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

Subject: SOI – Geophysical Field Assistance **Date:** 29 January 2008

To: Dr. Henry Lin
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Purpose:
Multiple electromagnetic induction (EMI) surveys have been completed of the Shale Hills Catchment in northern Huntingdon County, Pennsylvania. The purpose of these investigations is to assess spatial and temporal variations in apparent conductivity (EC_a) within a small, steeply-sloping, forested catchment in central Pennsylvania. In addition, a high-intensity EMI survey was conducted across research fields at Penn State University's Klepler Farm in Centre County.

Activities:
All field activities were completed on 8 thru 10 (Shale Hill Catchment), and 16 (Klepler Farm) January 2008.

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA
Ken Takagi, Graduate Student, Department of Crop & Soil Sciences, PSU, University Park, PA
Jun Zhang, PhD Student, Department of Crop & Soil Sciences, PSU, University Park, PA
Quing Zhu, PhD Student, Department of Crop & Soil Sciences, PSU, University Park, PA

Recommendations:

1. Over the next four months, monthly EMI surveys will be conducted over small grid sites located within the Shale Hills Catchment. The purpose of these surveys is to assess the short-range (large scale) spatiotemporal variability in EC_a. Ken Takagi is instructed to better define the existing grid sites and traverse lines, and to collect detailed topographic data within each of these sites. He will coordinate EMI survey activities with Jim Doolittle.

2. Over the next year, bi-monthly EMI surveys of the research fields at Klepler Farm will be conducted by Jim Doolittle and Quing Zhu. The purpose of these surveys is to assess broad (small scale) spatiotemporal variability patterns in EC_a. Quing Zhu will work with Jim Doolittle in establishing the surveying dates and insuring that an ATV is available to conduct these surveys.

3. In order to better understand the EMI data sets, a greater understanding by the Penn State Hydrology Team is needed on the effects of temperature correction on EC_a data. In addition, this team should be knowledgeable of the different protocol used in the temperature correction of EC_a data.

It was my pleasure to participate in these studies and to work with the graduate students at Pennsylvania State University.

With kind regards,

James A. Doolittle
Research Soil Scientist

National Soil Survey Center

cc:
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Materials and Methods:

The EM38 and EM38DD meters, manufactured by Geonics limited (Mississauga, Ontario) were used in this study.[1] These meters require only one person to operate. No ground contact is required with either instrument. Both meters have a 1-m intercoil spacing and operate at a frequency of 14,600 Hz. The EM38 meter weighs about 1.4 kg (3.1 lbs). Operating procedures for the EM38DD meter are described by Geonics Limited (1998). The EM38DD meter consists of two, coupled EM38 meters. This instrument weighs about 2.8 kg (6.2 lbs). Operating procedures for the EM38DD meter are described by Geonics Limited (2000). When placed on the soil surface, these meters provide theoretical penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively.

Reconnaissance EMI surveys of the Shale Hills Catchment were completed with the lighter-weight EM38 meter. In addition, three small grid surveys within this catchment and the survey at Klepler Farm were completed with an EM38DD meter. An Allegro CX field computer (Juniper Systems, North Logan, UT) was used to record and store both EMI and GPS data. Two GPS receivers were used in the investigations at Shale Hill: a Trimble AgGPS114 L-band DGPS (differential GPS) antenna (Trimble, Sunnyvale, CA); and a Garmin GPS Map76 receiver (with CSI Radio Beacon receiver and antenna) (Olathe, KS).[1] The Garmin GPS receiver was used in the survey conducted at Klepler Farm. Both receivers and antennas are mounted onto a backpack frame. During surveying, EC_a and GPS measurements were automatically recorded in the Allegro CX field computer. The DAT38W, Trackmaker38DD and Trackmaker38 software programs developed by Geomar Software Inc. (Mississauga, Ontario) were used to record, store, and process EC_a and GPS data.[1] All EMI data are expressed as values of EC_a in milliSiemens/meter (mS/m).

In order to make temporal comparisons of collected EC_a data, it is recommended that all EC_a data be corrected to a standard temperature. Apparent conductivity increases with soil temperature. As the soil temperature rises, the soil water become less viscous and dissolved ions become more mobile. This results in higher EC_a values (McNeill, 1980). As it is impractical to account for variations at each point and at different soil depths within the catchment, the correction factor was based on a single measurement made at a depth of 50 cm. All data shown in this report have been temperature corrected to a standard temperature of 75° F.

