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Subject: Geophysical Assistance **Date:** 29 October 1998

To: Shirley Gammon
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Purpose:
This is a continuance of the geophysical field activities that were conducted during the period of 24 to 28 August 1998 and reported in my trip report of 10 September 1998.

Participants:
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Activities:
All field activities were completed during the period of 28 September to 1 October 1998.

Equipment:
The electromagnetic induction meters used in this study were the EM38 and EM31, manufactured by Geonics Limited*. These meters are portable and require only one person to operate. McNeill (1980 and 1986) has described principles of operation. No ground contact is required with these meters. These meters provide limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. The EM38 meter operates at a frequency of 14,600 Hz and has theoretical observation depths of about 0.75 and 1.5 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter operates at a frequency of 9,800 Hz and has theoretical observation depths of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

The position of all observation points was obtained with a Rockwell Precision Lightweight GPS Receiver (PLGR)*. The receiver was operated in the continuous mode using an external power source (portable 9-volt battery). The Universal Transverse Mercator (UTM) coordinate system was used.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.* was used to construct two-dimensional simulations. Grids were created using kriging methods.

Results:

* Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-USDA-NRCS.

1. Electromagnetic induction is a suitable tool for the mapping riparian areas. Spatial patterns are evident in EMI data sets. This geophysical tool can provide in a relatively short time the large number of observations needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, selecting sampling sites, and for planning further investigations.

2. At the Price Creek site in Beaverhead County, within the riparian area, soils were similar and comparatively invariable in horizonation and composition. Depths to water table were more variable and ranged from 24 to 40 inches. Although sampling was restricted (N = 5), strong correlations were obtained by relating apparent conductivity to water table depth. Correlation coefficients were – 0.95614 and –0.90365 for measurements made in the horizontal and vertical dipole orientations, respectively.

3. At the Godfrey Creek site in Gallatin County, EMI did not detect any conspicuous plumes of high apparent conductivity emanating from an adjoining field that has received excessive applications of manure. If seepage or surface runoff of contaminants exists, concentrations are too low to afford detection by EMI methods.

4. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, 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 again in Montana and with members of your fine staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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Price Creek Site, Beaverhead County

Background:

Electromagnetic induction is a noninvasive geophysical tool that is used in high intensity surveys and site assessments. Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of materials below the transmitter and receiver coils. This apparent conductivity is a weighted, average measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Electromagnetic induction methods map lateral and vertical variations in apparent electrical conductivity. The resulting spatial patterns are used to infer changes in soils and soil properties.

Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the types and concentration of ions in solution, amount and types of clays in the soil matrix, volumetric water content, and temperature and phase of the soil water (McNeill, 1980). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Study Area:

The study area is located along Price Creek in southern Beaverhead County. The study area is located within an enclosed range site. Soils in the area have not been mapped. Based on field observations, the soils within the riparian area are members of the fine-loamy, mixed, Cumulic Cryaquolls family.

Field Procedure:

Five random traverses were conducted across the Price Creek Site. Traverses were conducted orthogonal to the creek in essentially west - east directions. Survey flags were inserted in the ground at irregular intervals along each traverse line and served as observation points. Generally, intervals conform to observed divisions in landscape or vegetative units. The coordinates of each observation point were obtained with a Rockwell Precision Lightweight GPS receiver. The five traverses formed a crude grid across the study area. On the second day of fieldwork, five soil profiles were described within the riparian area. On an adjoining, higher-lying side slope, an additional soil profile was also observed and recorded. Additional EMI measurements were recorded to fill in gaps in the spatial plots and to provide more complete coverage of the site. These procedures produced a total of fifty-three observation points.

The relative elevation at forty-four observation points was determined with a level and stadia rod. Elevations were not tied to a benchmark; the lowest measured ground surface served as the 0.0-foot datum. Figure 1 is a three-dimensional surface net of the study area. In Figure 1, the contour interval is one foot. Relief is 11.8 feet. In Figure 1, the approximate location of Price Creek has been shown. This stream channel is incised and is at a lower elevation (about 2 to 3 feet) than the flood plain.

At each observation point, measurements were obtained with the EM38 meter in both the horizontal and vertical dipole orientations. For each measurement, the meter was placed on the ground surface.

