USE OF ELECTROMAGNETIC INDUCTION TOOLS IN SALINITY ASSESSMENT/APPRAISALS IN EASTERN COLORADO

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Abstract

Electromagnetic induction (EMI) is a relatively low-cost and rapid method for measuring, assessing spatially soil salinity. The two studies were conducted to evaluate data obtained with a single-frequency (EM38 meter) and multi-frequency (GEM300 sensor) EMI instruments and to relate apparent conductivity measured by these instruments with the more conventional conductivity of the saturated soil extract. These two studies were geo-referenced for soil correlation sampling, salinity mapping and future monitoring of salinization and/or degradation. The one study area (54 hectares) utilized a subset sample area for the comparison procedure; the other site (323 hectares) was conducted solely with the EM38 instrument. Data was incorporated into modeling programs and further used into mapping software to develop two-dimensional maps.

Correlation coefficients between the two instruments ranged from 0.8039 to 0.8617. Although the GEM300 sensor predicted somewhat less accurately the conductivity of the soil samples collected and also produced higher apparent conductivity measurements, spatial patterns of apparent and electrical conductivity produced by the two instruments were similar, reasonable and practical for the end user, the agricultural producer.

Introduction

Across the western United States salinity is occurring at an alarming rate on irrigated lands. This "silent killer" is a major cause of reduced crop production, degraded crop quality, and degraded soil and water quality. In these areas, changes in soil salinity need to be measured, fully assessed and monitored to make future evaluations so as to minimize the advance of salinization and soil degradation. Strategies for resource agencies associated with irrigated growers have relied upon traditional soil sampling methods to ascertain the level of salinization which has not been very helpful to determining the quantifying of salinity degradation in a spatial sense. In the early 1980s, electromagnetic induction (EMI) gained acceptance as a useful method for rapid field identification and mapping of soil salinity (Johnston et al., 1997). In the past 20 years EMI has offered a set of tools to assess and assist in monitoring the advance of salinization.

Electromagnetic induction uses electromagnetic energy to measure and map spatial and temporal variations in the apparent conductivity (EC_a) of soils. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific depth (Greenhouse and Slaine, 1983). In areas of salinized soils, such as here in the major river valleys of Colorado, 65 to 70 percent of the variance in apparent conductivity can be explained by changes in the concentration of soluble salts alone (Williams and Baker, 1982). Moderate to high correlations have been found between apparent conductivity and saturated paste extract (EC_e), the most accepted and accurate method of determining soil salinity (de Jong et al., 1979; Williams and Baker, 1982; and Wollenhaupt et al., 1986). Studies have demonstrated that EMI can provide reasonably accurate estimates of soil salinity (Williams and Baker, 1982; van der Lelij, 1983; Diaz and Herrero, 1992).

Since the early 1980s, agronomists, conservationists, and soil scientists have used EMI meters developed by Geonics Limited.[1] In the 1990s, Dualem, Inc., Geophysical Survey Systems, Inc., and

Veris technologies developed additional EMI instruments. Our work in Colorado has concentrated on the use of the Geonics EM-38 for the assessment of salinity in agricultural fields. Our second emphasis is to utilize these tools with geographical positioning system (GPS) instruments, summarize these data and employ computer software to quantify the conductivity data into a spatial map for the agricultural producer. This apparent conductivity (EC_a) measured by the EMI instruments is related to the electrical conductivity of the saturated paste extract (EC_e) using equation developed by the scientists at the United States Salinity Laboratory, Riverside, California.

Materials and Methods:

EMI Instruments:

Involved in our salinity appraisals and assessments is predominantly one instrument, the Geonics EM-38 manufactured by Geonics Limited. We have made comparisons with the Veris instrument that USDA-Agricultural Research Service, Fort Collins, Colorado uses and the GEM300 sensor manufactured by Geophysical Survey Systems, Inc. The EM-38 and GEM300 are portable and require only one person to operate. The Veris unit is pulled behind a vehicle that can traverse rough terrain with the unit in constant contact with the soil surface layer. The EM38 meter is reasonably light at a weight of 2.5kg (5.5lbs). The GEM300 is approximately 8.0kg (17.6 lbs) and carried via a strap over one shoulder at hip height. Each of these units provides the user limited vertical resolution and depth information. Both instruments offer lateral resolution approximately equal to the intercoil spacing in the instrument.

