MAPPING THE VARIABILITY OF GROUNDWATER QUALITY IN AN ABANDONED TAILINGS DEPOSIT USING ELECTROMAGNETIC GEOPHYSICAL TECHNIQUES[1]

D. Alex Gore[2] and G. A. Olyphant

Abstract. A geophysical study was conducted at an abandoned coal mine site in southwestern Indiana in an effort to characterize the spatial variability of groundwater quality and to identify areas that contain high concentrations of total dissolved solids (TDS) and other indicators of acid mine drainage. The study utilized an EM34 terrain conductivity instrument to measure the apparent electrical conductivity of the underlying earth. Terrain conductivity is routinely attributed to the electrical conductivity of the underlying material, porosity, moisture content, and the dissolved electrolytes in pore fluid. To interpret the instrument response, terrain conductivity data were compared to field and laboratory chemistry of water samples collected from 27 monitoring wells.

Terrain conductivity values ranged from 17-58 millisiemens/meter over the extent of the study area which included mine refuse, levee material, and natural soils. The contribution of pore water chemistry to the overall terrain conductivity was analyzed by measuring the specific conductance (SpC) of ground water samples which is a reflection of the concentration of TDS. The specific conductance ranged from 1380-5410µmhos/cm at 25° C; where the higher SpC values correspond to a higher concentration of TDS due to pyrite dissolution. A map of the terrain conductivity values indicated that high conductivity values were concentrated in specific areas which will need special attention in remediation plans. The mapping also indicated that the majority of the site contains groundwater with a low SpC and should be amenable to less intensive remediation. A map of the contamination plume based on terrain conductivity values was consistent with a groundwater flow model constructed for this site. A correlation was also observed between subsurface hydraulic conductivity and terrain conductivity measurements (R^2=0.66) indicating an instrument response to soil permeability. This study indicates that shallow electrical geophysical exploration can be used to locate groundwater contamination plumes when subsurface hydraulic properties are taken into account.

Additional Key Words: Acid Mine Drainage, Geophysical exploration, Terrain Conductivity

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Introduction

Acid mine drainage (AMD) is produced by the weathering of pyrite in coal and shale overburden at abandoned mine sites. A multitude of environmental problems are associated with AMD, including increased acidity and the suspension of toxic metals in effluent streams, which has led to extensive publications on the subject (Barnes and Clarke, 1964, Gray, 1997, and Schüring et al., 1997). Planning remediation of abandoned mine land (AML) sites requires an understanding of AMD processes including the spatial variability of contaminated groundwater.

Subsurface geophysical exploration can be utilized to characterize and map groundwater quality at AML sites (Merkel, 1972, Stollar and Roux, 1975, Ebraheem et al., 1990, Brooks et al., 1991, and Spindler and Olyphant, 2004). Electromagnetic conductance was employed in this study in an attempt to locate spatial variations of groundwater quality. A Geonics Limited EM34 terrain conductivity unit was utilized because of its mobility, precision, and ability to quickly make measurements. The goal of this study is to: (1) map the spatial variability of contaminated groundwater in order to improve and/or enhance remediation decisions and (2) more carefully evaluate the EM34 instrument's ability to respond to fluctuations in groundwater quality associated with concentrations of total dissolved solids (TDS) and to quantify other controls.

Site Description

The Minnehaha AML study site is located in Sullivan County, southwestern Indiana (Fig. 1). Minnehaha is an abandoned surface coal mine that is complex, containing both coarse-grained and fine-grained coal refuse materials. The main coarse-grained refuse deposit has been reclaimed by the Indiana Department of Natural Resources - Division of Reclamation (IDNR-DOR) and includes a vegetated soil cap. The fine-grained refuse deposits have not been reclaimed, and any remediation methods employed will need to take into consideration the variability of sediment and water quality of the mine refuse.

The fine-grained refuse deposits reside close to the water table, experiencing near saturated conditions during most of the year. This makes Minnehaha an ideal site for the implementation of shallow geophysical techniques to examine variations in groundwater quality owing to in situ weathering and contaminant transport. A major AMD seep occurs along the levee that separates the refuse from Mud Creek, the principle stream that draws the region's groundwater (Fig. 1).

