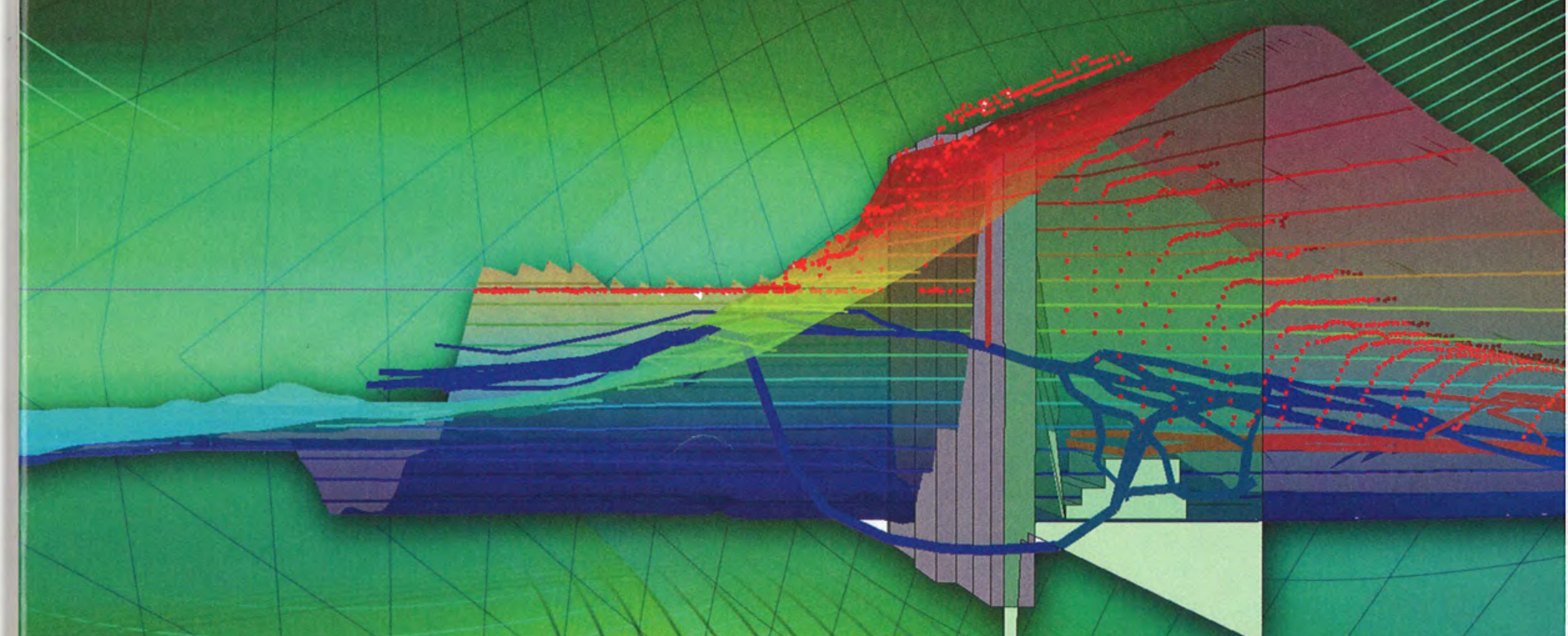
February 2011, Vol. 30, No. 2

TLE THE LEADING EDGE

THE SOCIETY OF EXPLORATION GEOPHYSICISTS
The international society of applied geophysics
ISSN 1070-485X

Special Section:

Near-surface geophysics



Unique applications of MMR to track preferential groundwater flow paths in dams, mines, environmental sites, and leach fields

VAL O. KOFOED, MIKE L. JESSOP, MICHAEL J WALLACE, and WEI QIAN, Willowstick Technologies

Groundwater systems have been notoriously difficult to map with high degrees of accuracy. As a result, not only have traditional geophysical methods proven inaccurate for groundwater characterization work, but they are often costly in terms of time, money, and environmental trauma. This paper describes a unique application of magnetometric resistivity or MMR (Edwards and Nabighian, 1991) for groundwater mapping and modeling, which is high-speed, accurate, minimally invasive, and cost effective. This method has now been deployed at many different sites all over the United States and in other countries like Canada, England, Peru, Sri Lanka, and Argentina. In 2007, the method was employed at 17 dams; some are large well-known structures in the United States. Through two case histories, this paper will assess the effectiveness of this methodology.

The application of our technology, as applied to groundwater characterization, is based on the principle that the naturally ionized groundwater is more conductive than the earthen materials in which it flows through. This method relies on the measurement of three orthogonal components of the magnetic field to track the subsurface electric current distribution. We choose to operate at 380 Hz signal to maximize the coil magnetometer sensitivity, while neglecting ground induction in data processing and interpretation. The electric current injection electrodes are placed in direct contact with groundwater to preferentially introduce electric current to follow the water of interest. The measured components of the magnetic field, after removing the electric wire contributions, and correction for topography, are contoured, and interpreted in conjunction with other hydrogeologic data, resulting in enhanced definition of preferential groundwater flowpaths. Resolution of the electric current flowpaths depends on spacing of the measurement stations and the depth of electric current flow. Cultural features such as metallic pipes, guardrails, power lines, and any other long continuous conductors between the electrodes, often obscure the effectiveness of this method.

Methodology

The electric current injection configurations used can be classified into two basic types: a horizontal dipole configuration or a vertical dipole configuration. Most often, a horizontal dipole electrode configuration is employed to create the horizontal electric current flow path in the subsurface study area. The existence of water flow will alter the subsurface electric resistivity distributions, thereby causing electric current channeling in the subsurface. The magnetic field measurement is the most sensitive to track the electric current channeling effect at depth. The placement of the electric current injection electrodes is the most important step in a survey design. In the case of a dam, the downstream electrode could be placed in a seep, a monitoring well, or other downstream waters (Figure 1a), while the upstream electrode is placed in the reservoir distal from the dam's face. A vertical dipole configuration creates a predominantly vertical electric current flow. Figure 1b contains a diagram of a typical vertical dipole where electrodes are placed in different wells a few meters apart. This setup is ideal to find preferential pathways from an upper layer through a layer with low transmissivity to an aquifer below or to track the preferential path for water to flow from the surface to depth through overburden. Applications where a vertical dipole is applicable are in envi-