The EM38 meter operates at a frequency of 14,600 Hz. The intercoil spacing is 1 m. It has effective observation depths of about 0.75 and 1.5 meters in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). Output is calibrated to read apparent conductivity (expressed in mS/m) and, with a data logger or computer, in-phase readings are converted into mutual coupling ratios (ratio of the secondary (induced) to the primary electromagnetic fields at the receiver coil) in parts per thousand.

The GEM300 sensor is configured to simultaneously measure up to 16 frequencies between 330 and 19,950 Hz with a fixed intercoil spacing of 1.3 m (Geophysical Survey Systems, Inc., 1998). Multiple frequencies are encoded in a pseudo-random binary sequence and transmitted in a step-frequency mode. The sensor records both in-phase and quadrature measurements. Output is the mutual coupling ratio in parts per million or apparent conductivity (mS/m).

The Study/Work Area:

The area of where our work is being conducted is located on the lower terraces of the South Platte River in Logan, Morgan, Sedgwick and Weld Counties, Colorado. For this project we studied two areas in eastern Logan County, Colorado (figure 1). Our assessments are being carried out in grain corn, sugar beets, small grains, and alfalfa fields. All of the fields have been leveled for irrigation in these two study areas. The soils are medium to heavy textured, somewhat poorly to well drained over stratified alluvium of the South Platte River. The large study area stretches mainly west to northeasterly, east of Crook, Colorado approximately 170 miles northeast of Denver, Colorado.

The fields (nine of them), we assessed contain portions of the following soils on the two farms for this study. The very deep, somewhat poorly drained Alda, Hayford, Loveland soil and the somewhat poorly drained and poorly drained Westplain soil formed in stratified alluvium on flood plains. The Alda soil is moderately deep over coarse sands and gravelly sands. Clay content averages 20 to 25 percent in the upper part of the soil profile. The Alda soil is a member of the coarse-loamy, mixed, superactive, mesic Fluvaquentic Haplustoll family. The Hayford soil is a member of the clayey over sandy-skeletal, smectitic, Aquic Argiustoll family. The clay content ranges from 29 to 45 percent in the upper 22 inches of the soil profile. Below 22 inches is stratified clay loam to fine sand. The Loveland soil is a member of the fine loamy over sandy skeletal, mixed, calcareous, mesic Fluvaquentic Haplaquoll family. The clay content averages 27 to 40 percent to 34 inches. Below 34 inches is gravelly sand. The Mosher soil is a member of the fine, smectitic, mesic vertic Natrustoll. Clay content averages 35 to 48 percent to 20 inches overlying stratified loamy sand to clay. 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 is a member of the clayey over sandy or sandy-skeletal, smectitic, calcareous, mesic Typic Haplaquoll family.

Field Procedures:

It is our practice to set out within field boundaries, a rectangular shaped grid across each agricultural field using a GPS Receiver. It is important to bring in the agriculture producers' management techniques, style and perceptions as we design the grid to have a minimum of 50 points of observations. The coordinates of all observation points were obtained with a GPS receiver. The distance between observation points varies according to the overall field size and our predetermination to obtain 50 points of data for statistical completeness. Early in our field procedures we placed survey flags inserted in the ground at regularly stepped off dimensions at each observation point. With the full utilization of GPS tools we have discarded that step. When revisits are needed to any one X,Y coordinate in the field, we return via the GPS receiver waypoint.

As measurements are obtained in both the horizontal and vertical dipole orientations and precise positioning of both instruments were required, EMI surveys are conducted in a station-to-station rather than a continuous mode. Apparent conductivity measurements were recorded at each observation point with an EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations. To remove residual signals arising from magnetic susceptibility, the EM38 meter was re-nulled before each measurement (Geonics Limited, 1998). At each observation point, in-phase, quadrature phase, and conductivity data were recorded with the GEM300 sensor at four different frequencies (6390, 9810, 14790, and 19590 Hz). Measurements were taken with the GEM300 sensor held at hip-height in both the horizontal and vertical dipole orientations. All apparent conductivity measurements were standardized to an equivalent conductivity at a reference temperature of 25^{o} C.

Soil samples are collected at several observation points derived from ESAP software (Lesch et al, 2000) calculations that have been developed by USDA-ARS scientists at the Salinity Laboratory, Riverside, California. The sampling sites were selected to span the observed range in apparent conductivity and to provide reasonable coverage of each study area. At each sampling site, soil samples were acquired in 30 cm intervals down to a depth of 120 cm. For each sample, particle-size was determined with the use of the Hach Chemical Co. SIW Salinity Appraisal Laboratory (Hach, 1998). Reference samples, have been taken for correlation and run by the National Soil Survey Laboratory, Lincoln, Nebraska, electrical conductivity was determined by the saturated paste extract method (Soil Survey Staff, 1996).