To help summarize the results of the EMI surveys, SURFER for Windows, version 8.0, developed by Golden Software, Inc. (Golden, CO), was used to construct the simulations shown in this report.[1] Grids of EC_a data were created using kriging methods with an octant search.

Survey Procedures:

Pedestrian and mobile EMI surveys were completed at Shale Hills Catchment and Klepler Farm, respectively. EMI meters were operated in the continuous mode with measurements recorded at a 1-sec interval. Meters were orientated with their long axis parallel to the direction of traverse. In the Shale Hills Catchment, where possible, the EM38 meter was held about 5 cm (2 inches) above the ground surface. However, steep slopes, tree limbs, and fallen forest debris made walking difficult and caused the meter to vary slightly in height. Where possible, traverses were conducted parallel to the slope contours. In an attempt to better define swales; multiple traverses were conducted across and along each of these features. Horizon obstructions, satellite shading, and multipath reception reduced the accuracy and reliability of GPS positioning on lower slopes and especially beneath the evergreen canopy along the lower reach of the stream channel. Detailed EMI surveys of three small grid sites within the catchment were completed with the EM38DD meter.

At Klepler Farm, the EM38DD meter was towed behind an ATV in a plastic sled at speeds of 1 to 3 m/sec. The EMI survey of Klepler Farm was completed by driving the ATV at a uniform pace, in a random or back and forth pattern across each research field.

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

Results:

1. Shale Hills Catchment:

Reconnaissance EMI Surveys:

Basic statistics for the three reconnaissance EMI surveys (October 2005, March 2006, and January 2008), which were all completed with the EM38 meter in the vertical dipole orientation, are listed in Table 1. All EC_a data have been temperature corrected to a standard temperature of 75° F. All EC_a measurements with negative values were removed from the data sets, as most were assumed to represent interference from metallic objects that are scattered throughout the catchment. At the time of the October 2005 survey, soils were noticeably droughty and stream flow was restricted to the stream channel in the lowest portion of the catchment. In the March 2006 survey, soils were considered moist and stream flow was observed in most reaches of the stream channel. Snow had recently melted from the catchment and the soils were moist at the time of the January 2008 survey. Survey results reflect these differences in soil moisture. In Table 1, the averaged EC_a can be seen to increase with increasing soil moisture contents (OCT 2005 < MAR 2006 < JAN 2008).

Table 1
Comparison of Basic Statistics for the Reconnaissance EMI Surveys of the Shale Hills Catchment.

	October 2005	March 2006	January 2008
Number Observations	5931	3448	6333
Minimum	0.00	0.00	0.22
Maximum	23.75	20.50	26.00
25% Quartile	1.25	1.50	2.99
75% Quartile	3.00	5.78	6.84
Mean	2.22	3.94	5.06
Standard Deviation	1.38	3.20	3.06

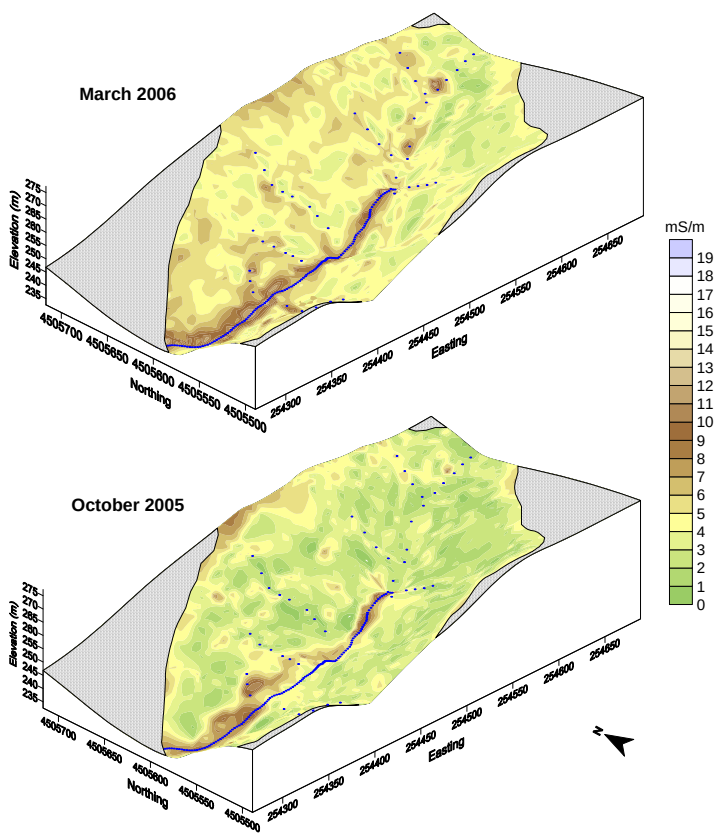

Figure 1. These plots show the spatial distribution of EC_a within the catchment at the time of the October 2005 (dry) and March 2006 (moist) EMI surveys.