The perennial discharge of AMD into Mud Creek lowered the stream's pH and has resulted in the deposit of extensive iron rich sediments.

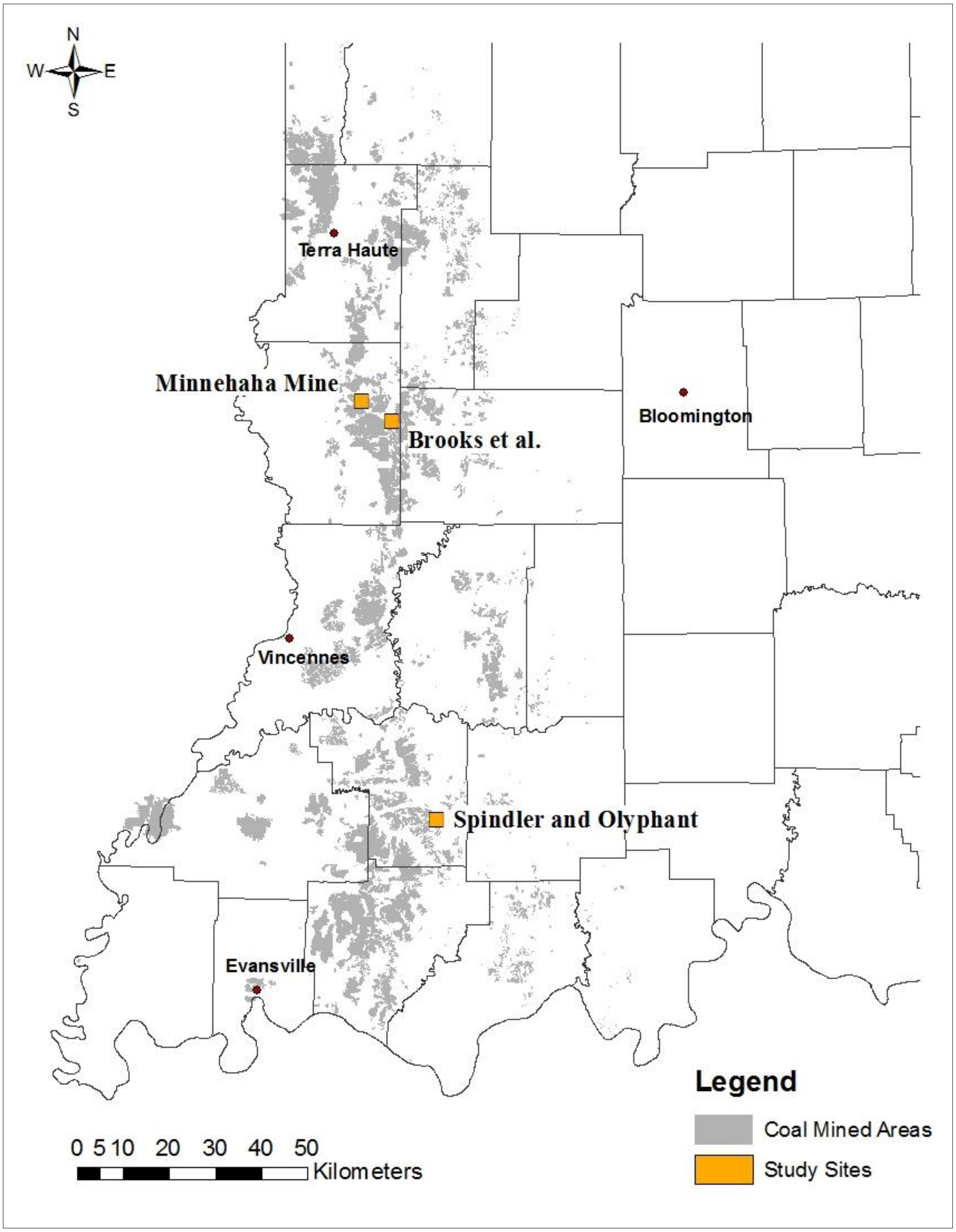

Figure 1. Location of Minnehaha AML study site in southwestern Indiana, U.S.A. Included are two other AML sites studied by Brooks et al. and Spindler and Olyphant having similar hydrogeological settings to Minnehaha.

