Geophysical Assessment of a Proposed Landfill Site in Fredericktown, Missouri

Carole D. Johnson
U. S. Geological Survey
Storrs, Connecticut, USA 06269
cjohnson@usgs.gov

Bio ▸

Katherine L. Pappas
U. S. Geological Survey
Storrs, Connecticut, USA 06269
kpappas@contractor.usgs.gov

Bio ▸

Eric A. White
U. S. Geological Survey
Storrs, Connecticut, USA 06269
eawhite@usgs.gov

Bio ▸

Dale D. Werkema
U. S. Environmental Protection Agency
Newport, Oregon, USA 97365
Werkema.D@epa.gov

Bio ▸

Neil C. Terry
U. S. Geological Survey
Storrs, Connecticut, USA 06269
nterry@usgs.gov

Bio ▸

Robert G. Ford
U. S. Environmental Protection Agency
Cincinnati, Ohio, USA 45220
ford.robert@epa.gov
Bio ▸

Stephanie N. Phillips
U. S. Geological Survey
Storrs, Connecticut, USA 06269
sphillips@contractor.usgs.gov

Bio ▸

Kurt W. Limes
U. S. Environmental Protection Agency,
Lenexa, Kansas, USA 66219
Limesand.Kurt@epa.gov

Bio ▸

John W. Lane, Jr.
U. S. Geological Survey
Storrs, Connecticut, USA 06269
jwlane@usgs.gov

Bio ▸

Abstract

In cooperation with the U.S. Environmental Protection Agency (EPA), the U.S. Geological Survey (USGS) collected numerous types of geophysical data at a site in Fredericktown, Missouri, in June 2018. Various geophysical surveys were collectively used to help evaluate the overall suitability of the site for use as a mine waste-soil and sediment repository, and to evaluate the suite of geophysical methods for rapid collection and preliminary assessment of sites with shallow sediments. Land-based geophysical methods, which included frequency-domain electromagnetic induction (FDEM), electrical resistivity tomography (ERT), horizontal-to-vertical spectral ratio passive seismic (HVSR), and shear-wave refraction, were used to determine the depths to crystalline bedrock and characterize the overlying unconsolidated sediments (or regolith). Water-borne FDEM profiles and forward-looking infrared (FLIR) thermal image surveys were conducted along the Fredericktown City Lake shoreline to identify locations of potential interactions between groundwater and surface water. Sediment temperature profilers were installed at two locations along the shoreline to characterize shallow unconsolidated sediment thermal properties and support the interpretation of the other geophysical surveys.

Geophysical reconnaissance methods including the FDEM and HVSR methods, were used to rapidly evaluate the vertical and lateral extent of overburden, or unconsolidated sediments, overlying the bedrock at the site. The results of these methods were compared to reference geophysical methods of ERT and shear-wave refraction surveys that have greater accuracy and are more labor intensive and time-consuming. A goal of the project was the evaluation of the validity and reliability of this suite of reconnaissance geophysical methods as a means by which shallow (less than 3 meters (m)) sediments can be rapidly assessed. Two orthogonal ERT survey profiles, which used 28 electrodes spaced 1 m apart in dipole-dipole and combined Wenner-Schlumberger configurations, were collected to determine the subsurface resistivity. The results were inverted to produce electrical resistivity profiles that were compared to the FDEM and HVSR survey results. The FDEM data were collected along cleared paths through the proposed disposal cell locations. The data were inverted to generate depth-dependent estimates of electrical conductivity along the transects. An analysis of the depth of investigation (DOI) indicated the FDEM imaged to depths of about 3 m below land surface. The ERT, FDEM, and HVSR indicated the depth to crystalline bedrock was approximately 1.5 m below land surface with shallower and deeper areas. Results from this investigation indicate this suite of methods will likely perform well at sites with shallow depths to bedrock and strong conductivity and acoustic impedance contrasts, where the FDEM and HVSR methods can provide estimates of the depth to bedrock, and ERT and shear-wave refraction surveys might not be worth the added time and expense.

Introduction

The Madison County Mines Site (designated under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980) in Madison County, Missouri, resulted from nearly 250 years of primitive and industrial mining and processing operations, primarily for lead, leaving at least 13 major mine chat (waste rock fragments) and tailings deposits across Madison County (U.S. EPA, 2018). Historically, contaminated soil and tailings were transported to residential properties for use in fill, topsoil, foundation base, and driveway aggregate. The mine wastes have migrated by water and wind erosion, affecting streams, their associated floodplains, and resulting in the contamination of soil, sediment, surface water, and groundwater. In the late 1990s, elevated blood-lead levels were detected in children, which triggered the response actions by the EPA starting in early 2000 (U.S. EPA, 2018). In 2003, the Madison County Mines Site was added to the National Priorities List (NPL).

Removal assessments and removal action activities expanded throughout the county, during which approximately 42 percent of residential and public-use properties were found to be contaminated with metals waste. To date, over 2000 residential properties in Madison County have been remediated through either removal or remedial actions. Residential yard and mine-waste cleanups are ongoing, and the City of Fredericktown has tentatively offered a tract of city-owned land for a new disposal repository. That property is contaminated by an adjacent abandoned rail bed constructed of metals-laden mine waste. The repository is intended to be developed specifically for the disposal of lead-contaminated soil and sediments from residential areas and the adjacent Fredericktown City Lake, should lake cleanup be deemed necessary.

