Reconnaissance spatial analysis of the hydrogeology of closed underground coal mines

Annie J. Morris, Joseph J. Donovan, and Jane E. Thies

ABSTRACT

A method is demonstrated to employ combined mapping and field techniques to unravel complexities in the hydrogeology of flooded and unflooded underground coal mines of shallow (<120 m, <400 ft) depth. For a study area in the Appalachian coal basin, underground mines, coal outcrop, coal structure, and mine-drainage discharge locations were mapped onto an integrated geographic information system platform. The Upper Freeport coal seam (Allegheny Group) in the study area is relatively shallow (<120 m, <400 ft), with many closed free-draining mines and numerous discharges. The mapping of coal outcrop and structure was accomplished using (1) high-resolution aerial orthophotographs, (2) digital outcrop polylines, and (3) a coal-bottom structure surface created by geospatial interpolation of point data mostly abstracted from original mine maps. Mapping results integrated with field measurements of mine-water discharge allow inference of likely pool locations and potential interconnections between underground workings, which are not apparent from mine maps alone. The results are reconnaissance level in that the interpreted pool locations and depths are unconfirmed by drilling or water level measurement; therefore, any action based on such results should be preceded by fieldwork to confirm hypotheses offered by the reconnaissance analysis. Nonetheless, such a preliminary interpretation of hydrogeological conditions based on little or no subsurface (well) water level information may be highly useful for both interpreting subsurface conditions and for planning future research. The technique is based on a combination of mine mapping, digital analysis of geologic structure, and surface reconnaissance fieldwork. Results are directly applicable to areas of reclamation of shallow coal mining where mine closures have resulted in an uncontrolled discharge of mine drainage.

DOI:10.1306/eg.05200808001

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ACKNOWLEDGEMENTS

Nick Fedorko, Dave Jones, and Taryn Bell of the West Virginia Geological and Economic Survey provided georeferencing and mine-mapping support. Fieldwork assistance in identifying mine discharges was provided by Christina Rhoads of West Virginia University and by Keith Pitzer and Doug Ferris of the Friends of Cheat Watershed Group. Helpful review comments were offered by two anonymous reviewers. This investigation was supported by United States Environmental Protection Agency Region 3 in its Regional Geographic Initiative Program, project number 97320501-0 to the second author.

INTRODUCTION

Groundwater flow through abandoned coal mines is the principal source of acid mine drainage (AMD). Since the enactment of the U.S. Legislation in 1977 to regulate the discharge of mine drainage, tremendous resources have been spent on the reclamation of closed coal mines that produce AMD. The natural recharge rate of underground mines increases in response to an increase in the degree of fracturing of overburden over the coal, particularly in areas of shallow overburden cover (Stoner, 1983; Booth et al., 1998; Booth, 2002). Underground mines are also responsible for much of the AMD produced in sulfide-rich coal deposits worldwide (Younger, 2001, 2004). Such discharge from underground mines may remain acidic for 10 to 100 yr or longer after mine closure (Demchak et al., 2004; Younger, 2004). The degree of saturation (flooding state) of closed mines, rarely monitored or directly observed, can be a major factor determining the duration of acidic water production because highly flooded mines tend to restrict the availability of oxygen for pyrite oxidation.

Commonly, information regarding the flooding state of underground mines, their hydrogeology, is desirable but not routinely collected by coal operators or regulatory agencies. Examples of such situations include planning for long-term control of mine waters, treating or mitigating discharges that already exist, or, in areas of good-quality mine water, exploration for water supplies. In such situations, available subsurface information from wells, such as depths to coal and water level depth, can be very sparse or completely absent. This is particularly the case in mining districts where mines are old and long abandoned.

Mine maps are sources of both mining and geological information that are useful in understanding the groundwater movement in mines. Mine maps display mine geometry, mine-barrier boundaries, and elevation survey information. The motivations for retaining mine maps were originally driven by mine engineering and safety, but the information mine maps convey is equally relevant to the hydrogeology of closed mines. Coal outcrop and elevation contours from mine maps represent necessary data for projecting the flooded areas of mines onto maps (Younger and Robins, 2002).

Compiling and integrating such information from mine maps presents some challenges. First, although mine map archives exist, map availability is commonly limited spatially as well as temporally. For closed mines that fill wholly or partly with water, it is only the final closure maps that are of interest. Second, many old maps are of less-than-optimal quality, either because of the quality of the original mapping itself or to their method of archiving. Third, mine maps require accurate georeferencing to allow the integration of different scales and sources of mapping. Just as for map quality, amenability to georeferencing is specific to the individual map(s) of interest.

These problems tend to be most acute for shallow above-drainage mines. These mines are commonly older than deeper mines, simply because shallow coal is easily accessed from the outcrop. The development of flooded mine areas, in the terminology of North American mining engineers, ''pools'', is commonplace in closed below-drainage mines but less common in shallow mining. Nonetheless, interest in the function of mine water within such workings exists, which are commonly the subject of reclamation efforts to control the discharge of poor-quality mine water (Harper and Olyphant, 1993).

Recently, new methods have been developed to map underground mines and allow the projection of mining hydrogeology. Geographic information system (GIS) techniques offer new tools potentially applicable to such problems. Leavitt et al. (2003) mapped the extent of a below-drainage-deep mine flooding in the Pittsburgh coal seam using GIS techniques. Coal barriers, pillars, and mine interconnections were spatially referenced, digitized, and mapped from hundreds of different mine maps at a variety of scales. Monitoring well data were projected onto the mine mapping to generate two-dimensional mapping showing the regional distribution of mine flooding. However, most of the area of mining contained large below-drainage mines. Because the mine mapping was relatively recent (1980–present), high-quality mine maps with absolute coordinates were available for many of the mines. Also, structure contours for the coal seam were generally available from published sources, allowing this mapping to be executed to relatively high vertical accuracy.

This study is an attempt to extend the methodologies developed by Leavitt et al. (2003) to a region of generally older mining (closure dates generally prior to 1968) that has a combination of below- and above-drainage workings and less control over coal elevations. The study area is in the Upper Freeport mining district (Allegheny Group, upper Pennsylvanian) in northern West Virginia and western Maryland, including Preston, Tucker, Grant, and Mineral counties in eastern West Virginia and Garrett and Allegany counties in western Maryland (Figure 1). This area lies within the Appalachian coal basin, a region with a more than 200-yr

