United States Department of Agriculture

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SUBJECT: SOI – Geophysical Assistance

October 11, 2012

TO: Denise C. Coleman
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NRCS, Harrisburg, Pennsylvania

File Code: 330-7

Purpose:
The purpose of this investigation is to use electromagnetic induction (EMI) to infer spatial and temporal variations in soil moisture in expanded areas surrounding four *Odyssey* well sites located in Crawford, Mercer, and Lackawanna Counties, Pennsylvania. Each well is equipped with an *Odyssey* soil moisture probe, which measures temporal changes in soil moisture content and records the information to a data logger. This information is periodically downloaded to a computer for documentation and analysis. This state-wide NRCS project is designed to collect data on seasonal soil moisture contents, duration of saturation, and depths to water table in Pennsylvania soils. The objective of this project is to improve the *soil moisture status data* in NASIS. This project will collect data on soil moisture contents, fluctuations, and movement across different soil-landscapes.

Participants:
John Chibirka, Resource Soil Scientist, USDA-NRCS, Leesport, PA
Jim Doolittle, Research Soil Scientist, USDA-NRCS-NSSC, Newtown Square, PA

Activities:
Field activities were completed on 15 and 16 August 2012.

Summary:

Recorded data were downloaded from data loggers attached to *Odyssey* soil moisture probes at four monitoring wells sites located in Lackawanna County. Maintenance was performed on each monitoring well and Odyssey soil moisture probe.

Hydropedological investigations were also completed using electromagnetic induction (EMI) in an expanded area around each monitoring well. Point-sampling methods (such as the monitoring wells) provide detailed, but highly site-specific soil and hydrologic data. Time-lapsed EMI surveys provide spatial and temporal information on variations in apparent conductivity, which is associated with changes in soil moisture contents. Advantages of EMI include increased sampling density across landscapes, extension of information gathered from point-based measurements, and recognition of variability within remote-sensing footprints. The time-lapsed (April 2011 (wet period) and August 2012 (dry period)) EMI surveys provide information on soil-landscape architecture and its impacts on water flow.

It was the pleasure of Jim Doolittle and the National Soil Survey Center to be of assistance to you and your staff in this study.

/s/ Jonathan W. Hempel

JONATHAN W. HEMPEL

Director

National Soil Survey Center

cc: See attached list

cc:

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Technical Report on the Use of Geophysical Methods for the Evaluation of Soil Water and Moisture Status at selected Sites in Lackawanna County, Pennsylvania, 15 to 16 August 2012.

James A. Doolittle

Background:
There is a recognized need for additional and improved data on seasonal soil moisture contents, duration of saturation, and depths to high water table in Pennsylvania soils. Data on *soil water status* are used for soil interpretations, conservation practices, risk management, and hydric soil identification. In addition, hydrological models require accurate information on temporal and spatial variations in soil moisture and flow patterns. To accommodate these needs, a study, entitled *Evaluating Soil Water and Moisture Status*, has been implemented to improve the *soil water status* data in NASIS. This study is designed to collect data on soil moisture contents, fluctuations, and movement within different soils and across different landscapes in Pennsylvania. This project will revise and update *soil moisture status* data in NASIS using graphs from data loggers on water table depths, analysis of Pennsylvania's Soil Climate Analysis Network (SCAN) data, and geophysical methods.

Equipment:
An EM38DD (manufactured by Geonics Limited, Mississauga, Ontario) was used in this investigation (see Figure 1).[1] Geonics Limited (2000) describes the operating procedures for this meter. The EM38DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical dipole orientation (VDO) and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation (HDO) with only the receiver switched on). The EM38DD meter weighs about 5.0 kg (11 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 theoretical penetration depths of about 0.75 and 1.5 m in the HDO and VDO, respectively.

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 CX field computer (Juniper Systems, North Logan, UT) with the Trackmaker 38DD software (Geomar Software, Inc., Mississauga, Ontario) (see Figure 1), 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.

