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Technical Article

Evaluation of Airborne Thermal Infrared Imagery for Locating Mine Drainage Sites in the Lower Kettle Creek and Cooks Run Basins, Pennsylvania, USA

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Abstract. High-resolution airborne thermal infrared (TIR) imagery data were collected over 90.6 km^2 (35 mi^2) of remote and rugged terrain in the Kettle Creek and Cooks Run Basins, tributaries of the West Branch of the Susquehanna River in north-central Pennsylvania. The purpose of this investigation was to evaluate the effectiveness of TIR for identifying sources of acid mine drainage (AMD) associated with abandoned coal mines. Coal mining from the late 1800s resulted in many AMD sources from abandoned mines in the area. However, very little detailed mine information was available, particularly on the source locations of AMD sites. Potential AMD sources were extracted from airborne TIR data employing custom image processing algorithms and GIS data analysis. Based on field reconnaissance of 103 TIR anomalies, 53 sites (51%) were classified as AMD. The AMD sources had low pH (<4) and elevated concentrations of iron and aluminum. Of the 53 sites, approximately 26 sites could be correlated with sites previously documented as AMD. The other 27 mine discharges identified in the TIR data were previously undocumented. This paper presents a summary of the procedures used to process the TIR data and extract potential mine drainage sites, methods used for field reconnaissance and verification of TIR data, and a brief summary of water-quality data.

Key words: Abandoned mine lands; acid mine drainage; thermal infrared imagery

Introduction

Problem Description

Drainage from abandoned mines is the largest source of surface water contamination in Pennsylvania (Rossman et al. 1997). More than 3,800 km (2,400 mi) of streams have been degraded by acid mine drainage (AMD), which, in addition to ecological damage, results in an estimated annual loss of $67 million in revenue associated with sport fishing. The cost for correcting the AMD-related problems with currently available technology has been estimated at $15 billion.

Remediation efforts by local watershed associations, working with State and Federal agencies, are underway in Pennsylvania to restore streams long damaged by mining (Williams et al. 1996). The success of these efforts hinges on the complete knowledge of all pollution sources within a watershed. Abandoned mine-land (AML) sites from the early 1900s contain many AMD sources. Many of these AML sites have revegetated naturally, so evidence of the once active coal mines is scarce. Locating and mapping AMD in areas of steep terrain with dense vegetation can be time consuming, labor intensive, and expensive, especially on watershed scales.

The purpose of this project was to evaluate the use of airborne thermal infrared (TIR) imagery for identifying sources of AMD in the Kettle Creek and Cooks Run Basins, tributaries of the West Branch of the Susquehanna River in north-central Pennsylvania. The TIR imagery was collected in a single night in late March 2002. The investigation compared locations of AMD sites identified by airborne TIR with previously known AMD sources. A field verification survey documented water quality at each of the TIR anomalies.

Site Description

The project area encompasses 90.6 km^2 (35 mi^2) within Clinton County, Pa. (Figure 1) within the Appalachian Plateaus physiographic province. Cooks Run and Kettle Creek drain most of the area. Local relief ranges from 201 m (above sea level) where Kettle Creek meets the West Branch of the Susquehanna River near Westport, Pa., to 631 m in the northwest corner of the study area. The temperate-humid climate of the area supports perennial streams and lush forests. Land cover in the watershed is predominantly forest with mixed deciduous and evergreen trees. Rocks in the area are of Pennsylvanian and Mississippian age, and include bituminous coal beds of commercial value.

Coal mining in the study area began in the late 1800s. The last underground mine closed in the late 1950s. Most of the underground mining was on the Lower