Figure 1 contains plots of the EC_a data that were collected in October 2005 (lower plot) and March 2006 (upper plot). Figure 2 is a plot of the EC_a data collected in January 2008. In each of these figures, the same color ramp and isoline interval (2 mS/m) have been used. These plots show the spatial distribution of EC_a data that were collected with the EM38 meter in the deeper-sensing (nominal penetration depth of 0 to 150 cm) vertical dipole orientation. Spatial EC_a patterns appear temporally consistent. The lowest EC_a is recorded on plane and convex shoulder and back slopes. These soils (Weikert and Berks) and landscape components are characteristically drier than other soils and landscape components within the catchment. Areas of higher EC_a are recorded along the stream channel. These soils (Earnest and Blairton) have higher moisture contents. Allred et al (2005) demonstrated that, in humid areas, spatial EC_a patterns remain relatively consistent over time. In humid areas, EC_a is largely controlled by relatively stable soil properties (i.e., soil texture, density, and depth) and fluctuates in relative magnitude with changes in soil moisture contents.

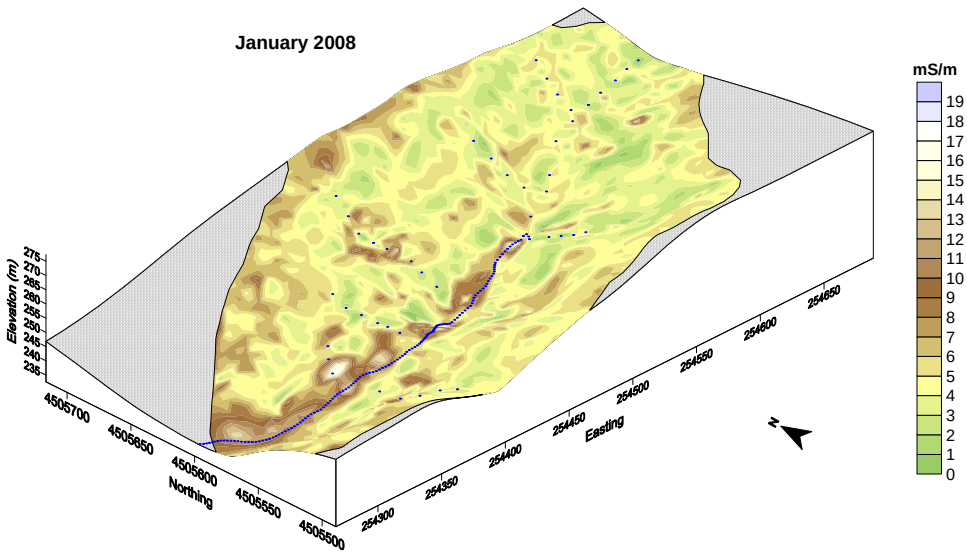

Figure 2. This plot shows the spatial distribution of EC_a within the catchment at the time of the January 2008 (very moist) EMI survey.

<u>EMI Surveys of Three Detailed Grid Sites:</u>

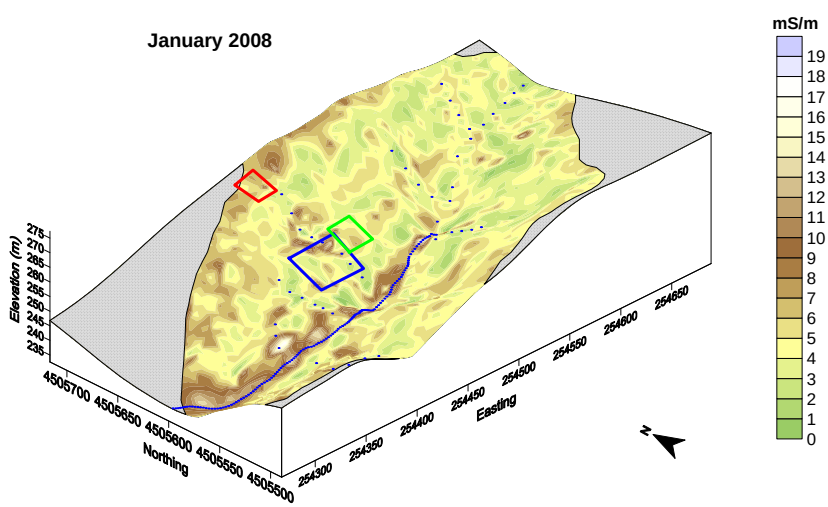

Figure 3. This plot shows the locations of the three detailed grid sites in the Shale Hills Catchment. Colored squares represent grids located on summit (red), side slope (green) and swale (blue) components.

