A preliminary evaluation of remote-sensing technologies for watershed assessment

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Abstract: Airborne thermal infrared (TIR) imaging and geophysical techniques were evaluated as tools for identifying groundwater flow paths and surface discharge locations. A geographic information system (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. 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 to efficiently target 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.

1 INTRODUCTION

The National Energy Technology Laboratory (NETL) is evaluating the use of remote or airborne sensing technologies as new tools for the 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 can take years or decades. The full value of the various remote-sensing technologies is realized when the data are coupled with geographic information system (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 the 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, such as coal mines or 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.

The remote sensing technologies being evaluated by NETL include thermal infrared (TIR) imagery and two geophysical techniques, electromagnetic (EM) conductivity and very low frequency (VLF) conductivity. The initial TIR work was completed in early 1999 using a helicopter platform to survey: the Sewickley Creek watershed (43,250 hectares) in Pennsylvania (PA), 150 km of the Youghiogheny River (from Connellsville to McKeesport, PA), 160 km of the Monongahela River (from McKeesport, PA to the West Virginia (WV) state line), and three 8 km segments (starting at each stream's confluence with the Monongahela River) of Dunkard Creek, Buffalo Creek and the West Fork River in WV. Subsequent remote sensing work occurred in late 1999, and included the application of airborne TIR, EM, VLF over: the Roaring and Muddy Creek watersheds in Northern WV, 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 Maryland (MD) state line, and the Winding Ridge Mine site, located near Friendsville, MD. The locations for these surveyed areas are shown in Figure 1.

To date, only a limited amount of the WV geophysical data has been processed. Consequently, the focus of this paper will be on the 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.

2 REMOTE SENSING TECHNOLOGIES

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 400 m 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.

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., 1976). EM conductivity techniques can also be used to delimit fracture systems and mine voids that contain water, and can be used along with VLF to identify fractures that are serving as groundwater conduits to recharge underground mines by dewatering streambeds. We have then

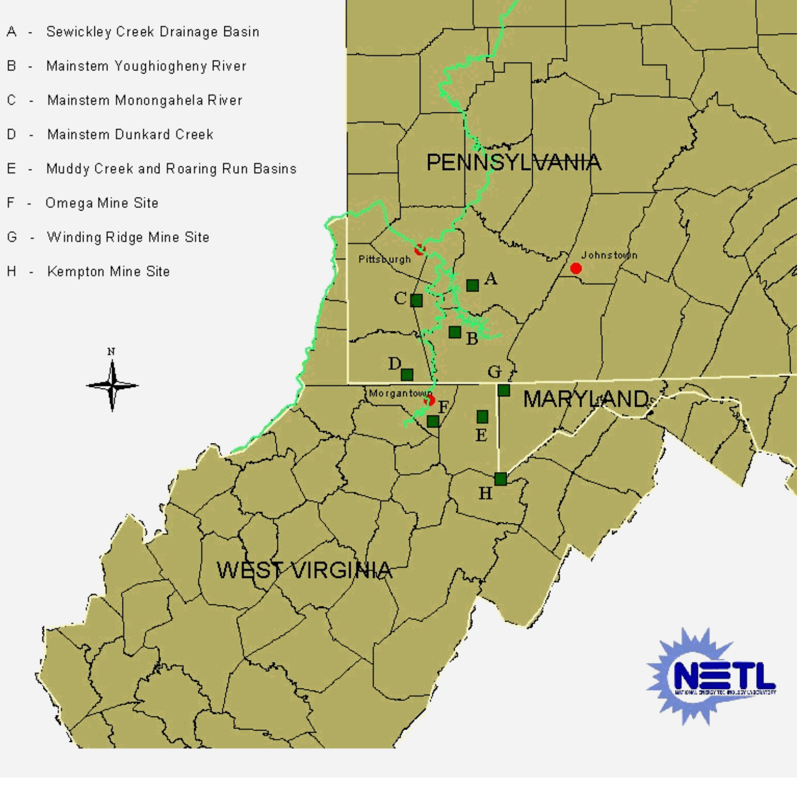

Figure 1 Location of project areas

selectively grouted these areas, restoring stream flow (Ackman et al., 1988, 1989, 1998). Using an airborne system, it may be possible to extend this technology to riverbeds similarly damaged by mine subsidence.

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, $\mathbf{H_P}$ is the primary electromagnetic field, $\mathbf{H_S}$ is the secondary electromagnetic field, **f** is current frequency, **s** is the distance between the transmitting and receiving coils, and $\mathbf{F_0}$ is the permeability of free space (Robinson & Coruh, 1988). The typical practice is to compare the $\mathbf{H_S}$ with a value $\mathbf{H_P}$, the intensity of the primary field. Since the coil positions and the current in the transmitter coil are known, the value of $\mathbf{H_P}$ 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 30 m for the coaxial mode and 60 m 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, which was towed by a helicopter over surveyed areas at a constant altitude of 30 m. The Dighem^{VRES} was designed specifically for conductivity mapping. It features five co-planar coil pairs that allow the calculation of conductivity at five widely separated frequencies. Because the frequencies are separated by a factor of four, the skin depth, or the

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

thickness of the strata being sensed, decreases by a factor of two f or each successively higher frequency. The co-planar coil geometry of this system is ideal for the resolution of horizontally layered geology and the detection of water tables and mine pools. Airborne conductivity data can then be displayed as separate contour maps for each of the five frequencies atop 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.

