United States Department of Agriculture | **Natural Resources Conservation Service** | **11 Campus Boulevard Suite 200 Newtown Square, PA 19073**

Subject: -- Geophysical Assistance -- **Date:** September 21, 2006

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Purpose:
The purpose of the study was to evaluate electromagnetic induction (EMI) as a possible tool for identifying and verifying the former wetland boundary on sites with altered hydrology, vegetation, and/or soils in southern Minnesota. The delineations of wetland boundaries are needed to identifying potential wetland mitigation and wetland impact areas.

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Activities:
All field activities were completed during the period of 16 to 18 August 2006.

Results:

1. Differences in apparent conductivity (EC_a) were associated with hydropedological properties and different soil, landscape, and vegetative components.

2. Spatial EC_a patterns appear to indicate the location of the hydric/non-hydric boundary line on some sites with altered hydrology, vegetation, and/or soils.

3. At a majority of the sites, a ring of noticeably higher EC_a surrounds depressions and deep and shallow marsh zones. In general, these peripheral areas conform to the wet meadow zone. Though more saturated and often having higher clay content, the central portions of depressions have lower EC_a than the surrounding peripheral areas. Lower EC_a in depressions is attributed to the downward flow of water and the resulting leaching and translocation of materials, especially soluble salts and carbonates. In the wet

meadow zone, which borders these depressions, evaporative discharge is suspected to have caused the accumulation of carbonates and other dissolved materials which results in higher EC_a.

4. Results support the continuation of this study. Crops encumbered, slowed, and restricted EMI surveys. No sampling was carried out to confirm the interpretations made in this report. Returning to these sites when the fields are dry and fallow would allow a mobile (use of ATV) EMI survey. A mobile EMI survey would provide more comprehensive site coverage, in a shorter period of time, and with less effort than the pedestrian surveys conducted in this reported study. The EMI survey should be supported with adequate soil sampling and characterization to confirm interpretations.

The principal investigators wish to express their appreciation for the assistance that was provided by the staffs of the Southern Research and Outreach Center and the Minnesota USDA-NRCS soil scientists. Special thanks are extended to Doug Miller for sharing his intimate knowledge of the soils at the Southern Research and Outreach Center.

With kind regards,

James A. Doolittle
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Background:

The Central Iowa and Minnesota Till Prairie (MLRA 103) is characterized by a nearly level to gently rolling glacial till plain with numerous lakes, swales, and depressions. This glaciated landscape has highly complex local groundwater flow systems, with many, small, depression-focused flow systems (Richardson et al., 2001). Depressions may act as either groundwater recharge or discharge wetlands and may be both at different times of the year (Lissey, 1971). Recharge wetlands are typified by soils with leached profiles and low contents of carbonates and soluble salts. In the central portion of some depressions, the downward flow of water results in the translocation and accumulation of clays, and the formation of Btg horizons (Richardson et al., 2001). In contrast, discharge wetlands accumulate large amounts of carbonates and soluble salts in the solum (Evans and Freeland, 2001). In many depressions, groundwater discharge is focused along the edges, resulting in the accumulation of carbonates and soluble salts. In these peripheral areas, Bk horizons form and dissolved materials accumulate near the soil surface as a result of evaporative discharge (Richardson et al., 2001).

Depressional wetlands are classified on the basis of recognizable vegetation zones (Stewart and Kantrud, 1971). Depressional wetlands typically have a central zone dominated by a deep marsh plant community. In succession, the deep marsh zone is surrounded by shallow marsh, wet meadow, and low prairie zones. Each zone represents a shorter period of ponding and soil saturation. The wet meadow zone temporarily ponds water for a few days in most springs and after heavy rains, and is considered the driest part of a jurisdictional wetland. In the Central Iowa and Minnesota Till Prairie, most areas are drained by tiles. Morphological indicators of soil moistures are often relic features indicative of earlier, pre-disturbance hydrologic conditions (Richardson et al., 2001). Under conditions of altered hydrology and vegetation, soils often provide the most meaningful indicator of former hydric conditions.

Wetland boundaries need to be identified for potential wetland mitigation and wetland impact areas. The identification and verification of the former wetland boundary in areas of altered hydrology, vegetation, and/or soils is a slow and labor intensive task. This study evaluates the use of electromagnetic induction (EMI) for the identification of former wetland boundaries on sites with altered hydrology, vegetation, and/or soils in southern Minnesota.

Electromagnetic induction is a non-invasive geophysical method that measures the apparent conductivity (EC_a) of earthen materials. Apparent conductivity is dependent upon the moisture, clay, and soluble salt contents of soils (McNeill, 1980). Areas with different EC_a have been associated with different soils and hydropedological properties. Increasingly, EMI is being used in hydropedological investigations to help characterize spatial and temporal variations in soil moisture contents, depth to water tables, and groundwater flow patterns at different scales and levels of resolution. Allred et al. (2005) observed that EC_a is strongly affected by the near-surface volumetric water content and the depth to the water table. Several researchers have documented the positive relationship that exists between EC_a and soil water content, and the negative relationships that exist among relative elevation, depth to water tables, and EC_a (Khakural et al., 1998; Sheets and Hendrickx, 1995; Kachanoski et al., 1990 and 1988). Because of these relationships, EMI has been successfully used to map spatial and temporal variations in water table depths (Schumann and Zaman, 2003; Doolittle et al., 2000) and drainage classes (Kravchenko et al., 2002).

