QUANTIFICATION OF THE FACTORS INFLUENCING THE PERFORMANCE OF HYDRAULIC BARRIERS IN WESTERN PENNSYLVANIA UNDERGROUND COAL MINES

by

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Present regulations prohibit surface-water-impairing discharges from abandoned underground coal mines. However, some recently abandoned mines in western Pennsylvania have experienced unplanned, high-flow discharges. The Surface Mining Control & Reclamation Act of 1977 requires underground coal mines with acid-forming potential to mine down-dip, establishing a protective barrier capable of containing the resultant mine pool. The primary factors responsible for the performance of 'down-dip' hydraulic barriers are complex and influence the design process.

This investigation characterizes down-dip coal barriers and produces a set of general guidelines or recommendations applicable to 'down-dip' barrier design. To identify factors influencing barrier performance, several detailed case studies are examined.

Case studies of the Solar 7 & 10, Little Toby, Dora 6, Grove 1, and Penn View mines were investigated. The research included detailed analysis and select modeling of hydraulic coal barriers constituting both successful and unsuccessful performances in western Pennsylvania underground coal mines. The analysis shows that the following factors impact the performance of hydraulic coal barriers:

- Primary Factors
    - Geology,
    - Extraction ratio,
    - Hydraulic conductivity, and
    - Overburden thickness

- Secondary Factors
    - Hydraulic gradient
    - Barrier thickness

These factors were quantified to provide guidelines to safely engineer a barrier given a set of conditions. Ultimately, this analysis will aid industry, responsible for designing these structures, and regulatory agencies, responsible for approving these designs, to utilize observations from this analysis to reduce the potential for high-flow discharges from abandoned coal mines.

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1.0 INTRODUCTION

This thesis examines interactions between coal mining and hydrogeology. These topics are directly related, since coal mining has the potential to alter the hydrogeologic characteristics of subsurface strata. More stringent environmental standards are requiring mining operations to reexamine how different mining systems impact groundwater and have resulted in more effective control systems. The Surface Mining Control & Reclamation Act (SMCRA) of 1977 was a major turning point for coal mining in the United States. Prior to 1977, mining proceeded in the up-dip direction. When mining occurs up-dip, operations proceed into the coal seam at a low elevation, progressively mining into higher elevations. The purpose is to allow mine water to flow away from the actively-mined face. Coal extraction, under certain geologic conditions, can allow groundwater to come in contact with pyritic-rich strata, producing increased acidity, elevated levels of iron, and the dissolution of other metals (thus creating acid mine drainage). Methods to prevent acid mine drainage have been put into place by the SMCRA of 1977. Since SMCRA, mine operations are required to prevent the discharge of impaired water to the surface. Mine pools can be a major obstacle to coal mining in western Pennsylvania, including the potential for mine water blowouts and in-rushes from abandoned mines. In general, mining down-dip as opposed to up-dip will allow water to pool up in an abandoned mine. This prevents water from freely discharging at the surface.

Coal mining regulations focus on preventing water from escaping the mine pool, either by seeping through the coalbed or adjacent strata, in high enough quantities so as to negatively impact water supplies. When mining operations induce fractures within these barriers, highly conductive flow paths can result. Controls designed to prevent these unwanted discharges include mine barriers, in-mine seals, and designing mine entries at the highest elevation of the coal reserve. A ‘seal’ is a control used to prevent in-mine flow from one section to another mined section, or prevent water from flowing out through the mine portal. A ‘barrier’ is a control and term used by regulators and mining operators referring to structures that prevent high-flow mine water through the strata surrounding a mine.

The problem with engineered coal barriers is that they do not always prevent mine water from discharging. The state regulatory agencies and mine operators in the northern Appalachian coal region have differing opinions on barrier design, due to different conditions. Mine operators have a need to keep barrier sizes to a minimum so as to maximize resource recovery. Conversely, environmental agencies need to minimize the risk of unplanned discharges. These different approaches often result in different opinions on the most appropriate barrier designs. Fundamentally, the problem lies in the uncertainty about factors influencing the performance of down-dip coal mine barriers. Clarification of these factors could provide guidelines for future design of down-dip coal barriers. The objective of this research is to determine the factors influencing the prevention of surface discharge from hydraulic coal barriers. More specifically, the aim is to understand the most important parameters controlling the performance of barriers that are susceptible to allowing discharges and to produce a set of general guidelines for their design.

2.0 BACKGROUND

2.1 OVERVIEW

The understanding of hydrogeology is fundamental when examining the effects of coal mining on surrounding strata. More specifically, when a coal mine is abandoned, the hydrologic properties of an underground mine system and its surroundings can change. This chapter will focus on literature pertinent to the case studies (associated with coal barrier performance) that have already been conducted.

One of the major issues with abandoned mine lands is the potential for water to discharge at the land surface from underground mine workings. This is caused by a hydraulic head potential from the mine pool. If the mine pool exists at an elevation higher than that of the land surface above the mine, there is a discharge potential at the lower location. The geologic formations (i.e., barriers) between the mine workings and discharge location control the transmission of water to the land surface. Barriers are classified as horizontal (predominantly coal barriers) or vertical (predominantly strata barriers). In this study, the focus is primarily on horizontal coal barriers. These barriers tend to fail when a hydraulic head potential exists where the coal outcrops in an area above (or near) a drainage (Figure 2.1).

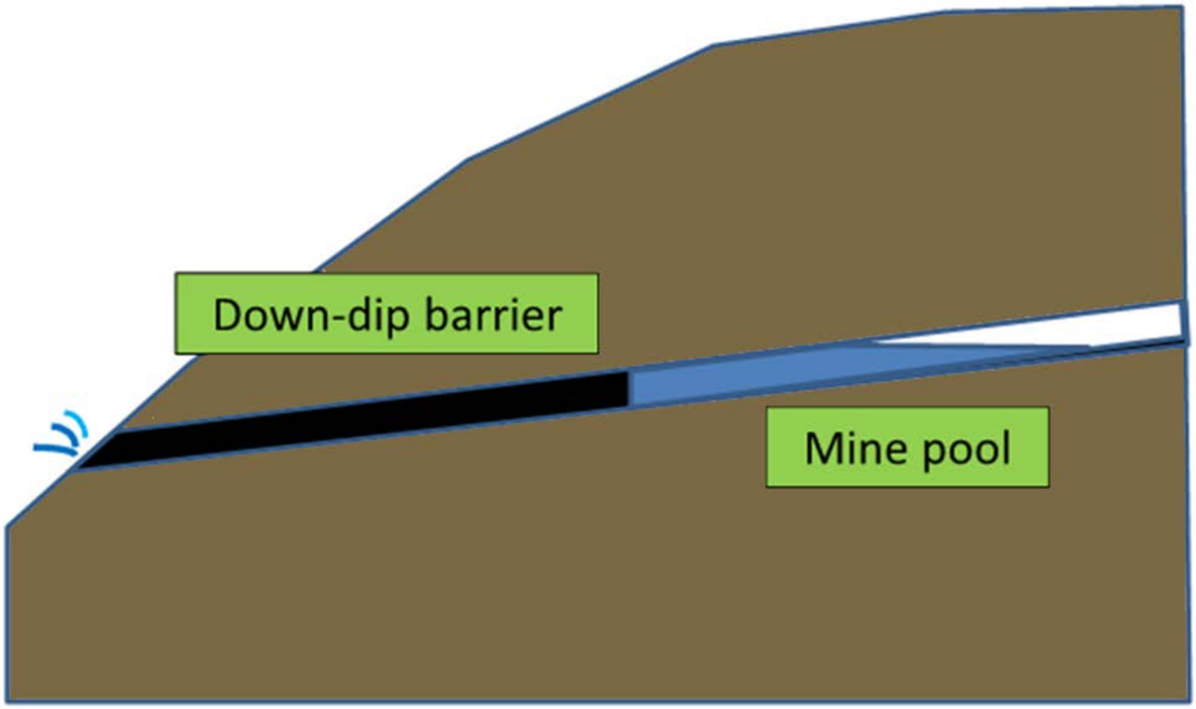


Figure 2.1: Typical down-dip coal barrier. The un-extracted coal prevents mine water from freely discharging at the surface.

The hydraulic properties of unaltered coal allows for more water transmission than surrounding strata in the Appalachian region (Kozar, 2012). The rate that water is transmitted through a medium under a hydraulic gradient is known as hydraulic conductivity (K), measured in length per time. Hydraulic conductivity varies with different media, dependent on effective porosity, fracturing, etc.. Hydraulic conductivity is an important variable in the modeling of a confined aquifer. A confined aquifer is a water-bearing layer bounded on the top and bottom by relatively less permeable media. The confinement of coal is the main reason that it’s K value is generally higher (on a larger scale) in the horizontal direction than vertical direction (Harlow, 1993; Kozar, 2012).

The dimensions of the barrier play a role in the effectiveness of the barrier in preventing mine pool water from reaching the coal seam outcrop at an excessive rate. An excessive flow rate refers to a volume of water per time that is distinctly measureable at a point source. Excessive flows are a problem due to their potential to negatively impact surface water quality. Darcy's Law utilizes the principal properties of an isotropic system to provide an accurate "barrier K" value, where:

- Q is the flow out of the aquifer [ft^3/d],
- K_h is the horizontal hydraulic conductivity [ft^2/d],
- b is the aquifer thickness [ft],
- L is the length of the barrier [ft],
- dh is the difference in hydraulic head from the discharge point to the top of the mine pool [ft], and
- w is the aquifer width [ft] (Kurt J. McCoy, Donovan, & Leavitt, 2006).

$$Q = K_h bL\left(\frac{dh}{w}\right) \quad \rightarrow \quad K_h = \frac{Q}{bL(\frac{dh}{w})}$$

An important assumption with Darcy's Law is that vertical infiltration through the overburden and into the coal barrier is negligible. This means that the actual K_h value would be lower due to mass balance. Darcy's Law also assumes that material is isotropic, which is not true for all materials. Coal is an anisotropic material, with face and butt cleats oriented perpendicular to each other. The orientation of these cleats influences hydraulic conductivity. The regional orientation of the face cleat is N 70° W (McCoy et al, 2006). Since the butt cleat is perpendicular, it lies at an orientation of S 70° E. This means that locally, flow should travel parallel to the N 70° W direction because the face cleat is wider than the butt cleat.

The geology of western Pennsylvania is unique in terms of rock-layer properties and arrangement. Different strata layers possess different properties, such as brittleness, which can lead to an increase in groundwater permeability. The Appalachian Plateau includes sequences of sandstones, siltstones, shale, claystones, limestone, and coal (Kozar, 2012; Peffer, 1991). More brittle units (sandstone, coal, and hard siltstones) tend to form aquifers due to open jointing, while softer shales and claystones tend to be less permeable (C.J. Booth, 1986; Peffer, 1991).

Some previous studies have observed different properties of coal formations in western Pennsylvania. The Stoner study (conducted in Greene County, PA) determined there to be a relationship between the Waynesburg and Greene coal formations. It was found that lower areas of the Waynesburg (more sandstone and coal) formation seemed to be more permeable than parts of the Greene formation (more shale). Permeability tests determined that interfaces between sandstone and shale were more water-bearing, as well as fractured sandstone and coal layers (Jeffrey D. Stoner, 1983). This is important in coal mine hydrogeology studies.

The topography of a mined region also influences groundwater flow. 'Groundwater recharge' is a process where the water flows through infiltration zones on a land surface to replenish groundwater. The concept of recharge is important when studying mine pools, because there are both sources and sinks of groundwater within a mine pool. A discharge of water from a mine pool is a 'sink,' while a groundwater recharge zone is a 'source.' Hilltop aquifers (topographic high) tend to have different characteristics than stream valley aquifers (topographic low). This could be due to several factors. One observed characteristic of hilltop aquifers is that they tend to be 'perched' or 'semi-perched.' A perched aquifer is one that contains a relatively impermeable zone overlain by a more permeable, saturated zone (Kenneth L. Johnson, 1985). Hilltops containing less permeable strata layers can form perched aquifers, thus limiting the amount of recharge transmitted to underlying strata. These are caused primarily by coal underclays, claystones, or shales, which act as near-impermeable layers (Kozar, 2012). These aquifers, along with stress-relief fractures and bedding separations, can greatly influence groundwater flow (Wyrick & Borchers, 1981). In coal seams, however, the interest is in deep aquifer flow rather than shallow groundwater aquifers. Deep mine aquifer zones will develop a hydraulic head pressure within a connected mine void. The static pressure of the water will be uniform within the mine workings. This water elevation is what is referred to as the 'mine pool' in the remainder of this thesis report. In theory, the maximum mine pool elevation that can be reached within a mine is thought to be the highest elevation of the workings, if the abandoned workings ever were completely flooded. However, hydraulic head pressures have been recorded at higher levels than a particular mine's highest elevated workings (Iannacchione et al, 2014). It is assumed that open fractures in overlying strata contribute to the additional hydrostatic pressures. Mines with a box-cut at the portal could also cause additional hydrostatic pressures (Iannacchione et al, 2014). This can be caused by unconsolidated backfill in an old box-cut, which can weather and open up into voids. Box-cuts are rectangular excavations that are typically used for portal entry to underground coal mines in western Pennsylvania. Few studies have been conducted on a box-cut's contribution to hydrostatic pressures in a mine.

Expanding further on the permeabilities of different materials are other geologic conditions. Using the Darcy model, flow is assumed to be laminar and confined. This is not always the case, especially in terms of fracture flow. In reality, a barrier lies in an unconfined system where turbulent groundwater is controlled by fracture flow. Modeling of fracture flow can be accomplished by simulating flow between two parallel plates using the Cubic Law (Romm, 1966).

Mining techniques are often responsible for hydrologic changes. For example, in most bituminous coal mines, room-and-pillar mining techniques are used to extract coal, leaving coal pillars to support overlying strata. The overlying strata (from the mine roof to land surface) is referred to as the overlying cover, or ‘overburden’. This technique can be used alone or prior to retreat mining methods. When a coal seam is room-and-pillar mined and then a second extraction of remaining coal is employed, it is referred to as ‘full extraction mining’. This technique removes nearly all of the coal in the seam, leaving no supporting pillars behind. Because of this, the roof of the mine is allowed to collapse behind the actively mined area. Similar to full extraction, is partial extraction (retreat) mining. This technique removes portions of the remaining pillars, rather than removing them entirely. In some cases, room-and-pillar mining methods are utilized to leave behind smaller pillars than normal, thus leaving behind thin-pillar sections. Normal pillars refer to those left behind by development room-and-pillar mining. Thin pillared areas may be more susceptible to pillar failure and long-term stability of partially extracted pillars is unknown. In addition to underground mining methods are surface mining methods. Strip mining is conducted by removing all overburden material in addition to the coalbed, usually near an outcrop. Here, overburden material is relatively low and coal seams are easily accessible. Operations will advance into increasing overburden depths until the coal can no longer be mined economically. This will leave the outcrop of the coal seam at a highwall and unconsolidated mine spoil is often used to fill the mined out area. This material will be unconsolidated and have a relatively higher K value than that of undisturbed strata (W. W. H. Aljoe, J.W., 1992; Rehm, 1980). In general, spoil piles found between mine workings and the potential discharge location will decrease the maximum width of a regulated coal barrier. The augering of coal can also be accomplished from a coal seam outcrop or highwall. The extraction of coal by augering will decrease the maximum width of a regulated coal barrier, similarly to strip mining (Zipf). This is because auger holes will simulate that of abandoned mine voids, with open-channel type water flow.

Mine subsidence is an effect of mining that can influence the permeability of strata surrounding a mine barrier. ‘Subsidence’ refers to the displacement (collapse) of the overlying strata, usually resulting in a deformation or depression at the land surface. Subsidence effects from high-extraction mining often alters the hydrologic characteristics of the surrounding strata (Booth, 2006; Bruhn). Mining-induced subsidence effects are thought to be one of the major causes of high flow discharges from underground coal mines. The subsidence effects due to fracturing and bedding separation of surrounding strata includes changes in fracture porosity and permeability, and also hydraulic gradients and groundwater levels (C. Booth, 2006). Induced fractures in barriers are often the result of adjacent full extraction sections.

