AIRBORNE SURVEYS IDENTIFY ENVIRONMENTAL PROBLEMS ON MINED LANDS

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Since 1999, the National Energy Technology Laboratory (NETL) has conducted almost 50 airborne surveys of mining areas or oil and gas producing areas in the United States. The intent of the surveys is to provide a rapid, comprehensive assessment of the hydrology at these sites and to identify environmental problems that may exist. The surveys utilize sensing technologies that were originally developed for other purposes but have been modified to provide useful hydrologic and environmental information pertinent to lands used for the production of fossil fuels. Airborne surveys were found to provide information more quickly and less expensively than equivalent ground investigations. In certain cases, airborne surveys can provide hydrologic information that is not available from any other source. Three case studies are discussed below that illustrate the usefulness of the airborne approach.

Case Studies

Kettle Creek Watershed, Pennsylvania
Kettle Creek is a mountain stream in the north-central part of Pennsylvania that flows through a rugged, forested gorge. Although few residents still living in the area are old enough to remember the coal mines that were once here, past mining is evident in the unreclaimed surface mines and miles of streams made lifeless by acid mine drainage. Making an inventory of mining-related environmental problems in the 35 square mile Kettle Creek Watershed was a daunting challenge given the size, ruggedness, vegetation, and limited access of the area. What was needed was a rapid means of reconnoitering the entire watershed to locate problem areas so that thorough investigations could be concentrated on small areas of particular concern. This need was met by two remote sensing surveys that can be carried out by low-flying aircraft.

Airborne Thermal Infrared Imagery
A thermal infrared scanner on a small twin engine airplane was used to identify water discharged from underground mines. This technology, which senses small differences in temperature, makes use of the temperature difference between groundwater and surface water to identify areas where groundwater is emerging at the surface. Groundwater, including mine water, is significantly warmer than surface water during the winter or early spring, a leaf-off time of year that is optimal for thermal infrared surveys. These surveys are flown in the early morning hours, just prior to sunrise to minimize the effect of solar heating. Thermal infrared images clearly show locations where warm groundwater emerges at the surface (Fig. 1) but cannot distinguish mine discharges from

other types of groundwater. This distinction is based on water chemistry, a determination that is best made by ground observations at the discharge site. The thermal infrared survey of Kettle Creek Watershed identified 103 groundwater discharges of which 53 were mine discharges. What is significant is that 27 of the 53 mine discharges were previously unknown. On the other hand, seven previously known mine discharges were not identified by thermal imagery because non-deciduous vegetation (conifers, rhododendron etc.) shielded the mine discharges from the airborne sensors. The value of thermal infrared imagery is that it can quickly direct ground personnel to groundwater discharges where water quality can be rapidly assessed. However, it should not be applied to areas with significant amounts of non-deciduous vegetation.

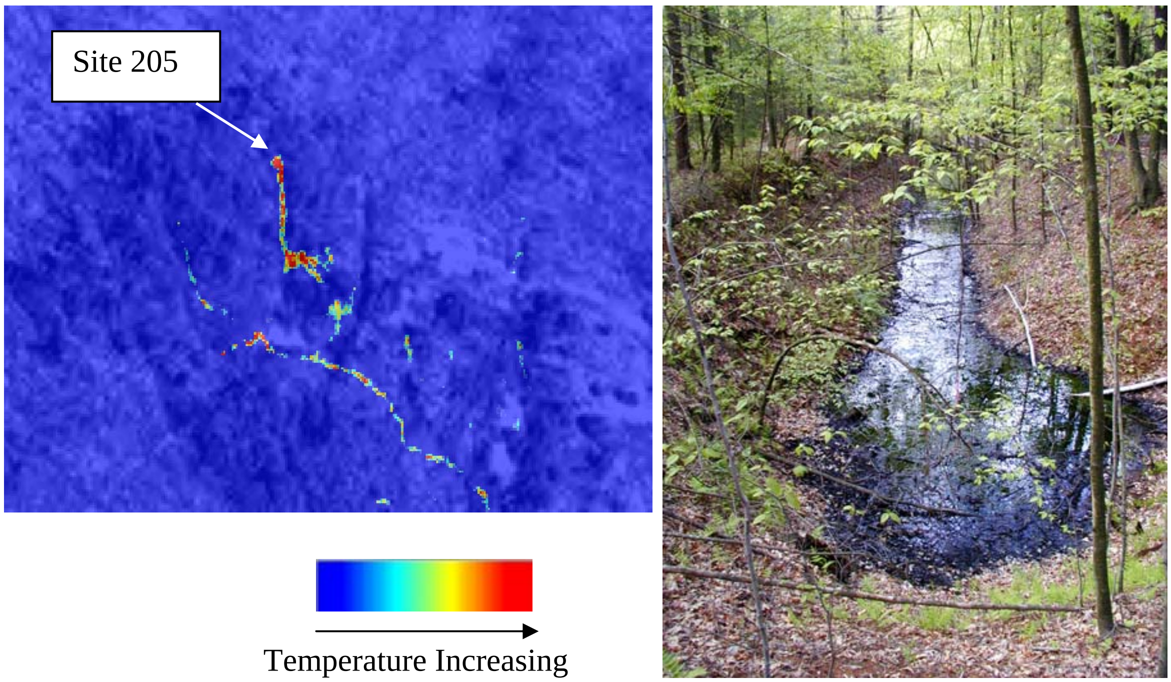

Figure 1 Color-enhanced TIR image showing location of mine discharge (left). Photograph of same mine discharge taken during ground investigation (right)

Helicopter Electromagnetic Surveys
Three months after the thermal infrared survey, residents of the Kettle Creek area witnessed a low-flying helicopter towing a cigar-shaped object or “bird” slowly back and forth across the Kettle Creek Watershed. The pilot was obviously keeping the bird about 100 ft above the ground and had to go up and down often in response to the rugged landscape. The helicopter was conducting an electromagnetic survey that provided information about the location and quality of groundwater. Helicopter electromagnetic (HEM) surveys (Fig. 2) are used to: 1) detect and map pools of acidic water impounded in underground mines where the cover is less than 150 ft, 2) locate concentrations of acid-generating material in surface mine spoil, 3) locate groundwater infiltration zones, and 4) locate potential areas for seeps and springs.