Apparent conductivity is sensitive to changes in soil water content, and the concentration and mobility of ions dissolved in the soil solution (Allred et al., 2005). In arid and semiarid areas, EMI has been used to characterize unsaturated flow (Scanlon et al., 1999), estimate rates of groundwater recharge (Cook et al. , 1992, 1989a, 1989b), map groundwater discharge zones (Richardson and Williams, 1994), and assess differences in soluble salt contents across landscapes (Cook et al., 1989a). In humid areas, where the concentration of soluble salts is generally low, spatial changes in EC_a have been principally related to changes in volumetric water content and soil texture (Kachanoski et al., 1990).

In this study, EMI was used to map EC_a across a landscape composed of the Webster-Nicollet-Clarion association in the Central Iowa and Minnesota Till Prairie (MLRA 103) of south central Minnesota. The objective of this study was to evaluate the potential of EMI to delineate former wetland boundaries on sites with altered hydrology, vegetation, and soils. The hydric/non-hydric soil boundary is indicated by a change from high (≥ 3) to low (≤ 2)

chroma colors. Low chroma colors, results from saturated conditions and the depletion, redistribution and translocation of iron.

Equipment:
The electromagnetic induction meter used in this study was the EM38DD (manufactured by Geonics Limited, Mississauga, Ontario).[1] Geonics Limited (2000) describes the operating procedures for this meter. The EM38DD meter consists of two EM38 meters bolted together and electronically coupled (see Figure 1). One meter acts as a master unit (meter that is positioned in the vertical orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal orientation with only the receiver switched on). The EM38DD meter weighs about 2.8 kg (6.2 lbs), is portable, and requires only one person to operate. No ground contact is required with this meter. The EM38DD operates at a frequency of 14,600 Hz. It has effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively.

Figure 1. EM38DD meter being operated in the field.

The Geonics DAS70 Data Acquisition System was used with the EM38DD meter to record and store both EC_a and position data.[1] The acquisition system consisted of the EM38DD meter; an Allegro CE or CX field computer (Juniper Systems, North Logan, UT) (see Figure 1) with the Trackmaker 38DD software (Geomar Software, Inc., Mississauga, Ontario); and a Garmin Global Positioning System (GPS) Map 76 receiver (with a CSI Radio Beacon receiver, antenna, and accessories that are fitted into a backpack) (Garmin International, Inc., Olathe, KS) (not pictured in Figure 1).[1] When attached to the acquisition system, the EM38DD meter is keypad operated and measurements are automatically triggered.

To help summarize the results of this study, the SURFER for Windows (version 8) program (Golden Software, Inc., Golden, CO) was used to construct the two-dimensional plots shown in this report.[1] Grids were created using kriging methods with an octant search.

Study Site:
Selected wetland sites were located in Section 24, T. 107 N., R. 24 S., on the University of Minnesota's Southern Research and Outreach Center, Waseca, Minnesota. Wetlands were in native grasses and forbs. Areas surrounding the wetlands were in cultivation (principally corn, soybean, and alfalfa). The selected wetland sites are located in MLRA 103, the Central Iowa and Minnesota Till Prairie. Soils have formed in calcareous glacial drift that was deposited within the Des Moines lobe during the Mankato substage of the Wisconsin glaciation (10,000 years before present). On the general soil map of Waseca County, the study sites are located in an area of the Webster-Nicollet-Clarion association. Differences in taxonomic classification of these soils are largely due to differing

[1] Manufacturer's names are provided for specific information; use does not constitute endorsement.

textures, carbonate status, and moisture regimes, which vary with topographic position (Steinwand and Fenton, 1995). The well drained Clarion soil is on summit and shoulder slope components. Clarion soil has a Bw horizon with high chroma (3 or 4) colors and no redoximorphic features. Nicollet soil is on back slopes and is intermediate in degree of saturation and development of a gray matrix (Khan and Fenton, 1994). While the B horizon can have chromas of 2 to 4, the upper part has either a low chroma (≤ 2) matrix or low chroma mottles. The poorly drained Webster soil is on slightly lower-lying positions and has a gleyed B horizon with low chroma (1 or 2) matrix colors, bright mottles and Fe-Mn concretions (Khan and Fenton, 1994). These features are the result of iron depletion, redistribution, and translocation (Khan and Fenton, 1994).

In this landscape, the hydrology is characterized by recharge under topographic highs, lateral flow on side slopes and discharge in depressions and swales (Steinwand and Fenton, 1995). However, during dry periods, portions of some swales act as recharge areas and lateral flow is reversed between depressions and swales (Steinwand and Fenton, 1995). Soils with higher soluble salt contents and/or Bk horizons develop around depressions as a result of edge-effect and evaporative discharge. Khan and Fenton (1994) observed higher ratios of calcite and dolomite in the solum than in the substratum of soils surrounding depressions. The difference is attributed to the accumulation of secondary carbonates in the sola of these soils and is related to discharge from shallow water tables (Khan and Fenton, 1994).

