United States Department of Agriculture

Natural Resources Conservation Service

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Subject: SOI -- Electromagnetic Induction (EMI) Assistance

Date: 3 August 1999

To: Shirley Gammon
State Conservationist
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Purpose: To provide EMI field assistance to the Riparian/Wetland Team.

Participants:
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Activities:
All field activities were completed during the period of 14 to 16 July 1999.

Equipment:
A GEM300 multifrequency sensor, developed by Geophysical Survey systems, Inc.,* was also used in this study. The GEM300 sensor is a newly developed EMI meter. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.8 m). Won and others (1996) have described the use and operation of this sensor.

The position of each observation points was obtained with Rockwell Precision Lightweight GPS Receivers (PLGR)*. The receiver was operated in the continuous mode. The mixed satellite mode was used. The Universal Transverse Mercator (UTM) coordinate system was used. Horizontal datum was the North American 1927. Horizontal units were expressed in meters.

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 with an octant search.

Conclusions:
1. 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 borings or well logs). The use of geophysical methods can reduce the number of coring observations, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

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

2. The study that was conducted near Polson demonstrated the use of EMI to identify and map the three types of wetlands described by Richardson and others (1994). Additional studies are needed to confirm this application.

3. At the Godfrey Creek site in Gallatin County, an EMI survey revealed high levels of apparent conductivity in the surface layers of soils located on lower slope positions and along drainageways. Although results remain inconclusive, plots suggest that these areas have higher levels of water and possibly soluble salts. Additional sampling and possibly wells are needed to verify that nutrients are concentrated along the lower slope components of the field located in the northwest portion of the survey area.

With kind regards,

James A. Doolittle
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EMI:

Background:

Electromagnetic induction is a noninvasive geophysical tool that can be used to provide comprehensive data on study sites. Advantages of EMI are its portability, speed of operation, flexible observation depths, and moderate resolution of subsurface features. Results of EMI surveys are interpretable in the field. This geophysical method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, planning further investigations, and locating sampling or monitoring sites.

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are caused by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the volumetric water content, temperature and phase of the soil water, type and concentration of ions in solution, and amount and type of clays in the soil matrix (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).

Electromagnetic induction measures vertical and lateral variations in apparent electrical conductivity. Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements 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.

Depth of Observation:

The theoretical observation depth of the GEM300 is dependent upon the bulk conductivity of the profiled earthen material(s)

and the operating frequency of the sensor. Observation depths are governed by the "skin-depth" effect (Won, 1980 and 1983). Skin-depth is the maximum depth of observation for an EMI sensor operating at a particular frequency and sounding a medium with a known conductivity. Observation depth or "skin-depth" is inversely proportional to frequency (Won et al., 1996). Low frequency signals travel farther through conductive mediums than high frequency signal. Decreasing the frequency will extend the observation depth. At a given frequency, the depth of observation is greater in low conductivity soil than in high conductivity soils. Mutifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

A nomogram was developed (Won, 1980) to approximate the observation depth for a given frequency and soil conductivity. Unfortunately, independent researchers have not extensively tested this nomogram. In addition, it is believed that the nomogram is off by about one order of magnitude (Dan Delea, Geophysical Survey Systems, Inc., personal communication). Assuming that this assumption is correct, the average values for apparent conductivity listed in Table 1 and 2 were used to establish a rough estimate of the observation depth at each frequency. At the Lake County site, the theoretical depth of observations were about 4.0 m at 9,810 Hz, 3.5 m at 11,550 Hz, 3.0 m at 14,610Hz, and 2.8 m at 15,990 Hz. At the Gallatin County site, the theoretical depth of observations were about 6.0 m at 1590 Hz, 2.5 m at 9,810Hz, and 2.0 m at 14,850 Hz. As these depths could not be verified, they represent merely estimates.

In most EMI studies, negative conductivity values are removed by electronic nulling of the data set. The negative offset was not taken out of the data. As a consequence, negative apparent conductivity values appear in the data set and simulated plots.

Lake County Study Site:

Background:

Recent interest in soils and hydrologic modeling has increased the need for data on the depth and movement of groundwater across landscapes. Hydrology plays an important role in the development of soils and is a critical factor in the classification of wetlands. The depth and movement of water through the subsurface has a direct effect on the physical and chemical properties and the morphology of soils (Richardson et al., 1992). Recharge processes remove soluble chemical constituents and translocates suspend colloids, while discharge processes adds materials to soils (Richardson et al., 1992).

Richardson and others (1992) observed relationships between the hydrological regimes of wetlands and soil properties. These authors noted three types of wetlands: recharge, discharge, and flowthrough wetlands. In North Dakota, recharge wetlands are typified by very deep, nonsaline and noncalcareous soils with argillic horizons. These soils have low electrical conductivity. Discharge wetlands are typified by very deep, saline and calcareous soils that lack well developed soil profiles. These soils have high electrical conductivity. Flowthrough wetlands have intermediate levels of soluble salt and carbonate concentrations, soil profile development, and electrical conductivity.

The objective of this study was to ascertain whether EMI could be used to identify and map the three types of wetlands described by Richardson and others (1994).

The study site was located in the northeast quarter of Section 35, Township 20 North, Range 20 West. The site was located on a ground moraine that was pitted with depressions. The area that had been mapped as Post-Ronan-Water complex, 2 to 8 percent slopes (Boast et al., 1997). Very little open water was observed within the study site. Most depressions were covered with wetland vegetation. The very deep, well drained Post soil formed on moraines in strongly alkaline clayey till. Post is a member of the very-fine, illitic, frigid Typic Natrixerolls family. The very deep, well drained Ronan soil formed on dissected lake plains in glaciolacustrine deposits. Ronan is a member of the very-fine, illitic, frigid Typic Natrixeralfs family. A few small slick spots of sodium-affected soils were observed within the study site. Soils on knolls and the periphery of depressions were calcareous. Saline soils were observed around a discharge depression. With the exception of the wetlands, the site was recently cultivated.