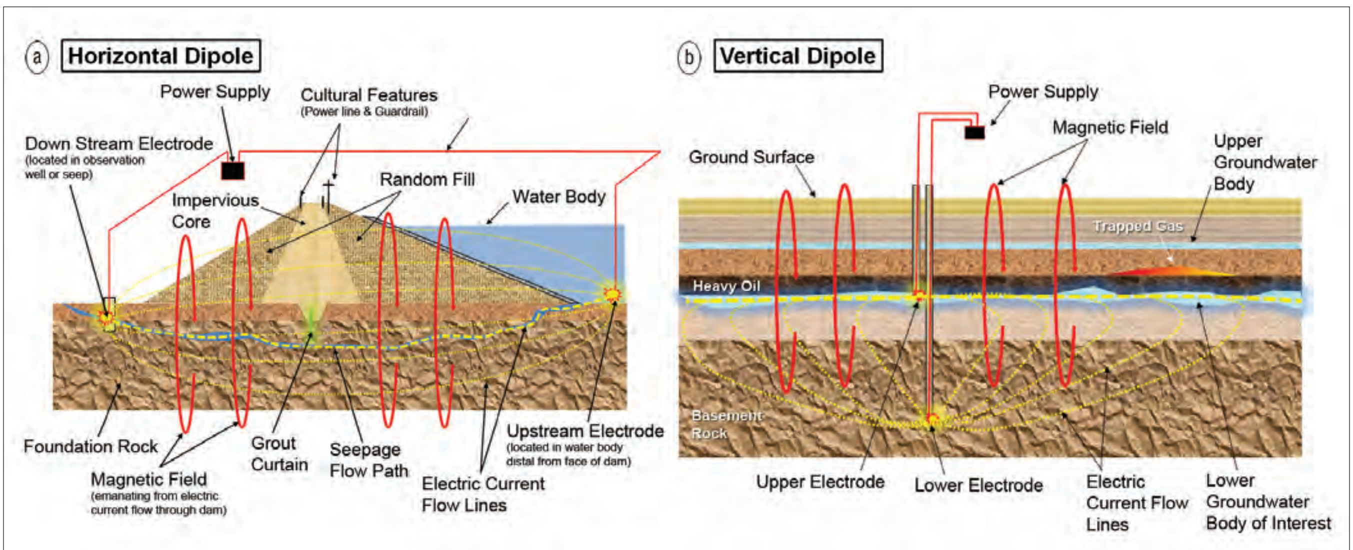


Figure 1. *(a) Horizontal dipole injection and (b) vertical dipole injection.*

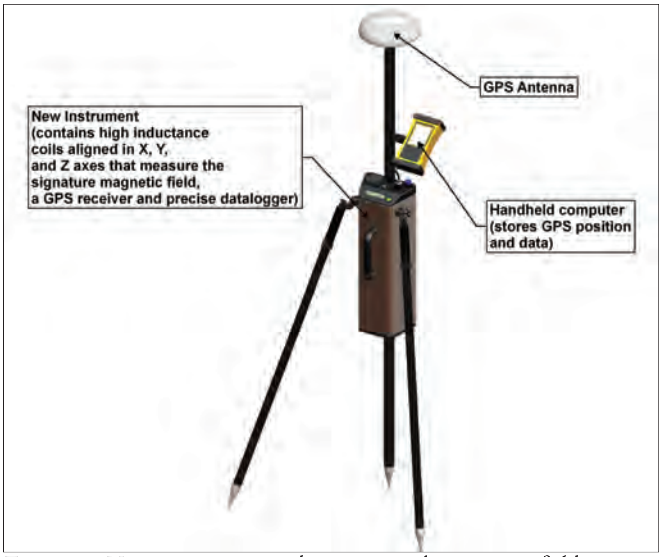


Figure 2. New instrument used to measure the magnetic field.

ronmental sites, such as finding how contaminants flow from surface to depth, leaks into underground mines, or characterizing surface water loss from mining operations.

Multiple electric current injections are often necessary to understand the groundwater regime. Electric current injection electrodes should be placed to allow the maximum amount of electric current to flow through the area of interest, thereby creating electric current channeling due to water-caused electric resistivity decreases.

A portable instrument mounted on a surveyor's pole has been designed to measure the magnetic field in three directions. Figure 2 shows a rendering of the instrument which is hand-carried to each measurement station. The principal components of the instrument are the GPS, magnetic field receiver, and handheld computer. The magnetometer consists of three coils arranged orthogonally. The magnetic coils are high-inductance and yet compact due to a proprietary design. The inductance of each coil is approximately 60 henries. The size is about 5.7 cm in length and 3.8 cm in diameter.

Signals from the coils are amplified, filtered and digitized by a datalogger. The datalogger is programmed to calculate spectra and stack them to reduce incoherent noise like spherics and other short-lived events. An intelligent algorithm calculates margin of error and will stack more or less data to improve the precision of the measurement. Measurements are statistically analyzed and repeated until they fall within an acceptable deviation (within 10%). A warning is issued by the instrument if the signal strength is too low to meet the requirements. This takes anywhere from 2 to 4 minutes per station to measure and calculate the magnetic field strength at 380 Hz. Figure 3 shows samples of the frequency spectrum plot where the 380-Hz signal (red bar) is noted to be several times stronger than any other signal within the frequency spectrum. The 380-Hz signal is not a harmonic of the 60-Hz used in the United States or 50-Hz power used in Europe, Asia, and Africa.

The signal-to-noise ratio is computed for each measurement as the ratio of the signal at 380 Hz to the mean ambient field noise, which is determined from a sampling of other nonharmonic frequencies around 380 Hz. The signal-to-noise value is contoured and presented for each survey to help assess the degree of data reliability (Figure 4). A low signal-to-noise ratio in a particular area indicates that the electric current injected into the ground does not reach that area. Considering the vastly different possibilities of cultural interferences, geologic, electrical and hydrologic conditions, every project is highly unique and a principal challenge is to establish electric current flow in the zone of interest. The degree of success is often largely dependent upon this factor.

After the magnetic field is measured, the data are then sent to a handheld computer and merged with GPS data. Field crew members can check the reading's initial quality and then provide additional information about the measurement such

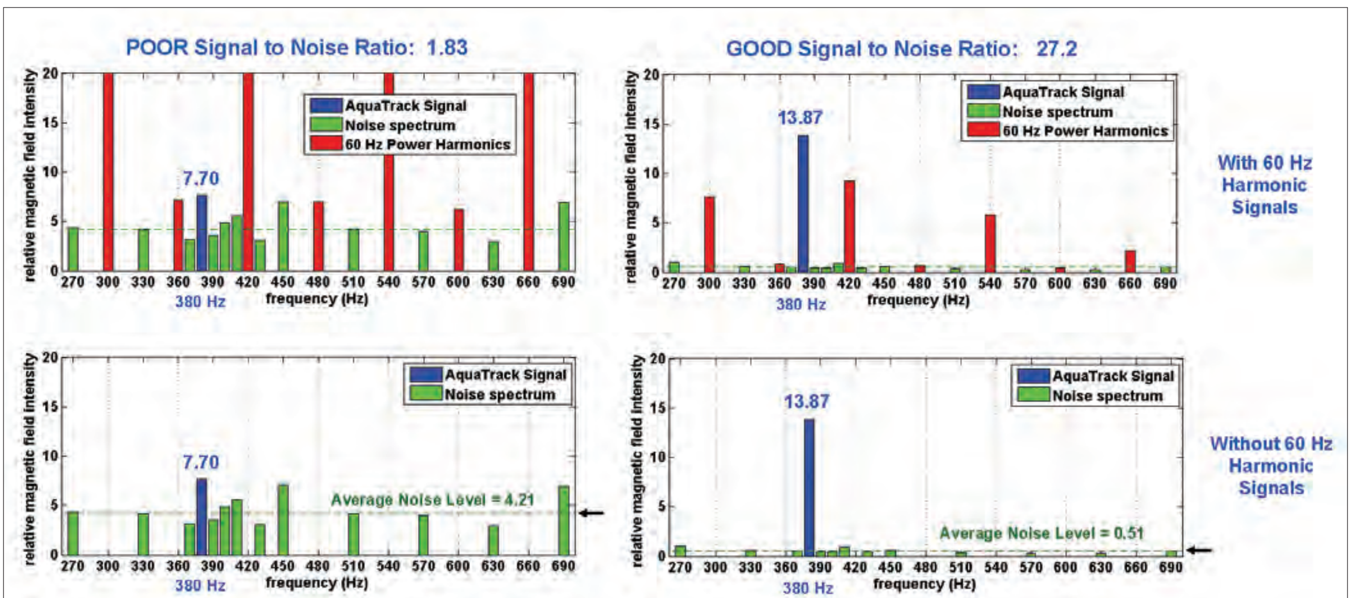


Figure 3. Sample frequency spectra from several measurements.