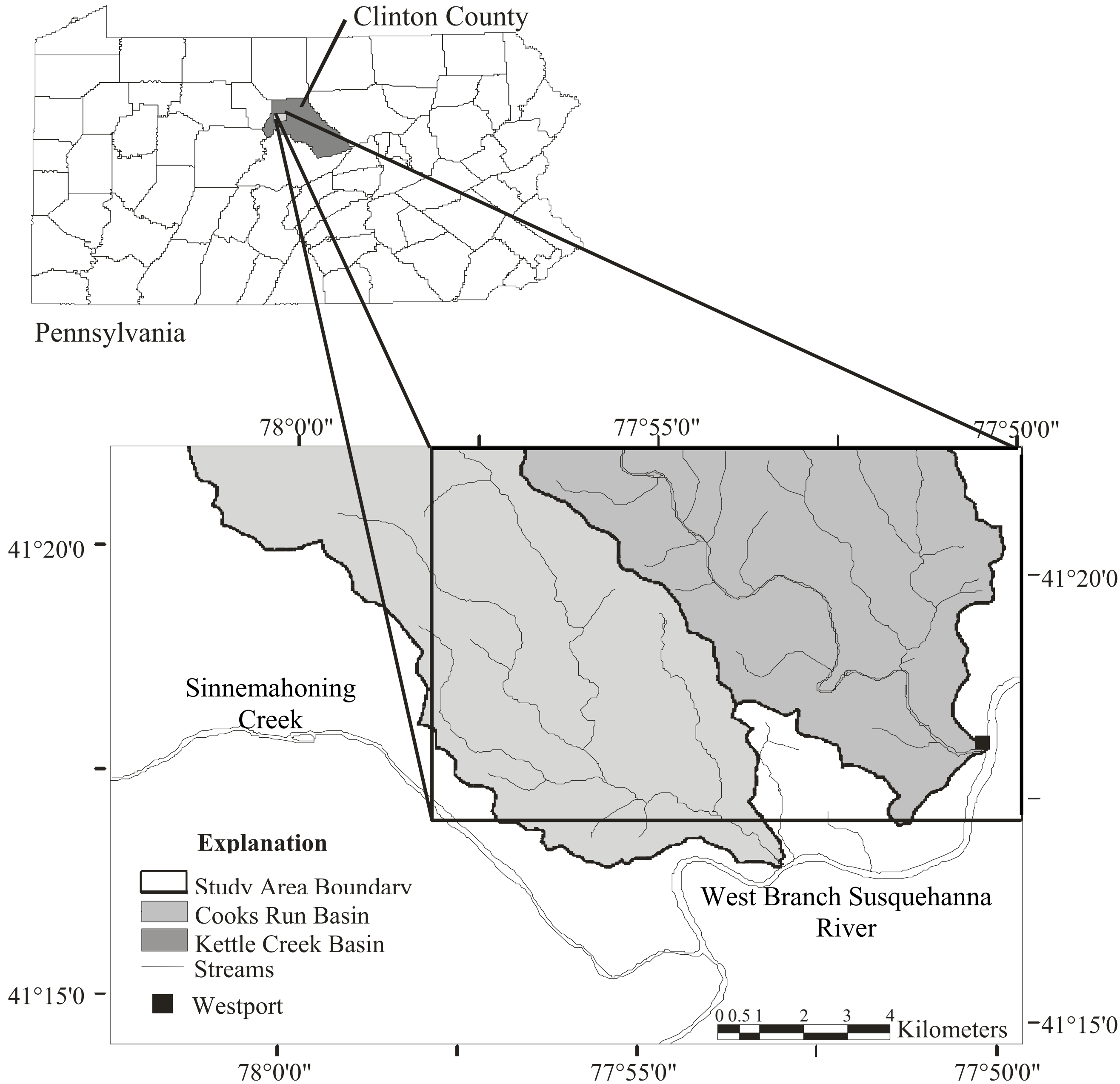


Figure 1. Location of study area in Pennsylvania

Kittanning coal seam. The coal ranged in thickness from 1 to 2 m. The coal was mined up-dip using the room and pillar method. This allowed the water that entered the mine to flow away from the working face of the mine entry. Today, many of these drift openings continue to drain AMD from abandoned and partially collapsed mines. The AMD is a result of pyrite oxidation at exposed rock surfaces within the abandoned deep mines and surface-mined backfill.

The development of modern earth-moving equipment made surface coal mining feasible on a large scale. Surface mining in the study area began shortly after World War II and ended in the late 1970s. Coal was mined from both the Lower and Middle Kittanning coal seams. Approximately 10%, or 8.4 km^2 (3.25 mi^2) have been surface mined within the study area. The sites were reclaimed to what generally is considered "old law" standards, which included rough grade backfilling and tree planting.

Analysis of water quality data bases identified 33 mine discharges (Michael Klimkos, Pennsylvania Dept of Environmental Protection (PADEP), personal commun. 2002). The location and water-quality data for many of these sites were from assessment studies conducted in the early 1970s and lacked accurate geographic information.

Methods

GIS Development

A comprehensive geographic information system (GIS) was developed to assist in site characterization and analysis of the thermal imagery. Significant data themes were used in image processing software for analysis of raster data, in GIS software for vector analysis, and on a mobile GIS system (ESRI, Arcpad) for navigation and data analysis in the field (Table 1).

Thermal Imagery

Two-band imagery (Sams et al. 2003) was acquired using a Synsytech 11 channel multispectral line scanner (MLS) coupled to a position and orientation system (POS) (Sensytech Inc.) that provided trajectory data used to record the orientation of the sensor head on the MLS. This instrument configuration allows data to be corrected for distortions associated with changes in aircraft attitude (pitch, roll, and yaw) (Brewster 1999). The data were processed to a ground resolution of 1 m^2. The TIR data were geometrically processed using data from a geometric correction system and orthorectified using a 30-m U.S. Geological Survey (USGS) digital elevation model (DEM). Ortho-rectification improves positional accuracy of the data by eliminating distortions due to vertical relief displacement. This produced a spatial accuracy of approximately 5-10 m with respect to map coordinates. The platform was a Rockwell Aero Commander fixed-wing aircraft flown at an altitude of 860 m. Two channels of the MLS were configured for nighttime thermal operation with sensor spectral sensitivity ranges of 3.0-5.0 µm (band 1) and 8.5- 12.5 µm (band 2). Band 1 exhibits peak radiant-energy emission for objects ranging in temperature from 330 to 730ºC; band 2 is most sensitive for objects between -20 to 100ºC. Thus, band 2 provides a better response for differentiating water features from land features. Band 2 also is optimal in terms of atmospheric transmission because it is least affected by absorption of atmospheric gases (Sabins 1997). The original 12-bit integral data values were calibrated radiometrically and converted to floating point numbers to reflect radiant temperature values, with a resolution of 0.1ºC.

