DETECTION OF SUBSURFACE DIESEL CONTAMINATION USING ELECTROMAGNETIC INDUCTION GEOPHYSICAL TECHNIQUES

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Abstract

Delineating the extent of petroleum hydrocarbon spills/plumes in subsurface soil and groundwater is typically done by soil boring and installation of monitoring wells. These methods are labor intensive and expensive. Site heterogeneity tends to introduce errors. In this study, we investigated electromagnetic induction survey as an alternative technique to map the extent of subsurface hydrocarbons in a nondestructive, noninvasive way. This study was designed to demonstrate the effectiveness and accuracy of such a survey in its response to subsurface diesel contamination.

Geophysical surveys were undertaken at two mining sites near Gillette, Wyoming, using a EM34-XL™ unit. Samples from monitoring wells at the two sites were correlated to the survey results for validation. Data from the survey well matched the readings from sample analysis. Results from this study indicate that electromagnetic induction surveys could be an effective tool in mapping the subsurface petroleum contaminants.

Introduction

The detection of subsurface diesel contamination has traditionally been accomplished by mechanical coring and placing groundwater monitoring wells into the suspected aquifer and sampling (Peterson and Nobes, 2003). Not only is this method intrusive, costly, and time consuming it also lacks sufficient detail to characterize the entire extent of a site. Improper completion of monitoring or sampling wells can also lead to greater contamination in previously unaffected aquifers. Sampling results from study sites in remote locations can also be compromised by long turnaround times. The use of a variety of near-surface geophysical techniques has been proposed and used as a noninvasive, efficient method for environmental investigations in a variety of locations and conditions (Bermejo et al., 2000; Brewster and Annan, 1994; Daniels et al., 1995; Guy et al., 2000; Olhoeft, 1992; Pehme et al., 1992; Petterson and Nobes 2003; Vickery and Hobbs, 1998). In a study by Pettersson and Nobes (2003), ground penetrating radar (GPR) was compared against an electromagnetic induction (EM) method in determining hydrocarbon contamination. Areas of known hydrocarbon contamination were consistent with resistive anomalies identified by EM, which the GPR failed to identify (Pettersson and Nobes, 2003). In theory, the use of EM to identify areas of hydrocarbon contamination would likely result in a resistive anomaly, since the majority of these compounds would displace porewater, decreasing the overall conductivity of a formation (Pehme et al., 1992). In the case of diesel, the decrease in bulk apparent conductivity typically occurs at the interface between the low conductivity unsaturated zone and the conductive saturated material below, giving a contrast between the lower confining unit and contaminant (Pehme et al., 1992). However geologic and cultural noise can accidentally be mapped as false anomalies (Petterson and Nobes, 2003). Many case histories have failed to falsely attribute these areas of low conductivity to contamination due to these interferences (Pehme et al., 1992). Therefore, site background information is critical to the successful application of EM techniques.

In this study, EM was conducted on two active mining site located in Gillette, Wyoming. At the first site, the area of concern covered approximately 31,000 m^2. General groundwater gradient is in an easterly direction. Existing diesel storage tanks were located on the west border of the study site. The extent and location of the contamination plume was unknown and no attempts had been made prior to the study to map its delineation. To our knowledge, the site had only been impacted by diesel range organics (DRO). Four monitoring wells were located in the area, though only three contained sufficient water for sampling. The location was ideal in that it was also relatively free of geologic and cultural noises.

The second site was approximately 2,500 m^2. A fuel station was located at the south end of the site and an embankment bordered the west. A railroad used at the mine was located nearby to the east. Three groundwater monitoring wells were located within the study site. According to the site manager, DRO had impacted the site from the fuel station.

The EM ground conductivity unit that was chosen for this project was the EM-34 XL from Geonics Limited (Mississauga, Ontario, Canada). This unit provides effective operating depths of up to 60 m (McNeill, 1980). This is also the only commercially available unit that is capable at operating at such depths (Catalano, 2006).