Fracture networks are associated with the presence of lineament structures. Evidence of the alteration of geologic structures near mine workings is sometimes visible through satellite imagery. The term ‘linear’ or ‘lineament’ refers to a line-like appearance on an aerial image that signifies a naturally occurring geologic feature within the earth’s surface (Winston). The linears are often found to show higher concentrations of fracture networks in the subsurface strata. Geologic discontinuities commonly associated with linear mapping are fractures, faults, folds, clay veins, washouts, and channels. The ability to utilize lineament studies in regions overlying mine workings and down-dip barriers has many benefits (Chugh; Galya, 2008; Iannacchione, 1981). Any geologic discontinuities (jointing, faulting, fracturing, etc.) revealed from the mapping of linears can help to distinguish barrier characteristics.

If a barrier is deemed to be ruled by fracture-network flow, different assumptions should be made. To give a perspective of fracture flow through a hydraulic barrier, one can estimate the parameters that would be associated with a single, vertical fracture extending through a barrier. This would connect a mine pool to a discharge point at the land surface. This case can be modeled using the Cubic Law, which has been derived from the form Q=KiA (Romm, 1966).

$$Q = \frac{\rho_w g b^2}{12\mu}(bh_f)\frac{\partial H}{\partial w_f}$$

Q = volumetric flow rate (ft^3/d) [448.8 gpm = 1 ft^3/s]

h_f = saturated fracture height (ft)

w_f = length of the fracture through the barrier (ft)

dH = difference in hydraulic head, discharge point to the top of the mine pool (ft)

b = fracture aperture (ft)

ρ_w = density of water (1.94-slugs/ft^3)

g = gravitational constant (32.17-ft/s^2)

μ = viscosity of water (2.34×10^{-5} lb. s/ft^2)

$\frac{\partial h}{\partial L_f}$ = hydraulic gradient

2.2 RELATED STUDIES

The most applicable investigations to coal mining hydrology studies are those that have been conducted in the Appalachian coal region. These studies contain information that is particularly important for comparison in the study of down-dip coal barriers. In two studies by K.J. McCoy, an in-depth examination of the horizontal hydraulic conductivity of coal barriers and vertical infiltration into underground mines was carried out. These studies are important due to the relative location of the studies (West Virginia and Pennsylvania) and similarity to down-dip coal barrier analysis. In the study by McCoy et al., barrier K values were estimated to range from 0.12 to 0.59 ft/d using an isotropic model (McCoy et al, 2006). The anisotropic model estimated K values to range from 0.24 ft/d to 1.1 ft/d for face cleat (Kf) and 0.072 ft/d to 0.32 ft/d for butt cleat (Kb). Prior to 2006, literature values of Appalachian coal hydraulic conductivity ranged from 1.1 x 10^{-4} to 14.4 ft/d (McCoy et al, 2006). In 1992, a study in New Mexico focused primarily on the effects of cleat orientation and pressure on the permeability of coal. Gash et al explains that coal permeability is greatest parallel to the face cleat and bedding planes. At 1,000 psi, permeability ranged from 1.97 to 5.58 ft/d (face cleat) and 0.98 to 3.28 ft/d (butt cleat) (Gash, 1992). A more recent study by the United States Geological Survey numerically modeled coal barrier flow and came up with values ranging from 0.028 – 7.27 ft/d (Kozar, 2012). K values have also been found to increase due to mining (Table 2.1) (Galya, 2007). Methods used for K value estimations in the Appalachian region have included modeling, packer tests, well tests, aquifer tests, and lab tests. The wide range of values could be due to varying conditions surrounding or within the coal barrier for each case. Figure 2.2 demonstrates that the K value generally decreases under greater overburden thicknesses (due to increasing vertical strain).

Table 2.1 Range of horizontal permeabilities for barrier seepage analysis (Galya, 2007)

Material	Premining ----------------------> Post Mining		
Coal	1.0 ft/d	3.21 ft/d	4.86 ft/d
Overburden	0.01 ft/d	0.74 ft/d	4.25 ft/d
Clay	0.0005 ft/day		0.013 ft/d

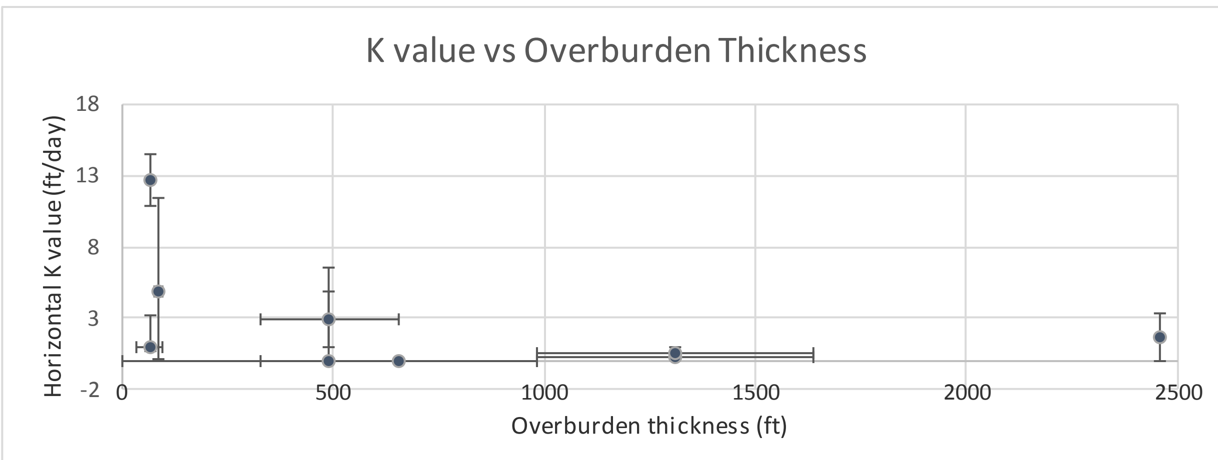


Figure 2.2 Plot of K (hydraulic conductivity) values from previous literature versus the overburden thickness at the respective investigation site.

The publication by Rehm et al (1980) also focuses on the hydraulic properties of coal and surrounding sediments (coal spoil piles). Even though the study was aimed at the K-values of lignite and sub-bituminous coal in the Northern Great Plains and western regions, it still provides useful insight on the hydraulic characteristics of coal. The authors explain that coal is an anisotropic material, since its permeability is controlled by fractures (including cleat). It was found that the mapping and investigation of lineaments plays a substantial role in determining regional fracture orientations. The authors claims that the average hydraulic conductivity of unaltered coal is approximately 0.57 ft/d (Rehm, 1980). Additional K values of lignite and sub-bituminous coal from parts of the Midwest and Rocky mountains (in 5 additional studies) were discovered to range from 0.49 to 8.2 ft/d (Kurt J. McCoy et al., 2006).

Even though K values of coal are known to be higher in horizontal directions, vertical K values have been briefly studied. In a USGS study, vertical K values from modeling experiments were found to range from 0.002 – 0.042 ft/d, of impermeable underclays to stress-relief fractured areas, respectively (Kozar, 2012). The vertical permeability of coal is said to be almost non-existent due to cleat structure (Gash, 1992). Vertical permeability of overburden strata has also been measured. In 2008, an investigation cited two articles that gave a range of overburden K values from 0.74 to 2.92 ft/d (Galya, 2008). In other areas of the literature are the observed and theorized effects of full-extraction mining. Full-extraction mining leaves a different footprint than that of room-and-pillar mining, due to the allowance of roof collapse behind the face. There are several articles discussing these hydrologic effects.

In two of the studies by C.J. Booth, the impacts of longwall coal mining on groundwater are addressed. Case studies recording loss of water in wells, springs, streams, etc. are important, because they can lead to further assumptions about the potential changes to subsurface properties. High-extraction pillar removal often results in similar subsidence effects to full-extraction mining (C. Booth, 2006). Subsidence effects have often been classified into three zones of deformation, including the lower, severely fractured zone, the intermediate, compressional zone, and the uppermost fracture zone (Figure 2.3) (C. Booth, 2006; Colin J. Booth, 2002).

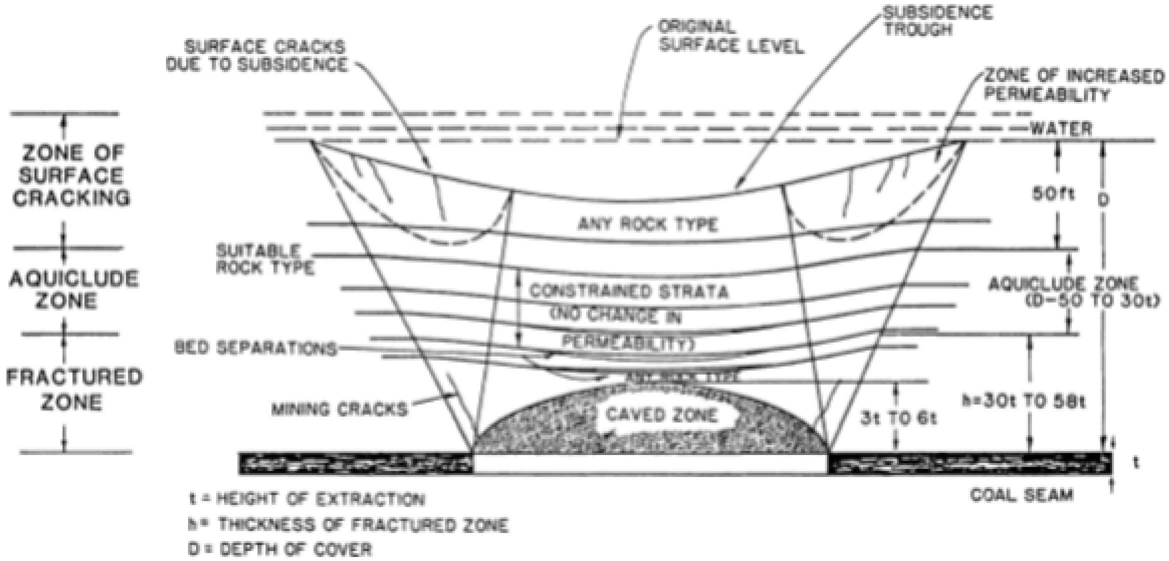


Figure 2.3 A schematic of the three zones of deformation in full-extraction underground coal mining techniques: the fractured zone, aquiclude zone, and surface cracking zone (C. Booth, 2006)

In a United States Bureau of Mines study by Aljoe, strong hydrologic connections were found to exist between two collapsed mine entries using a tracer. The study estimated hydraulic conductivities to be greater than 14 ft/day (similar to that of a mine spoil). Flow velocities within a flooded, abandoned mine void were found to range from 11 to 65 ft/day, with the higher velocities measured nearest the discharge. A slug test was performed to calculate hydraulic conductivities of strata adjacent to a mine void and compared with the hydraulic conductivity of pillar strata. It was found that the hydraulic conductivity of adjacent strata (geometric avg. = 9.7 ft/d) was higher than that of pillar strata (geometric avg. = 0.35 ft/d). This is consistent with strata mechanics theory of tensile stresses in strata adjacent to mine voids and compressional stresses in pillars surrounded by mine voids (W. W. H. Aljoe, J.W., 1992).

The effects of deep mining on groundwater in northern Appalachia were examined by R.W. Bruhn and J.D. Stoner. Effects of both subsided and uncollapsed workings on surrounding rock were examined. It is assumed that the hydrologic properties of the overburden is controlled primarily by jointing and fracture networks. Bruhn claims that weathering, fracturing, and specific storage decreases with depth from the surface prior to mining. After mine workings collapse, fractures and bedding plane separations are more intense in the immediate roof rock. This pertains especially to subsided workings, because unsubsided workings usually have less adverse effects on shallow systems (C.J. Booth, 1986). These types of effects can greatly influence the hydrologic cycle of surrounding strata, and even the performance of a coal barrier. In an investigation by J.D. Stoner, permeability tests indicate that permeability decreases by one order of magnitude for every 100 feet of depth. Packer tests also determined that hydraulic conductivities for claystones, shales, and sandstones were from one to five orders of magnitude less at greater depths than shallower (Bruhn). The Bruhn study also included piezometric measurements at a mine using retreat techniques. It was found that developmental mining had minimal effects on water levels. On the other hand, retreat mining sections caused water pressure fluctuations and/or dewatering of the overburden. Long-term effects were expected of piezometric water levels to return to pre-mining conditions (Bruhn). It is not uncommon for retreat and longwall mining to connect shallow aquifers to deep mines through fracturing (Jeffrey D. Stoner, 1983) (C. Booth, 2006). However, the hydraulic effects of subsidence on permeabilities and porosities of all rock types in the Appalachian region, decline with depth (C. Booth, 2006; C.J. Booth, 1986; Callaghan, 1998; Kozar, 2012; Jeffrey D. Stoner, 1983). The lithostatic pressures of increasing overburden decreases the frequency and magnitude of fractures (Kozar, 2012).

In 1991, a study examining the hydrologic changes due to coal mine subsidence was performed in Illinois. The authors used pump, slug, and hydraulic injection tests to determine K values of the overburden prior to, and after mining. Values for shales and sandstones in the overburden prior to mining ranged from 2.8 x 10^{-4} to 2.8 x 10^{-3} and 2.8 x 10^{-3} to 0.28 ft/d, respectively. These conductivity values increased by 2 to 3 orders of magnitude for the shale and 1 order of magnitude for the sandstone after mining occurred (Kelleher, 1991).

Kendorski (F. S. Kendorski & Bunnell, 2007) specifically addresses the design and performance of a coal-barrier for slowing inter-mine flow. Even though the barrier was intended to prevent significant flow from entering new mine workings rather than discharging at the land surface, the same concept of barrier design applies. This article analyzes several of the design methods and rules that have been used for coal mine water-barrier pillars historically. The barrier pillar was designed to meet mechanical and hydraulic performance criteria. The proposed barriers were 165 and 350 ft. wide, respectively, and would need to withstand 550 ft. of hydraulic head. Particular attention was focused on the potential for natural discontinuities in the barriers, including dikes and faults. These discontinuities can allow excessive water inflow from the adjacent mine workings. To determine the barrier width, design equations were based on coal seam thickness, hydraulic head, and overburden thickness. Results for barrier width ranged from 105 to 859 ft. Others have also tried to develop equations to determine the permeability of coal, under differing amounts of stress/strain. The effect of strain on flow rate through an in-mine barrier was modeled. The increase in strain due to abutment loading most likely compresses bedding planes, diminishing flow gaps. Additionally, strain on vertical fractures could either compress or dilate the gaps, alternatively increasing or decreasing flow through the barrier. The overburden thickness at the site was relatively high (~ 2,000 ft.), and it was decided that the mechanical and hydraulic designs would prove sufficient.

The hydraulic conductivity, or permeability, of an inter-mine barrier controls the potential for excessive inflow from an up-dip mine section. A barrier with a low K-value and no major deformities will cause relatively more hydraulic head loss than a barrier with a high K-value and/or discontinuities (Figure 2.4) (Donovan, 2000). Figure 2.4 below shows how the mine pool elevation differs from contrary barrier K value conditions. This is nearly the same concept as a hydraulic barrier, however, the void in the down-dip mine would be represented by the above-ground discharge location.