The Shale Hills Catchment is characterized by relatively low and invariable EC_a. These characteristics are generally not considered to be favorable for the production of valuable EMI results, as instrument and measurement errors share the same range as a majority of the EC_a measurements. However, reconnaissance EMI surveys did reveal broad spatial patterns and relationships. Unfortunately, because of the surveying scale (few, widely-spaced survey lines), the reconnaissance surveys provide only a broad perspective into the changing dynamics of the catchment. Results from the reconnaissance EMI surveys can not be used to address short-range spatial and temporal variability in EC_a. In order to better understand the short-range variability in EC_a, three sites were selected within the catchment for more detailed and repeated EMI investigations. Sites were located on representative areas of three landforms: summit, side slope, and swale (see Figure 3 for locations of the three detailed grid sites). Two additional grid sites were established along the stream channel, but the proper positioning of observation points was obstructed and significantly diminished by interference from topographic and vegetal features. Even on the higher-lying sites, the positioning of observation points could only be considered adequate for these high resolution investigations.

Basic statistics for the three detailed EMI surveys, which were completed with an EM38DD meter, are listed in Table 2. Measurements were obtained at each site in the shallower-sensing horizontal (HDO) and deeper-sensing vertical (VDO) dipole orientations. Across these sites, EC_a was relatively low (range of 0 to 14.9 mS/m) and invariable (standard deviations of 1.47 to 2.49 mS/m). The grid located on the side slope displayed the lowest averaged and least variable EC_a; while the grid located on the swale displayed the highest average and most variable EC_a. The following trend in averaged EC_a was observed among the three grid sites: Swale ≥ Summit > Side slope. Within the Shale Hills Catchment, Lin (2006) observed the following trend in soil moisture storage: Valley > Swale > Side slope > Summit. At all sites, EC_a increases with increasing nominal penetration depths (averaged EC_a obtained in the HDO (0 to 75 cm) are less than those obtained in the VDO (0 to 150 cm).

Table 2.
This table shows the basic statistics for the detailed EMI surveys that were conducted across the three grid sites.

	Summit HDO	Summit VDO	Side slope HDO	Side slope VDO	Swale HDO	Swale VDO
Observations	250	250	228	228	546	546
Minimum	0.00	0.00	0.00	0.00	0.00	0.22
25%-tile	2.14	3.85	1.71	2.36	3.21	3.64
75%-tile	3.85	7.06	2.99	5.78	7.26	6.84
Maximum	8.34	11.33	8.12	11.54	12.61	14.95
Mean	3.10	5.43	2.38	4.09	5.39	5.37
Std. Deviation	1.64	2.30	1.47	2.26	2.49	2.47

Figures 4, 5, and 6 show the spatial distributions of EC_a within the Summit, Side Slope, and Swale detailed grid sites, respectively. In each of these figures, the same color ramp and isoline interval (2 mS/m) are used. In Figure 6, the location of the centerline of the swale has been approximated. In each figure, the locations of measurement points are shown in the HDO plots.

In each detailed grid site, plots of EC_a data collected in the vertical dipole orientation display conspicuous bands of higher and lower conductivity. These bands are orientated in a general east-west direction. Similar, but less apparent trends can be observed in the EC_a data presented for the reconnaissance surveys of the entire catchment (see Figures 1 and 2). These trends suggest linear features varying ever-so-slightly in EC_a. While these lineations may reflect measurement and instrument errors, they could also indicate differences in lithology, soil depth, and/or soil moisture. As the approximate locations of these lineations appear to remain constant over the three reconnaissance surveys (where it is unlikely that similar paths were taken, or instrument and measurement errors consistently repeated), these patterns are assumed to reflect relatively stable properties of the soil and rock.

While distinct spatial patterns are evident in each plot, traverse lines are considered too widely spaced with some observation points poorly positioned. A larger number of more controlled survey lines is needed in conducting subsequent surveys. These three sites can be flagged and additional surveys can be conducted at monthly intervals to help characterize the large-scale spatial and temporal variability in EC_a.