The objective of this study was to validate using EM surveys as an effective and non-intrusive technique in assessing and monitoring subsurface petroleum contamination.

Materials and Methods

Instrumentation

The EM-34 XL unit consists of a transmitting (Tx) coil, which broadcasts the signal at a set frequency, and receiving Coil (Rx) to receive the signal at a set distance (10 or 20 m). The Tx coil was placed on each monitoring station and the Rx was placed SE, along the transect, at the set distance. Ground conductivity was measured at each station in both the horizontal (vertical dipole) and vertical (horizontal dipole) orientations with coil separations of 10m (400 Hz) and 20m (1,600 Hz), which allowed the conductivity measurements at effective depths of 10, 15, 20 and 30 m. Though the EM-34XL is capable of measuring at effective depths of 40 and 60 m, these surveys were omitted since the location of the diesel was generally to be significantly less than the operating depth at that particular frequency (Duysen, 2006).

Field EM Survey

At the first site, the survey area was first determined by roughly outlining the impacted zone and was also drawn to include as many monitoring wells as possible. A baseline was drawn across this area and sectioned into 15.25 m intervals. With a right-angle prism, 12 transects were drawn in a NW to SE orientation. Measuring stations were established every 15.25 m along each transect. The overall length of each transect varied to accommodate the terrain and other obstructions. Once the Grid was established, each measuring point was georeferenced with a differentially correctable GPS. Starting in the northeast corner of the grid the EM Survey was completed by taking readings on each of the grid points, moving up one line and down the other, toward the southwest corner. The grid was bounded by a fueling station as well as bordered storage tanks on the west. Also placed within the grid was a hauling road for coal which was situated between earthen embankments on each side of the grid. On the east side of the area there was a large embankment reaching downward from the test area.

A similar grid was established at the second site. Because the area was smaller, it was possible to create better resolution by moving the measuring stations closer than those at the first site. This was done by placing the stations approximately 9.14 m apart. Transects were established in an E to W orientation using the method as outlined above.

Groundwater Sample Analysis

At the first site, groundwater samples were collected from the three existing monitoring wells. Well depths and water table levels were measured during the sampling event. Samples were contained without headspace and immediately shipped on ice to the laboratory for analysis. The same protocol for sampling at the first site was applied to the second.

Diesel Range Organics (DRO) hydrocarbons were extracted using methylene chloride (CH_2Cl_2) and analyzed using a method equivalent to EPA Method 8015 on an Agilent 6890 (Santa Clara, CA) GC equipped with a FID detector (EPA, 1996).

Data Processing

Conductivity was measured at each station and recorded on an Allegro Cx data logger (Geonics Limited). At the end of each survey the data was uploaded to a computer for further processing. At this point, conductivity data was combined with the geospatial data of each measuring station. This resulted in a file containing latitude (X), longitude (Y) and conductivity (Z). The conductivity (mS/m) was then converted to the standard unit of resistivity (ohm/m). The following equation was used for this conversion:

$$\text{Resistivity (ohm/m)} = (1/\text{Conductivity (mS/m)}) \times 1000 \text{ (Bevan, 1986)}$$

The data was imported into the processing software, Surfer v. 6.04 Surface Mapping System by Golden Software, Inc. (Golden, CO). The gridding method used to generate the contours in the map was Kriging, which was used because of its flexibility and its use of the data to look for global trends.

Results and Discussion

Results from two of the surveys at the first site are shown in figures 1 and 2. It was first thought, by examining the well depth data, that it would only be possible to correlate analytical data with 10-m surveys. It is most likely that the wells are cased somewhere between the effective depth (d[m]) of the 10-m vertical (horizontal dipole) and horizontal (vertical dipole) surveys. Previous studies have identified areas of hydrocarbon contamination as resistive anomalies, compared to overall background resistivity (Vickery and Hobbs, 1998). If this holds true, then by looking at the 10-m surveys, it appears that contamination could be found in several areas, located centrally, with general migration to the north. Examining the 20-m, vertical dipole survey (figure 2) reveals a singular anomaly located in the south with general migration to the north and west. This survey also reveals generally higher resistivity in the west.