Field Procedures:

Random traverses were made across the study area. Figure 1 shows the location of traverse lines and observation points. Depressional areas were sampled at a greater intensity than upland areas. Where possible, observation points were located along the centerline and periphery of each depression. The spacing among these observation points was unequal. Along the other traverse lines, measurements were taken at a distance of about 100 feet. This process provided a total of 250

observation points. The coordinates of each observation point were obtained with a Rockwell PLGR. Measurements were taken with the GEM300 sensor held at hip-height in the vertical dipole orientation. At each observation point, inphase, quadrature phase, and conductivity data were recorded with the GEM300 sensor at four different frequencies (9,810, 11,550, 14,610, and 15,990 Hz). Two of these frequencies are comparable to those of the EM31 meter (9,800 Hz) and the EM38 meter (14,800 Hz). Conventionally, EMI data is displayed as apparent conductivity expressed in milliSiemens per meter (mS/m). This convention has been followed in this report. While inphase and quadrature data were recorded and stored on disc, these values are neither shown nor discussed in this report.

Results:
Spatial distributions of apparent conductivity data collected at various frequencies with the GEM300 sensor are shown in Figure 2. The frequency at which data were collected is shown above each plot. The depth of observation is assumed to increase as the frequency decreases. However, with the four frequencies selected, observation depths are assumed to vary only from 2.8 to 4.0 m. As a consequence, the spatial patterns are similar in each plot. The observed spatial patterns reflect actual measured values of apparent conductivity, the number and distribution of observation sites, and the computer simulated expression of the data sets.

Table 1

Basic Statistics for theGEM300
Apparent Conductivity
(All values are in mS/m)

			Quartiles			
Frequency	**Minimum**	**Maximum**	**1st**	**Median**	**3rd**	**Average**
9,810	-1.03	70.35	5.10	12.51	22.86	16.44
11,550	0.09	70.82	5.14	12.50	23.22	16.43
14,610	-1.36	72.64	5.20	12.20	23.80	16.94
15,990	-2.43	73.33	5.97	12.50	25.30	17.44

Table 1 summarizes the results of this survey. Values of apparent conductivity were variable across the site. This variability is attributed to variations in the soluble salt, clay and water contents of the soils. The averaged apparent conductivity value was moderate (about 16.5 to 17.5 mS/m) and decreased slightly with increasing observation depths (lower frequency).

Values of apparent conductivity were remarkably similar for data collected at each frequency. Considering the similarity in observation depths, this is to be expected. The frequency range (9,810 to 15,990 Hz) used in this study was too high and narrow to provide a deeper and wider range in observation depths. Because of the similarity of these data sets, only data collected at 14,610 Hz (similar to the frequency of the EM38 meter) will be discussed further in this report.

The data collected at a frequency of 14,610 Hz is plotted in Figure 3. The location of each depressional wetland is shown. Prior to the EMI survey, wetland specialists had categorized the groundwater flow pattern within each depressional wetland. Three types of wetlands are identified in Figure 3.

Several observations were made during the course of the survey by visual correlation. Areas with apparent conductivity values greater than 35 mS/m are in depression or at the base of slopes. These areas have high moisture and salt contents. Areas with apparent conductivity values of 10 to 35 mS/m represent areas of calcareous soils with inclusions of sodium affected soils. Areas with apparent conductivity values of less than 10 mS/m are on slightly higher lying, better-drained knolls that have large concentrations of rock fragments. The lower clay and moisture contents of these better-drained soils would produce lower values of apparent conductivity.

As evident in Figure 3, apparent conductivity appears to provide a satisfactory measure to distinguish recharge, discharge, and flowthrough depressional wetlands. Recharge processes remove soluble chemical constituents and translocates suspend colloids. Recharge depressional wetlands are characterized by very deep, nonsaline and noncalcareous soils that have low

electrical conductivity. Within the study site, based on landscape, soil, and vegetation criteria, three depressional wetlands were designated as being recharge areas. For these wetlands, apparent conductivity averaged 11.67 mS/m with a range of −1.36 to 30.09 mS/m. One half of the observations made in these recharge depressional wetlands had values of apparent conductivity ranging from 4.46 to 16.76 mS/m.

According to Richardson and others (1994), flowthrough wetlands have intermediate levels of soluble salt and carbonates, soil profile development, and electrical conductivity. Within the study site, based on landscape, soil, and vegetation criteria, three depressions were characterized as being flowthrough. For these wetlands, apparent conductivity averaged 24.65 mS/m with a range of 2.28 to 55.66 mS/m. One half of the observations made in these flowthrough depressional wetlands had values of apparent conductivity ranging from 14.57 to 32.68 mS/m.

Discharge processes adds materials to soils. Discharge wetlands are typified by very deep, saline and calcareous soils that have high electrical conductivity. Within the study site, one depressional wetland was characterized as being recharge areas. For this wetland, apparent conductivity averaged 37.06 mS/m with a range of 3.30 to 72.64 mS/m. One half of the observations made in the discharge depressional wetland had values of apparent conductivity ranging from 12.47 to 54.75 mS/m.