Theory and Methods

Theory of Operation

Geophysical techniques are employed to measure the contrasts of subsurface materials in order to understand the distribution and characteristics of the materials that cause these variations (Burger et al., 2006). The EM34 terrain conductivity unit uses an electromagnetic current to measure apparent ground conductivity from the ratio of the secondary magnetic field (H_s) to the primary magnetic field (H_p). The EM34 instrument measures apparent bulk ground conductivity (referred to as terrain conductivity) which is the inverse of resistivity. The instrument reports values in millisiemens per meter (ms/m). An alternating current in the transmitter coil creates the primary magnetic field (H_p) which in turn induces a very small current in the earth that produces the secondary magnetic field (H_s) (McNeill, 1980b) Fig. 2.

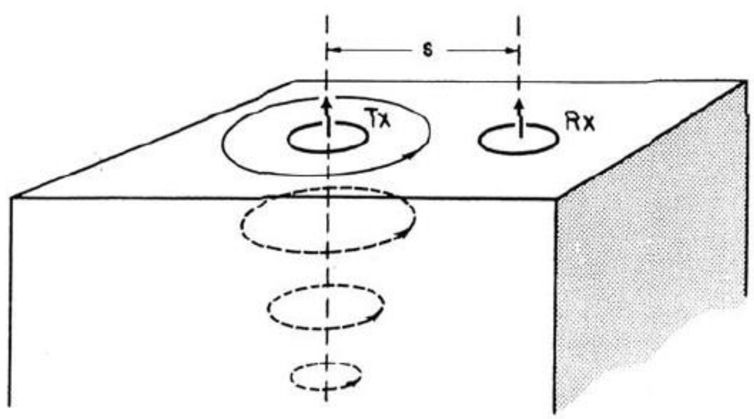

Figure 2. Induced current flow, where Rx is the receiver coil, Tx is the transmitter coil, and s is the intercoil spacing. Figure from McNeill, 1980b page 5.

Soils and rocks are generally electrical insulators making up the matrix in which induced current flows. Conductivity is electrolytic in nature and takes place through the moisture-filled pores of this insulating matrix (McNeill, 1980a). The underlying porewater is much more conductive than the solid subsurface materials; therefore, the factors affecting terrain conductivity measurements are attributed to:

(1) soil moisture content

(2) permeability of the soil and rock

(3) total dissolved solids (TDS) contained in the porewater

(4) subsurface material (e.g. conductive minerals)

Determining Instrument Response

To interpret the EM34 instrument response to contrasting subsurface characteristics; terrain conductivity data were compared to field and laboratory chemistry, hydraulic conductivities, and refuse deposit distribution. Groundwater samples were collected from 27 monitoring wells located across the study site. Depth to water (DTW) measurements were taken at each well as an indicator of the instrument response to the depth of contaminated water. Hydraulic conductivity was calculated at each monitoring well from slug test data. Slug tests were conducted by adding a known volume of water to each monitoring well and logging the water elevation change with time using a pressure transducer. Hydraulic conductivity was calculated using Aqtesolv® software and employing the Bouwer and Rice (1976) method to fit the slug test response curve. The calculated hydraulic conductivity allowed for the comparison between terrain conductivity values and soil permeability. Fluid specific conductance (SpC) was measured at each monitoring well in order to compare terrain conductivity readings to the TDS of porewater. In an effort to determine to what degree subsurface material affected measurements, terrain conductivity values were plotted over an aerial photo of the original refuse deposits.

Mapping Spatial Variation in Terrain Conductivity

The terrain conductivity survey was conducted in successive stages after a preliminary study of 60 locations. Subsequent measurement locations were guided by what were considered to be zones of higher and lower contamination. A GPS unit was used to record the location of all 280 point measurements taken over the extent of the study area. For this study, a 10 m intercoil spacing was utilized because the water table provided a shallow target depth. ESRI ArcGIS software was used to plot the locations and relative values of terrain conductivity data. The point measurements were used to interpolate a continuous terrain conductivity distribution throughout the deposits by using a standard ArcGIS inverse distance weighting method. The inverse distance weighting method used five neighboring point conductivity measurements to interpolate a contour of local terrain conductivity on a grid having a 2 by 2 meter cell size.