Data collected from the HEM survey is used to construct conductivity/depth images (CDI) that show the vertical distribution of conductivity from the ground surface to depths of about 300 ft. In Figure 3, the water table is depicted as a green-yellow-red band that parallels the topography. Acidic mine pools are denoted by red areas. In areas of Kettle Creek Watershed where mine maps are available, the mine pools interpreted from CDIs are always located within underground mines. Underground coal mining within the Kettle Creek Watershed was up-dip so that water would freely drain from the mines. Since mining ceased almost a century ago, roof falls have blocked entries and impounded acidic water in parts of these mines. Acidic mine pools are the suspected sources of mine discharges. Accurately knowing the location of mine pools is important

Figure 2 Helicopter electromagnetic survey of coalbed methane field in the Powder River Basin in Wyoming

if in-mine alkaline addition is being considered as a potential water treatment. HEM can locate pools of water in underground mines if: 1) the water is conductive (acid mine drainage is conductive), 2) the overburden is resistive (predominantly sandstone, siltstone, or limestone), and 3) the overburden is not more than 150-ft thick.

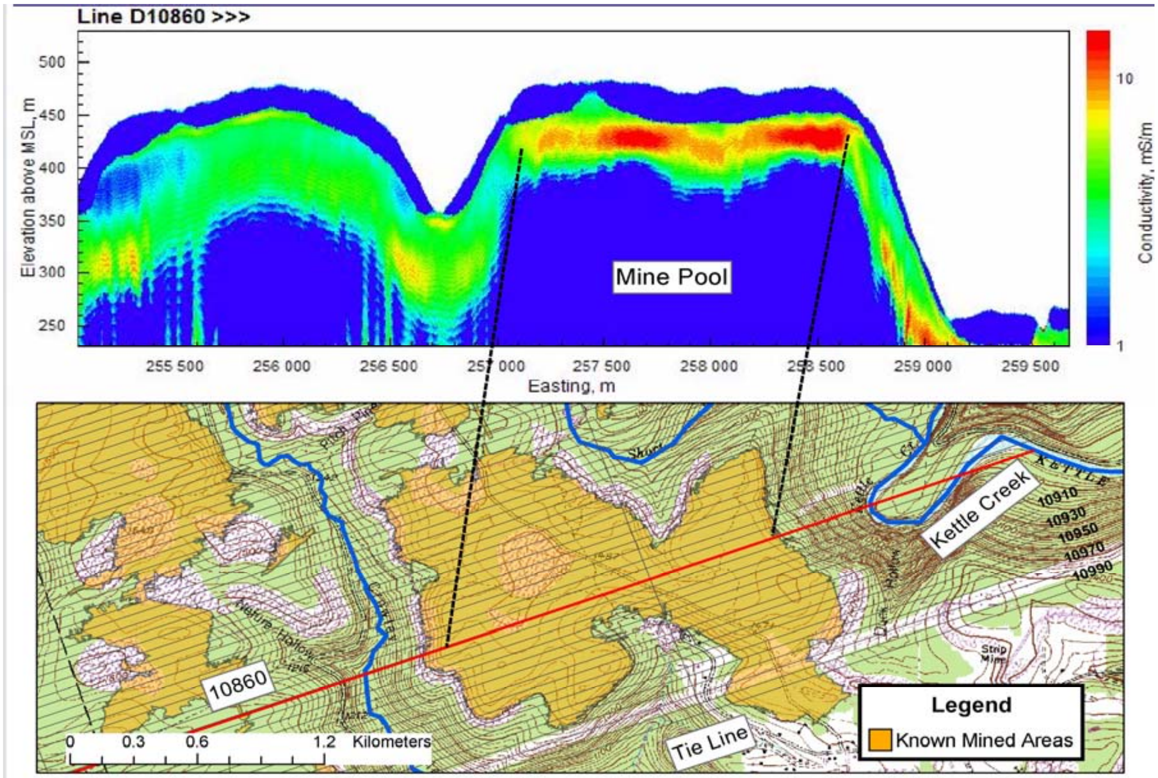

Figure 3 Conductivity/depth image (top) showing the location of underground mine pools (red areas) and the relationship of mine pools to known mined areas (bottom map).