Godfrey Creek, Gallatin County

Background:
An EMI survey of this site was conducted in September of 1998 with the EM38 and EM31 meters. The Riparian/Wetland Team is monitoring this site because large quantities of manure had been applied on adjoining cultivated fields. Concerns of groundwater contamination have prompted interest in site monitoring methods to help assess 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.

Although, EMI 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), few studies have characterized and assessed the fate of animal wastes when dispersed across fields. Typically, apparent conductivity is noticeably higher in soils affected by animal wastes than in adjoining, unaffected soils. Jaynes and others (1995) used EMI to estimate pesticide-soil-partitioning coefficients over croplands. 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 shows a strong correlation 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. 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 are 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:
Random traverses were made across the study area. Figure 4 shows the location of traverse lines and observation points. Along each traverse line, measurements were taken at a distance of about 100 feet. Additional traverses were completed along Godfrey Creek and a intermittent drainageway that crossed the study area. The intermittent drainageway extends downslope from near the southwest corner of the site to the flood plain of Godfrey Creek. The traverses provided a total of 109 observation points. The coordinates of each observation point were obtained with a Rockwell PLGR.

At each observation point, measurements were taken with the GEM300 sensor held at hip-height in both the horizontal and the vertical dipole orientations. Apparent conductivity was recorded with the GEM300 sensor at three different frequencies (1,590, 9,810, and 14,850Hz). These frequencies are comparable to those of the EM34 meter with a 20-meter intercoil spacing (1,600), the EM31 meter (9,800 Hz) and the EM38 meter (14,800 Hz). Conventionally, EMI data is displayed as apparent conductivity expressed in milliSiemens per meter (mS/m). This convention has been followed in this report. While inphase and quadrature data were recorded and stored on disc, these values are not shown or discussed in this report.

Results:
Table 2 summarizes the apparent conductivity measurements obtained at different frequencies. Apparent conductivity increased with increasing depths of observation. This relationship may be attributed to increasing water, soluble salts, and/or clay contents with increasing depths of observation.

Table 2

Basic Statistics for theGEM300
Apparent Conductivity
(All values are in mS/m)

				Quartiles			
Frequency	**Orientation**	**Minimum**	**Maximum**	**1st**	**Median**	**3rd**	**Average**
1,590 Hz	Horizontal	26.49	69.96	41.60	46.19	50.94	46.85
1,590 Hz	Vertical	31.25	67.47	40.30	43.70	47.77	44.49
9,810 Hz	Horizontal	14.09	71.89	32.39	45.82	53.66	43.99
9,810 Hz	Vertical	16.48	50.86	32.25	36.99	43.03	37.29
14,850 Hz	Horizontal	1.92	65.09	24.79	38.84	46.37	36.26
14,850 Hz	Vertical	2.13	44.34	24.55	29.66	36.19	29.71

The spatial distributions of apparent conductivity within the Godfrey Creek site are shown in figures 5 to 7. Each figure represents data collected at a specified frequency. Each figure contains plots of measurements taken in the horizontal dipole orientation (left-hand plot) and vertical dipole orientation (right-hand plot). In each plot, the isoline interval is 5 mS/m.

In Figures 5, 6, and 7, values of apparent conductivity are highest along Godfrey Creek. These values reflect wetter soils, higher soil moisture contents, and possibly excess nutrients. A former hog operation was located to the immediate north of the study area and along Godfrey Creek. Higher values of apparent conductivity along this stream channel could be attributed to wastes from the hog operation.

In each figure (5, 6, and 7), higher values of apparent conductivity extend upslope from Godfrey Creek into the lower portions of the field located in the northwest portion of the study site (presently in hayland). Surprisingly, this pattern does not extend into the field located in the southwest portion of the study site (presently in grain). In the field located in the northwest portion of the study site, values of apparent conductivity are higher near the surface (horizontal dipole orientation) than at greater soil depths (vertical dipole orientation). These spatial relationships could reflect the concentration of excess nutrients on lower slope positions of the field and within the upper part of soil profiles. On these lower slope positions, surface runoff may have increased the concentration of soluble salts in surface layers.

At each frequency, more conductive surface materials (horizontal dipole orientation) can be found along the intermittent drainageway that drains the fields where animal wastes have been applied. These values could reflect the accumulation of nutrients in surface layers. Measurements made in the vertical dipole orientation are more sensitive to conductivity at greater soil depths. In contrast to measurements made in the horizontal dipole orientation, measurements made in the vertical dipole orientation are lower along the drainageway and on lower slope position. These lower values are presumed to reflect changes in subsurface lithology. Along the drainageway and on lower slope position, it is possible that the GEM300 sensor, in the vertical dipole orientation, is discerning more electrically resistive strata.

The results of the EMI survey at Godfrey Creek remains inconclusive. Additional sampling and possibly wells are needed to verify that nutrients are concentrated along the lower slope components of the field located in the northwest portion of the study site. As lower values of apparent conductivity were measured along the lower slope components in the field located in the southwest portion of the study site, a well here would help resolve the interpretation. Electromagnetic induction did detect an area of high apparent conductivity that extended from Godfrey Creek into adjoining cultivated field. These fields have received excessive applications of manure.

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contamination 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.

