverses were made across the study site. Figure 1 shows the locations of the observation points. The coordinates of each observation point were obtained with a Rockwell PLGR. Survey flags were inserted in the ground at each observation point. At each observation point, the relative elevation of the surface was determined with a level and stadia rod. Elevations were not tied to an elevation benchmark; elevations were tied to an arbitrary 50-foot datum. The radar survey was conducted by pulling the 200 mHz antenna by hand along each of the seven north-south trending lines. As the radar antenna was pulled passed each flagged observation point, the operator impressed a vertical mark on the radar record. The vertical marks identified the observation points. This process provided a total of 57 observations. Soil cores were taken at three observation points. Data recorded at these coring sites were used to depth scale the radar imagery and confirm interpretations.

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):

$$v = 2d/t \qquad [1]$$

Calibration trials were conducted at the Roggen 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 Roggen site, brief profile descriptions were made at three observation sites. A high correlation (0.9984) was found between the two-way travel time to a conspicuous subsurface interface and the measured depth to a coarse-loamy paleosol. The measured depths to the paleosol ranged from 40 to 66 inches. The depth to the paleosol was used to depth scale the radar imagery.

Results:

A conspicuous, continuous subsurface interface was discernible on all radar profiles. As the depth to this interface was deeper under higher-lying dunes and shallower under lower-lying interdunal areas, it was initially assumed to be the water table. Ground-truth observations conducted at three observation points confirmed that the interface represents the upper boundary of a medium textured (sandy loam) paleosol.

Within the study site, based on radar interpretations at 57 observation points, the depth to paleosol averaged 60.54 inches and ranged from 23.8 to 113.6 inches. One-half of the observations had depths to the paleosol between 49.5 and 66.0 inches. Seven percent of the observation points had the paleosol occurring at depth of 20 to 40 inches. The paleosol was deep (40 to 60 inches) at forty-four percent of the observation points. The paleosol was very deep (>60 inches) at forty-nine percent of the observation points. Thirty-seven percent of the observation points had the paleosol at depth of 60 to 80 inches. Twelve percent of the observation points had the paleosol at depth greater than 80 inches. The spatial distribution of interpreted depths to the paleosol is shown in Figure 2. Depths to the paleosol are greater beneath higher-lying dunes and shallower in lower-lying interdunal areas.

2. Electromagnetic Induction

Use in Salinity Appraisals

In the South Platte River Valley of northeastern Colorado, soil salinity is a major cause of degraded soil and water quality and reduced crop production on many irrigated lands. Changes in soil salinity must be mapped and monitored to optimize water management practices, conserve water, and minimize salinization. Visual crop observations and electrical conductivity measurements are methods that have been used to recognize and map phases of soil salinity (Soil Survey Division Staff, 1993). While visual observations are often adequate for salinity mapping, results provide only qualitative measures of salinity and are often dependent on the presence of plant cover and surface salts.

Electrical conductivity is measured by the saturated paste extract (EC_e), resistivity, or electromagnetic induction methods. In the early 1980s, EMI and the EM38 meter developed by Geonics Limited gained quick acceptance by soil scientists and agronomists involved in mapping salinity. Compared with other methods, advantages of EMI are its noninvasiveness, speed of operation, low survey costs, and more comprehensive coverage of sites. Presently, EMI is considered the most useful method for the rapid field identification and mapping of soil salinity (Johnston et al., 1997).

Electromagnetic induction is a noninvasive geophysical tool that uses electromagnetic energy to measure the bulk soil electrical conductivity of soil below the transmitter and receiver coils. This apparent conductivity (EC_a) 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 soils. 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). 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 conductivity. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity values have been used to infer changes in soils and soil properties. Generally, the use of EMI for salinity appraisals 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., salt content) dominate over the other properties (e.g., clay and water contents). 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, van der Lelij (1983) observed that dissolved salts are the dominant factor affecting apparent conductivity. William and Baker (1982) estimated that 65 to 70 percent of the variance in apparent conductivity could be explained by changes in the concentration of soluble salts alone. Moderate to high correlations have been found between apparent conductivity and soil salinity. These relationships have demonstrated that EMI can provide reasonably accurate estimates of soil salinity (William and Baker, 1982, van der Lelij, 1983, Diaz and Herrero, 1992).

The saturated paste extract method is accepted as the most accurate measure of soil salinity. However, this method requires the expenditure of considerable resources for field sampling and laboratory analysis, thus limiting the number of soil samples that can be analyzed. A prominent challenge in the use of EMI for soil salinity mapping has been the conversion of apparent conductivity (EC_a) into a more commonly used measure of soil salinity (EC_e). Several models have been developed to predict soil salinity levels from acquired EMI data (Corwin and Rhoades, 1990, Wollenhaupt et al., 1986, McKenzie et al., 1989; Rhoades et al., 1989a and 1989b, Slavich, 1990; Cook et al., 1992, Lesch et al., 1995a and 1995b, and Johnston et al., 1996). Models have been improved by including the effects of different types of salinity profiles and clay and water contents (Rhoades et al., 1989a and 1989b, Cook et al., 1992). However, as these properties vary both laterally and vertically, they are difficult to predict.

Models are not perfect and tend to be both time dependent and site specific (Lesch et al., 1998). Lesch and others (1998) noted that errors in instrument calibration, instrument-to-instrument variations, variations in soils, moisture, temperature, and differences in the distribution of salts within soil profiles are factors that contribute to the time and field dependencies of models. Models are often only valid for the geographic area and soil types from which the relationships were derived. Because of the non-uniform response with depth, the conversion of EMI measurements into meaningful measures of soil salinity has been difficult (Johnston et al., 1997). While soil salinity levels predicted from EMI data and the various calibration models

provide reasonable estimates of soil salinity, they are often not as accurate as desired (Rhoades et al., 1989a, Johnston et al, 1997). Nevertheless, these models appear to provide reasonable estimates of soil salinity and satisfy mapping requirements.

Different theories and instrumentation

In a theoretical discussion on EMI, McNeill (1980) postulated that the measured apparent conductivity is a function of instruments calibration, coil separation, coil orientation, and frequency. Furthermore, McNeill noted that the depth of observation is dependent on coil separation, coil orientation, and frequency. Larger coil separations and lower frequencies are used to achieve greater depths of observation. Won and others (1996) believe that changing the transmitter frequency will change the depth of observation. Won (1980 and 1983) contends that observation depths are governed by the skin-depth effect: low frequency signals travel farther through conductive mediums than high frequency signal.

Skin depth represents the maximum depth of observation for an EMI meter or sensor operating at a specific frequency and sounding a medium of known conductivity. Observation depth or skin depth is inversely proportional to frequency (Won et al., 1996). Low frequency signals have longer periods of oscillation and loose energy less rapidly than high frequency signals. As a consequence, low frequency signals travel farther through conductive mediums than high frequency signals. Greater depths of observation can be achieved by decreasing the frequency. At a given frequency, the depth of observation is greater in a soil having a lower conductivity than in a soil having a higher conductivity. However, because of other factors, such as the geometry of the meter or sensor, the depth of observation may be less than the skin depth (Greenhouse et al., 1998).

With meters developed by Geonics Limited, the depth of observation is considered to be "geometry" limited (intercoil spacing) rather than skin depth limited (McNeill, 1980). Under conditions of low induction numbers, the depth-response functions of meters developed by Geonics Limited are assumed to be independent of soil conductivity. Conditions of low induction numbers are usually satisfied in soils having relatively low conductivities (McNeill, 1980). However, these conditions are not satisfied in areas of saline soils. Slavich (1990) and de Jong and others (1979) reported that the depth of observation would vary depending on the bulk electrical conductivity of the profiled material(s). Greenhouse and others (1998) have recently commented that the electrical conductivity of soils play a critical role in the depth of observation that can be obtained with EMI.