With 50 plus observations per field, correlation soil samples at 30cm intervals from statistical representative X,Y points across the field we are able to construct two dimensional maps of isolines that a producer can comprehend the spatial variability of the soil salinity. Examples from our two study areas are in figures 2,3, and 4. Our intent armed with this information is to provide the agriculture producer management alternatives and conservation practices that can minimize the growing salinization. The strategies we can offer depend upon the soil survey and salinity survey with the tools discussed.

Theories of Operation:

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

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

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

where '<u>s</u>' is the ground conductivity (mS/m) and '<u>f</u> ' is the frequency (kHz).

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

Slavich (1990) and others reported that the depth of observation would vary depending on the apparent electrical conductivity of the profiled material(s). Greenhouse and others (1998) have recently commented that the electrical conductivity of soils plays a critical role in defining the depth of observation that can be obtained with EMI. Furthermore, these authors noted that electromagnetic induction instruments would not penetrate a fixed distance under all circumstances.

Under conditions of low induction numbers, instrument responses are directly proportional to the conductivity of the soil. Conditions of low induction numbers are fulfilled when the intercoil spacing is less than the skin depth in all profiled horizons or layers (McNeill, 1980). Conditions of low induction numbers are satisfied in most soils. However, in soils having apparent conductivity greater than 80 mS/m, these conditions are not fulfilled, and therefore, EMI measurements are no longer linearly related to soil conductivity (McNeill, 1980).

Results

Soil Analysis:

Variations in apparent conductivity are produced by changes in the electrical conductivity of soils. The electrical conductivity of soils is influenced by several factors: the types and concentrations 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). In soils, apparent conductivity increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Flood plain soil map units are recognized for their high textural and taxonomic variability over short distances (Daniels and Hammer, 1992). In general, within the work/study area, the clay content decreased with increasing soil depth, but at variable rates. The principal soils mapped within the study area include Alda, Hayford, Loveland, Mosher, Westplain, and Fluvaquentic Haplaquoll (Amen, 1977).

Apparent Conductivity Data:

In the large study area (far eastern portion of Logan County, near Crook, Colorado - see figure 4) we assessed an area of 323 hectares (800 acres) and we collected 475 measurements. The observations in the horizontal dipole orientation (with an effective observation of about 75 cm) with the EM38 the average reading, 475 data points collected is 49.62 mS/m. In the vertical dipole orientation, (with an effective observation of about 150 cm) the average reading of all the points collected is 49.97 mS/m. Fifty-nine percent of the observations had an apparent conductivity of less than the average of 49.66 mS/m. The range of apparent conductivity observations was 21 to 173 mS/m in the horizontal dipole orientation and range for the vertical dipole orientation was 23 to 168 mS/m. A majority (51%) of the observation points, apparent conductivity increased with increasing soil depth (vertical dipole measurements greater than horizontal dipole measurements). At thirty-nine percent of the observation points, apparent conductivity remained relatively uniform throughout the soil profile.

In the second study area (central portion of Logan County, near Iliff, Colorado) we assessed a 54 hectare (133 acres) field and collected 136 measurements. The observations in the horizontal dipole orientation (with an effective observation of about 75 cm) with the EM38 the average reading of 136 data points collected is 39.48 mS/m. In the vertical dipole orientation, (with an effective observation of about 150 cm) the average reading of all the points collected is 42.85 mS/m. and the mean reading is 48.05 mS/m. Fifty-six percent of the observations had an apparent conductivity of less than the average. The range of apparent conductivity observations was 10 to 86 mS/m in the horizontal dipole orientation and range for the vertical dipole orientation was 7 to 91 mS/m. A majority (64%) of the observation points, apparent conductivity increased with decreasing soil depth (horizontal dipole measurements greater than vertical dipole measurements). At thirty percent of the observation points, apparent conductivity remained relatively uniform throughout the soil profile.

At the central Logan County site we made a comparison subset with the GEM300 sensor. Assuming an average apparent conductivity of about 157 mS/m, skin depths of 15.7, 12.7, 10.4, and 9.0 m are projected at frequencies of 6390, 9810, 14790, and 19590 Hz, respectively. Data obtained in the vertical dipole orientation (VD) were higher than data obtained in the horizontal dipole orientation (HD). Data obtained in like dipole orientation but at different frequencies were closely similar. In each dipole orientation, the close similarities in the data suggest that variations in response with depth are mitigated by the strong response of the GEM300 sensor to the salts that occur in the upper part of the profiled soil materials. In areas of saline soils, the use of multiple frequencies does not appear to offer significantly different depth-responses and provides no additional information.