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EMI Survey of Depressional Wetlands
Lake County, Montana
Location of Observation Points

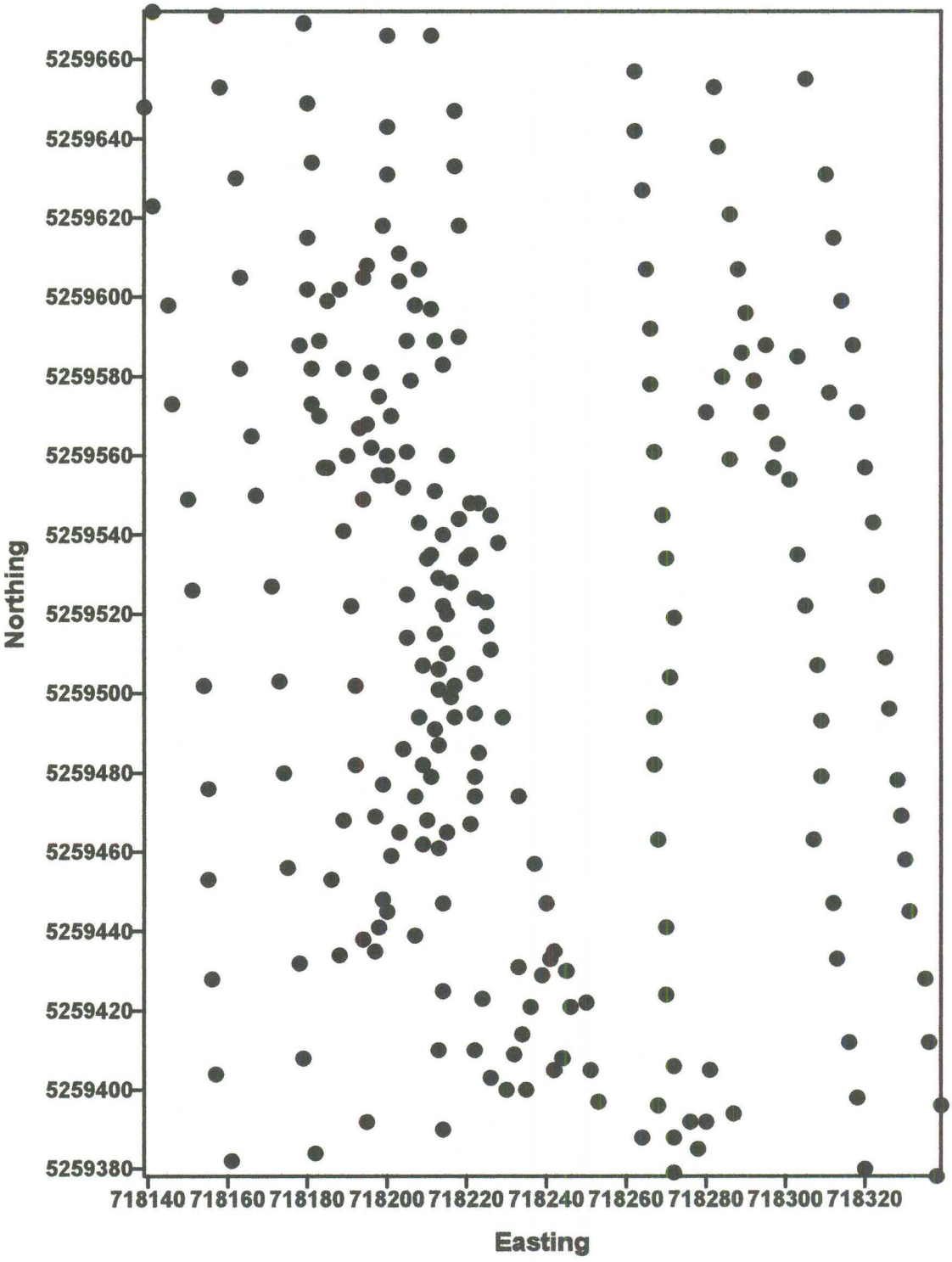

Figure 1

EMI Survey of Depessional Wetlands
Lake County, Montana
GEM300 Sensor