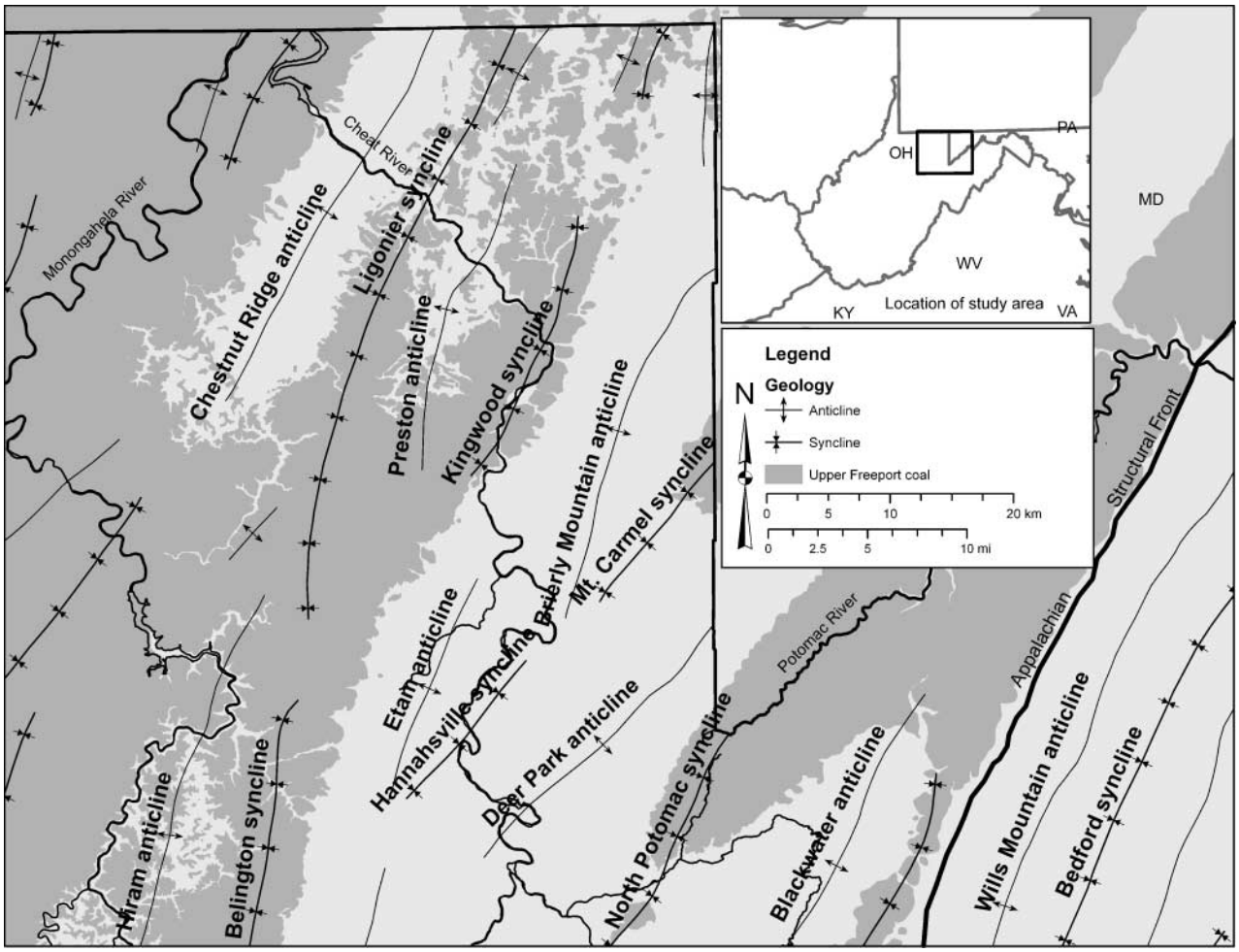

Figure 1. Location map of the study area, extent of the Upper Freeport coal (gray), and regional fold axes.

mining history; peaks in coal production occurred here during the two world wars and from 1970 to 2000 (Ruppert and Rice, 2000). Most mines in the study area are either above-drainage underground mines or surface mines near the outcrop, extracted by contour cut-and-fill methods.

The term ''above-drainage mines'' refers to those located more than 90% (an arbitrary percentage) above regional stream drainage elevation. Such mines in this area are commonly relatively shallow in depth (<60 m, <200 ft) and might, in general, be anticipated to be only partly flooded and open to circulation of oxygen in their unsaturated parts. As a result of this and the native high sulfur content of the Upper Freeport coal, these mines tend to produce acidic, low-pH discharge, typically found as springs or seeps from mine portals, fractured stream beds, or outcrops, commonly near the lowest elevation of mines. The term ''below-drainage mines'' refers to underground mines that lie beneath the regional stream drainage; these mines are generally deeper than above-drainage mines. These workings typically occur within large synclinal basins, like the Pittsburgh Basin, and cover large areas having limited visible outcrop exposure (McCoy et al., 2006).

PURPOSE

The purpose of this investigation is to examine the applicability of GIS-based mapping techniques in mapping the hydrogeology in an area of dominantly shallow above-drainage closed underground mines. Specifically, techniques are examined for their capability to (1) integrate mining with geological information, (2) develop geometries of coalbed structure and outcrop from a combination of mine-map and other mapping resources, and (3) infer flooded parts of underground workings from confirmed discharge locations. The study area chosen is a mining district in northern West Virginia in the northern

part of the Appalachian Coal Basin (Figure 1). This area consists of mostly (>90%) closed underground mining operations that are either flooded or free draining and have a well-established set of postmining hydrological conditions.

Several factors affect this set of objectives. First, the underground mining in this area generally occurred before 1968, so high-quality mine maps with absolute coordinates are not the rule. Second, the available geologic or coal elevation data, where present, were projected onto different base maps that, in some cases, are not adequately legible. Finally, many contour surface mines of uncertain dimensions are concentrated in the outcrop areas and also contribute mine discharges that may be confused for those of underground mines. These objectives are, however, relevant to ongoing reclamation efforts to intercept and treat the water from these mines. As a result, this research has direct bearing on the planning and execution of remediation efforts, where the identification of targets for water treatment may be aided by the knowledge of the location, size, and hydrologic conditions of source mines.

METHODOLOGY

GIS Framework

Reference data sets used in this study include 1:4800 3-m (10-ft) digital elevation models (DEMs), 1:24,000 digital raster graphics (DRGs), 1:24,000 national hydrography dataset surface hydrology, and digital natural-color leaf-off 1:4800-scale aerial orthophotography flown in February 2003 (West Virginia State GIS Technical Center, 2007). The digital photos have a vertical accuracy of ±3 m (10 ft). The DRGs are 8-bit rasters of U.S. Geological Survey topographic maps. All spatial analyses were performed using ArcMap© v. 9.2.

Mapping of Underground Mines

Since 1968, mine maps have been routinely collected and archived by the U.S. Office of Surface Mining, as well as by several state agencies. The mine mapping part of this study was completed in conjunction with the West Virginia Geological and Economic Survey (2006) and used original maps from their collection, most scanned at approximately 200 dots per inch (dpi). Of the various maps available for each mine, maps were selected based on date (closest to closure), legibility, quality of surface feature (roads, railroad, streams, buildings, and portals), quality of geologic information (structure and outcrop), degree of detail of mine workings, and availability of information on adjacent mines. Maps with a survey grid of known projection (e.g., State Plane) and datum were preferred, but most pre-1968 maps have either a proprietary survey grid or none at all. The latter could still be georeferenced in cases where multiple correlative surface features could be clearly identified on both mine maps and on DRGs.

The selected maps were spatially referenced to Universal Transverse Mercator (UTM) North American Datum 83 (NAD83) and cataloged by the index number of the map. The georeferencing approach varied case by case but the most common technique was by surface feature correlation at 1:24,000. In rare cases, georeferencing was based on the correlation of the mine-map outcrop to the one estimated from topographic contours and/or air photos. Georeferenced maps were checked for accuracy with respect to independent surface features such as streams, confluences, roads, bridges, outcrops, and other mine maps. Efforts that did not pass this consistency check were redone using other features or approaches. Errors in georeferencing may be indicated by gross distortion of the mine-map image or, alternately, by discrepancies between geological information and mine mapping. For example, an error in one or the other of the two map features is indicated when mine outlines overlap the outcrop.

Following the verification of accurate georeferencing, mine outlines were digitized to show as much detail as was visible on the original scanned mine maps. Internal coal barriers of more than 4 ha (>10 ac) were also digitized. Individual pillars were not mapped because the accuracy of their location and preservation from retreat mining is not verifiable and likely highly variable from map to map.

Mapping of Mine Discharges

Mine discharges were most commonly located by walking major tributaries of the Cheat River drainage and noting locations where mine drainage, recognizable by low pH and/or metal-rich chemistry, enters these tributaries. Such confluences were mapped using 20-m (66-ft) or better handheld GPS instruments, and in many cases, the mine-drainage influent stream could be traced a short distance upgradient to its source, which was also accurately located. If not, the confluence location was used to search for the mine-drainage source discharging from the ground. The actual ground-surface source location for the mine drainage, not the stream

confluence, was mapped. Sources included mine portals, pipes, culverts, wetland drainage, and features resembling springs. Mine drainage originates from both surface and underground mine workings in this area, with the latter tending to be larger in area and generally having larger discharge rates. If the discharge was sufficient, flow measurements were taken by either flowmeter or bucket-and-stopwatch techniques. Water chemistry was estimated using portable field meters for pH and specific conductance to discriminate mine from nonmine discharges. Standard methods were used to calibrate these instruments and collect these data.