The Profiler EMP-400 sensor (hereafter referred to as the Profiler) is manufactured by Geophysical Survey Systems, Inc. (Salem, NH) (see Figure 2).[1] Operating procedures for the Profiler are described by Geophysical Survey Systems, Inc. (2008). The Profiler has a 1.22 m (4.0 ft) intercoil spacing and operates at frequencies ranging from 1 to 16 kHz. It weighs about 4.5 kg (9.9 lbs). The Profiler is a multifrequency EMI meter that can simultaneously record data in as many as three discrete frequencies. For each frequency, both in-phase (susceptibility) and quadrature phase (apparent conductivity, EC_a) data are recorded. The calibration of the Profiler is optimized for 15 kHz and, as a consequence, EC_a is most accurately measured at this frequency (Dan Delea, GSSI, personal communication). Surveys can be conducted with the sensor held in the shallower-sensing HDO or the deeper-sensing VDO orientations. The sensor's electronics are controlled via Bluetooth communications with a Trimble TDS RECON-400

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

Personal Data Assistant (PDA).[2] To collect geo-referenced data, the PDA is configured with an integral 12-channel WAAS (Wide Area Augmentation System) GPS.

Figure 1. The EM38DD meter operated with a field computer and GPS receiver.

Figure 2. The Profiler EMP-400 is operated by a hand-held PDA configured with an integral GPS.

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

To help summarize the results of the EMI surveys, the SURFER for Windows (version 10.0) software (Golden Software, Inc., Golden, CO) was used to construct the simulations shown in this report. [3] The same gridding methods were used on all data.

Field Sites:
The two Odyssey well sites are located in areas of idle land about 1.8 kilometers southeast of Factoryville, Pennsylvania. Site 1, the Wellsboro site (about 75.769 N. latitude and 41.551 W. longitude), is located on a higher-lying, convex slides slope in a delineation of Wellsboro channery loam on 8 to 15 % slopes (WcC). The very deep, moderately well drained and somewhat poorly drained Wellsboro soils formed in till derived from red sandstone, siltstone, and shale. Depth to the fragipan ranges from about 30 to 76 cm.

Site 2, the Morris site (about 75.773 N. latitude and 41.515 W. longitude), is located on a lower-lying, concave foot slope and includes delineations of Morris channery loam on 3 to 8 % slopes (MrB), Morris channery loam on 8 to 18 % slopes (MrC), and Norwich and Chippewa channery silt loams on 0 to 3 % slopes (NcA). These very deep soils formed in till derived from red sandstone, siltstone, and shale. Morris soils are somewhat poorly drained and have a fragipan at depths ranging from about 25 to 55 cm. The Norwich and Chippewa soils are poorly drained and very poorly drained and have a fragipan at depths ranging from about 25 to 60 cm and 20 to 50 cm, respectively. The taxonomic classifications of the named soils at both sites are listed in Table 1.

Table 1 - Taxonomic Classification Of The Soils Recognized At The Odyssey Well Sites.

Soil Series	Taxonomic Classification
Chippewa	Fine-loamy, mixed, active, mesic Typic Fragiaquepts
Morris	Coarse-loamy, mixed, active, mesic Aeric Fragiaquepts
Norwich	Fine-loamy, mixed, active, mesic Typic Fragiaquepts
Wellsboro	Coarse-loamy, mixed, active, mesic Typic Fragiudepts

Field Methods:
Pedestrian surveys were completed with both the EM38DD meter and the Profiler across each site. Both instruments were operated in the continuous mode. Measurements were recorded at a rate of 1/sec and 2/sec for the EM38DD and the Profiler, respectively. The long axis of each device was orientated parallel to the direction of traverse, and held, where possible, about 20 cm above the ground surface. For the EM38DD meter, EC_a data were recorded for both the VDO and HDO orientations. For the Profiler, EC_a data were recorded at 15 kHz in the VDO. All EC_a data were temperature corrected to a standard temperature of 75° F.

Results:
Site 1-Wellsboro Soil:
At the time of this survey, soils were very dry. Table 2 provides basic statistics for the EC_a data that were collected at this site with the EM38DD meter and the Profiler. With both instruments, EC_a was exceedingly low and relatively invariable in this area of Wellsboro soils. Compared to the April 2011 survey, EC_a was noticeably lower across the site at the time of this survey. The soils were very moist at the time of the April 2011 survey.