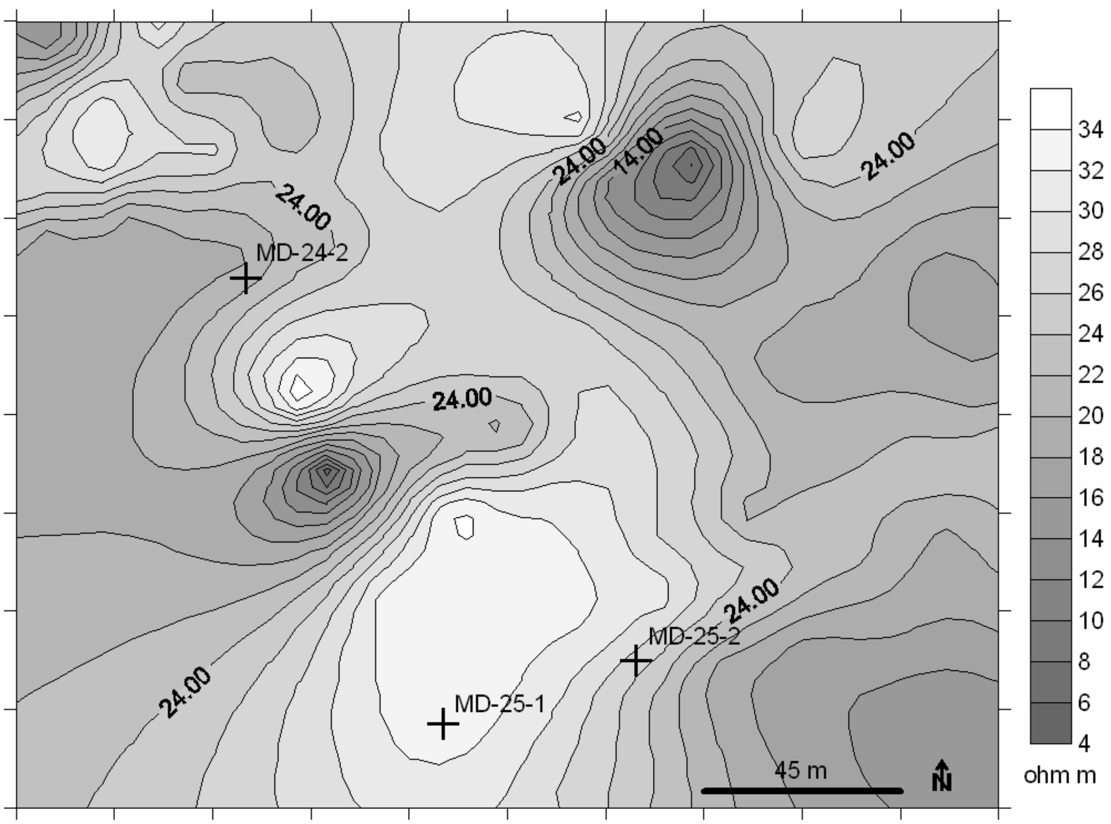

Figure 1. Results from the 10-meter, horizontal dipole EM survey. The effective depth (d[m]) in the horizontal dipole position is approximately equal to the coil spacing. Locations of the three sampled monitoring wells (+) are shown. Lighter areas represent areas of high resistivity, which could be related to diesel contamination. In this case, contamination would be sporadically placed throughout the survey area.

