An Evaluation of Remote-Sensing Technologies for Watershed Assessment

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Abstract – A survey to locate all potential pollution sources in a watershed can be overwhelming in terms of the commitment of capital, equipment, and manpower. For this reason, alternative methods were sought that could lessen the time and cost of these initial watershed surveys. In this paper, airborne thermal infrared (TIR) imaging and geophysical techniques, such as electromagnetic conductivity and very low frequency conductivity, were evaluated as tools for identifying groundwater flow paths and surface discharge locations. These methods offer the advantage of being able to quickly survey large areas with a minimum commitment of manpower and capital. Airborne surveys also minimize the land access problems that slow land-based surveys. To test the utility of these techniques, surveys were conducted over well-characterized mines with known groundwater discharge sites. A geographic information system (GIS) was used for geo-referencing and correlating remote sensing data with existing GIS data sets that pertain to coal resources and coal mining in the surveyed areas. The GIS was used to overlay data such as mined-out areas, crop lines, and mine workings over data layers for the TIR imagery and geophysical data. The results of these tests indicated that TIR imaging was very effective for identifying sites where groundwater was discharged to the surface. TIR imaging could not determine groundwater quality or if the water was from a mine or a natural seep; however, it accurately mapped large numbers of locations that could be used by watershed stewards to efficiently pursue ground-based characterization work. Multiple-frequency electromagnetic conductivity provided the most useful information on the location of mine pools and lateral groundwater flow paths. Very low frequency conductivity was effective for the detection of vertical, water-filled fractures, which could be indicative of potential groundwater recharge zones and vertical flow paths.

Key Words—thermal infrared imaging, electromagnetic conductivity, very low frequency conductivity, coal mines, acid mine drainage, geophysics, water quality

INTRODUCTION

Watershed Scale

Conducting a holistic watershed assessment is an overwhelming challenge due to the large scale of the problem and limited resources. The assessment or characterization of an entire watershed by foot is usually not feasible because of the lack of labor, land accessibility and/or lack of organization and direction.

Holistic Approach

The National Energy Technology Laboratory (NETL) is presently pioneering the development of remote or airborne sensing technologies as new tools for the holistic assessment of watersheds. The advantage of this aerial approach is that large land areas can be surveyed using various technologies in a matter of days or weeks, whereas assessing the same large areas by foot may take years or decades. The full value of the various remote-sensing technologies is not realized until these data are coupled with geographic information systems (GIS) and global positioning system (GPS) technologies. When various overlays (topographical maps, aerial photos, maps of underground mine workings, and geological maps) are combined with remote-sensing data, a holistic view of a watershed can be realized.

Watershed stewards, such as government agencies, industry, or watershed coalitions, can then make informed decisions, establishing priorities and providing specific direction to field people. Thus field characterization is more efficient in terms of time and cost because of the increased accuracy of mapped pollution targets. Moreover, a preliminary assessment of a watershed can be completed prior to fieldwork to establish the presence or absence of potential water pollution sources (coal mines, sewage). This will make it easier to accurately identify and characterize the most common pollution types, and will permit the strategic implementation of remedial measures that will maximize cleanup with a minimum expenditure of funds. In cases where pragmatic remedial measures are not available, the identification of the most significant pollution problems could direct ongoing research and result in the greatest positive impact for the watershed.

Remote Sensing Applications

The four remote sensing technologies that NETL is currently evaluating include thermal infrared (TIR) imagery and two geophysical techniques, electromagnetic (EM) conductivity and very low frequency (VLF) conductivity. NETL was the first government agency to utilize TIR imagery as an environmental tool for a holistic watershed assessment. In addition, NETL was the first government agency to apply a selected combination of airborne sensors (TIR, EM and VLF) as an attempt to accurately identify groundwater recharge and discharge locations, and potential groundwater flow paths.