In figure 2 depicts two-dimensional plots of data collected with the EM38 and the GEM300 sensor at the central Logan site. Each figure contains plots of apparent conductivity collected at a specified frequency in either the horizontal or vertical dipole orientation. In each plot the isoline interval is 10 mS/m.

At the central Logan County site we completed an assessment for the producer, that is depicted in the figure 3. This salinity assessment is converted from the apparent conductivity observations to EC_e that which is equivalent to saturated paste conductivity completed in soil testing laboratories.

In a theoretical discussion on EMI, McNeill (1980) observed that the measured apparent conductivity is a function of the instruments' calibration, coil separation, coil orientation, and frequency. Apparent conductivity values are seldom diagnostic in themselves. However, spatial patterns and the relative magnitudes of apparent conductivity do provide inferential clues as to differences in soils and soil properties. With minor exceptions and regardless of device, purported observation depth, or frequency, the plotted spatial patterns were similar. Because of the magnitude of measurements, spatial patterns are presumed to principally correspond with differences in soil salinity.

It has been our challenge in the use of EMI for soil salinity mapping to make the conversion of apparent conductivity (EC_a) into a more commonly used measure of soil salinity (EC_e) for different depth intervals. At numerous sampling sites at both study areas, responses from both instruments were related to the electrical conductivity of the saturated paste extracts. Moderate to high correlations were obtained with both instruments (see Table 1). For each instrument, correlations were higher for the upper soil layers (0 to 60 cm), than for the lower soil layers (60 to 120 cm). With the exception of the 0 to 30 cm and 90 to 120 cm layers, correlations were slightly higher for the EM38 meter than for the GEM300 sensor. For the EM38 meter, with the exception of the 0 to 30 cm depth interval, correlations were slightly higher for measurements taken in the vertical than in the horizontal dipole orientation. With the GEM300 sensor and for all depth intervals, correlations were slightly higher in the horizontal than in the vertical dipole orientation. For 0 to 30 cm layer, measurements taken with the GEM300 were more strongly correlated with soil salinity than those obtained with the EM38 meter.

In our study of the central Logan County site, we (Doolittle, 2000.) used depth-response functions of the EM38 to convert EC_a to EC_e a well accepted measurement of salinity throughout the irrigated world. All the Geonics Limited instruments have depth-response functions developed and established. No depth-response function has been developed for the GEM300 sensor and no models have been developed. Estimation of soil salinity (see figure 3) were restricted best to the 0 to 60 cm interval because of the increased variability of soil textures across each study area at lower depths. Using methods described by Wollenhaupt and others (1986), values of EC_e for each depth interval were weighted by the depth response function of the EM38 meter (McNeill, 1980) and summed to provide a single value for each sampling site. This weighted value was correlated with the response of the EM38 meter in both the horizontal and vertical dipole orientations by simple linear regression. Correlation coefficients of 0.9790 and 0.9903 were obtained for the weighted EC_e and the meter's responses in the horizontal and vertical dipole orientations, respectively. A predictive equation was developed and used to convert the vertical dipole measurements of EC_a into estimates of EC_e at each observation point:

$$EC_e = 0.0291 + (0.0825 * EM_V) \qquad [2]$$

where EC_e is the soil salinity (mS/cm) and 6390 Hz HD the response (mS/m) of the GEM300 sensor operating at a frequency of 6390 Hz in the horizontal dipole orientation. For the six sampling sites, using this predictive equation, the average difference between the measured and the predicted soil salinity was 0.41 mS/cm with a range of -0.46 to 0.69 mS/m.

Spatial patterns as exhibited in figure 2 are similar for both instruments and models on the subset of the central Logan County site. Figure 3 shows the spatial distribution of soil salinity within the 0 to 30 cm depth interval as estimated with the EM38 meter for the entire field. For the EM38 meter, the estimated salinity averaged 1.47 mS/cm and ranged from 0.2 to 6.23 mS/cm. Based on EMI data and predictive equation [2], the 0 to 30 cm depth layer would be classified as being very slightly saline (2 to <4 mS/cm). Classes of salinity as follows: nonsaline (< 2 mS/cm), very slightly saline (2 to <4 mS/cm), and slightly saline (4 to <8 mS/cm). Based on our knowledge of the site, these estimates and spatial patterns appear reasonable.

