United States Department of Agriculture

Natural Resources Conservation Service

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Subject: ENG -- Electromagnetic Induction (EMI) Assistance **Date:** 30 May 2006

To: Judith Doerner
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Purpose:

Electromagnetic induction (EMI) surveys were completed on cultivated fields that border Morey Road in Sheldon Township, Franklin County, Vermont. Several nearby residential wells have high concentrations of nitrate. Electromagnetic induction was used to better understand the near-subsurface (0 to 15 m) and to detect potential flow paths for nitrates beneath the cultivated field.

Participants:

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Activities:

This EMI survey was completed on 9 and 10 May 2006.

Observations:

1. The EC_a data collected with three EMI meters supports the models advanced by geologists from geologic information and interpretations. A zone of higher EC_a (12 to 20 mS/m) extends across the field and towards three contaminated residential wells on the opposite side of Morey Road. While EC_a values are not considered excessive and can not be in anyway correlated with contaminants alone, the orientation of this zone of higher EC_a conforms to major fracture traces (N-NE lineations) observed within this area and may be associated with possible flow of groundwater under pressure towards the wells.

2. Plots of EC_a data, may assist the placement and interpretation of lysimeters and monitoring wells.

3. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations are interpretive and do not substitute for direct ground-truth observations (soil samples and lysimeters). The use of geophysical methods can reduce the number of lysimeters and soil cores, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

It was my pleasure to work in Vermont and to be of assistance to your staff.

With kind regards,

James A. Doolittle
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cc:
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Background:
Electromagnetic induction (EMI) uses electromagnetic energy to measure the apparent conductivity (EC_a) of earthen materials. Apparent conductivity is the weighted, average conductivity for a column of earthen materials (Greenhouse and Slaine, 1983). Variations in EC_a are produced by changes in the electrical conductivity of earthen materials. Electrical conductivity is influenced by the volumetric water content, type and concentration of ions in solution, temperature and phase of the soil water, and amount and type of clays in the soil matrix (McNeill, 1980a). The EC_a of soils increases with increased soluble salt, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976). Apparent conductivity is related to the total ion concentration in soils. These ions can be either cations (Ca^{++}, Mg^{++}, K^+, Na^+, and H^+) or anions (NO_3^-, SO_4^-, HCO_3^-, CO_3^-, and OH^-).

Electromagnetic induction measures vertical and lateral variations in EC_a. Values of EC_a are seldom diagnostic in themselves. However, lateral and vertical variations in EC_a can be used to infer changes in soils and soil properties. Interpretations are based on the identification of spatial patterns within data sets. To assist interpretations, computer simulations are normally used.

Electromagnetic induction is a noninvasive geophysical tool that has been used to assess spatial and temporal variations in soil nutrient contents at different depths and levels of resolution. Advantages of EMI are its portability, speed of operation, flexible observation depths, and moderate resolution of subsurface features. Electromagnetic induction can provide a large number of measurements in a relatively short time. Maps prepared from properly interpreted EMI data provide the basis for assessing site conditions and locating sampling or monitoring sites.

Electromagnetic induction has been used to map spatial and temporal variations in the concentration of soil nutrients (Cockx et al., 2005). Cockx et al. (2005) used EC_a to delineate zones with different risks of NO_3^- loss within a small pasture. At low concentrations, differences in nutrient contents are unlikely to be detected with EMI as differences in clay and moisture contents will often mask changes in nutrient levels (Heiniger et al., 2003). Eigenberg and Nienaber (1998) used EC_a maps to delineate soils with high nutrient buildup resulting from the application of animal wastes. They observed that differences in EC_a were primarily dependent on the ionic content of the soil. Temporal variations in EC_a have been related to nutrient leaching, diffusion, and plant uptake within composting sites (Eigenberg and Nienaber, 2003).