Results:

Table 1 contains the basic EMI statistics for the survey area. Apparent conductivity increased and became slightly more variable with increasing depths of observation. Within the study area (shown in Figure 1), apparent conductivity of the upper 30 inches (measured with the EM38 meter in the horizontal dipole orientation) averaged 18.32 mS/m with a standard deviation of 8.71. The apparent conductivity of the upper 60 inches (measured with the EM38 meter in the vertical dipole orientation) averaged 23.43 mS/m with a standard deviation of 9.22. The increased conductivity with depth was attributed to increased moisture and soluble salt contents at greater soil depths.

Figure 2 contains two-dimensional plots of data collected with the EM38 meter in the horizontal (left-hand plot) and vertical (right-hand plot) dipole orientations. In Figure 2, the left-hand plot represents the spatial distribution of apparent conductivity within the upper 30 inches of the soil profile. The right-hand plot represents the spatial distribution of apparent conductivity within the upper 60 inches of the soil profile. In each plot, the isoline interval is 4 mS/m.

Table 1
Basic Statistics for EMI Survey
Price Creek Site
N = 53
(All values are in mS/m)

Meter	Orientation	Minimum	Maximum	Quartiles 1st	Quartiles 3rd	Average	Standard Deviation
EM38	Horizontal	5.0	38.1	10.8	24.6	18.3	8.71
EM38	Vertical	6.6	41.6	16.7	29.2	23.4	9.22

Electromagnetic induction integrates the bulk physical and chemical properties of soils into a single apparent conductivity value for a defined observation depth. Intrinsic physical and chemical properties, as well as temporal variations in soil water and temperature, establish a unique and characteristic range of apparent conductivity values for each soil. This range can be influenced by differences in use or management practices (Sudduth and Kitchen, 1993, Sudduth et al., 1995). At low total soluble salt levels, EMI maps soil types (Cook et al., 1992). Variations in apparent conductivity have been associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993, Doolittle et al., 1996).

In Figure 2, areas with apparent conductivity greater than 12 mS/m are on the flood plain. Soils within this area are members of the fine-loamy, mixed, Cumulic Cryaquolls family. Areas with apparent conductivity values less than 12 mS/m are on higher-lying slopes and represent dissimilar, well drained upland soils

The spatial patterns evident in Figure 2 are believed to represent patterns of soils and soil properties. Soils were observed at five observation points within the flood plain. These soils were remarkably similar in the arrangement, thickness, and texture of soil horizons; and depths to redoximorphic features and gravel layers. Depths to water table were more variable and ranged from 24 to 40 inches.

Apparent conductivity is principally affected by changes in the electrolyte concentration of the soil water and the soil water content (Johnston, 1997). However, at low soil moisture contents, EMI is relatively insensitive to changes in soil-water content. At high soil moisture contents, EMI is sensitive to changes in soil-water content (Hanson, 1997). Although sampling was restricted (N = 5) at the Price Creek site, strong correlations were obtained by relating apparent conductivity to water table depth. Correlation coefficients were – 0.95614 and – 0.90365 for measurements made in the horizontal and vertical dipole orientations, respectively.

The highest correlation was found between water table depths and data collected with the EM38 meter in the horizontal dipole orientation. The coefficient of determination, r^2, between water table depth and apparent conductivity was 0.9142 (significant at the 0.05 level). Apparent conductivity data collected with the EM38 meter and water table depths measured in auger holes were used to develop a predictive regression equation:

$$WTD = 54.357 + (-0.833 * EM38H) \qquad [1]$$

Where "WTD" is water table depth (in inches) and "EM38H " is the apparent conductivity (mS/m) measured with the EM38 meter in the horizontal dipole orientation.

Table 2 contains the EMI measurements, the observed water table depths, and the predicted water table depths for the five observation points. The average difference in the depth to the water table as measured in auger holes and predicted from measurements made with the EM38 meter in the horizontal dipole orientation and equation [1] was 1.68 inches. Differences between observed and predicted water table depths ranged from 0.63 to 2.72 inches. Although the sample population was exceedingly small, the observed relationships were considered favorable and support a possible use for EMI in riparian areas.