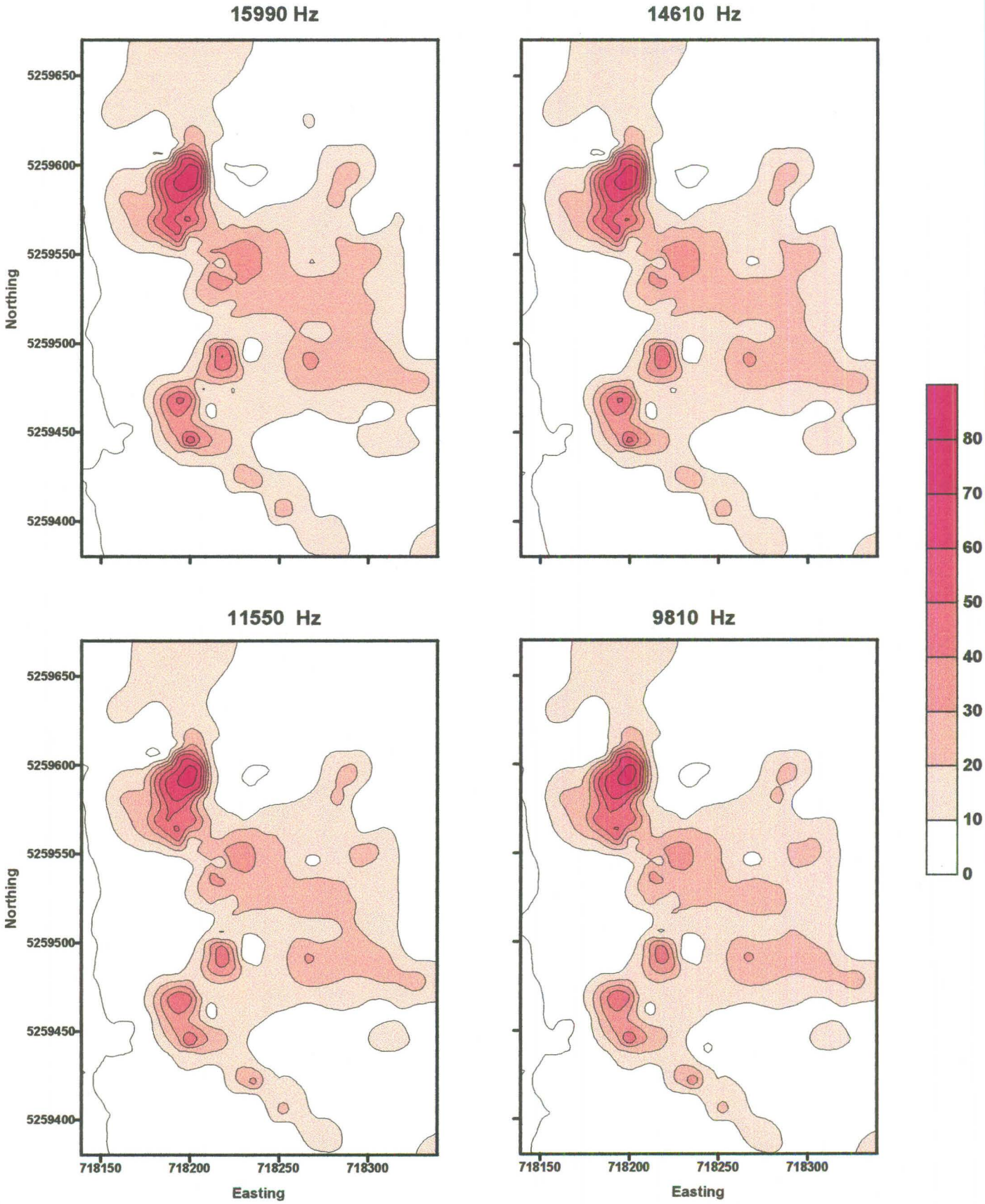

Figure 2

EMI Survey of Depressional Wetlands
Lake County, Montana
14610 Hz

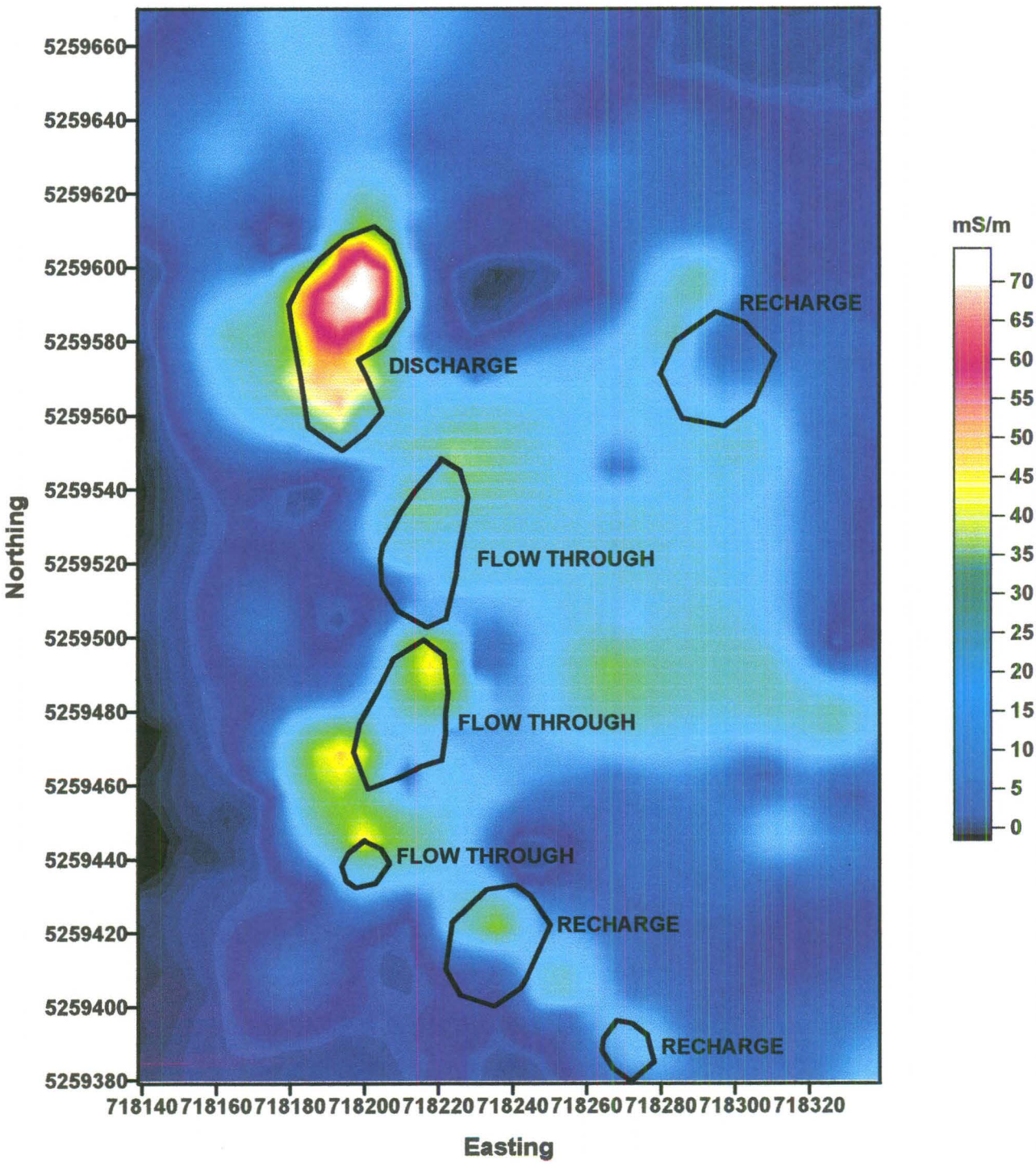

Figure 3

EMI Survey of Godfrey Creek
Gallatin County, Montana
Location of Observation Points