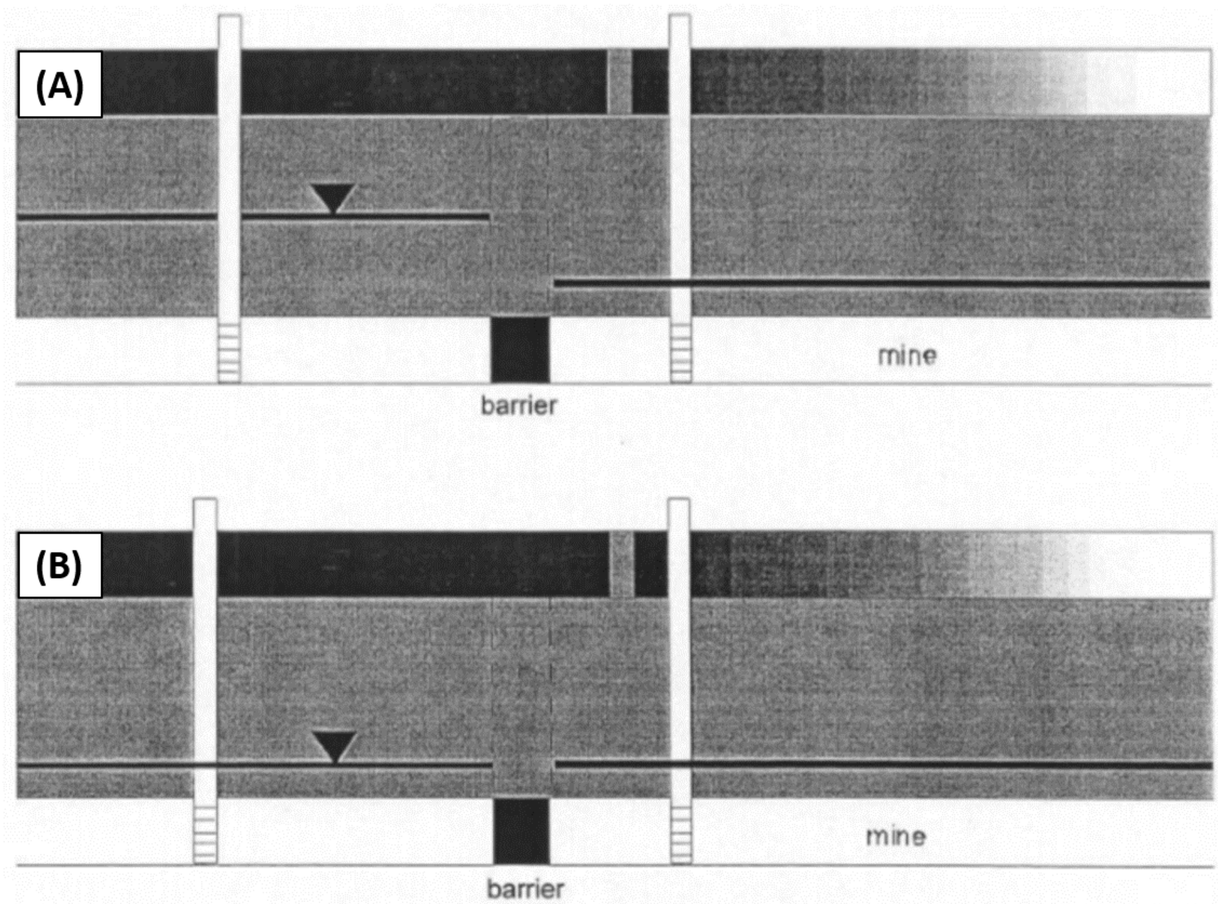


Figure 2.4 A schematic showing two different barrier conditions. "A" depicts a barrier with a low K value. "B" depicts a barrier with a relatively high K value. The mine pool level varies due to the hydraulic head loss over the barrier with a lower K value (Donovan, 2000)

In 2007, the United States Office of Surface Mining conducted a study on the design of coal barriers to prevent catastrophic “blowouts” at coal outcrops. A blowout is an extreme case of water flow from an abandoned mine, which may be capable of causing damage to surface structures, etc. The study identified several factors responsible for the production of major hydraulic blowouts. They were: overburden thickness, physical properties of the overburden, surface slope and soil condition, hydrostatic head, coal characteristics, proximity of active and abandoned flooded mines, roof falls, multiple seam mining, and partial mining (Kohli, 2007). A similar study was conducted by Moebs et al. in 1989 that included the intensity of weathering and abundance of fractures in the engineering factors responsible for barriers. Several methods for barrier design have been used in the past (Kohli, 2007; Moebs, 1989). These formulas have been used on the basis of stress to prevent coal barrier “blowouts.”

Mine Inspector’s or Ashley’s Formula: $W = 20 + 4T + 0.1D$

W = barrier width; ft

T = mining height; ft

D = maximum water head possible; ft

Rule of Thumb Formula: $W = 50 + H$

W = barrier width; ft

H = maximum water head; ft

GCSI Formula: $$W = S(0.385Hc + 0.48Hw)$$

W = barrier width; ft

S = slope (H:V)

Hc = coal thickness; ft

Hw = total hydrostatic head; ft

These formulas use the factors of mining height, hydraulic head, and slope for the determination of coal barrier width. Even though these design equations may have been used with success in the past, they do not account for detailed factors that may cause mine blowouts. Since the formulas are not designed adequately for the prevention of "blowouts" at coal outcrops, they are also not applicable for preventing relatively high rates of flow through hydraulic coal barriers. Moebs, (1989) states, "In absence of anomalous geologic conditions an interior coal barrier 200 ft. in width generally is adequate for impounding water with a hydrostatic head of up to 300 ft. without serious leakage". This means that an unaltered coal barrier should be able to withstand a hydraulic gradient of up to 1.5 (head difference/barrier width).

In a recent report prepared by the U.S. Geological Survey, an abandoned underground coal mine was studied with particular attention given to the hydrogeology, groundwater flow, and groundwater quality (Kozar, 2012). Several methods were used in the investigation, including monitoring well installation and analysis, detailed borehole geophysical logging, water quality sampling, and aquifer testing. This study utilizes both aquifer testing and geophysical methods to characterize an aquifer. Few studies use borehole geophysical methods to characterize the extent of fracture networks and bedding separations. The borehole logging activities in the USGS report were designed specifically to evaluate distribution, orientation, and flow properties of an aquifer. The methods included use of caliper and acoustic televiewer logs for fracture characterization. The primary orientation of fractures are in the north-south and northeast-southwest direction, essentially aligning them with the strike of bedding. In addition, larger fractures are associated with bedding plane changes. The authors believe that groundwater flow in the Appalachian region is controlled by the orientation and permeability of sedimentary rocks (sandstone, siltstone, shale, limestone, and coal). Flow primarily makes its way through these fractures, bedding plane separations, and in limestone dissoluted openings (Kozar, 2012). Results of well aquifer testing showed that K values ranged from 4-12 ft/d in stress-relief fractured areas. Results of modeling the underground coal mine aquifer determined K values of coal to be in the range of 0.028 – 7.27 ft/d (Kozar, 2012).

Many attempts to develop a numerical or computer model for gaining a better understanding of hydrologic changes due to mining are also available (Biao, 2011; Gale, 2005; Havenga, 2005; Islam; Owili-Eger, 1987). In 1994, a study evaluating mine water inflow to an open pit through a coal aquifer was conducted. The investigation compared two scenarios using numerical modeling. The first model calculated groundwater inflow from a coal seam with no geologic discontinuities (faults or fractures). The second model estimated groundwater inflow from a coal seam containing geological discontinuities, where fracture intensity was estimated to be 7-10 per meter and joints occurred at a frequency of 1-3 per meter. Both models assumed unconfined flow and used the same width of rock strata in the coal deposit (853 ft). Low K values were assigned to strata such as shale and clay, and higher K values were assigned to sandstones and siltstone strata. The K value of the coal seam ranged from 2.67×10^{-2} – 0.376 ft/d (Bai, 1994). These simulations show that inflow rates in these cases were not significantly different. The slope angle of the model containing discontinuities induced closure of fracture networks and jointing. The authors have shown that the amount of groundwater in a system can affect slope stability, and slope stability decreases with increased water pressure. If slopes are more prone to failure due to water pressure, barrier areas near steeper sloped areas should be carefully evaluated. The following key points were identified from the study (Bai, 1994):

- The faulting of strong rocks will create larger increases in K values to weaker rocks
- Strata in tension will produce open faults
- Strata in compression will produce closed faults
- Old faults tend to be closed
- Recent faults tend to be open
- An observed decrease in flow rate reflects closure of the fracture aperture

The permeability of the strata surrounding an abandoned mine is influenced by stress caused by overlying layers. The compressional stress (confining pressure) on an underlying layer of strata increases with increasing depth of overburden. There can also be resultant stresses in the upward direction on stream valleys when considering topographical influences (Kenneth L. Johnson, 1985). Stream valley aquifers tend to have more tensional stresses, thus creating extended fracture networks and more groundwater storage. Stoner (1983) found that aquifers beneath stream valleys had higher hydraulic conductivities than aquifers beneath hilltops. A report by Moody & Associates, Inc. (1997) states that on average, fractures beneath stream valleys reach as deep as 50-60 ft. in western Pennsyvlania. Compressional stresses can also affect K values of coal. Gash et al (1992) conducted laboratory experiments to show the permeability of coal decreases with increasing confining pressure; an increase (450 – 1000 psi) in confining pressure on coal lowers the permeability by approximately 5-fold in all cleat directions, lowering cleat porosity by a factor of 1.7. Kendorski and Bunnell (2007) determined that confining pressure from the overburden can either compress or dilate gaps in the coal seam (F. S. Kendorski & Bunnell, 2007). In study by Matetic (1992), on the effects of longwall mining on groundwater quantity, monitored groundwater levels dropped due to subsidence, but levels quickly recovered after nearly 10 days. This effect is attributed to the "healing" of fractures under high overburden pressures (R. J. Matetic & Trevitis, 1992; E. Pigati & Lopez, 2006). These differing stresses can effect groundwater movement (Figure 2.5).

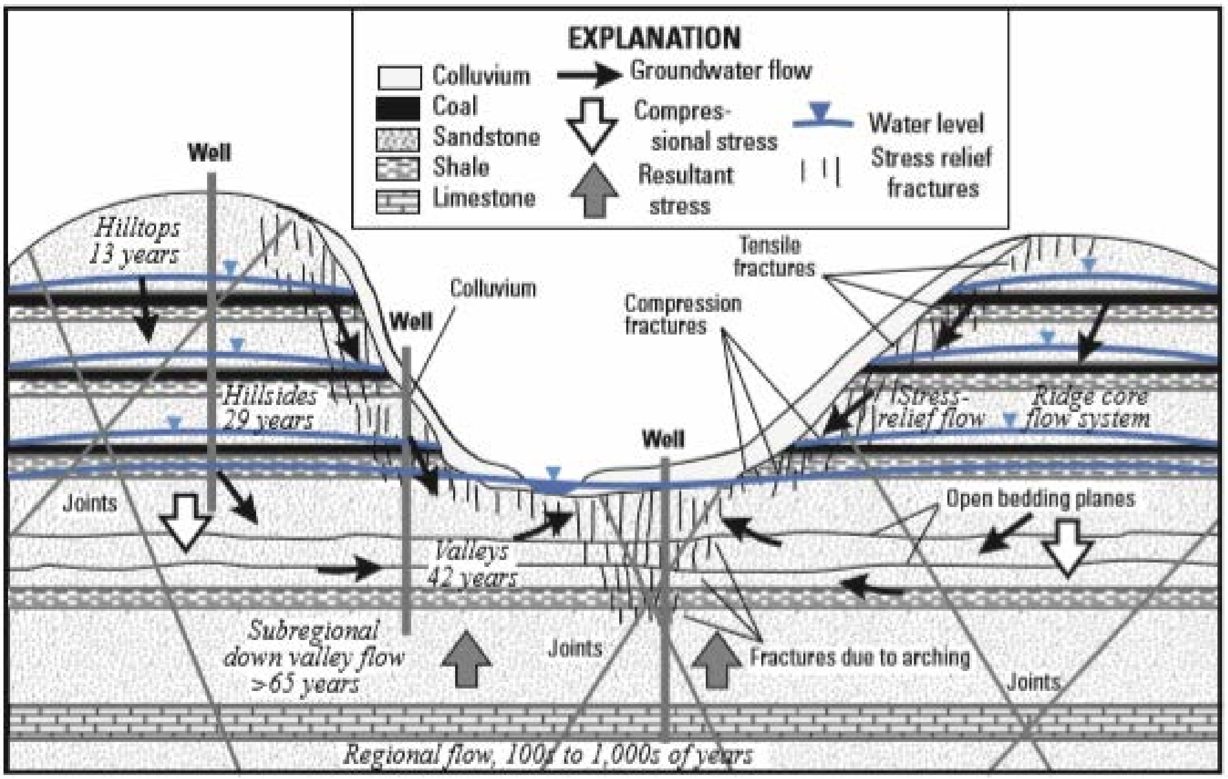


Figure 2.5 Schematic representation of hydrogeologic features and stress-relief fracturing of a typical stream valley in the Appalachian region (Kozar, 2012)

2.3 KEY POINTS

Historically, coal barriers have been designed based on stress factors. In general, the stress-based designs were used to engineer barriers prior to the SMCRA of 1977 to prevent “blowouts.” Coal barrier failures were referred to as “blowouts,” because the amount of hydrostatic pressure acting on the coal barrier was great enough to cause the barrier to burst and allow a significant amount of flow to exit the mine workings. Formulas used for coal barrier design utilized hydrostatic pressure (hydraulic head), mining height (or coal seam thickness), and slope to determine the width of the coal barrier. Coal barriers designed to prevent a major blowout event differ from hydraulic coal barriers designed to prevent significant impacts to surface waters. Stress-based coal barriers are generally shorter in width, producing a greater hydraulic gradient of the barrier. The hydraulic gradient measures the amount of hydraulic head acting on the barrier divided by the width of the barrier. Hydraulic coal barriers engineered today often result in more significant barrier widths due to the adversity of environmental regulators. The case studies used in this studies contain permitted barriers that have shown a general increasing barrier width trend over the last few decades (Table 2.2).

Table 2.2 Hydraulic coal barrier widths permitted for the case studies. (* no permitted barrier found on six-month mining maps at the Dora 6 mine)

Date	Mine	Permitted Barrier Width (ft)
Pre-1977	Solar 7/10	200 and 1800
Early 1980s	Dora 6	≈ 300 – 700*
1997	Penn View	400 - 1100
Early 2000s	Little Toby	800 - 1200

Studies have shown how several factors play a role in coal barrier performance. General K values for unaltered coal range widely, from 1.12 x 10^{-4} to 14.4 ft/d. The numbers from Kozar et al. and McCoy et al. for bituminous coals in Appalachia are similar to the range given by the U.S. Bureau of Mines study by Aljoe et al., which averaged 0.35 to 9.7 ft/d. The lower K value was measured in coal pillars, while the higher K value was measured in the adjacent, tensile-stressed strata. The K value range measured by Kozar et al (2012) and Galya (2007) could be from similar mining effects. An interesting argument might be that these observed experimental effects could be due to the compressional stresses (vertical strain) of the overburden alone, and that adjacent barrier pillar K values are higher because of lower overburden heights. Is the stress relief of adjacent strata due to mining or is it coincidental that vertical strain is higher on pillars, therefore producing stress-relief in barriers? It makes more sense to believe that a great change in vertical strain over a short span is the cause of stress-relief in these areas. From previous studies, these factors seem to be influential on coal barrier performance:

- Hydraulic conductivity of coal – Variance of the K value will alter the flow rate of water through a porous media, given a constant area and hydraulic head potential
- Geology – Different rock layers have different hydraulic properties and will be altered by mining in different ways based on their strength characteristics (Figure 2.6)

Figure 2.6 Image of fracturing of a hard sandstone overlaying a coalbed in western Pennsylvania

- Compressional stresses and tensional stresses/relief fracturing
- Hydraulic head levels – Increasing the water pressure on a barrier will increase the potential for water to 'push' through barriers of some resistance.