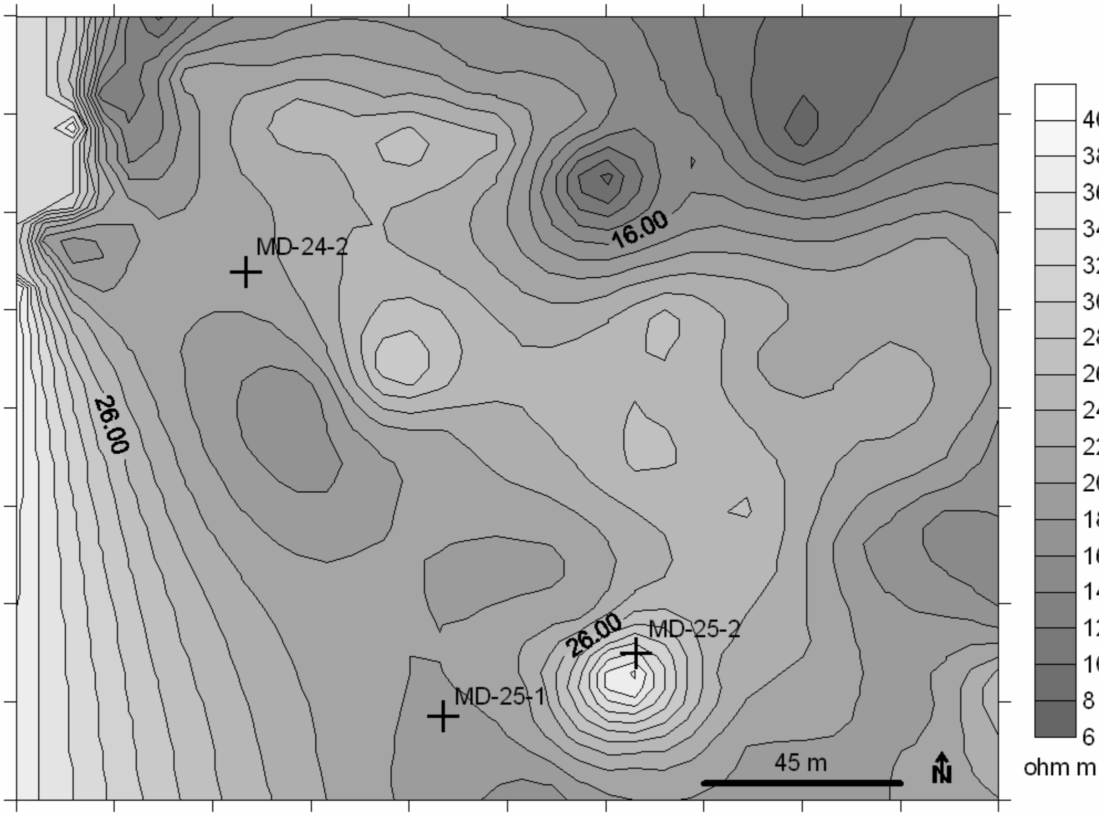

Figure 2. Results from the 20-meter, vertical dipole EM survey. The effective depth (d[m]) in the vertical dipole position is approximately equal to 1.5 times the coil spacing. Locations of the three sampled monitoring wells (+) are shown for reference. Lighter areas represent areas of high resistivity, which could be related to diesel contamination. In this case, the source of contamination could come from the circular anomaly in the south, or the large anomaly in the west.

Analytical data from the monitoring wells at the first site is found in table 1.

Table 1.: Well data from wells found within study site. Well depth refers to the depth to water.

Monitoring Well	***Well Depth (m)***	***Diesel Range Organics (mg/L)***
MD-24-2	11.1	110
MD-25-1	13.0	< 3
MD-25-2	12.3	> 1000

This data was used to find the optimal survey to map the extent of the subsurface contaminant plume. This was accomplished by looking at changes to bulk resistivity in the areas surrounding the monitoring wells as it related to the DRO concentration in the wells. Though the d[m] of the both 20-m surveys most likely goes beyond the cased depth of the monitoring wells, these surveys offered the best correlation. The survey taken to the highest d[m], or the 20-m, vertical dipole survey, offered the optimal correlation, showing distinct differences in ground resistance. In this survey, the well containing the highest DRO (MD-25-2) was found to have the highest bulk ground resistivity between 36 and 38 ohm/m, which was significantly higher than the area around the other monitoring wells (table 2).