With the GEM300 sensor, the depth of observation is considered "skin depth" limited rather than "geometry' limited (Won, 1980 and 1983, Won et al., 1996). The theoretical observation depth of the GEM300 sensor is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency. Mutifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

Logan County Study

This study was conducted to evaluate the performances of the EM38 meter and the GEM300 sensor in an area of saline soils. A second goal of this investigation is to relate apparent conductivity (EC_a) measured with the EM38 meter and the GEM300 sensor 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). This portion of the study must await the return of results from soil samples delivered to the National Soil Survey Laboratory.

Study Site:

The study site is located in Logan County about 9 miles northeast of Sterling, Colorado. It is in the southeast quarter and the southern half of the northeast quarter of Section 32, T. 9 N., R. 50 W. The site was in irrigated (center pivot) hayland. It has been leveled for irrigation. Principal soils mapped within the study site include Alda, Westplain, and Fluvaquentic Haplaquolls. The very deep Alda soil is moderately deep over coarse sands and gravelly sands. This somewhat poorly drained soil formed in stratified alluvium on flood plains. Clay contents averages 20 to 25 percent in the upper part of the soil profile. Alda soil is a member of the coarse-loamy, mixed, superactive, mesic Fluvaquentic Haplustolls family. The very deep, somewhat poorly drained and poorly drained Westplain soil formed in stratified alluvium on flood plains. Westplain soil is shallow over sands or gravelly sands. Clay content averages 35 to 50 percent in the upper part of the soil profile. Westplain soil is a member of the clayey over sandy or sandy-skeletal, smectitic, calcareous, mesic Typic Haplaquolls family.

Field Procedures:

Random traverses were made across the study area. Figure 3 shows the location of traverse lines and observation points. The coordinates of each observation point were obtained with a Rockwell PLGR. Survey flags were inserted in the ground at each

observation point. Measurements were taken at each observation point with an EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations. Two surveys were completed with the EM38 meter to verify the repeatability of measured data. In addition, measurements were taken at each observation point with the GEM300 sensor held at hip-height in both the horizontal and vertical dipole orientations. At each observation point, inphase, quadrature phase, and conductivity data were recorded with the GEM-300 sensor at four different frequencies (6690, 9,810, 14,790, and 19,590 Hz).

The skin depth (depth of observation) can be estimated for the GEM300 sensor using the following formula (McNeill, 1996):

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

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

With the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 146.7, 149.3, 145.0, and 151.36 mS/m at frequencies of 6,390, 9,810, 14,790, and 19,590 Hz, respectively. Using equation [2], the estimated skin depths are about 0.52 m at 6,390 Hz, 0.41 m at 9,810 Hz, 0.34 m at 14,790 Hz, and 0.29 m at 19,590 Hz. With the GEM300 sensor held at hip height in the horizontal dipole orientation, apparent conductivity averaged 92.4, 95.5, 92.2, and 98.4 mS/m at frequencies of 6,390, 9,810, 14,790, and 19,590 Hz, respectively. Using equation [2], the estimated skin depths are about 0.65 m at 6,390 Hz, 0.52 m at 9,810 Hz, 0.42 m at 14,790 Hz, and 0.36 m at 19,590 Hz.

Apparent conductivity changes 2.2 percent per degree centigrade (McNeill, 1980). All measurements were standardized to an equivalent electrical conductivity at a reference temperature of 25° C.

Soil samples were collected at five observation points (see Figure 3). The sampling sites were selected to span the observed range in apparent conductivity and to provide reasonable coverage of the study site. At each sampling site, soil samples were acquired in 1-ft intervals down to a depth of 3 ft.

Results:

EM38 Surveys:

Figures 4 and 5 contain two-dimensional plots of data collected with the same EM38 meter at two different times in the same day. In each figure, the spatial distributions of apparent conductivity within the upper 30 inches and within the upper 60 inches of the soil profile are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 10 mS/m.

Comparing the two surveys, spatial patterns are similar. In general higher values of apparent conductivity were recorded in the northern, western, and southeastern portions of the study site. A band of lower apparent conductivity extends across the central and eastern portions of the study site in a southwest to northeast direction. This band may reflect differences in salinity and/or soils and soil materials (coarser textures).

For each survey, values of apparent conductivity recorded at each observation point differed slightly. However, strong correlatons were observed between the two sets of data in both the horizontal ($r^2 = 0.9852$) and vertical ($r^2 = 0.9097$) dipole orientations. Basic statistics for these surveys are displayed in Table 1.

For the first survey with the EM38 meter, apparent conductivity within the upper 30 inches of the soil profile averaged about 103.6 mS/m. One-half of the observations had an apparent conductivity between 80.8 and 123.2 mS/m. The apparent conductivity within the upper 60 inches of the soil profile averaged about 99.3 mS/m. One-half of the observations had an apparent conductivity between 83.8 and 113.2 mS/m. For the second survey with the EM38 meter, apparent conductivity within the upper 30 inches of the soil profile averaged about 111.9 mS/m. One-half of the observations had an apparent conductivity between 91.6 and 133.7 mS/m. The apparent conductivity within the upper 60 inches of the soil profile averaged about 99.6 mS/m. One-half of the observations had an apparent conductivity between 80.0 and 114.0 mS/m.

Although similar, differences exist in the two data sets collected with the EM38 meter. Differences are attributed to errors in instrument calibration, placement, and measurement. These differences lessen the predictive accuracy of salinity models. The *salt program* developed by the Salinity Laboratory provides estimates of soil electrical conductivity (EC_e) within depth intervals of 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm. In this program, different predictive equations are used for soil profiles in which EC_a increased with depth (normal salt profile), decreased with depth (inverted salt profile), and remained constant with depth (uniform salt profile). In this model, EMI data are transformed (fourth-root transformation) to obtain normal

distributions. Estimates assumed that the water content of the soils is at or near field capacity and that the soils are isotropic. In addition, the model requires an estimate of the average clay content within the soil profile. Soil texture affects the relationship between apparent conductivity and saturated paste extract conductivity (Halvorson et al., 1977). With the *salt program*, the broad groups of available textural classes used were 15, 20, 25, 30, 35, and 40 percent clay. Reasonable estimates (r^2 of 0.78) of soil salinity have been made in the field using these predictive equations, measurements of apparent conductivity obtained with EMI meters, and estimates of soil water and clay contents made by the "feel" methods (Rhoades et al., 1990).

Table 1
Basic Statistics
EMI Surveys conducted with an EM38 Meter

(All values are in mS/m)

					Quartiles		
	Orientation	**Average**	**Minimum**	**Maximum**	**1st**	**2nd**	**3rd**
First Survey	Horizontal	103.55	61.80	159.85	80.77	99.53	123.17
	Vertical	99.27	47.17	153.91	83.85	97.73	113.21
Second Survey	Horizontal	111.94	65.40	180.44	91.58	107.27	133.67
	Vertical	99.65	63.34	160.38	80.03	97.10	113.95

In both surveys made with the EM38 meter, uniform, inverted, and regular salt profiles were observed. For the first survey made with an EM38 meter, apparent conductivity increased with increasing soil depth (regular salt profile) at 13 observation points. At 20 observation points, apparent conductivity decreased with increasing soil depth (inverted salt profile). In addition, at 16 observation points the distribution of salts remained relatively uniform through the soil profile (uniform salt profile). For the second survey, apparent conductivity decreased with increasing soil depth at 32 observation points. At 17 observation points, apparent conductivity remained essentially uniform throughout the soil profile. This variability made modeling with the *salt program* very challenging. In addition, it was assumed that the soil profile contained about 25 percent clay and the clay was uniformly distributed throughout the profile. These assumptions are incorrect owing to the stratified nature of the alluvial deposits and the varying textures and depths to sands or gravelly sands in the soil profiles.

After the apparent conductivity data was converted into electrical conductivity by the *salt program*, a moderate ($r^2 = 0.7257$) correlation was observed between the two sets of survey data for the 0 to 30 cm layer. Lower and less significant correlations were observed for the 30 to 60 cm layer ($r^2 = 0.4365$) and for the 60 to 90 cm layer ($r^2 = 0.1736$). In this area of Alda and Westplain soils, the model appears to break down at lower soil depths. This is probably a consequence of the stratified and highly contrasting properties of the substratum.