An order-two soil map, which includes the study sites, is shown in Figure 2. The principal soil map units that occur in the study sites are listed in Table 1. The taxonomic classifications of the named soil components are listed in Table 2. The most extensive map unit is Webster clay loam, 0 to 2 percent slopes (M.U. L83A). This ubiquitous unit interconnects and occurs on all of the study sites.

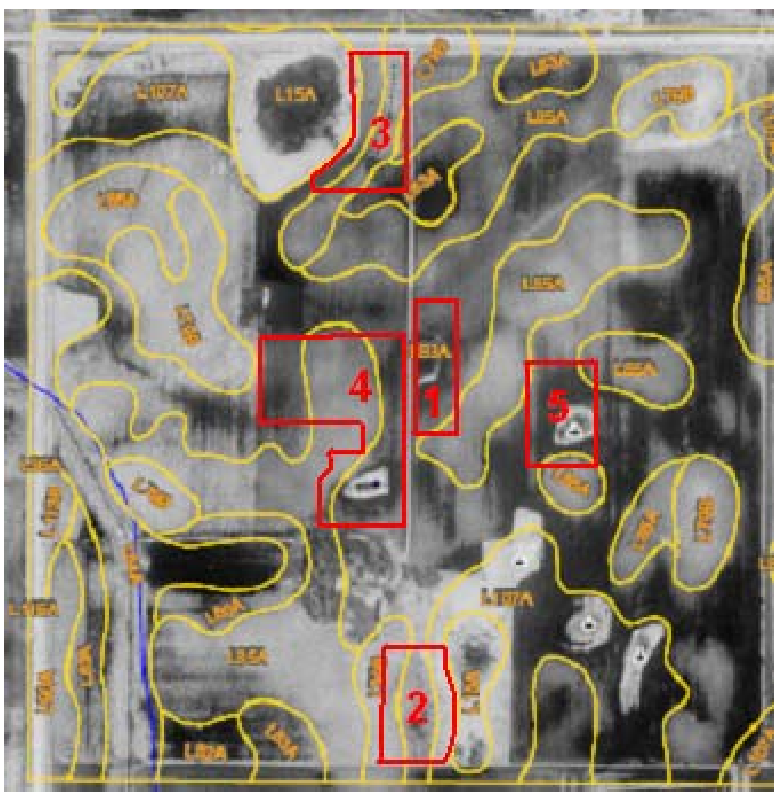

Figure 2. Soil polygons and symbols overlay an ortho-photograph of the study area. The locations and name of the five study sites are shown in red.

The locations and identifications of the five study sites are shown in Figure 2. Study Site 1 is border on the west by a farm road. It consists of a depression and bordering areas. Because of the small size of this depression, it was included in mapping within a larger unit of Webster clay loam, 0 to 2 percent slopes. A small area of Nicollet clay loam, 1 to 3 percent slopes (M. U. L85A), occurs on the slightly higher-lying, southeast corner of this site.

Table 1
List of Soil Map Units found in the Study Sites

Symbol	Soil Map Unit Name
L15A	Klossner, Okoboji, and Glencoe soils, ponded, 0 to 1 percent slopes
L79B	Clarion loam, 2 to 5 percent slopes
L83A	Webster clay loam, 0 to 2 percent slopes
L84A	Glencoe clay loam, 0 to 2 percent slopes
L85A	Nicollet clay loam, 1 to 3 percent slopes
L107A	Canisteo-Glencoe, depressional, complex, 0 to 2 percent slopes

Study Site 2 borders the western side of a depressional wetland (deep and shallow marsh wetlands), which was mapped as Klossner, Okoboji, and Glencoe soils, ponded, 0 to 1 percent slopes (M.U. L15A). Ascending the slopes away from this depressional wetland are, in succession, units of Canisteo-Glencoe, depressional, complex, 0 to 2 percent slopes (M. U. L107A), Webster clay loam, 0 to 2 percent slopes, and Clarion loam, 2 to 5 percent slopes (M. U. L79B). The site is border on the south and west by farm roads.

Study Site 3 borders the eastern side of a depressional wetland (deep and shallow marsh wetlands), which was mapped as Klossner, Okoboji, and Glencoe soils, ponded, 0 to 1 percent slopes. This site is border on the east by a farm road and on the north by a county road. This site contained the most relief and consists of units of Webster clay loam, 0 to 2 percent slopes, and Clarion loam, 2 to 5 percent slopes, and Nicollet clay loam, 1 to 3 percent slopes.

Study Site 4 consists of a unit of Webster clay loam, 0 to 2 percent slopes, and Nicollet clay loam, 1 to 3 percent slopes. This site is border on the east by a farm road. Included in mapping with the Webster unit is a small depression (shallow marsh wetland). Study Site 5 also consists of units of Webster clay loam, 0 to 2 percent slopes, and Nicollet clay loam, 1 to 3 percent slopes. Included in mapping with the Webster unit is a small depression (shallow marsh wetland).