The study area was flown in an east-west direction and was covered by nine overlapping flight lines. The overlap between adjacent flight lines was approximately 30%. The flights were conducted late at night, in late March, under clear skies, to optimize the thermal contrast between land and water features. The thermal "inertia" of water features, compared to the more rapid cooling of land features, makes

Table 1. Geographic information system data themes used for evaluation of thermal infrared data

Theme	Type	Description
DEP AMD sites[1]	point	Historic location of mine discharge sites
Streams[1]	line	Centerline streams
Roads[1]	line	Local roads
Trails[1]	line	State forest trails
Coal outcrop[1]	line	Outcrop of the Lower Kittanning coal seam
Syncline[1]	line	Clearfield-McIntyre Syncline
Lineaments[2]	line	Lineations, linears, or fracture traces, shown or presumed to be related to stratigraphy or geologic structure
Study area[2]	polygon	Boundary of study area
Clinton Co.[1]	polygon	County boundary
Surf. mines[2]	polygon	Area disturbed by mining
Deep mine	polygon	Extent of deep mining
Basins[2]	polygon	Drainage basins in area
Underground mine map[1]	raster	Scanned/georeferenced 1930 mine map
Study area DOQ[3]	raster	Study area, USGS digital ortho quarter quad
Study area DRG[3]	raster	Study area, USGS Digital Raster Graphic
Study area DEM[3]	raster	Study area, USGS digital elevation model
TIR image (1-9)[2]	raster	Thermal infrared image by line (1-9)

Source of data: [1]PADEP; [2]U.S. DOE, NETL; [3]USGS

nighttime data acquisition well suited for this type of investigation (Lillesand and Kiefer 1994). Furthermore, vegetative cover from deciduous trees was minimal.

The data-processing procedures were designed to separate land features from water features and warmer groundwater from cooler surface water. Groundwater features such as AMD discharges to the surface as a spring or seep with a temperature that is characteristic of the local groundwater flow system. During March 2002, the groundwater was warmer than surface streams, which in turn were warmer than land. Processing the TIR data resulted in a classified image that distinguished these features (Figure 2).

The first step in this process was to distinguish land from water. Water was then separated into features representing shallow surface water (small tributaries or the edges of large streams), deep channel flow, and groundwater, such as emerging springs, seeps, and mine drainage. The thermal signatures from each of

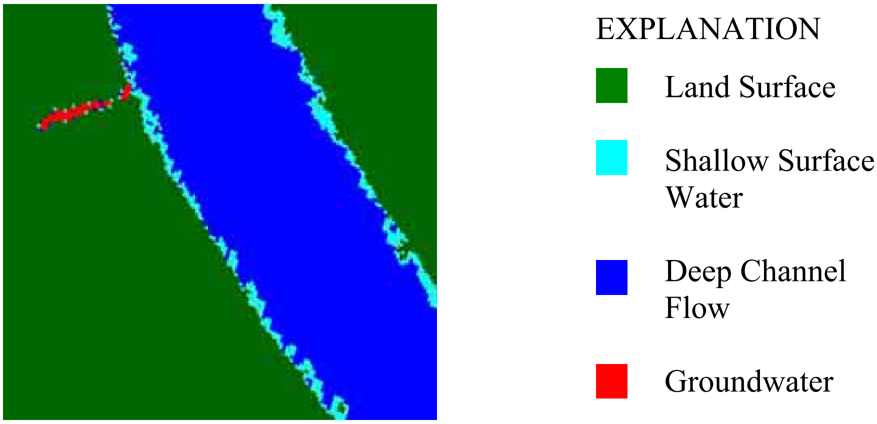


Figure 2. Classified image of TIR data showing land and water features (Sams and Veloski 2003)

these features were identified using imaging processing software. The raw data was color enhanced to highlight water features. Digital number values were studied by navigating through the flight line and focusing on the water feature of interest; values from several examples of each type of water feature from each flight line were sampled in order to develop a classification range for the raw data. Each flight line was processed separately because of sensor drift that resulted in recalibration of the MLS instrument. Recalibration of the instrument created slight differences in thermal signatures between flight lines. Only the threshold values for groundwater were adjusted for each flight line.