Results

Measured terrain conductivity values ranged from 17-58 ms/m across the study site corresponding to a groundwater SpC range of 1380-5410 µmhos/cm. The highest values of terrain conductivity were concentrated at the southeast corner of the fine-grained tailings deposit

(Fig.3). This area represents the upper 15% of the terrain conductivity values and occurs over the base of a fine-grained refuse delta deposited when the mine was still active. An access road separates the two fine-grained refuse deltas deposited separately when the mine was active.

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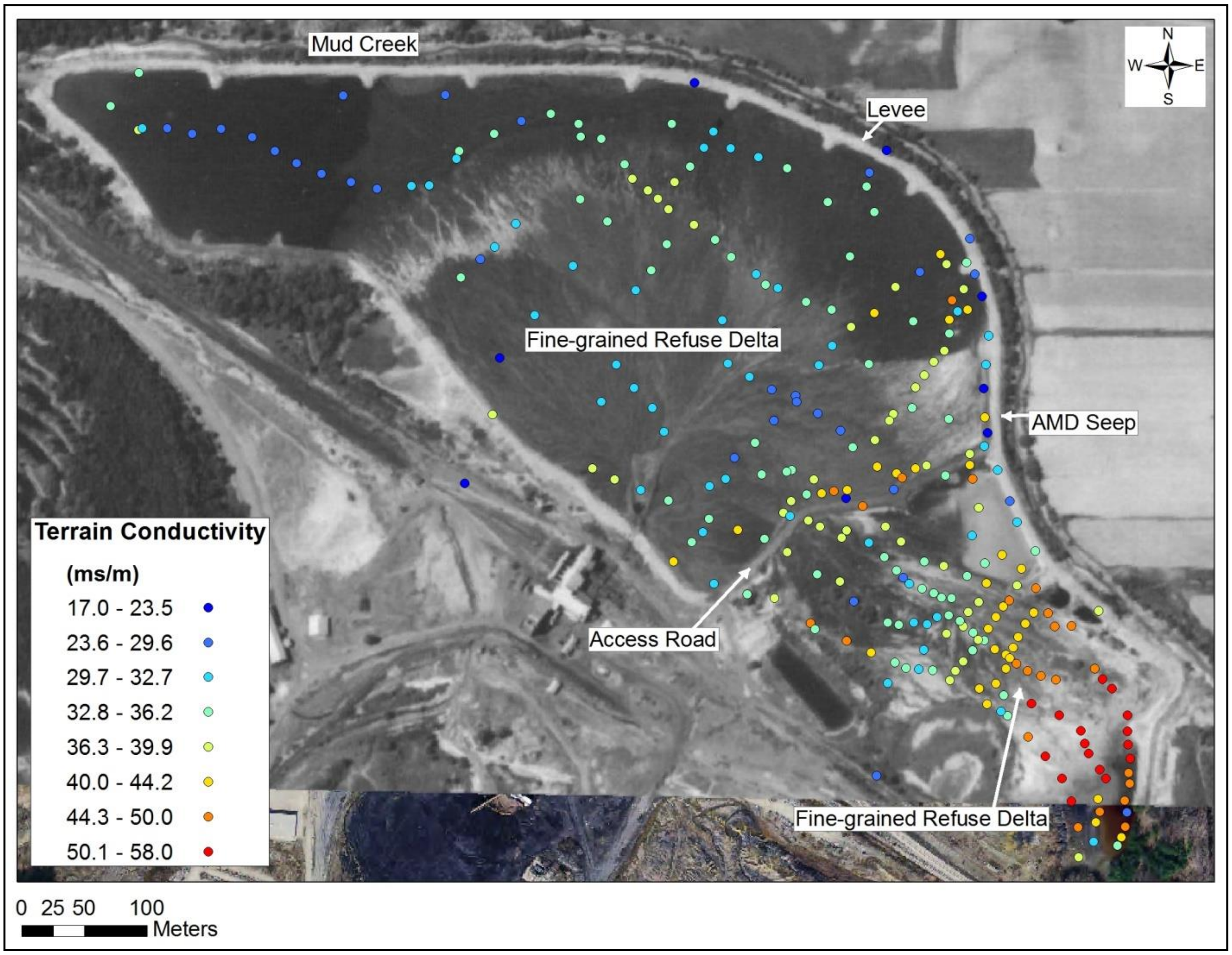

Figure 3. Terrain conductivity measurements plotted over a 1954 aerial photo of active refuse deposits.