Spatial Analysis of Coalbed Structure and Outcrop

A four-step procedure was used to map coalbed structure and outcrop: (1) point bottom-coal elevation sampling from multiple sources, (2) interpolation of coalbed structure contours from the point data and error and outlier analysis, (3) digital intersection of coal surface with ground surface from the DEMs to create the outcrop as a polyline, and (4) cropping of the structure contour polylines to the outcrop.

Coal elevation data were compiled from several sources: mine-map structure contours, mine-map outcrop locations, and borehole logs of coal stratigraphy. Coal elevation points were sampled along mine-map structure contours, using the contour elevation as the Z value; at outcrop locations shown on mine maps, again obtaining the Z value from the contour values; and where outcrop data were unavailable from mine maps, from the outcrop of Ruppert et al. (2000), verified using orthophotography and with elevations determined from their location using the 3-m (10-ft) DEM values. The sampling of outcrops and coal-mine structure contours was done every 200–400 ft (656–1312 ft), on average. Approximately 5042 points were compiled within the study area.

Interpolation of the bottom-coal elevations into structure contours was performed using Surfer© v. 8.0. The coal is folded in the study area along a more or less uniform strike azimuth, and thus, a strong nonstationary regional trend in coal elevation is observed, because of which, kriging was not used as an interpolation approach. Instead, a local polynomial regression method was employed to interpolate the data using 30-m (100-ft) grid centers, employing anisotropic sampling regions around each grid cell and performing local high-order polynomial fitting. The point data set was searched for outliers using, arbitrarily, a four-standard deviation separation from the residual mean to define the outer limit of valid point data. Six-meter (20-ft) structure contour lines of coal elevation were interpolated from the resulting coal elevation grid then smoothed to remove jagged-edged digital artifacts. Polyline lengths were calculated as a new field and sorted, and lines shorter than 500 m (1640 ft) were eliminated if possible to reduce interpolation artifacts.

From the gridded coal elevation surface, an outcrop polyline was interpolated by subtracting this raster from the 3-m (10-ft) DEM to create a difference grid. Its values were positive valued where the coal lies in subcrop and negative valued where the coal has been eroded away. Grid cells of nearly zero value represent the approximate location of the outcrop. Grid cells within 1.5 m (5 ft) ± zero difference were attributed and vectorized into a polyline representing the outcrop location, and smoothed to a tolerance of 75 m (246 ft) to minimize pixilation. Isolated very short (<100 m, <328 ft) polyline segments were interpreted as artifacts of interpolation where point density was sparse and removed. Hand editing was performed to adjust the outcrop polyline to the digitized mine polygons by extending the outcrop around mine areas where the two overlapped. If a scanned mine map showing the outcrop existed, the outcrop polyline was edited to agree with the map. If the mine maps lacked adequate outcrop data, the high-resolution orthophotography was used to edit the outcrop; these photos mark the outcrop by a line of revegetation on top of the mine-spoil piles along the perimeter of surface mines. If both mine maps and air photo images were unhelpful, the outcrop was edited to fit published coarse-scale outcrop mappings (Ruppert et al., 2000). Finally, the outcrop polyline was converted to a polygon representing the subcrop area of the coal. The aerial photos were useful to confirm the location of the outcrop with respect to vegetation disturbance and perimeter sediment-control ditches.

Once the outcrop mapping was finalized, the structure contours were clipped to lie within the final subcrop area. For areas where only outcrop point data were available (e.g., no points from mine maps), structure contours were not produced because these areas lacked sufficient elevation data to create accurate contours.

Estimation of Groundwater Conditions

The mine-flooding extent was estimated using georeferenced underground mine maps, DRGs, coalbed structure contours, outcrop location, and accurately measured locations of mine-water discharges. A key element of this interpretation was the correlation of specific

mine discharges to specific underground or surface mines. Commonly, mine discharges would occur close to and on the same side of the watercourse as mapped portals of underground mines; in such cases, the correlation between mine source and discharge was straightforward. In other locations, discharge would occur not from portals or mine openings but from pipes or culverts whose source within a mine was buried. These were interpreted as wet seal discharges; the source mine was inferred from the direction of the pipe with respect to mine mapping. The key feature, in both cases, was to look for portals on the mine maps in the downdip part of mines or complexes of mines; experience indicates that, in this mining district, these downdip portals were preferred locations to drain water during mining operations. Discharges from surface mines could be recognized by a dendritic drainage pattern with sources (springs) along mine-spoil slopes. In general, more than half of the mine discharges could be confidently associated with specific mines using mine mapping and discharge locations, and the balance was correlated but with a lower degree of confidence.

Once discharges were correlated with mines, the flooded part(s) of each mine were projected assuming that the elevation of its discharge was a spatially uniform hydraulic head throughout the mine. If the discharge elevation was to lie below the elevation of most or all of the mine workings and no higher discharges were present, the mine's water status was interpreted to be free draining, that is, no mine pooling.

The projected flooded extent within the mine was mapped as polygons bounded on the updip direction by the interpolated line of saturation (the beach), a structure contour line at the exact elevation (hydraulic) head of the discharge itself. The other boundaries of the polygons were the saturated perimeter coal barriers of the mine, at elevations lower than the beach. Downdip of the beach, the mine is interpreted to be fully saturated, and above it, partially or wholly unsaturated. This extrapolation-based interpretive technique has potential for several types of errors, including (1) error in the structure, (2) error in the mine mapping or the original mine map itself, (3) error in the identification of the mine source of the discharge, (4) error in the assumption of minimal head variation within the mine, or (5) lack of awareness of multiple pools within a mine. The interpretation of actual pool area and extent requires confirmation by water level measurements within wells in the mine before it may be accepted as reliable. However, if the mine geometry, coalbed mapping, and discharge source interpretation are all accurately mapped, this extrapolation can be a useful preliminary predictor of actual groundwater conditions, as well as a tool in further data collection, location of potential well sites, and design of reclamation.

RESULTS

Spatial Analysis of Geology and Structure

Because of the elongate nature of the study area and folding with strike parallel to this orientation, some special challenges are offered for interpolation of structural data. Kriging of this data set would seem an attractive option, but because of the presence of strong regional trend, it would be impossible without an unambiguous separation of this large-scale trend from local-scale, more random-like variations. Therefore, the use of a local interpolator with a capability for search anisotropy was favored, given that a spatially continuous distribution of points in this study is observed; this is counter to past comparisons between local interpolation and ordinary kriging (e.g., Yang et al., 2004).

The coal structure was interpolated by a local polynomial regression with sectored elliptical search regions, placed around 30 × 30-m (98 × 98-ft) grid centers (100 × 100 ft, 30 × 30 m). To accommodate the folded nature with consistent strike from place to place, the interpolation employs anisotropic (1200 × 500 m, 3937 × 1640 ft) search regions with a long axis oriented parallel to strike; initial interpolation results are shown in Figure 2. The search ellipse for each grid node was broken into four sectors; within each ellipse, a minimum of 8 points were required to avoid blanking of data for that node. The mapping of Figure 2 extends beyond the actual outcrop and includes the extrapolation of the coal in areas where it is currently eroded away. It therefore includes a perimeter with edge effects (incorrect contour levels created by extrapolation past the extent of actual data) and a few data points that are interpreted as outliers. These outliers were identified by residual analysis of the surface in Figure 2; these residuals are normally distributed (Figure 3) and most lie within ±3 m (±10 ft) of the near-zero mean residual. This magnitude of error is probably lower than the absolute accuracy of the outcrop elevations interpolated from DEMs based on location. In the first iteration of residual analysis, the standard deviation of the residual distribution (Figure 3) was 5.0 m (16.3 ft), a value elevated by the relatively large residuals at the perimeter of the coal outcrop where edge effects are incipient.