The reclassified imagery was processed using several models within the image processing software. These models were designed to filter and clean the reclassified data. This process was used to identify contiguous areas of similar pixels for converting the raster data into a polygon vector format. In vector format, each polygon was attributed with data fields for their feature temperature classification code (1 = shallow surface water, 2 = deep channel flow, 3 = groundwater source), area (m^2), and a unique ID number for identification purposes.

Selecting features for field review was completed through GIS data analysis (Table 1). The study area was divided into a 9 x 9 grid of equal areas to organize data analysis. A new theme was created and called TIR points to mark locations of potential AMD sites selected for field review. The TIR point layer was opened for editing to start the selection process. The TIR polygon theme was viewed as a transparent data layer along with the boundary lines for deep mines, surface mines, and coal outcrops. These data were overlain on the USGS DOQQ. In systematic order, data within each cell of the 9 x 9 grid were analyzed. A point was digitized on screen within the TIR polygon and added to the open TIR point theme to mark a selected site location that would be field checked. Selection was based on the following criteria: proximity to a mine or coal outcrop; feature extent; feature shape (linear); feature position (topographic depression); and feature temperature code (from TIR classification). The point was digitized at the upstream location of the feature. An example of a selected site is shown in Figure 3. When each cell in the matrix was checked, the point theme was intersected with the polygon theme to capture the polygon attributes and data values. In addition, the point theme was attributed with x- and y-coordinates, in UTM meters. A total of 132 sites were selected within the study area as possible AMD sources.

Data from the TIR point theme in ESRI shapefile format were uploaded to handheld PDA-type computers equipped with global positioning system (GPS) navigation software (ESRI, Arcpad). The navigation software is designed to intercept the GPS data that contain range and navigation information in an ASCII readable format. This output is then translated into a position fix and rendered by the software into a moving map type presentation for the purpose of navigation. A status line presents coordinate information that was used to navigate to any feature in the "points" database. The software also allows for multiple map objects to be presented as ordered layer overlays. USGS DOQQ and DRGs were used as the base layers for the purpose of orientation. The 132 potential AMD sites selected from TIR data were plotted on top of the DRG or DOQQ. In addition, color-enhanced data from each TIR flight line were converted to a compressed MrSID image (LizardTech Inc.) for use on the PDA to view the raw imagery in the field and to confirm site locations. Data layers for roads and trails within the project area were used as part of the navigation system to minimize travel by foot. The trails data layer represented old logging and maintenance roads within the state forest land. Paper maps at a scale of 1 to 6,000 were plotted for the study area with the TIR sites overlaid on the study area DRG. These maps