Table 2.
Taxonomic Classification of Soils

Series	Taxonomic Classification
Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls
Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
Cordova	Fine-loamy, mixed, superactive, mesic Typic Argiaquolls
Delft	Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls
Glencoe	Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls
Klossner	Loamy, mixed, euic, mesic Terric Haplosaprists
Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
Okoboji	Fine, smectitic, mesic Cumulic Vertic Endoaquolls
Rolfe	Fine, smectitic, mesic Typic Argialbolls
Webster	Fine-loamy, mixed, superactive, mesic Typic Endoaquolls

Figure 3. Conducting an EMI survey at Site #3 with an EM38DD meter towed behind the operator in a toboggan (not visible).

Field Procedures:
The EM38DD meter was operated in the continuous mode with measurements recorded at 1-sec intervals. As each site was cropped, only a pedestrian survey was possible at this time. The EM38DD was towed along the ground surface in a plastic toboggan with its long axis parallel to the direction of traverse (see Figure 3). Traverses were conducted along row between the cultivated crops.

At each site, soil scientists determined the hydric/non-hydric soil boundary based on the presence or absence of a hydric soil indicator. The hydric soil indicators identified were *A11-Depleted Below Dark Surface* and *A12-Thick Dark Surface* as described in Field Indicators of Hydric Soils in the United States (USDA-NRCS, 2006). The identification of these indicators is based on the presence of a depleted or gleyed matrix below the Mollic epipedon. The observed locations of the hydric/non-hydric soil boundary lines are indicated by red-colored dots on the accompanying plots of each site (see Figures 4 to 8).

Results:
Basic statistics for the EMI surveys of the five study sites are listed in Table 3. In general, at all sites, EC_a increases with increasing depth of observations (measurements obtained in the shallower-sensing horizontal dipole orientation (HDO) were generally lower than measurements obtained in the deeper-sensing vertical dipole orientation (VDO)). This relationship is attributed to distribution of soil moisture, the specific conductance and depth of the groundwater, and the distribution of clays, carbonates, and bases.

Table 3
Basic Statistic for the Five Survey Sites.
(Values of EC_a are expressed in mS/m.)

Site	Dipole	Number	Minimum	25%-tile	75%-tile	Maximum	Mean	St.Dev.
1	VDO	1342	34.63	55.75	70.88	91.63	62.62	10.91
1	HDO	1323	22.50	40.00	56.00	74.75	48.02	10.98
2	VDO	1159	10.38	24.63	34.25	75.88	29.70	7.38
2	HDO	1159	7.88	15.38	24.13	64.00	20.25	6.36
3	VDO	982	32.88	47.38	56.63	90.38	52.85	8.51
3	HDO	982	21.00	34.63	43.88	86.13	40.62	9.23
4	VDO	744	40.88	56.13	67.63	95.63	62.58	9.30
4	HDO	744	27.13	41.13	53.00	87.13	47.73	9.69
5	VDO	1006	38.50	51.75	65.38	77.25	58.16	8.98
5	HDO	1006	20.00	36.13	52.25	75.00	43.90	10.20

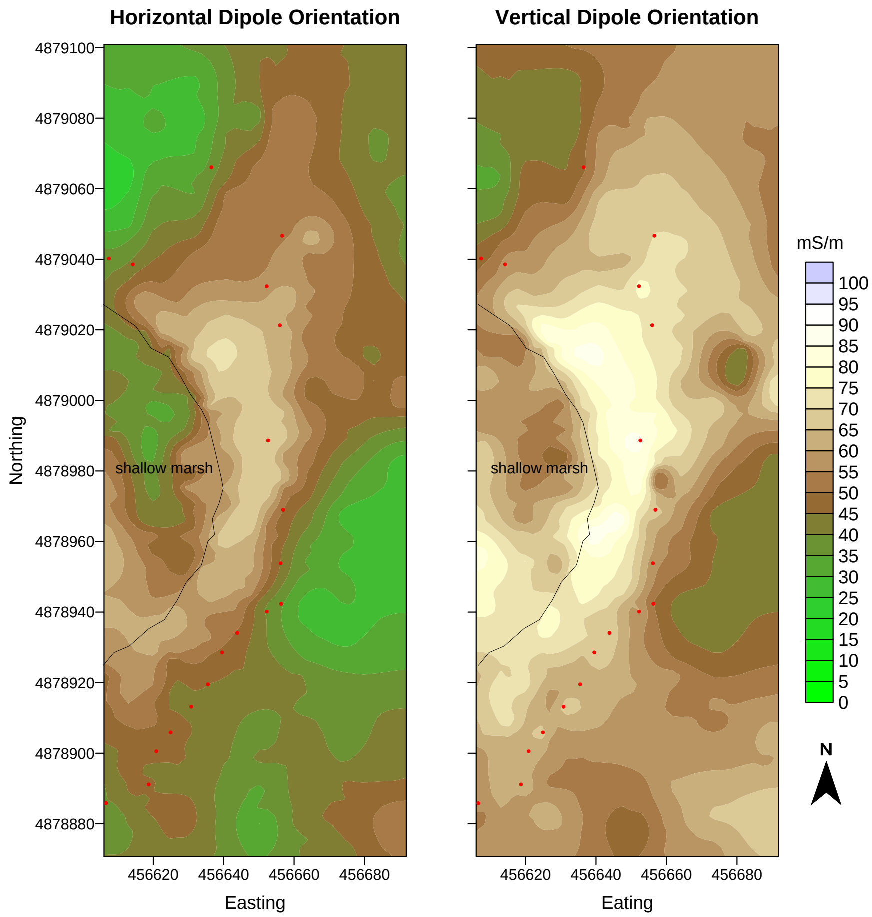

Figure 4. The spatial distribution of EC_a within Site #1.