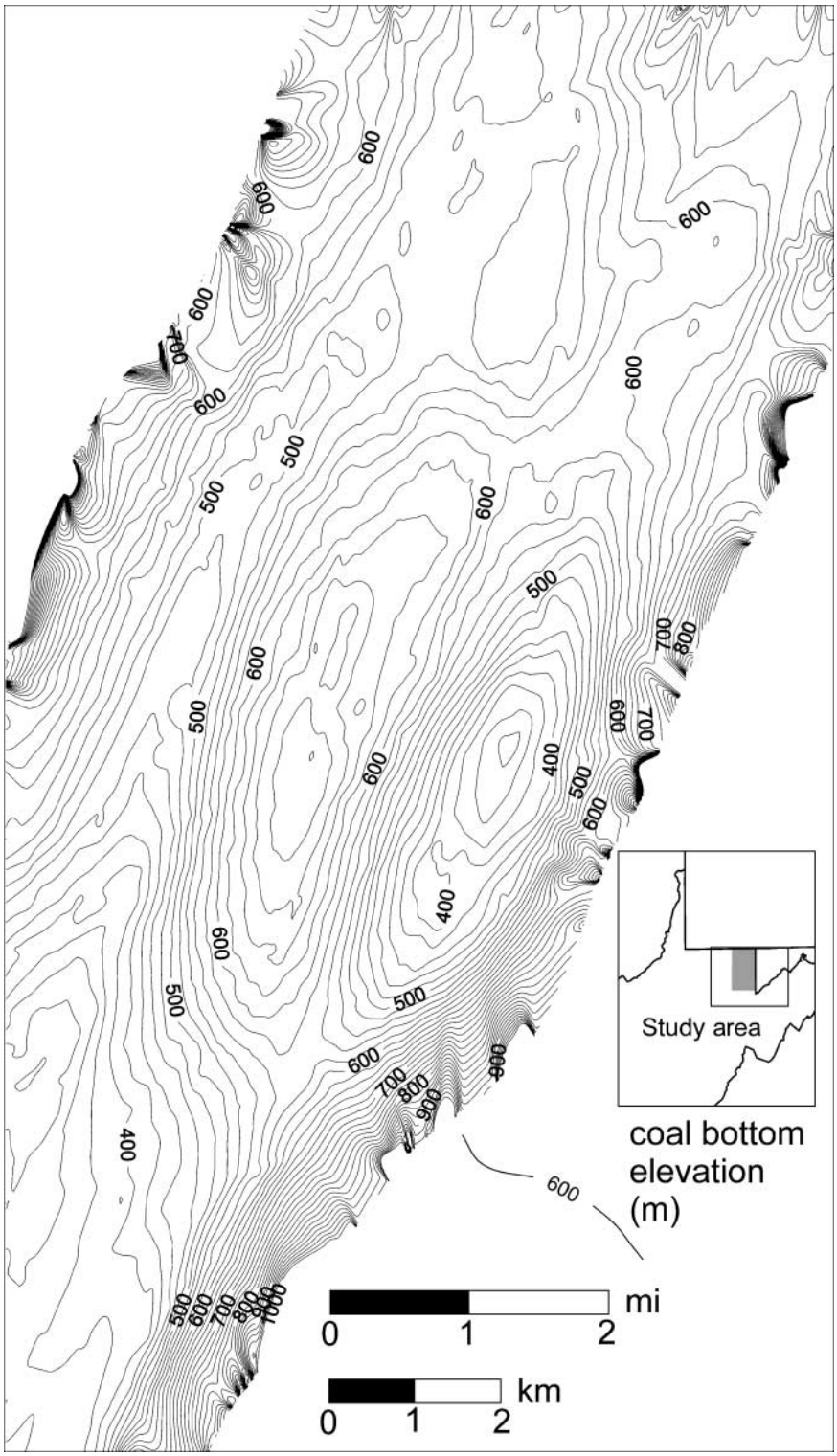

Figure 2. Preliminary interpolated coal-bottom contours, in meters above sea level (ASL); without outcrop, not shown. See Figure 1 for the location.

Seventeen (out of 5042) residuals more than 4 standard deviations (>19.5 m, >64 ft) were identified and deleted as outliers interpreted as either inaccurate or bad data, or unmapped faulting. For the final culled elevation points, the interpolation yielded an R^2 of 0.9953 for modeled vs. observed elevations (Figure 4), a mean residual of 0.002 m (.007 ft), and a standard residual deviation of 2.10 m (6.91 ft). Edge effects appear to have little impact within the area of interpolation. The distribution of residuals is shown in Figure 5, contoured

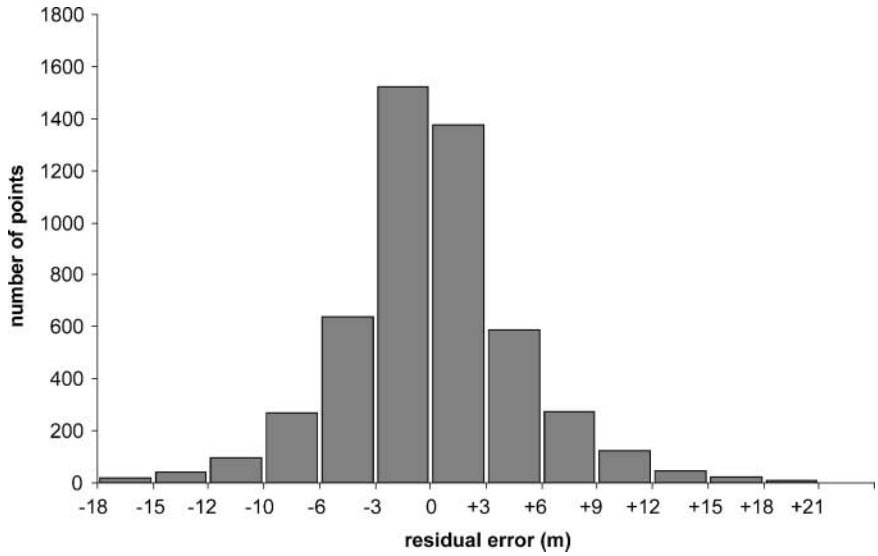

Figure 3. Histogram of residual errors (meters) between data point and interpolated coal-bottom elevations at the same locations.

from −3 to 0 m (−10 to 0 ft) (white pattern) and from 0 to +3 m (+10 ft) (dark pattern). Virtually all modeled elevations lie within ±3 m (±10 ft) of the point data used to generate the surface. These results suggest that the interpolation is both unbiased and robust.

Figure 6 shows the final version of the geologic model, with the outcrop superimposed on the coal surface and stream coverages added.

Spatial Analysis of Hydrogeology

Figure 7 shows a map of mining hydrogeology within a series of inferred saturated and unsaturated (mine pool) areas that underlie the vicinity of Heather, Lick, and Pringle runs (see Figure 6 for the index location). This map is exemplary of the features used to develop the GIS data set for hydrogeology, including

- vector outlines of original mine maps (medium gray in Figure 7);
- Upper Freeport coal subcrop (light gray in Figure 7);
- coal outcrop (line enclosing subcrop);
- saturated pools within partially flooded mines (darkest gray);
- structure contours of the bottom of the coal, shown with 30-m (98-ft) contour intervals; and
- mine discharge locations (circles).