Electromagnetic induction has been used effectively to investigate the migration of contaminants from animal waste-holding facilities (Eigenberg et al., 1998; Bowling et al., 1997; Drommerhausen, et al., 1995; Ranjan and Karthigesu, 1995; Radcliffe et al., 1994; and Brune and Doolittle, 1990; Siegrist and Hargett, 1989; Stierman and Ruedisili, 1988). Typically soils affected by animal wastes have higher EC_a than soils that are unaffected by these contaminants. Electromagnetic induction has been used to infer the relative concentrations, extent, and movement of contaminants. Stevens et al. (1995) used EC_a as an indirect measure for NH_4 and K in animal waste slurries. While EMI does not provide a direct measurement of specific ions or compounds, EC_a has been correlated with concentrations of chloride, ammonia, and nitrate nitrogen in soils (Eigenberg et al., 1998; Ranjan and Karthigesu, 1995; Brune and Doolittle, 1990).

Equipment:
The EM31, EM34-3, and EM38 meters were used in this study. These meters are manufactured by Geonics Limited (Mississauga, Ontario).[1] No ground contact is required with these meters. For each meter, lateral resolution is approximately equal to their intercoil spacing.

McNeill (1980b) described the principles of operation for the EM31 meter. The EM31 meter has a 3.66-m intercoil spacing and operates at a frequency of 9,810 Hz. When placed on the soil surface, the EM31 meter provides theoretical penetration depths of about 6-m in the vertical dipole orientation (McNeill, 1980b).

Geonics Limited (1990) describes the operation of the EM34-3 meter. The EM34-3 meter consists of a receiver and transmitter coil, three reference cables (10-, 20-, and 30-m), and receiver and transmitter consoles. The operation of this meter requires 2 people: one handles the transmitter coil and one handles the receiver coil. In this investigation, the EM34-3 meter was used in the horizontal dipole orientation with a 20-m intercoil spacing. With a 20-m intercoil spacing, the EM34-3 meter operates at a frequency of 1,600 Hz and has a theoretical penetration depth of about 15-m in the horizontal dipole orientation (Geonics Limited, 1990).

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

Geonics Limited (1998) describes the operation of the EM38 meter. The EM38 meter is light weight (1.4 kg) and needs only one person to operate. The EM38 meter has a 1-m intercoil spacing and operates at a frequency of 14,600 Hz. When placed on the soil surface, it has a theoretical penetration depth of about 1.5 m in the vertical dipole orientation (Geonics Limited, 1998).

The DAS70 Data Acquisition System (Geonics Limited, Mississauga, Ontario) was used to record and store both EC_a and position data.[2] The acquisition system consists of an EMI meter, an Allegro field computer (Juniper Systems, North Logan, UT), and a Garmin Global Positioning System (GPS) Map 76 receiver (with CSI Radio Beacon receiver, antenna and accessories that are fitted into a backpack) (Garmin International, Inc., Olathe, KS).[2] When attached to the acquisition system, EMI meters are keypad operated and measurements can be automatically triggered. Geonics Limited provides suitable software to operate the EM31, EM34-3, and EM38 meters with the acquisition system.

To help summarize the results of this survey, SURFER for Windows, version 8.0 (Golden Software, Inc., Golden, CO), was used to construct some of the simulations shown in this report.[2] Grids of EC_a data were created using kriging methods with an octant search.

Survey Site:
The survey area is located in Sheldon Township, Franklin County, Vermont. Figure 1 is a soil map and aerial photograph of the survey area from the Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/).

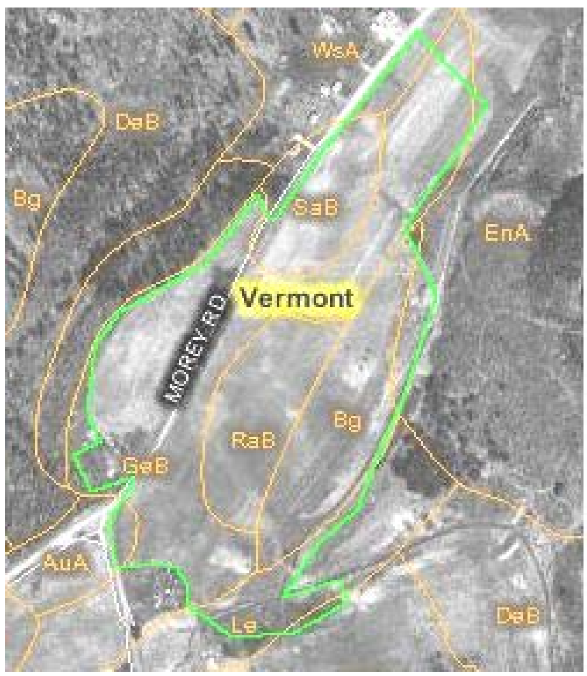

Figure 1. Soil map of the study area (enclosed by green colored line).