Table 2
Relationship between Apparent Conductivity and Depth to Water Table
Price Creek Site

EM38H	EM38V	Observed	Predicted	Difference
19.3	27.4	40	37.28	2.72
27.2	31.5	29	30.70	-1.70
26.8	32.4	32	31.03	0.97
31.2	37.4	28	27.37	0.63
38.1	41.6	24	21.62	2.38

Figure 3 is a two-dimensional plot showing the distribution of water table depths overlaid on a three-dimensional surface net plot of the site. The contour interval is 4 inches. Based on five EMI measurements and the predictive equation [1], water table depths were estimated to range from about 23 to 42 inches within the flood plain. A noticeable, linear band of comparatively shallow water table depths can be seen to the east of the stream channel. This band is located at slightly higher elevations than the stream channel and is believed to represent a discharge area. Water within this discharge area is believed to be seeping from the adjoining slopes. Isolated pockets of shallower or deeper water table depths reflect the microtopography of the flood plain.

The strength of relationships between apparent conductivity and soil properties or features will depend on the EMI meter used, and the depth and variability of the soil features and properties. The more variable the soil properties, the weaker the correlations. Differences in the degree of correlation often demonstrate the importance of selecting the meter and coil orientation that provides the best resolution and most suitable observation depth. The highest frequency (shallowest observation) meter should be used to improve the resolution of subsurface features. However, the observation depth of a meter should be sufficient to include the range in depths to the investigated feature(s). Predictive equations are generally only applicable on the soils and recharge regimes that they were derived from.

Some dissimilar materials have similar values of apparent conductivity and therefore produce non-unique (equivalent) solutions. This occurs where differences in apparent conductivity caused by changes in one property (e.g., layer thickness; soluble salt, clay, or water contents) are offset by variations in another property. Many soils have subsurface layers that vary in thickness and in chemical and physical properties, but have closely similar conductivity values. Where these dissimilar layers occur in the same landscape, they can produce equivalent solutions or measurements. Equivalent solutions are caused by the simultaneous change in two or more properties (e.g., layer thickness; soluble salt, clay or water contents). Equivalent solutions obscured results and limited the effectiveness of EMI. In studies conducted by Jaynes and others (1995a, 1995b) in Iowa, coexistent changes in the moisture, clay, and carbonate contents weakened relationships between apparent conductivity and moisture stress or drainage classes.

Godfrey Creek, Gallatin County

Background:
Large quantities of manure had been applied on fields adjoining the study site. Concerns of potential environmental risks have prompted interest in site monitoring methods to determine the concentration and extent of contamination.

Four wells have been installed within the study area (see Figure 4). Well depths ranged from about 51 to 100 inches. Chemical analyses have provided direct measurements of contaminant levels at four monitoring wells. One well (well #2) has consistently shown higher levels of nitrate-nitrogen. Levels of nitrate-nitrogen ranged from 2.6 to 6.3 ppm. Chemical analysis of the surface layer at one well site (well #1) revealed high levels of phosphorous (36.8 mg/kg). This well is located closest to the fields receiving the large applications of manure.

Monitoring wells have been used to determine the distribution of contaminants plumes caused by runoff and seepage (Collins et al., 1975, and Philips and Culley, 1985). However, monitoring wells are expensive, time consuming, and do not provide comprehensive coverage of sites (can miss contaminant plumes). Because of nonuniform and unpredictable flow patterns, it is often difficult to assess groundwater and surface water contamination from localized monitoring and sampling techniques.

Electromagnetic induction (EMI) can be used to supplement information derived from monitoring wells. Advantages of EMI are its portability, speed of operation, flexible observation depths (with commercially available systems from about 0.75 to 60 m), moderate resolution of subsurface features, and comprehensive coverage. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions and for planning further investigations.

Electromagnetic induction has been used to infer the relative concentration, extent, and movement of contaminants from animal waste-holding facilities (Brune and Doolittle, 1990; Drommerhausen, 1995; Eigenberg et al., 1998; Radcliffe et al., 1994; Ranjan and Karthigesu, 1995; and Stierman and Ruedisili, 1988). Typically, apparent conductivity is noticeably higher in soils affected by animal wastes than in adjoining, unaffected soils. Jaynes and others (1995b) used EMI to estimate pesticide-soil-partitioning coefficients over crop lands. These researchers found that maps prepared from EMI data were useful in assessing the leaching potential of herbicide applications within fields.