In addition to these mapping features, interpreted divides between regions of the mines contributing to

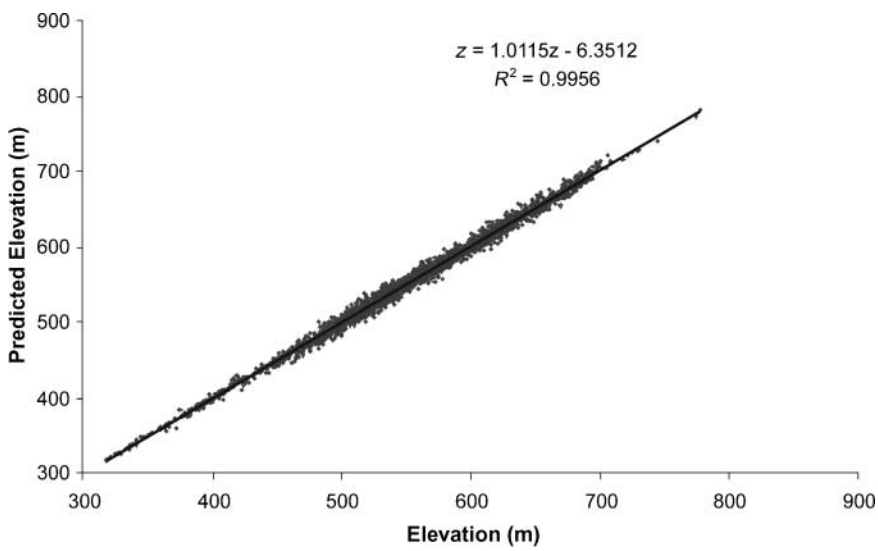

Figure 4. Correlation between data point and interpolated coal-bottom elevations.

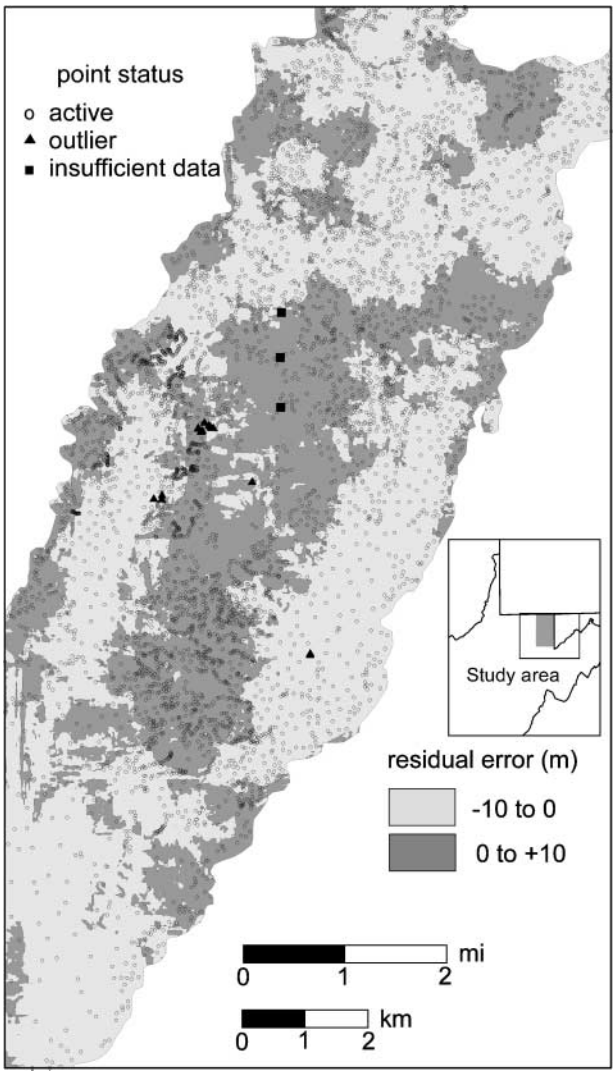

Figure 5. Contoured values of residual error in interpolated elevations, with data-point locations (circles), outliers (triangles), and locations where no interpolation was performed because of data shortage (squares).

distinct discharges are sketched in (dashed lines) as well as interpreted schematic flow paths of water in the vadose parts of these mines (arrows). The pattern of mapping allows a detailed estimation of the source areas for water of the various discharges and of the approximate flow directions in both vadose and saturated areas of these mines (arrows in Figure 7).

Figure 7 shows that the coal dips eastward (left to right), in the same direction as the flow of the three parallel streams. Because of the somewhat complex coal structure and the nonlinear slope of the streams, the coal displays a somewhat unusual exposure pattern, with outcrops forming several islands where coal is eroded away along stream bottoms as well as a downslope-trending vee pattern of the outcrop along Lick Run; in horizontally bedded strata, outcrops invariably form upstream-trending vees. This unusual pattern results from the deformation of the coal at both large and small scales.

The pattern of mine discharges to streams is a telling indicator of the hydrogeologic relationships between mines and, in particular, the integrity of mine barriers in restricting flow. From the mine mapping alone, most of the workings within mine A appear to be hydraulically interconnected, with no apparently continuous internal coal barriers. In contrast, apparently intact barriers between the mine D (Lick Run), mines B and C (Heather Run), and mine A exist; as a result, water discharges from these three mines into their respective streams at the crop, reflecting small pools, and does not simply flow downdip into mine A. Mine A itself, however, has only a single water discharge (the circled 1 in Figure 7) along Lick Run, a very large flow (by one measurement, 7570 L/min or 2000 gal/min) at the downstream end of its undermining of Lick Run; it also clearly is undermined beneath three different streams, with discharges to each in different locations dictated by mine openings and internal barriers. The volume of the discharge (circled 1 in Figure 7) combined with a lack of similar downdip-end discharges beneath undermined Heather and Pringle runs corroborates that the Lick Run discharge captures mine water from an extremely large catchment and as a result is preventing discharges to these other streams.

Several types of mine pools are shown in Figure 7: main pools, pools suspended on pillars, and perched pools. The feature labeled as circled 2 is a partially flooded mine in which two separate pools straddling Heather Run discharging to two separate portals are observed, on either side of the stream. Neither discharge is at the lowest coal elevation mined, indicating that a pool must be present in both cases. The feature labeled as circled 3 is an internal pool, suspended on an interior coal pillar instead of the downdip limit of the mine. In this case, the pillar was visible on the original mine map allowing for the delineation of the pool, but that it is continuous and relatively impervious may only be extrapolated from its hydraulic behavior, i.e., the discharge location. Downdip of this discharge location, only a single large discharge (feature 1) at the most downdip edge of the mine complex is seen. The location of this discharge indicates that it is not accompanied by a pool and is a free-draining discharge. However, several spill pools updip of this main discharge in locations where groundwater is impounded to some depth against unmined coal are