The proposed repository location, which is on the west-northwest shore of Fredericktown City Lake (*i.e.*, Site), has the potential to be out of the floodplain and have the appropriate soil/geotechnical characteristics that render it an appropriate site for safe and long-term contamination storage. The Site is the area of focus of this geophysical investigation, in which electromagnetic induction (EM), electrical resistivity tomography (ERT), horizontal-to-vertical spectral ratio (HVSR)

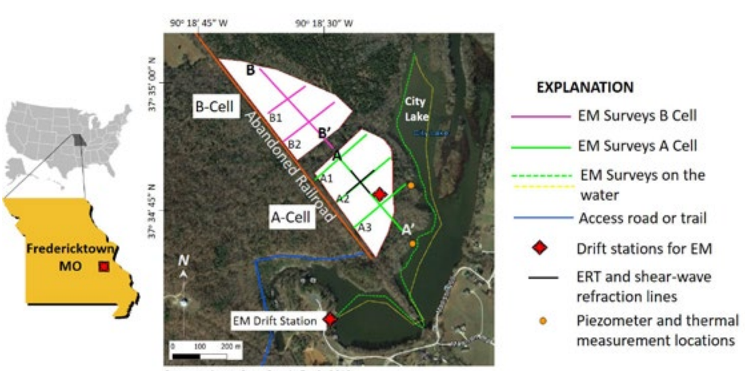


Figure 1: General location of the Madison County Missouri Mines Waste Site and data collection locations with explanation. The two cells (i.e., A-Cell and B-Cell) of the proposed repository are located between the former railroad and Frederick City Lake.

passive seismic, shear-wave refraction, and forward looking infrared (FLIR) were used to characterize the depth to bedrock, the unconsolidated sediment/regolith above the hard rock, the hydrology, and the overall suitability of the Site for use as a waste-soil and sediment repository (Figure 1).

Methods of Investigation and Analysis

Five geophysical methods were used to provide a rapid evaluation and assessment of the shallow overburden. These methods were used in an attempt to determine 1) the depth extent of the unconsolidated overburden and regolith, 2) if a clay layer exists within the unconsolidated regolith, and 3) if there is groundwater seepage into the lake. FDEM data were collected along transects that were cut through the dense vegetation that spans the two zones (*i.e.*, "cells") under evaluation for the proposed landfill (Figure 1). HVSR point data were collected at the ends and intersections of the transects. FLIR and temperature data were collected in two areas along the lake shore, which were collocated with shallow sediment temperature and sediment core collection sites. A shallow piezometer was installed at CL-2 (at the orange point near the A' end of the A cell center line); however, the water level in the piezometer did not equilibrate over a 3-day period. Hence a steady-state water level could not be acquired there. Water-borne FDEM profiles were collected along the shoreline of the lake. All data collected for this investigation are described in detail and provided in Johnson *et al.* (2020).

Continuous FDEM data were collected along cleared paths through the proposed disposal cell locations using a multifrequency antenna to distinguish the contact between the unconsolidated sediment and crystalline bedrock (Abraham et al., 2006). FDEM data were collected using a GEM2 with five combined frequencies ranging from 450 to 18,330 Hertz (Hz) (Geophex Ltd., 2009). GEM2 data were acquired along each of the transects at walking speeds of 3 to 4 kilometers per hour (km/hr) with the instrument hand-carried at a height of approximately 1 m above land surface and with its antennae coils in the horizontal coplanar/vertical-dipole orientation. Drift station measurements were taken at the beginning and end of each set of surveys to assess measurement drift. Water-borne FDEM surveys were conducted with the GEM2 affixed to a raft and towed behind a canoe along the lake shore at speeds of about 2 km/hr to determine the subsurface characteristics and to identify potential areas of groundwater seepage into the surface water. All measurements were georeferenced with a global positioning system (GPS) integrated to the instrument. The GEM2 instrument individually measures the primary and secondary magnetic fields, and the ratio of the secondary to the primary field is recorded and separated to the in-phase and quadrature components in units of parts per million. The in-phase signal component is typically used to identify variations in magnetic susceptibility, whereas the quadrature component is typically used to identify variations in apparent electrical conductivity (Huang and Won, 2000). The FDEM data were checked for drift and plotted to identify possible sources of contamination, EM interference, or unknown buried structures that should be avoided by the other methods. Data were processed in Workbench software (Aarhus GeoSoftware, 2019) to manually remove erroneous data points that were characterized by extreme high and/or low values. All negative quadrature data were omitted. In addition, a smoothing filter with a 1-m lateral spacing using 3 m of surrounding data was used. The data were inverted to generate depth-dependent estimates of electrical conductivity along the transects. The quadrature data were inverted in the ground-conductivity module of Workbench software with a Laterally Constrained Inversion (LCI) using a 20-layer, smooth model down to a depth of 25 m below land surface (Auken and Christiansen, 2004). During inversion, a depth of investigation (DOI) was computed by the Workbench software and represents the estimate of the depth to which the FDEM data are reliable (Christiansen and Auken, 2012).