Generally, higher terrain conductivity values were measured over the deltaic deposit to the southeast of the access road. An area of low terrain conductivity occurred in the northwest corner of the study site which is outside the edge of a large delta deposited when the mine was active.

The interpolated continuous distribution of terrain conductivity revealed that terrain conductivity decreased radially outward from the southeast corner of the study area. A second area of high terrain conductivity (36-44ms/m) is located across from the access road and extends as a linear lense towards the largest AMD seep on the edge of the refuse deposit (Fig. 4).

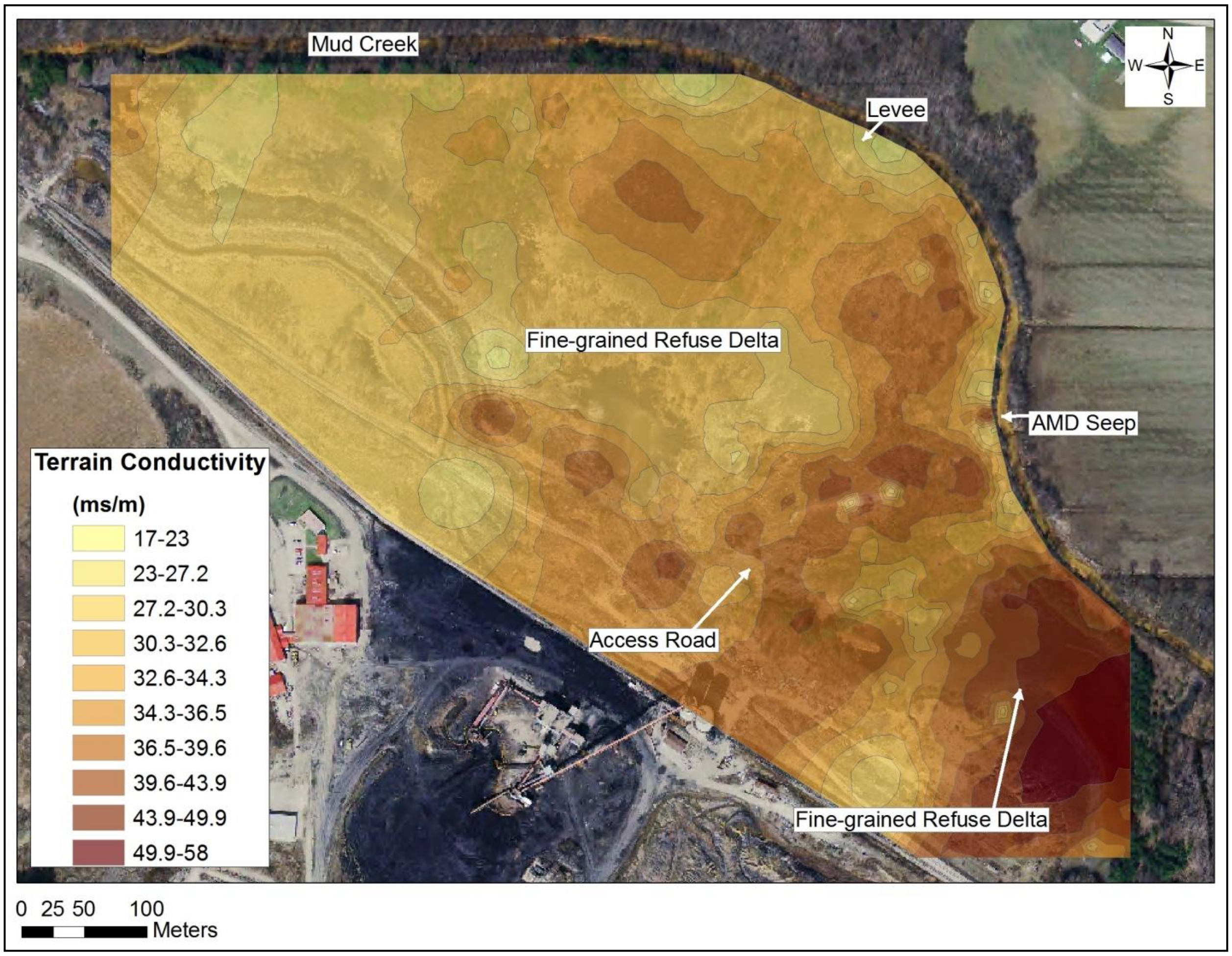

Figure 4. Aerial photo of Minnehaha abandoned mine land with interpolated terrain conductivity measurements. An inverse distance weighting method was used for interpolation.

The terrain conductivity and SpC data were compared to two other electromagnetic geophysical studies at AML sites conducted by Brooks et al. (1991) and Spindler and Olyphant

(2004). Figure 1 shows the location of these two other study sites existing in similar hydrogeological settings to Minnehaha. The observed relationship between terrain conductivity and porewater SpC was in agreement with the previous electromagnetic geophysical explorations of contaminated groundwater (Brooks et al. 1991 and Spindler and Olyphant 2004). Terrain conductivity values had a positive correlation to porewater SpC with R^2=0.76 for the cumulative data from Minnehaha and the two other study sites (Fig. 5). The data from the Minnehaha site also indicated a positive statistical correlation between terrain conductivity and hydraulic conductivity (R^2=0.66). There was a negative correlation between terrain conductivity and the depth to the water table; however this was not statistically significant from zero at the 95% confidence level (R^2=0.075).