Electromagnetic induction does not provide a direct measurement of specific ions or compounds. However, with adequate sampling, apparent conductivity can be correlated with specific ions that are mobile in the soil and associated with animal wastes. Apparent conductivity is positively correlated with concentrations of chloride, ammonia, and nitrate-nitrogen in the soil (Brune and Doolittle, 1990; Ranjan and Karthigesu, 1995; Eigenberg et al., 1998).

Study Area:

The site is located in a pasture along a tributary to Godfrey Creek. The topography of the survey area is simulated in the two-dimensional contour plot shown in Figure 4. In Figure 4, the tributary is represented as a blue segmented line. The contour interval is 1 foot. Relief is about 15.5 feet. The surface slopes towards the east and northeast. Based on surface observations alone, this is the presumed direction of ground-water flow.

Principal soils mapped within the site include members of the Amesha, Bonebasin, Fairway, and Threeriv series. These soils formed in alluvium. The very deep, well drained Amesha soils are on stream terraces. The Amesha soils are members of the coarse-loamy, mixed, superactive, frigid Aridic Calciustepts family. The very deep, very poorly drained Bonebasin soils are on low stream terraces and flood plains. The Bonebasin soils are members of the fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Fluvaquentic Endoaquolls family. The very deep, somewhat poorly drained Fairway soil is on stream terraces and flood plains. The Fairway soils are members of the fine-loamy, mixed, superactive, frigid Fluvaquentic Haplustolls family. The very deep, very poorly drained Threeriv soil is on flood plains. The Threeriv soils are members of the fine-loamy over sandy or sandy-skeletal, mixed, superactive, calcareous, frigid Typic Fluvaquents family.

Field Procedure:

A rectangular grid was established across the site. The grid interval was about 30 feet. Survey flags were inserted in the ground at each grid intersection and served as observation points. Wire fencing bound the western boundary of the survey area. To reduce interference, the grid was offset 10 feet from the fence line. The relative elevation of each grid intersection was determined with a level and stadia rod. Elevations were not tied to a benchmark; the lowest measured observation point served as the 0.0 foot datum. Measurements were taken at each observation point with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations. The coordinates of each observation point were obtained with a Rockwell Precision Lightweight GPS receiver.

Results:
Table 3 summarizes apparent conductivity measured with the two meters and coil orientations. Apparent conductivity increased with increasing depths of observation. This relationship was attributed to increasing water, soluble salts, and clay contents with increasing depths of observation.

Figure 5 contains two, two-dimensional plots of apparent conductivity that have been overlaid upon a three-dimensional surface net diagram of the site. The left-hand plot represents data collected with the EM38 meter in the horizontal dipole orientation. The right-hand plot represents data collected with the EM38 meter in the vertical dipole orientation. In each plot, the isoline interval is 4 mS/m.

Table 3

Basic Statistics for EMI Survey
Grid Interval = 30 feet
N = 80
(All values are in mS/m)

Meter	Orientation	Minimum	Maximum	Quartiles 1st	Quartiles 3rd	Average	Standard Deviation
EM38	Horizontal	09.3	46.0	14.2	25.8	21.4	9.057
EM38	Vertical	15.2	49.9	22.3	33.2	28.8	8.293
EM31	Horizontal	30.0	57.0	41.0	49.0	44.3	7.149
EM31	Vertical	30.0	62.0	42.0	49.0	45.6	6.639

Measurements obtained with the EM38 meter in the horizontal dipole orientation averaged 21.4 mS/m. One-half of the observations had values of apparent conductivity between 14.2 and 25.8 mS/m. Values of apparent conductivity measured with this meter and orientation increase in a downslope direction and towards the drainageway. This spatial relationship is believed to reflect wetter soils and increase soil moisture contents. A former hog operation was located to the immediate north of the study area and along the tributary. Higher values of apparent conductivity along this tributary could be attributed to the hog operation. In the left-hand plot of Figure 5, three fingers of higher apparent conductivity (> 16 mS/m) extend into the study site from the west and from the fields that received large applications of manure. These fingers suggest surface runoff and the concentration of soluble salts in surface layers. One finger includes well #1. Samples collected in the surface layers of this well contained anomalously high level of phosphorous (36.8 mg/kg).