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). Anisotrophic soil properties reduce the reliability of EMI interpretations and models. As a consequence, soil salinity levels predicted from EMI data and various models are not as accurate as desired (Rhoades et al., 1989; Johnston et al, 1997). Nevertheless, these models appear to provide reasonable estimates of soil salinity and satisfy most mapping requirements.

Conclusions

In the central Logan study, EMI measurements were obtained with two instruments. Results were found to be quite similar, but not identical. Both instruments can be used to infer areas of high salinity and delineate areas with widely differing salinity. Once these areas have been delineated other methods can be used to more intensively sample and relate the measured values of apparent conductivity to soil salinity.

The EM38 meter is the established geophysical tool for salinity appraisals here in Colorado. The EM38 meter is very sensitive and often requires frequent and tedious scale adjustments. The GEM300 sensor is operated by a keypad. It is easier to operate and requires less field time to complete a survey. Both instruments provided similar spatial patterns of apparent conductivity. Measurements of apparent conductivity collected with the GEM300 sensor, though comparable, were higher and more variable than those collected with the EM38 meter. With the GEM300 sensor, data obtained in similar dipole orientation but at different frequencies were closely similar. Different dipole orientations produced different responses. In areas of saline soils, the use of multiple frequencies provides little additional information and does not improve interpretations.

At the eastern Logan County study site of 323 hectares (figure 4) the EM38 instrument was used exclusively. It is expected with the variability of the substratum of the soils that the number of observations per field will remain the same or decrease (never below the statistical minimum 50) due to the overall field management techniques with irrigation, fertilization and tillage practices. With the advancing utilization of Precision Farming methods the geo-referenced saline soils assessments will be very valuable to the integration of resource management practices in salinized areas.

Predictive models have been developed to estimate soil salinity from the data collected with the EM38 meter. Two models were applied to data collected with the EM38 meter and one to the GEM300 sensor. Spatial patterns and values of soil salinity were similar for both instruments and models. These models provided reasonable estimates of soil salinity and appear to satisfy mapping requirements.

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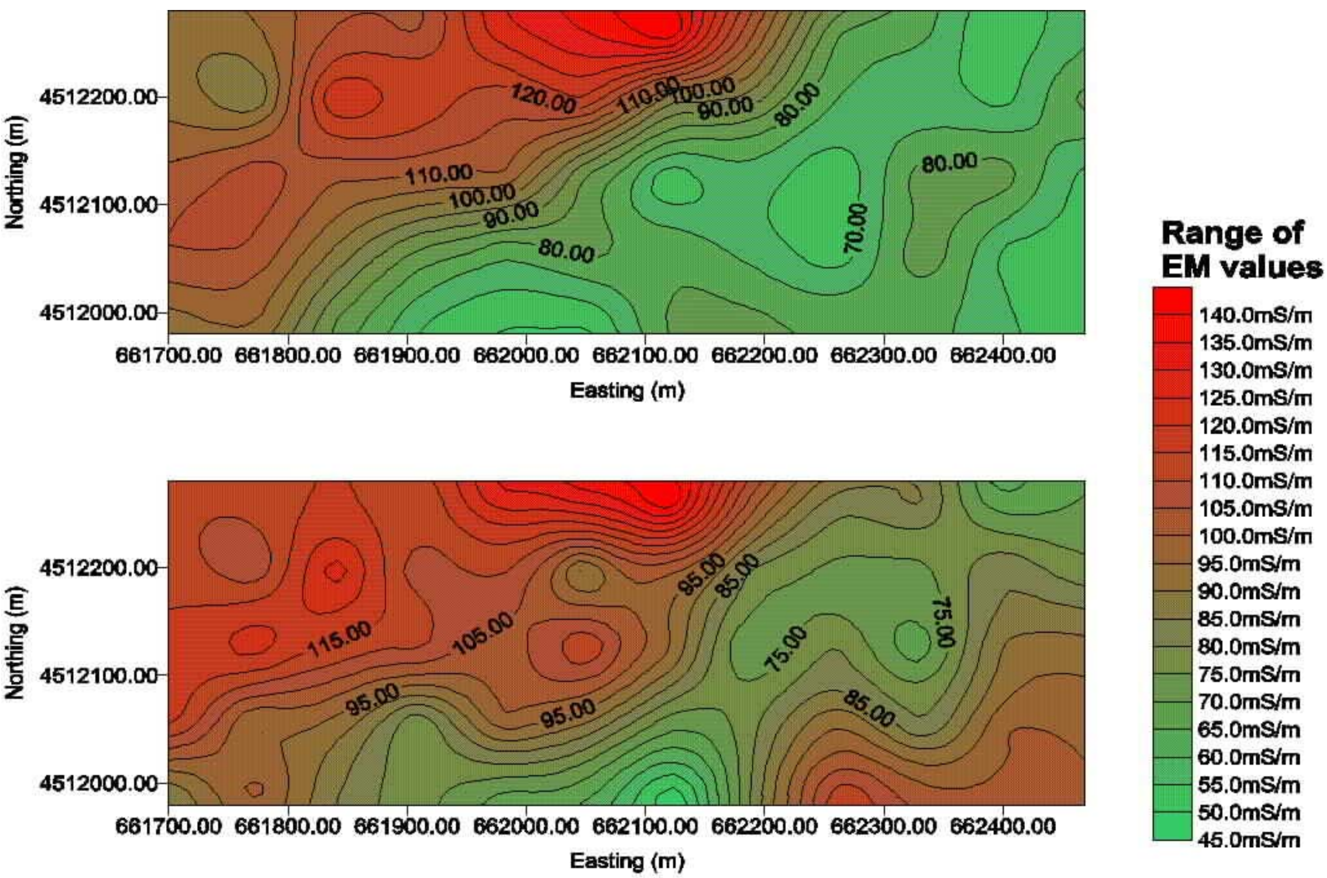