Figure 4 shows the spatial distribution of EC_a at Site 1. The order-two soil survey (see Figure 2) depicts this site as being predominately Webster soil. Because of scale limitations, the depression, which corresponds to a shallow marsh zone, was not delineated. However, an order-one soil survey delineated an area of Okoboji silty clay loam in this depression (Doug Miller personal communication). Though influenced by the bordering road, the area of Okoboji soil has a lower EC_a than adjacent areas of Webster soil, which surrounds the depression. Okoboji soil has higher clay and moisture contents than the Webster soil and should presumably have higher EC_a. The higher EC_a of Webster soil is attributed to the accumulation of carbonates and soluble salts in the solum from edge-effect discharge. The red dots in Figure 4 define the observed hydric/non-hydric soil boundary. At this site, in both dipole orientations, the outer reaches of a conspicuous band of higher EC_a, which encompasses the depression, closely approximates the observed hydric/non-hydric soil boundary.

Figure 5 shows the spatial distribution of EC_a at Site 2. The site borders a large depressional wetland that was mapped as Klossner, Okoboji, and Glencoe soils, ponded, 0 to 1 percent slopes. Of the five study sites, Site 2 had the lowest averaged and least variable EC_a in both dipole measurements (Table 3). In general, the low EC_a at Site 2, suggest a recharge area with little or no edge-effect discharge in the areas peripheral to the shallow and deep marsh zones. The order-two soil survey (see Figure 2) depicts, from east to west, sequential units of Canisteo-Glencoe, depressional, complex, 0 to 2 percent slopes; Webster clay loam, 0 to 2 percent slopes; and Clarion loam, 2 to 5 percent slopes. An order-one soil survey resulted in the delineation of the following three units: Canisteo clay loam, Webster clay loam, and Oxyaquic Hapludolls, 2 to 5 percent slopes on this site (Doug Miller personal communication). The depressional area was mapped as Okoboji silty clay loam. Though the difference is slight, the area of Canisteo clay loam does have slightly higher EC_a than the area of the Webster clay loam. The red dots in Figure 5 define the observed hydric/non-hydric soil boundary. At this site, the outer reaches of a zone of slightly higher (> 35 mS/m) EC_a measured in the deeper-sensing vertical dipole orientation, appears to approximate the observed hydric/non-hydric soil boundary. However, compare with Site 1, the demarcation is less obvious and convincing.