Figure 6 shows the spatial distribution of soil electrical conductivity estimated from EM38 measurements and the *salt program* for the two surveys. In Figure 6, measurements are expressed in deciSiemens per meter (dS/m). The salinity classes are: non-saline (<2 dS/cm), very slightly saline (2 to < 4 dS/cm), slightly saline (4 to < 8 dS/cm), moderately saline (8 to < 16 dS/cm), and strongly saline (> 16 dS/cm). Variability between the predicted salinity classes in the two plots arises from meter calibration, placement and measurement errors, variations in moisture and clay contents, and differences in the shape of the salinity profile.

While similarities exist in the gross spatial distribution of salinity classes, estimated values and line placement are more variable between the two surveys. In the first survey, electrical conductivity averaged 8.66 dS/m within the 0 to 30 cm depth interval. For the upper 30 cm, one-half of the observations had electrical conductivity between 5.66 and 11.72 dS/m. In the second survey, electrical conductivity averaged 10.42 dS/m within the 0 to 30-cm depth interval. For the upper 30 cm, one-half of the observations had electrical conductivity between 7.54 and 13.57 dS/m. Table 2 summarizes the placement of observation points within the salinity classes. This study shows both the limitations and potentials of EMI for salinity appraisals. For the 0

to 30-cm layer, reasonably repeatable predictions of soil salinity can be made using EMI and the *salt program*. However, for deeper and more contrasting layers, the methods appear less appropriate.

Table 2

Comparison of Salinity Class Predictions
From EM38 Surveys of Study Site

(Percent of observation points)

	First	Second
Very Slightly Saline	10	0
Slightly Saline	41	35
Moderately Saline	49	59
Strongly Saline	0	6

GEM-300 Multifrequency Electromagnetic Sensor:
Measurements of apparent conductivity collected with the GEM300, though comparable, were slightly higher and more variable than those collected with the EM38 meter. The GEM300 sensor was not *zeroized* (accurately set the instrument to zero) in the field as was done with the EM38 meter. This and differences in equipment calibration by the manufacturers are believed to explain the relatively higher values of apparent conductivity recorded at each observation point by the GEM300 sensor than by the EM38 meter. In addition, differences in the depth of observation, volume of soil material measured, and resolution of each tool affected measurements.

The coefficients of determination (r^2) between measurements obtain at each of the four selected frequencies (6,390, 9,810, 14,790, and 19,590 Hz) and measurements obtained with the EM38 meter in the horizontal dipole orientation were similar and ranged from 0.8581 to 0.8617. The coefficient of determination (r^2) between measurements obtain at each of the four selected frequencies and measurements obtained with the EM38 meter in the vertical dipole orientation were also similar, but slightly lower, and ranged from 0.8039 to 0.8075. The similarities in these correlations are believed to reflect the restricted and closely similar skin depths that were obtained at the selected frequencies. In these salt-affected soils, skin depths ranged from 0.29 to 0.65 m at the selected frequencies and associated soil conductivities.

Table 2 summarizes the results of the survey with the GEM300 sensor. Data obtained at each frequency and dipole orientation are closely similar. The similarities in data attest to the restricted and equivalent skin depths. The GEM300 sensor has a frequency range of 330 to 20,000 Hz. In areas of saline soils, lower frequencies must be used to achieve significantly greater depths of observation. Assuming a soil conductivity of 160 mS/m, the maximum depth of observation attainable with the GEM300 (at a frequency of 330 Hz) is about 2.2 m.

Table 3

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

	Frequency (Hz)							
	6,390V	6,390H	9,810V	9,810H	14,790V	14,790H	19,590V	19,590H
AVERAGE	155.5	97.9	158.2	101.2	153.7	97.7	160.4	104.3
MINIMUM	99.3	61.9	101.6	65.9	97.2	68.0	103.5	68.3
MAXIMUM	273.5	161.2	274.7	164.3	269.5	159.7	275.3	166.5
FIRST	121.6	78.2	124.1	81.2	120.2	79.6	126.9	85.0
MEDIAN	140.8	88.9	143.6	91.7	139.4	88.2	146.5	94.7
THIRD	187.8	117.0	189.9	121.0	185.6	117.2	192.0	123.7

The spatial distribution of the apparent conductivity data collected with the GEM300 sensor is shown in figures 7 to 10. Each figure contains plots of apparent conductivity collected at a specified frequency in either the horizontal (upper plot) or vertical (lower plot) dipole orientation. In each plot the isoline interval is 10 mS/m. The depth of observation is assumed to increase slightly as the frequency decreases. Data and spatial patterns are comparable in each plot. As with the EM38 data set, higher values of apparent conductivity were recorded in the northern, western, and southeastern portions of the study area. Also, a conspicuous band of lower apparent conductivity extends across the central and eastern portions of the study area in a southwest to northeast direction. This band is presumed to reflect differences in salinity or soils and soil materials (coarser textures).

In this study, EMI measurements were obtained with two instruments. Results were found to be similar, but not identical. The EM38 meter is the established geophysical tool for salinity appraisals. Predictive models have been developed to estimate soil salinity from the data collected with the EM38 meter. However, the EM38 meter is very sensitive and often requires frequent and tedious scale adjustments. The GEM300 sensor is easier to operate and requires less field time to complete a survey. The suitability of the data sets for salinity appraisals must await the return of the samples sent to the National Soil Laboratory. In many situations, the EM38 information will prove more useful, while in other situations the GEM300 sensor may be better suited to determine soil variability. The results of this and ongoing research projects will benefit users of EMI. Information obtained from these studies will provide a better understanding of the advantages and limitations of both tools. The results will also benefit soil scientists, conservationists, and agronomist, who may need to understand the differences between these tools for research or demonstration purposes.

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GPR Survey of Roggen Site
Relative Topography