- Regional faulting- faulting can be found from the examination of linears or even from underground observations. Faults are associated with intense fracturing of strata.
- Depth of overburden – shallower barriers are more vulnerable to open fracture or faulting networks because there is less overlying pressure. Deeper strata is compressed, thus restricting groundwater movement (lower K values).
- Mining method/s – differing mining methods will leave different footprints. This can influence the maximum mine pool elevation and coal extraction ratio.
- Coal extraction ratio – Extracting higher amounts of coal will shift the stress field in different ways than if lesser amounts of coal are extracted. High-extraction mining will tend to cause induced fractures and can change K values of surrounding strata. Full-extraction mining causes subsidence and has similar immediate effects on surrounding strata/barriers.
- Weathering – The weathering of joints and fractures can cause openings to change by dissolution or deposition of minerals or particles.

3.0 METHODOLOGY

To investigate the performance of coal barriers, several possible case studies were chosen for analysis. Only a handful of the cases are presented, chosen for the insight provided on barrier effectiveness. Both successful and failed barriers are invested to optimize understanding. Included data collection sources included meetings with state, federal, and industry officials to gather case information. Preliminary information gathered for a case study may include the history of the mine and a chain of events explaining the latest known conditions at the mine.

3.1 SIX-MONTH MINING MAPS

The initial data collection step is obtaining the most recent six-month mining maps. A six-month mine map is the map of an underground coal mine that is updated (every six months) due to the constant mine development. These maps are scanned for use in geographic information system (GIS). Information obtained from six-month mining maps includes the mine outline, mining methods used, survey points, permitted barrier areas, and other information. Hundreds of six-month mining maps have been scanned and analyzed in this study.

3.2 COMPANY DATA

Additional data is collected including barrier permit files, geologic logs, hydrologic monitoring reports, drawdown and pump-tests, aerial images, and other supplementary reports characterizing barrier conditions. The permitting of a hydraulic coal barrier gives baseline data helpful for analysis. Geologic data, such as logs and core locations, are used to reconstruct the strata surrounding the coal barrier, which play an important role in barrier performance. Geologic logs with core (drilled) locations are used to create cross-section maps of mine strata. Hydrologic monitoring reports include important data used for illustrating the water level (mine pool) in the mine. Reports can include monitoring well water levels, piezometer measurements, discharge flow rates, water chemistry, or similar characteristics. Aerial images can assist with identifying surface features near a mine, especially when visiting a site.

3.3 FIELD RESEARCH

Significant information has been collected from field visits accompanied by agents from the government or industry. Background data and information from previous investigations at a mine site is a useful resource. Important data collected from field investigations includes verifying locations of significant structures or monitoring points, measuring the mine pool elevation, measuring flow rates of discharging mine water, and the sampling and analysis of mine water chemistry.

3.4 DATA ANALYSIS

The GIS software utilized is ArcGIS by Environmental Systems Research Institute (ESRI). GIS allows for the georeferencing of 6-month mining maps and creation of a full mine outline for each case study. The application of GIS also allows for the visualization of mined areas relative to other data layers. A mine outline is drawn as a shapefile in GIS and separated into unique divisions. These divisions are based on areas where distinct mining methods were employed, including traditional room-and-pillar, thin pillaring, pillar retreat or full extraction mining, augered areas, and strip mining.

Once the pertinent information is collected, barrier analysis can begin. If barrier flow is believed to be primarily through the coalbed, a model using Darcy's Law can be applied. When modeling a coal barrier, either the flow rate or hydraulic conductivity parameters are estimated. Hydraulic conductivity estimates are based on typical hydraulic conductivity values for coal in the Appalachian region. From the estimation of hydraulic conductivity, conclusions can be drawn as to whether a coal barrier is mostly intact (free of geological discontinuities) or flow is primarily through fracture networks. Fracturing is detected by measuring unrealistically high K values of a rock. If the measured K values are significantly greater than those found for coal, it is known that fracture systems are present.

If the barrier seems to be unsuccessful based on K value estimates and the groundwater flow seems to be via fracture flow, a different flow model must be used. A simple model based Cubic Law, arranged for a single fracture, can be used to predict fracture flow through a barrier. The Cubic Law is an equation derived from the form Q=kiA (Romm, 1966). Given a flow rate, the equation will yield a fracture opening, where the width and aperture of the opening are directly related.

Additional selective modeling was performed using a groundwater modeling software, GMS (Groundwater Modeling Software) 9.1, by Aquaveo. The software utilizes MODFLOW, a widely utilized program generated by the United States Geological Survey. The software was used to analyze the effects of hydraulic pressure (head) on a barrier given the boundary conditions. Visualizations are produced to simplify the understanding of hydraulic coal barrier performance and groundwater flow.

4.0 CASE STUDIES

This chapter presents the details of case studies for this thesis. The case studies include the Solar 7 & 10, Little Toby, Dora 6, and Penn View mine. For each case study, the following features have been examined:

- Mine history
- Geology/hydrogeology
- Discharge & mine pool characteristics
- Mining methods & effects
- Coal barrier analysis

4.1 SOLAR 7 & 10

The Solar 7 & 10 underground coal mines are neighboring room-and-pillar mines in the Upper Kittanning (UK) coal seam of northern Somerset County, Pennsylvania. Operations for the Solar No. 7 mine began in 1975 by Lunar Mining, Inc. followed by the opening of Solar No. 10 in 1976 by Solar Fuel Company Inc. The Solar No. 7 & 10 mines closed in 2002, while being operated by Genesis Inc, and Solar Fuel Company Inc. Rosebud Mining Co. currently owns the Solar No. 7 mine property and Solar Fuel currently owns the Solar No. 10 mine property (Figure 4.1).

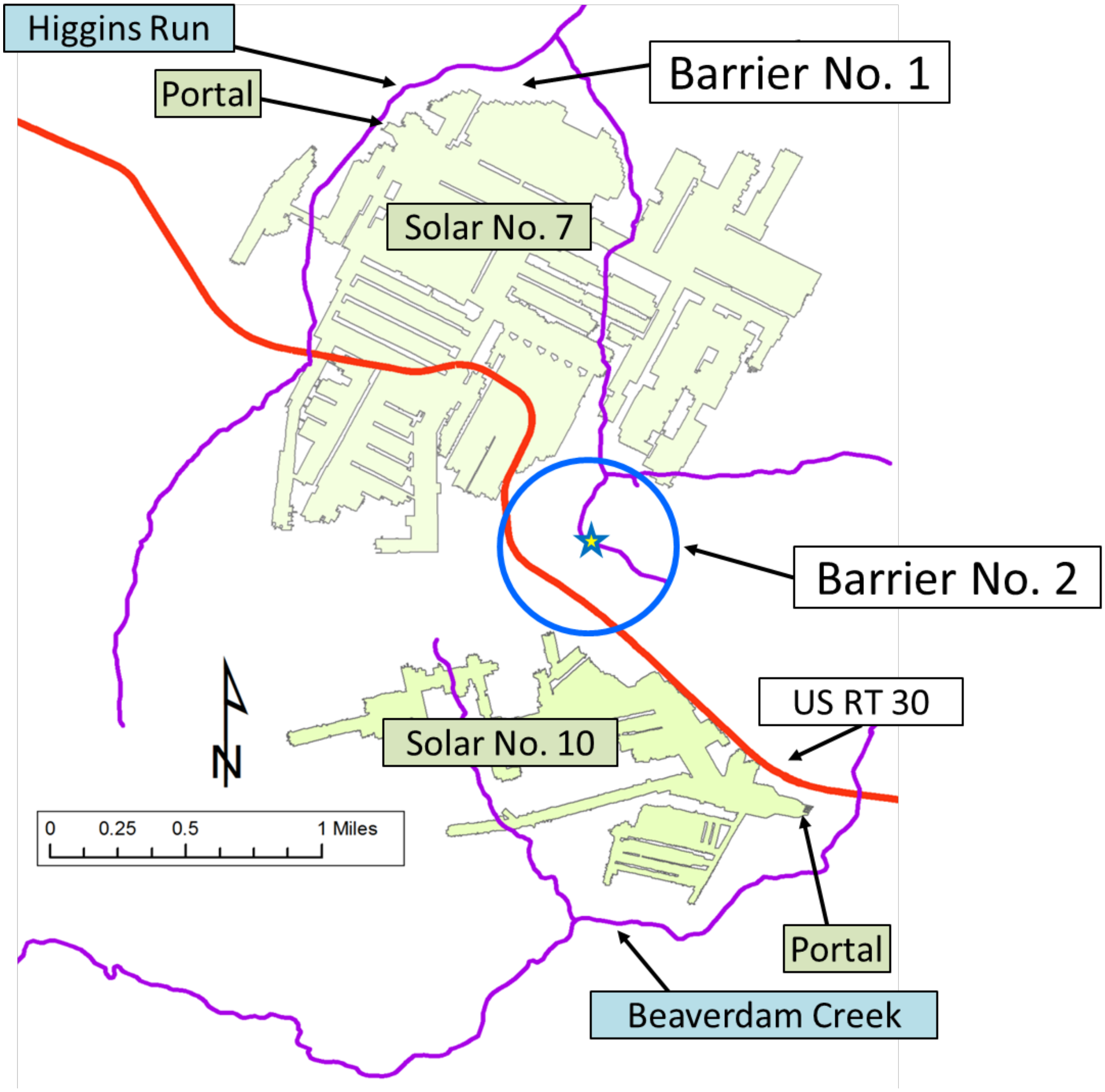


Figure 4.1 Layouts of the Solar 7 & 10 Mines. Locations of Higgins Run, Beaverdam Creek, and U.S. route 30 are shown, along with the locations of barriers 1 & 2.

The geology of the Solar 7 & 10 mines was reconstructed from 70 borings reaching the Upper Kittanning coal seam (Iannacchione et al, 1981). The thick, Freeport sandstone, a dark-gray laminated shale, and a lateral transition zone (comprised of slickensided shale and thin sandstone stringers) between the sandstone and shale forms the roof strata. The Upper Kittanning coalbed is 4-5 ft. thick in most areas and underlain by claystones and the Johnstown limestone. The Upper Kittanning coalbed at the Solar No. 7 and Solar No. 10 mines lies within the Somerset Syncline where the structure contour elevations are approximately 1,600-ft and gently rise 2° to 4° to the Boswell Dome in the northwest and the Negro Mountain Anticline in the southeast (A. T. Iannacchione, Ulery, J.P., Hyman, D.M., Chase, F.E., 1981). This influences the dip direction of the coal seam overlying the Solar mines. To the north of Solar 7, the coal dips inward toward the mine. In the area between Solar 7 and 10, the coal dips to its lowest point, to an elevation of approximately 1610 ft msl. Four municipal water wells are located in the valley separating the Solar 7 and Solar 10 mines.

An observable discharge was recorded at the Solar 7 mine by officials at the Pennsylvania Department of Environmental Protection in the winter of 2004. This discharge contained levels of Fe similar to waters in the Solar 7 mine pool. The barrier 1 discharge is located on the north-facing hillside along Higgins Run at an elevation of 1660 ft.. This discharge was recognized to be a potential above-drainage coal barrier issue. The ArcGIS software was used to generate an overburden map from in-mine survey points. This analysis allowed the coal outcrop near Higgins Run to be defined and to aid in measuring the proximate barrier width (averaging 456 ft.) (Figure 4.2). Upon further analysis, it was found that the mine pool reached its maximum height near the time of the discharge. The mine pool reached an elevation of 1681 ft. in early 2004 (Figure 4.3). A flow rate of 30-75 gpm was estimated to be coming from the discharge area 10-40 ft. wide during the time that the mine pool reached its maximum elevation. The discharge was surveyed to be located at an elevation of 1660 ft.. This would create a hydraulic head 21 ft. from higher than the land surface. A wetlands area approximately 300 feet to the west of the discharge was seemingly unaffected by mine water. After the discharge was recorded, the mine operator began to pump-and-treat water to lower the mine pool. The mine pool was lowered to an elevation of 1655 ft., where the rapid discharge ceased to occur. A borehole water sample taken on February 26, 2004 shows that the Solar 7 mine water is net acidic and contains elevated levels of mining-related contaminants (Table 4.1).

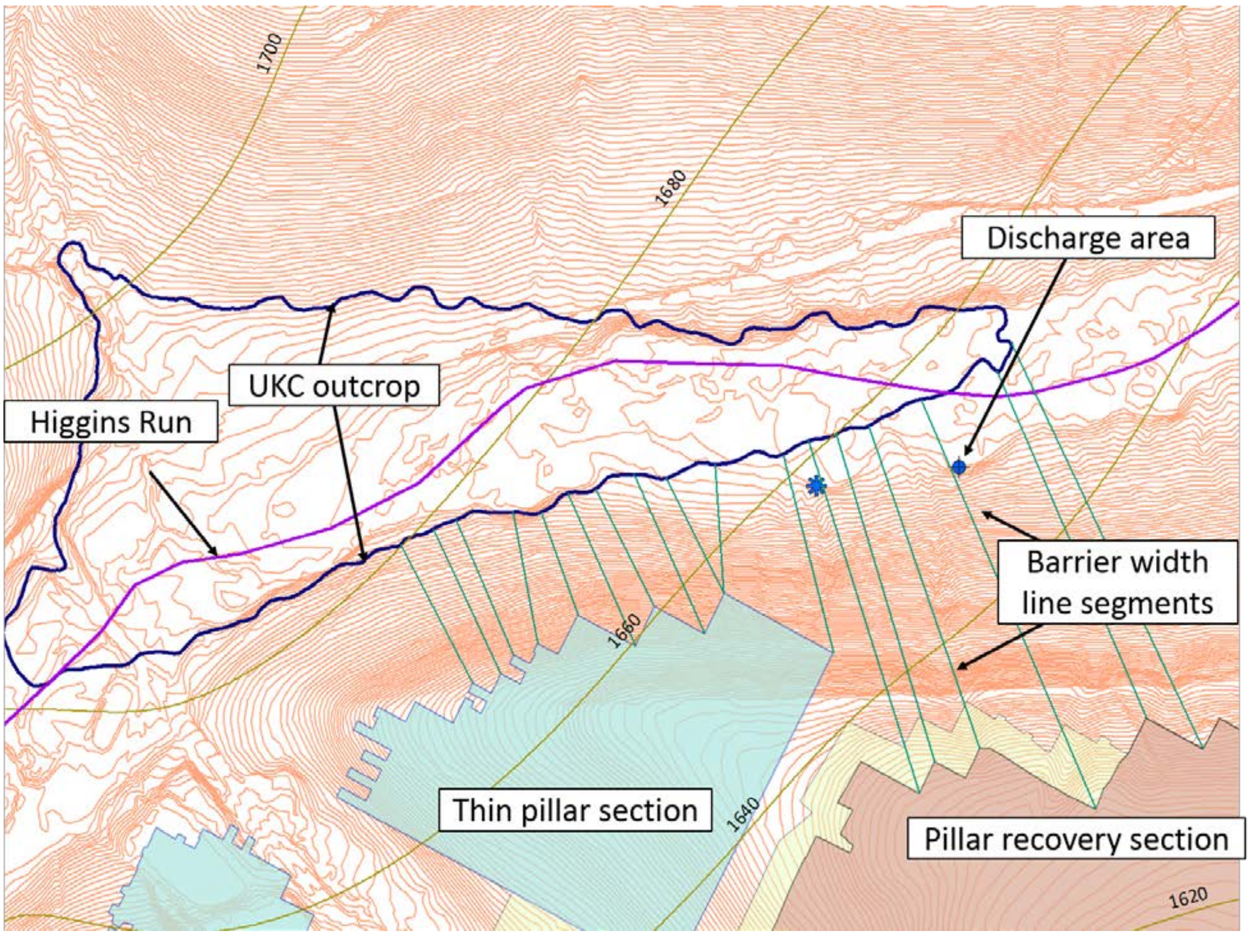


Figure 4.2 Barrier 1 measured line segments at the Solar 7 mine extending from the adjacent mined sections to the Upper Kittanning coal outcrop.