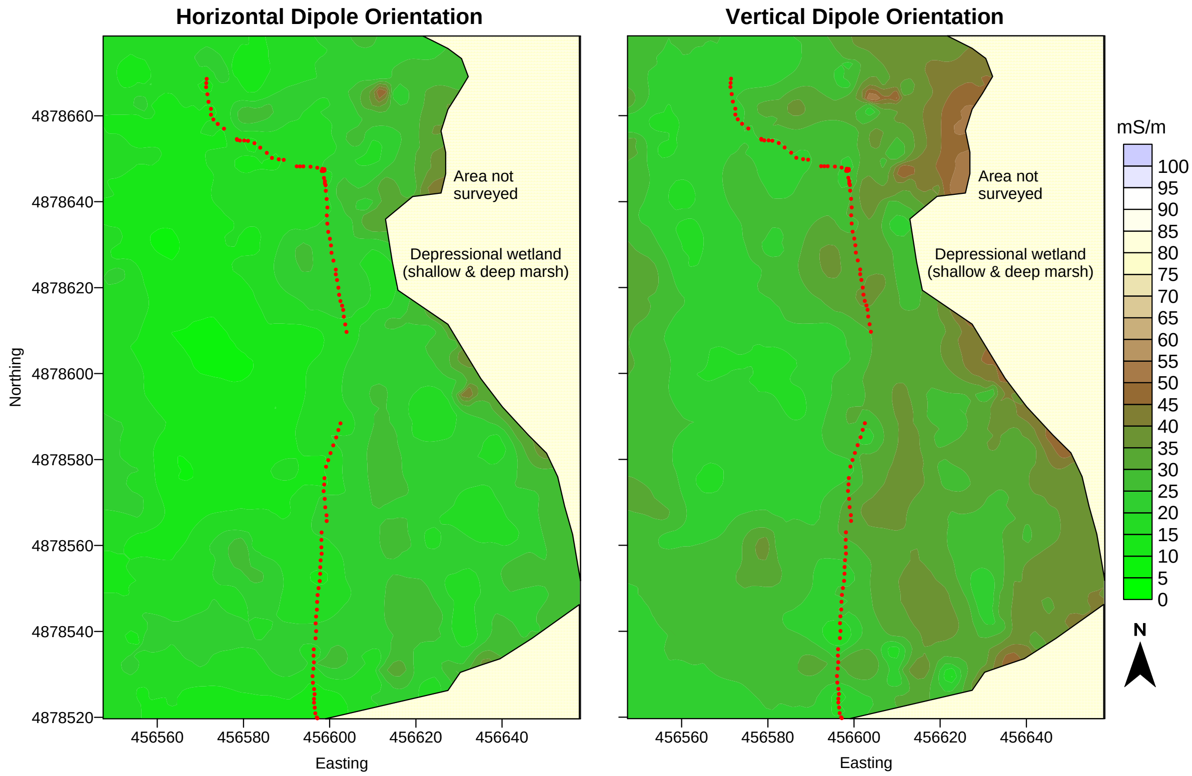

Figure 5. The spatial distribution of EC_a within Site #2.

Figure 6 shows the spatial distribution of EC_a at Site 3. At this site, the order-two soil survey (see Figure 2) depicts areas of Webster clay loam, 0 to 2 percent slopes; Clarion loam, 2 to 5 percent slopes; and Nicollet clay loam, 1 to 3 percent slopes. The order-one soil survey resulted in more intricate patterns and a number of additional units (Delft clay loam, Okoboji clay loam and Oxyaquic Hapludolls, 2 to 5 percent slopes (Doug Miller personal communication). In Figure 6, the line of red dots that parallels the boundary of the depressional wetlands (area that was not surveyed) defines the observed hydric/non-hydric soil boundary. On the order-one soil survey map (not shown or available), the area of Delft clay loam conforms to an area with comparatively low EC_a (30 to 40 mS/m in the vertical dipole orientation). Compared to Webster soil, Delft has a thicker mollic epipedon and greater depth to carbonates; two factors that suggest a recharge area. This area of Delft soil and lower EC_a forms a narrow zone that appears to conform to the hydric/non-hydric soil boundary. In Figure 6, the line of red dots that trends in a southeast direction away from the depressional wetland represents the location of a drainageway. In both dipole orientations, EC_a along this drainageway is relatively high (> 60 mS/m) and suggest a discharge area with the accumulations of soluble salts, bases, and carbonates in the soil profile. This area corresponds to an area that was mapped as Webster clay loam on the order-one soil survey map (not available or shown).

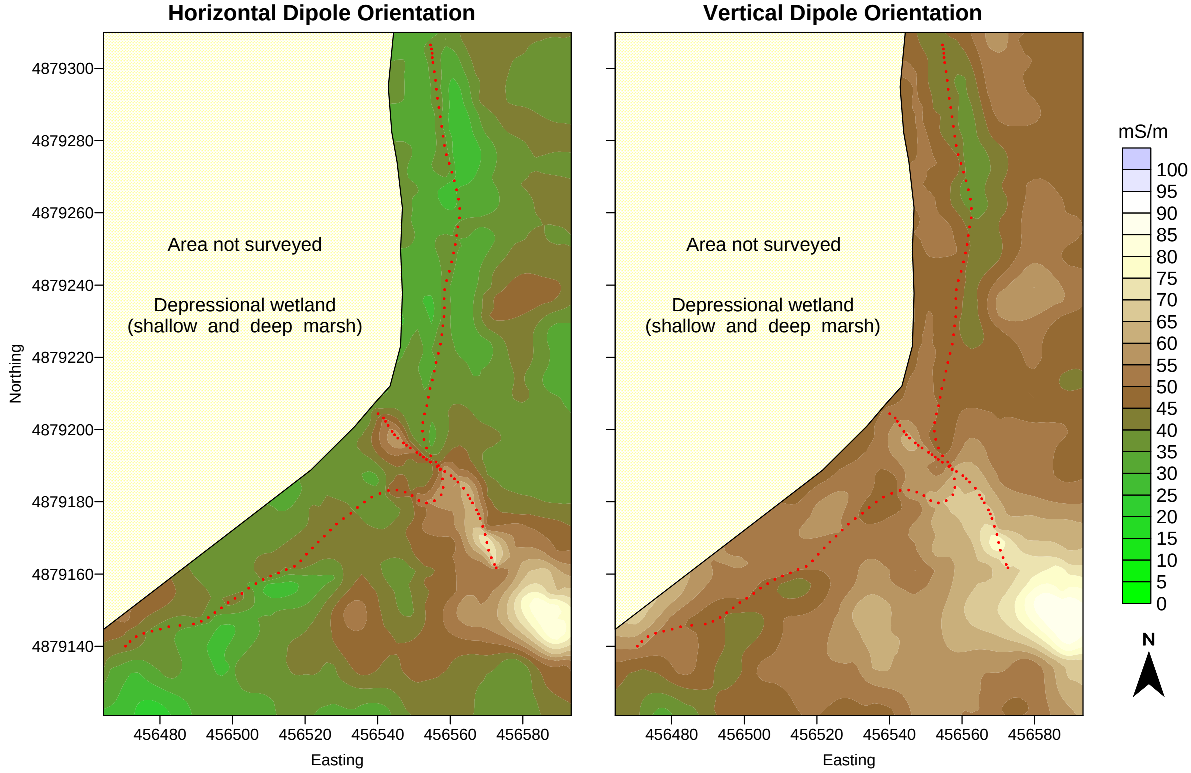

Figure 6. The spatial distribution of EC_a within Site #3.