Four Tromino™ seismometers were used to collect a total of 32 HVSR passive seismic measurements, which aid in the characterization of the regolith-bedrock contact, throughout the Site. The HVSR signal source is ambient seismic noise in the range of approximately 0.1 to 1 Hz that is generated by ocean waves, large regional storms, and/or tectonic sources. Once firmly planted into the soil, the Tromino uses a three-component seismometer to measure seismic noise in the vertical and two horizontal directions for 15 to 20 minutes. Given a substantial contrast (greater than 2:1) in shear-wave acoustic impedance between the overburden and bedrock contact, a resonance frequency (f_0) is induced in the unconsolidated sediments and can be determined using a ratio of the signal components (Koller *et al.*, 2004). The passive seismic data were interpreted to determine the f_0 by analyzing the spectral ratio of the horizontal and vertical signal components. The thickness of the overburden can be related to f_0, and, in general, an increase in f_0 corresponds to a decrease in sediment thickness (*i.e.*, decrease in depth to bedrock). The depth to bedrock at a measurement location is calculated as the shear-wave velocity (Vs) multiplied by a quarter of the resonance frequency (*i.e.*, Depth = $Vs/(4 \cdot f_0)$), and the relationship between the Site resonance frequencies and depth to bedrock was established using a Vs of 270 m/s, which is the average of the shear-wave velocity values measured at the Site with an active-source seismic method. HVSR data processing was conducted using the Grilla software program (2018) and included the use of band-pass filtering to remove instrument drift, data spikes, and other high-frequency noise as well as a post-processing spectral smoothing method described by Konno and Ohmachi (1998). The Grilla program computes the average spectra of the two horizontal components and the vertical component for a user-specified time-window, and then calculates the ratio of the horizontal to vertical amplitude spectra. The plotted spectra were examined to determine the resonance peak and value of f_0 for each location. The outlined methods are fully documented in the associated USGS data release by Johnson *et al.* (2020).

Two orthogonal ERT profiles were collected using both dipole-dipole and Wenner-Schlumberger electrode configurations following industry standards proposed by the American Society for Testing and Materials (ASTM) in document D6431-99 (2011) and methods described by Loke (2000). A Supersting™ R8 Induced Polarization and Resistivity meter, which was manufactured by Advanced Geosciences Inc. (AGI), was used with 28 electrodes spaced 1 m apart to collect the ERT data. During an ERT measurement, electrical current is injected into the subsurface through two current electrodes and voltage is measured sequentially across multiple pairs of potential electrodes. The process is repeated numerous times using various electrode pairs to inject current, and the source current and voltage signals are used to determine the apparent resistivity of the subsurface. ERT data can be inverted to obtain two-dimensional resistivity profiles, and variations in them can be interpreted as subsurface features and/or layers. The ERT data were processed and inverted using AGI EarthImager 2D (2018). Data processing involved the removal of negative resistivity values and noisy measurements. The ERT data were filtered to remove negative values, and values that fall outside the limits of the data removal criteria, which include minimum voltage requirement, maximum apparent resistivity, and minimum resistance. ERT data were further filtered to remove noisy data using the data misfit histogram utility. Data with a root mean squared (RMS) value greater than 100 percent were removed. Resistivity profiles were recovered through the smooth-model inversion of the processed ERT data using a starting model equal to the average apparent resistivity, which was approximately 662 ohm-meters (ohm-m).

Active-source seismic refraction data were collected near the locations of the ERT surveys. The main objective of the method was to obtain an estimate of the shear-wave velocity (Vs) for the Site that can be used in the HVSR method to estimate the depths to bedrock. A secondary objective of the method was to determine the depth to seismic interfaces, such as bedrock for comparison to ERT and FDEM results. The surveys were conducted following the ASTM industry standards outlined in document D5777-00 (2011), and further details of the data collection are provided in Johnson *et al.* (2020). Two surveys were conducted using 24 low frequency (4.5 Hz) horizontal geophones that were spaced 1 m and then 0.5 m apart. A total of five “shot points” were used for each survey, including two shot points on each end of the line and one in the middle. The shear-wave sound source was a 10-pound sledgehammer and a 100-pound strike plate that was used to collect data in two horizontal directions, by stacking five strikes on both sides of the strike plate normal to the survey line. The data were recorded with an Exploration Seismograph along with the Seismodule Controller Software, both of which are manufactured by Geometrics Inc. Because of the shallow depths to bedrock, the data with the most first arrivals from the unconsolidated unit were acquired with the shorter geophone spacing. Data were processed and interpreted using ReflexW, a processing and interpretation package developed by and available through Sandmeier Geophysical Research (Sandmeier, 2012).

Although dense vegetation limited access to the shoreline, FLIR imagery was collected at two locations along the shoreline of City Lake that coincided with sediment temperature profiling and core sample collected. A handheld FLIR T620 camera was used as a means of reconnaissance and evaluation of the embankment and nearshore to identify thermal anomalies and possible locations where groundwater discharges into the lake. Generally, during hot months, groundwater discharge will be represented in a FLIR image as a low temperature anomaly, whereas, in cooler months, groundwater discharge produces a higher temperature anomaly relative to the surface temperature of the surrounding body of water. The thermographic images taken by the T620 show the surface temperature as a function of color, which were scaled so that darker colors represent cooler temperatures and brighter colors represent warmer temperatures. Traditional, true-color photographs were collected concurrently with the FLIR thermal images to help identify the features associated with any thermal anomalies as well as help interpret the FLIR images that might be adversely affected by reflections or obstructed by the dense vegetation along the shoreline. Additionally, the images were collected in at dusk to avoid reflections off the water surface while pointing at the shoreline. FLIR images record the spatial variations in apparent temperature as Joint Photographic Experts Group (.jpg) files, which also include information such as time of capture, GPS location, distance of camera to target, image bearing, and camera settings.