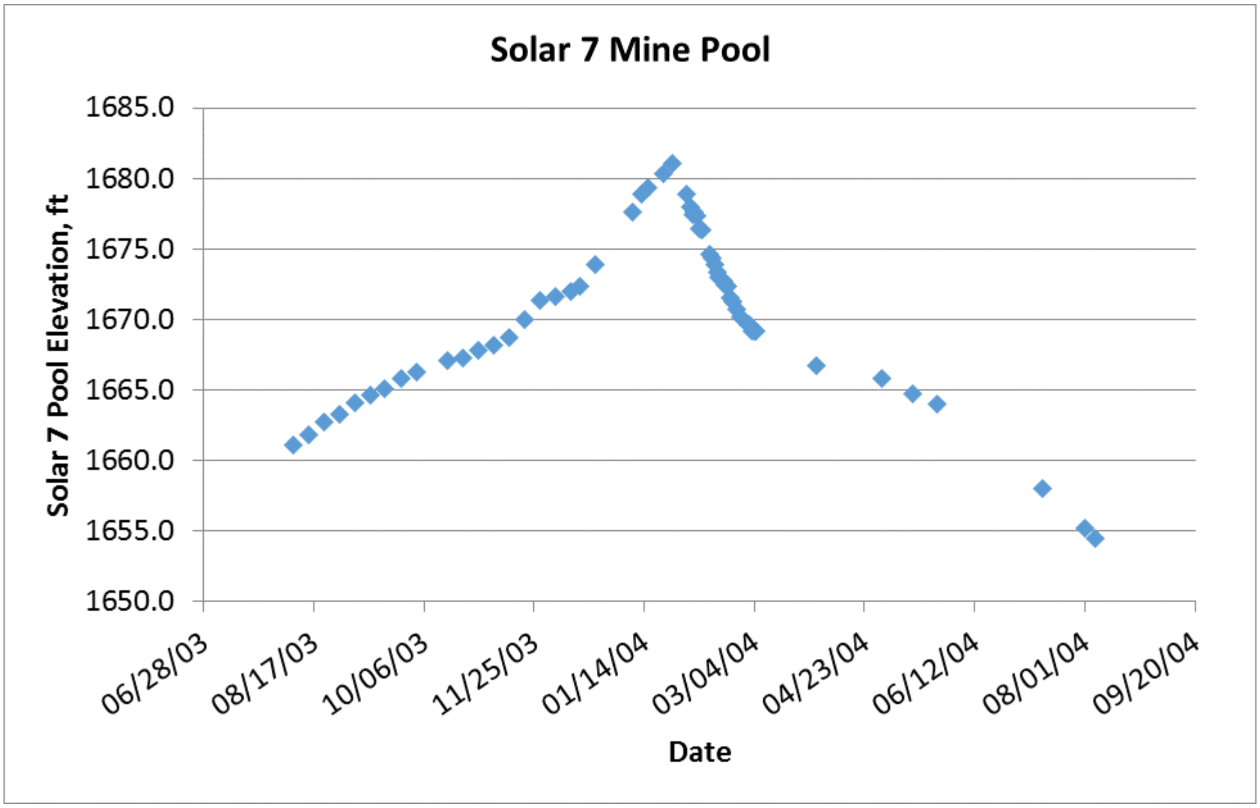


Figure 4.3 Solar 7 mine pool elevations measured from August 2003 to August 2004

Table 4.1 Water quality sample from a borehole in the Solar 7 mine (Feb. 26th, 2004)

Parameter	Values
Flow, gpm	1,000
Iron, mg/l	190
Suspended Solids, mg/l	74
Manganese, mg/l	4.08
Aluminum, mg/l	0.46
Sulfates, mg/l	560
Specific Conductance, umho	1,753
Alkalinity, mg/l	59.3
Acidity, mg/l	138.3
Field pH (S.U.)	6.5
Laboratory pH (S.U.)	5.85

An additional coal barrier area adjacent to both the Solar 7 and 10 mines surrounds the Stoystown municipal water supply wells. The wells are located at a surface elevation of approximately 1892 ft. and run from 260 - 397 ft. deep. The elevation of the Upper Kittanning coalbed at the wells is approx. 1645 ft. (Figure 4.4). From this information it can be said that the wells are in contact with groundwater from the UK aquifer. The 1800 ft. radial barrier extends in the direction of both the Solar 7 mine (to the north) and the Solar 10 mine (to the south). Since the mine pool elevation at Solar 7 was 1655 ft., a hydraulic head potential of 10 ft. on the Stoystown wells would have existed. However, the Solar 10 mine pool is allowed to reach the portal elevation, which is 1765 ft.. This would create a hydraulic head potential of approximately 120 ft. on the Stoystown wells. The Stoystown wells are seemingly unaffected by mine water contaminants (Table 4.2). This is because the Solar 10 mine pool water quality is not impaired and cannot be detected in the Stoystown water quality records.

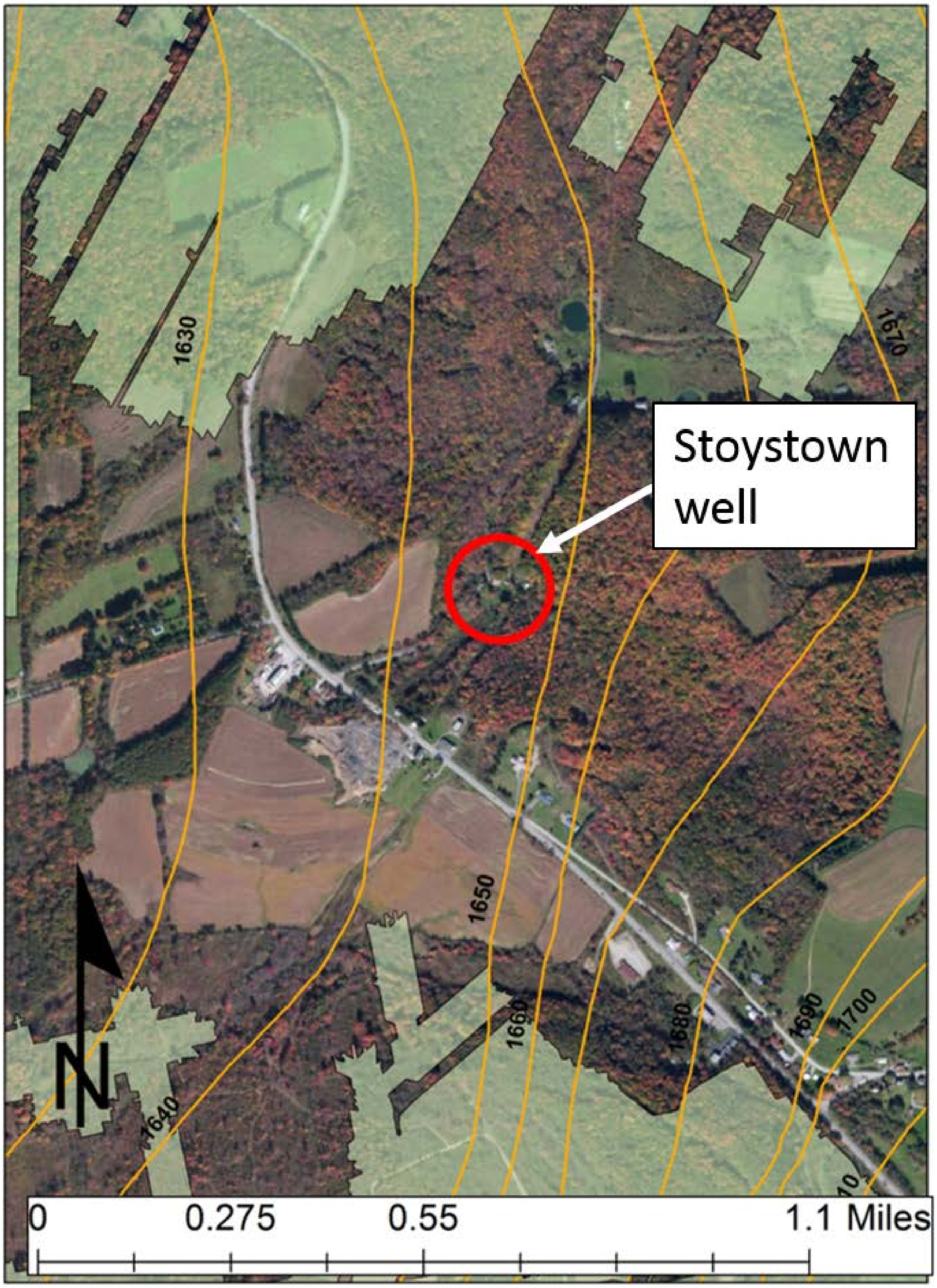


Figure 4.4 Aerial image of the Stoystown water well overlain by UK structure contours; the well is located between the Solar 7 and Solar 10 mine.

Table 4.2 CWPD monitoring point water quality sampling at the Solar 10 mine.

Parameter	Monitoring dates							
Date sampled	29-Mar-11	10-May-11	16-Aug-11	24-Oct-11	21-Feb-12	13-Jun-12	28-Sep-12	7-Nov-12
Flow, gpm	0.072	0.072	0.072	60	50	50	50	50
Iron, mg/l	2.95	3.19	9.41	4.83	5.5	5.3	10.5	0.75
Suspended Solids, mg/l	5	<5	21	9	15	6	15	<5
Manganese, mg/l	0.57	0.59	0.68	0.55	0.48	0.64	0.6	0.1
Aluminum, mg/l	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.1
Sulfates, mg/l	94	99	98	96	79	80	77	56
Specific Conductance, umho	698	633	647	657	621	682	622	289
Alkalinity, mg/l	153	147	164	163	160	162	159	43
Acidity, mg/l	-135	-135	-156	-151	-142	-132	-149	-33
Field pH (S.U.)	7.5	8	7.5	7.5	7	7.5	7.5	7.5
Laboratory pH (S.U.)	7.58	8.14	7.25	7.45	7.19	7.49	7.44	7.71

Mining methods used at the Solar 7 and 10 mines were similar (Figure 4.5). Room-and-pillar mining sections were often mined twice with either full or partial pillar recovery during the second mining. In areas of full extraction, no standing supports are left behind, allowing for roof collapse. This area of rock debris is known as the gob, and removes vertical stress from surrounding structures. In areas of partial pillar recovery, thin pillars are left behind to support the roof. The long-term strength of thin pillars is unknown. Both mines experienced full and partial pillar recovery. Pillar extraction ratios for the section of Solar 7 adjacent to the Higgins Run barrier ranged from 0.7 to greater than 0.9 (Iannacchione et al, 2013). Pillar extraction ratios for the sections of Solar 7 and 10 adjacent to the Stoystown coal barrier ranged from 0.67 to greater than 0.9 (Iannacchione et al, 2013). The depth of overburden at the mine section adjacent to Higgins Run reaches as high as 193 ft. The depth of overburden in sections adjacent to the

Stoystown water wells range from approximately 200 ft. to greater than 400 ft.. From previous studies it is clear that higher extraction ratios can play a major role in subsidence, and subsequently, the alteration of hydrogeologic conditions (Booth, 2006; Bruhn).

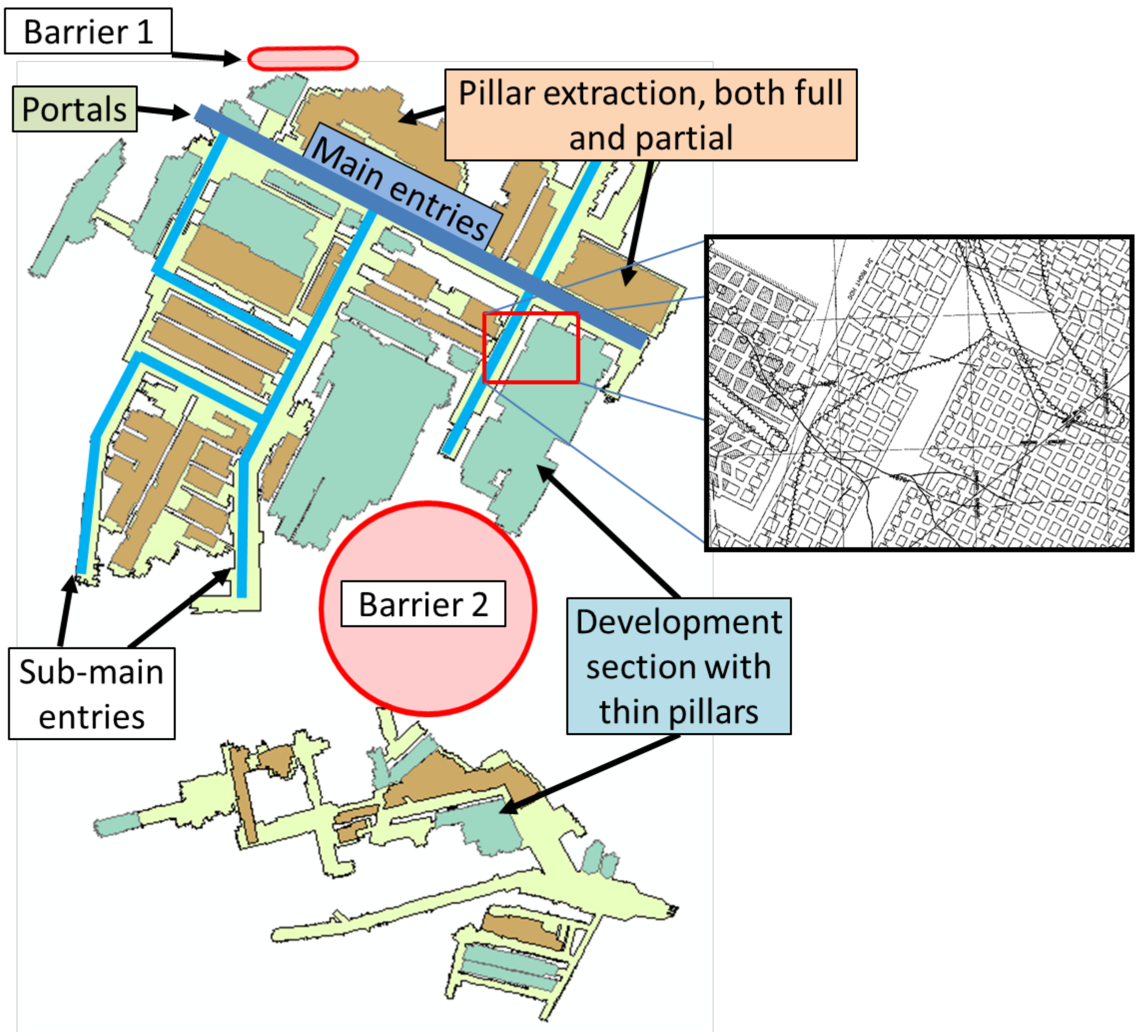


Figure 4.5: Mining methods at the Solar 7 & 10 mines are shown, which include multiple-entry room-and-pillar, pillar extraction sections (brown), and thin pillar development sections (green). Barriers 1 & 2 are also shown (red areas).

To fully understand the behavior of groundwater flow between the Solar 7 mine pool and the discharge location at barrier 1, two extreme conditions are considered. Calculations regarding flow through the barrier are solved using Darcy's equation and the Cubic Law. The purpose of using Darcy's Law is to model the flow strictly through an unaltered coalbed and entering the stream valley spanning a wide area. On the other end of the spectrum is fracture flow. Here, the Cubic Law is used to model the horizontal flow through a single, vertical fracture. For strictly coalbed flow, several properties are used to estimate the hydraulic conductivity of the barrier and characterize barrier condition and performance. Given the parameters of the barrier (width, length, and thickness) and the discharge rate range, values for hydraulic conductivity were calculated to range from 20-50 ft/d. (Table 4.3). These values are relatively high for coalbed flow, out of the literature range for coal in the region (1.12 x 10^{-4} to 14.44 ft/d) (Harlow, 1993; McCoy, Donovan, & Leavitt, 2006).

Table 4.3 Darcy calculations representing the possible hydrogeologic conditions of the Solar 7 barrier.