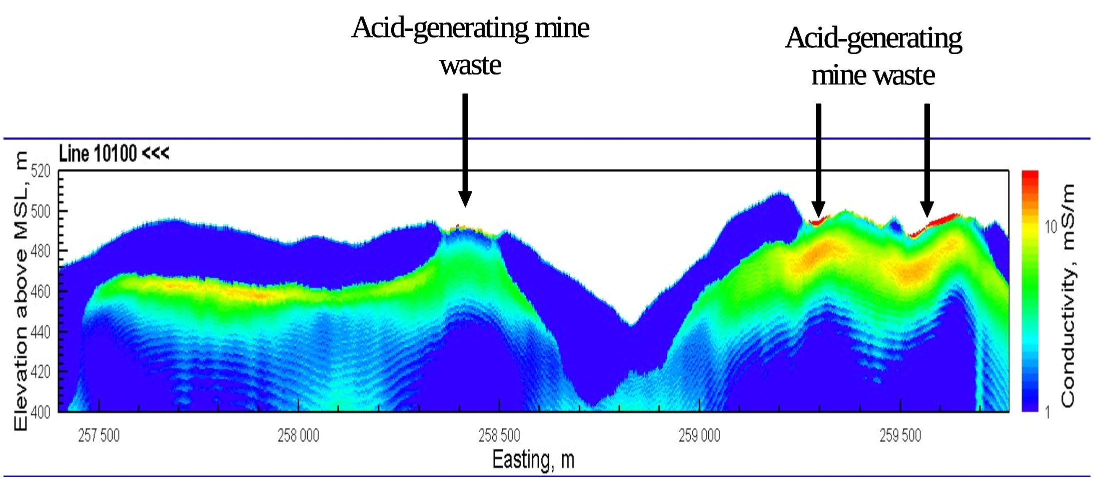

Figure 4 Conductivity/depth image showing location of acid-generating spoil material on surface mined lands.

Water infiltrating through surface mines is made conductive by the contact with weathering spoil material (Fig. 4). After contacting surface mine spoils, the infiltrating water can be seen in CDIs as a slightly conductive zone extending from the surface down to the water table (Fig. 5). Thin, red layers at or near the surface (Fig. 4) denote the location of acid-generating spoil (pyrite-rich spoil) or acid groundwater in a nonreclaimed surface mine. Accurately knowing the location of groundwater infiltration zones and acid generating spoil can focus reclamation efforts on small areas, thereby reducing cost.

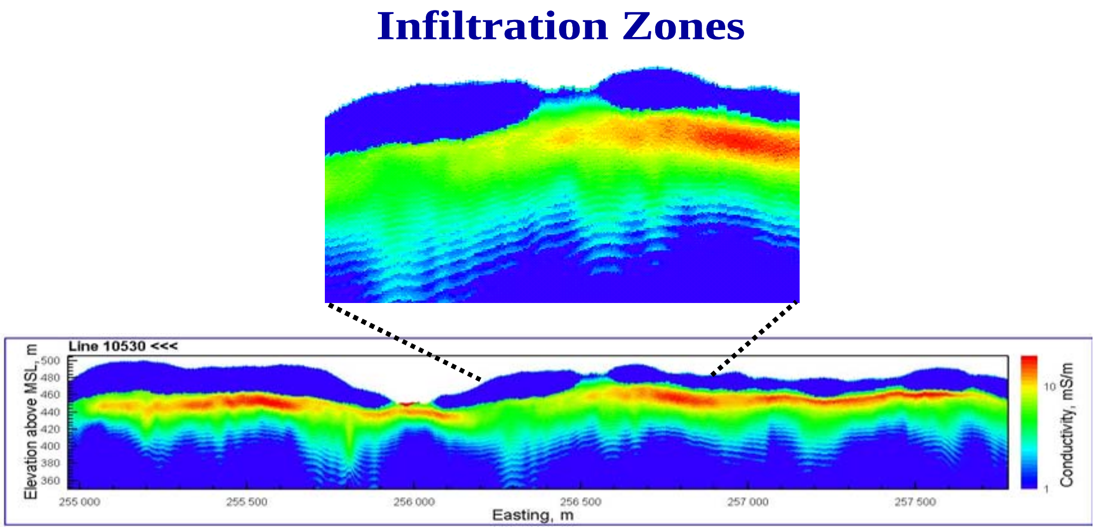

Figure 5 Water infiltration zones below surface mines are denoted by areas where the conductive water table is near the surface.

In CDIs, the likely locations for springs, seeps, and wetlands are denoted by areas where the water table is at or near the ground surface (Fig.6). This property of CDIs is useful for predicting mine discharges in areas of non-deciduous vegetation, where thermal infrared imagery is ineffective. In figure 6, conductive water from an underground mine is flowing down gradient along the water table until it emerges as an acidic seep down slope. In this case, there is no discharge at the elevation of the mine and the seep is well below the mine. Without the CDI, it would not be evident that the acidic water in the seep is from the underground mine.

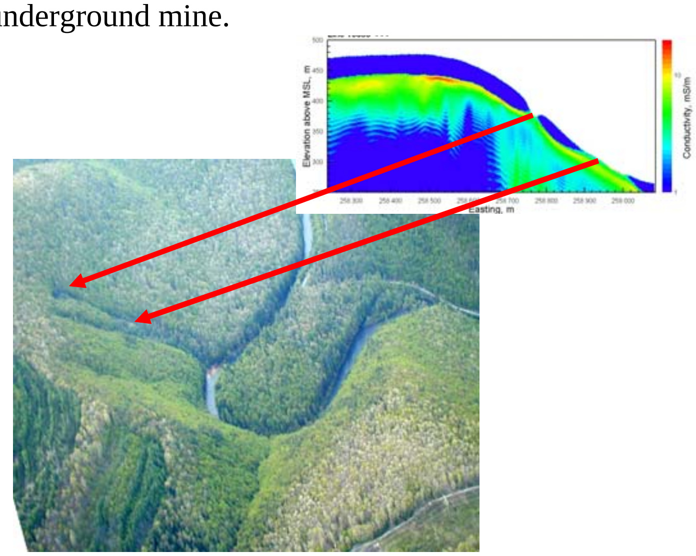

Figure 6 Slope areas where the water table is at the surface are likely locations for seeps and springs.