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

With the EM38DD meter, EC_a decreased slightly with depth (compare the average measurement obtained in the deeper-sensing, VDO with the average measurement obtained in the shallower-sensing HDO). This is opposite the trend that was observed in the April 2011 survey when the soils were exceedingly wet and conductivity decreased with depth. For the present survey, the slightly higher and more variable values recorded in the HDO are attributed to higher water contents in near surface layers associated with more abundant ground vegetation and recent rains, and the very dry subsurface soil moisture conditions. For measurements obtained in the shallower-sensing (0 to 75 cm exploration depth), HDO, EC_a averaged about 1.8 mS/m and ranged from about -3.6 to 8.8 mS/m. One-half of these measurements were between about 1.0 and 2.9 mS/m. These values are considerably lower than the values measured with the 50-cm intercoil spacing of an EM38-MK2 meter in April 2011. In April 2011, with this intercoil spacing, EC_a averaged about 5.7 mS/m, and ranged from about -17 to 31 mS/m. The higher values and more variable EC_a recorded with the EM38-MK2 meter in April 2011 are principally attributed to higher and more spatially variable soil moisture contents.

Table 2. Apparent Conductivity Data from Site 1 – Wellsboro Soils

	EM38DD HDO	EM38DD VDO	Profiler VDO
Number	1103	1103	2321
Minimum	-3.63	-4.38	-4.78
25%-tile	1.00	0.38	2.11
75%-tile	2.88	2.25	5.69
Maximum	8.75	7.88	12.77
Average	1.84	1.18	3.98
St. Dev.	1.63	1.51	2.68

For the deeper-sensing (0 to 150 cm exploration depth) VDO, EC_a averaged about 1.2 mS/m, and ranged from about -4.4 to 7.9 mS/m. One-half of these measurements were between about 0.4 and 2.2 mS/m. These values are considerably lower than the values measured with the 100-cm intercoil spacing of an EM38-MK2 meter in April 2011. Then, EC_a averaged about 8.6 mS/m and ranged from about -3 to 13 mS/m. The higher and more variable EC_a recorded with the EM38-MK2 meter in April 2011 are principally attributed to higher and more spatially variable soil moisture contents. The two time-lapsed, EMI surveys of this site revealed temporal differences in EC_a that are associated with differences in soil moisture contents.

While operating at a different frequency and having a greater intercoil spacing and exploration depth, the EC_a data collected with the Profiler, though slightly higher and more variable, are considered comparable to the data collected in the VDO with the EM38DD meter. With the Profiler operated in the VDO, EC_a averaged about 4.0 mS/m and ranged from about -4.8 to 12.8 mS/m. One-half of these measurements were between about 2.1 and 5.7 mS/m. The slightly higher and more variable EC_a measured with the Profiler can be attributed to its greater exploration depth (the assumption being that soil moisture content will increase at lower soil depths), and differences in calibration and frequency.

Figure 3 shows the spatial EC_a patterns that were measured across the Wellsboro soil site in the VDO with the EM38DD meter (upper plot) and the Profiler (lower plot) during the present survey (2012). In each plot the same color scale and ramp has been used to aid comparison. The locations of the two monitoring wells have been identified with point symbols. A comparison of the two plots reveals that EC_a is extremely low across this site with values increasing in an upslope direction (towards the lower-right or south east in each plot). The southeast corner consists of a higher-lying, less sloping, area that contains inclusions of the somewhat poorly drained Wellsboro and Morris soils. In each plot, intermediate values of EC_a are measured near the paired well sites.