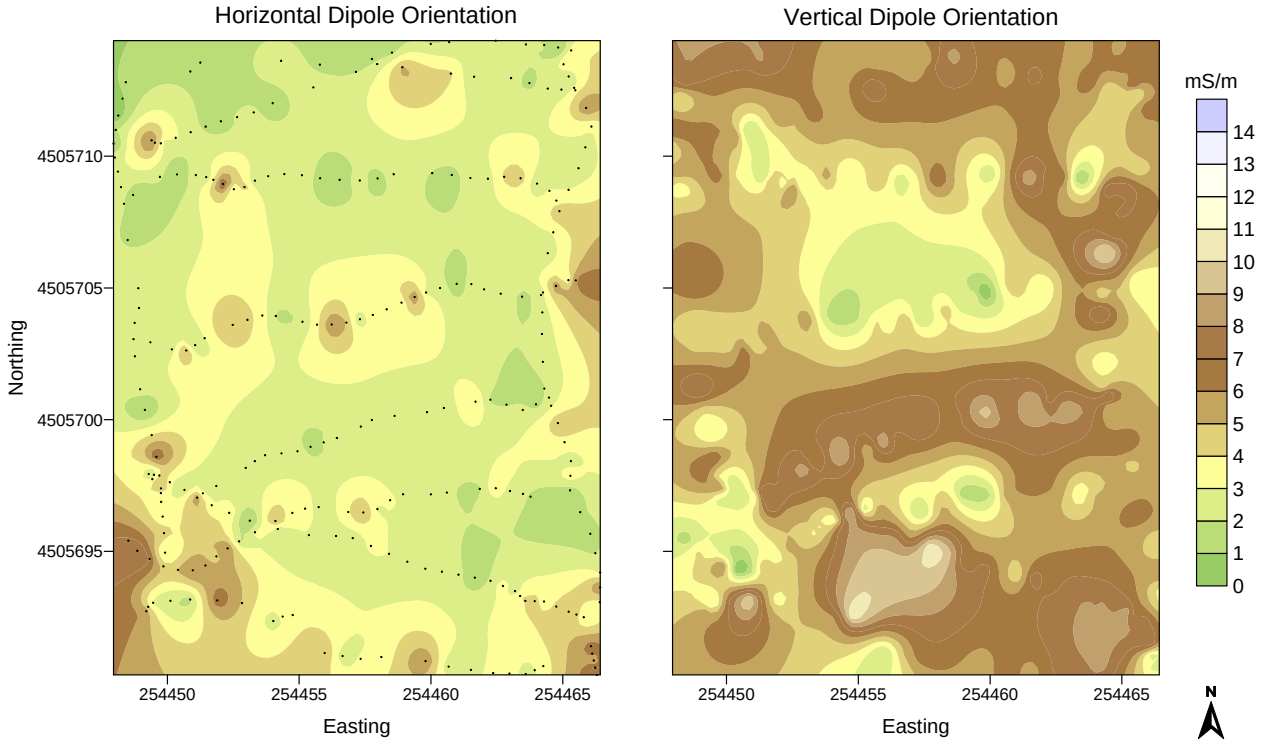

Figure 4. Plots of EC_a collected on the Summit Site with the EM38DD meter in the horizontal (left-hand plot) and vertical (right-hand plot) dipole orientations.