Table 2.: Bulk ground resistivity as it relates to diesel found in the accompanying monitoring wells.

Monitoring Well	***Bulk Ground Resistivity (ohm/m)***	***Diesel Range Organics (mg/L)***
MD-24-2	20-22	110
MD-25-1	18-20	< 3
MD-25-2	36-38	> 1000

This contrast was most likely due to the fact that a larger column of diesel was required to have an effect on the bulk resistivity reading. Readings taken at a shallower d[m] were most likely greater influenced by geological differences. Though this wasn't the intended application, it could help determine potential pathways of transport. However, because the 20-m, vertical-dipole survey had the best correlation with the monitoring wells, it was used as the primary model of diesel in the survey area.

Using the 20-m survey as a model, the outline of the subsurface contamination plume can be effectively mapped. The most prominent feature is the area, near the monitoring well MD-25-2, is circular resistive anomaly (figure 2). This most likely represents a potential source of contamination at the site. The area around well containing 110 mg/L DRO (MD-24-2) was found to have a resistivity of only 2 ohm/m higher than the area surrounding the well with a much lower concentration (MD-25-1). The lack of monitoring wells in the survey area inhibited making any conclusions as to the sensitivity of the instrument to detect a certain concentration of diesel in the area. However, it can be assumed that areas of resistivity greater than 24 ohm/m most likely contain high amounts of diesel. By using this assumption, it was possible to model the main plume of contamination on the 20-meter, vertical-dipole EM survey (figure 3).