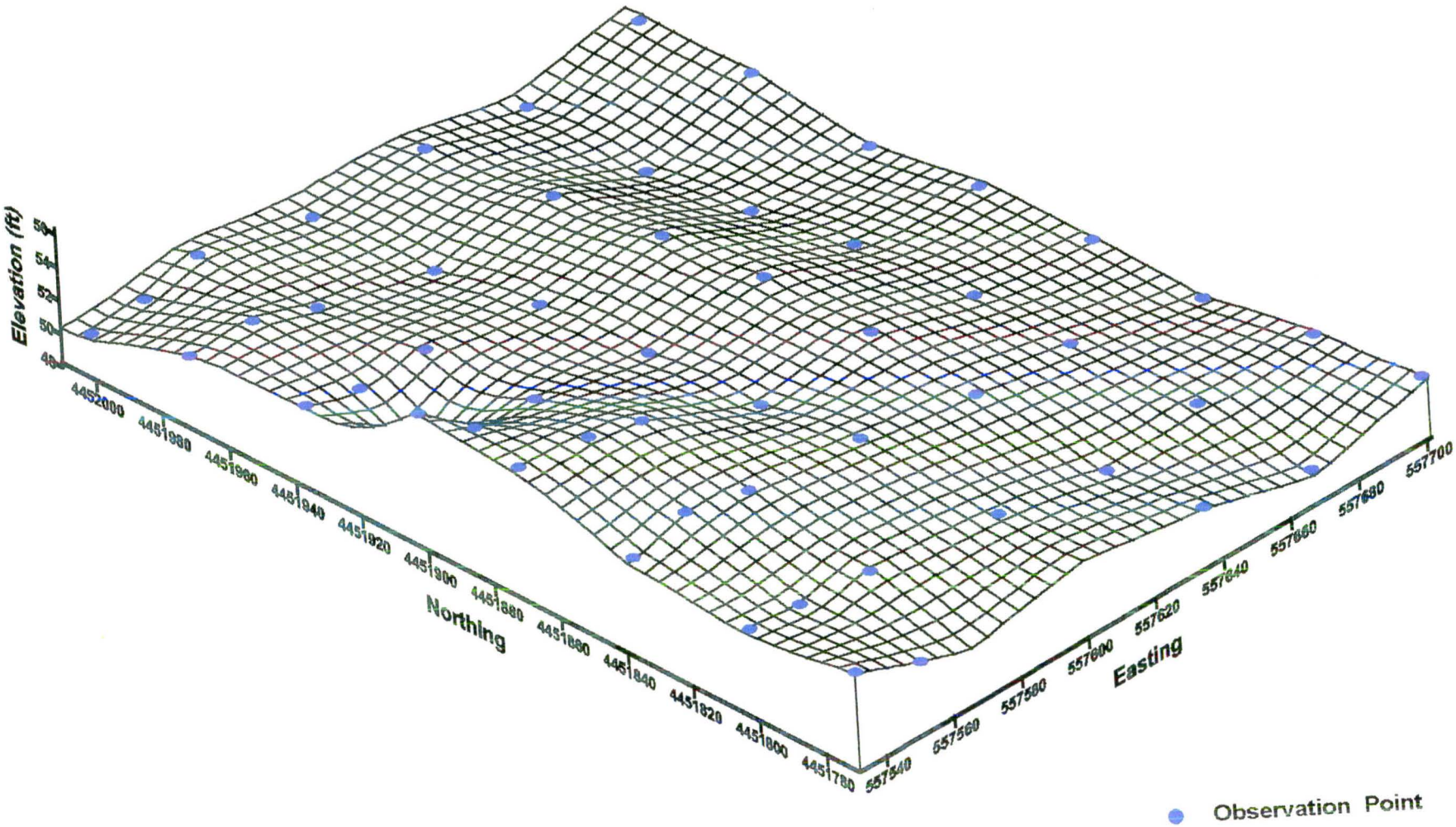


Figure 1

GPR Survey of Roggen Site
Interpreted Depth to Paleosol

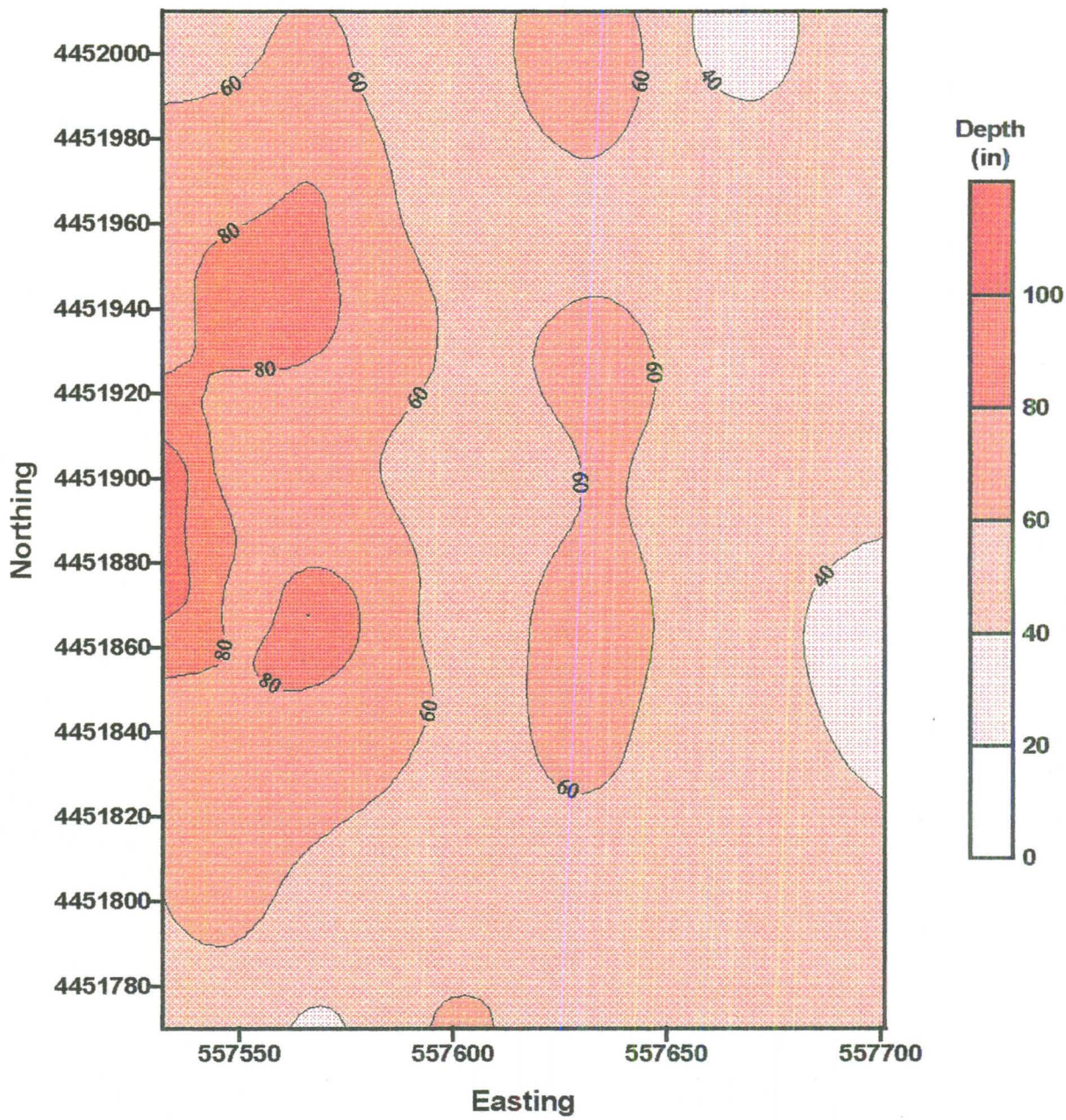


Figure 2

LOCATIONS OF OBSERVATION POINTS