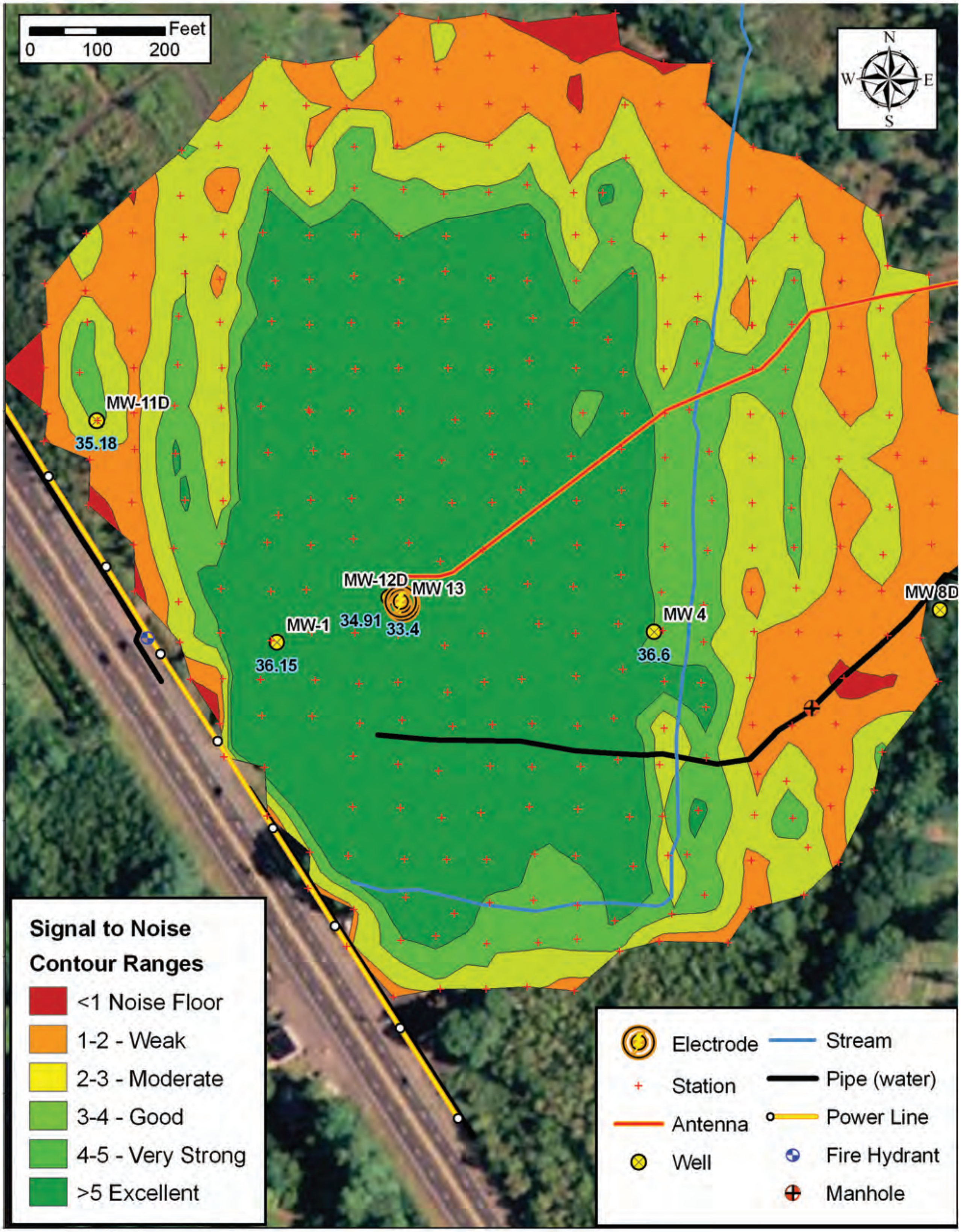


Figure 4. *Sample signal-to-noise ratio map.*

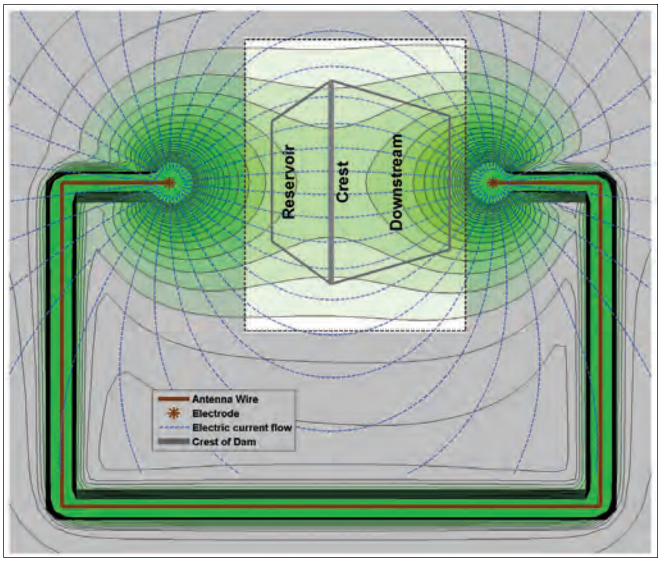


Figure 5. Electric current flow and magnetic field across a dam's embankment.

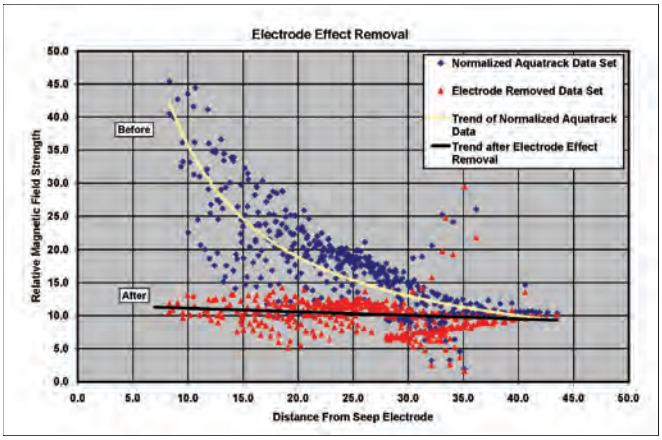


Figure 6. Profile view of the electrode effect correction on the horizontal magnetic field intensity.

as the type of reading, local coordinates, and notes regarding geology and culture. A base station is established within the survey area where each instrument is placed at the beginning, middle, and end of each day. The readings at the base station allow instrument differences to be compensated for. At the base station, a static receiver is left to log the magnetic field all day. The static receiver is used to understand and correct for any variability in the magnetic field. In addition to logging the magnetic field, the power supply current is logged and used to correct for any drift in the magnetic field data due to electrical current fluctuations.

Data interpretation

The first step in data interpretation is to remove the magnetic field (horizontal magnetic field intensity) distribution due to a homogeneous Earth. Figure 5 shows a homogeneous environment around a dam in which the magnetic field is created by placing electrodes on either side of a dam's embankment. The two electrodes are placed at different depths, causing the difference in the magnetic field intensity at each electrode. The dotted lines represent flow of electric current between the two electrodes. Electrode effect corrections are made by removing empirically-derived decay functions from the data. One example of such correction is shown in Figure 6, where the yellow line represents the decay. The horizontal magnetic field intensity is plotted (blue dots) in relation to its distance from the electrode. The red dots show the results after correction. Note how the red dots form a flat line in comparison to the blue dots (yellow line).

Once the correction is made, preferential electric current flow paths generally become much more pronounced. For quality control, we require that the electric current preferential flow paths revealed after the correction must also be evident in the raw data. The goal of the correction is simply to enhance those electric current flow paths. Figure 7 visually portrays how the electrode effects are removed from the

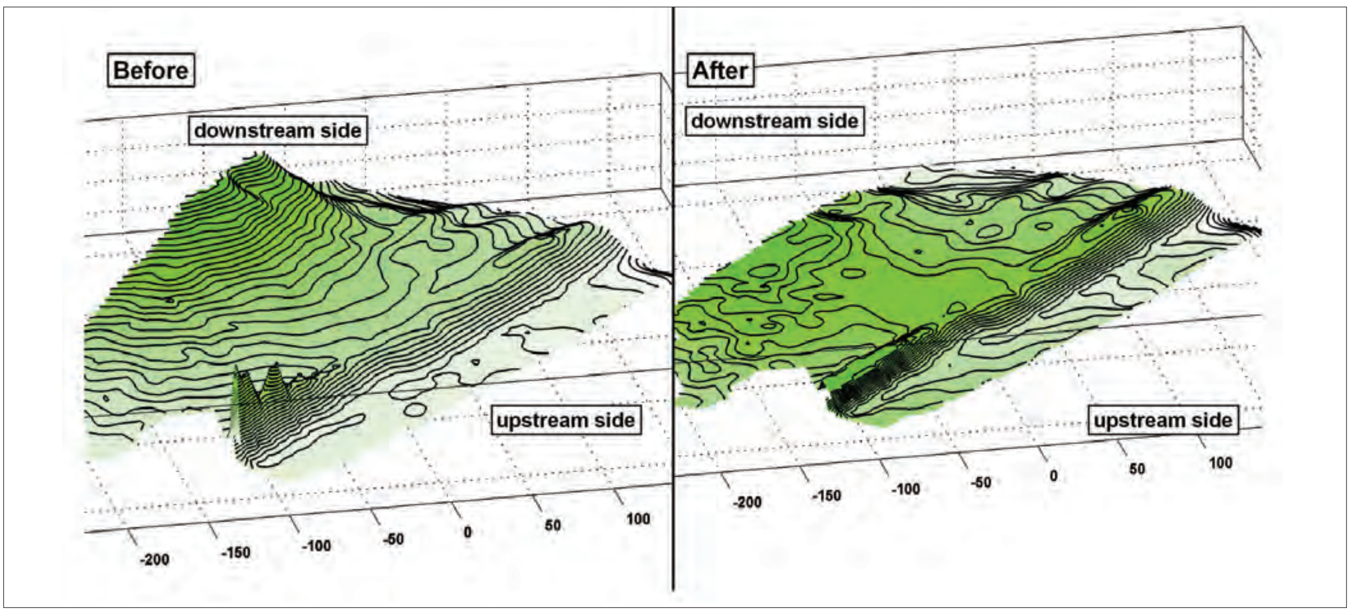


Figure 7. 3D view of electrode effect correction on the horizontal magnetic field intensity.

data. Note that the upstream reservoir electrode in this case is further from the survey area and has less of an impact on the data.