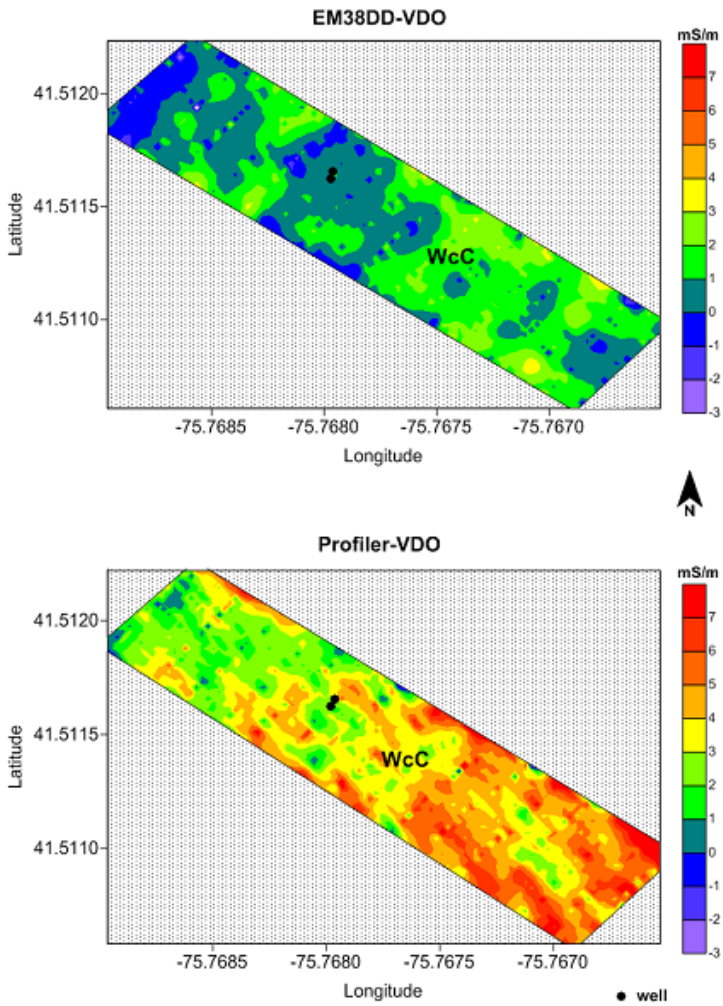

Figure 3. These plots of spatial EC_a patterns were prepared from data collected with an EM38DD and Profiler operated in the VDO at the Wellsboro site.

Site 2 – Morris soils

Table 3 provides basic statistics for the EC_a data that were collected at the Morris soil site with the EM38DD meter and the Profiler. For the EM38DD meter, EC_a increased slightly and was slightly less variable with increasing soil depth (compare measurements collected in the deeper-sensing VDO with measurements collected in the shallower-sensing HDO). The higher values recorded in the VDO are associated with more poorly drained soils that have greater soil moisture contents with increasing depth. For measurements obtained in the shallower-sensing HDO, EC_a averaged only about 2.0 mS/m with a range of about -4.6 to 9.2 mS/m. One-half of the measurements recorded in the HDO were between only about 1.0 and 3.2 mS/m. This EC_a data is slightly higher, but less variable, than the EC_a measured with the 50-cm intercoil spacing of an EM38-MK2 meter in April 2011 survey. Then, EC_a averaged only about 1.7 mS/m with a range of about -15 to 22 mS/m. The greater range in EC_a values recorded with the EM38-MK2 meter in the April 2011 survey are attributed to spatially more variable soil moisture contents in near surface layers.

For the deeper-sensing VDO, EC_a averaged 2.7 mS/m and ranged from about -1.6 to 7.5 mS/m. One-half of these measurements were between about 1.5 and 3.9 mS/m. Compared with the higher-lying Wellsboro soil site, the deeper-sensing (0 to 150 cm) EC_a measurements recorded at the Morris site are

higher and more variable. Once again, this can be explained by the Morris site's lower-lying position in the landscape and its more imperfectly drained conditions. The values recorded in the present survey are lower and less variable than the values measured with the EM38-MK2 meter (with a 100-cm intercoil spacing) in April 2011. Then, EC_a averaged about 12 mS/m and ranged from about 4 to 18 mS/m. The higher values recorded with the EM38-MK2 meter in April 2011 are attributed to higher soil moisture contents.

Table 3. Apparent Conductivity Data from Site 2 – Morris Soils

	EM38DD HDO	EM38DD VDO	Profiler VDO
Number	552	552	1422
Minimum	-4.63	-1.63	-10.77
25%-tile	1.00	1.50	-0.58
75%-tile	3.25	3.88	3.95
Maximum	9.25	7.50	11.51
Average	1.95	2.70	1.83
St. Dev.	1.93	1.64	3.25