The FLIR and water-borne FDEM surveys, which were acquired along the lakeshore to determine groundwater-surface water (GW-SW) discharge locations (Röper *et al.*, 2013), were co-interpreted using the surface water temperature data collected near the shoreline. The in-situ temperature of surface water and saturated sediments were recorded over time, and the measurements were used to support calculations of seepage flux. Methods of collection are detailed by the EPA (U.S. EPA, 2014). The temperature of surface water of City Lake near its shoreline was continuously logged using a Solinst Levelogger® Edge Model 3001 datalogger, which has a reported temperature accuracy of 0.05 degrees Celsius (°C) with 0.003 °C resolution. The temperature of saturated sediments was monitored at two locations (*i.e.,* CL2 and CL3 at the end of A-A' and A3, respectively, orange points on Figure 1) using a total of 10 Model DS1922L Maxim iButton Temperature Loggers, which have a reported accuracy of 0.5 °C with 0.0625 °C resolution when using the 11-bit setting. Each temperature logger was deployed in a protective case to a specific depth below the sediment surface using a custom drive rod consisting of a polyvinyl chloride (PVC) drive shoe attached to a 2.54-centimeter (cm; 1-inch) diameter steel pipe. At each location, five iButton loggers were advanced to depths of 0.04, 0.15, 0.30, 0.61, and 0.91 m below the sediment surface. Each iButton was set to record temperature every 30 minutes for 3 days.

The bulk thermal conductivity measurements of saturated sediment for the two temperature sensor deployment locations were collected to support seepage flux calculations. Sediment cores were collected using an Aquatic Research Instruments Universal Percussion Corer with polycarbonate core barrel, of 6.8 cm inside diameter. Following retrieval, the top of the core barrel was cut off to eliminate free-standing water and capped. The sealed sediment core was then laid horizontally in a shaded location and approximately 0.3-cm diameter holes were drilled in a row through the top surface of the core barrel at approximately 5-cm (2-inch) intervals. Thermal conductivity was measured using a Decagon KD2 Pro thermal properties analyzer equipped with a KS-1 single needle probe. The probe was inserted vertically through each drilled hole into the saturated sediment such that the needle was fully submerged in sediment in a direction parallel to the cross section of the core barrel. Duplicate and replicate measurements at three different intervals were conducted to ensure measurement repeatability, and a minimum of 5 minutes was allotted between each measurement to allow complete thermal recovery. Vegetable shortening was used as a reference material to check the accuracy of instrument response prior to and following completion of measurements for each core (Yi *et al.*, 2009).

Sediment temperature profile data, collected over the period June 25-28, 2018, were modeled using 1DTempPro v2.0 (Koch *et al.*, 2016), in which, a single value of seepage flux was iteratively calculated for the entire data record for each measurement location. The shallow sediment was modeled as two layers, with an upper 10-cm layer with thermal conductivity of 0.71-0.76 Watts per meter per degree Celsius (W/m/°C) and a lower 70-cm thick layer with thermal conductivity of 1.71-1.73 W/m/°C. Using the measured values of sediment thermal conductivity, the default values assigned in 1DTempPro for the hydraulic conductivity and porosity for a silty-clay textured sediment, and with an assigned dispersivity of 0.001 m, the seepage flux was optimized to fit the calculated depth-dependent temperature to the observed temperatures.

Results

The processed FDEM results were mapped onto a 1/3 arcsec digital elevation model (DEM), as the elevation data measured by the GEM2 unit were not reasonable given an insufficient GPS fix. The depth of investigation for the EM surveys is estimated to be about 3 m below land surface. The location of the FDEM surveys are shown on areal plots for the land- and water-based surveys. The color of the data point along the line (Figure 2A) shows the apparent conductivity for the highest frequency (18,330 Hz) of the low-frequency suite. The plot shows that most of the water-borne apparent conductivity is conductive (greater than 15 milliSiemens per meter (mS/m)). On land the apparent conductivity is generally less than 15 mS/m. Three-dimensional (3D) ribbon plots were generated from the inverted FDEM models (Figure 2B). The ribbon plots or fence diagrams provide a visual assessment of the spatial distribution of electrical conductivity. Zones of high conductivity are denoted as red. These zones were identified along the western side of the Site and correspond to metal-contaminated mine waste chat along the railroad grade. Additionally, localized

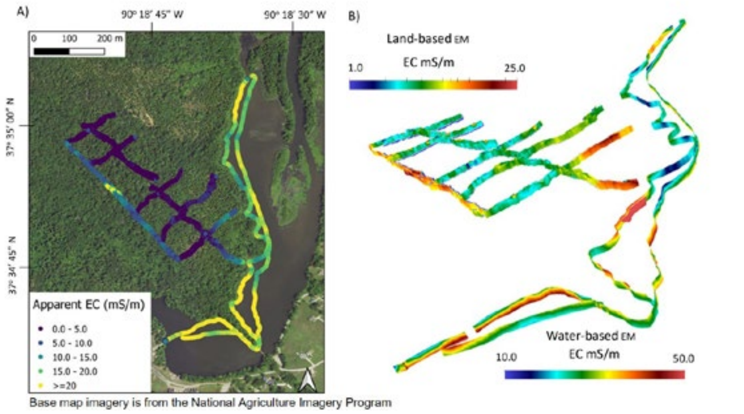


Figure 2. Land- and water-based EM electrical conductivity in milliSiemens/meter (mS/m) A) Locations of FDEM surveys where color indicates the apparent conductivity from the 18,330 Hertz measurement, and B) Ribbon plots showing the inverted electrical conductivity to a depth of 5 meters below land surface.

zones of high conductivity were evident on the eastern side near the shoreline and in the water along the shoreline. These high conductivity zones likely represent areas of finer-grained overburden versus the predominantly sand-rich overburden throughout the rest of the Site. The land-based inverted electrical conductivity had a median value of 4.0 mS/m (ranging from 1.2 to 49.9 mS/m), and the water-based results had a median value of 19.8 mS/m (ranging from 10.5 to 73.5 mS/m). The ribbon plot shows that there are thin or absent sediments above the bedrock over much of the Site. The sediments were too thin and discontinuous for the GEM2 to resolve the thickness of the sediments across the entire Site.