Barrier Number	Barrier width (w_b), ft	Barrier length (L_b), ft	Hydraulic head (dh), ft	Flow Rate (Q), gpm	Flow Rate (Q), gpd	Hydraulic Conductivity K_h, ft/d
1	456	1,400	21	30	4.32 x 10^4	19.9
				75	10.8 x 10^4	49.8

The Romm's theory of the Cubic Law was also used in modeling the barrier 1 discharge (Figure 4.6). Using this derivation, the dimensions of a joint (or fracture) can be estimated from a flow rate and hydraulic gradient measurement. Given the Solar 7 mine conditions (30-75 GPM, 21 ft. of hydraulic head, and an approximate 500 ft. barrier width) at the time of discharge, a single fracture could have properties similar to those calculated from the cubic law in this analysis (Table 4.4). Calculations produced a fracture aperture range of 0.08 to 0.11 in. for the discharge.

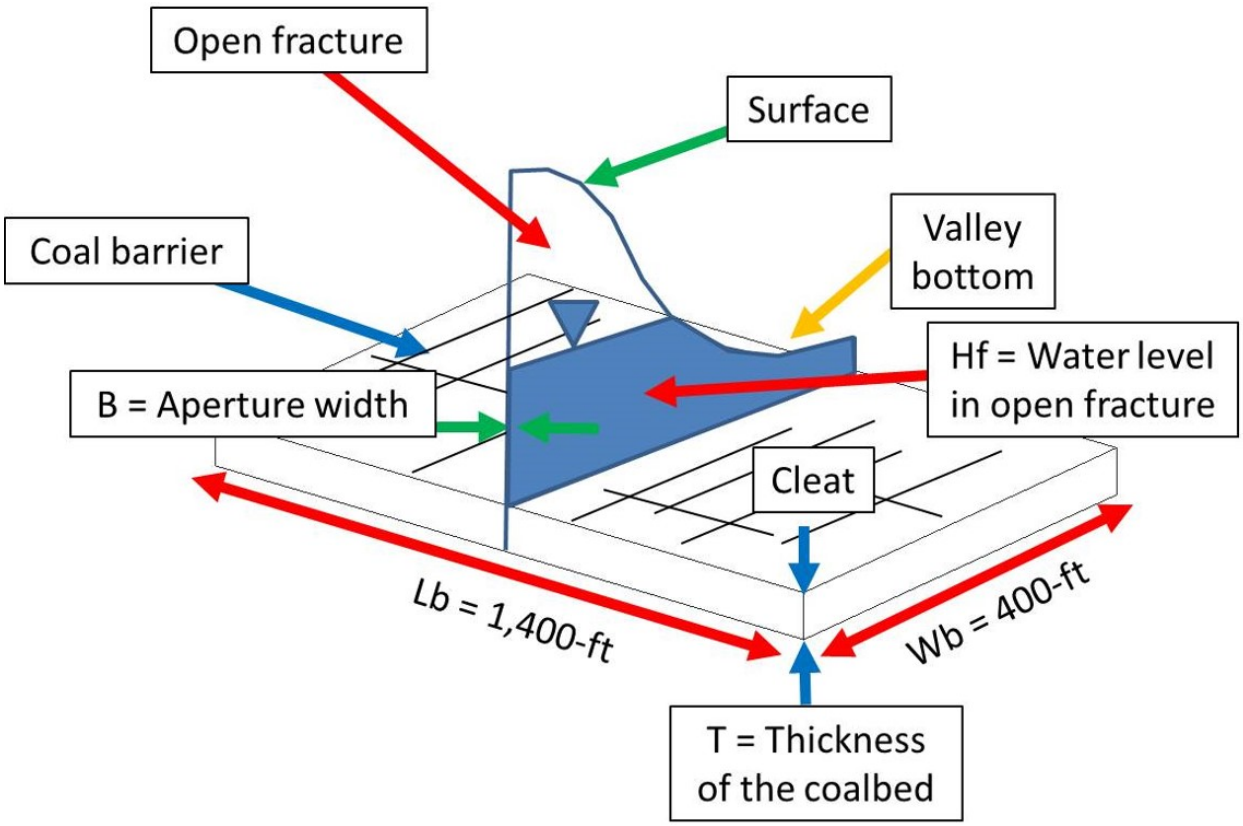


Figure 4.6 Romm's theory of the Cubic Law derived from Q=kiA (Darcy's Law). The schematic represents the single, vertical fracture case at barrier 1 of the Solar 7 mine.

Table 4.4 Cubic Law calculations representing the possible hydrogeologic conditions at barrier 1.

Flow Rate (Q), gpm	Fracture Height (w), ft	Fracture Aperture (b), ft	Fracture Aperture (b), in
30	21	0.007	0.081
75		0.009	0.110

Based on modeling of barrier flow, it is likely that the barrier flow is ruled by networks of connected fractures due to the following:

- The rapid discharge of water occurred in a narrow zone
- The discharge was adjacent to a thin pillar and pillar recovery mining section
- Low overburden thicknesses exist (Avg. ≈ 90 ft.)
- A fault is located near the barrier area

The relatively high hydraulic conductivity values estimated using Darcy's equation backs up this assumption. At the Stoystown water wells, an 1800 ft. radial barrier may have been successful in preventing the detection of mine water. From the north of barrier 2, a hydraulic head potential of 10 ft. exists from Solar 7. The mine pool from Solar 7 has not reached the wells, since there has been no indication of mine water contaminants in the Stoystown wells. The Solar 10 mine pool puts 120 ft. of hydrostatic pressure on the southern portion of barrier 2. It is unclear as to whether the Solar 10 mine water has reached the wells. This is because the Solar 10 mine pool is not impaired.

4.2 LITTLE TOBY

The Little Toby coal mine is a room-and-pillar mine located in the Lower Kittanning coal seam of Elk County, Pennsylvania. Mining operations began in 2003 by Rosebud Mining Co. and ceased in November of 2011.

Roof rock near the southwest portion of the Little Toby mine is composed mainly of shale. Core logs show that shale thickness decreases and coal thickness mainly decreases near the stream valleys. Pillar retreat and thin-pillaring of barriers was not used at the Little Toby mine. The southern-most portion of Mead Run is of concern because the coal dips to the west and land surface elevations are lowest in the southern portion of the Mead Run stream valley (Figure 4.7).

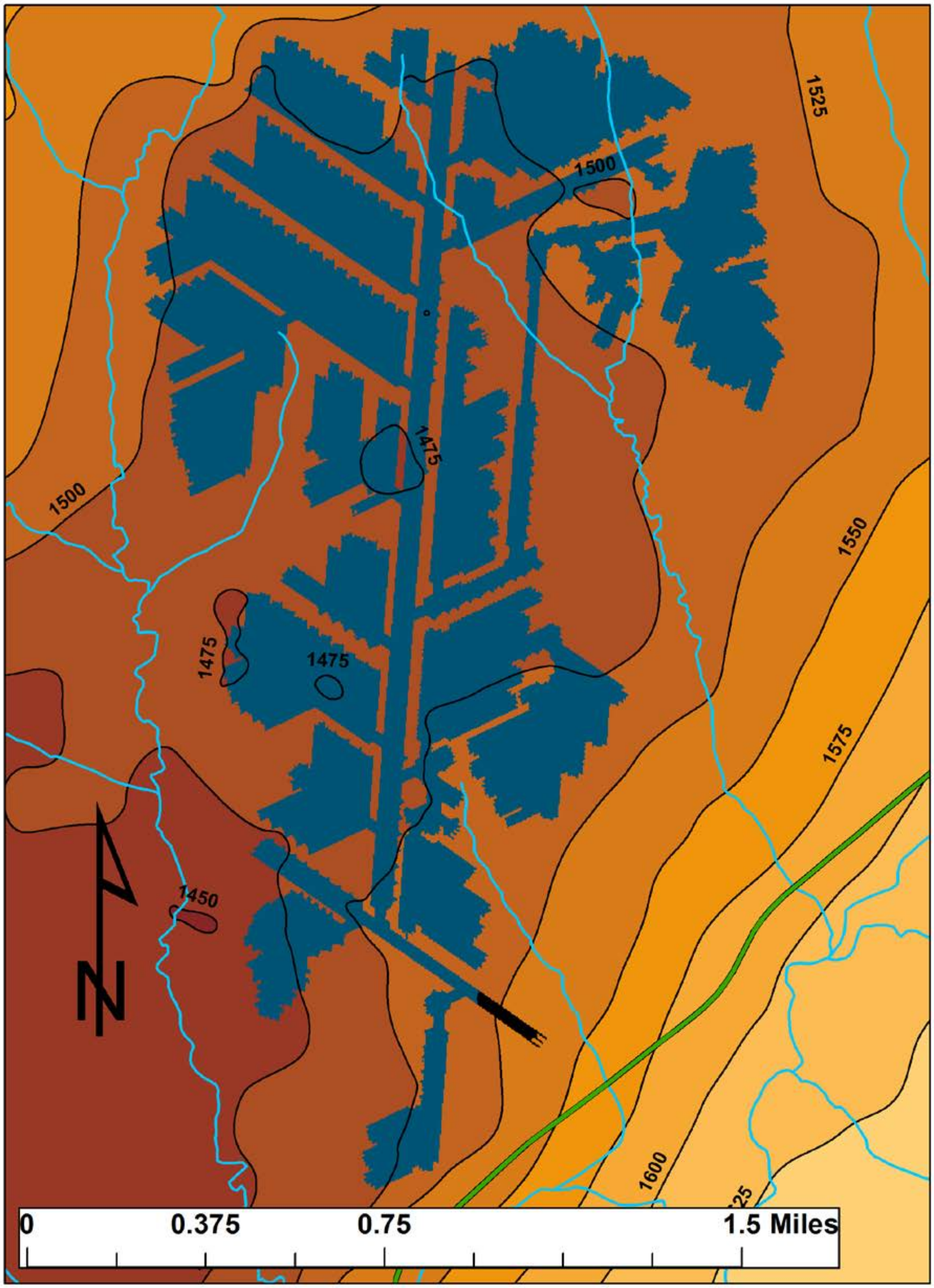


Figure 4.7 Little Toby mine with LK structure contours reaching lower elevations in the southwest.

Mine pool data for the Little Toby mine is limited to three piezometer nests and several monitoring wells. One of three deep piezometers in the Lower Kittanning coalbed is positioned in the mine void. Two monitoring wells are also positioned in the mine workings. The hydrologic monitoring of the Lower Kittanning coal bed began with several monitoring wells in 2001, while piezometer monitoring initiated in 2003. These monitoring points show mine pool fluctuations, however, records of the mine pool elevation are not up-to-date. The monitoring of mine pool elevations in two additional wells (LTMW-1 & LTMW-2) began in 2012 and continues to date. The most recent mine pool head measurements were recorded on June 20, 2013, 1528.65 ft. and 1528.95 ft., respectively. The hydraulic seal installed near the portal of the mine is at an elevation of 1520 ft.. Digital Elevation Models (DEMS) show surface elevations in the Mead Run area to be as low as 1483 ft.. The coalbed dips mainly to the west, toward Mead Run, and lies at an elevation as low as 1450 ft. beneath the stream (Figure 4.8). At the edge of mining bordering Mead Run, the coal elevation is approximately 1490 ft.. Overburden depths at the edge of mining adjacent to Mead Run are as high as 250 ft.. Overburden depths in Mead Run range from 0 ft. (at the outcrop) to nearly 50 ft.. The Lower Kittanning coalbed outcrops in Mead Run, adjacent to the southwest corner of the mine. Water quality records of the deep piezometer PB-002 (LK) has shown that mining has negatively impacted the water. The water has low pH conditions along with elevated levels of acidity, specific conductivity, Fe, SO_4^{2-}, and Mn. As of now, there is no observable indication that a high rate discharge is occurring in Mead Run or Little Toby Creek.

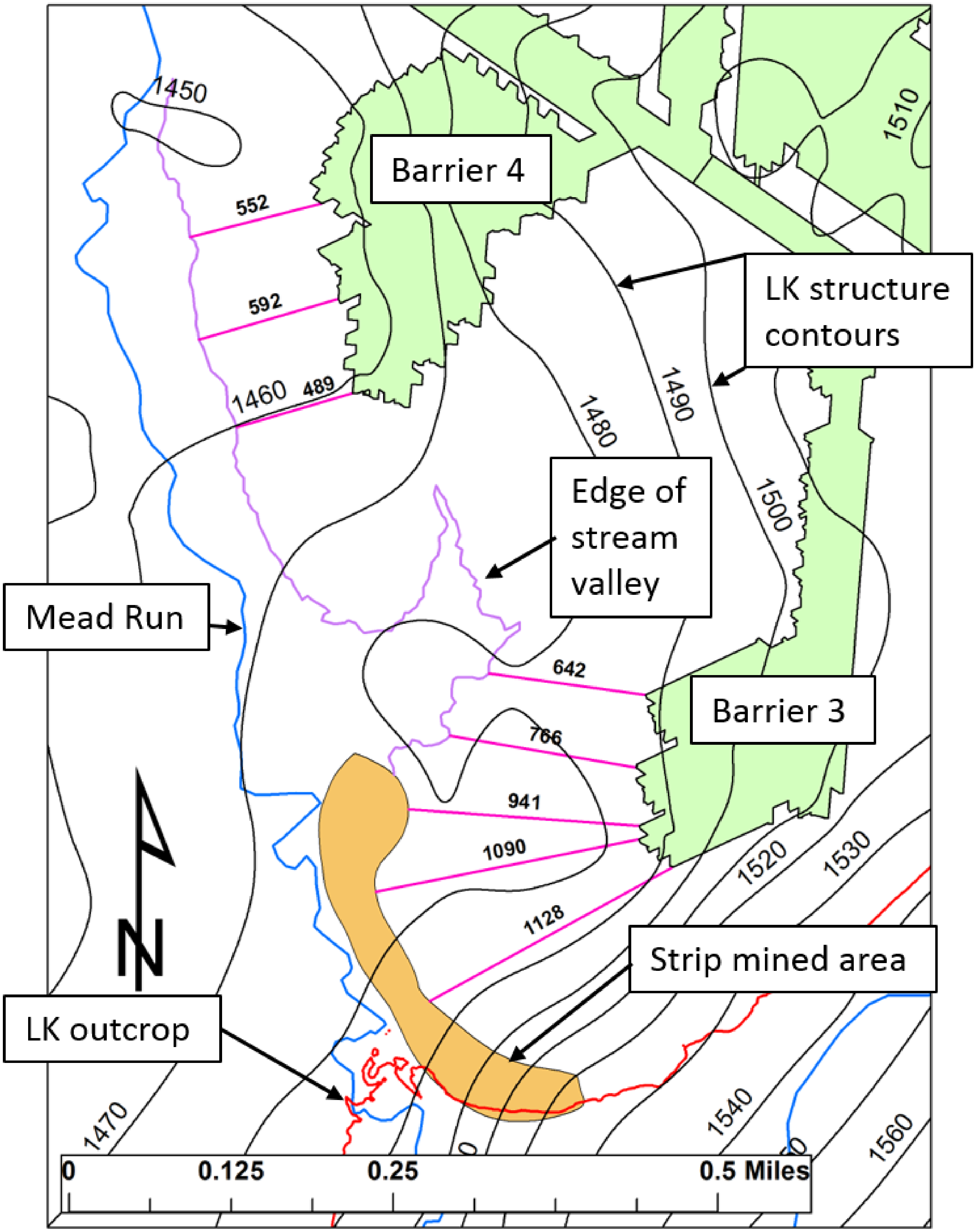


Figure 4.8 Hydraulic coal barrier segments of barriers 3 and 4 at the Little Toby mine

The only underground mining method used at the Little Toby mine was the room-and-pillar technique. Extraction ratios in the mined sections adjacent to the barrier areas of Mead Run range from 0.64 to 0.72, averaging 0.67. In addition, strip mining and augering of the Lower Kittanning, Upper Kittanning, and Lower Freeport coal seams in the Little Toby mine region has been conducted. An area was strip mined at the edge of barrier 3, decreasing its overall width. Post-strip mining activities typically deposit unconsolidated material in place of the natural overburden strata.