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, which may represent zones of groundwater recharge, 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.

Global positioning system and Geographic Information System data

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

Geographic Information System (GIS) data were used to geo-reference and validate the 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 orthographic quarter quadrangles (DOQQ). Once a sufficient number of links are established between the imagery and DOQQ, the image processing software is used to complete a polynomial stretch of the imagery in an attempt to fit it to the DOQQ. The geo-referenced imagery in a coordinate system can then 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.

GIS data sets pertaining to coal resources and coal mining have been compiled by various U.S. Federal and state agencies. These geo-referenced databases were used in this study to evaluate potential mine discharge sites identified by the thermal imagery.

3 DATA ANALYSIS

Thermal infrared imagery

Previous work has demonstrated the ability of TIR technology to accurately 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 our TIR data has identified numerous 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.

The extensive flooded underground workings in the Sewickley Creek watershed produce numerous artesian discharges in the region. Unfortunately, the colorful images produced by these thermal anomalies do not show up well in black and white, and so will only be seen by those attending the conference. However, not only were known artesian discharge displayed in appropriate locations, but two previously unknown mine discharges were identified: a seep within a wetland and a pond. The wetland was created as the result of surface mining activities adjacent to the shallow underground mine workings during the 1950's. GIS technology was used to overlay TIR and DOQQ data on the mine map, which identified four mine entries as the apparent source of seepage into the wetland. The pond was created by mine subsidence in an area where the mined Pittsburgh Coalbed has shallow cover (<6 m).

Numerous groundwater discharges along the banks of the Youghiogheny River have also been clearly identified from TIR data. 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.

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 11 to 37 m 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. We have observed an apparent parallel fracture-related system of discharges within the Youghiogheny River channel. However, the validation and characterization of such data is much more challenging than those associated with small streams, land, ponds, and wetlands.

The Monongahela River is much deeper than the Youghiogheny River. Since the TIR technology measures only surface temperatures, we considered it unlikely that a temperature gradient would be observed in the TIR imagery, due to a deeper column of water, but some apparent thermal anomalies have been observed near where underground mining has occurred beneath the river. The environmental impact of these apparent discharges is not known at this time, but does illustrate that TIR can be a valuable tool for efficiently directing field investigations and characterization work.

Electromagnetic conductivity

The Omega Mine Site is located approximately seven miles southeast of Morgantown, WV (Figure 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.

Conductive zones detected using a frequency of 102 KHz are between the surface and about 10-m depth. This is referred to as the skin depth or the thickness from the surface to the maximum depth of detection. At a frequency of 25 KHz, the skin depth is twice that at 102 KHz, or about 20 m thick. 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. At a frequency of 6200 Hz, the skin depth would be expected to be about 40 m thick and would begin to be influenced by the mine workings in topographic low areas. At a frequency of 1400 Hz, the skin depth would be expected to be 80 m thick, 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. However, this conductive anomaly may also be an artifact of harmonics from the 60-Hz electrical lines along the highway. At a frequency of 380 Hz, the skin depth is more than 150 m, 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.

Very low frequency conductivity

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.

Although northeast-trending water-filled fractures are apparent in the VLF data, the predominant trend for water-filled fractures appears to be northwest. Both sets of fractures are 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.

4 CONCLUSIONS

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.

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 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 the 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 a sufficient depth to detect the conductive anomaly evident in the 380 Hz airborne EM conductivity map.

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.

5 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 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 in mining regions. 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. One pollution prevention approach 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 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.

ACKNOWLEDGEMENTS

This work has been sponsored, in part, through an interagency agreement with EPA Region 3. The authors also would like to thank Robert Dilmore, Ph.D. candidate in Environmental Engineering at the University of Pittsburgh, for his contributions in processing thermal imagery and GIS data.

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Wstępna ocena zastosowania w obszarach górniczych technologii teledetekcyjnych

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Streszczenie: Dla określenia dróg krążenia wód podziemnych i obszarów ich powierzchniowego drenażu w rejonach górniczych zastosowano metody zdjęć lotniczych w podczerwieni (TIR) oraz metody geofizyczne. Geograficzny system informacyjny (GIS) został wykorzystany do zestawienia danych geograficznych i wyników badań. System TIR okazał się efektywny do ustalenia stref drenażu wód podziemnych na powierzchni, natomiast mało efektywny do oceny źródeł pochodzenia tych wód jak i ich zakresu. Zastosowanie geofizycznej metody przewodności elektromagnetycznej o zmiennej częstotliwości umożliwiło określenie położenia wodnych zbiorników kopalnianych i dróg poziomego przepływu wód. Zastosowanie metody elektromagnetycznej o bardzo niskiej częstotliwości umożliwiło wykrywanie pionowych szczelin wypełnionych wodą, które mogły stanowić potencjalne strefy zasilania wód podziemnych.