In general, most of the HVSR measurements showed good coupling with the earth, yet only 10 of the measurements provided acceptable quality for the interpretation of the f_0 and the determination of the depth to bedrock. The median value of the depth to bedrock calculated with the information from the 10 reliable measurements (shown as green and purple points in Figure 3A) was 1.6 m. The lack of resonance exhibited by the other two thirds of the HVSR measurements is interpreted as the local sediment layer being too thin (less than 1.5 m) to produce measurable resonance. These results suggest that the sediments are too thin or lack acoustic impedance contrast in places for the HVSR method to be effective at this site. However, it may still be a valid indicator of the thin overburden thicknesses. Hence a measurement with good coupling and an absence of resonance is consistent with the thin overburden at this site. The HVSR measurement that resulted in the lowest f_0 (7.75 Hz) was at the lake-side end of Transect A3 (Figure3 B&C, collected at the purple square on Figure3 A). Using the Vs from the active shear-wave survey resulted in the f_0 of 7.75 Hz and suggests the depth to bedrock is 8.7 m below land surface at this location, which is consistent with a sandy overburden; however, the sediments by the lake appear in the FDEM profiles and in the shallow core to be silty clay and fine sands, which would have a lower Vs than sand. For example, if the Vs of the silty clay was ~180 m/s, the depth would be ~6.4 m. Thus, if the regolith is predominantly composed of fine

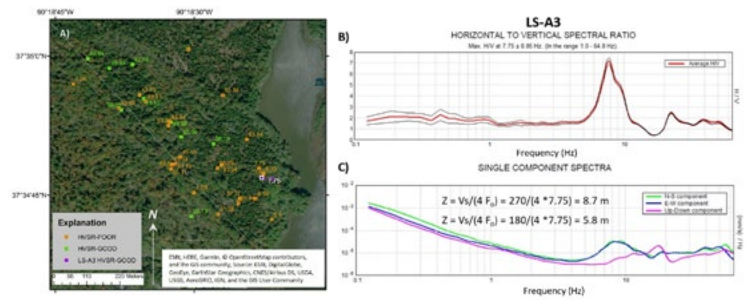


Figure 3: Horizontal-to-vertical spectral ratio (HVSR) (A) seismic data collection locations with resonance frequency (f_0); color indicates the quality of the curve and f_0, and the purple point indicates the location of the HVSR in (B) resonance and (C) single-component spectra.

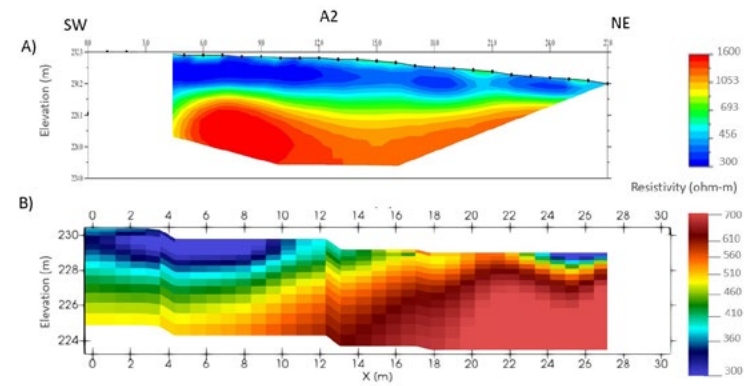


Figure 4: (A) Electrical resistivity tomography (ERT) profile and (B) Frequency Domain Electromagnetic induction (FDEM) profiles along A2; shown as resistivity in ohm-meters.

sediments it would require either another Vs measurement in the clay or an independent depth to bedrock measurement in order to calculate the slower velocity. This highlights the need to collect and validate Vs in each type of material across a study site.

The FDEM-produced electrical resistivity profile was comparable to that produced by the ERT method (Figure 4), and thus, FDEM is indicated to be a good reconnaissance method for rapidly estimating the shallow distribution of electrical properties of the subsurface. The inverted ERT profile shows the overburden-bedrock contact, which is indicated by a conductive layer overlying a resistive mass, at a depth of about 1.5 to 2.0 m. This is consistent with the FDEM surveys whereby they both indicate a similar resistivity trend with depth (Figure 4). Although the depth to rock was identified by the ERT profile and supported by the FDEM and HVSR measurements, there is no clear or distinctive indication of a water table.

The temperature and thermal conductivity data, which were collected in fine-grained sediments with a moldable, silty-clay texture, were fairly uniform at both locations. The sediment temperature profile data simulated in 1DTempPro produced a single value of seepage flux for the entire data record at each temperature monitoring location. A binary distribution of bulk sediment thermal conductivity was used for these model runs, which resulted in calculated values for seepage flux at locations CL2 and CL3 of -0.003 meter per day (m/d) (upward) and +0.015 m/d (downward), respectively. The 1DTempPro results indicated good fits of the calculated and observed sediment temperature