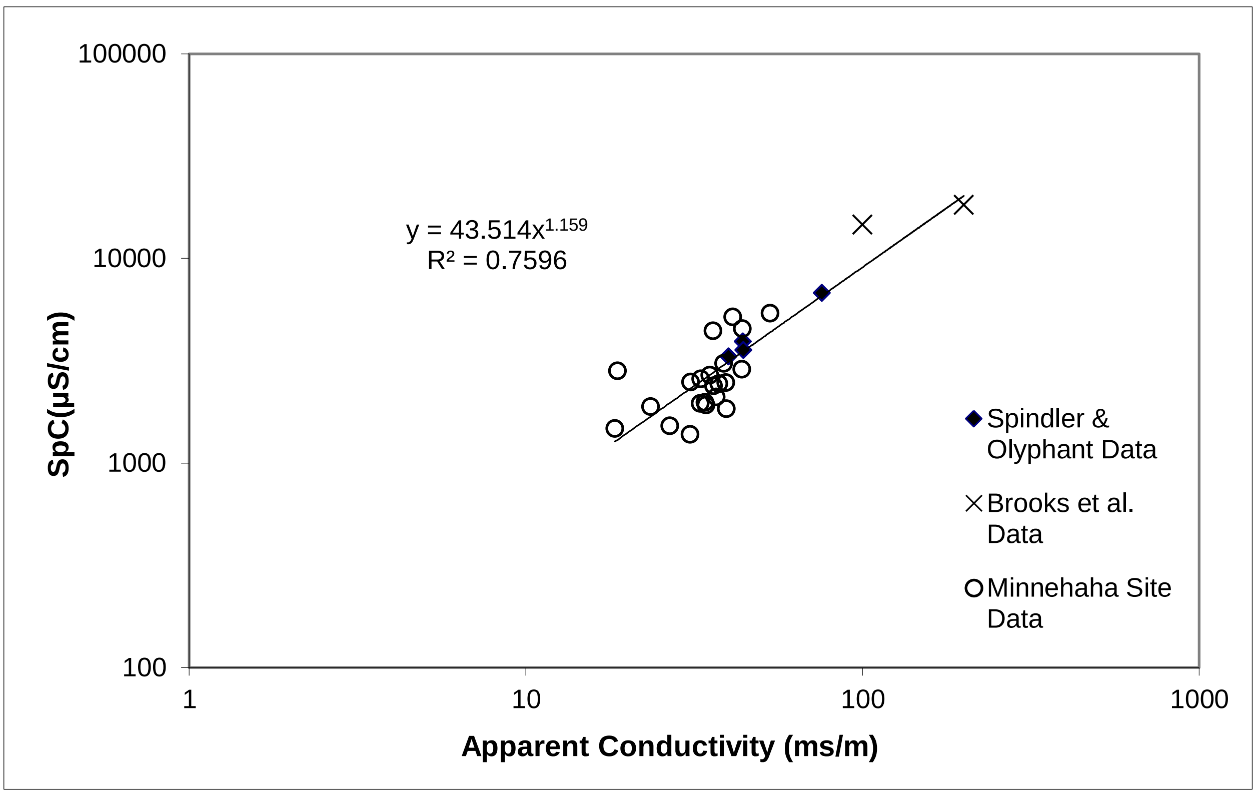

Figure 5. Plot showing relationship between apparent conductivity (terrain conductivity) and porewater SpC for three AMD sites in southwestern Indiana (Figure 1).

Discussion

The interpolated terrain conductivity measurements are in accordance with a groundwater flow model constructed for Minnehaha[1]. The groundwater flow model shows flow lines coming from the two largest areas of high terrain conductivity and flowing towards the main AMD seep (Fig. 4). The interpolated terrain conductivity map likely represents possible groundwater contamination plumes as the sources of AMD. Monitoring wells having high SpC values often had surrounding areas of high terrain conductivity. Increased terrain conductivity values were not specific to any localized refuse deposits (Fig. 3); thus the EM34 instrument response was mainly attributed to fluctuations in groundwater SpC and hydraulic permeability.

Although it was apparent that a positive correlation did exist between terrain conductivity and porewater SpC at the Minnehaha site; this correlation alone could not fully account for the observed spatial variations in terrain conductivity. The positive correlation seen between terrain conductivity and hydraulic conductivity likely confounds the correlation between terrain conductivity and porewater SpC for the Minnehaha data, and this should be considered by others who might employ shallow geophysical methods in AML site characterizations. The EM34 instrument response to hydraulic conductivity is in agreement with the physical parameters that allow a greater amount of current to flow between saturated interconnected pores. The lack of a statistically significant correlation between terrain conductivity and the depth to the water table is not surprising because the EM34 instrument does not linearly respond to depth (McNeill, 1980b) and the water table was consistently shallow. Sufficient data have not been collected to run a full multiple regression analysis to quantify the total and relative response of terrain conductivity to SpC and hydraulic conductivity, but those data are currently being collected. Once collected and analyzed, it should be possible to determine the partial effects of the two response controls. The existing correlation between terrain conductivity and groundwater SpC is evidence that high terrain conductivity values are an indicator of areas with a higher concentration of total dissolved solids. Furthermore, the interpretation of spatial variations in