Figure 7 shows the spatial distribution of EC_a at Site 4. The order-two soil survey (see Figure 2) depicts two units on this site: Webster clay loam, 0 to 2 percent slopes, and Nicollet clay loam, 1 to 3 percent slopes. The Webster soil is on lower-lying areas that borders the farm road (eastern boundary of site). This portion of the site has the highest EC_a. The Nicollet soil is on slightly higher-lying areas and dominates the remainder of the site. On both plots shown in Figure 7, the area of Nicollet soil has lower EC_a ($\leq$ 50 mS/m in the horizontal dipole orientation and $\leq$ 65 mS/m in the vertical dipole orientation). Because of scale limitations, the depression was not delineated, but was included in the area mapped as Webster soil. Though other differences exist, the EC_a of the depression is more similar to Nicollet than to Webster soil. On the order-one soil survey map, the depressional wetland has been delineated as a unit of Rolfe silty clay loam. Rofle soil has an argillic horizon and the depth to carbonates ranges from 42 to 80 inches. These attributes suggest that downward translocations of materials. An area of Cordova silty clay loam was mapped in the order-one soil survey in the area to the immediate south of the depressional wetland (Doug Miller personal communication). For Cordova soil, the depth to free carbonates ranges from 24 to 50 inches. In both dipole orientations, the areas mapped as Webster and Cordova soils have higher EC_a ($\geq$ 50 mS/m in the horizontal dipole orientation and $\geq$ 65 mS/m in the vertical dipole orientation) than areas mapped as Nicollet and Rolfe soils. While the hydric/non-hydric soil boundary line was not identified at this site, spatial patterns of EC_a appear to suggest its location.

Figure 8 shows the spatial distribution of EC_a at Site 5. Because of scale limitations, the depression was not delineated on the order-two soil survey (see Figure 2), but included it in a larger unit of Webster clay loam, 0 to 2 percent slopes. Also included within this site on higher-lying surfaces are units of Nicollet clay loam, 1 to 3 percent slopes. The depressional wetland was delineated on the order-one soil survey as Okoboji silty clay loam (Doug Miller personal communication). In Figure 8, patterns of lower EC_a ($\leq$ 45 mS/m in the horizontal dipole orientation and $\leq$ 50 mS/m in the vertical dipole orientation) define the depressional area of Okoboji soil and higher-lying areas of Nicollet soil. The depressional wetland is surrounded by a belt of higher EC_a which suggests edge-affect discharge. Though the number of observations was limited and the placement of the hydric/non-hydric soil boundary line difficult to define on this landscape, the outer boundary of the zone of higher EC_a appears to define this boundary.