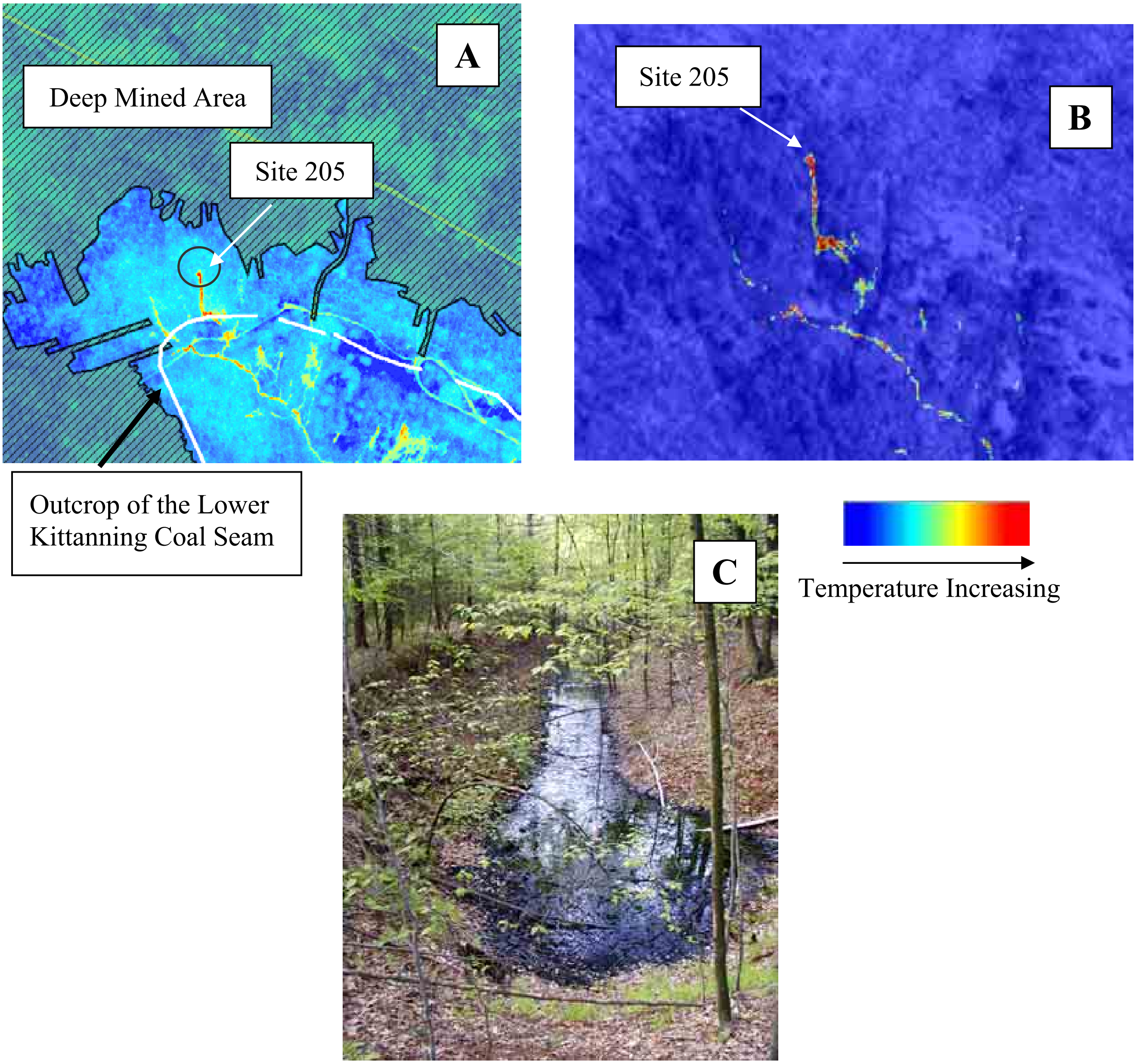


Figure 3. Thermal infrared images and photograph of site number 205 acquired in 2002; A, combined TIR and GIS information; B, expanded view of the color enhanced TIR image; C, photograph of discharge taken during field verification survey

provided an overview of the study area and were used to plan efficient routes for checking the TIR sites.

The field verification survey was conducted in June 2002. Although a survey concurrent with the TIR imagery would have been ideal, time was needed to process the TIR data. Four teams completed the field survey in approximately 5 days. Field checks were completed at 103 of the 132 sites identified in the TIR data. Sites in the far western end of the study area were not field checked because of time constraints.

Information about site conditions and field water-quality measurements from an YSI model 556 multi-parameter probe (water temperature, pH, and specific conductance) were collected at each site. Field methods followed guidelines set forth for the USGS National Water-Quality Assessment Program (Shelton 1994). A water sample was collected at the site for lab analysis if the field pH was less than 4.0 or specific conductance was greater than 400 µS/cm. These constituents were used to classify the site as AMD. Generally, springs unaffected by mining had near-neutral pH and specific conductance less than 200 µS/cm. Most commonly, other evidence suggested the area was affected by mining, such as areas of inhibited tree growth and areas with extensive deposition of ferric iron precipitates. Each site was digitally photographed.

Three water quality samples were collected at each AMD site: raw, raw/acidified, and filtered/acidified. A 0.45 um cartridge-type syringe assembly was used to filter the water samples. Samples were acidified with 12N HCl. All samples were stored on ice until delivery to the laboratory for analysis of metals and sulfate concentration by inductively coupled plasma emission spectroscopy (ICP). At the AMD sites, the flow volume was measured by volumetric or incremental area/velocity methods depending on the flow volume. Flow data coupled with chemical characteristics were collected for load calculations used by the PADEP for remediation planning.

All water samples collected during the field reconnaissance were analyzed in the laboratory according to EPA and ASTM standards. EPA protocols were used for the analysis of metals (EPA 200.7), sulfate (EPA 375.4) and specific conductance (EPA 120.1). Daily quality-control standards assured reproducibility and accuracy. Concentration of metals by ICP was calibrated with standards as specified in the methodology. External reference standards were compared to calibration standards to insure accuracy. Duplicates were run on every five samples along with matrix spikes that were analyzed for recovery. Percent relative standard deviation (RSD) for duplicate samples and recoveries from matrix spikes were within acceptable limits. Laboratory pH was measured according to ASTM E70 using standard method 4500H. Acidity and alkalinity were performed according to ASTM D1067 standard method 2310B and ASTM D1067 standard method 2320B.

Results and Discussion

Thermal Infrared Anomalies

Based on field reconnaissance, the 103 TIR anomalies were classified into 10 categories as shown in Table 2. Of the 103 total sites, 90 sites or 88% were considered groundwater discharge sites (mine discharges, springs) or a site recharged through groundwater (headwater streams, wetlands, small surface ponds, and standing water).

Fifty-three of the 103 sites (51%) were classified as AMD sites (Table 2, Figure 4). As described earlier, a site was classified as AMD if the field pH was less than 4.0 or specific conductance was greater than 400 µS/cm. The high percentage of mine-drainage sites was expected because of the feature-extraction methods described earlier, such as proximity to mine workings (Figure 3).