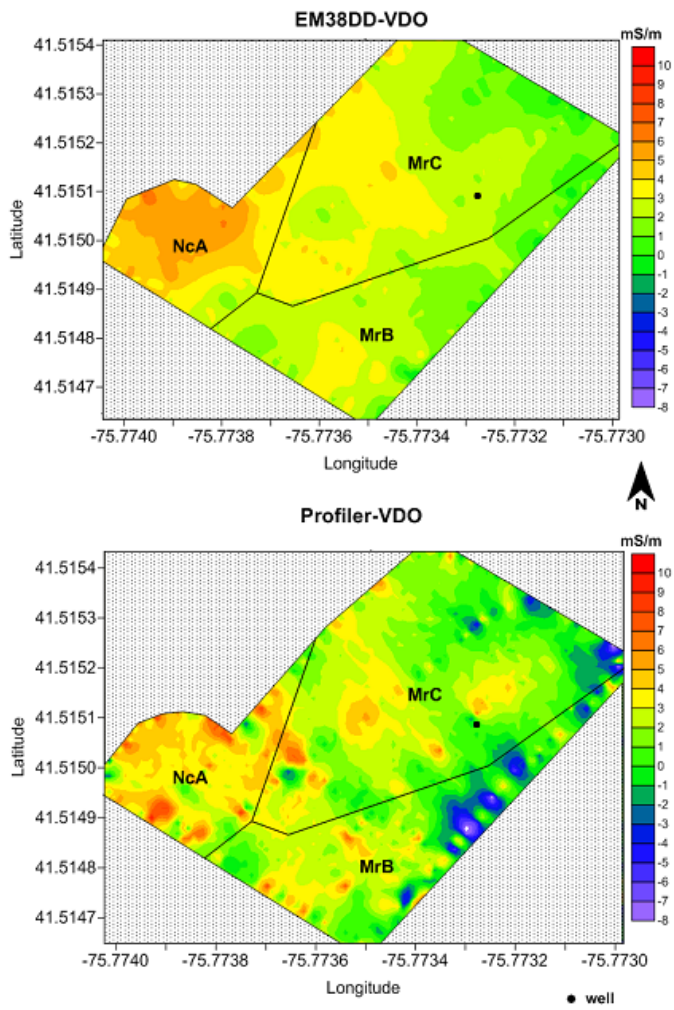

Figure 4. These plots of spatial EC_a patterns were prepared from data collected with an EM38DD and Profiler operated in the VDO at the Morris site.

Figure 4 shows the spatial EC_a patterns that were measured across the Morris soil site in the VDO with the EM38DD meter (upper plot) and the Profiler (lower plot) during the present survey (2012). In each plot the same color scale and ramp has been used to aid comparison. In each plot, the location of the paired wells has been identified with a point symbol. Soil boundary lines have been digitized from Web Soil Survey data.[4]

A comparison of the two plots shown in Figure 4 reveals the relatively low EC_a measured across the Morris soil site with the two different EMI sensors. Apparent conductivity is highest in the northwest corner of the site (middle-left side of each plot) where an area of poorly drained and very poorly drained Norwich and Chippewa soils (NcA) have been mapped. In general, EC_a decreases in an up slope direction towards the east. In each plot, intermediate values of EC_a are measured near the paired well site.

Comparison:
For both the Morris and Wellsboro soil sites, EC_a data collected with the EM38-MK2 meter (100-cm intercoil spacing) in April 2011 were compared with the data collected with the EM38DD meter (VDO) in August 2012. These meters and these geometries provide similar exploration depths and depth weighted EC_a averages. Using the *Grid Math* function in Surfer 10, the August 2012 data were subtracted from the April 2011 data. In the resulting grid files, positive values indicate an increase in EC_a from the April 2011 survey to the August 2012 survey. Negative values indicate a decrease in EC_a from the April 2011 survey to the August 2012 survey. These relative values are associated with changes is soil moisture, a dynamic soil property that affects EC_a. The magnitude of change is a reflection of the relative increase or decrease in soil moisture content at a particular soil-landscape position.

Figure 5 contains plots showing the relative change in EC_a between the two sampling periods at the Wellsboro (upper plot) and Morris (lower plot) soil sites. The same color ramp, but different color scales have been used in these plots. In each plot the locations of the wells have been shown with spot symbols. Soil boundary lines have been digitized from Web Soil Survey data.[4]

In the plots of both sites, all EC_a values are negative, signifying a reduction in EC_a and soil moisture content from the April 2011 (wetter soil conditions) to the August 2012 (drier soil conditions). The plot of Wellsboro soil site (Figure 5, upper) shows a slightly greater difference between the two surveys. From this plot, a greater reduction in soil moisture is assumed to have occurred on lower-lying, more sloping areas of Wellsboro soils located in the northern (upper-left) part of the survey area. In higher-lying, less sloping areas of Wellsboro soils that are located in the southeastern (lower-right) portion of the survey area, the reduction in EC_a and associated soil moisture contents is less. This area contains inclusions of more imperfectly drained Morris and Wellsboro soils. The spatial EC_a patterns are believed to reflect the microtopography and potential pathways of moisture flow or infiltration.