The initial TIR work was completed in early 1999 using a helicopter platform to survey: (1) the 167 square-mile Sewickley Creek watershed, (2) 90 miles of the Youghiogheny River (from Connellsville to McKeesport, PA), (3) 100 miles of the Monongahela River (from McKeesport, PA to the West Virginia state line), and (4) three, 5-mile segments (starting at each stream's confluence with the Monongahela River) of Dunkard Creek, Buffalo Creek and the West Fork River. Subsequent remote sensing work occurred in late 1999, and included the application of airborne TIR, EM, VLF. The survey areas included: the Roaring and Muddy Creek watersheds in Northern West Virginia (within the headwaters of the Cheat River basin), the Omega Mine site located near Morgantown, WV, the T&T Mine site located near Albright, WV, the Kempton Mine complex which underlies the WV and MD state line, and the Winding Ridge Mine site located near Friendsville, MD. The locations for these surveyed areas are shown in Figure 1.

Because of the extended time needed for post-flight processing, only a limited amount of the WV geophysical data has been received at the time this paper is being written. Consequently, the focus of this report will be on the successful TIR data collected in southwestern PA and a limited amount of airborne geophysical data related to the Omega Mine, with the understanding that additional evaluations are necessary and forthcoming. The TIR data, unlike the geophysical data, does not require ground-intrusive measures to confirm observations. Ground-truthing the geophysical data will require more time and cooperation from the public and private sectors. The compilation of results from a limited drilling campaign with existing data (e.g., monitoring well data, mine maps, hydrological data) in a GIS database will be needed to confirm geophysical observations.

REMOTE SENSING TECHNOLOGIES

Thermal Infrared Imaging

Airborne TIR sensing was evaluated for its ability to locate areas where mine drainage or groundwater is surfacing via natural fracture zones (seeps) or man-made features (boreholes and mine shafts). The general concept is that the temperature of groundwater (including water from polluted underground mine pools) is typically warmer than the temperature of surface water particularly in the late fall and winter months. The U.S. Department of Energy's Remote Sensing Laboratory, located in Las Vegas, NV, performed the predawn airborne surveys during winter when vegetation was down. Infrared data was collected with a Daedalus AADS1268 multispectral scanner using a dual thermal infrared detector configuration. The data from these two detectors were radiometrically calibrated and converted to apparent temperature. Data was collected from an altitude of 1,300 feet and had spatial and temperature resolutions of 1-meter and 0.1 degrees centigrade, respectively. A Geometric Correction System coupled to the scanner was used to geometrically correct scanner imagery. The colors red and yellow shown in the thermal infrared imagery presented below (fig. 2-6) indicates warmer temperatures with red being the warmest temperature. Again, ground truthing is needed to confirm the water quality at locations of interest.

Electromagnetic Conductivity

Electromagnetic (EM) conductivity techniques have demonstrated utility for groundwater studies including: (1) groundwater exploration, (2) mapping industrial groundwater contamination, (3) mapping general groundwater quality (i.e., salinity) and saline intrusion, and (4) mapping soil salinity for agricultural purposes (Telford, et al.). We have found that EM conductivity techniques can also be used to delimit fracture systems and mine voids that contain water (Ackman, et al., 1988, 1989, 1998)

EM conductivity techniques use a transmitter coil to generate an electromagnetic field (primary field) with a frequency between 100 Hz and 100 KHz. This primary field propagates through the surrounding area until it encounters a conductive body in which it induces a flow of alternating current. This ground current, in turn, induces a second electromagnetic field (secondary field) which has a field strength that is proportional to the conductivity of the geoelectric structure. The secondary field also propagates through the surrounding area, and with the primary field, make up the complete electromagnetic field that is detected at the receiver coils of the EM conductivity instrument.

EM conductivity instruments measure apparent conductivity, which is expressed in millisiemens per meter (mS/m). The apparent conductivity is calculated as follows:

$$\sigma_a = (4/2\pi f F_0 s^2)(H_S/H_P)$$

where σ_a is the apparent ground conductivity, H_P is the primary electromagnetic field, H_S is the secondary electromagnetic field, **f** is current frequency, **s** is the distance between the transmitting and receiving coils, and F_0 is the permeability of free space (Robinson and Coruh, 1988). The typical practice is to compare the H_S with a value H_P, the intensity of the primary field. Since the coil positions and the current in the transmitter coil are known, the value of H_P can be calculated. The apparent conductivity is a composite of true conductivities for each geoelectric layer that comprises the semi-infinite half-space below the ground surface.