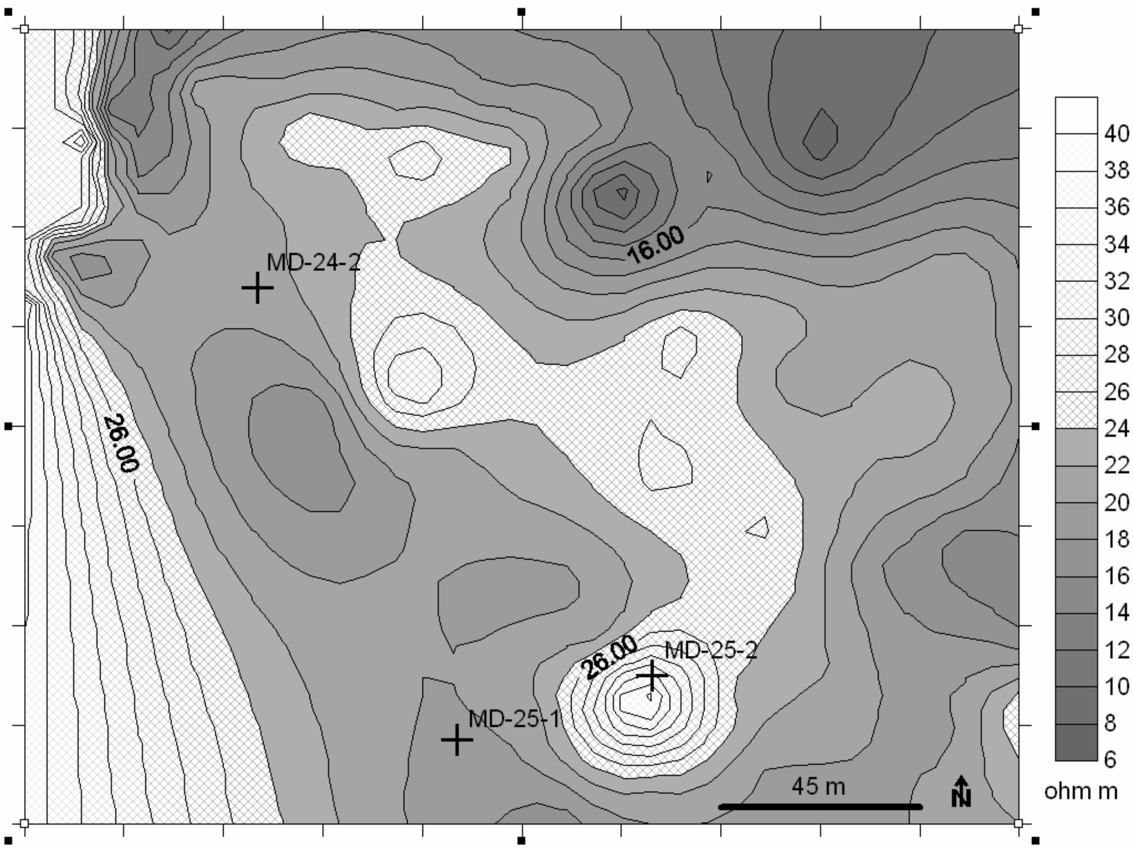

Figure 3. Map of the extent of the diesel contamination in the study site. Areas of diesel contamination, as determined by the model, are hatched. This model was developed using the best correlated survey to the analytical data. The spread of the plume from the source appears to be in a north easterly direction.

These results suggest the main subsurface plume is located in the center of the study site and there appears to be a collection of large concentrations of diesel to the west of the site. The high resistivity in this area is most likely caused by a zone of low hydraulic conductivity, where the diesel could be collecting. However, it could also represent a separate source of contamination, since this is near a large diesel storage area.

Comparing the analytical data to the resitivity data, using a simple linear regression, revealed the following relationship may apply:

Mg DRO/L = (55.5 x Resistivity (ohm/m))-1053

It is likely that the correlation between diesel concentration and resistivity could be better related with a greater number of sampling points. However, due to the limited number of monitoring wells at the study site, a better relationship could not be defined. It is also likely that by sampling other sites, a universal correlation may also be developed. This would ultimately lead to not only a qualitative delineation of the subsurface contamination, but also a more useful qualitative one. For this study site, the EM proved to be a useful tool in site characterization.

After careful analyses of the water from the second site was performed, DRO concentrations were found to be too low to quantify. It was assumed that the impacted zone was most likely beyond the cased area of the monitoring wells (>13 m). Though this made correlation impossible, it eliminated choosing the 10 m surveys to map the extent of the contamination. The results from the 20 m surveys are shown below (figures 4 and 5).