In the plot of Morris soil site (Figure 5, lower), the lower reduction in EC_a in the western portion of the site is associated with a more modest decrease in soil moisture. This lower-lying, less sloping area consists of poorly drained and very poorly drained Norwich and Chippewa soils (NcA). Moving upslope and towards the east across the Morris site, the reduction in EC_a from the time of the April 2011 to the time of the August 2012 surveys appears to be greater. Once again, this is believed to reflect a greater change in soil moisture content. Though all negative (reflecting a decrease in water content), linear trends of greater or lesser differences in EC_a extend in an east-southeast to west-northwest orientation across the Morris site. This trend is in a down slope direction and may reflect the microtopography, underlying soil architecture, and/or potential pathways of moisture flow or storage.

[4] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [3/17/2011].

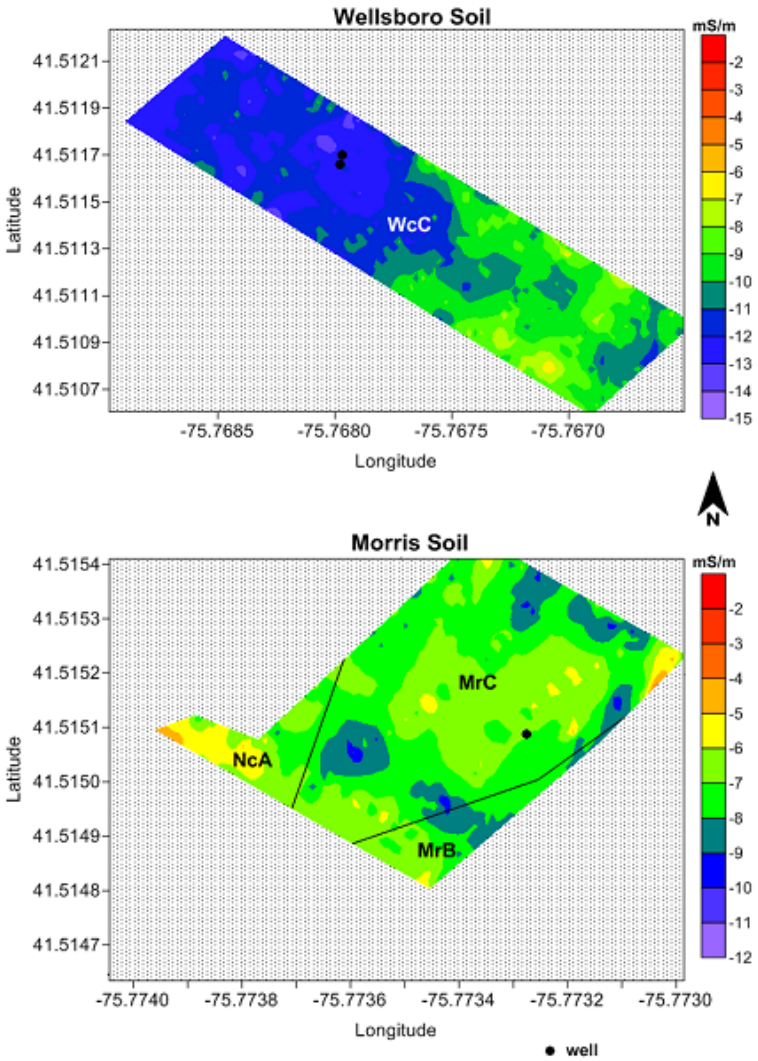

Figure 5. These plots show the difference in apparent conductivity at the two Lackawanna County sites for April 2011 and August 2012. Negative values indicate the decline in EC_a from a relatively wet (April 2011) to dry (August 2012) time of the year.