Ground EM Conductivity – A Geonics EM-34 conductivity instrument was used with a 40-m inter-coil separation for the ground survey of the Omega Mine site. The depth of penetration for this instrument is a function of the inter-coil separation, orientation of the transmitter and receiver coils, and conductivity of the geologic strata. The EM-34 can be operated with transmitter and receiver coils in either a coplanar or a coaxial geometry. The coplanar mode is more effective at detecting flat-lying conductive bodies whereas the coaxial mode is better for detecting vertical conductive features. Each mode gives a significantly different response (sensitivity) with depth. The effective exploration depths for the two modes are approximately 0.75 (coaxial) and 1.5 (coplanar) times the inter-coil spacing in a layered earth geometry. Therefore, the effective depth for the EM-34 with a 40-m inter-coil separation is about 100 ft. for the coaxial mode and 200 ft. for the coplanar mode.

Airborne EM Conductivity - Airborne EM conductivity information was acquired using the Dighem^{VRES}[1], a 5-frequency, electromagnetic transmitter and receiver with an 8-m coil separation, that was towed by helicopter over surveyed areas. The Dighem^{VRES} was designed specifically for conductivity mapping and features five coplanar coil pairs that allow the calculation of conductivity at five widely separated frequencies (400 Hz, 1600 Hz, 6400 Hz, 25 KHz, and 100 KHz). Because the frequencies are separated by a factor of four, the skin depth, or the thickness of the strata being sensed, decreases by a factor of two for each successively higher frequency. For example, a conductivity survey conducted at 400 Hz senses the conductivity of geologic strata between the surface and a depth of approximately 300 ft, whereas a survey conducted at the next highest frequency (1600 Hz) would only sense the conductivity of strata between the surface and 150-ft depth. The coplanar coil geometry of this system is optimized for the resolution of horizontally layered geology and the detection of water tables and mine pools. Airborne conductivity data were displayed as separate contour maps for each of the five frequencies overlain on a topographic background. The multiple frequency nature of the Dighem^{VRES} data permits a three-dimensional interpretation of the conductivity distribution in the earth. For the Omega Mine site, processed conductivity data were draped from the topographic profiles along flight lines to form vertical conductivity sections.

[1] The United States Government does not endorse manufacturer or company.

Very Low Frequency Conductivity

Very low frequency (VLF) conductivity is a variant of EM conductivity that uses military transmitters instead of a transmitter coil to generate the primary field. VLF transmitters are in operation at a number of sites throughout the world, including North America, and typically operate at a frequency between 15 and 30 kilohertz (kHz). A VLF transmitter consists of a vertical cable several hundred meters long that emits a very powerful (300-1000 kilowatt) transmission signal. The primary electromagnetic field emitted by the antenna is horizontal, and its magnetic lines are comprised of concentric rings that ripple out from the transmitter (McNeill, 1980). Otherwise, VLF conductivity is similar to coaxial EM conductivity in theory and data interpretation. VLF conductivity instruments are generally lighter, less cumbersome, and less expensive than the corresponding EM conductivity instruments.

The information obtained from VLF conductivity surveys is similar to that obtained from EM conductivity except that VLF is more sensitive to vertical conductors (usually water-filled fractures, conductive ore bodies, or man-made features) that are oriented in the direction of the transmitter. Two U.S. Navy transmitters were used for these surveys. A transmitter at Cutler, Maine (24 KHz) was ideally located for the detection of vertical, water-filled fracture zones oriented parallel to the major NW structural trend in the surveyed areas. A second transmitter at Seattle, Washington (24.8 KHz) was appropriately located for the detection of water-filled fractures with trends normal to the major NW structural trend. Although VLF conductivity would not be as sensitive as EM conductivity for the detection of water tables and mine pools, it would be better suited for the detection of vertical, water-filled fractures that may represent zones of groundwater recharge.