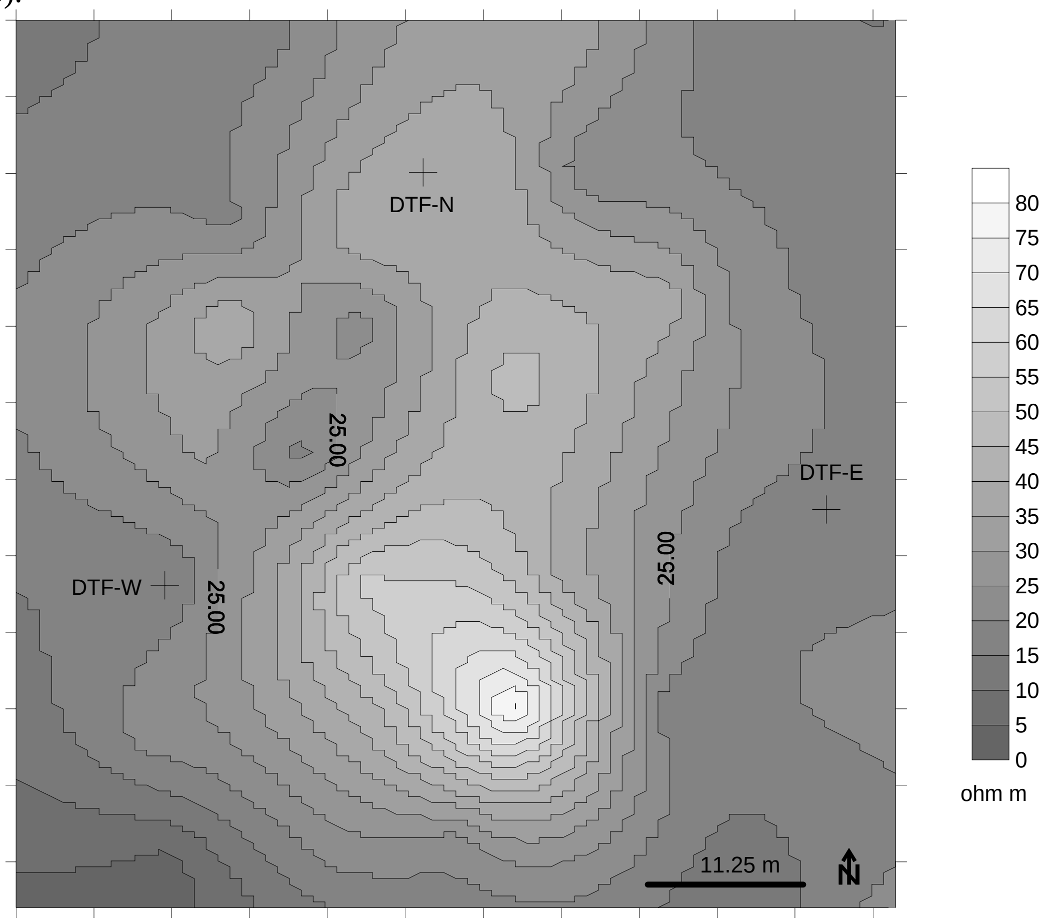

Figure 4. Results from the 20-meter, horizontal dipole EM survey at the second site. Locations of the three sampled monitoring wells (+) are shown. Lighter areas represent areas of high resistivity, which could be related to diesel contamination. In this case, contamination would be generally centralized with a hot spot located in the southern portion.