[1] Waddle, R.C. and G.A. Olyphant. 2010. Groundwater flow modeling of an abandoned mine lands site scheduled for reclamation. Figure 4. *In:* Proceedings 2010 National Meeting of the American Society of Mining and Reclamation, Pittsburgh, PA ***Bridging Reclamation, Science and the Community*** June 5 - 11, 2010. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502. This volume.

terrain conductivity compared to the physical location of contaminated groundwater and its flow direction suggests that terrain conductivity contours reflect contaminated groundwater.

Conclusion

This study indicates that shallow electromagnetic geophysical techniques can be utilized to characterize subsurface variations in hydraulic and hydrochemical properties of coal mine refuse. Terrain conductivity had a positive correlation with pollutant concentration represented by groundwater SpC. However, apparent conductivity (terrain conductivity) is not synonymous with the concentration of contaminants at the study site; as hydraulic conductivity was also shown to be statistically correlated to the EM34 instrument response. These findings indicate that additional subsurface parameters, especially soil permeability, should be taken into account when interpreting variations in terrain conductivity at AML sites. The observed correlations between terrain conductivity, specific conductance of porewater, and hydraulic conductivity emphasize the need for further data in order to fully quantify the factors affecting instrument measurements. Furthermore, this study has shown the importance of electrical geophysical exploration as an initial indicator of subsurface characteristics that could guide the selection of boring locations and monitoring stations. Once all the controlling factors are quantified, subsurface electromagnetic exploration should be a powerful assessment tool capable of indicating contamination sources caused by high concentrations of TDS which may be used to improve remediation efforts.

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