Carrier Phase Differential Global Positioning System

Carrier-phase, differential global positioning system (GPS) is an integral part of airborne remote sensing. GPS was used in this study to: (1) guide the helicopter along parallel swaths (flight lines), (2) precisely correlate results from thermal infrared imagery and geophysical surveys with location, (3) append results from the current study to existing GIS databases, (4) correlate mine workings/grouting operations with observed anomalies, (5) groundtruth airborne imagery/geophysics, and (6) map water quality monitoring stations.

Application of Geographic Information System Data

Geographic Information System (GIS) data were used to geo-reference and validate remote sensing data. Remote sensing data in raw format is not referenced to a spatial coordinate system. Therefore, the raw data must be geo-referenced using image processing software to link locations (road intersections, buildings etc.) seen in remote sensing data to corresponding locations in geo-referenced digital ortho quads (DOQ).

Once a sufficient number of links are established between the imagery and DOQ, the image processing software is used to complete a polynomial stretch of the imagery in an attempt to fit it to the DOQ. The geo-referenced imagery in a coordinate system of UTM17 NAD83 can now be displayed with other GIS data in a similar coordinate system. Next, a classification algorithm is run on the georeferenced and georectified data to enhance the features of interest (mine drainage seeps and discharges). The identified mine drainage sites (thermal anomalies) can then be extracted as geo-referenced polygons, which encompass the area of interest. These polygons range in size from one pixel to many pixels and can be combined with other GIS data to locate potential mine discharge sites.

GIS datasets pertaining to coal resources and coal mining have been compiled by various federal and state agencies. These geo-referenced databases were used in this study to evaluate potential mine discharge sites identified by thermal imagery. The datasets are listed below:

Coal extent and resource (USGS): (Polygons)
- Coal extent in the Appalachian coal fields
- Pittsburgh: extent, crop line, bed elevation, bed thickness, overburden thickness
- Freeport: extent, crop line, bed elevation, bed thickness, overburden thickness

Mined out areas (polygons)
- Pittsburgh mined areas (USGS)
- Freeport mined areas (USGS)
- Mine permit boundaries
- Company mine maps

Abandoned mine lands (point data)
- Office of Surface Mining AMLIS system

Mine discharge locations (point data from various sources)

Streams affected by mine drainage (line data)
- USEPA fishless streams from mine drainage.

DATA ANALYSIS

Data are provided for known, well-characterized groundwater discharge sites that demonstrate the utility of the remote sensing techniques under evaluation. The analysis of the remote sensing data from these sites is primarily based on varying degrees of field knowledge either from ground-based data gathering or from historical knowledge. Also included are previously unknown sites that have attracted the authors' attention and are considered worthy of future investigations. Again, as mentioned above, it is acknowledged that additional evaluations are necessary and forthcoming.

Thermal Infrared Imagery

Previous work has demonstrated the ability of TIR technology to locate groundwater discharges based on temperature differences. However, ground characterization of targeted sites is still required because TIR technology is unable to distinguish water quality, quantity, or source. A general analysis of TIR data has identified numerous potential groundwater discharge sites that were previously unknown. A preliminary characterization of these unknown sites can be made using GIS data (including TIR data) even before ground-based fieldwork is initiated. For example, by combining overlays of TIR data, locations of existing coal seams, available topography, and mine maps, the character of targeted discharges often can be predicted.

Brinkerton Mine Site – Figure 2

The Brinkerton Mine Site is located near New Stanton, PA and is within the Sewickley Creek Watershed. The Brinkerton Mine is an abandoned, early 1900's coal mine in the Pittsburgh Coalbed. The extensive underground workings are flooded and produce numerous artesian discharges in the region. Figure 2 shows the source of a large artesian discharge (average is 4,200 gallons per minute (gpm)), which emerges from a small, shallow shaft (approximately 20-ft deep) dug into the workings during the 1940's to drain the mine complex. This drainage is alkaline with a circumneutral pH and an average iron content of 52 milligrams per liter (mg/L). The shaft and narrow ditch that are shown on the mine map underlay of fig. 2. clearly lines up with the thermal anomaly (red and yellow zones), indicating that the water that is flowing out of the shaft and along the ditch is warmer than the surface water in Sewickley Creek.