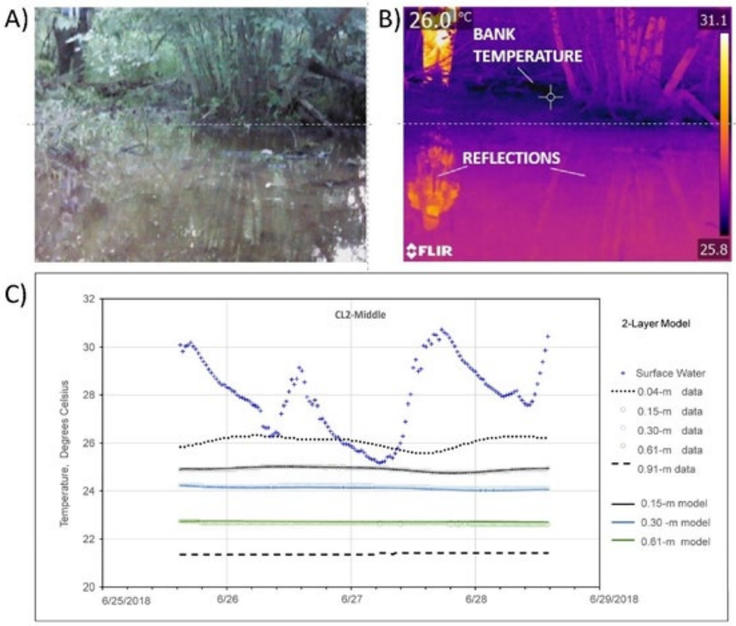


Figure 5: (A) Photo of stream bank (B) forward-looking infrared images showing temperature with lowest temperature at 25.8 and highest at 31.1 degrees Celsius, and (C) Temperature in thermistors installed in the lakebed.

trends. The temperature monitoring and modeling indicates a very weak upward vertical gradient and weak seepage flux, which is consistent with the silty clay and fine materials observed on the edge of the lake and the higher conductivity values determined near those locations by the FDEM.

Conclusions

The combination of reconnaissance measurements, which included the continuous land- and water-borne FDEM surveys, the discrete measurements of FLIR and HVSR, and the high-resolution measurements (*i.e.*, ERT, shear-wave seismic refraction, and data from the piezometers), allowed for a rapid assessment of the Site with the opportunity for data-quality checks by ground-truthing the results of the reconnaissance with the high-resolution measurements. Collectively, the geophysical surveys conducted within and adjacent to Fredericktown City Lake provided useful information about the distribution of unconsolidated subsurface materials. The results from this investigation suggest a thin layer of unconsolidated sediments overly the bedrock. Additionally, there appears to be a discrete zone of silty clay and fine sands extending into the lake as identified in the FDEM, HVSR, and confirmed by visual sediment core inspection. The lake and shoreline hydrogeology investigations found little groundwater connection with the lake at those locations, which is interpreted to be due to a dense low permeability clay unit. This interpretation is consistent with the emplacement of the piezometer whose water level did not equilibrate over a 3-day period. Because subsurface properties can be heterogeneous, any future work would benefit from additional measurements along the shoreline for characterization and monitoring. The placement of thermal sampling and piezometers could target small-scale anomalies in the FDEM data in efforts to capture variability in hydraulic properties.

To determine GW-SW water relations and co-interpret with temperature-monitoring data along the shoreline, water-based FDEM data were acquired along the shoreline. FLIR images were compared to the GW-SW data collected at the same sites, and no clear zones of focused groundwater inflow were identified. However, the FLIR images do suggest a diffuse leakage of groundwater at the shoreline. The temperatures of the embankments were measured to be approximately 26° C, which is consistent with the groundwater thermistor data, and were up to 4° C cooler than the surface water (Figure 5). The lake and shoreline hydrogeology investigations suggest minimal groundwater communication with the lake. Hydrologic connectivity is limited due to the presence of a low permeability clay unit. This interpreted clay unit is consistent with the electrically conductive zone identified in the FDEM survey (Figure 4) and is collocated with a lower f_0 (*i.e.*, increased depth bedrock), denoted as the purple point shown in Figure 2. Thermal conductivity, temperature, and seepage flux modeling indicated there is little vertical flux (*i.e.*, -0.003 and -0.03 m/d) through the sediments at the lakeshore.

This study demonstrates the ability for geophysical methods to provide cost-effective means for rapid, initial site assessments. A comparison of the FDEM to the ERT surveys along with the HVSR soundings indicates that there is a good comparison showing an increase in the resistivity (*i.e.*, transition to bedrock) at a depth of about 1.5 to 2.0 m below land surface. Because the results of the FDEM method are coincident with those provided by the more cumbersome ERT method, FDEM is suggested to be an effective reconnaissance geophysical tool at this site. An analysis of the time required for data collection indicates that these reconnaissance methods can be both time- and cost-efficient for obtaining a first order approximation of a site. One HVSR passive seismic measurement takes approximately 15 to 20 minutes and requires only the emplacement of a small, three-component seismometer. Conversely, the field set up for a direct Vs survey is comparatively heavy and complicated, involving geophones, cables, seismograms, a computer, and a seismic source. A comparison of the effort, time, and cost in mobilizing, setting up, and acquiring Vs surveys as compared to using the HVSR method indicates the Vs survey takes approximately five times longer than an HVSR survey. Hence, at sites with a strong acoustic impedance contrast, the HVSR may perform well and full Vs surveys might not be worth the added time expense. A comparison of the time required to collect the FDEM and ERT surveys indicates that all the FDEM transects for this investigation were collected in the same amount of time as a single ERT survey. Hence, at sites with strong conductivity contrasts that are shallow, FDEM may perform well and ERT surveys might not be worth the added time expense.

Thus, the reconnaissance approach may be appealing if used to provide a rapid assessment and a first cut to determine if additional investigations are warranted. Furthermore, the preliminary results might also provide valuable information for designing a future full-field campaign. Such a phase field investigation approach is appropriate for projects with limited budgets and/or at sites where little to no subsurface geologic and hydrogeologic information is known. At this site, the preliminary geophysical work underscored the lack of overburden to provide volume and stability for a subgrade landfill, and the geophysical results can inform future data-collection efforts necessary to further evaluate both the suitability and design challenges to construct a permanent and protective repository in this location, should this prove to be a potentially cost-effective solution for future cleanup actions.