Measurements obtained with the EM38 meter in the vertical dipole orientation averaged 28.8 mS/m. One-half of the observations had values of apparent conductivity between 22.3 and 33.2 mS/m. Values of apparent conductivity measured with this meter and orientation increase in a downslope direction and towards the drainageway. This spatial relationship is believed to be related to wetter soils and increase soil moisture contents nearer to the drainageway. On higher-lying surfaces, the pattern of apparent conductivity isolines resembles contour lines. This relationship suggests the possible influence of alternating strata of sediments within the underlying Tertiary deposits. Wells # 1 and #2 are located in a swale that cuts across the upland. At well #2, soil samples revealed comparatively high concentrations of sodium (152-158 mg/kg) in subsurface layers. Wells located within this swale may have intercepted a subsurface layer containing higher amounts of sodium.

Figure 6 contains two-dimensional plots of apparent conductivity that have been overlaid upon a three-dimensional surface net diagram of the site. The left-hand plot represents data collected with the EM31 meter in the horizontal dipole orientation. The right-hand plot represents data collected with the EM31 meter in the vertical dipole orientation. In each of these plots, the isoline interval is 4 mS/m.

Measurements obtained with the EM31 meter in the horizontal dipole orientation averaged 44.3 mS/m. One-half of the observations had values of apparent conductivity between 41and 49 mS/m. On higher-lying areas, values of apparent conductivity measured with this meter and orientation increase in a downslope direction and towards the drainageway. However, values of apparent conductivity were considerably higher on lower-lying, slightly convex surfaces than in the drainageway. As no significant change in clay contents were found in subsurface layers (18 to 36 inches), this spatial pattern may represent a discharge area near the base of the slope. Higher values of apparent conductivity within the discharge area are attributed to seepage and the deposition of soluble salts near the surface.

Measurements obtained with the EM31 meter in the vertical dipole orientation averaged 45.6 mS/m. One-half of the observations had values of apparent conductivity between 42 and 49 mS/m. Values of apparent conductivity measured with this meter and orientation increase in a downslope direction and towards the drainageway. Again, this spatial relationship is believed to reflect the influence of terrain and wetter soils and increase soil moisture contents on lower slope positions. In the right-hand plot of Figure 5, a conspicuous finger of higher apparent conductivity (> 52 mS/m) extend into the study site from the west and the fields that received large applications of manure. After entering the study area and extending downslope to include well #1, this fingers bends to the north and closely follows the slope contours. This finger may represent subsurface flow of contaminants from the adjoining field.

The results of the EMI survey at Godfrey Creek were inconclusive. Electromagnetic induction did not detect any conspicuous plumes of high apparent conductivity emanating from an adjoining field that has received excessive applications of manure. If seepage or surface runoff of contaminants exists, concentrations are too low to afford detection by EMI methods.

References

Brune, D. E. and J. A. Doolittle. 1990. Locating lagoon seepage with radar and electromagnetic survey. Environ. Geol. Water Sci. 16:195-207.

Collins, E. R. T. G. Ciravolo, D. L. Hallock, D. C. Martens, H. R. Thomas, and E. T. Komegay. 1975. Effect of anaerobic swine lagoons on groundwater quality in high water table soils. 303-305, 313 pp. IN: Managing Livestock Wastes. Proceedings of the Third International Symposium on Livestock Wastes. ASAE, St. Joseph, MI.

Cook, P. G., and G. R. Walker, G. Buselli, I. Potts, and A. R. Dodd. 1992. The application of electromagnetic techniques to groundwater recharge investigations. J. Hydrol. 130:201-229.

Drommerhausen, D. J., D. E. Radcliffe, D. E. Brune, and H. D. Gunter. 1995. Electromagnetic conductivity survey of dairies for groundwater nitrate. J. Environmental Quality, 24: 1083-1091.

Doolittle, J., R. Murphy, G. Parks, and J. Warner. 1996. Electromagnetic induction investigations of a soil delineation in Reno County, Kansas. Soil Survey Horizons 37:11-20.