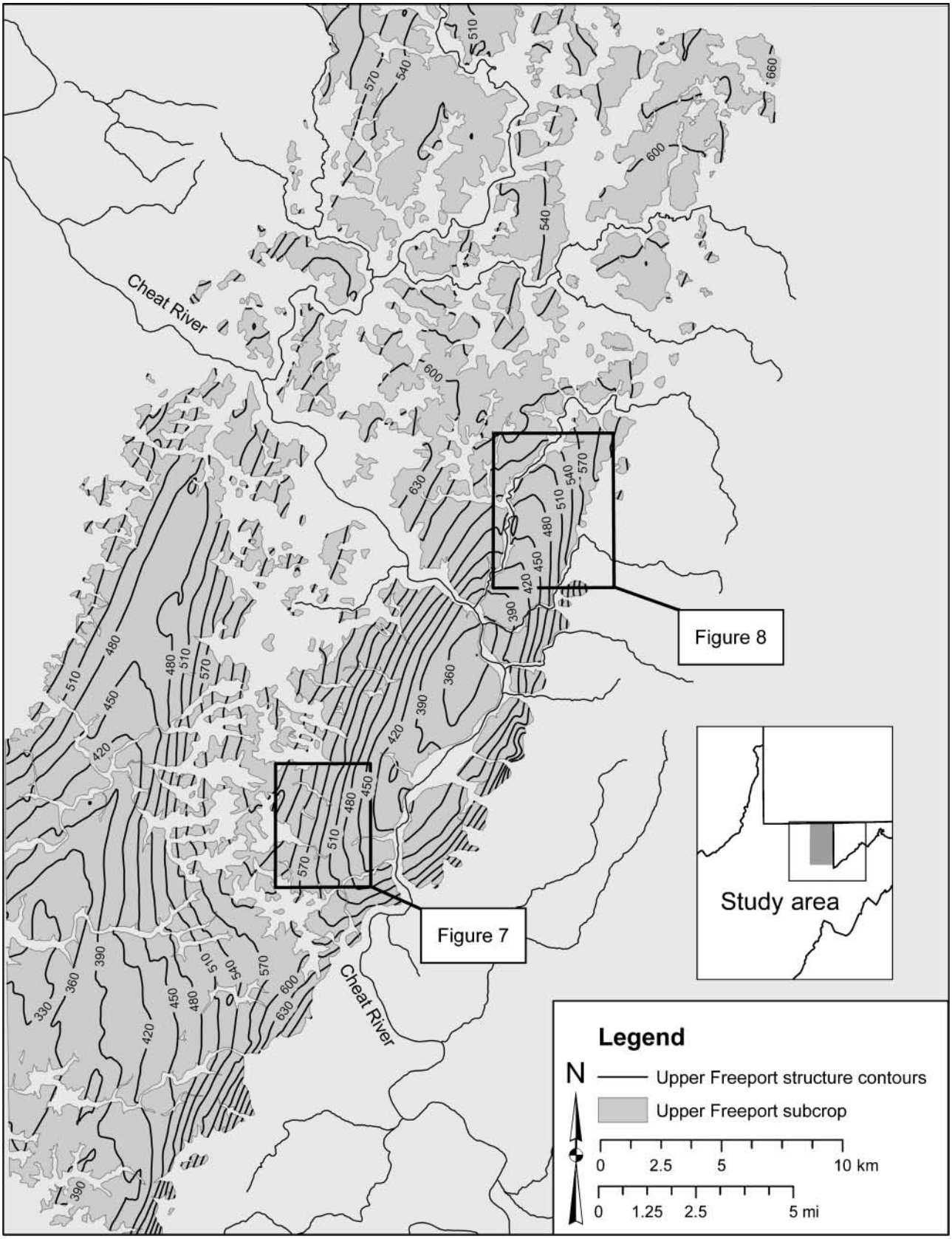

Figure 6. Final interpolated surface with GIS overlays of coal outcrop and stream locations.

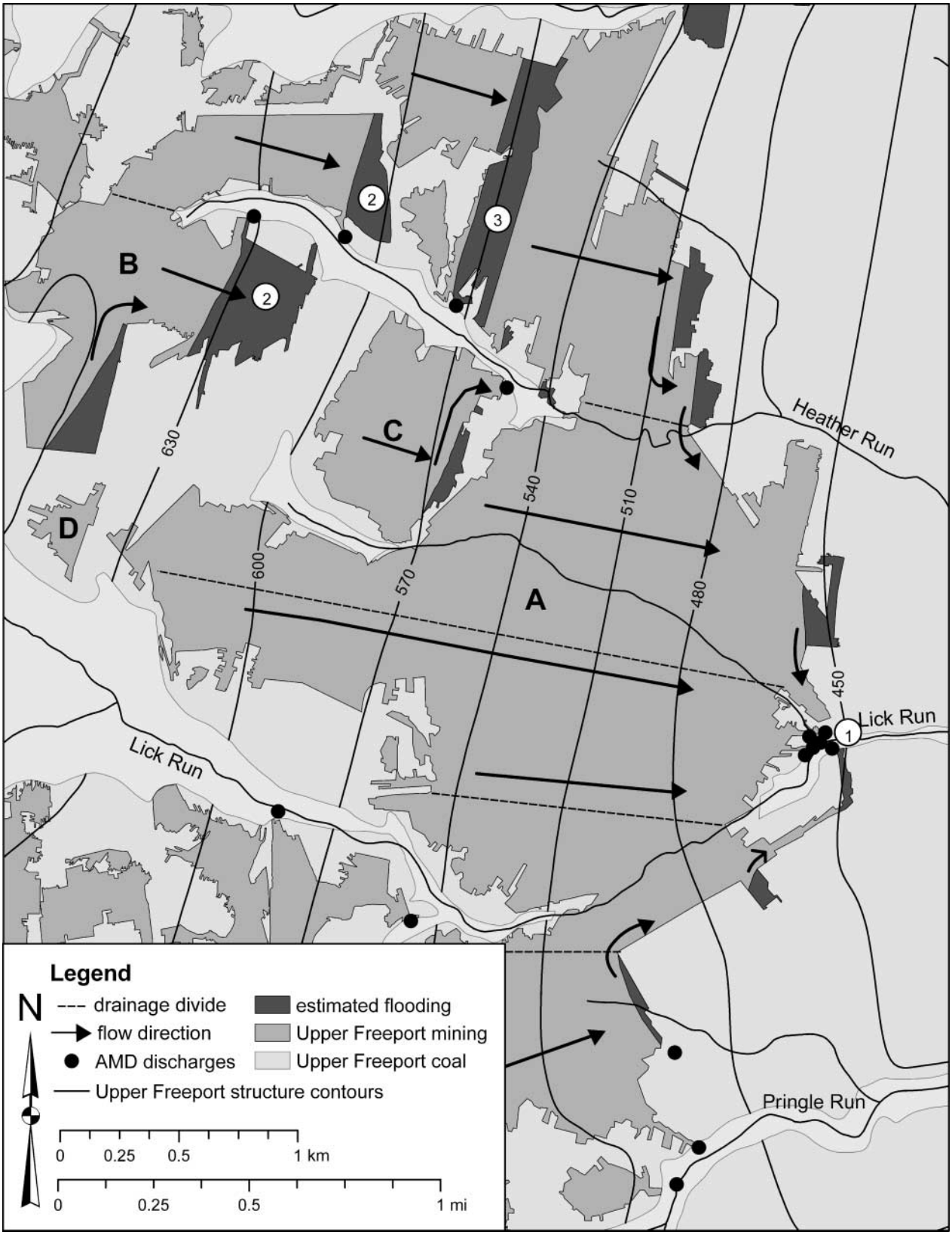

Figure 7. Hydrogeology of mines A, B, C, and D near Lick, Heather, and Pringle runs, Preston county, West Virginia, showing coal subcrop (light gray), unsaturated mine areas (medium gray), and saturated mine pools (dark gray). Also shown are mine discharges (circles), approximate groundwater flow paths (arrows), and flow divides within mines (dashed lines). Numbered circles indicate saturated mine areas referenced in text. See Figure 6 for the location and the text for a detailed discussion of circled features 1–4. AMD = acid mine drainage.

observed. Such spills mark points along the flow path of groundwater in the vadose zone leading to discharges farther downdip. In summary, four different styles of mine-water hydrology are shown in Figure 7: composite pools, interior pools, spill pools, and free-draining discharges without pools.

Also visible in Figure 7 are mine-water divides, locations in a mine where mine-water flow paths diverge toward separate discharge locations. Such divides are defined by a combination of the geometry of the mine, the geometry of the coal surface, and the location of discharges. Because the coal in mine A dips instead uniformly to the east, the locations of all divides are determined simply by mine geometry and discharge location.

Figure 8 shows a similar hydrogeological map for mining in the Muddy Creek watershed (see Figure 6 for the location). This is a more conventional outcrop pattern, which vees upstream along Muddy Creek and coal outcrop following an approximate contour. The mine mapping shows intact coal barriers between a series of five mines lying between parallel south-flowing tributaries to the Cheat River (Muddy Creek, left; Roaring Creek, right; Figure 8). The coal lies in a south-plunging syncline whose axis is close to the location of Muddy Creek itself. The mines adjacent to Roaring Creek (mines G, H, and I) are all at a higher structural elevation than mines E and F along Muddy Creek. The closure dates of each of these mines are as follows: mine E, 1943; mine F, 1947; mine G, 1991; mine H, 1998; mine I, 1971. Because each mine is relatively small (<60 ha, <150 ac) and shallow (mostly <100 m, <328 ft), it would be expected that if hydraulically isolated from its neighbors, each mine would have its own discharge. Based on mine maps and portal locations, the likely sites for the discharges of mines E and F would be located along Muddy Creek and of mines G, H, and I along Roaring Creek.