Coal barrier analysis was conducted for two barriers adjacent to the Mead Run stream valley (Figure 4.9). The barriers begin at the edge of the mine workings and dip-downward in the west, to the edge of the stream valley (Barrier 4) and the LK highwall (Barrier 3). This marks the end of the coal barrier, due to the high density of fractures in stream valleys in the western Pennsylvania region and unconsolidated characteristic of strip mine fill (Ferguson, 1967). Barrier 3 (the southernmost barrier) contains coal elevations as high as 1490 ft. and as low as 1475 ft., to the LK highwall. Coal elevations dip as low as 1468 ft. beneath Mead Run. Surface elevations run as high as 1720 ft. at the up-dip end of Barrier 3 creating overburden thicknesses greater than 230 ft. Surface elevations at the down-dip end of Barrier 3 and Mead Run reach as low as 1500 ft. and 1483 ft., respectively. Barrier 4 contains coal elevations as high as 1460 ft. in the east, and as low as 1450 ft. at the edge of the stream valley. However, coal elevations below Mead Run adjacent to Barrier 4 only reach as low as 1455 ft.. With a mine pool elevation of approximately 1529 ft., a potential for discharge in the Mead Run stream valley exists (Figure 4.10). Little Toby barrier analysis was conducted similar to the Solar 7 and 10 barrier calculations. Since the Little Toby barriers are seemingly successful with no observable discharges, it can be said that the barriers are well intact. Instead of estimating K values to characterize barrier performance, the amount of flow reaching Mead Run over a wide span (1000 ft.) for each barrier was estimated. This range of flow rates was computed using the lowest and highest K values reported from the literature and an intermediate K value (1.12×10^{-4} to 14.44 ft/d; 0.13 ft/d). The table below represents the parameters that were chosen for calculation of flow rate into Mead Run at the Little Toby barriers (Table 4.5).

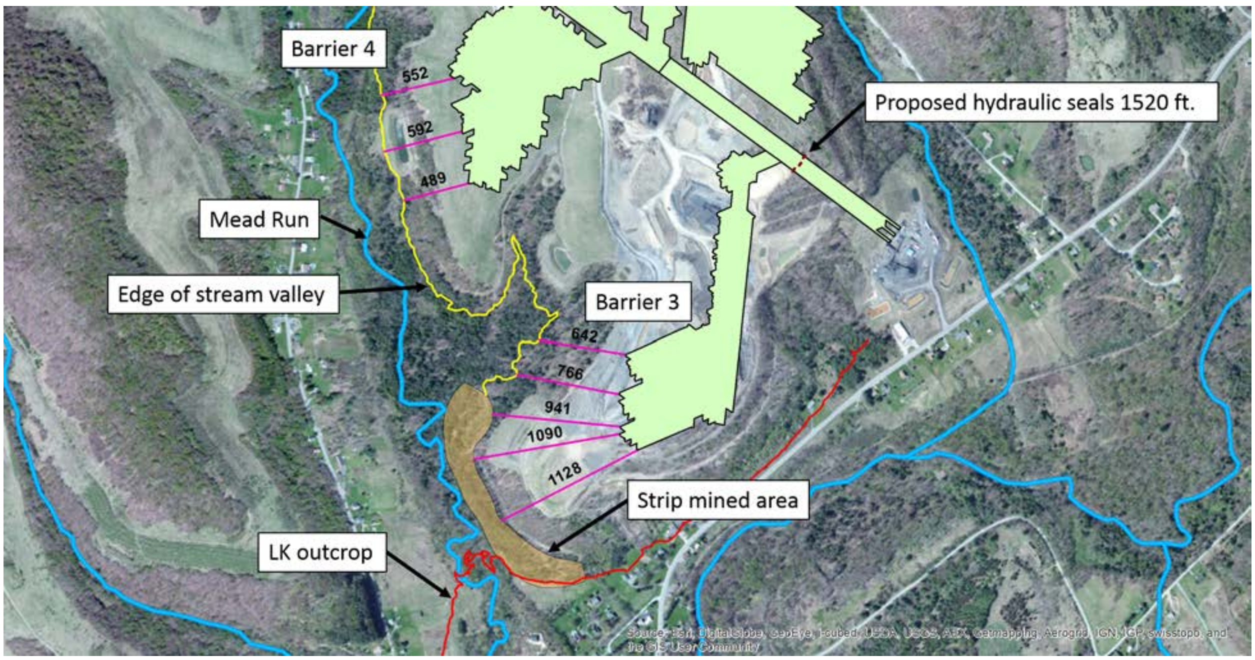


Figure 4.9 Aerial image of the hydraulic barrier area of the Little Toby mine

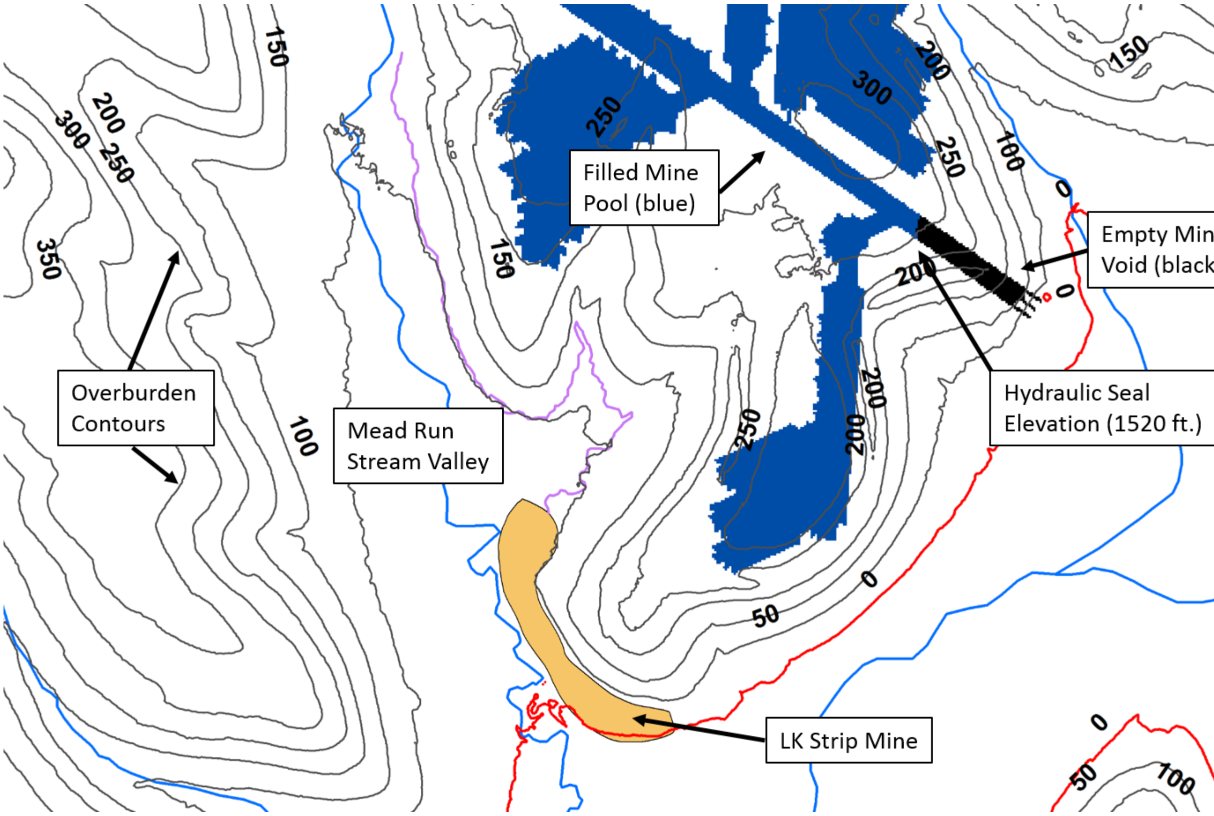


Figure 4.10 Overburden contours overlaying the water-filled mine pool outline of the Little Toby mine.

Table 4.5 Darcy calculations representing the possible hydrogeologic conditions of barriers 3 & 4 of the Little Toby mine. K values used represent the highest, median, and lowest values from the literature.

Barrier Number	Barrier width (w_b), ft	Barrier length (L_b), ft	Hydraulic head (dh), ft	Hydraulic Conductivity K_h, ft/d	Flow Rate (Q), gpd	Flow Rate (Q), gpm
3	914	1,000	29	*1.12×10^{-4}*	*0.120*	*8.31×10^{-5}*
				14.44	*1.54×10^{4}*	*10.7*
				0.13	*139*	*9.64×10^{-2}*
4	566	1,000	41.5	*1.12×10^{-4}*	*0.276*	*1.92×10^{-4}*
				14.44	*3.56×10^{4}*	*24.7*
				0.13	*321*	*0.223*

The amount of groundwater reaching Mead Run was estimated based on the latest mine pool conditions and variance of the barrier K values. For each barrier, a wide range of flow rates are computed showing differences of up to five orders of magnitude. This predicts the sensitivity of Darcy's Law to the K value assumption. The calculated flow rates into Mead Run from the Little Toby mine pool show that an observable discharge is possible if the coal barrier is altered (contains higher ordered K values). As of now, the barrier seems to be performing as designed. If the mine pool water reaches an area of the barrier that contains some type of significant geologic discontinuity, an observable discharge in Mead Run is possible. The following factors may be affecting the performance of the Little Toby barriers:

- Mining method – no pillar retreat mining was employed
- Barrier width is acting sufficiently
- Hydraulic head – relatively low
- Geology – roof strata in mine and barrier area is primarily shale

Additional analysis of the Little Toby coal barrier was conducted using GMS 9.1 (MODFLOW-based software). The goal of the groundwater modeling was to identify the amount of hydraulic coal barrier flow to reach Mead Run through a single, vertical fracture. To quantify the volume of water reaching Mead Run, a particle tracking method was used to release a set number of particles in the mine workings. The particles travel through the coal seam and end either at Mead Run or at the end of the coal barrier (passing the fracture). Representation of a vertical fracture by altering the vertical hydraulic conductivity was necessary, since relatively little data exists on the ratio of vertical to horizontal K values of coal in Pennsylvania. A correlation was found in the percent of particles that reach Mead Run versus the K_v/K_h ratio (Figure 4.11). K_v/K_h is a measure of the vertical permeability anisotropy through porous media. The coal barrier model was run using the following assumptions:

- Groundwater is moving laterally through the coalbed from the filled mine workings
- A single, vertical fracture simulates the Mead Run stream valley fracturing (one single fracture is assumed to represent an inplace system of discontinuous fractures)
- No significant vertical fractures exist in the remainder of the coal or surrounding strata (vertical permeability anisotropy is several orders of magnitude lower, creating a confined hydraulic coal barrier)
- Steady state (constant head boundaries at the ends of the coal barrier (145 and 110 ft.) and constant head boundary at Mead Run (113 ft.)
- K values for the four layers in the model are represented in Table 4.6

Table 4.6 K values used in the modeling of the Little Toby hydraulic coal barrier. Coal modeling techniques typically use horizontal K values near 1 ft/d; horizontal K values for shale are typically found to be 2 or 3 orders of magnitude lower than coal.

Layer	Kh (ft/d)	Kv (ft/d)
Soil	0.01	0.0001
Shale	0.001	0.00001
Coal	1	0.3
Shale	0.001	0.00001
Fracture (extending through coal, shale, and soil to Mead Run)	Same as respective layer	Varies

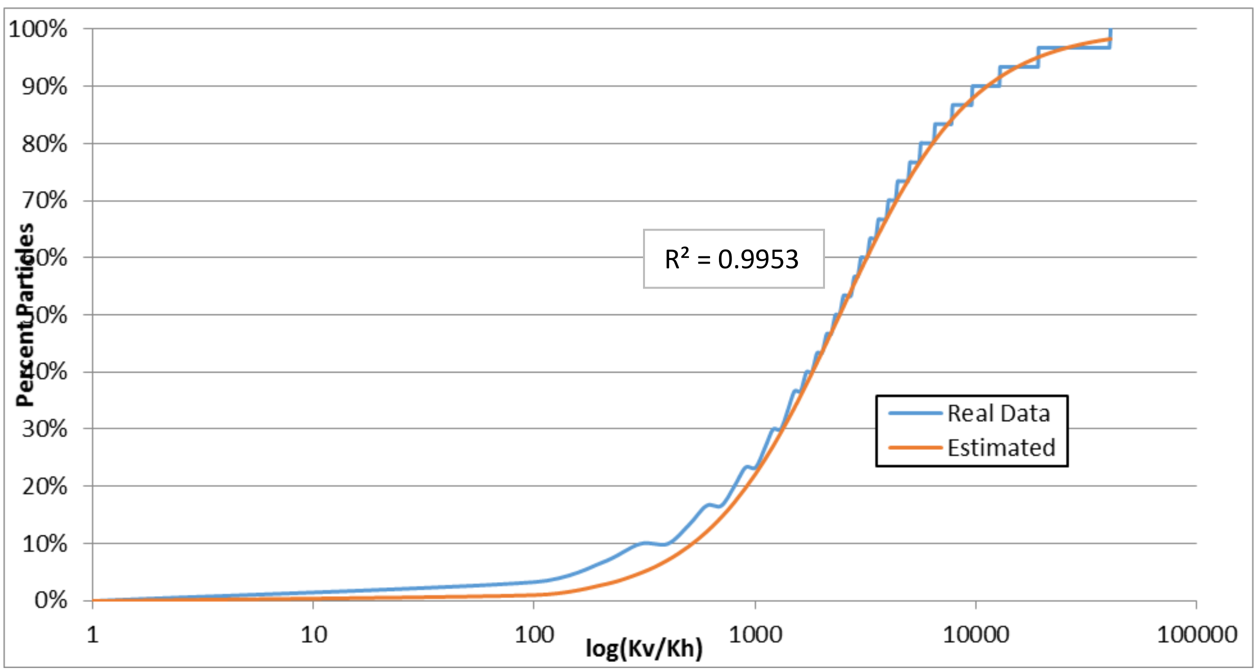


Figure 4.11 Plot of the percentage of particles to reach Mead Run versus the Kv/Kh ratio of the fracture in the Little Toby barrier flow model.

Figure 4.11 demonstrates the relationship of the percentage of particles to reach Mead Run via a fracture by varying the K_v/K_h ratio. In other words, the percentage of particles represents the proportion of coal barrier flow reaching Mead Run. With high resistance (low vertical anisotropy (K_v/K_h)), a lower percentage of flow is expected to reach Mead Run. In general, coal barrier flow takes the path of least resistance where K values are highest and hydraulic head pressures are lowest (flow direction is oriented from areas of higher pressure to areas of lower pressure). The relationship is shown by:

$$Particle\ percentage = \frac{1}{1 + (\frac{2400}{x})^{1.43}}$$

The formula for particle percentage shows that 10% of coal barrier flow (particles) enters the vertical fracture when the K_v/K_h ratio 300. At a K_v/K_h ratio of 2400, fracture flow coordinates 50% of the coal barrier flow to Mead Run. The remaining 50% of coal barrier flow continues horizontally through the coal seam as indicated by particle tracking. For the actual case of Mead Run coal barrier flow, the value of K_v/K_h needed (in the streambed strata) to produce an observable impact to the stream is unknown. On a log scale, the model shows that when the K_v/K_h ratio is greater than approximately 300, the amount of flow reaching the stream drastically increases. Since mine water impairment of Mead Run is currently unobservable, the K_v/K_h ratio is apparently not significant enough (less than 300) to conduct substantial hydraulic coal barrier flow.