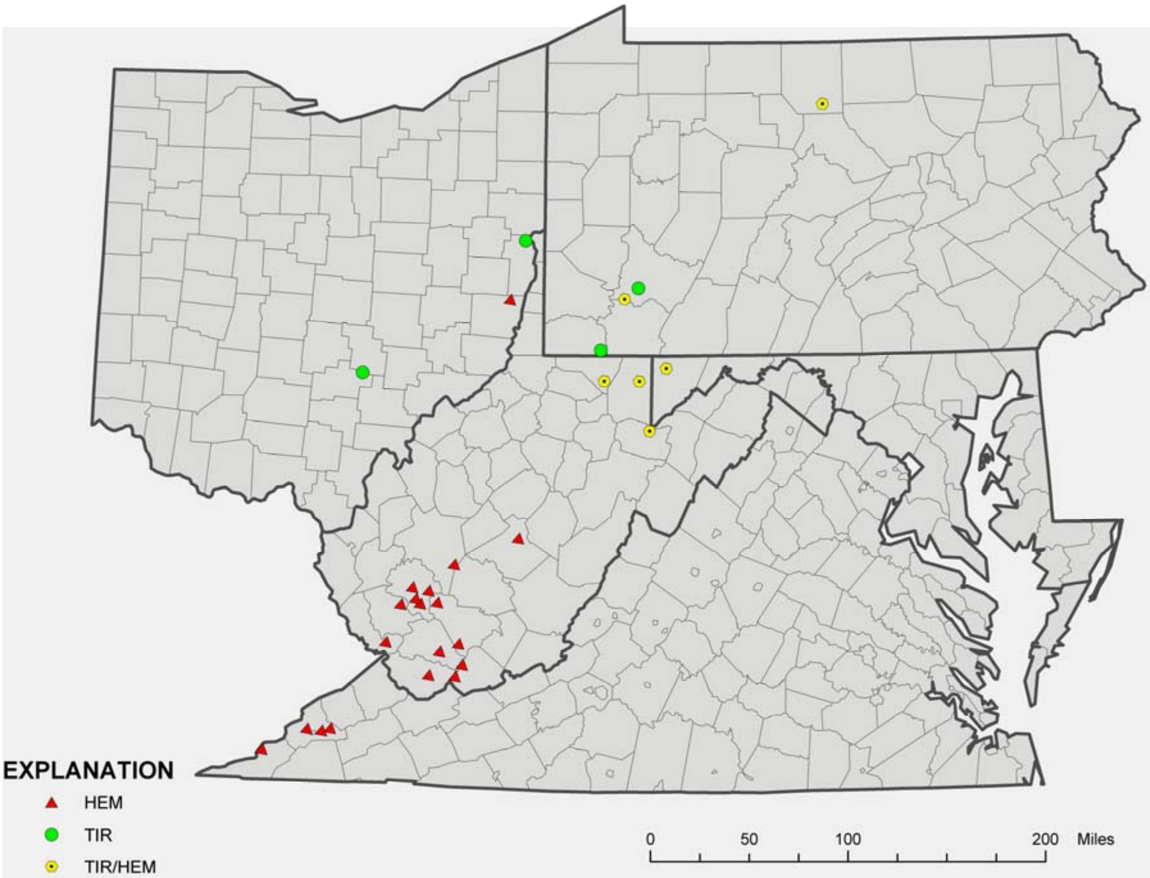

Figure 7 Map showing NETL airborne surveys in the coal mining regions of the eastern United States.

Sulphur Bank Mercury Mine Superfund Site, California

The Sulphur Bank Mercury Mine (SBMM) Superfund Site is located on the eastern shore of Clear Lake, about 80 miles north of San Francisco. Initially sulfur and later mercury were mined intermittently from this site for almost a century. Mining ceased about 1960 and today, the now flooded open pit is the most notable visual remnant of past mining. In 1986, the State of California posted a fish consumption advisory for fish taken from Clear Lake because of mercury contamination. Because of its proximity to Clear Lake, SBMM was suspected to be the source of most of the mercury contamination. In 1993, SBMM became an EPA Superfund Site and after some remedial actions were made to fix obvious problems, a comprehensive characterization of the site began. As part of the characterization plan, a dense network of monitoring wells was established at the site to determine the hydrology and chemistry of groundwater.

A 600 ft segment of land separates the acidic, metal-containing waters of the flooded open pit from Clear Lake (fig. 8). Called the Waste Rock Dam, this area of land is, in reality, a dump area for waste rock excavated from the open pit. It was never intended to be a dam. The water level in the flooded open pit is approximately 13 ft higher than the level of Clear Lake, which creates a hydrologic gradient for groundwater flow through the coarse, broken rock that comprises most of the “dam”. Acidic water flowing from the open pit through the Mine Waste Dam is thought to be the predominant source of