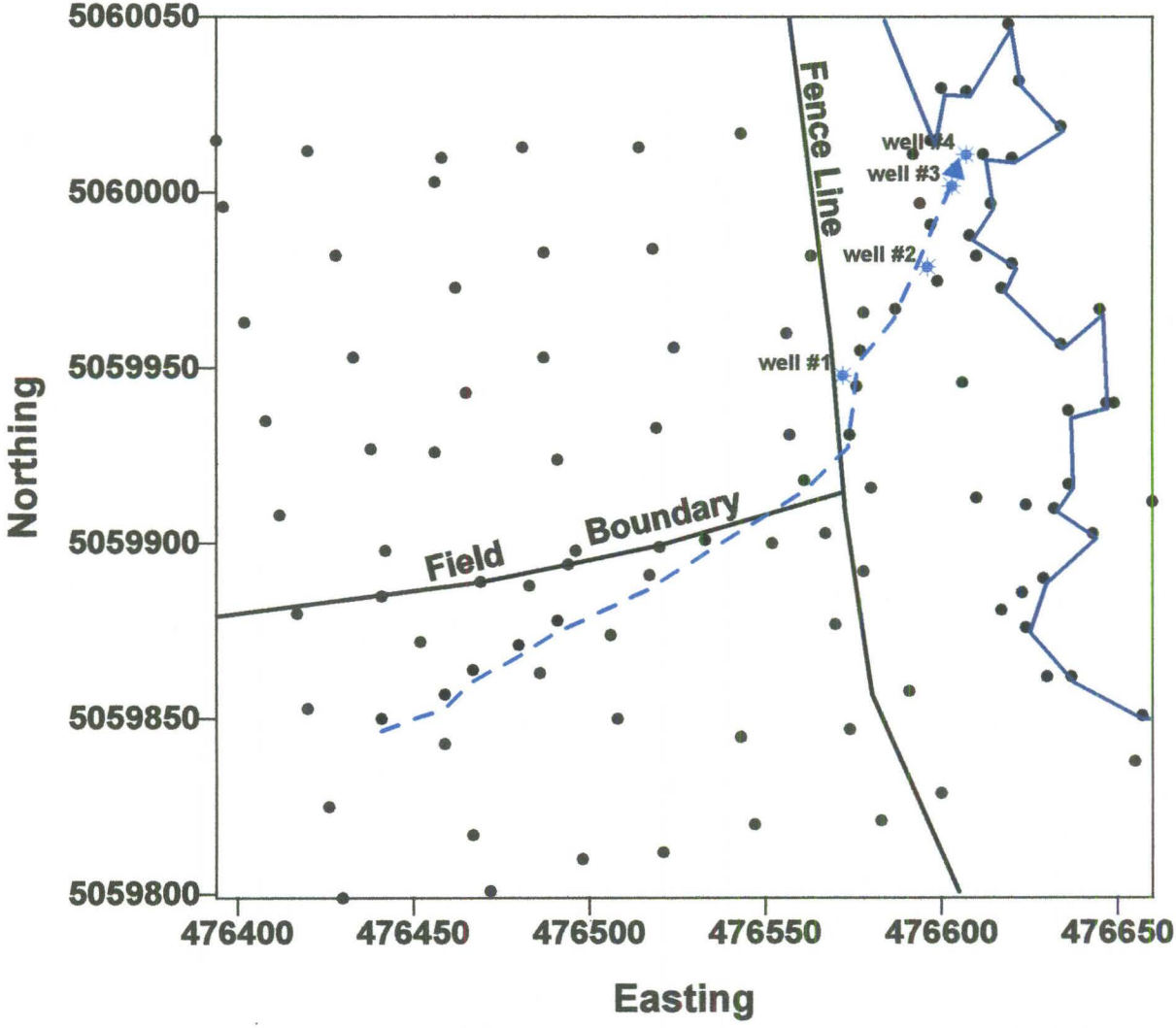

Figure 4

EMI Survey of Godfrey Creek
Gallatin County, Montana
GEM300 Sensor
1590 Hz