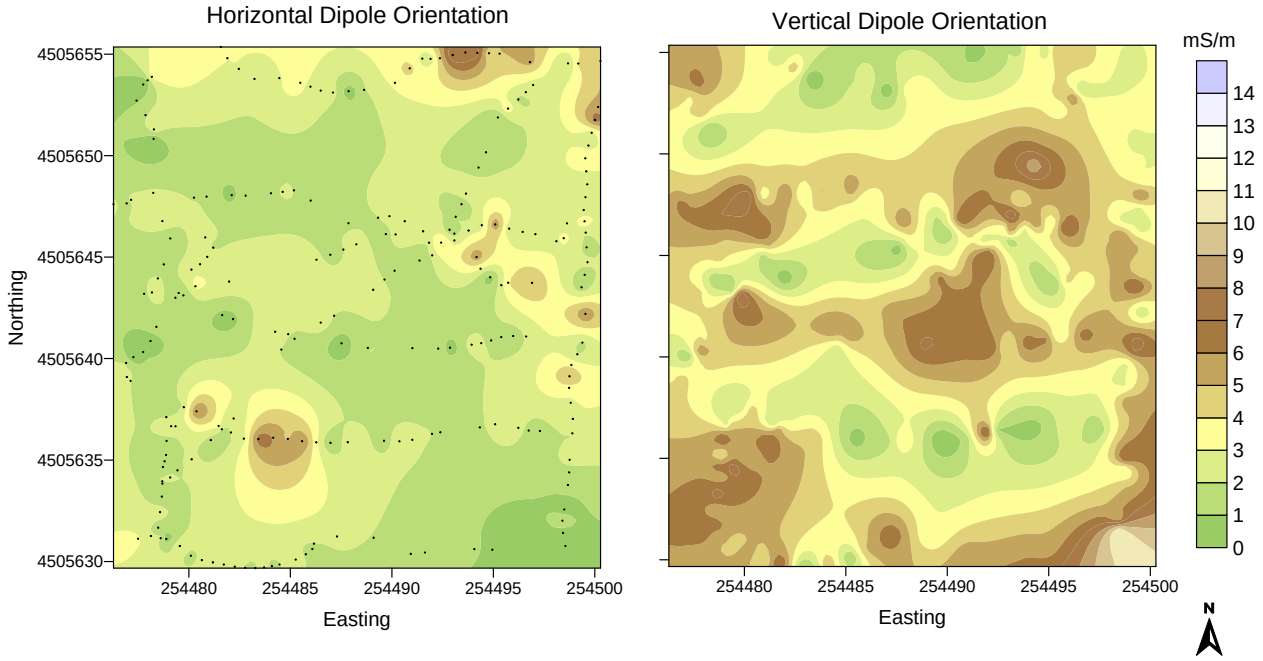

Figure 5. Plots of EC_a collected on the Side Slope Site with the EM38DD meter in the horizontal (left-hand plot) and vertical (right-hand plot) dipole orientations.

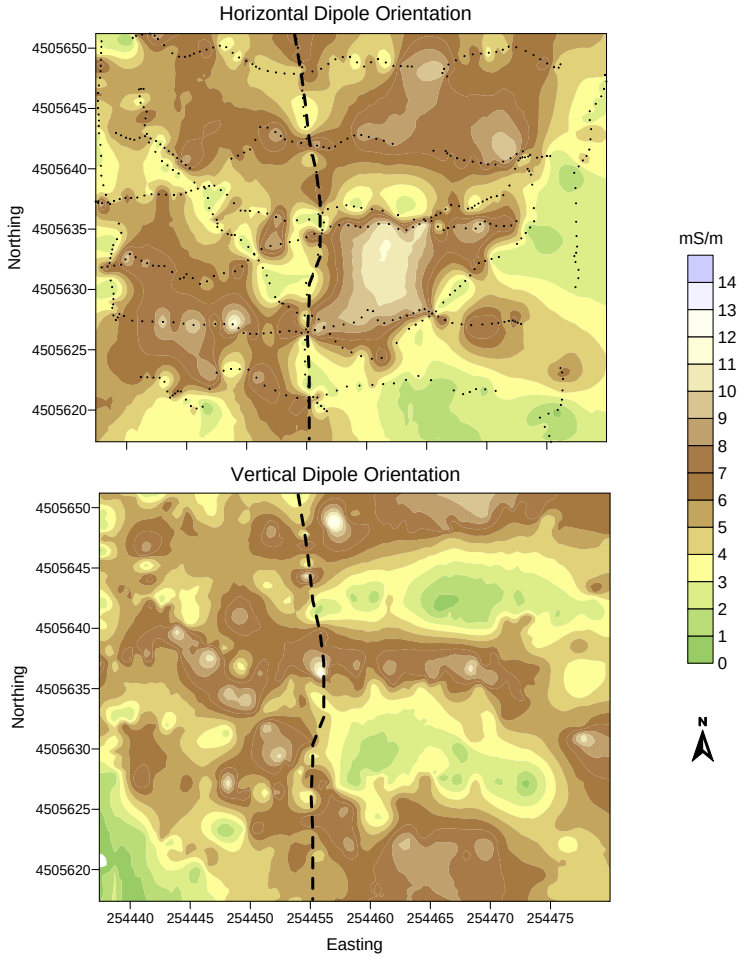

Figure 6. Plots of EC_a collected on the Swale Site with the EM38DD meter in the horizontal (upper plot) and vertical (lower plot) dipole orientations.

Relationship between TDR and EMI measurements:

Within the Shale Hills Catchment, soil moisture is regularly monitored at 77 sites. These monitoring sites are distributed across all soil types and landforms within the catchment. At each site, multi-depth soil moisture estimations are obtained with time domain reflectometry (TDR). Measurements are made at specified depths within 0.051-m diameter, PVC access tubes (Lin, 2006). Lowering a TRIME-T3 probe down the access tubes, two measurements are obtained at depths of 20, 40, 60, 80, and 100 cm (Lin, 2006). These measurements are averaged and used to calculate soil profile moisture storage.