The basic physics for the data interpretation is shown in Figure 8. The following rules apply:

- Directly above the electric current, the horizontal magnetic field component reaches maximum, while the vertical (z) component is zero. The horizontal component is perpendicular to the line electric current.
- Horizontally adjacent to the line current, the horizontal magnetic field component is zero, and the vertical (z) component is maximum and changes direction from one side to the other.
- The derivative of the vertical magnetic field (dHz/dx) is proportional to the width of the electric current flow. Width of the horizontal magnetic field intensity is proportional to depth and width of the electric current. Correlation of vertical and horizontal component data can be used to clarify ambiguities of width and depth.

In this simplest case, the magnitude of the horizontal x–y component will locate the electric current and the vector direction will help determine the electric current orientation. The z-component, although less helpful due to the observation points being confined to the space above the ground surface (always above the electric current sources), can aid the determination of the depth and size of the electric current.

The horizontal magnetic field intensity map is the most robust and it provides the first pass of a qualitative data interpretation. There are generally three factors that cause subsurface electric current channeling: groundwater, culture and geology. Auxiliary information is required to make distinction of the three factors.

Cultural features such as pipelines, power lines, or other long continuous conductors, although not always present, cause problems in data interpretation as they produce large anomalies that mask the subsurface signal. The shading of the magnetic field contours helps to identify the magnetic field anomalies in linear trend. The magnetic field distribution due to homogeneous half space, electric current wires and topography (Oppliger, 1984) are removed in the data processing. The centroid (horizontal location) of preferential electric current channeling can often be identified from the magnetic field maps. For complicated electric current channeling systems, and for the determination of depth of electric current channeling, 3D forward modeling and inversion algorithms have been developed. A simple electric wire model has been formulated from the Biot-Savart Law. Two approaches to the modeling process are currently used to help determine depth of preferential electric current flow. Inversion algorithms provide an electric current intensity distribution (ECID model) within a volume of subsurface based on the magnetic field measurements. The ECID inversion model does not currently take into account the vertical component of electric current flow; neither does it enforce the conservation of the electric current. We are developing some more precise optimization

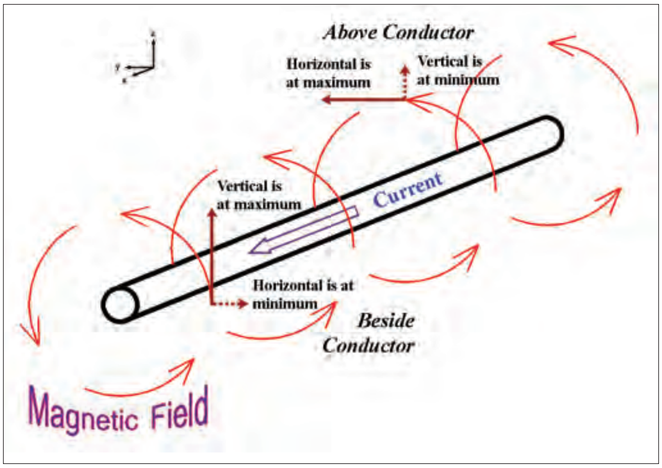


Figure 8. *Magnetic field generated by a line electric current.*

methods for determining electric current flow paths depth. One of these is a more sophisticated 3D Occam (Constable et al., 1987; deGroot-Hedlin and Constable, 1990; Chen et al., 2002; Key, 2009) inversion approach for data interpretation, where electric current density distribution will be generated that produces the measured magnetic field, under the constraint of Maxwell's equations.

A forward-modeling approach, used in many cases, utilizes a number of discrete pathways that simulate only the zones of the subsurface electric current flow exhibiting a high degree of channeling. These models, referred to simply as electric current flow (ECF) models, consist of pseudo wires and/or ribbons that simulate channelized flow. Once the preferential electric current flow paths have been identified in the horizontal dimension, a finite-element method is used to simulate the magnetic field created by the electric current flow at some depth, and appropriate depth adjustments are made until the model produces a magnetic field response that fits the shape of observed anomalies. In some cases where the anomaly is tight and revealing, good accuracy can be achieved (depths to within 10% error). The horizontal resolution of the electric current flow is generally between one-fourth and one-half of the measurement station spacing. The vertical resolution depends largely on the degree of electric current channeling.

The magnetic field maps and profiles are generally shown superimposed upon or in conjunction with aerial photographs and/or CAD drawings (plan or cross-section views) to help aid in the interpretation of the data. Any identified cultural features relative to the survey are highlighted to aid in data interpretation. It is crucial to integrate additional geological, hydrogeological, or structural information for the success of the project as shown in Figure 9. Included in these 3D views of the model are surface and subsurface features pertinent to the investigation. The information contained in these maps and models is assessed with known site information so that groundwater remediation and/or monitoring programs can be evaluated.

Case history I: Torside Reservoir, UK

Torside Reservoir is the second of five reservoirs in the east-

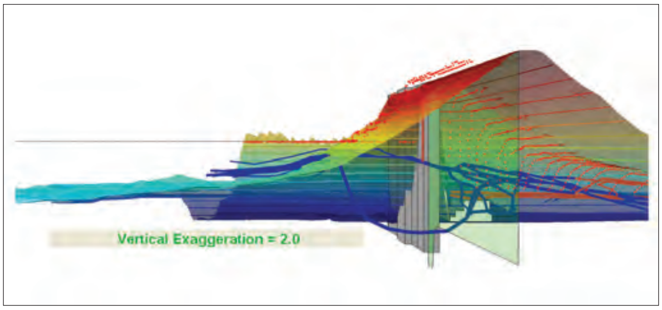


Figure 9. 3D model, cross-sectional view of seepage through embankment.

west trending Longendale Valley that supplies water to Manchester, UK (Figure 10, left). Upon filling the dam in 1851, it initially stretched on its base and ruptured drawoff pipes set in the foundation. The northern abutment lays on top of porous, fractured rock that conducts groundwater from the northern hills to the Longendale Valley's center. Barriers and drains were installed to siphon groundwater away from the dam and keep reservoir water from seeping into the rock. To channel groundwater away from the dam, a tunnel with drawoff pipes was installed through the bedrock. A rubble trench, adit, and box drain were placed under the reservoir to divert groundwater into the drawoff pipes. To keep water from leaving the reservoir, the rock was grouted and a clay liner was placed on top of the bedrock and connected to the dam's clay core. Also, a puddle-clay-filled arm trench was constructed as a barrier to groundwater entering the reservoir. In 2004, engineers monitoring the dam noticed that discharge from drawoff pipes had increased significantly, so United Utilities, owner of the Torside Reservoir, decided to use our method to delineate seepage from the reservoir (Kofoed et al., 2008).

We performed two surveys in December, 2005, and our data indicate that the embankment was intact and that most seepage was related to the drawoff pipes underneath the reservoir. However, the surveys did not cover enough area to fully delineate the sources of water flowing into the drawoff pipes. Th us, another survey was conducted in December, 2006, while the water was low. A horizontal dipole (Figure 11, right) was set up to generate predominately horizontal electric current flow in the seeps. The downstream electrode was placed in the drawoff pipes where water discharged. The upstream electrode was placed in wet soils on the hillside north of the reservoir to map the paths groundwater took to reach the drawoff pipes. An antenna wire (orange line in Figure 10, right) is positioned in a large loop around the survey area. The strong magnetic field generated by the electric current flowing through the antenna wire is calculated and subsequently removed from the measured magnetic field. This electric current injection is designed to allow the greatest