In Figure 1, the survey area has been enclosed by a green colored line. The site is located principally in a cultivated field on the southeast side of Morey Road. The survey area contains complex patterns of sandy, silty, and loamy soils that have formed in different parent materials and belong to different soil drainage and depth classes. The very deep, somewhat poorly drained Au Gres soils formed in sandy glacial drift. The very deep, poorly drained Binghamville soils formed in silty glaciolacustrine deposits. The very deep, moderately-well drained Deerfield soils formed in sandy glaciofluvial deposits. The very deep, poorly drained Enosburg soils formed in sandy glaciofluvial deposits that are underlain by loamy glaciolacustrine deposits. The very deep, moderately well drained Georgia soils formed in loamy till. The very deep, poorly drained Limerick soils formed in loamy alluvium on flood plains. The very deep, poorly drained Raynham soils

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

formed in silty glaciolacustrine deposits. The deep, well drained St. Albans soils formed in coarse-loamy glacial till. The very deep, excessively drained Windsor soils formed in sandy glacial outwash. Table 1 list the names and symbols of the soil map units that occur within the survey area. The taxonomic classifications of these soils are listed in Table 2.

Table 1
Map Units delineated within the survey area.

Map Symbol	Map Unit Name
AuA	Au Gres loamy fine sand, 0 to 6 percent slopes
Bg	Binghamville silt loam
DeB	Deerfield loamy fine sand, 0 to 8 percent slopes
EnA	Enosburg loamy fine sand, 0 to 3 percent slopes
GeB	Georgia stony loam, 3 to 8 percent slopes
Le	Limerick silt loam
RaB	Raynham silt loam, 3 to 8 % slopes
SaB	St. Albans slaty loam, 3 to 8 percent slopes
WsA	Windsor loamy fine sand, 0 to 3 percent slopes

Table 2
Taxonomic classification of soils

Soil Series	Taxonomic Classification
Au Gres	Sandy, mixed, frigid Entic Haplaquods
Binghamville	Coarse-silty, mixed, nonacid, mesic Typic Haplaquepts
Deerfield	Mixed, mesic Aquic Udipsamments
Enosburg	Sandy over loamy, mixed, nonacid, mesic Mollic Haplaquents
Georgia	Coarse-loamy, mixed, mesic Aquic Dystric Eutrochrepts
Limerick	Coarse-silty, mixed, nonacid, mesic Typic Fluvaquents
Raynham	Coarse-silty, mixed, nonacid, mesic Aeric Haplaquepts
St. Albans	Coarse-loamy, mixed, mesic Typic Dystrochrepts
Windsor	Mixed, mesic Typic Udipsamments

Field Procedures:
The EM31 and EM38 meters were operated in vertical dipole orientation and continuous mode with measurements recorded at 1-sec intervals. The EM31 meter was held at hip-height with its long axis parallel to the direction of traverse. The EM38 meter was orientated with its long axis parallel to the direction of traverse and held about 5-cm above the ground surface. Surveys conducted with the EM31 and EM38 meters were completed by walking at a rather slow pace, in a random back and forth pattern across the recently tilled fields.

Based on results from EMI surveys conducted with the EM31 and EM38 meters, a small portion of the survey area was surveyed with the EM34-3 meter operated in the horizontal dipole orientation. Measurements were manually triggered along parallel lines spaced about 20-m apart. To record measurements, the coils of the EM34-3 meter were placed on the ground surface, orientated in the direction of traverse, and adjusted to the correct intercoil distance. With a 20-m intercoil spacing the area covered by this meter is comparatively large and resolution of subsurface features is considered coarse.