Figure 2. Apparent Conductivity of the GEM300 Horizontal dipole (14790 Hz) top diagram, lower diagram is apparent conductivity of the Geonics EM38.

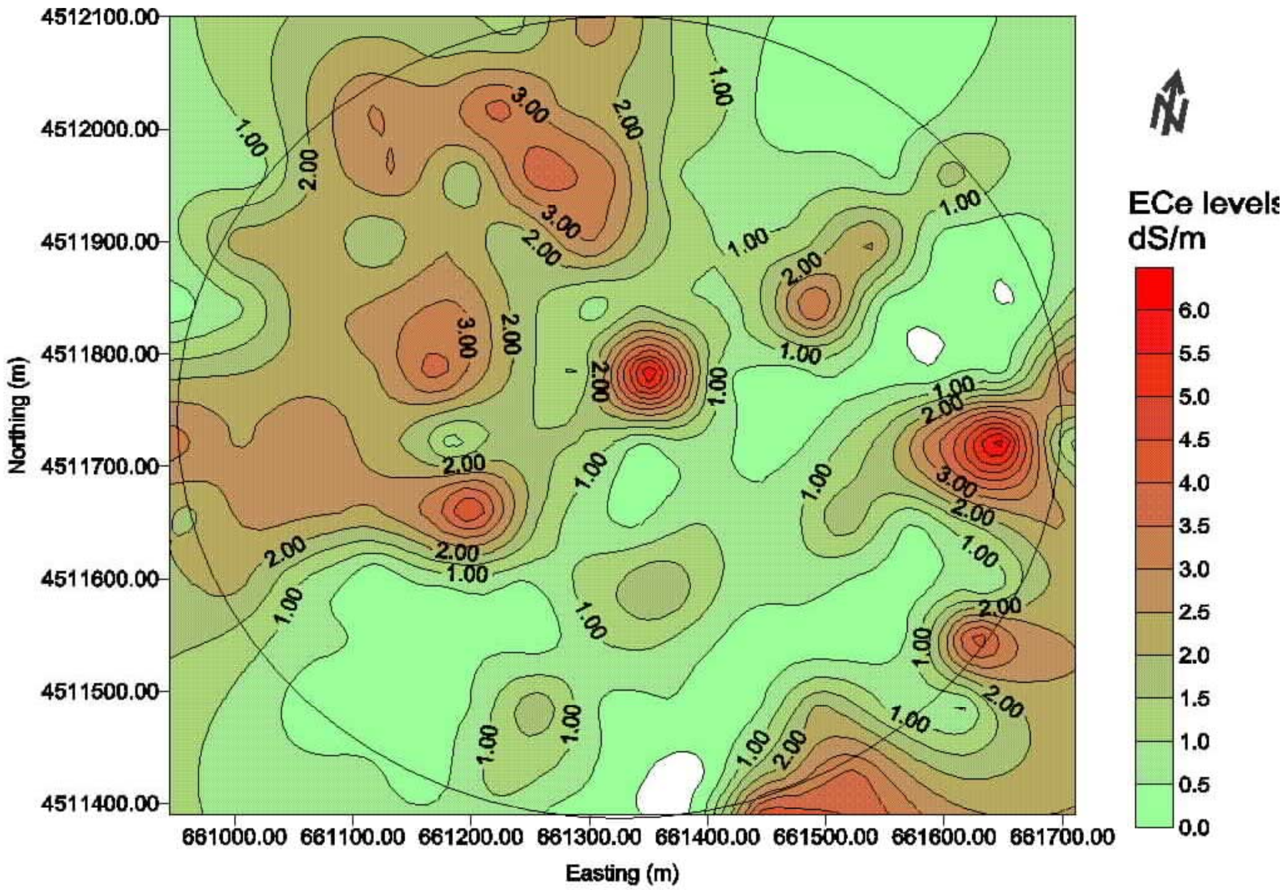

Figure 3. Spatial depiction of Central Logan County, CO site Isolines are in dS/m at 0.5m Intervals.

Table 1
Correlations between the saturated paste extract conductivity (mS/cm) and EMI response (mS/m) for selected depth intervals and different instruments, dipole orientations, and frequencies.

	Saturated Paste Extract Conductivity by Depth Interval						
Device	**0-30 cm**	**30-60 cm**	**60-90 cm**	**90-120 cm**	**0-60 cm**	**0-90 cm**	**0-120 cm**
EM38 HD	0.917	0.875	0.752	0.638	0.965	0.916	0.907
EM38 VD	0.905	0.912	0.781	0.651	0.986	0.942	0.931
6390 Hz HD	0.928	0.822	0.701	0.676	0.933	0.875	0.889
6390 Hz VD	0.924	0.796	0.676	0.646	0.914	0.852	0.862
9810 Hz HD	0.942	0.802	0.668	0.704	0.925	0.855	0.885
9810 Hz VD	0.923	0.797	0.677	0.646	0.914	0.853	0.863
14790 Hz HD	0.935	0.816	0.688	0.679	0.932	0.869	0.886
14790 Hz VD	0.924	0.800	0.681	0.645	0.917	0.856	0.865
19590 Hz HD	0.935	0.818	0.690	0.682	0.933	0.870	0.888
19590 Hz VD	0.923	0.802	0.684	0.645	0.917	0.858	0.866