FOR EMI SALINITY SURVEY LOGAN COUNTY, COLORADO

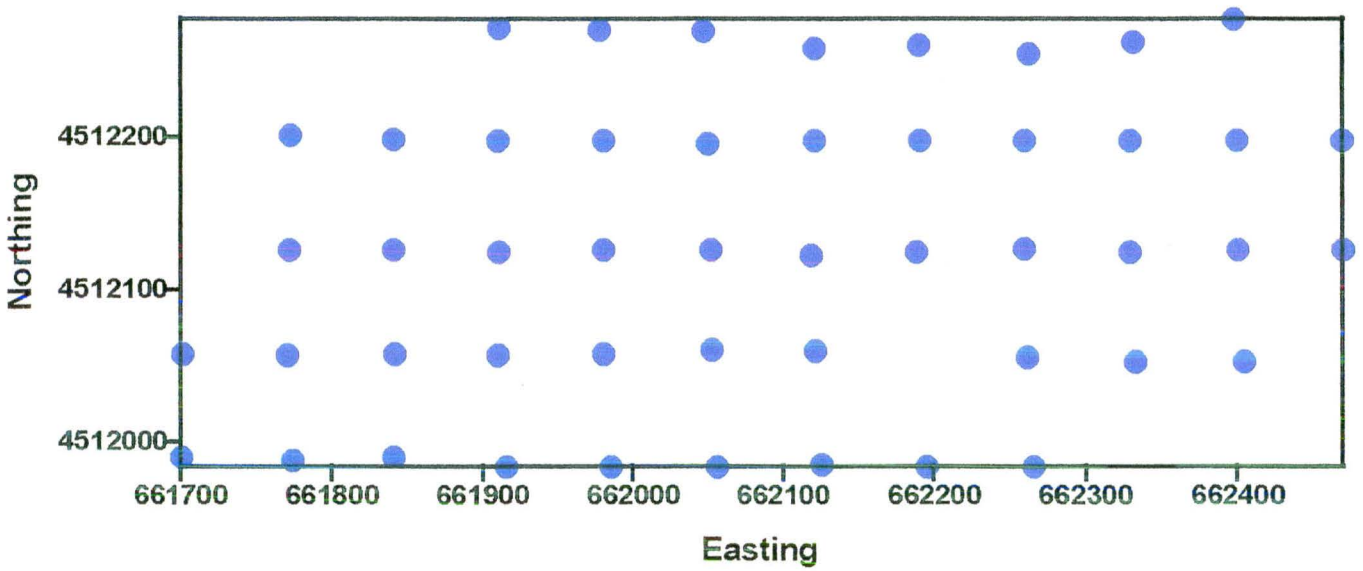


Figure 3

Observation Point

EMI SURVEY
AREA OF SALINE SOILS
EM38 METER
Survey #1