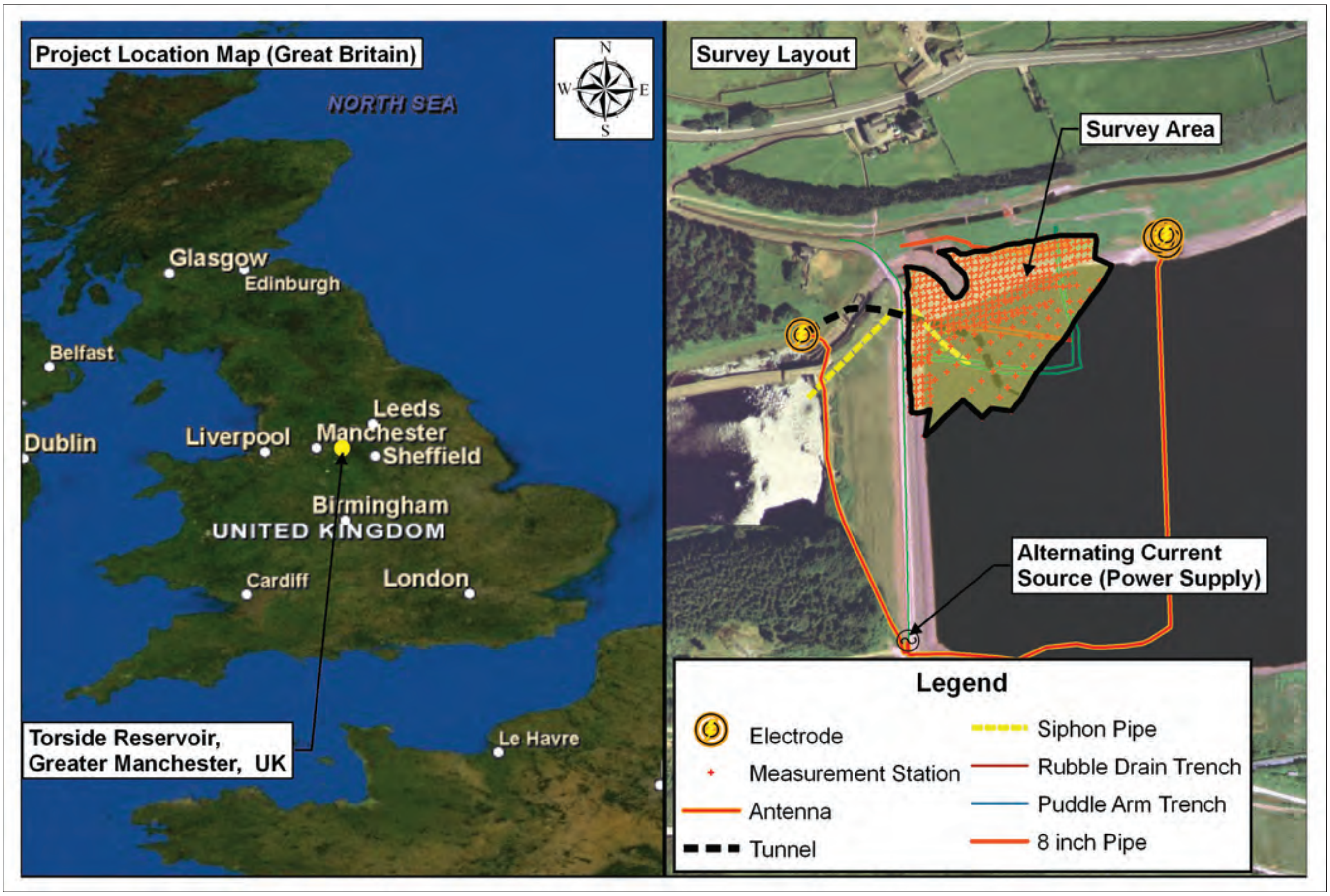


Figure 10. (left) Project location east of Manchester, UK. (right) Survey layout. Some measurements (red crosses) were made on a boat. The survey covered most of the area bounded by the puddle-arm trench.

Figure 11. Field crew surveying on the water. Only the measurement of the magnetic field provides such logistic advantages in terms of data coverage.

amount of electric current to flow through the area of interest while minimizing the magnetic field generated by the antenna wire.

A quarter of the 403 measurements were performed from a boat on the reservoir. The capability of performing measurements on water provides a huge advantage in delineation of reservoir water seepages. A tie line was used to stabilize the boat and guide crew members as shown in Figure 11.

The measured magnetic field contour map is shown in Figure 12 in comparison to the modeled magnetic field map of tunnel and siphon pipe. The measured magnetic field is dominated by the siphon pipe (yellow dashed line) and drawoff pipes or tunnel (black dashed line). The model is made up of finite elements representing the center of the channeled electric current pathways. An electric current strength and its position are derived to fit the measured magnetic field in a least square sense.

To illuminate the subsurface water pathways, the magnetic field from these two cultural features is subtracted from the measured data. The result is shown in Figure 13, where two dominant electric current flow paths are revealed, that indicate two possible sources of water flowing into the drawoff pipes. The first source flows from the north near Point B and another source of water from the south crosses the southern puddle-arm trench at Point C. Point B and Point C have the highest magnetic field reading locally and appear not to be

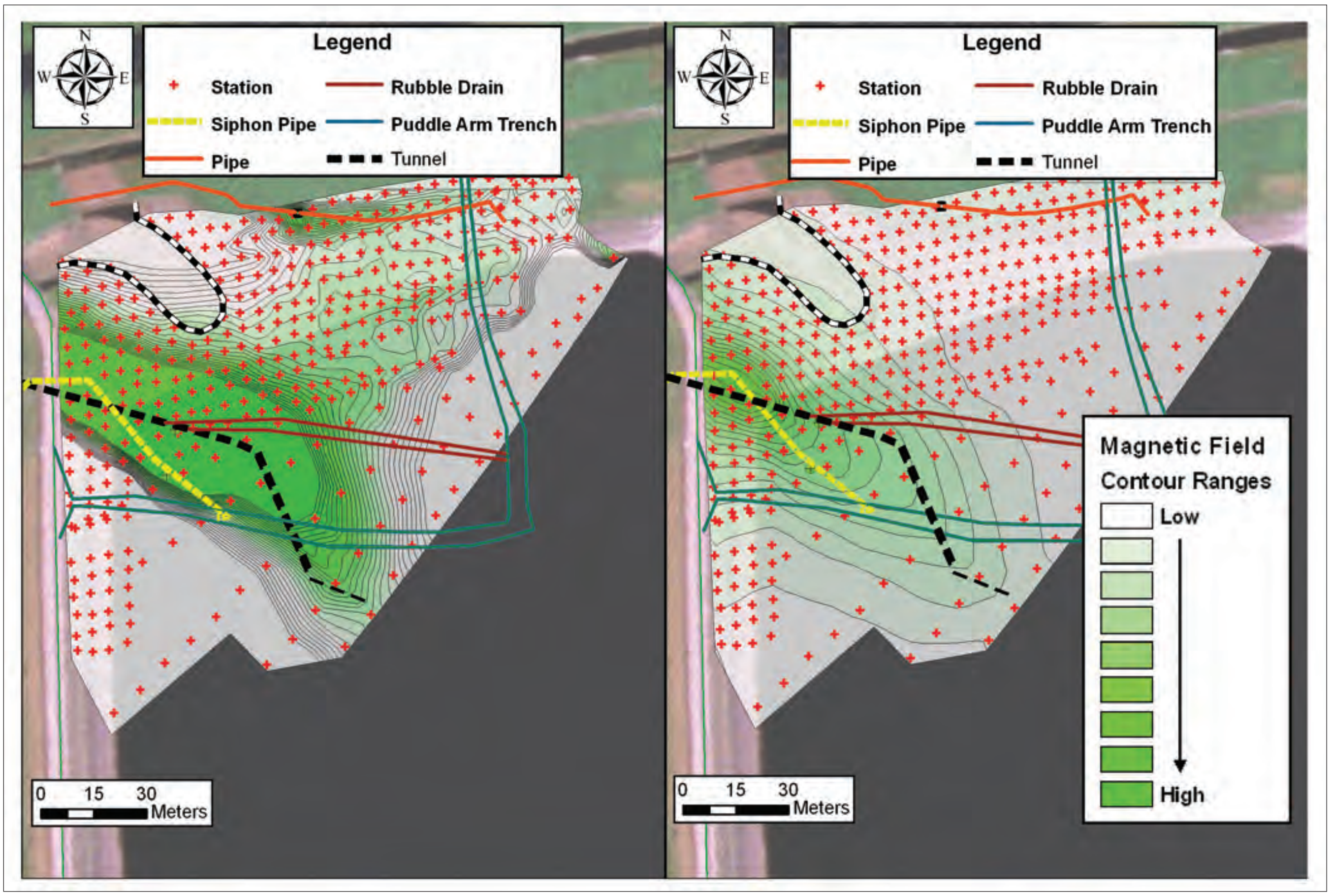


Figure 12. (left) The measured magnetic field responds primarily to cultural features. (right) The modeled magnetic field is due to the tunnel and siphon pipe.