One objective of the project was to determine how well the TIR mine-discharge locations correlated with historic or documented mine-discharge sites from a PADEP database. Through GIS analysis, the point location of the 33 historic sites, with a 100-m buffer were plotted along with the 53 AMD sites identified by TIR. The 100-m buffer accounted for possible errors in the coordinate locations of the historic sites. GPS technology was not available when coordinate locations were determined for most of the PADEP sites so locations were plotted on topographic maps based on landmarks. A TIR site outside the 100-m buffer was considered a new AMD site. A total of 27 of the 53 sites (51%) met this criteria and were determined to represent new or previously undocumented sites. The remaining 26 sites were within the buffer and were considered previously documented.

Seven historic sites were not identified in the TIR data (Figure 4). Field review found that these sites were under coniferous or other evergreen tree canopy (mountain laurel) and therefore not visible to the TIR sensors (Figure 5). Particularly prevalent within the imaged area were groves of native hemlock, which were also coincidently abundant in and around ravines below the coal outcrop.

Thirty-seven TIR anomalies were classified as groundwater sources other than AMD (springs, headwater streams, wetlands, small surface ponds, and standing water). These false positives were not distinguishable in the TIR data and were identified during the field reconnaissance (Figure 6).

The eight sites classified as undetermined (Table 2) had no obvious heat source in the field to distinguish them from the background land surface. These transient heat sources could be areas of high animal density. The region is known to support both deer and bear populations. In addition, one undetermined site was at a staging area for a logging operation where

Table 2. Results of field reconnaissance of selected TIR sites

Site Type	# of Sites
Mine Drainage	53
Surface Pond	13
Standing Water	10
Undetermined	8
Wetlands	6
Spring	4
Stream	4
Residential, source undetermined	3
Dry Stream Channel	1
Treatment Plant Discharge	1
Total	103