Eigenberg, R. A., R. L. Korthals, and J. A. Nienaber. 1998. Geophysical electromagnetic survey methods applied to agricultural waste sites. J. Environmental Quality, 27:215-219.

Greenhouse, J. P., and D. D. Slaine. 1983. The use of reconnaissance electromagnetic methods to map contaminant migration. Ground Water Monitoring Review 3(2):47-59.

Hanson, B. R. 1997. Response of electromagnetic conductivity meter to soil salinity and soil-water content. Journal of Irrigation and Drainage Engineering 123:141-143.

Hoekstra, P., R. Lahti. J. Hild, R. Bates, and D. Phillips. 1992. Case histories of shallow time domain electromagnetics in environmental site assessments. Ground Water Monitoring Review. 12(4):110-117.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1993. Soil type and crop yield determination from ground conductivity surveys. 1993 International Meeting of American Society of Agricultural Engineers. Paper No. 933552. ASAE, St. Joseph, MI. 6 p.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1995a. Yield mapping by electromagnetic induction. pp. 383-394. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Site-Specific Management for Agricultural Systems. Minneapolis, Minnesota. March 27-30, 1994. American Society of Agronomy, Madison, Wisconsin.

Jaynes, D. B., J. M. Novak, T. B. Moorman, and C. A. Cambardella. 1995b. Estimating herbicide partition coefficients from electromagnetic induction measurements. J. Environmental Quality. 24:36-41.

Johnston, M. A., M. J. Savage, J. H. Moolman, and H. M. du Plessis. 1997. Evaluation of calibration methods for interpreting soil salinity from electromagnetic induction measurements. Soil Sci. Soc. Am. J., 61:1627-1633.

Kachanoski, R. G., E. G. Gregorich, and I. J. Van Wesenbeeck. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68:715-722.

McNeill, J. D. 1980. Electrical Conductivity of soils and rocks. Technical Note TN-5. Geonics Ltd., Mississauga, Ontario. 22 pp.

McNeill, J. D. 1986. Geonics EM38 ground conductivity meter operating instructions and survey interpretation techniques. Technical Note TN-21. Geonics Ltd., Mississauga, Ontario. 16 pp.

Phillips, P. A. and J. L. B. Culley, 1985. Groundwater nutrient concentrations below small-scale earthen Manure Storage. pp. 244-251. IN: Agricultural Waste Utilization and Management. Proceedings of the Fifth International Symposium on Agricultural Wastes. ASAE, St. Joseph, MI.

Radcliffe, D. E., D. E. Brune, D. J. Drohmerhausen, and H. D. Gunther. 1994. Dairy loafing areas as sources of nitrate in wells. p. 307-313. IN: Environmentally Sound Agriculture; Proceedings of the Second Conference. 20-24 July 1994. American Society of Agricultural Engineers. St. Joseph, MI.

Ranjan, R. S., and T. Karthigesu. 1995. Evaluation of an electromagnetic method for detecting lateral seepage around manure storage lagoons. ASAE Paper 952440. ASAE, St. Joseph, MI.

Rhoades, J. D., P. A. Raats, and R. J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40:651-655.

Stierman, D. L. and L. C. Ruedisili. 1988. Integrating geophysical and hydrogeological data: An efficient approach to remedial investigations of contaminated ground water. p. 43-57. IN: Collins, A. G. and A. J. Johnson (eds.) Ground water contamination field methods. ASTM STP 963. American Society for Testing Materials, Philadelphia.

Sudduth, K. A., and N. R. Kitchen, 1993. Electromagnetic induction sensing of claypan depth. Paper No. 93-1550. Presented at the December 1993, Winter Meetings of the American Society of Agricultural Engineers. St. Joseph, Michigan. 18 pp.

Sudduth, K. A., N. R. Kitchen, D. H. Hughes, and S. T. Drummond. 1995. Electromagnetic induction sensing as an indicator of productivity on claypan soils. pp. 671-681. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Site-Specific Management for Agricultural Systems. Minneapolis, Minnesota. March 27-30, 1994. American Society of Agronomy, Madison, Wisconsin.

Williams, B. G. and S. Arunin. 1990. Inferring recharge/discharge areas from multifrequency electromagnetic induction measurements. Division of Water Resources, Institute of Natural Resources and Environment, CSIRO, Canberra, Australia. Technical Memorandum 90/11. 7 pp.