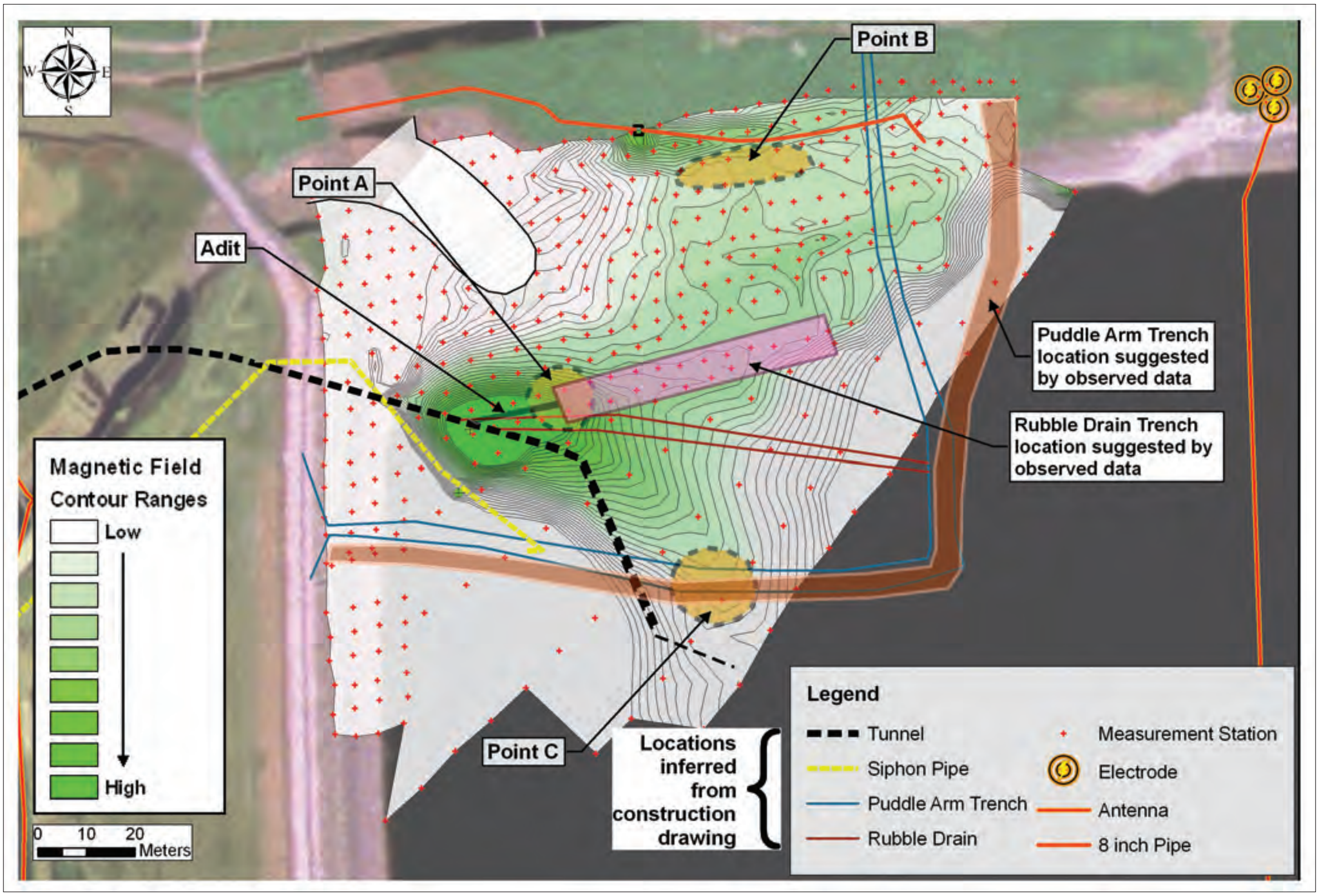


Figure 13. Two dominant electric current flow paths are revealed that indicate two possible sources of water flowing into the drawoff pipes. The first source flows from the north near Point B and another source of water from the south that crosses the southern puddle-arm trench at Point C.

influenced by current bias or cultural effects. Point C is interesting because the high magnetic field suggests water passes through or over an impermeable boundary (puddle arm trench).

The location of certain construction features have been highlighted on the map as shown in Figure 14. Their interpreted location as well as the location provided by United Utilities is shown for comparison. For example, Point A is interpreted to be the point where water from the rubble drain trench enters the adit because the magnitude of the magnetic field changes (darkest green-dark green). With this information, United Utilities felt confident to investigate the source of seepage by lowering the reservoir. A sinkhole (Figure 14) was found at point C above the puddle arm trench. The hole was excavated to discover that puddle clay in the arm trench was eroded by groundwater and the sediments on top collapsed compromising the clay liner in this area. The arm trench and clay liner were fixed, and upon filling the reservoir, the volume of water flowing from drawoff pipes was reduced by 75%.

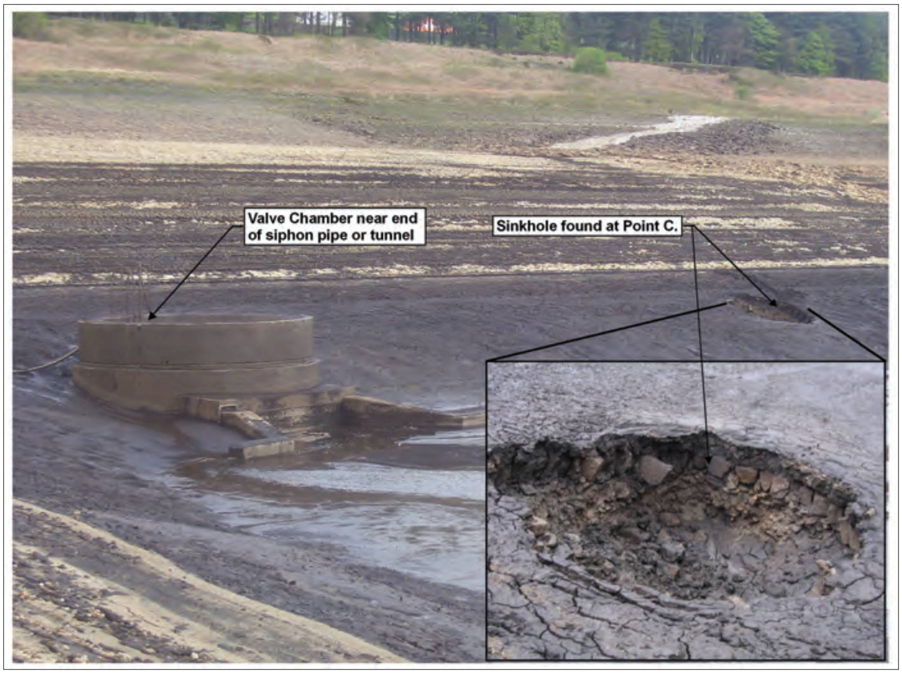


Figure 14. After the reservoir was drained, a sinkhole was found at Point C.