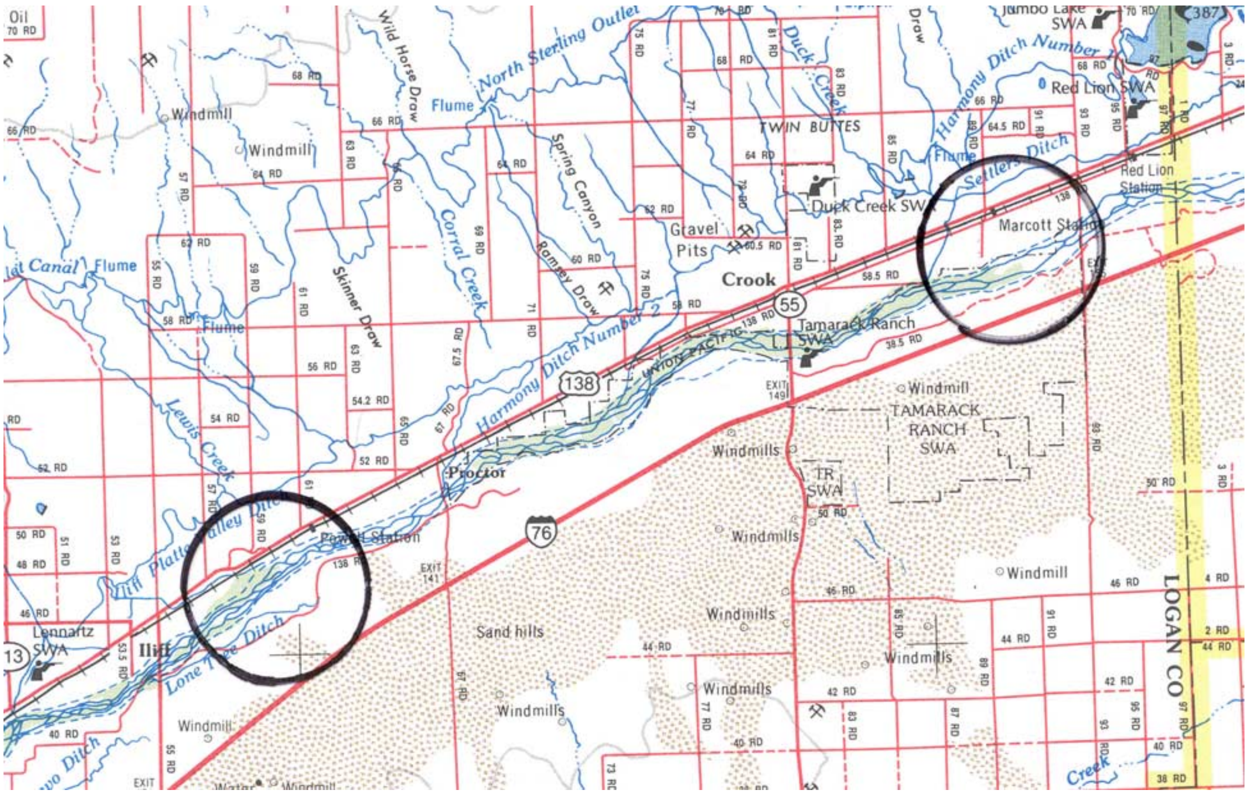

Figure 1. Geographic region of two study areas east on Highway CO 138 near Iliff and Crook.