As both EMI with TDR measurements are influenced by soil moisture, it is desirable to compare these measurements and to examine their relationships. In the United Kingdom, Waine et al. (2000) obtained a coefficient of determination (R^2) of 0.88 between total available water capacity and measurements obtained with an EM38 meter. In a comparison of EC_a and averaged volumetric water content in Minnesota, Khakural et al (1998) obtained R^2 values of 0.71 and 0.52 for EC_a measured for nominal depths of 150 and 75 cm, respectively. In Australia, Huth and Poulton (2007) obtained an R^2 value of 0.93 between EC_a and total soil moisture in the surface 0.9 m of the soil. In Canada, Kachanoski et al (1988) obtained R^2 of 0.96 between total available water content and EMI response. In another study, Kachanoski et al (1990) found that EC_a explained more the 80% of the variation in water storage in the upper 1.7 m of the soil. Sheets and Hendrickx (1995) only obtained a correlation (R^2) of 0.64 between EC_a (measured with an EM31 meter) and soil water content measurements (measured with a neutron probe). Hezarjaribi and Sourell (2007) obtained a R^2 of 0.77 between EC_a measured with the Veris 3100 system (for shallow measurements; 0 to 50 cm) and total available moisture, but lower correlations for measurement obtained with the EM38 meter (R^2 of 0.5597 and 0.3501 for measurements obtained in the vertical and horizontal dipole orientations, respectively). Hezarjaribi and Sourell (2007) reasoned that the poorer correlations with the EM31 and EM38 meters were attributed to the deeper column and greater volume of soil measured with these meters.

A comparison of EMI and TDR measurements were made at 35 of the monitoring sites within the Shale Hills Catchment. The results are shown in Table 3. These results are disappointing as they are poorer than anticipated and documented in the above mentioned

research articles. Many factors are involved and can be used to help explain the very poor relationships: differences in the volume of soil measured with the two instruments, the presence of bedrock at relatively shallow depths at some monitoring sites, vertical and spatial differences in bulk density, differences in soil temperature, and instrument and measurement errors. Future work within the catchment should be directed towards a better understanding and/or improvements in the relationships between EMI and TDR.

Table 3.
Correlation coefficients (r) between EC_a measured with the EM38 meter and soil water estimations made with a TRIME-T3 TDR probe.

	10 cm	0-20 cm	0-40 cm	0-60 cm	0-80 cm
VDO	0.370	0.389	0.400	0.569	0.529
HDO	0.518	0.517	0.457	0.438	0.530

2. Klepler Farm:

Table 4 summarizes the results of the EMI survey that was completed on the research fields at Klepler Farm. All EC_a data were temperature corrected to a standard temperature of 75° F. For the shallower-sensing (0 to 75 cm), horizontal dipole orientation (HDO), EC_a ranged from about 8.5 to 266.4 mS/m. The large range and some anomalously high EC_a values reflect the presence of buried utility lines and artifacts within these fields. In the HDO, EC_a averaged 24. 7 mS/m with a standard deviation of 8.4 mS/m. One-half the EC_a measurements recorded in the HDO were between 21.6 and 26.7 mS/m. For the deeper sensing (0 to 150 cm), vertical dipole orientation (VDO), EC_a ranged from about -203.6 to 105.6 mS/m. Once again, the large range and the anomalous EC_a values reflect the presence of buried artifacts. In the VDO, EC_a averaged 25.4 mS/m with a standard deviation of 8.3 mS/m. One-half the EC_a measurements recorded in the HCP were between 22.43 and 27.1 mS/m.

Table 4
Basic EMI Statistics for EMI survey of the Klepler Farm Research Site, Pine Grove Mills, Centre County.
(Other than the number of observations, all values are in mS/m)

	HDO	VDO
Number	8274	8274
Minimum	8.46	-203.58
25%-tile	21.58	22.43
75%-tile	26.66	27.09
Maximum	266.44	105.61
Average	24.67	25.41
Standard. Deviation	8.45	8.33

In general, measurements obtained in the HDO (shallow) and VDO (deep) were similar suggesting a similarity in aggregate soil properties (including soil moisture content) within the nominal profiled depths. The range of EC_a was noticeably affected by the presence of buried utility lines within the fields. Buried utility lines parallel the northern boundary and buried power cables entered the south-central portion of the study site along a farm road. These utilities produced electromagnetic interference resulting in anomalous EMI responses. In addition, some anomalous EC_a values are attributed to metallic artifacts that were discarded or buried in the field and crossed or closely approached with the meter during the survey.