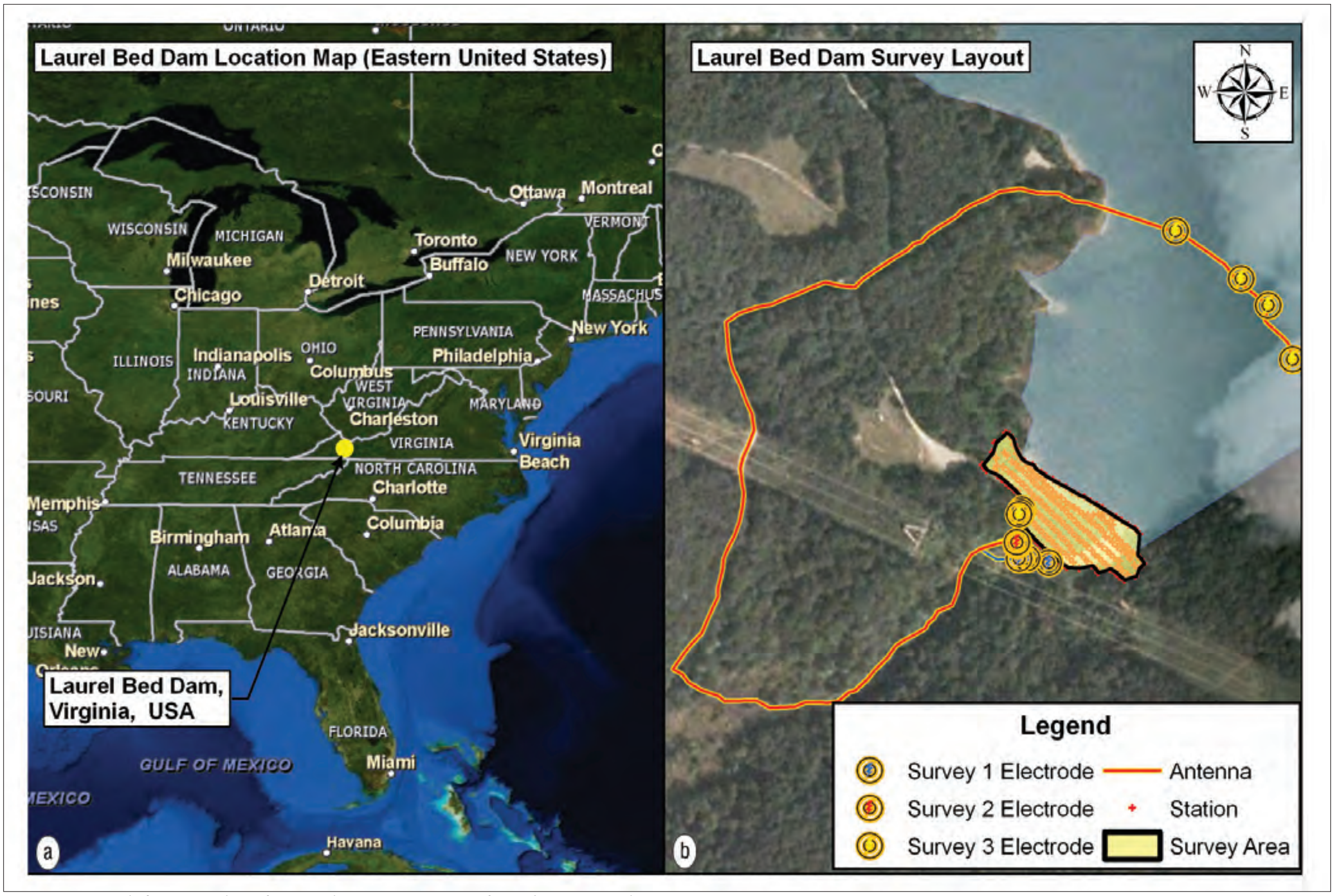


Figure 15. *(left) Laurel Bed Dam location map and (right) survey layout.*

Case history II: Laurel Bed Dam, SW Virginia

Laurel Bed Dam, Virginia, USA (Figure 15a) is owned and operated by the Virginia Department of Game and Inland Fisheries (VDGIF). Seepage is visible at the end of the spillway flowing from drain pipes and cracks in the concrete. There are also wet areas on the dam's face and excessive discharge from the toe drain. Boreholes had identified porous weathered rock below the spillway as probable contributor to the seepage problem. After test grouting in front of the spillway failed to cut off the flow of water, Froehling and Robertson Inc., consulting engineers in charge of fixing seepage problems, decided to use groundwater mapping methodology to delineate seepage flowpaths through Laurel Bed Dam.

Three surveys were used at Laurel Bed Dam to investigate seepage flowpaths. Multiple survey configurations were used to target electric current through specific seeps or regions of the embankment to better delineate individual seepage flowpaths. For instance, survey 1 (Figure 15 right) was designed to investigate the seepage appearing at the bottom of the spillway; therefore, downstream electrodes for survey 1 were placed at the end of the spillway in contact with the seepage. Survey 2 targets electric current through the entire dam to perform a more general investigation of the seepage flowpaths, and electrodes were centered on the dam near the toe drains. Survey 3 targets electric current through a small seep in the right miter joint to better investigate its source and path through the dam. All three survey areas overlap to some degree which helps to correlate results between surveys. The upstream electrodes were placed in the reservoir.

As shown in Figure 15, an antenna wire (orange line) which completes the above-ground part of the electrical circuit is positioned in a large loop around the survey area to minimize the magnetic field generated by the wire. Magnetic field measurements were acquired on the dam's crest and downstream face, along the shore and from a boat on the reservoir. A tie line was used to stabilize the boat and guide crew members. The dam was surveyed by two people in six days. Survey work consists of laying the antenna wire, setting up the power supply and then measuring the magnetic field. After the fieldwork was complete, it took two weeks to complete the data reduction, modeling and interpretation. Each day, 552 measurements can be made. By using three electric current injections, we can compare the positions of electric current flowpaths between surveys. At this particular dam, a few main flowpaths show up in all three surveys. Water is seeping under the spillway in two places and approximately 10 ft below ground. This water then intersects the ground surface under the spillway and flows underneath the concrete downhill to the west, saturating fill material on the downstream face of the embankment. The excess water in the toe drain is more than likely from seeps under the spillway. There is also a seep that has formed in the core of

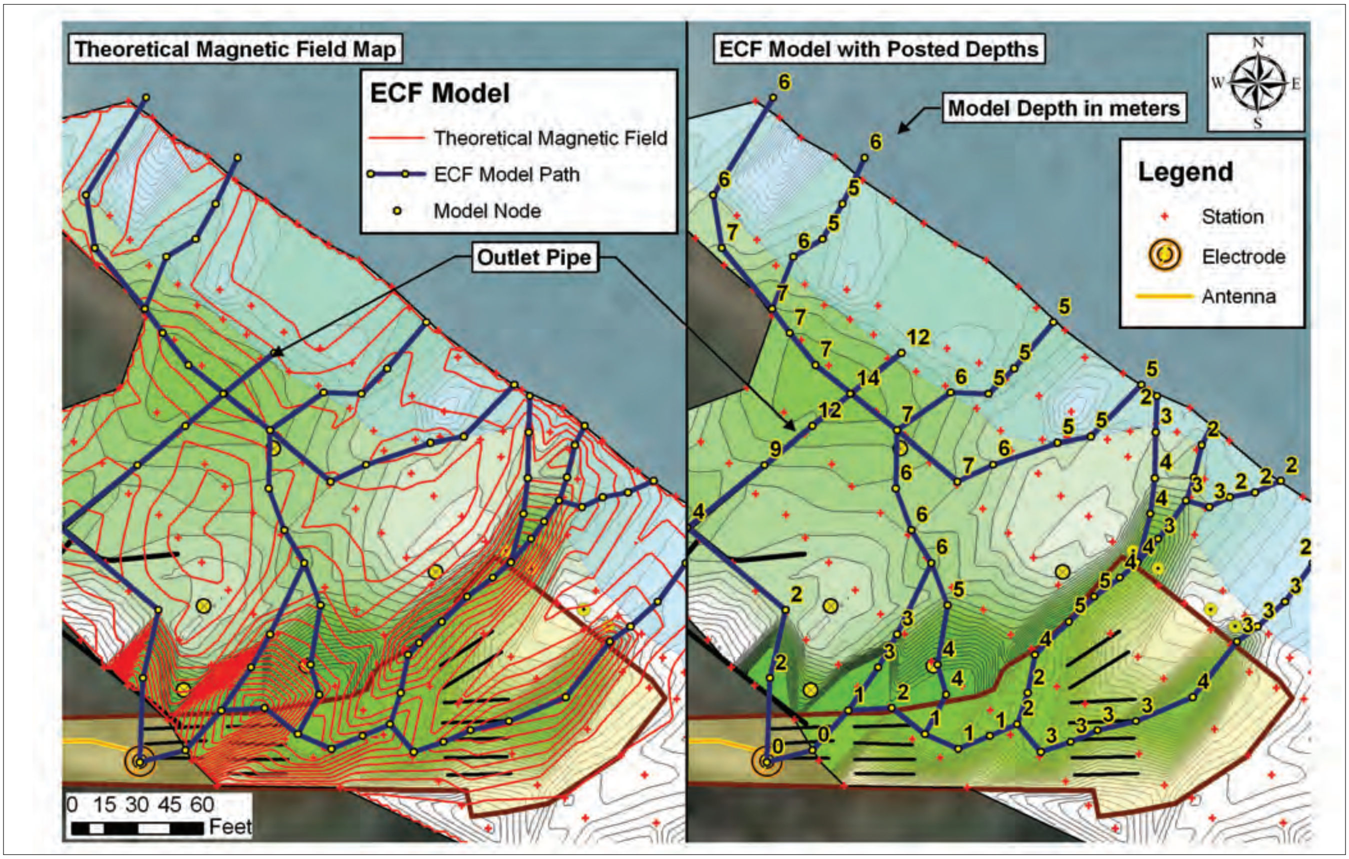


Figure 16. *(left) Comparison of Survey 1 ECF model, theoretical magnetic field with the measured magnetic field. (right) ECF model with posted depths indicates two shallow flow paths under spillway.*

the dam above and east of the central outlet pipe. Water passing through this seep path traverses across the dam to where it daylights near the right miter joint.