Results:
Basic statistics for the EMI surveys are listed in Table 3. Measurements were obtained with the EM31and EM38 meters in the vertical dipole orientation (V). The bulk of the EC_a measurements was low and reflects comparatively resistive soil materials. Negative and high positive EC_a measurements reflect interference from buried metallic artifacts or overhead power lines and the effects of highway deicing applications (areas adjacent to Morey Road; higher concentrations of chloride and sodium). For the EM31 meter, based on 11,349 measurements, EC_a averaged 12.8 mS/m with a range of -43.4 to 76.2 mS/m. At one-half of the observation points, the measured EC_a was between 9.4 and 16.4 mS/m. For the EM38 meter, based on 9735 measurements, EC_a averaged 11.7 mS/m with a range of -69.5 to 74.2 mS/m. At one-half of the observation points, the measured EC_a was between 7.0 and 16.1 mS/m.

Measurements were obtained with the EM34-3 meter in the horizontal dipole orientation (H). With the EM34-3 meter, based on 143 measurements, EC_a averaged 10.0 mS/m with a range of 5.2 to 63.2 mS/m. At one-half of the observation points, the measured EC_a was between 7.0 and 9.4 mS/m.

Table 3
Basic Statistics for EMI Surveys
(EC_a measurements are expressed in mS/m)

	EM31V	EM34-3H	EM38V
Number	11349	143	9735
Minimum	-43.38	5.20	-69.50
Maximum	76.17	63.25	74.25
25%-tile	9.40	7.00	7.00
75%-tile	16.40	9.40	16.13
Mean	12.78	9.98	11.72
Standard Deviation	6.12	7.51	7.21

Figure 2 contains plots of EC_a data. In Figure 2, the spatial EC_a patterns recorded with the shallower-sensing (0 to 1.5 m) EM38 and the deeper-sensing (0 to 5 m) EM31 meters are shown in the left- and right-hand plots, respectively. Except for a small cultivated field and residential area, Morey Road forms the northwest boundary of the study area. Also shown in these plots are green-colored point symbols representing domestic wells that are located near the study area. The three wells that are located in the small residential area that was surveyed north of Morey Road contain high levels of nitrate.