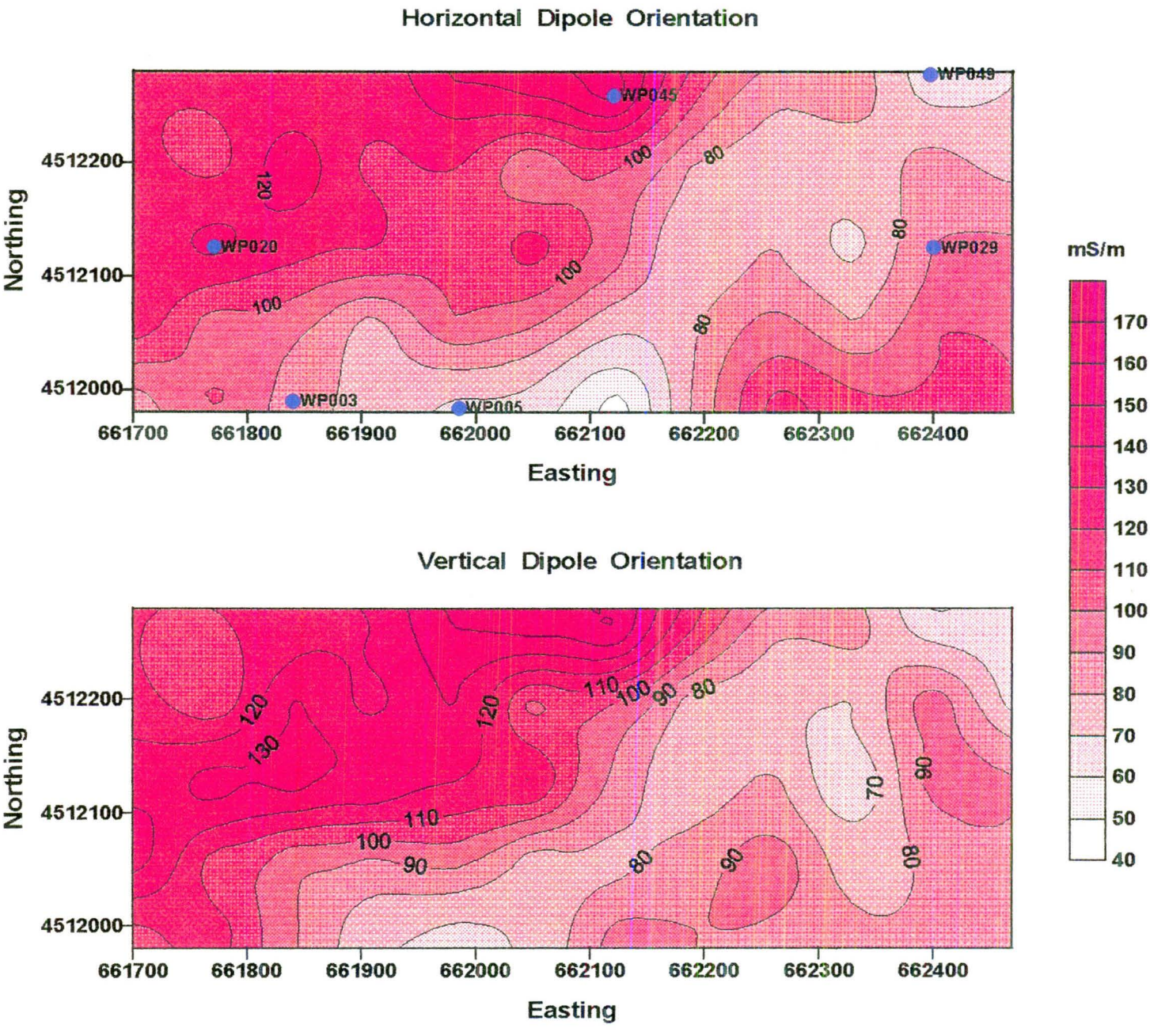


Figure 4

● Soil Sample Site

EMI SURVEY
AREA OF SALINE SOILS
EM38 METER
Survey #2

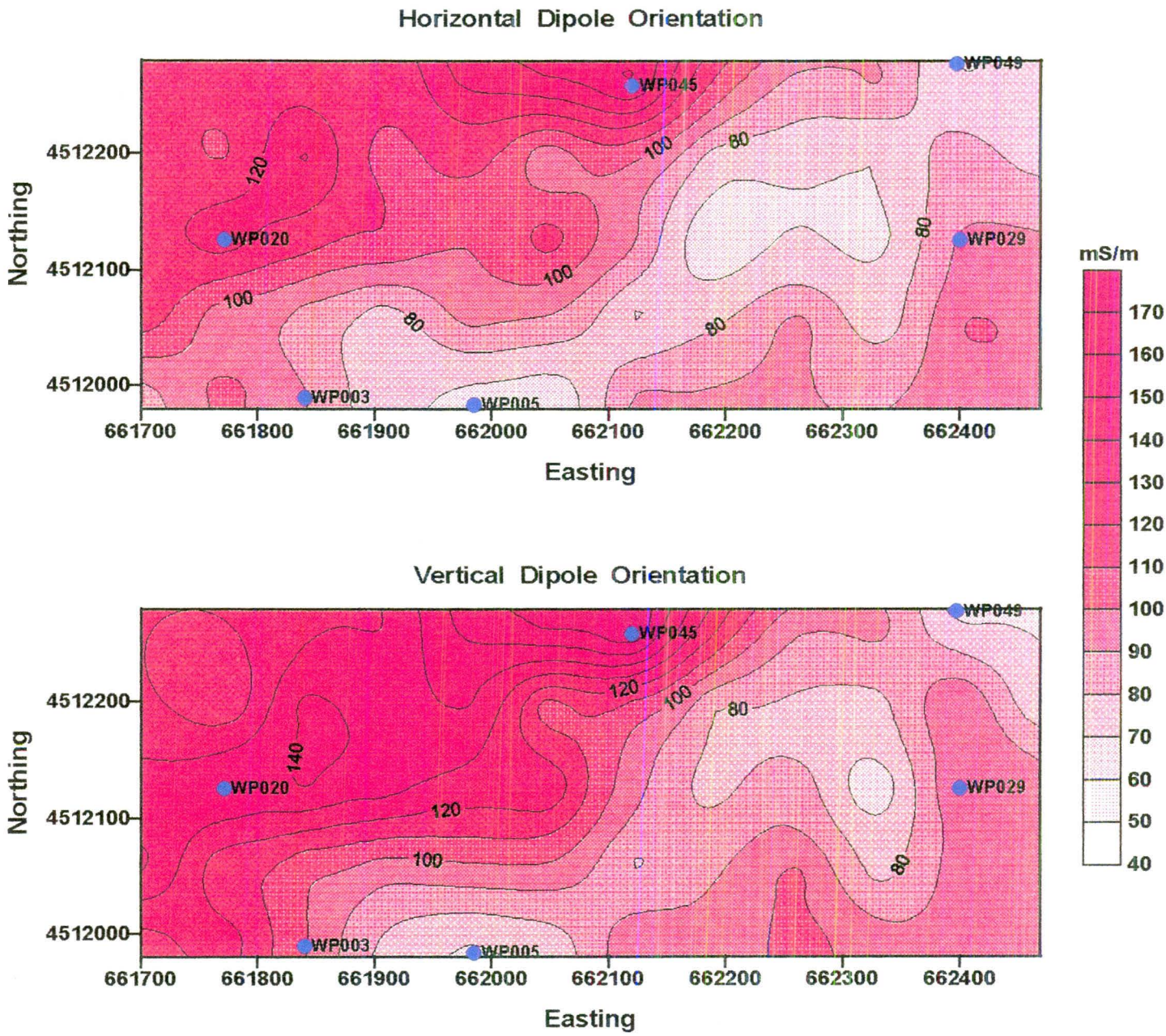
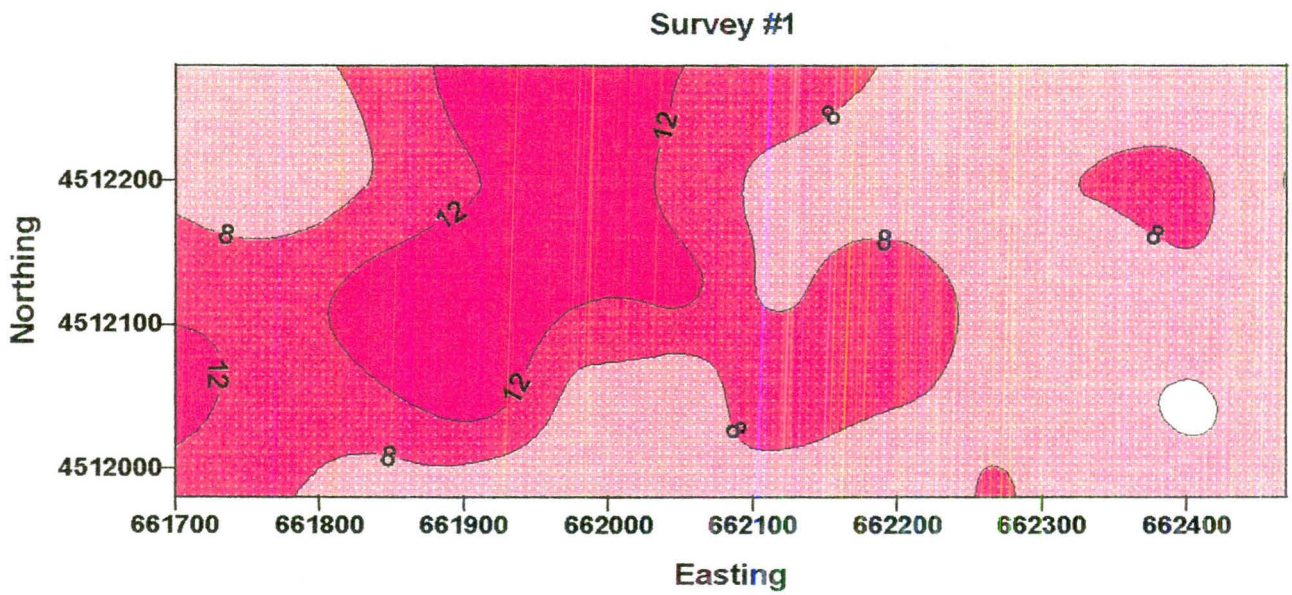