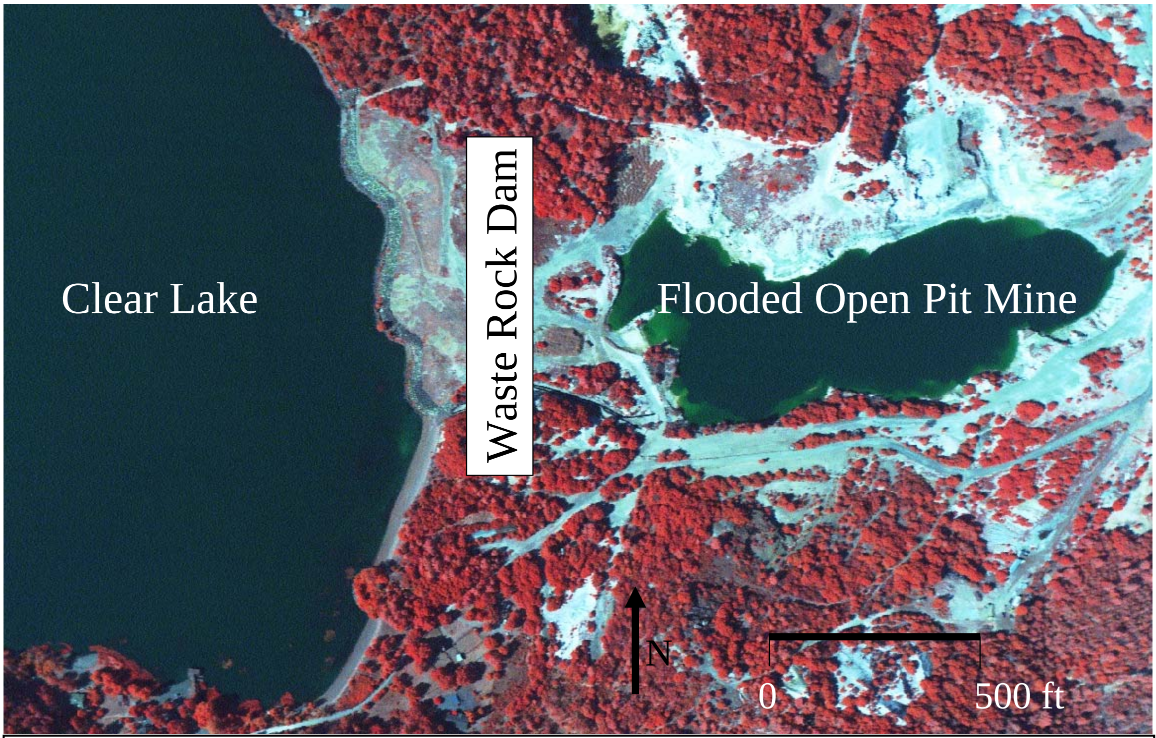

Figure 8 False color infrared air photo of Sulphur Bank Mercury Mine showing open pit and Waste Rock Dam.

mercury entering Clear Lake. The US EPA seeks to prevent additional mercury contamination of Clear Lake by decreasing the groundwater flow through the Waste Rock Dam. For this, an accurate knowledge of groundwater flow paths through the Waste Rock Dam is needed and the information available from the existing network of groundwater monitoring wells was inadequate. Therefore, NETL was asked to conduct an HEM survey over the SBMM Superfund Site with funding provided by EPA's Mine Waste Technology Initiative.

Figure 9 is a HEM conductivity map that shows the most likely flow path taken by conductive water flowing between the flooded open pit and Clear Lake. This information will help EPA formulate a strategy to prevent the flow of mercury containing groundwater into Clear Lake. Figure 10 is a conductivity/depth image from a flight line across the Sulphur Bank Mercury Mine which shows the location of three groundwater monitoring wells that lie along this flight line. The perforated intervals from the monitoring wells coincide in elevation and thickness with the location of conductive zones in the CDI. Our results show that water bearing zones (perforated zones) exactly coincide with the location of conductors in CDIs about 66% of the time. Further improvements in the accuracy of CDIs may allow HEM surveys to be substituted sometimes for traditional hydrologic assessments that use monitoring wells.

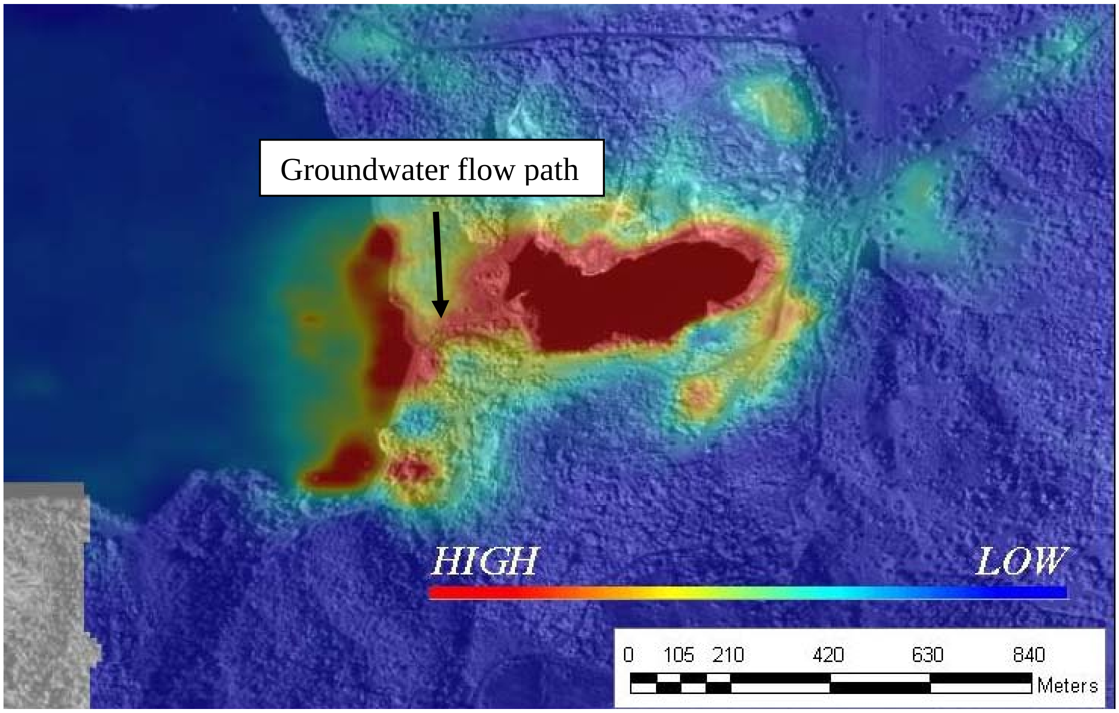

Figure 9 HEM conductivity map (52 kHz) of Sulphur Bank Mercury Mine showing likely flow path taken by conductive groundwater through the Waste Rock Dam.