Two previously unknown mine discharges are also shown, a seep within a wetland and a pond, which are located near the center and lower left portions of fig. 2, respectively. The wetland was created as the result of surface mining activities adjacent to the shallow underground mine workings during the 1950's. The use of GIS technology to overlay TIR and DOQ data on the mine map identifies four mine entries as the apparent subsurface conduits and source of seepage into the wetland. The pond was created by mine subsidence in an area where the mined Pittsburgh Coalbed has shallow cover.

Wilson Run Site – Figure 3

Like the previous site, the Wilson Run Mine Site also contains a small drainage shaft (15-ft deep) that drains extensive underground mine workings at an average rate of 2,000 gpm. The water quality is also similar, such that it is alkaline with a circumneutral pH and averages 30 mg/L of iron. At this site the mine drainage enters a man-made pond that has small stands of cattails around its perimeter and a baffle that directs flow in such a manner to maximize retention time prior to entering the natural waterway, Wilson Run (a tributary of Sewickley Creek).

In fig. 3, a thermal plume of warm groundwater can be seen emerging from a shaft, flowing along a long, narrow ditch, and discharging into a pond. The warm water then flows around a baffle that directs the flow away from Wilson Run and towards the highway. Leakage across the baffle is evident at two points. A close examination of Wilson Run, slightly downstream (left) of pond discharge ditch, shows a red (warm) spot that is the location where mine drainage is known to be piped under the road and into the stream beneath the water. Flow rates for this location are unknown.

Youghiogheny River – Figure 4

Numerous groundwater discharges along the banks of the Youghiogheny River have been clearly identified from TIR data in fig. 4. These discharges are known to be mine drainage and artesian discharges and have been or can be easily characterized. Riverbank discharges represent approximately 15 percent of the metals loading in the Youghiogheny River.

Youghiogheny River – Figure 5

Underground mine excavations are known to extend beneath the river at numerous locations within the surveyed segment of the Youghiogheny River. The depth of overburden between the river bottom and mine workings ranges from 35- to 120-ft thick within the study area. The hydrologic setting (known artesian discharges), the results from previous water quality surveys, and some visual evidence suggests that mine drainage enters the river through vertical fractures between flooded mine workings and the stream channel. Approximately 25 percent of the metals loading in the river are attributed to such inflows. TIR imagery offers an opportunity to pinpoint the locations where mine drainage (or groundwater) is entering the river. Figure 5 shows an apparent parallel fracture within the Youghiogheny River channel. However, the validation and characterization of these data is much more challenging than those associated with small streams, land, ponds, and wetlands. This challenge exists because of the impact of the exponentially larger river flow on mine drainage inflows (within the river channel) in terms of differentiating quantity and quality.

Monongahela River – Figure 6

The Monongahela River is much deeper than the Youghiogheny River. Since the TIR technology measures only surface temperatures, it is unlikely, due to a deeper column of water that a temperature gradient would be observed in the TIR imagery unless there was a major source of groundwater inflow. Figure 6 shows a 100-ft wide linear thermal feature crossing the Monongahela River. Nearby and to the southeast, a distinct thermal anomaly on the land appears to align with the strike of the river feature. Whether these features are related has not been confirmed. It is known that underground mining has occurred beneath the river in this region near California, PA. The environmental impact of these targeted thermal anomalies is not known at this time, but this figure serves to demonstrate that TIR is a valuable tool for efficiently directing field investigations and characterization work.

Geophysics

Geophysical technologies, unlike TIR imagery, require ground intrusive techniques for validation or ground-truthing. The geophysical technologies applied in this study are well established and have been successfully applied and reported on in various applications (e.g., ground water investigations and mineral prospecting). NETL is the first to apply and evaluate airborne geophysical technologies as holistic watershed tools. Consequently, efficient validation procedures and approaches are being developed.