However, the field survey of discharges found only one discharge from these five mines, issuing from the main portal of mine E. It is a historic discharge that has been flowing for several decades, likely prior to 1970 (the most recent map for mine E is dated 1943, and it likely closed prior to 1960). Its current discharge ranges seasonally between about 750 and 2650 L/min (200 to 700 gpm) based on profile measurements in different seasons with a Doppler-style flowmeter. None of the other four mines shows a current acidic discharge, except one small (<15 L/min, <4 gpm) discharge thought to issue from a surface mine along Roaring Creek.

The lack of drainages from these five closed mines, all closed for 10 yr or much longer, suggests that these mines have been hydraulically interconnected resulting in flow by gravity drainage to the mine E discharge. Figure 8 shows the inferred mine-pool distribution based on assumptions: (1) accuracy of the general distribution of mining and of coal structure, (2) drainage by gravity of mines H and I water through unmapped openings into mine G, and (3) drainage by gravity of mines G and F through unmapped openings into mine E. Although speculative, these hypothetical interconnections will only be disproved either by drilling or surface discharge from mines F, G, H, and I after these mines completely fill with water. The inferred pool geometry under this interconnected mines hypothesis (Figure 8) may be reconstructed by (1) coalbed geometry, (2) locations of inferred spill points between pools, and (3) speculated locations of openings between mines. Although pools are indicated to be present in mines G and H, no pool is indicated in mine E, which appears to be almost completely free draining to the discharge outlet.

These hypotheses go beyond the mine mapping, and in fact suggest that the available mine maps are at least partly in error. This is because the hydrogeologic observations (mapped discharge locations or lack thereof) are at direct odds with the lack of interconnection between mines. The hypothesized configuration of mine water would have to be the result of either an inadvertent or operational interconnection of mines to allow drainage to a single location. This interconnection is in fact environmentally advantageous in that it allows the capture and treatment of acidic mine waters from a single discharge location and has been instrumental in preserving one of these two streams (Roaring Creek) from acidic mine-water pollution. The speculated interconnections have not been proven and would require additional facts (perhaps, locations of pools with the indicated hydraulic heads) to prove or disprove these hypotheses. Therefore, the mine mapping of this particular complex is likely to become the basis for future planning to ascertain the long-term fate (or, perhaps, its present condition) in this two-stream basin. This is a good example of a case where, despite being speculative, such mapping is a key tool for testing scientific hypotheses instrumental to solving or preventing environmental accidents related to mine discharges.

Sources of Uncertainty

It must be re-emphasized that this is a reconnaissance method based exclusively on mine mapping, geologic reconstruction, and surface reconnaissance of mine discharges. In the absence of specific subsurface information

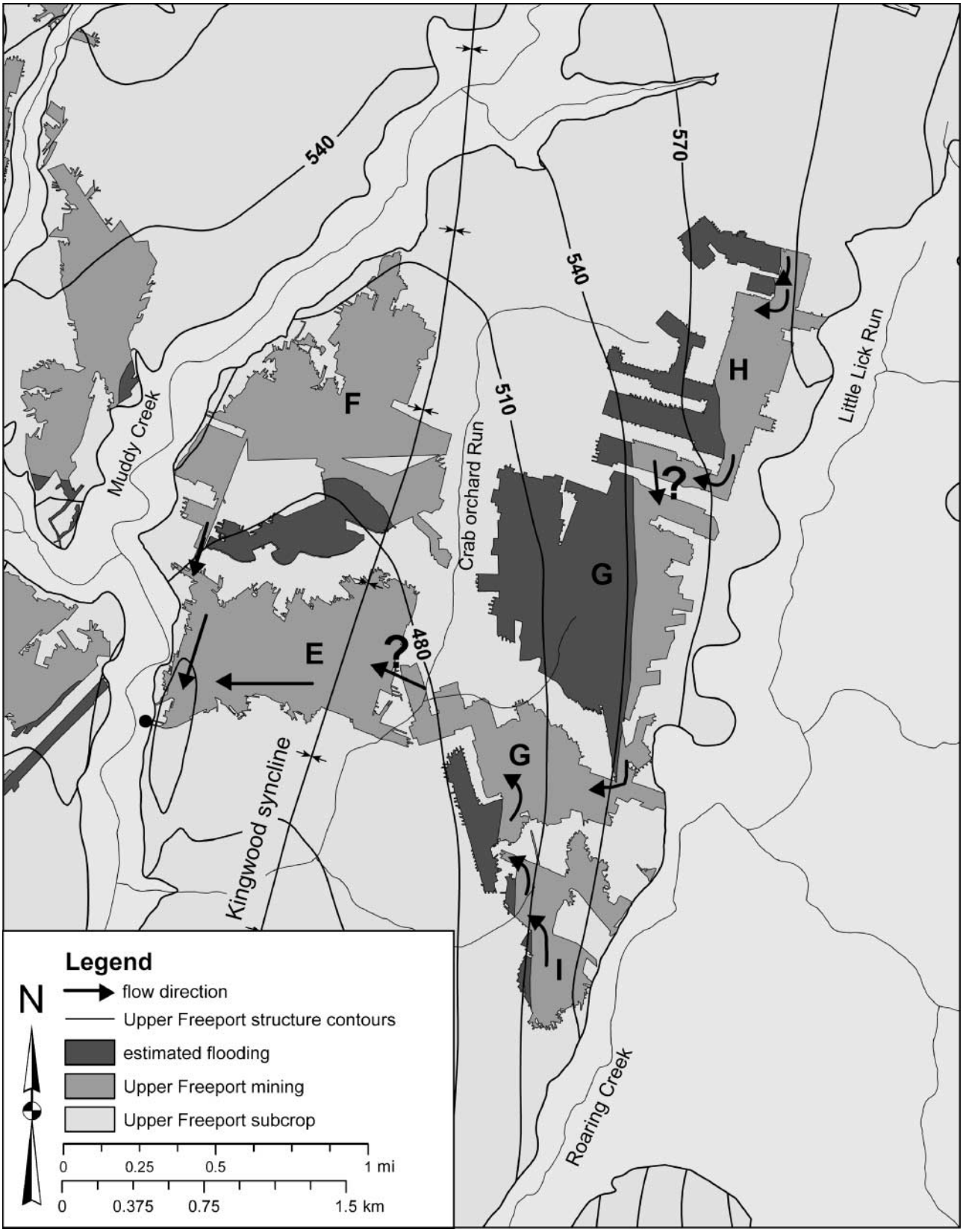

Figure 8. Hydrogeology of mines E, F, G, H, and I, east of Muddy Creek, Preston county, West Virginia, showing coal subcrop (light gray), unsaturated mine areas (medium gray), and saturated mine pools (dark gray). Also shown are mine discharge (circle) and approximate groundwater flow paths (arrows). See Figure 6 for the location.

describing water levels in underground mines, these results must be considered tentative and hypothetical. A considerable potential of error in the foundation of information on which these interpretations are based is also observed. The greatest among these sources of error are thought to be (1) unreliably georeferenced or poor-quality mine mapping, (2) missing or partially available maps of underground mining, (3) poor documentation of the interconnections between mine mapping, and (4) incorrect correlation of mine-discharge water with its source mine.

Despite the shortcomings and risks of these data, their projection onto a common map base can by itself be a powerful tool for developing hypotheses that can be tested by collection of field data, and of great utility in identifying where subsurface information is needed. Therefore, the development of reconnaissance mapping of this type is considered a major step forward in the understanding of the postmining hydrogeology of underground coal mines and a prerequisite step for further investigation.