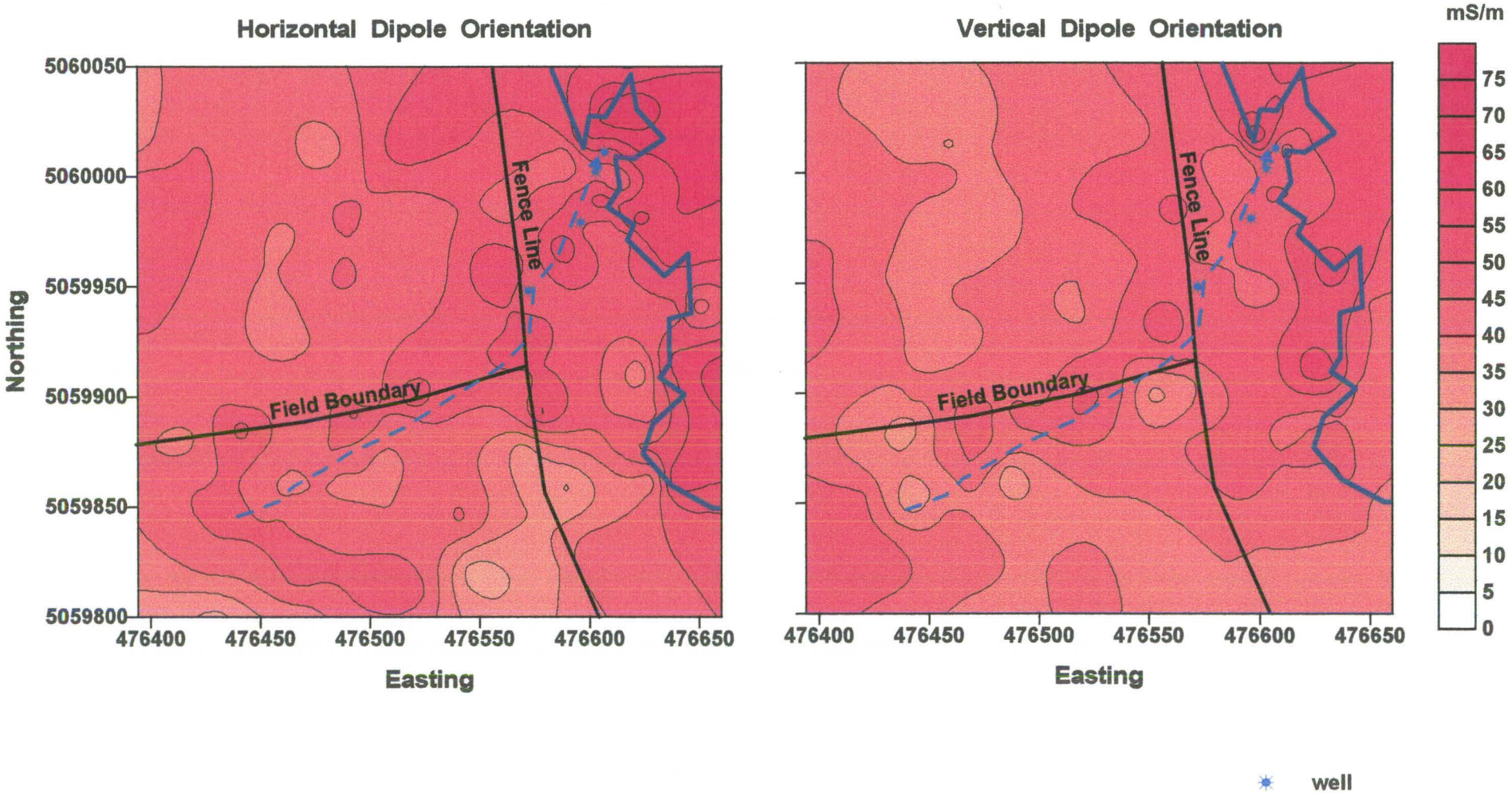

Figure 5

EMI Survey of Godfrey Creek
Gallatin County, Montana
GEM300 Sensor
9810 Hz

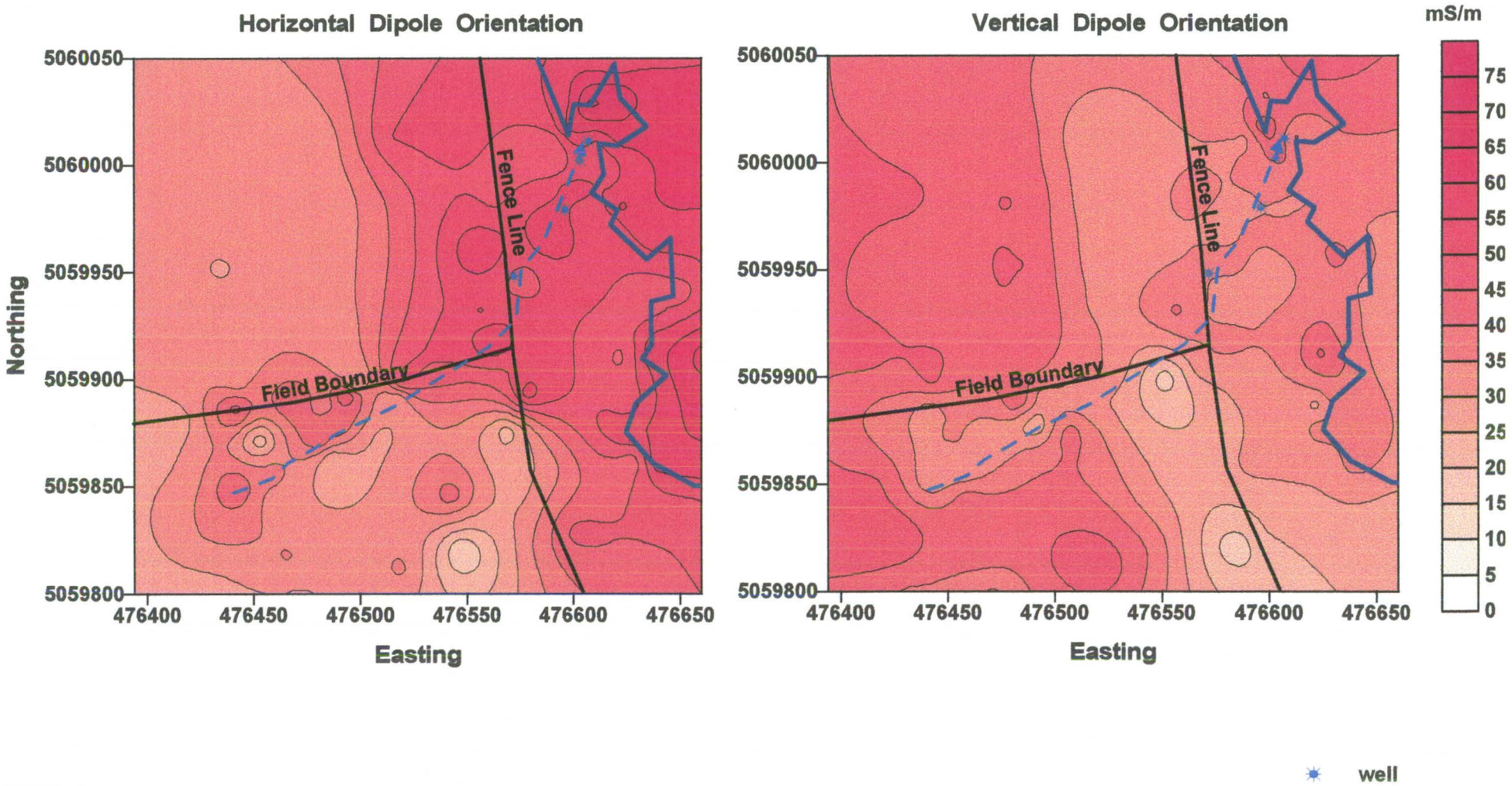