The areas selected by NETL for aerial remote sensing were known to include well-characterized sites such as the Omega Mine. In general, because of the broad aerial coverage, ground-truthing and characterization must be a collaborative effort between all watershed stewards. Fortunately, existing data, such as monitoring well, geological, exploration, mining, and other data can and will be used for both validation and characterization activities.

Electromagnetic Conductivity

<u>Omega Mine -- Figures 7 to 12</u>
The Omega Mine Site is located approximately seven miles southeast of Morgantown, WV (fig. 1). It is an abandoned mine in the Upper Freeport Coalbed that was mined during the 1980's and is a problematic source of acid mine drainage. This site was selected for testing airborne EM and VLF conductivity techniques because the mine and the drainage from it are well characterized.

Figure 7 is an airborne EM conductivity map of the Omega Mine site that was acquired at a frequency of 102 KHz. Also visible on this map is part of the underground workings of the Omega Mine. The black dots and blue dots are locations of grout injection wells, and the magenta rectangles indicate surface cultural features. The range of measured conductivity is color mapped with blue representing the least conductive and red the most conductive.

Conductive zones that are detected using a frequency of 102 KHz are between the surface and about 10-m (33-ft.) depth. This is referred to as the skin depth or the thickness from the surface to the maximum depth of detection. The conductive zone that is visible south of the area of grout injection wells is well above the level of the mine and probably represents a perched water table.

Figure 8 is an airborne EM conductivity map acquired at a frequency of 25 KHz. At this frequency, the skin depth is twice that at 102 KHz, or about 20-m thick (66-ft). Although the sensed interval is still above mine level, the conductive areas occupy more of the map, representing an expansion of saturated strata with increased depth.

Figure 9 is an airborne EM conductivity map acquired at a frequency of 6200 Hz. The skin depth would be expected to be about 40-m thick (132-ft) and would begin to be influenced by the mine workings in topographic low areas. A northwest-trending line of discontinuous conductive areas parallels the highway in this figure.

Figure 10 is an airborne EM conductivity map acquired at a frequency of 1400 Hz. At this frequency, the skin depth would be expected to be 80-m thick (264-ft), although somewhat less in areas of high conductivity. A mine pool in the underground workings, if present, would be detected at this frequency. The apparent low conductivity of the area where grout was injected into the mine workings may be evidence that mine water has been effectively excluded from the grouted area. A conductive anomaly that may represent a mine pool is evident along the western margin of the grouted area. This conductive anomaly may also be an artifact of harmonics from the 60-Hz electrical lines along the highway.

Figure 11 is an airborne EM conductivity map acquired at a frequency of 380 Hz. The skin depth at this frequency is more than 150 m (480 ft), depending on ground conductivity. The areas of high conductivity are more widespread, possibly indicating a regional water table. The highly conductive areas at 380 Hz that were not present on the map acquired at 1400 Hz may be indicative of water-saturated strata that is below mine level. However, the interference of harmonics from 60-Hz electrical lines is expected to be more significant in the 380 Hz EM conductivity map than other maps acquired at higher frequencies. Moreover, electrical lines in the area of study appear to coincide with conductive anomalies identified on the 380 Hz EM conductivity map, and any interpretation based on this map is suspect.

Figure 12 is an EM conductivity map of a small part of the Omega Mine site that was surveyed using a ground-based EM conductivity instrument. The area of this survey is represented by a black bordered rectangle in fig. 7 - 11. Few conductive features are evident on the ground-based map, which is corroborated by airborne conductivity results. The conductive feature within the black square shown on figure 11 (380 Hz), which was identified by airborne EM conductivity, is below the skin depth for the ground-based instrument.

Very Low Frequency Conductivity

<u>Omega Mine – Figures 13 and 14</u>

Figures 13 and 14 are very low frequency conductivity maps that were acquired using transmitters at Cutler, Maine (24 KHz) and Seattle, Washington (24.8 KHz), respectively. VLF is most sensitive to water-filled, vertical fractures that trend in the direction of the transmitter. Therefore, prior to the survey, the transmitter at Cutler, Maine was selected because the signal would arrive at the Omega Mine from the northeast, the expected trend for most of the fractures in the area. Another predominant fracture trend was expected to be normal to the regional strike, making the transmitter at Seattle, Washington ideal.