Acknowledgements

The authors acknowledge funding support provided by the EPA through its Office of Research and Development, Engineering Technical Support Center. This manuscript has been subjected to Agency review and approved for publication. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Aarhus Workbench Software accessed June 13, 2018, available online at: http://hgg.au.dk/software/aarhus-workbench/

Abraham, J.D., Deszcz-Pan, M., Fitterman, D.V., and Burton, B.L., 2006, Use of a handheld broadband EM induction system for deriving resistivity depth images: in Conference Proceedings: 19th Annual Symposium on the Application of Geophysics to Engineering and Environmental Problems, Gamey, J. (ed), Seattle, Washington, April 2 - 6, 2006, 18 p.

ASTM D5777-00 Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation: ASTM International, West Conshohocken, PA, 2011, www.astm.org

ASTM D6431-99 Standard Guide for Using the Direct Current Resistivity Method for Subsurface Investigation: ASTM International, West Conshohocken, PA, 2011, www.astm.org

Auken, E, and Christiansen, A.V., 2004, Layered and laterally constrained 2D inversion of resistivity data: Geophysics, v. 69, no. 3, p. 752-761.

Christiansen, A. V. and Auken, E., 2012, A global measure of depth of investigation: Geophysics, v. 77, p. WB171-WB177.

EarthImager available from Advanced Geosciences Inc, accessed October 23, 2018, available online at: https://www.agiusa.com/agi-earthimager%E2%84%A2-2d

Geophex, Ltd. 2009, GEM-2 Broadband EMI sensor: accessed January, 2009 at http://www.geophex.com/GEM-2/GEM-2%20home.htm

Grilla, 2018, Grilla V6.1 available from Micromed s.p.a., Treviso, Italy, Accessed June 13, 2018 available online at: info@tromino.it

Huang, H. and Won, I.J., 2000, Conductivity and susceptibility mapping using broadband electromagnetic sensors, Journal of Environmental and Engineering Geophysics, v. 5, no. 4, p. 31-41.

Johnson, C.D., White, E.A., Terry, N.C., Phillips, S.N., Werkema, D.D., Ford, R., Pappas, K.L., and Lane, J.W., Jr., 2020, Geophysical Data Collected for an Assessment of a Proposed Landfill Site in Fredericktown, Missouri, June 2018: U.S. Geological Survey data release, https://doi.org/10.5066/P9EL99BD.

Koch, F. W., Voytek, E. B., Day-Lewis, F. D., Healy, R., Briggs, M. A., Lane Jr., J. W., & Werkema, D. (2016). 1DTempPro V2: New features for inferring groundwater/surface-water exchange. Groundwater, 54, 434-439.

Koller, M.G., Chatelain, J-L., Guillier, B., Duval, A-M., Atakan, K., Lacave, C., Bard, P-Y., 2004, Practical user guidelines and software implementation of the H/V ratio technique: measuring conditions, processing method and results interpretation, in 13th World Conference on Earthquake Engineering, Vancouver, British Columbia, Canada, August 1-6, 2004.

Konno, K. and Ohmachi, T., 1998, Ground motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor: Bulletin of the Seismological Society of America, v. 88, p. 228-241.

Kurylyk, B. L., Irvine, D. J, Carey, S. K., Briggs, M. A., Werkema, D., & Bonham, M. (2017). Heat as a groundwater tracer in shallow and deep heterogeneous media: Analytical solution, spreadsheet tool, and field applications. Hydrological Processes, 31, 2648-2661.

Loke, M.H., 2000, Electrical imaging surveys for environmental and engineering studies - A practical guide to 2D and 3D surveys, short course training notes: Penang, Malaysia, University Sains Malaysia, 67 p. https://www.semanticscholar.org/paper/Electrical-Imaging-Surveys-for-Environmental-and-Loke/efa943ffb44f5a217e2d22255f7e334778932248

Oldenburg, D.W., and Li, Y., 1999, Estimating depth of investigation in dc resistivitiy and IP surveys: Geophysics, v. 64, no. 2, p. 403-416.

Röper, T., Greskowiak, J. and Massmann, G., 2013, Detecting Small Groundwater Discharge Springs Using Handheld Thermal Infrared Imagery: Ground Water, doi: 10.1111/gwat.12145

Sandmeier, K.-J., 2012, ReflexW version 6.0. Program for processing of seismic, acoustic or electromagnetic reflection, refraction, and transmission data. Software Manual.

Solinst available from Solinst Canada Ltd., accessed June, 2018, available online at: https://www.solinst.com/products/dataloggers-and-telemetry/3001-levelogger-series/ltc-levelogger/

U.S. Environmental Protection Agency, 2018, accessed October 23, 2018, available online at: https://cumulis.epa.gov/supercpad/cursites/srchsites.cfm

U. S. Environmental Protection Agency, 2014, Quantifying Seepage Flux using Sediment Temperatures. U.S. Environmental Protection Agency, Washington, DC, EPA/600/R-14/454. https://nepis.epa.gov/Adobe/PDF/P100MP4G.pdf

Yi, M., Panchawagh, H. V., Podhaysky, R. J., & Mahajan, R. L. (2009). Micromachined hot-wire thermal conductivity probe for biomedical applications. IEEE Transactions on Biomedical Engineering, 56, 2477-2484.