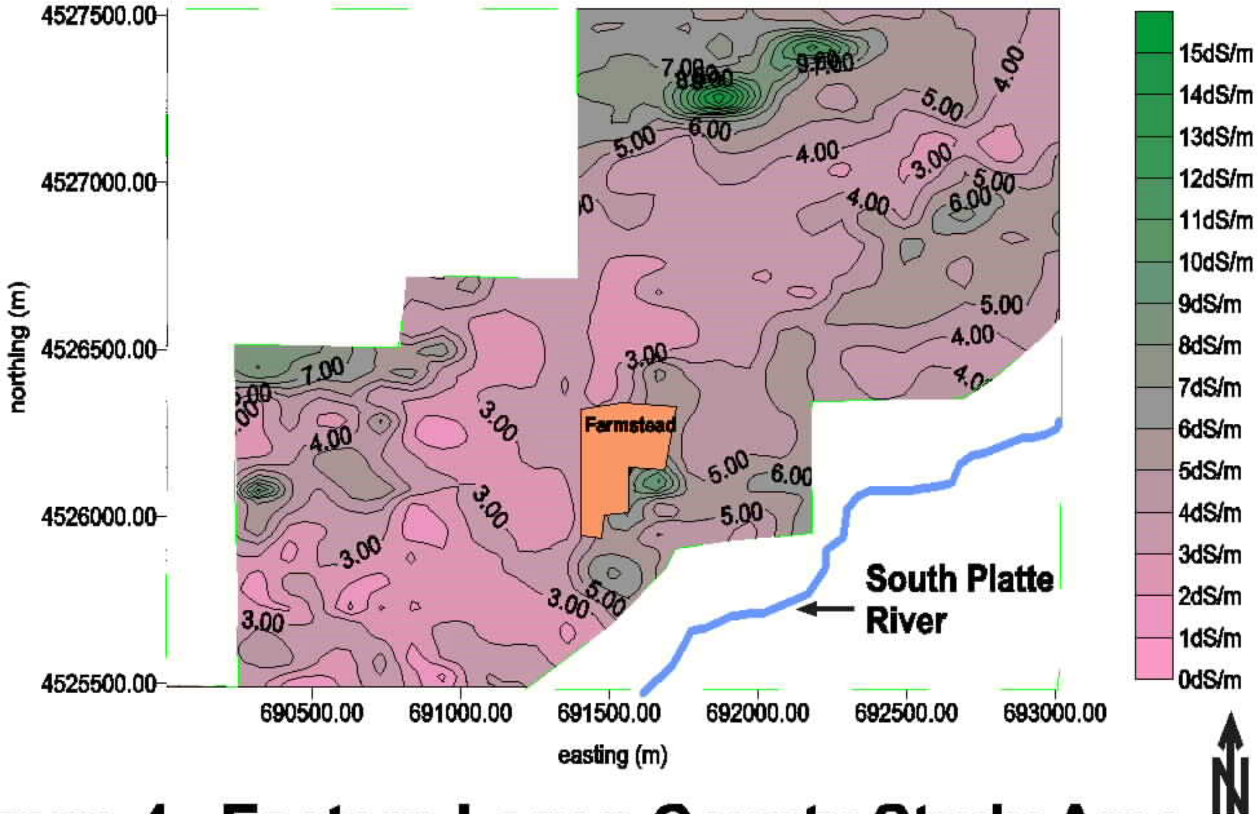

Figure 4. Eastern Logan County Study Area Salinity Map of Entire 323 ha. (800 acres) farm