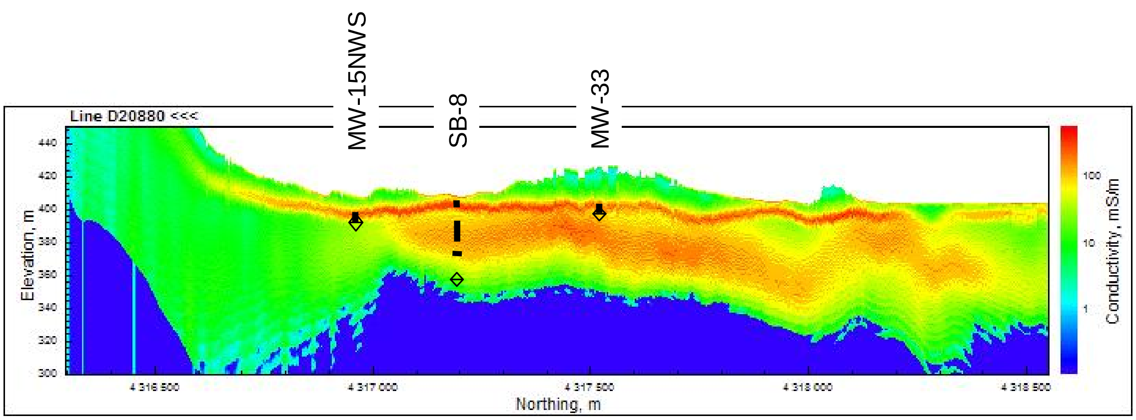

Figure 10 Conductivity/depth image fromSulphur Bank Mercury Mine showing the relationship between conductors (interpreted to be aquifers) and the perforated intervals in groundwater monitoring wells. Black vertical lines indicate perforated interval; horizontal line through diamond indicates bottom of well.

Powder River Basin, Wyoming and Montana
This region of the U.S. has seen a boom in drilling for coalbed methane (CBM), the natural gas contained in coal seams. Historically, the Appalachian areas of West Virginia, Virginia, Kentucky, and Tennessee, along with the Black Warrior basin of Alabama and Mississippi were the major producers. Today, the Powder River basin (PRB) of northeastern Wyoming and southeastern Montana (Figure 1) has attracted the most interest of the CBM developers. Currently, there are over 25,000 CBM wells drilled in the PRB in Wyoming. Western coalbeds with softer bituminous coals contain a wealth of coalbed natural gas, but produce large quantities of water during the extraction process. Typically produced from coal seam reservoirs at shallow depths, the natural gas is released by pumping groundwater to the surface to reduce the hydrostatic pressure in the coalbeds.

Ranchers, conservationists, industry, and state and local governments are all concerned with the fate of the water extracted when the methane is produced. The quality of produced water from CBM wells in the Powder River Basin is quite variable. The average total dissolved solids (TDS) concentration is 850 mg/L, with a range of 370 to 2000 mg/L.

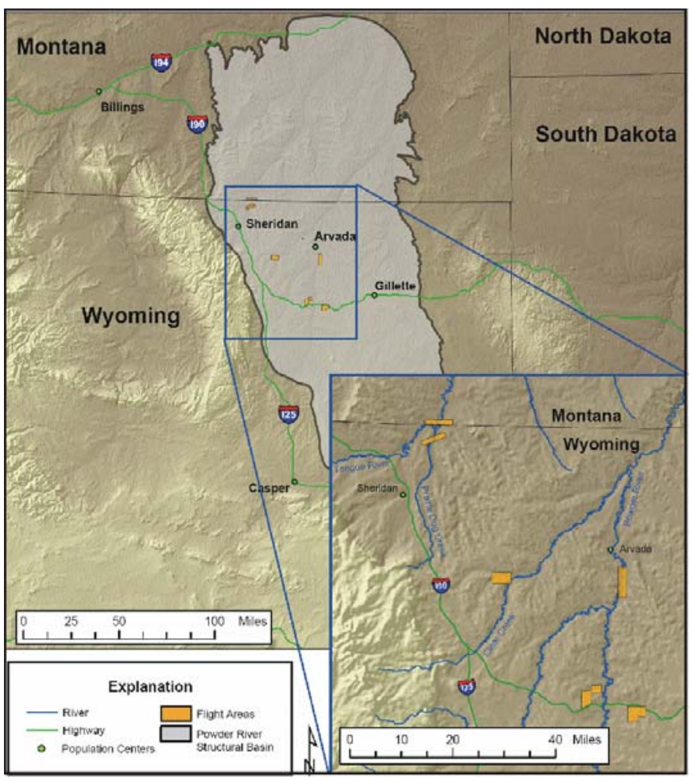

Figure 3. Location of Coalbed methane development and study areas in the Powder River Basin of Wyoming and Montana.

Helicopter Electromagnetic Surveys

Helicopter electromagnetic (HEM) surveys were performed over seven areas in the Powder River Basin of Wyoming and Montana on June 19-29, 2003. The intent of this survey was to evaluate HEM for the large-scale mapping of near-surface aquifers and produced water plumes. The HEM surveys of the Northern Wyoming Site, Powder River Site, and the Tongue River Site provided new insight into the groundwater hydrology of these areas. Examples that demonstrate the utility of the HEM surveys from these study areas are described below.

Infiltration Impoundment- The purpose of an infiltration impoundment is to store produced water until it can infiltrate into underlying shallow aquifers through an intentionally permeable base. An airborne conductivity map of an infiltration impoundment on the floodplain of the Powder River is shown in figure 2. Water seeping from the impoundment appears to dilute or displace the more conductive native groundwater in the alluvial aquifer north of the impoundment.