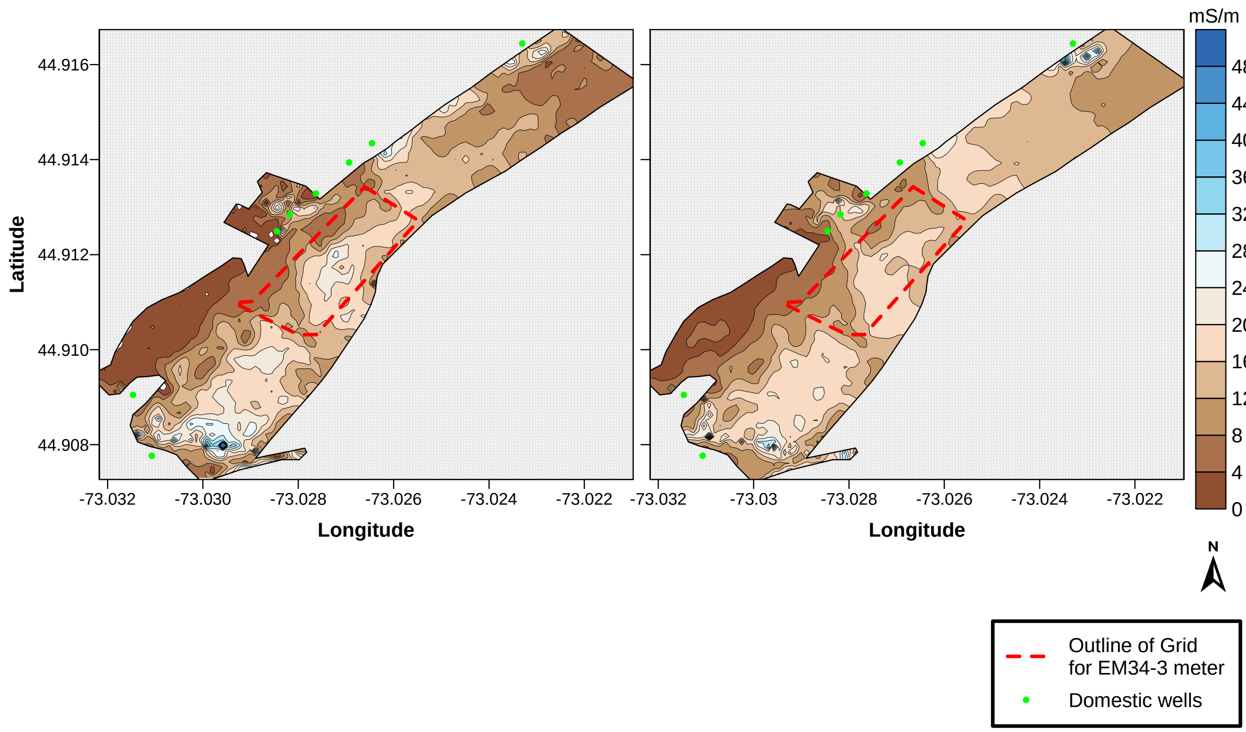

Figure 2. Plots of EC_a data collected with the EM38 (left) EM31 (right) meters. In each plot, the area enclosed by segmented red lines was surveyed with the EM34-3 meter (see Figure 4).

In the extreme western portion of the survey area, very low (< 4 mS/m) EC_a measurements are associated with higher-lying, better drained areas of Georgia stony loam, 3 to 8 percent slopes, and St. Albans slaty loam, 3 to 8 percent slopes.

Outcrops of parent rock (slate?) were exposed in this area. The very low EC_a in this portion of the survey area is attributed to shallower depths to electrically resistive bedrock. In the south and central portions of the survey area, higher EC_a measurements are associated with areas of poorly drained Binghamville and Raynham soils which formed in silty glaciolacustrine deposits.

In each plot shown in Figure 2, higher values of EC_a along Morey Road and the northwest boundary of the survey area are attributed to road salts, and interference from utility lines and buried artifacts. An area of high EC_a in the northern-most part of the survey area is linear and believed to reflect buried artifacts associated with a concrete well located in the cultivated field. In the extreme southern portion of the survey area, the linear, east-west orientated line of higher EC_a represents the buried metallic water pipeline for the East Fairfield Fire District. Electromagnetic induction surveys crossed portions of an adjoining stream channel and lower-lying, poorly drained areas of Binghamville and Limerick soils where the water table was very close to the soil surface. Apparent conductivity measurements were seemingly not affected by the presence of surface or ground water; an observation that attests to the low specific conductance of the water.