DISCUSSION AND CONCLUSIONS

Using spatially referenced public archive maps of closed mines, coal structural information abstracted from these, mine discharge locations, and GIS and geostatistical tools, this investigation produced reconnaissance GIS mapping of mining, coalbed structure or outcrop, and extrapolated (yet unsubstantiated) mine-flooding areas. The accuracy of these mapping products is spatially variable and mostly dependent on the availability and quality of the original mine maps. Areas with dense coverage of well-surveyed mine maps are likely to show accurate mapping. Areas lacking a good-quality mine-map coverage are likely to display lower quality mapping.

Mine workings in the Upper Freeport coal seam consist of mostly above-drainage underground mines, but some local areas of below-drainage mines are observed, in which pools of mine water are concentrated. Mining operations tend to be concentrated around synclinal basins whose structure controls stream geomorphology, influencing larger drainages to run parallel to the northeast–southwest regional strike. Because of the structural location of the coal and mine design, most above-drainage mines are free draining.

Mining hydrogeology may be substantially represented by (1) mapping the area of mine resaturation (flooding) and (2) mapping the location(s) of discharges from specific mines. For closed mines without treatment, these two may be related if the discharge is of an overflow, or spill, variety (Younger, 2004). Therefore, a key feature of the mapping is to correlate specific mine discharges with specific mines. With mining information, spill elevations, and structural information, the extent of flooding area(s) (pools) may be interpolated. Alternately, if the mapping shows that the discharges occur at or near the deepest opening in a particular mine, an interpretation may be drawn that the mine water is free draining, with a corresponding unrestricted access of oxygen to the mine.

The mapping of underground mines has several implications relevant to the hydrogeology of mine water. First, the style of mining in this terrain and depth of coal involves mining of coal beneath interfluves of major streams and only in some locations undermining creeks themselves. Stream undermining seems to have been performed only locally, perhaps in response to local conditions of roof leakage. Second, most discharges report to portals or openings along stream drainages. Third, the discharges generally report to streams at or near the lowest point in mines or, in complexes of multiple mines, at the lowest mine in the complex.

The hydrogeology of flooded mines is to a large degree determined by coalbed structure and discharge location. The elevation of mine pools is commonly controlled by either (1) spill points or (2) portal discharge location. Many mines have their portals at the lowest structural elevation of mined coal, and numerous discharges are found here. Only mines with higher elevation discharges, internal coal barriers, or irregular geometries (i.e., Figure 8, mines F, I, G, and H) are likely to form pools. The distribution of discharges, and of contaminated watersheds resulting from these, is controlled by a regional geologic structure, which in turn controls stream location and the location of underground mining.

The purpose of the investigation was to test the viability of extending the hydrogeological mapping of underground mines from deep below-drainage mines to shallower, less saturated mostly above-drainage mines. This test result was positive in that (1) sufficient mine maps were available to continuously map mines and preserve barrier relationships between mines over a regional mining district and (2) mapping of mine discharges allowed inference of the likely extent of flooding in several cases. Two key factors allowed for the mapping to attain success in this area: the availability of high-resolution aerial photographs and the ability to develop an effective geologic model by digital methods. The state addressing and mapping board photos were are

an effective aide to both mapping and discharge location. The spatial projection of the Upper Freeport outcrop was modified to fit land features in the orthophotographs. The high resolution of the photos made it possible to successfully link discharges to their source mines. This is a key advantage in implementing hydrogeologic mapping where orthorectified high-altitude photography is available. Without the availability of both the aerial orthophotography and the high-resolution digital outcrop model, the accuracy of mapping results would have been greatly lessened.

Despite the potential for inaccuracies in reconnaissance mapping of this style, the products show strong utility for planning and implementation of mine-water treatment and reclamation projects, and may also become techniques for water development in areas of suitable mine-water quality. In mines of this depth, mine size is commonly closely correlated with mine discharge rate; therefore, simply correlating mines with their respective discharges can, based on mine area alone, give a useful indication of the expected magnitude, on a long-term basis, of discharge from specific locations. Such benefits accrue from a close integration of geological, mine, and hydrogeological mapping techniques described herein. These techniques are thought to have broad applicability because, in many mined areas, both mine mapping and GIS resources are broadly available; however, implementation will require the integration of field hydrologic studies with map- and geological-data synthesis of the style outlined in this work.

REFERENCES CITED

Booth, C. J., 2002, The effects of longwall coal mining on overlying aquifers, *in* P. L. Younger and N. S. Robins, eds., Mine water hydrogeology and geochemistry: Geological Society (London) Special Publication 198, p. 17–45.

Booth, C. J., E. D. Spande, C. T. Pattee, J. D. Miller, and L. P. Bertsch, 1998, Positive and negative impacts of longwall mining on a sandstone aquifer: Environmental Geology, v. 34, no. 213, p. 223–233.

Demchak, J., J. Skousen, and L. M. McDonald, 2004, Longevity of acid discharges from underground mines located above the regional water table: Journal of Environmental Quality, v. 33, p. 656–668.

Harper, D., and G. A. Olyphant, 1993, Statistical evaluation of hydrologic conditions in the vicinity of abandoned underground coal mines around Cannelsburg, Indiana: Journal of Hydrology, v. 146, no. 1–4, p. 49–71.

Leavitt, B. R., J. J. Donovan, A. J. Morris, and E. Werner, 2003, Modeling of mine flooding in the Pittsburgh Coal Basin, U.S.A.: Proceedings of the 6th International Committee on Acid Rock Drainage, Cairns Australia, p. 1065–1071.

McCoy, K. J., J. J. Donovan, and B. R. Leavitt, 2006, Horizontal hydraulic conductivity estimates for intact coal barriers between closed underground mines: Environmental and Engineering Geoscience, v. 12, p. 273–282.

Ruppert, L. F., and C. L. Rice, 2000, Coal resource assessment methodology and geology of the northern and central Appalachian Basin coal regions, chapter B, *in* Northern and Central Appalachian Basin Coal Regions Assessment Team, ed., 2000 resource assessment of selected coal beds and zones in the northern and central Appalachian Basin coal regions: U.S. Geological Survey Professional Paper 1625-C, 21 p.

Ruppert, L. F., S. J. Tewalt, R. N. Wallack, L. J. Bragg, D. K. Brezinski, R. W. Carlton, D. T. Butler, and F. J. Calef III, 2000, A digital resource model of the middle Pennsylvanian Upper Freeport coal bed, Allegheny Group, Northern Appalachian Basin coal region, chapter D, *in* Northern and Central Appalachian Basin Coal Regions Assessment Team, ed., 2000 resource assessment of selected coal beds and zones in the northern and central Appalachian Basin coal regions: U.S. Geological Survey Professional Paper 1625-C, 97 p.

Stoner, J. D., 1983, Probable hydrologic effects of subsurface mining: Ground Water Monitoring Review, v. 3, no. 1, p. 128–137.

West Virginia Geological and Economic Survey: http://www.wvgs.wvnet.edu/ (accessed September 2006).

West Virginia State GIS Technical Center: http://wvgis.wvu.edu (accessed August 2007).

Yang, C., S. Kao, F. Lee, and P. Hung, 2004, Twelve different interpolation methods: A case study of Surfer 8.0: International Archives of Photogrammetry, Remote Sensing, and Spatial Information Sciences, v. 35, p. 778–785.

Younger, P. L., 2001, Mine water pollution in Scotland: Nature, extent and preventative strategies: Science of the Total Environment, v. 265, no. 1–3, p. 309–326.

Younger, P. L., 2004, Environmental impacts of coal mining and associated wastes: A geochemical perspective: Geological Society (London) Special Publication 236, p. 169–209.

Younger, P. L., and N. S. Robins, 2002, Challenges in the characterization and prediction of the hydrogeology and geochemistry of mined ground, *in* P. L. Younger and N. S. Robins, eds., Mine water hydrology and geochemistry: Geological Society (London) Special Publication 198, p. 1–16.