Figures 7 contain two-dimensional plots of the EC_a data that were measured with the EM38DD meter in the horizontal (upper plot) and vertical (lower plot) dipole orientations. In each plot, the isoline interval is 2 mS/m and the same color ramp is used. Spatial EC_a patterns appearing in Figure 7 are presumably related to differences in soil wetness, thickness of the residuum, and depth to limestone. Areas with lower EC_a are on higher-lying, more sloping, better drained landscape positions. These areas are inferred to have thinner caps of residuum and shallower depths to limestone bedrock. Areas with higher EC_a are on lower-lying, more imperfectly drained plane and concave slopes. These areas are wetter and were inferred to have thicker caps of residuum or deeper depths to bedrock. In Figure 7, prominent, east-to-west trending, linear band can be identified in the plots of EC_a data. This pattern closely conforms to the crest of a prominent ridgeline.

In the plots shown in Figure 7, the approximate locations of the buried utility lines can be identified by anomalous EC_a values plotted along the northern boundary (mostly masked by blanking files) and in the extreme south central portion (most evident in the upper plot) of the research fields.

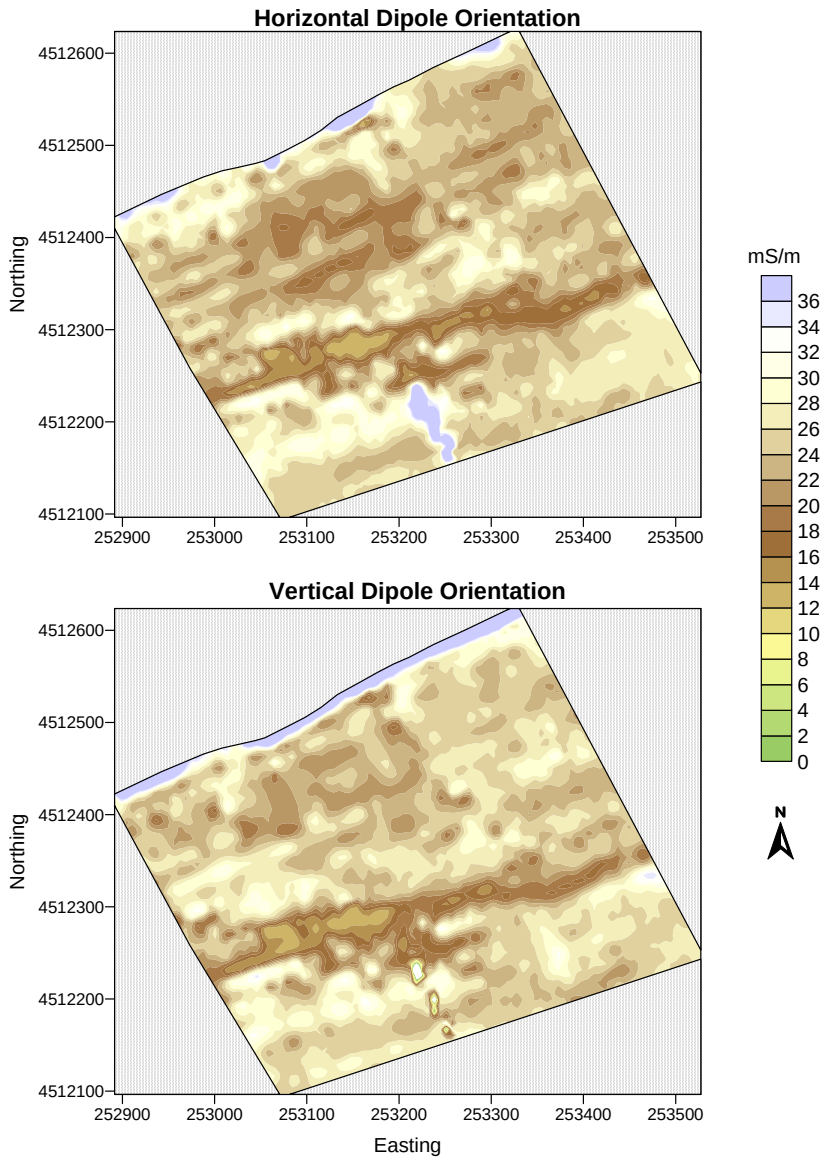

Figure 7 Plots of EC_a collected at Klepler Farm with the EM38DD meter operated in the horizontal (upper plot) and vertical (lower plot) dipole orientations.

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