Figure 5

Soil Sample Site

SOIL SALINITY ASSESSMENTS FOR THE 0 TO 30 CM DEPTH INTERVAL BASED ON EMI SURVEYS WITH EM38 METER



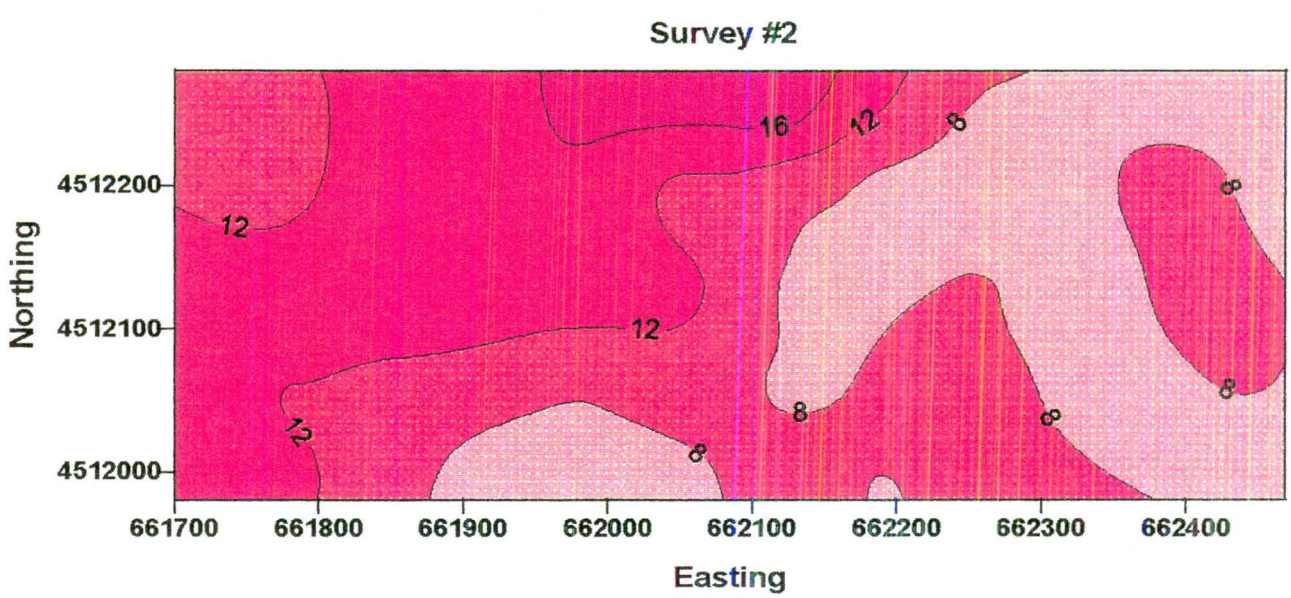


Figure 6

EMI SURVEY
AREA OF SALINE SOILS
GEM300 SENSOR
6390 Hz

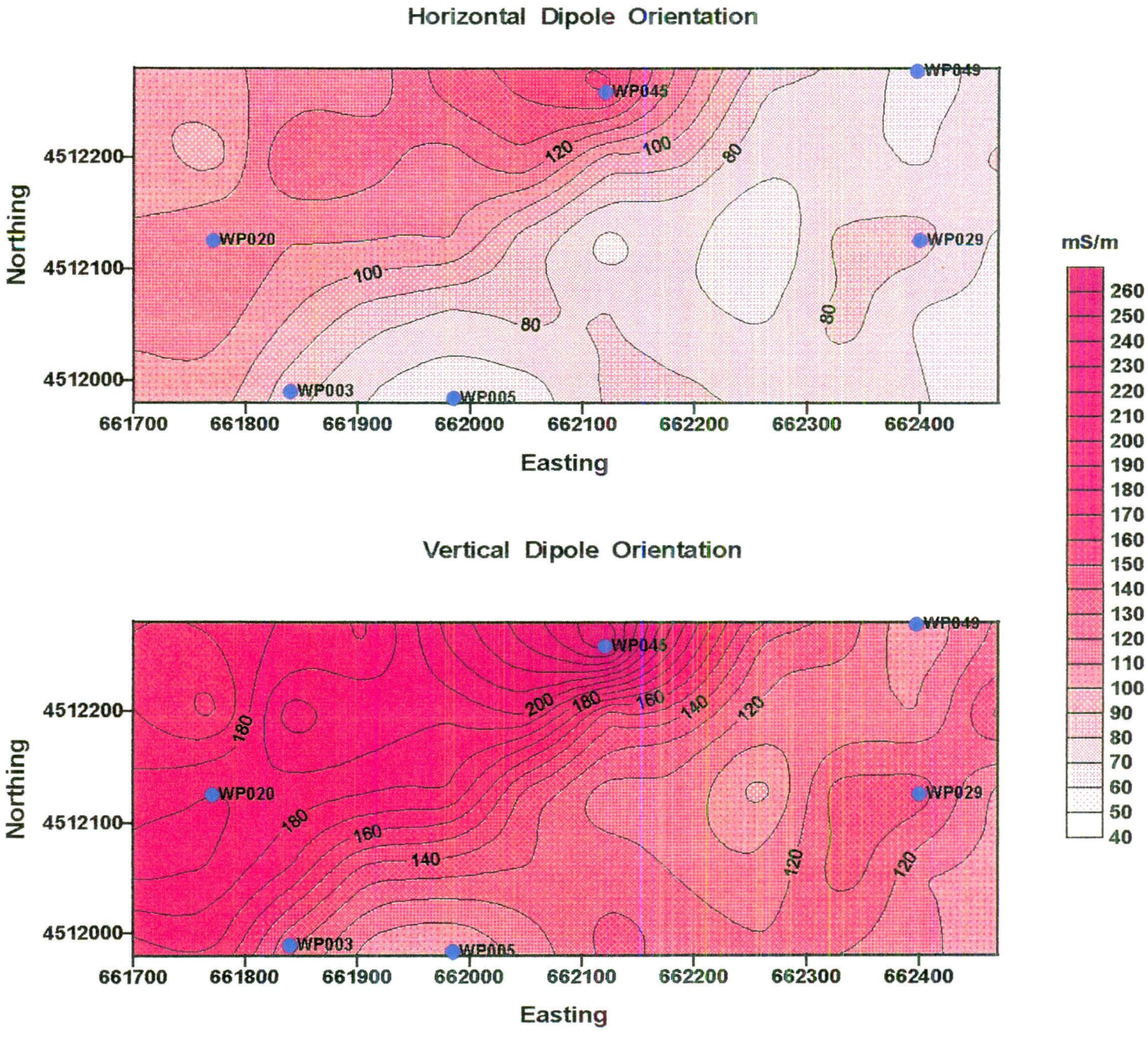
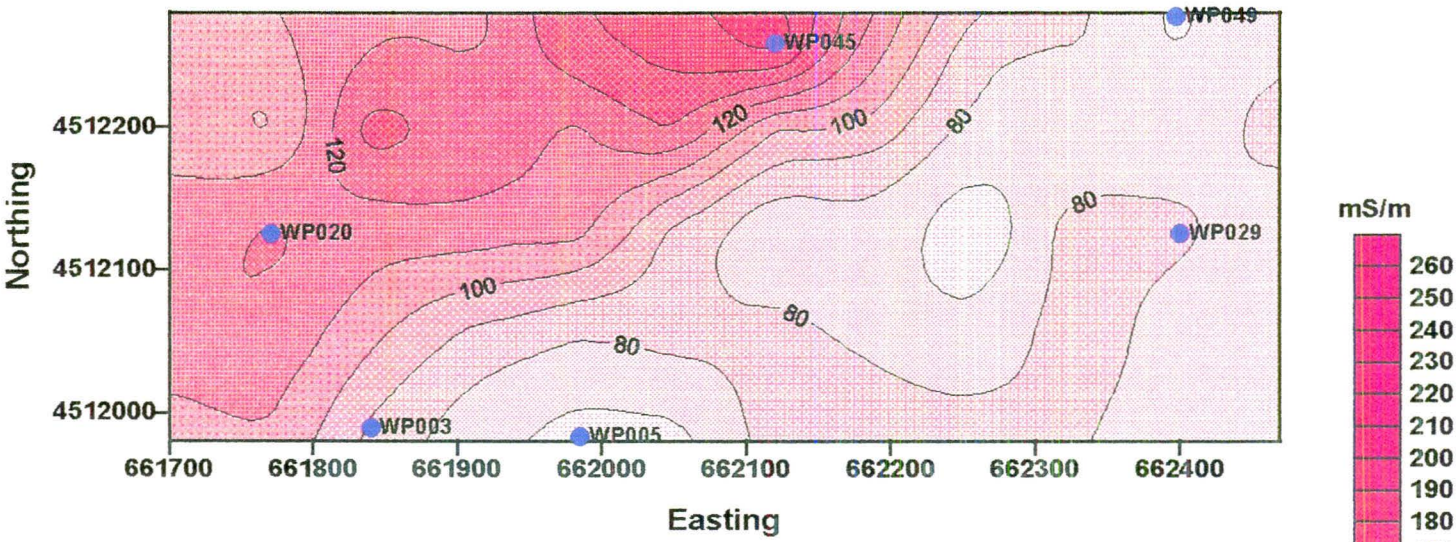