Author Bios

Carole D. Johnson
U. S. Geological Survey
Storrs, Connecticut, USA 06269
cjohnson@usgs.gov

Carole D. Johnson, P.G. is a hydrologist with the Hydrogeophysics Branch of the U.S. Geological Survey (USGS), Water Resources Mission Area, Earth System Processes Division (WMA, ESPD, HGB) in Storrs, Connecticut. Carole provides support to USGS hydrologists nationally on development and application of hydrogeophysical methods to USGS groundwater studies through applied research, training, and policy development. She is a member of EEGS, GSA, and NGWA and is a licensed professional geologist in the State of New Hampshire.

Katherine L. Pappas
U. S. Geological Survey
Storrs, Connecticut, USA 06269
kpappas@contractor.usgs.gov

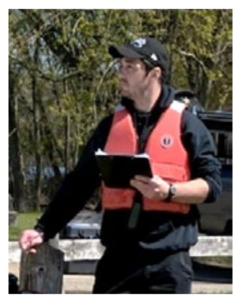
Katherine L.C. Pappas received a B.S. degree in Geology and Mathematics from the University of North Carolina Wilmington (2016). She began with the USGS as a 2015 USGS-National Association of Geoscience Teachers (NAGT) Intern at the USGS, WMA, ESPD, HGB in Storrs, Connecticut. Katherine currently conducts applied hydrogeophysical work as a contractor with USGS.

Eric A. White
U. S. Geological Survey
Storrs, Connecticut, USA 06269
eawhite@usgs.gov

Eric A. White is a Hydrologist with the USGS, WMA, ESPD, HGB in Storrs, Connecticut. He received his B.S. in geology in 1998 and is working on completing his M.S. in geophysics from the University of Connecticut. Eric provides support to USGS hydrologists nationally on the development and application of hydrogeophysical methods to groundwater studies, with a focus on surface, waterborne, and small unmanned aircraft system (sUAS) methods.

Dale D. Werkema
U. S. Environmental Protection Agency
Newport, Oregon, USA 97365
Werkema.D@epa.gov

Dale Werkema is a Research Geophysicist working in the Office of Research and Development for the U.S. Environmental Protection Agency (EPA). He performs basic and applied research on the geophysical response to various contaminants, remediation methods, and for conceptual site model development. Dale serves the EPA Regions, EPA Offices, State, Tribal, and local governments on the application of geophysical methods to various contaminants and site-specific technical issues.



Neil C. Terry
U. S. Geological Survey
Storrs, Connecticut, USA 06269
nterry@usgs.gov

Neil C. Terry, Ph.D., is a postdoctoral hydrologist at the USGS, WMA, ESPD, HGB, where he assists with the Branch's mission to support USGS hydrologists nationally in near-surface geophysics, modeling, and water-related projects. Particular focus areas include groundwater-quality monitoring, hydrogeological characterization, contaminant detection, and groundwater/surface-water interactions. He also supports software/methods development efforts, specifically focusing on linking electrical geophysical measurements with soil and hydrogeological properties.

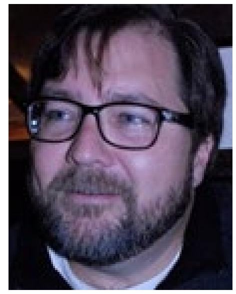
Robert G. Ford
U. S. Environmental Protection Agency
Cincinnati, Ohio, USA 45220
ford.robert@epa.gov

Robert Ford, EPA Office of Research and Development

Robert is on the staff of the EPA's Office of Research and Development (ORD) and provides technical assistance to EPA Regions through ORD's Engineering and Technical Support Center. His expertise is in development of technical knowledge and tools/processes that can be used to facilitate cleanup of inorganic contaminants in groundwater and surface water. His past work includes development of technical guidance for use of Monitored Natural Attenuation for cleanup of groundwater contaminated with metals and radionuclides. More recent work includes implementation of field research to support EPA Regions and States tackling cleanup at large, complex Superfund sites. He holds a Bachelor's degree in civil engineering from Missouri Science and Technology and a Doctoral degree in environmental engineering from Clemson University.

Stephanie N. Phillips
U. S. Geological Survey
Storrs, Connecticut, USA 06269
sphillips@contractor.usgs.gov

Stephanie N. Phillips was a student contractor intern at the USGS, WMA, ESPD, HGB in Storrs, Connecticut, from 2015 to 2019. Stephanie is currently pursuing a Ph.D. in geophysics at the University of Wyoming and is a Volunteer for Science with the Branch.



Kurt W. Limes
U. S. Environmental Protection Agency,
Lenexa, Kansas, USA 66219
Limesand.Kurt@epa.gov

Kurt Limesand is a geologist by training and has worked for 30 years as an environmental consultant, in state contaminated sites investigation and cleanup programs, and at the EPA in the RCRA Corrective Action, TSCA PCB and Superfund Programs. He is currently the EPA Remedial Project Manager for the Madison County Mines Superfund Site in Madison County, Missouri.

John W. Lane, Jr.
U. S. Geological Survey
Storrs, Connecticut, USA 06269
jwlane@usgs.gov

John W. Lane, Jr., Ph.D., is Chief of the Hydrogeophysics Branch of the USGS Water Resources Mission Area Earth System Processes Division, where he provides leadership and support to USGS and cooperating agencies on the application of geophysical methods for groundwater investigations. John's current applied research focuses on the development of quantitative geophysical methods in fractured rock and porous media, geophysical assessment of hydrologic processes, and the application of hydrogeophysical methods for water resource and contamination assessment