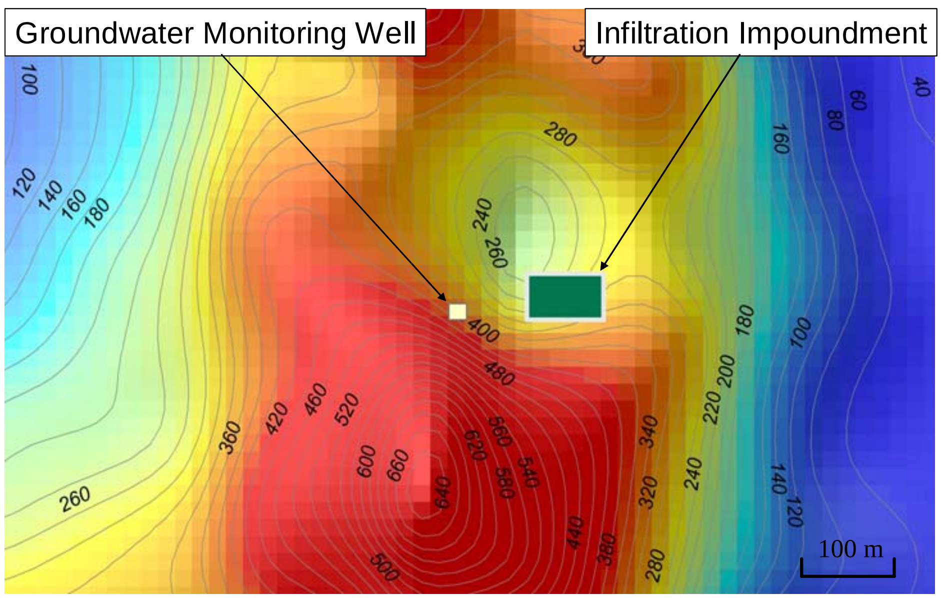

Figure 2 Airborne conductivity map showing a dilution anomaly caused by the infiltration of produced water

Alluvial Aquifer Systems - The flood plain (soils and alluvial aquifer) of the Powder River are more conductive than terrace and upland areas (figure 3). The groundwater of the Powder River alluvial aquifer is of fair to poor quality due to high concentrations of dissolved solids.

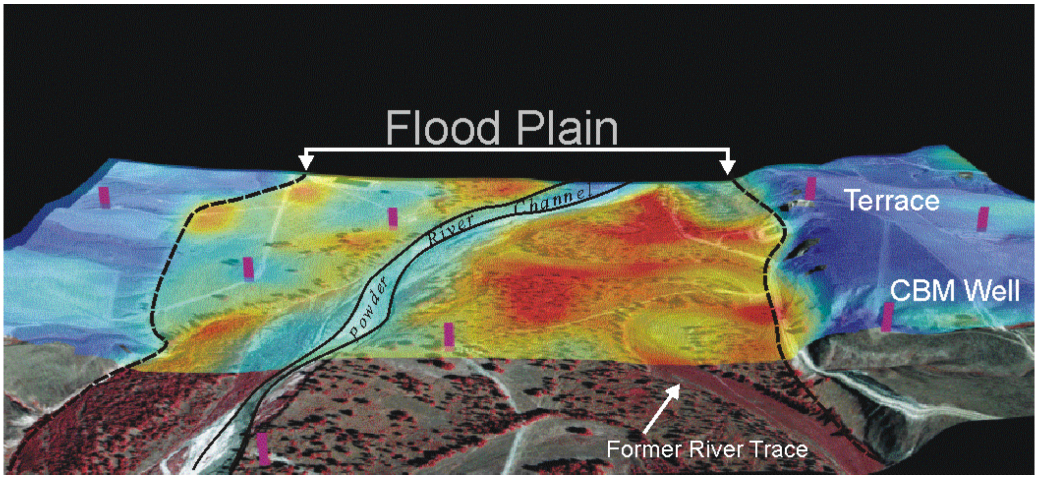

Figure 3. View of Powder River Flood Plain showing results of airborne conductivity survey.

In contrast, airborne conductivity data collected along the Tongue River (Figure 4) shows the floodplain and alluvial aquifer system to be less conductive than upland areas. This airborne technique provides opportunities for improved management of CBM water through mapping of the shallow groundwater system.

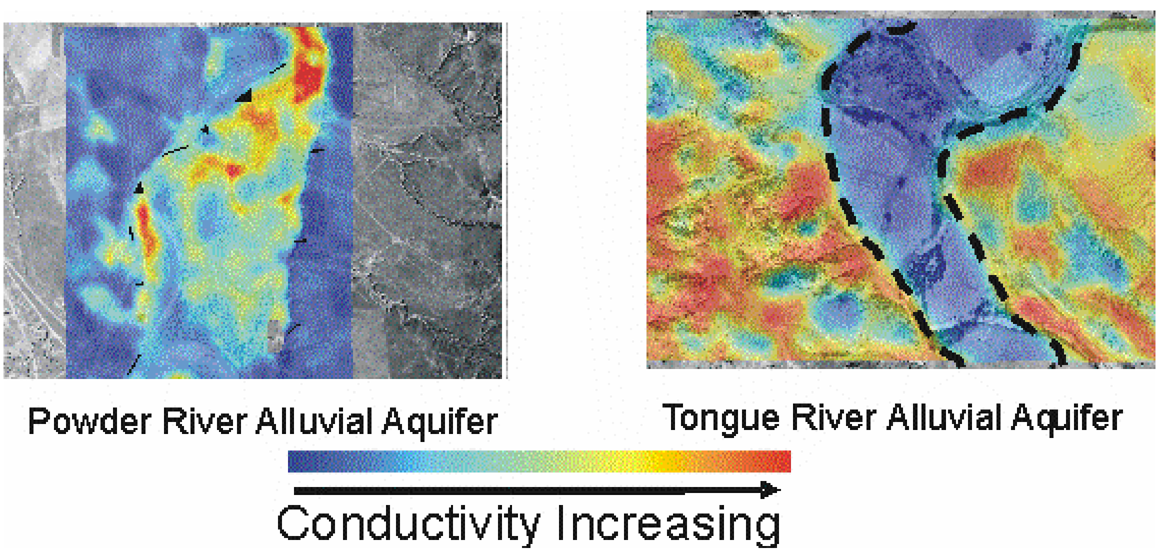

Figure 4. Comparison of airborne conductivity survey for the Powder River and Tongue River Flood Plains.