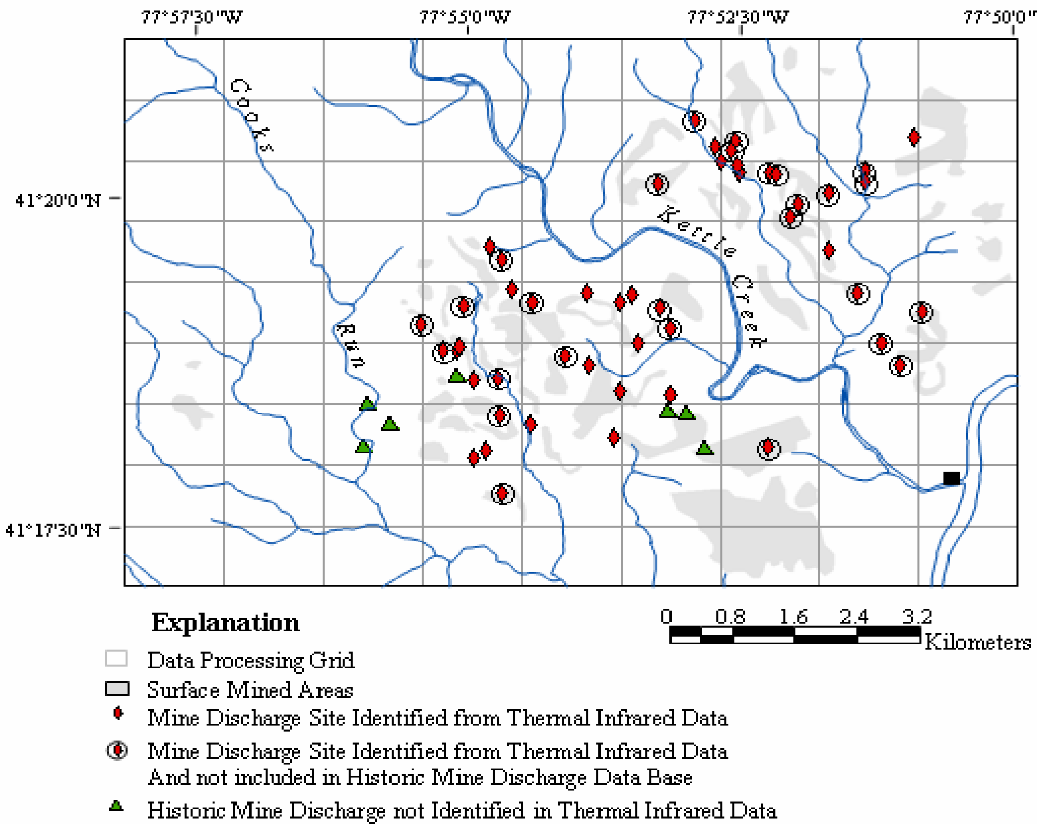


Figure 4. Locations of potential mine drainage sites derived from TIR data

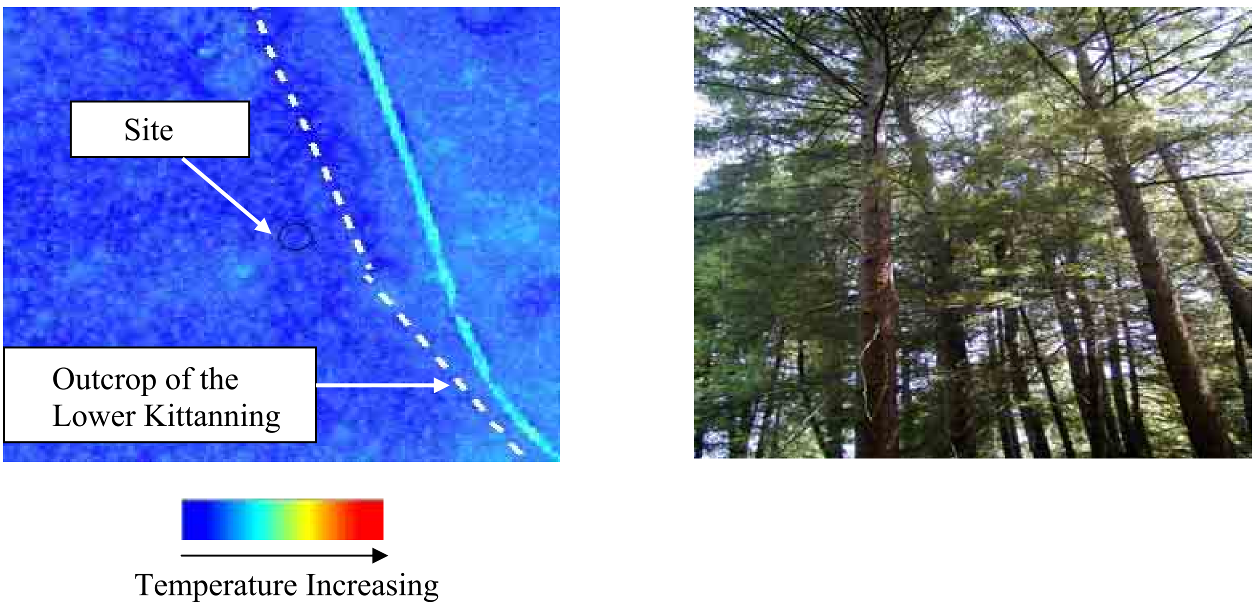


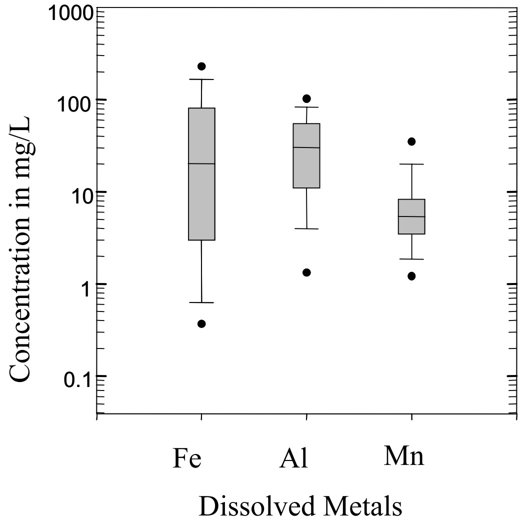
Figure 5. TIR image CWR6 and photograph of coniferous tree canopy over site

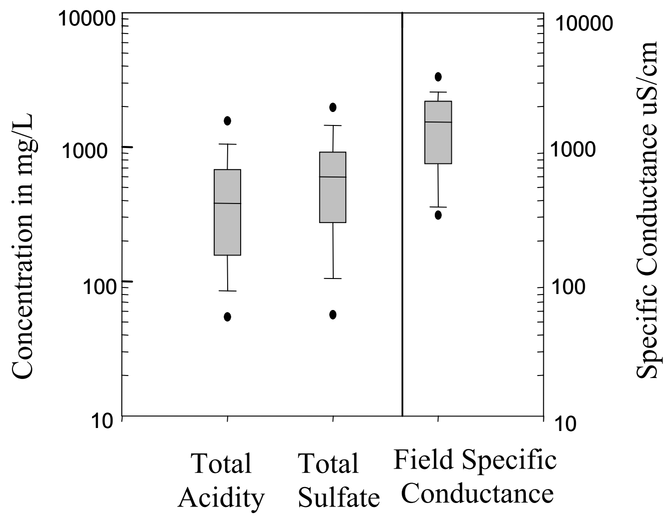
heavy equipment was parked. The heat source at the residential sites could be from a smoke stack, ventilation duct, or sewage discharge.