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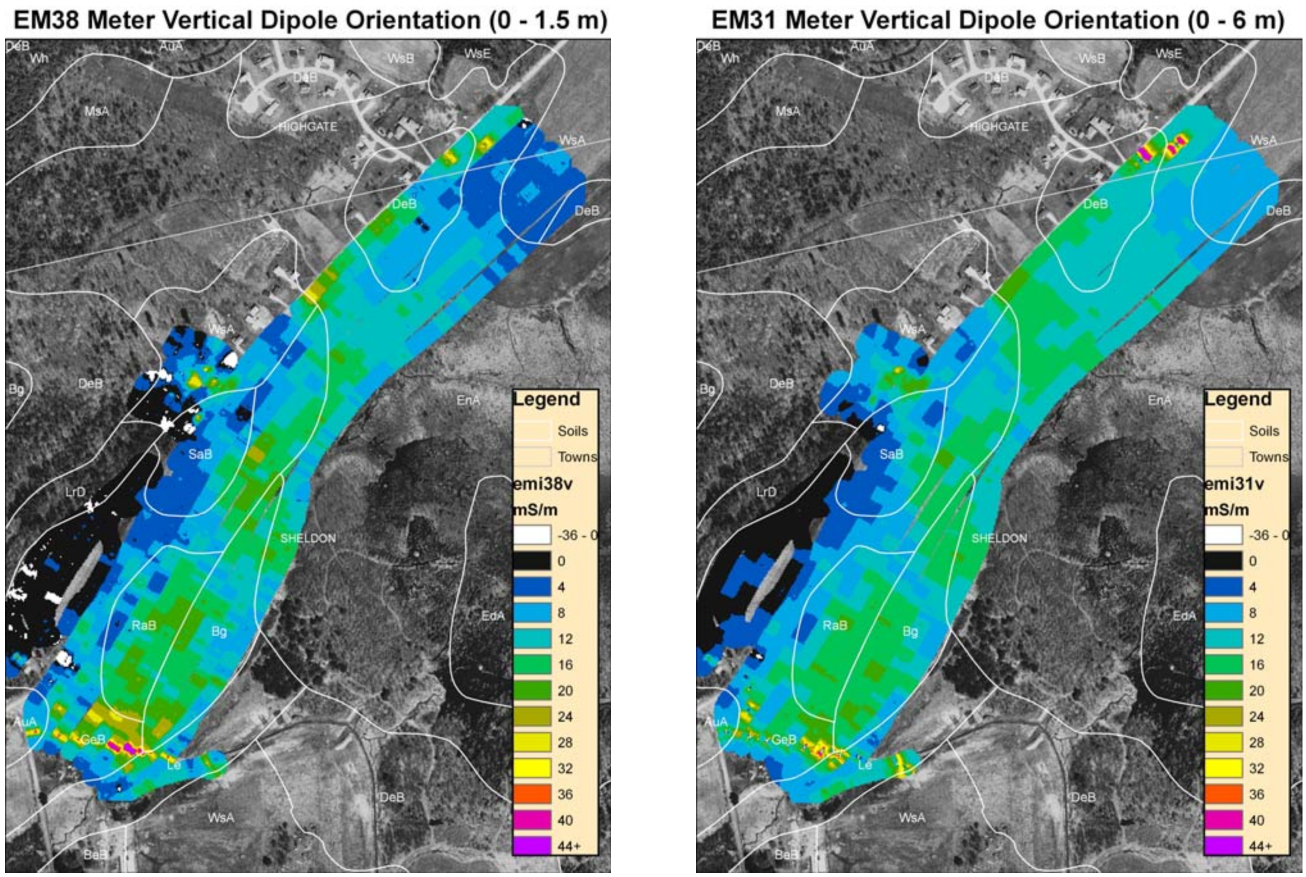

Figure 3. Alternative plots of EC_a data collected with the EM38 (left) EM31 (right) meters. These plots were prepared using interpolation methods contained in ArcView GIS (courtesy of Reed Sims).

In each plot shown in Figure 2, a noticeable pattern of lower EC_a (8 to 12 mS/m) extends across Morey Road and into the adjoining portions of two cultivated fields. In this portion of the study area, low EC_a is associated with shallower depths to bedrock. It is assumed that this pattern reflects the depth to the underlying bedrock and its general topography. A noticeable zone of higher EC_a (12 to 20 mS/m) parallels this zone of lower EC_a and conforms to a major structural pattern of rock fractures. This zone of higher EC_a attracts our attention as it aligns with the three contaminated residential wells on the opposite side of Morey Road. It is possible that this zone of higher EC_a could reflect a trough in the bedrock surface, a zone of weaker parent rock, deeper soils, and/or a thoroughfare for nitrates to migrate from the field to the wells. It may also represent an area with higher clay content soils. As finer-textured soils would have lower permeability, there would be greater potential for denitrification in this area.

The plots shown in Figure 3 were prepared from the same datasets but using different interpolation techniques available in ArcView GIS. These plots provide a alternative view of spatial EC_a patterns within the survey area. Spatial patterns evident in these plots are similar to those shown in Figure 2 and reinforce, but do not detract from the previous interpretations.

The area with the intriguing linear pattern of relatively higher EC_a that extends across the southern portion of the survey area and into the residential area with the contaminated wells was investigated to greater depths with the EM34-3 meter. The portion of the survey area that was surveyed with the EM34-3 meter is identified by a segmented red-colored line in the plots shown in Figure 2.