Detection of Impoundment Leaks- The purpose of a containment basin is to store produced water for irrigation. Containment basins generally have an impermeable liner that prevents the infiltration of produced water into underlying strata. Figure 5 is an airborne conductivity map of a containment basin and surrounding area. This containment basin was built with a clay liner that failed, allowing produced water to reach permeable strata (coal and sandstone) where it traveled laterally through the southwest wall and formed a line of down-slope seeps. Water conductivity at the seep was four times the conductivity of the impoundment water. This implies that the leaking impoundment water is either dissolving salts from the strata through which it is traveling or it is displacing the more conductive native groundwater from this strata.

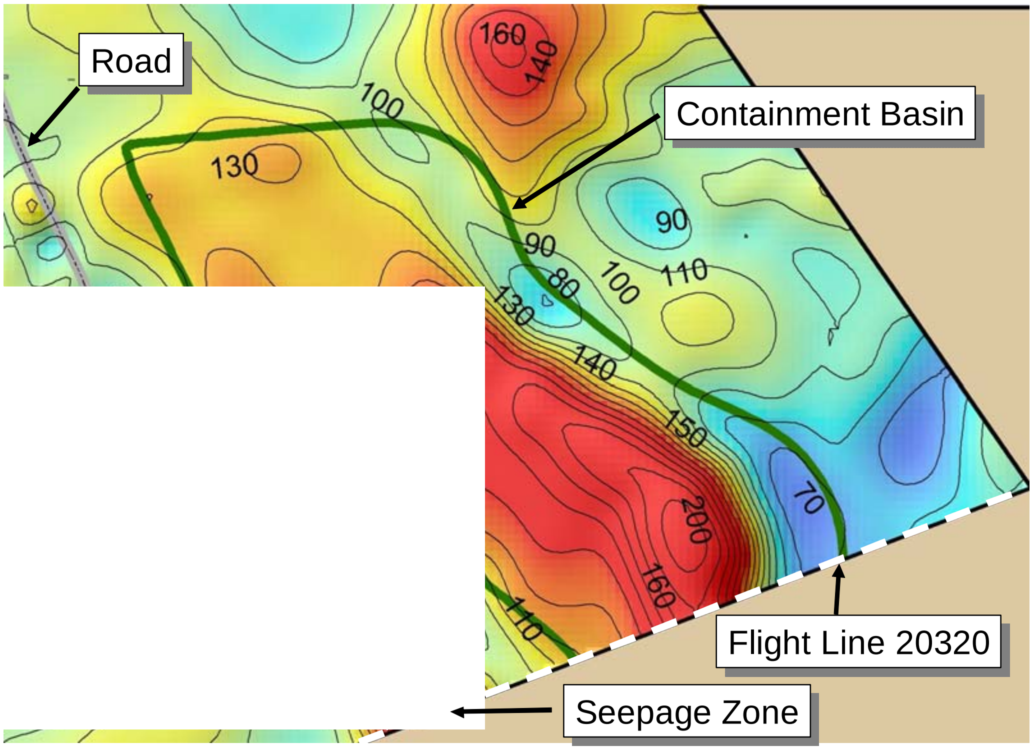

Figure 5. Airborne conductivity map of a leaking containment basin showing down-slope seeps.

Conclusions

Airborne reconnaissance can screen large watersheds quickly and delimit areas of concern for remediation or additional investigation. The airborne TIR survey and follow-up ground investigation at Kettle Creek Watershed were completed in less than two weeks. This airborne/ground survey identified 27 mine discharges that had been missed by a conventional ground survey that was conducted intermittently over a 5-year period.

Although airborne surveys seem expensive, costing as much as $2500/square mile for TIR (including the cost of data acquisition and processing), the cost of a ground investigation would be much higher, when one considers manpower cost and the time that would be required to survey large areas of rugged terrain on foot. An HEM survey costs about $5000/square mile, which is inexpensive when compared to the cost of a drilling a dense network of groundwater monitoring wells, the only other source of hydrologic information.

Airborne data and interpretations always need to be validated with limited ground investigations. The locations of groundwater discharges identified in TIR surveys must be field checked to determine whether the water is mine drainage or an unpolluted spring or wetland. Likewise, the processing of HEM data can provide multiple "correct" interpretations (from a geophysical perspective) whereas only one interpretation is correct geologically. Induction logs from drill holes located on HEM flight lines are needed to calibrate data processing and confirm that the resulting CDIs represent actual geologic or hydrologic conditions at the site. The time and cost of these "ground-truthing" activities must be included in the schedule and budget of airborne surveys.

Certain conditions at potential TIR or HEM survey sites can degrade data or make it unusable. The shielding effect of non-deciduous vegetation on TIR imagery has already been mentioned. HEM data is seriously degraded by electrical power lines. When possible, power lines should be avoided or turned off during HEM surveys. Currently, there is no satisfactory way to correct HEM data for power line interference.

NETL Surveys and Data Availability

Results from some of the TIR and HEM surveys flown by NETL are available online at www.netl.doe.gov/ and more areas are being added daily. For additional information pertaining to airborne NETL surveys contact Richard Hammack at (412) 386-6585 (email: hammack@netl.doe.gov).