A horizontal magnetic field intensity map (Figure 16) visualizes the horizontal flow of electric current through the survey area. Electrical current flow (ECF) paths were identified from the magnetic field contour map. Electric current amperage was estimated for each identified ECF path, and the predicted magnetic field from the Biot-Savart Law is shown by red contour lines in Figure 16. The flowpath depth, position and width are adjusted by trial-and-error process until the predicted magnetic field matches that of the measured one. From Figure 16, we can see that the red contour lines match fairly well where the flowpaths pass under the upstream part of the spillway. Therefore this model is one possible solution for electric current flow under the spillway.

For survey 1, where the electric current is injected under the spillway, two fairly shallow flowpaths were identified from the magnetic field anomalies. These flowpaths are shallow because the anomaly is only 5–10 m wide. These flowpaths are estimated to be 1–2 m wide and 2.5–5 m deep. In Figure 16 right panel, the ECF depth is posted in meters below the ground surface. Other ECF flowpaths that branch off from the spillway show that the seeps from the spillway spread out and saturate the downstream fill of the dam and probably contribute most of the water collected in the toe drains.

Figure 17 shows the results of all three surveys. Similar ECF flow paths are highlighted by the yellow lines for surveys 1–3. Two flowpaths were indentified traversing under the spillway in surveys 1 and 2. Surveys 2 and 3 confirm that there is a minor seep in the embankment's right miter joint. In all surveys, high magnetic fields are observed above the central outlet pipe.

There are two seepage flowpaths under the spillway that were not intercepted by the test grout holes (yellow circles at the upstream edge of the spillway in Figure 17). Seepage from the spillway likely spreads out and flows to the east saturating the dam's downstream face. A lot of this water is collected in the toe drains. The depth of these flowpaths is well within the weathered rock zone indicating an area of weakness. Another small seep traverses across the dam from east to west appearing in the right crotch. Electric current flowed uniformly through the rest of the dam's right abutment, indicating no other obvious seepage problems.

With this information, Froehling and Robertson grouted the weathered rock under the spillway. The seepage flow rate was reduced from 500 gallons per minute (gpm) to 100 gpm. Some of the remaining water flow is attributed to springs. The entire project (grouting and characterization) came in under budget, saving the state of Virginia US$600,000. This project just recently won a Grand Award by the American Council of Engineering Companies of Virginia.

Conclusions

This paper describes an optimized implementation of the

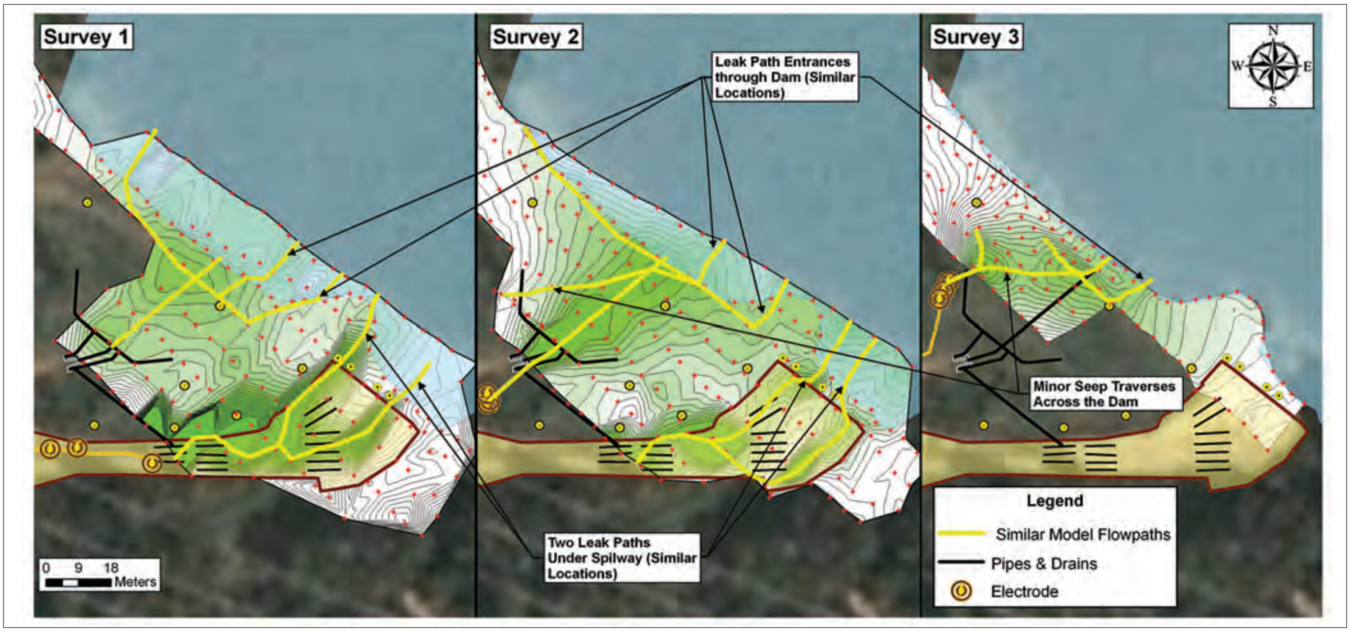


Figure 17. *The three surveys correlate rather well when compared side by side.*

MMR method to track preferential groundwater flowpaths. This method explores the low-resistivity region in the subsurface, and it is primarily sensitive to elongated resistivity contrast. Although other geophysical methods can be used to map the groundwater flow, we feel that our unique implementation of MMR provides the best data sensitivity and logistic advantages, where measurements can be made on a boat. These advantages are achieved by measuring the magnetic field at 380 Hz and placing the electric current injection in strategic locations. We have established qualitative data interpretation procedures that would identify major features in the data and delineate such features in a short period of time. The quantitative data interpretation schemes that we are developing will enable us to map the complicated electric current flow that produces various textures of the signature magnetic field. As is well understood, the MMR method is the best in mapping electric current channeling at depth or underneath a moderately conductive cover.

Similar to any geophysical methods in groundwater applications, our method should not be viewed as a means of providing absolute answers with calculated margins of error, risk or vulnerability classifications. Like any geophysical investigation in groundwater applications, our results can be used to make informative decisions concerning how to further confirm, monitor and possibly remediate groundwater problems. As always, our results should be integrated with other information to fully characterize a site. TLE

References

Chen, J., E. Haber, and D. W. Oldenburg, 2002, Three-dimensional numerical modeling and inversion of magnetometric resistivity data: Geophysical Journal International, **149**, no. 3, 679–697, doi:10.1046/j.1365–246X.2002.01688.x.

Constable, S. C., R. L. Parker, and C. G. Constable, 1987, Occam's inversion—A practical algorithm for generating smooth models from electromagnetic sounding data: Geophysics, **52**, no. 3, 289–300, doi:10.1190/1.1442303.

deGroot-Hedlin, C. and S. Constable, 1990, Occam's inversion to generate smooth two-dimensional models from magnetotelluric data: Geophysics, **55**, no. 12, 1613–1624, doi:10.1190/1.1442813.

Edwards, R. N. and M. N. Nabighian, 1991, The magnetometric resistivity method, in M.N. Nabighian, ed., Electromagnetic methods in applied geophysics; Investigations in Geophysics, Volume 2: SEG, 47–104.

Froehling and Robertson Inc, 2009, FandR Wins ACEC-VA Grand Award for Laurel Bed Dam Project, http://www.fandr.com/newsroom_Content.asp

Jakosky, J. J., Exploration geophysics (second edition), 1950: Times-Mirror Press.

Key, K., 2009, 1D inversion of multicomponent, multifrequency marine CSEM data: Methodology and synthetic studies for resolving thin resistive layers: Geophysics, **74**, no. 2, F9–F20, doi:10.1190/1.3058434.

Kofoed, V. O., K. D. Gardiner, and A. A. George, 2008, Locating the leakage route at Torside Reservoir using the Willowstick AquaTrack system: Proceedings of the 15th Conference of the British Dam Society, 1–12.

Oppliger, G. L., 1984, Three-dimensional terrain corrections for mise-a-la-masse and magnetometric resistivity surveys: Geophysics, **49**, no. 10, 1718–1729, doi:10.1190/1.1441579.

Williams, B. C., J. A. Riley, J. R. Montgomery, and J. A. Robinson, 1996, Hydrologic and geophysical studies at Midnite Mine, Wellpinit, WA: Summary of 1995 Field Season: U.S. Bureau of Mines Publication RI–9607, available at http://www.ntis.gov/

Acknowledgments: The authors acknowledge Willowstick Technologies field crew for all their hard work on these two projects. We are grateful to United Utilities, Froehling and Robertson Inc., Andy Hughes, and Atkins Global for their willingness to collaborate and provide information that generated successful projects.

Corresponding author: mwallace@willowstick.com