Figure 4 shows spatial EC_a patterns that are based on data collected with the EM34-3 meter in the horizontal dipole orientation. The locations of the three contaminated residential wells are shown by green-colored spot symbols in Figure 4. Also shown in Figure 4 are the locations of the EMI measurement points. Overhead power lines interfered with EMI responses in areas near Morey Road and produced anomalously high EC_a measurements. As a consequence, in Figure 4, this portion of the survey area was “blanked” or omitted from view. Major spatial patterns shown in the plot of EC_a data collected with the deeper-sensing (0 to 15-m) EM34-3 meter are similar to those collected with the shallower-sensing EM31 (0 to 6-m) and EM38 (0 to 1.5-m) meters.

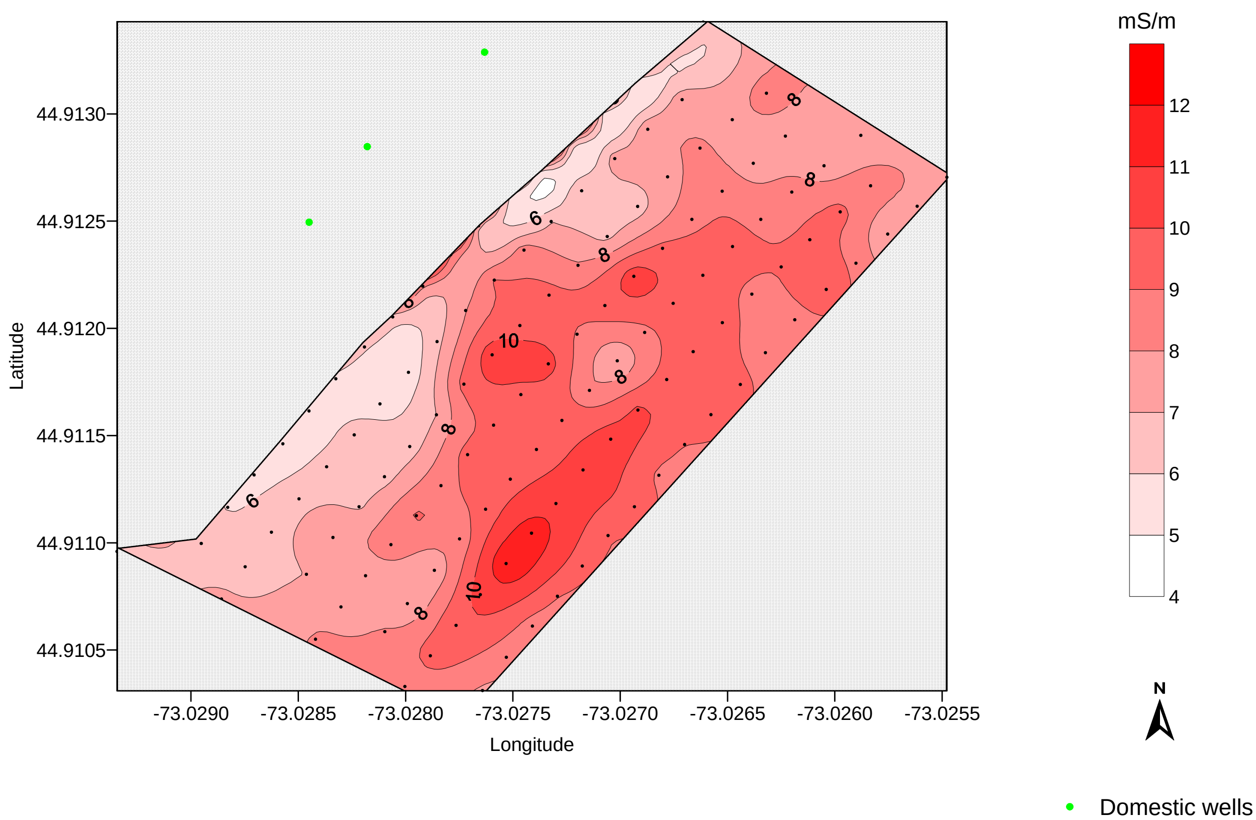

Figure 4. Plot of EC_a data collected with the EM34-3 meter in the horizontal dipole orientation and with a 20-m intercoil spacing.

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