Figure 6

EMI Survey of Godfrey Creek
Gallatin County, Montana
GEM300 Sensor
14850 Hz

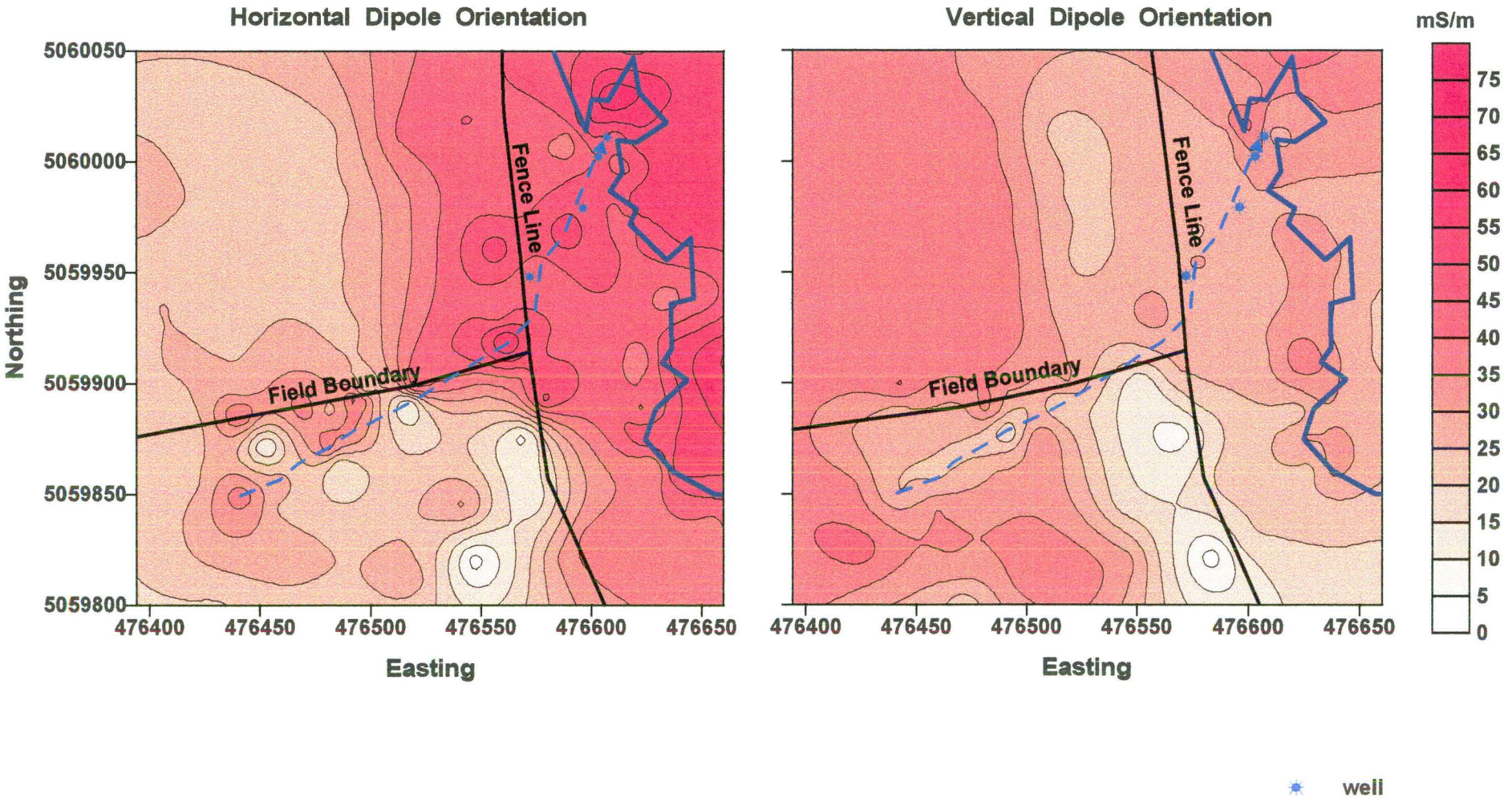

Figure 7