Figure 7

Soil Sample Site

EMI SURVEY
AREA OF SALINE SOILS
GEM300 SENSOR
9810 Hz

Horizontal Dipole Orientation



Vertical Dipole Orientation

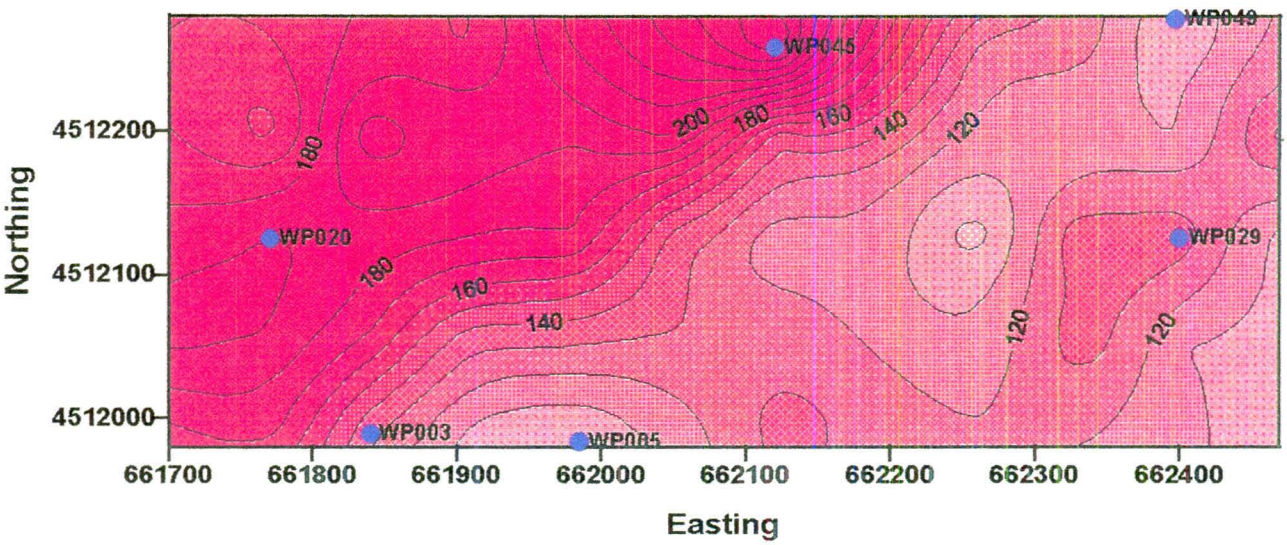


Figure 8

Soil Sample Site

EMI SURVEY
AREA OF SALINE SOILS
GEM300 SENSOR
14790 Hz

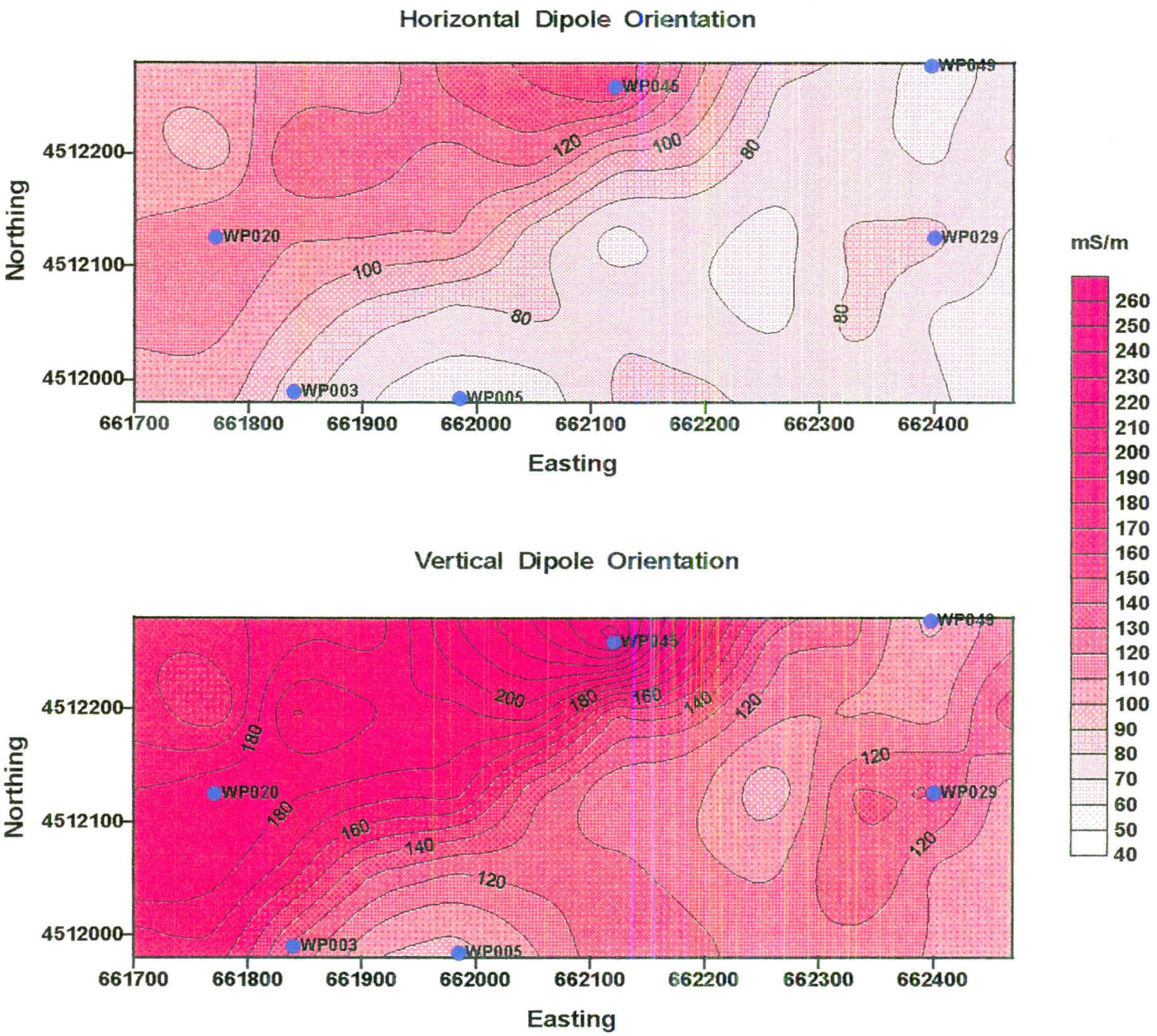
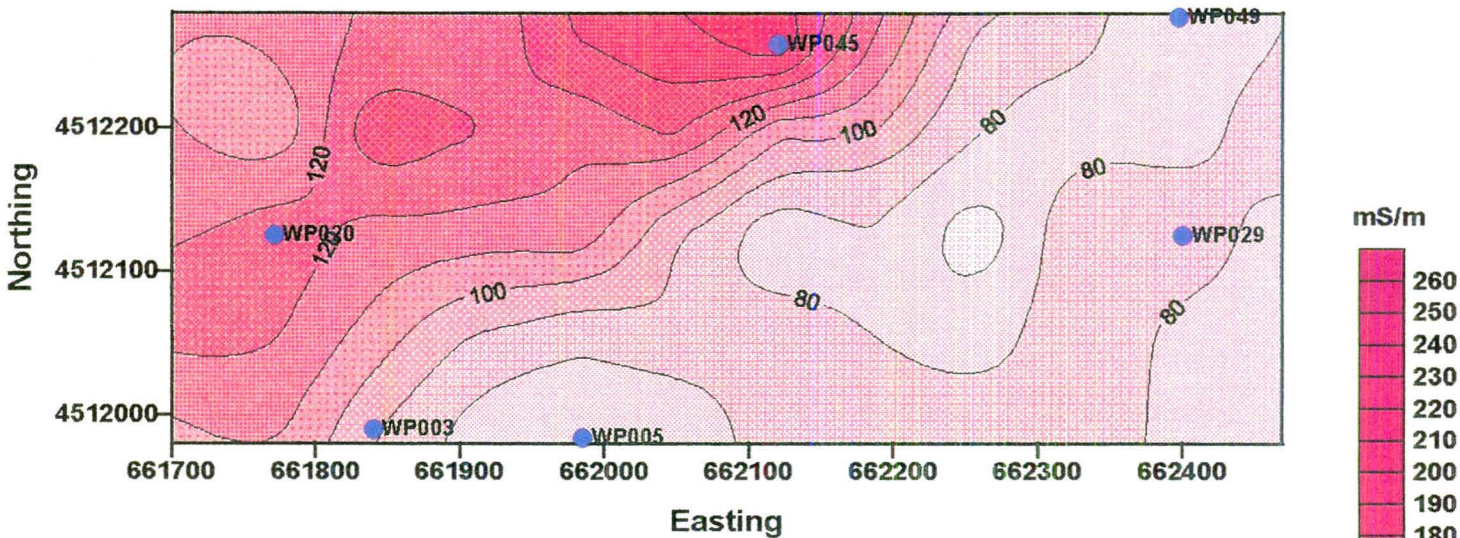


Figure 9

● Soil Sample Site

EMI SURVEY
AREA OF SALINE SOILS
GEM300 SENSOR
19590 Hz

Horizontal Dipole Orientation



Vertical Dipole Orientation

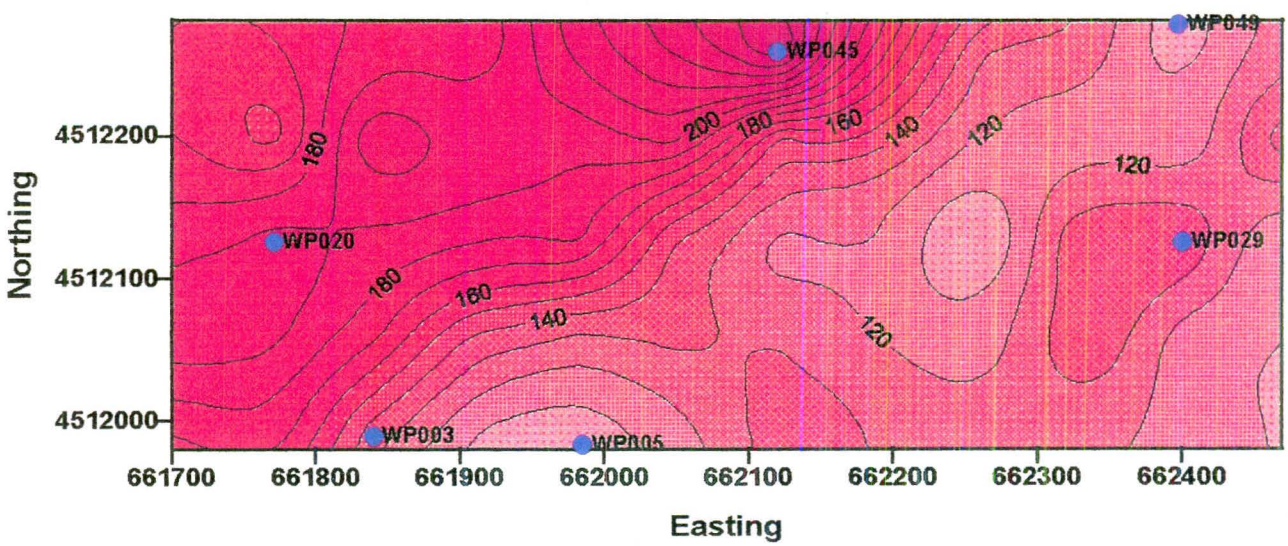


Figure 10

● Soil Sample Site