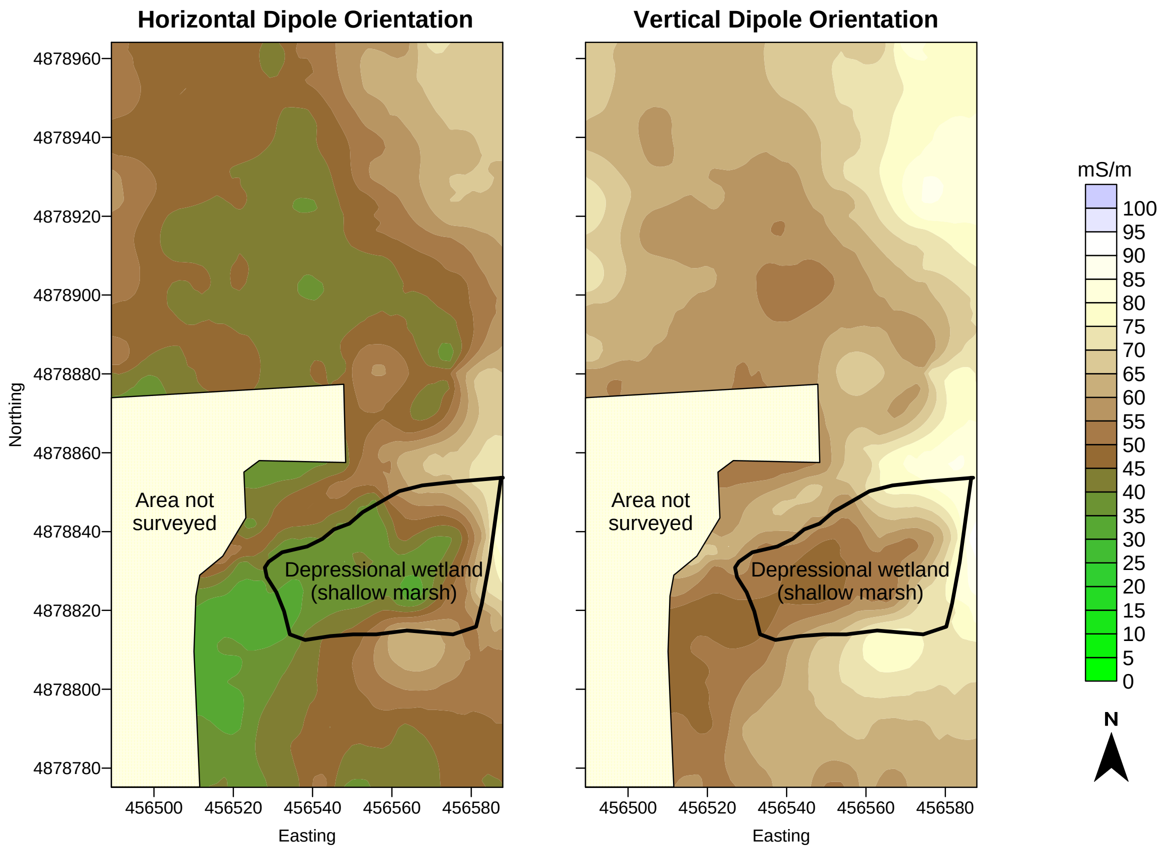

Figure 7. The spatial distribution of EC_a within Site #4.

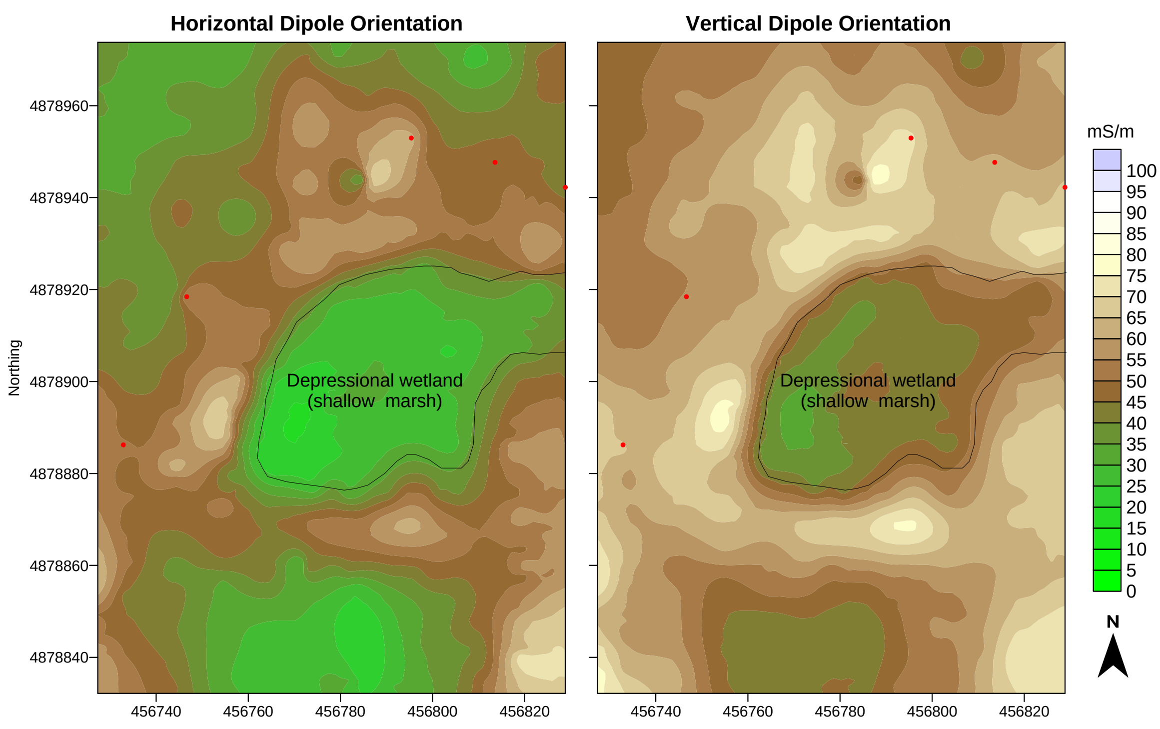

Figure 8. The spatial distribution of EC_a within Site #5.

Discussion:
At a majority of the sites, a ring of noticeably higher EC_a surrounds the depression and the deep and shallow marsh zones (see Figures 4 thru 8). In general, these peripheral areas conform to the wet meadow zone. Though more saturated and often having higher clay content, the central portions of depressions have lower EC_a than the surrounding peripheral areas. Lower EC_a in the deep and shallow marsh zones is attributed to the downward flow of water and the resulting leaching and translocation of materials, especially soluble salts and carbonates. In the wet meadow zone, evaporative discharge causes the accumulation of carbonates and other dissolved materials which results in the band of higher EC_a surrounding deep and shallow marsh zones.

The core areas of these depressions are typified by soils with leached profiles and low contents of dissolved materials and calcium carbonate. In the central portion of some depressions, the downward flow of water results in the leaching and translocation of materials and the formation of Btg horizons through the accumulation of translocated clays (Richardson et al., 2001). In many depressions, groundwater discharge is focused along the edges resulting in accumulation of carbonates and soluble salts in these areas. The presence of secondary carbonates in the sola of these soils is related to discharge from a shallow water table (Khan and Fenton, 1994). These soils also have relatively high pH and base saturation near the surface (Khan and Fenton, 1994). These factors contribute to the relative higher EC_a in these wet meadow zones.

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