RELATIVE TOPOGRAPHY
GODFREY CREEK TRIBUTARY
GALLATIN COUNTY, MONTANA

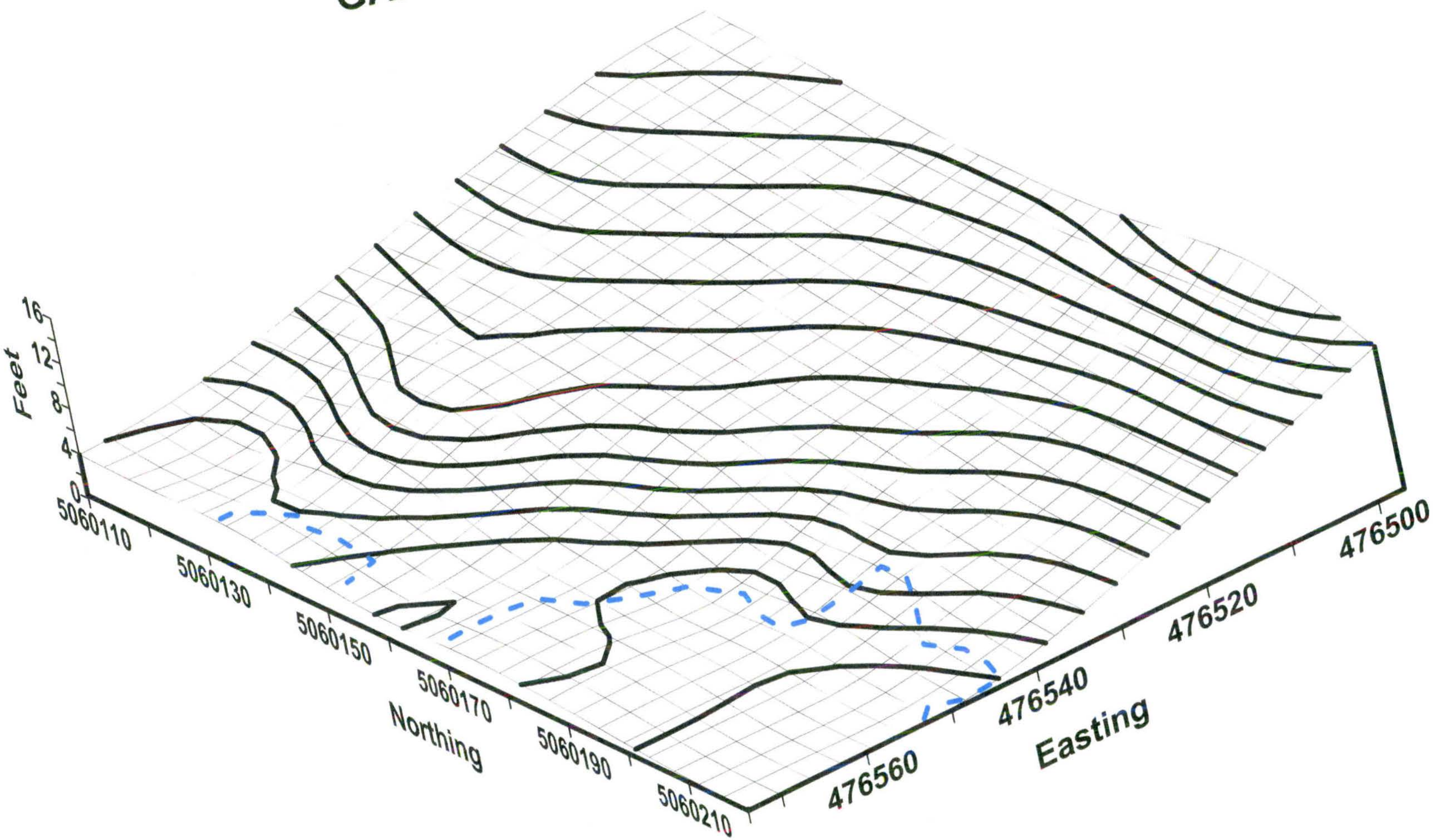

Figure 4