Water Quality

Water-quality data for the mine drainage sites are summarized in Figure 7. Water samples were collected for lab analysis at only 48 of the 53 AMD

Figure 6. Thermal infrared image of site 148 and photograph of wetland area at site 148





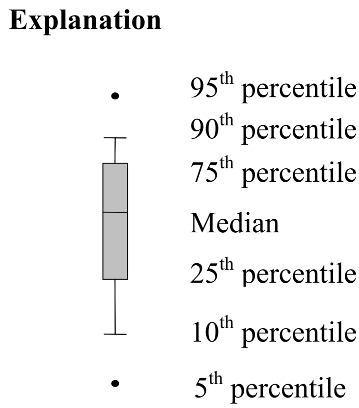


Figure 7. Boxplots of selected water quality parameters

sites. Low-flow conditions at the time of the field reconnaissance resulted in flow that could not be measured accurately at some mine-drainage sites. At some of these sites, the flow was very diffuse along a broad seepage zone. These sites were classified as AMD because of site conditions such as iron staining.

The water quality at all the AMD sites was acidic. Thirty-five of the 48 sites had a pH value less than 3. The AMD also contained high concentrations of dissolved sulfate and metals, especially iron, manganese, and aluminum. The mean aluminum concentration for the mine-drainage sites was 37.5 mg/L. The high concentrations of acidity and metals from mine drainages within the study area have resulted in 12.6 km of Cooks Run and 14.3 km of Kettle Creek being designated as stream reaches that do not support fish communities (U.S. EPA 1994).

Summary

The Kettle Creek and Cooks Run Basins are heavily affected by past coal-mining practices. Very little detailed mine mapping information was available for the study area, particularly on the source locations of AMD. This study demonstrated the utility of TIR data for watershed-scale assessment of mine drainage. Potential AMD sources were extracted from airborne TIR data employing custom image processing algorithms and GIS data analysis. A total of 132 TIR anomalies were identified as possible AMD sites. Based on field reconnaissance of 103 TIR anomalies, 53 sites (51%) were classified as AMD on the basis of their low pH (<4) and high specific conductance (> 400 µS/cm), plus visual appearance of ferric iron precipitates. Of the 53 AMD sites, 26 sites could be correlated with previously documented sites, based on historic data provided by the PA DEP. Twenty-seven mine discharges identified in the TIR data were not previously documented. Seven documented historic sites were not visible in the TIR data because of shielding by dense non-deciduous vegetation (conifers and mountain laurel).

The field and laboratory analysis of the mine discharges suggest that AMD sites were highly impacted by pyrite oxidation at nearby abandoned coalmines. The mean total acidity for the AMD sites was 704 mg/L (as $CaCO_3$). The pH ranged from 2.0 to 4.4 standard units. The mean concentration of dissolved aluminum was 37.5 mg/L.

Airborne remote-sensing technologies have unique advantages over the more traditional approaches of watershed-scale mine-drainage assessment. The TIR survey over 90.6 km^2 (35 mi^2) of remote and rugged terrain was completed in a single night. The development of a GIS database and TIR processing were completed by a two person team in approximately 3 weeks. Subsequent field verification involved another week by 4 teams of 3 persons. In comparison, a similar watershed investigation of mine discharges in the Stonycreek River Basin, although somewhat larger than the Kettle Creek Basin, took several years to complete (Williams et al. 1996). The TIR data collected for this study provided well-defined locations of thermal anomalies. The use of GPS for navigation saved significant field time in locating the sites, especially considering the terrain, and in some places, thick vegetative cover. Navigating to the sites in a quick and efficient manner made it possible to sample a large number of sites under the same hydrologic conditions, which is important when calculating loads for evaluating AMD priorities and designing remediation systems.

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References

Brewster SB (1999) Geometric correction system capabilities, processing, and applications. Proc, 4th International Airborne Remote Sensing Conf and Exhibition, Ottawa, Ontario, Canada

Lillesand TM, Kiefer RW (1994) Remote Sensing and Image Interpretation. John Wiley & Sons, NY, 3rd edit, 390 p

Rossman W, Wytovich E, and Seif JM (1997) Abandoned Mines -- Pennsylvania's Single Biggest Water Pollution Problem. Accessed Sept 10, 2002 at http://www.dep.state.pa.us/dep/deputate/minres/bamr/mining_012397.html

Sabins FF (1977) Remote Sensing: Principles and Interpretation. WH Freeman, NY, 3rd edit, pp136-147

Sams JI III, Veloski GA (2003) Evaluation of airborne infrared imagery for locating mine drainage sites in the Lower Youghiogheny River Basin, Pennsylvania, USA. Mine Water and the Environment (in this issue)

Shelton LR (1994) Field Guide for Collecting and Processing Stream-Water Samples for the National Water-Quality Assessment Program. USGS OFR 94-455, 42 p

Williams DR, Sams JI III, Mulkerrin ME (1996) Effects of Coal-Mine Discharges on the Quality of the Stonycreek River and its Tributaries, Somerset and Cambria Counties, Pennsylvania. USGS Water-Resources Investigations Report 96-4133, 103 p

U.S. EPA (1995) Streams Impacted by Acidic Drainage from Coal Mines in EPA Region 3, accessed June 14, 2002 at http://www.epa.gov/nsdi/projects/r3_mines.html#section6