Figure 6 contains three-dimensional (3D) wireframe simulations of the two sites, each with a superimposed contour plots of the differences in EC_a data measured at the time of the two EMI surveys. These plots provide a clearer image of the temporal changes in EC_a that occur with landscape position. The same color ramp, but different color scales have been used in these plots. In each plot the locations of the wells have been shown with spot symbols. Soil boundary lines have been digitized from Web Soil Survey data.[5]

Spatial trends and patterns can be seen the 3D simulations of each site. For the Morris soil site, lineations of slightly higher or lower differences in EC_a are evident descending the more sloping areas of Morris soil towards the depressional area of Norwich and Chippewa soils. These lineations are assumed to reflect changes in soil moisture contents that are related to the underlying soil architecture. For the Wellsboro

[5] Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed [3/17/2011].

soil site, a broad area with greater changes in soil moisture content is evident on the lower-lying portions of the survey area. Smaller differences in EC_a measurements are evident on higher-lying slope components that contain inclusions of the more imperfectly drained Morris soils. Zhu et al. (2010) observed that repeated, time-lapsed EMI surveys have merits of revealing temporal changes in heterogeneous soilscapes such as subsurface hydrologic dynamics.

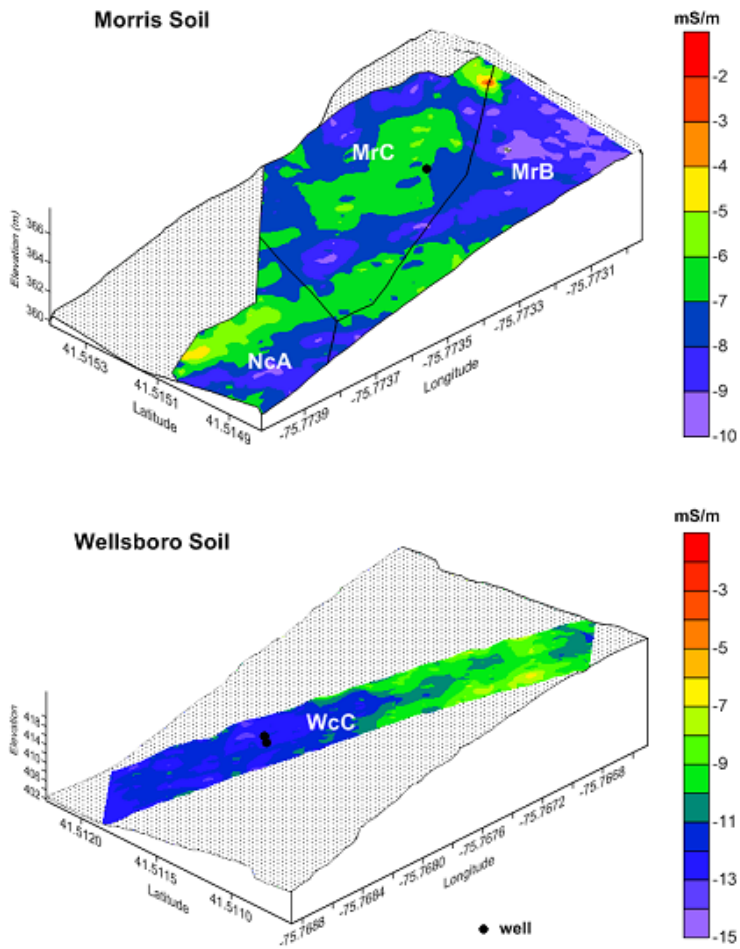

Figure 6. These three-dimensional wireframe images show the difference in apparent conductivity between the April 2011 and the August 2012 relative to soil-landscape components.

References:

Geonics Limited, 2000. EM38DD ground conductivity meter: Dual dipole version operating manual. Geonics Ltd., Mississauga, Ontario.

Geophysical Survey Systems, Inc., 2008. Profiler EMP-400 User's Manual. Geophysical Survey Systems, Inc., Salem, New Hampshire.

McNeill, J.D. 1980. Electromagnetic terrain conductivity measurements at low induction numbers. Technical Note TN-6. Geonics Ltd., Mississauga, Ontario.

Zhu, Q., H.S. Lin, and J.A. Doolittle. 2010. Repeated electromagnetic induction surveys for determining subsurface hydrologic dynamics in an agricultural landscape. *Soil Science Society of America, J.* 74: 1750-1762.