Figure 13 indicates that there are northeast trending, water-filled fractures within the area of study. However, figure 14 suggests that the predominant trend for water-filled fractures is northwest, and that they are primarily located in a band that extends across the area from northwest to southeast. Both VLF maps show the Omega Mine workings to be likely areas for groundwater recharge via infiltration through vertical fractures.

CONCLUSIONS

Thermal Infrared Imagery

TIR accurately identified numerous known groundwater discharges and seeps at various abandoned mine site locations within the Sewickley Creek Watershed and Youghiogheny River Basin. This technology alone is unable distinguish water quality or quantity. However, it is an extremely useful tool for accurately locating groundwater discharge points on the land, in wetlands, and small streams. TIR can be used to establish priorities and efficiently focus labor and other resources for watershed characterization activities.

EM Conductivity

Airborne, multiple-frequency EM conductivity appears to be a promising tool for detecting mine pools. The mine pool interpreted from the conductivity anomaly at 1400 Hz (fig. 10) is consistent with information currently known about the mine. However, firm evidence will be obtained from a scheduled hydrologic investigation that is intended to verify the existence and extent of the mine pool inferred from EM conductivity data.

Results from a ground-based EM conductivity survey corroborated the results obtained by an airborne survey using the same technique. However, the ground-based method could not penetrate to sufficient depth to detect the conductive anomaly evident in the 380 Hz airborne EM conductivity map (fig. 11).

VLF Conductivity

No conclusions can be made at this time regarding the utility of VLF conductivity for the assessment of mining-impacted watersheds. The verification of VLF conductivity results would require oriented core drilling or drilling with borehole camera evaluations to determine the density and orientation of fractures. The expense of this validation does not appear justified because VLF conductivity relies on military transmitters whose future is uncertain.

DISCUSSIONS

All remote-sensing technologies discussed in this paper have been successfully applied in other applications in similar circumstances and studies. Consequently, it is likely that this approach will be successful when applied to watershed assessments. A limited review of the data in this study supports this conclusion. If successful, the combination of remote sensing technologies described above offers unprecedented potential to non-intrusively map and view the underground hydrological pathways (to a depth of about 300 feet) over very large land segments. This technology may also provide information for the calibration of watershed models for managing groundwater and surface water.

Currently, modeling ground water resources is very expensive due to drilling activities associated with data collection and is very difficult to execute throughout this region. This difficulty is due to the topography and extensive underground mining that has disturbed natural groundwater tables over the past century. Remote sensing data can potentially serve as a road map for drilling activities and hydrological investigations.

A major aspect of managing watershed resources is considered to be pollution prevention, particularly in this region. One pollution prevention approach, currently being pursued by NETL, is locating and sealing fracture zones that underlie surface streams and serve as a conduit to the pollution-generating mine environment. Ground-based geophysical techniques have been effective in locating fracture zones in stream channels, and with subsequent channel grouting, preventing water loss into the underground workings. Successful airborne conductivity and VLF surveys would direct and drastically improve the efficiency and practicality of conducting land-based, watershed-scale stream surveys using the same technologies.

Another prevention measure could involve interception via boreholes (vertical, horizontal and/or angled) to pump or siphon clean groundwater before it enters the underground workings. The clean water could be stored, utilized, or returned to its natural waterways, without contacting pollution-generating sources. This approach would only be feasible with reasonably accurate (e.g., less than 10 meters) three-dimensional maps of the ground water pathways and storage areas.

The application of airborne remote sensing technologies offers opportunities to view, model, and address clean water issues from new perspectives, never before available. The GIS technology is considered to be a very valuable tool for watershed management. The successful application of these airborne technologies, and subsequent coupling of their data with available GIS tools, will significantly enhance watershed management abilities.

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