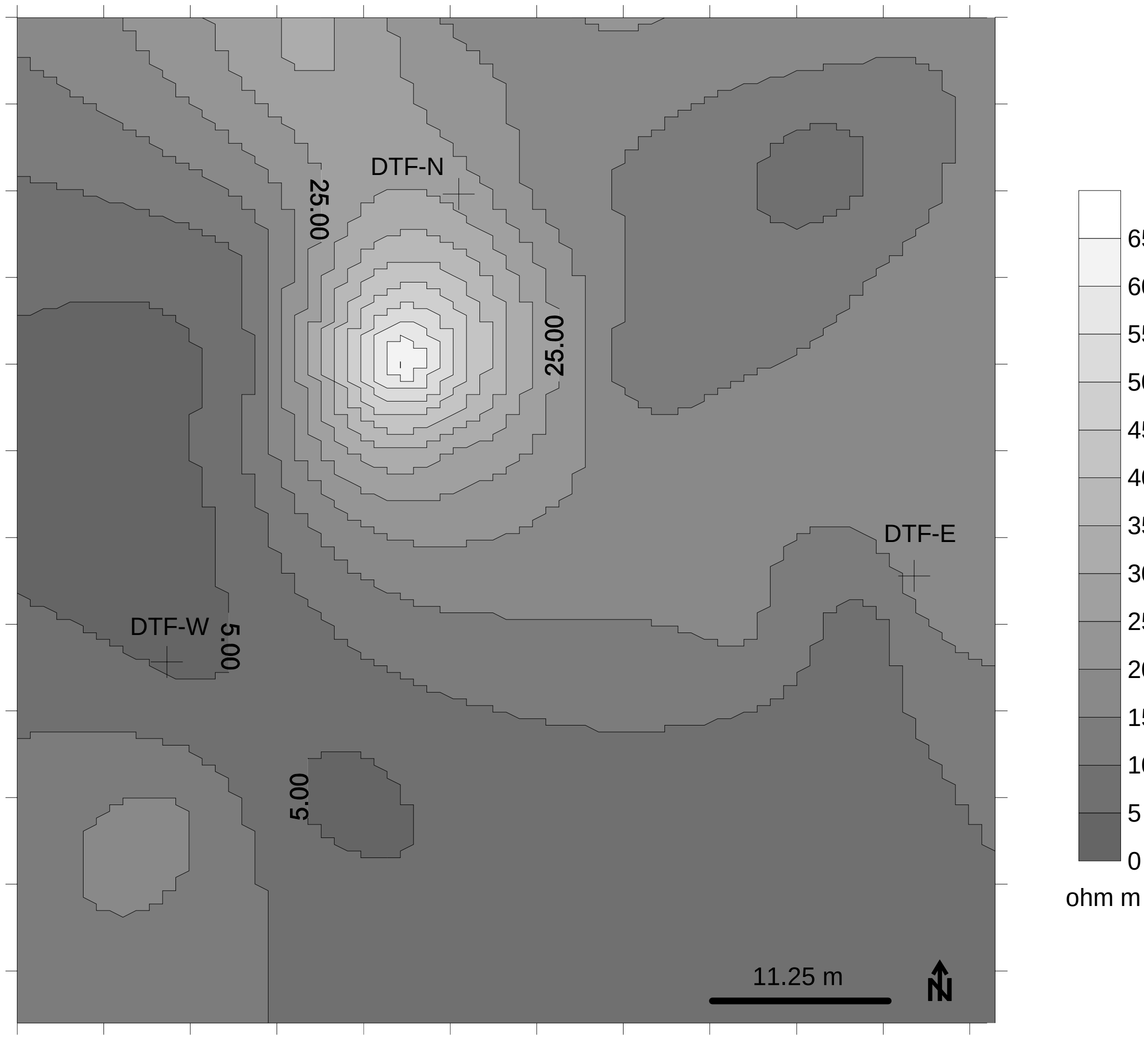

Figure 5. Results from the 20-meter, vertical dipole EM survey at the second site. Locations of the three sampled monitoring wells (+) are shown. Lighter areas represent areas of high resistivity, which could be related to diesel contamination. In this case, contamination would be generally centralized with little extent throughout the area.

Based on the results from these surveys and applying the model developed for the first site, levels of DRO could be as high as 2600-3400 mg/L in areas of the greatest impact. From the information from the site manager that the original contamination came from the fueling station located in the south, it is likely that the 20-m horizontal dipole survey provides the greatest information as to the extent of the plume, with the highest concentration in the south and general migration to the north and west. This survey also reveals that the three monitoring wells were poorly placed outside of the impact zone, which would explain the lack of DRO in the groundwater samples. A single monitoring well could be placed in the highest areas of contamination to confirm the validity of this survey. A well of this nature could also provide greater insight as to the utility of the model developed at the first site.

Conclusions

The results from the EM survey conducted at the first mine site, in conjunction with the well data, demonstrate that EM may be an effective tool in mapping the extent of diesel in the subsurface. Areas containing high amounts of diesel had an overall higher ground resistivity than areas containing less or non-detectable amounts of diesel. Significant quantities of diesel were required to show a noticeable change in bulk ground resistivity. This was most likely necessary to overcome the overall resistance caused by the geologic nature of the area. Likewise, the EM was useful in mapping geologic variations, which could be important to any site characterization. A qualitative relationship could also be developed, which could potentially be applied to different sites. This was attempted at the second site in this study. The 20-m horizontal survey at this site revealed a resistive anomaly near the suspected source.

Based on results from this study, using EM surveys may be considered as a quick, reliable, and non-invasive tool to determine diesel impact in the subsurface. Future studies are warranted to develop a universal, quantitative relationship between subsurface DRO, as well as other hydrocarbon contaminants, and resistitivty.

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