4.3 DORA 6

The Dora 6 and 8 mines are room-and-pillar mines located in the Lower Kittanning coal seam of Jefferson and Indiana County, Pennsylvania near the town of Hamilton. Mining operations at Dora 6 began as early as the year 1980 by Doverspike Brothers Coal Co. and ceased in November of 1998. At this time, pumping of the mine pool stopped and the elevation rose slightly higher than 1260 ft.. Homeowners in the town of Hamilton have had well water supplies affected by the mine water. The main section of mining that is of concern is bordered by Perrysville Run to the east, Foundry Run to the west, and Hamilton and Mahoning Creek to the south (Figure 4.12).

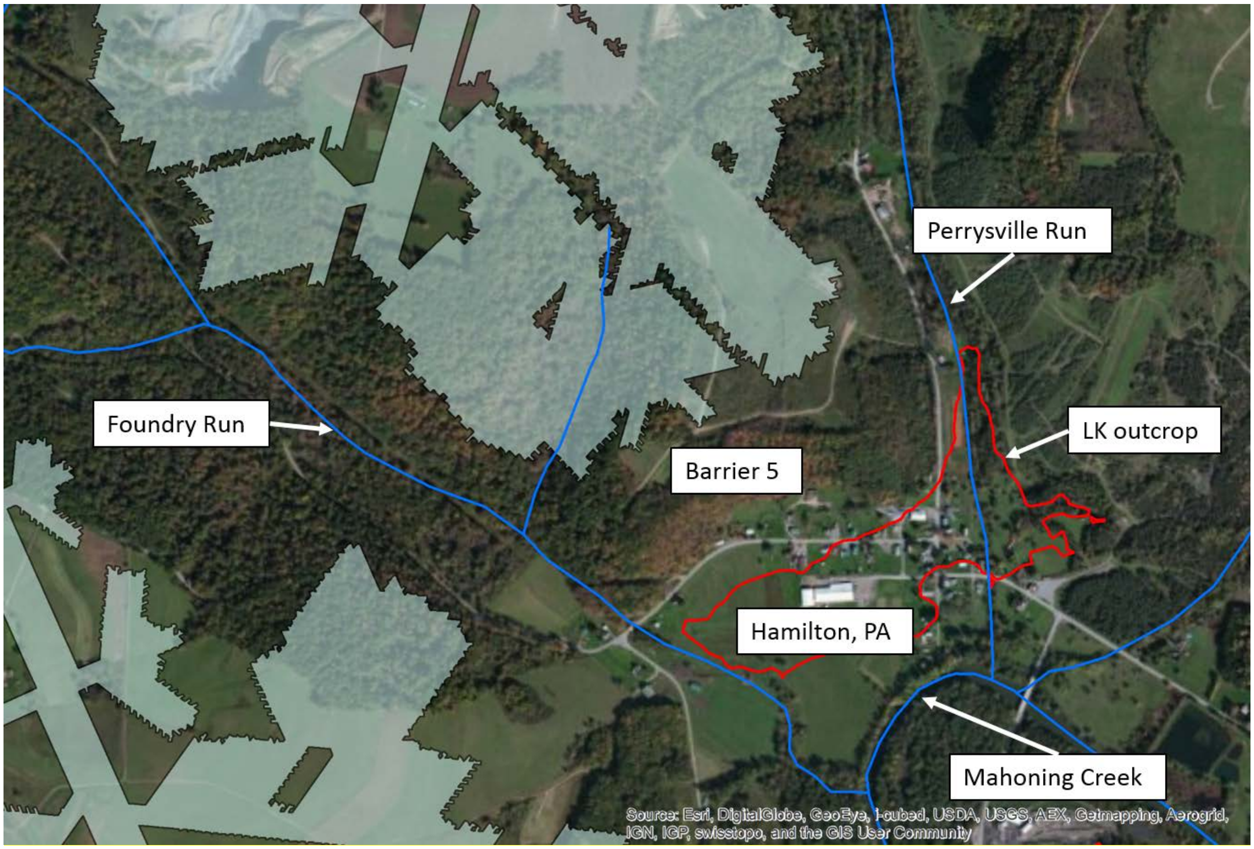


Figure 4.12 Aerial image of the town of Hamilton, PA. Also pictured is the Dora 6 mining section adjacent to barrier 5 and the LK outcrop (red).

The geology in the Dora 6 region is revealed by geologic cross-sections and the production of a coal structure contour map. The cross-sections show that shale is the primary material in roof rock and a combination of shale and sandstone forms the floor strata of Dora 6. The in-mine survey points were combined with in-mine survey points from the Dora 8 mine. The coal gently dips generally in the south-southwest (SSW) direction (Figure 4.13).

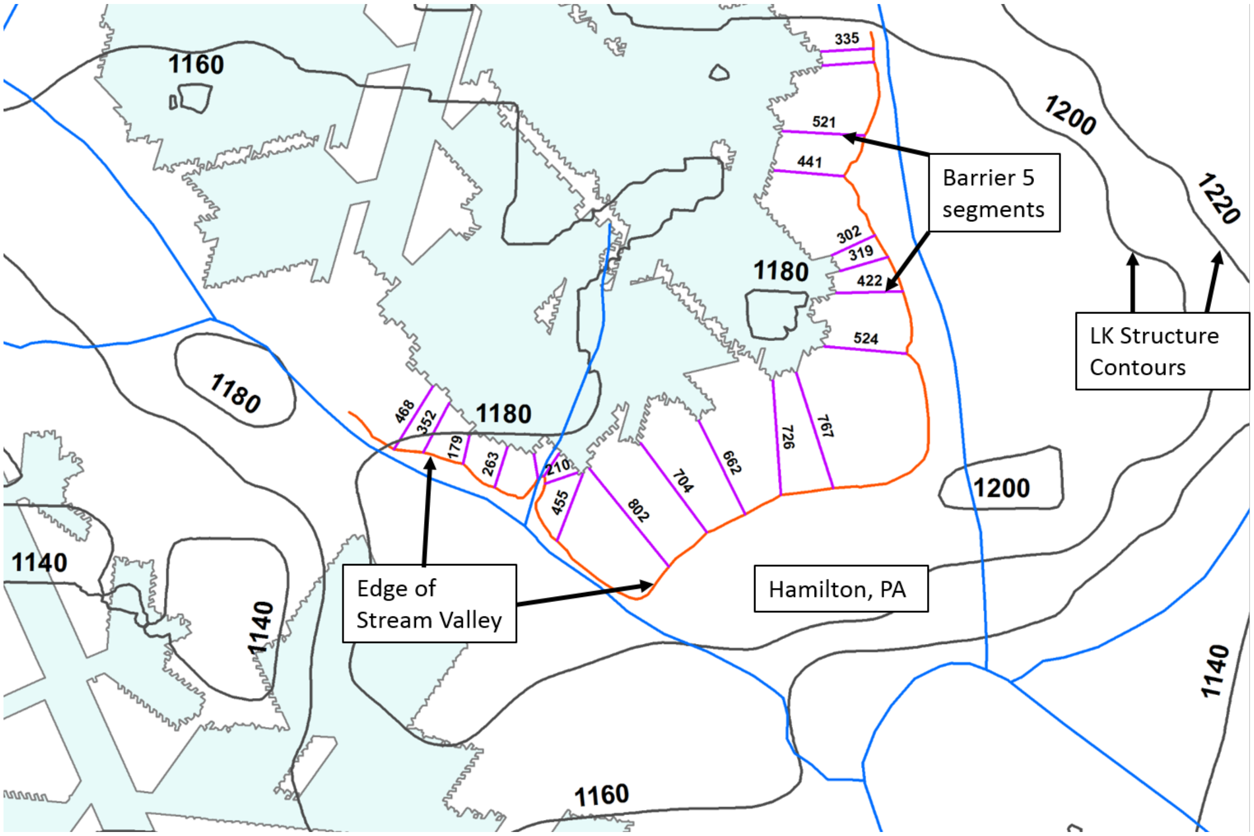


Figure 4.13 Barrier 5 segments and the LK structure contours at the Dora 6 mine.

Monitoring of the Dora 6 mine pool by the PA DEP has shown the pool elevation dropping over the years The goal of the PA DEP Bureau of Abandoned Mine Land Reclamation project was to lower the mine pool to an elevation of 1210 ft. by drilling horizontal boreholes into the mine workings at an elevation of 1198 ft. (Figure 4.14). The boreholes discharge into a settling pond near Perrysville Run. The project was established due to the potential for a coal barrier blowout. Records of the mine pool elevation in June 2009 show that it has reached as high as 1263 ft.. From 2009, the pool elevation has steadily dropped until it reached 1230 ft., which it reached in April of 2010. The mine pool has since maintained its elevation of approximately 1230 ft.. The latest known record of the mine pool elevation was in June of 2010, where the pool was recorded to be at 1230.25 ft. in elevation. Other monitoring points have also been monitored over periods of time. Two boreholes reaching the mine workings have been monitored through June of 2011. Water levels in borehole “I” were recorded dating back to 2000, when the water elevation was approximately 1250 ft.. The highest water level recorded at Borehole I was at 1261.80 ft. in June of 2009. From that point it has steadily declined to the elevation of 1229.15 ft. in June of 2011. The lowest recorded water elevation was 1222.80 in September of 2010. Borehole “K” has been monitored since July 2009. This borehole was used to inject sludge collected from the treatment of iron-rich mine water. Water elevations in this borehole have ranged from approx. 1260 ft. in late 2009 to approx. 1218 ft. in December of 2010. The latest recorded water elevation of borehole K was 1228.65 ft. in June of 2011. An old fan shaft and monitoring well supplement the mine pool data. A de-watering report from the time span of Jan. 12, 2012 through March 29, 2012 documents the mine pool at an average elevation of approx. 1230 ft.. Overall, the mine pool elevation has decreased from elevations near 1260 ft. to 1230 ft. over a few years.

Figure 4.14 Horizontal borehole inflow to the Dora 6 settling pond near Perrysville Run.

A precipitation gauge was closely monitored during this time. Precipitation has contributed to small increases or delays in the decreasing mine pool elevation. Precipitation in the Dora 6 region has had minor effects on the mine pool elevation. From the monitoring of the settling pond inflow/outflow the average flow rate is approximately 350 gpm. Since the mine pool has maintained a near constant elevation, this is the approximate amount of water entering the mine as recharge. Water quality monitoring reports have shown that the Dora 6 mine water entering the settling pond is net alkaline with a pH above 7.0 (Table 4.7). Elevated levels of Fe and SO_4^{2-} are also present. Seeps in the town of Hamilton have also shown elevated levels of

SO_4^{2-}. Perrysville Run lies to the east of the town of Hamilton and has been monitored for indications of mine contaminants. The water quality of this area of the stream has shown that the water is above pH 7, with low concentrations of Fe and SO_4^{2-}. In contrast, water chemistry at the mouth of Perryville Run has a pH above 7 but carries intermittently elevated concentrations of Fe and SO_4^{2-}. These enriched concentrations of SO_4^{2-} at the mouth of Perryville Run and the two seeps are interpreted as arising from mine pool contributions.

Table 4.7 Average water quality values of the Dora 6 mine pool dating from 5-26-2009 to 3-29-2012 (applicable units in ppm)

pH	6.9
Alkalinity	131
Hot Acidity	-93.4
Fe	33.8
Mn	0.6
Al	< 0.5
SO4	470.0
TSS	27.4
Na	140.0

The topography of the Dora 6 mine is rugged, spanning 540 ft. of relief 1200-1700 ft. and as low as 1160 ft. in the Mahoning Creek valley (Figure 4.15). Since the mine pool elevation is above 1200 ft. and the coal dips toward the lowest surface elevations, this is a concern.

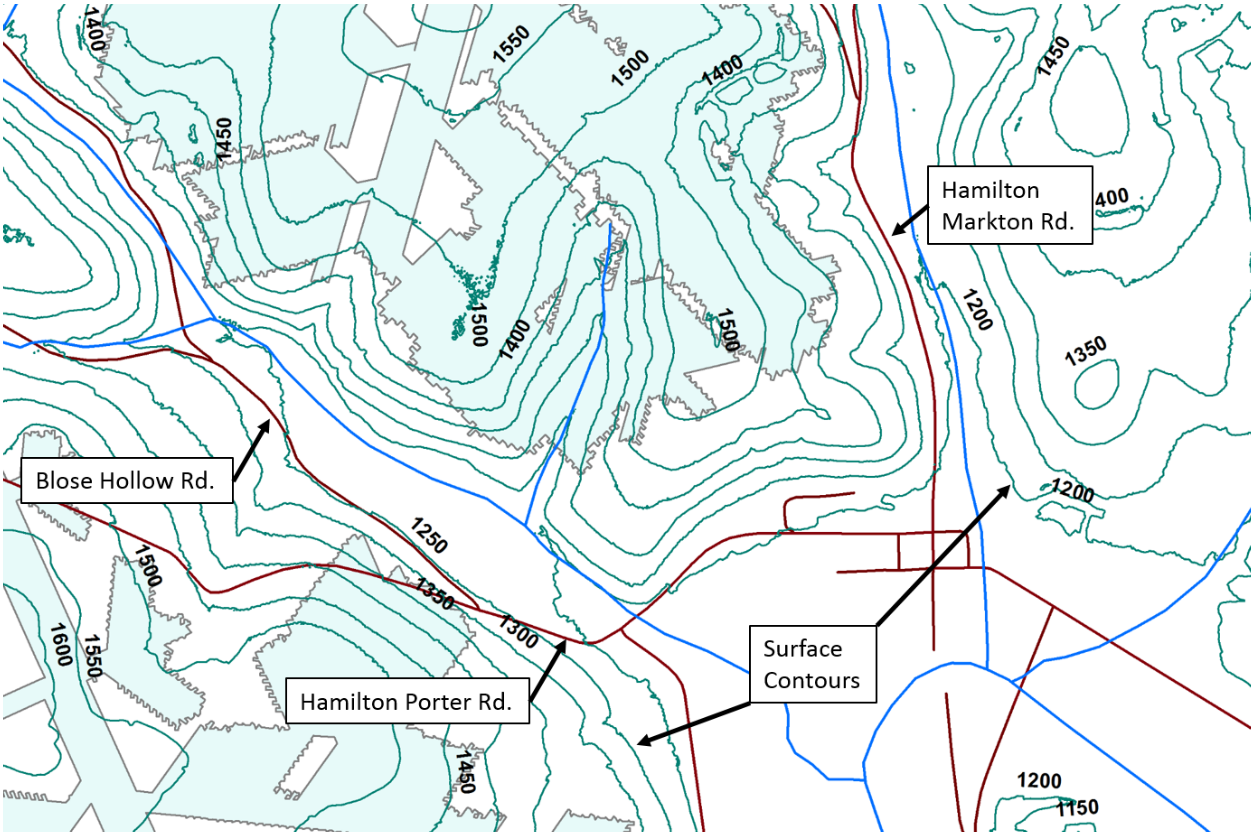


Figure 4.15 Topographic map showing the roadways near barrier 5 at the Dora 6 mine.

The mining methods employed at the Dora 6 mine consisted of room-and-pillar mining only. Extraction ratios in the section just north of the town of Hamilton range from 0.63 to 0.75. This section of mining has been the major concern to the PA DEP. The initial amount of hydraulic head in the mine (1260 ft.) was enough to cause concern of mine water to blowout, and subsequently introduce horizontal boreholes to lower the mine pool. While the goal was to lower the pool to an elevation of 1210 ft., it has been stabilized at approximately 1230 ft. for nearly two years. The barrier length used for analysis is approximately 100 ft.. The top portion of barrier begins at the edge of mining and the bottom portion ends at the edge of the stream valley, and near the outcrop on the most southern edge (Figure 4.16). Barrier analysis was conducted using Darcy's Law (that the coal is 100% unaltered) (Table 4.8). K values were calculated using the seep recorded near the LK outcrop in the town of Hamilton (1 gpm est.). The K value responsible for the barrier 5 seep is low and fits into the median K values determined from previous studies. It is less likely that fracture flow is responsible for barrier 5 flow.

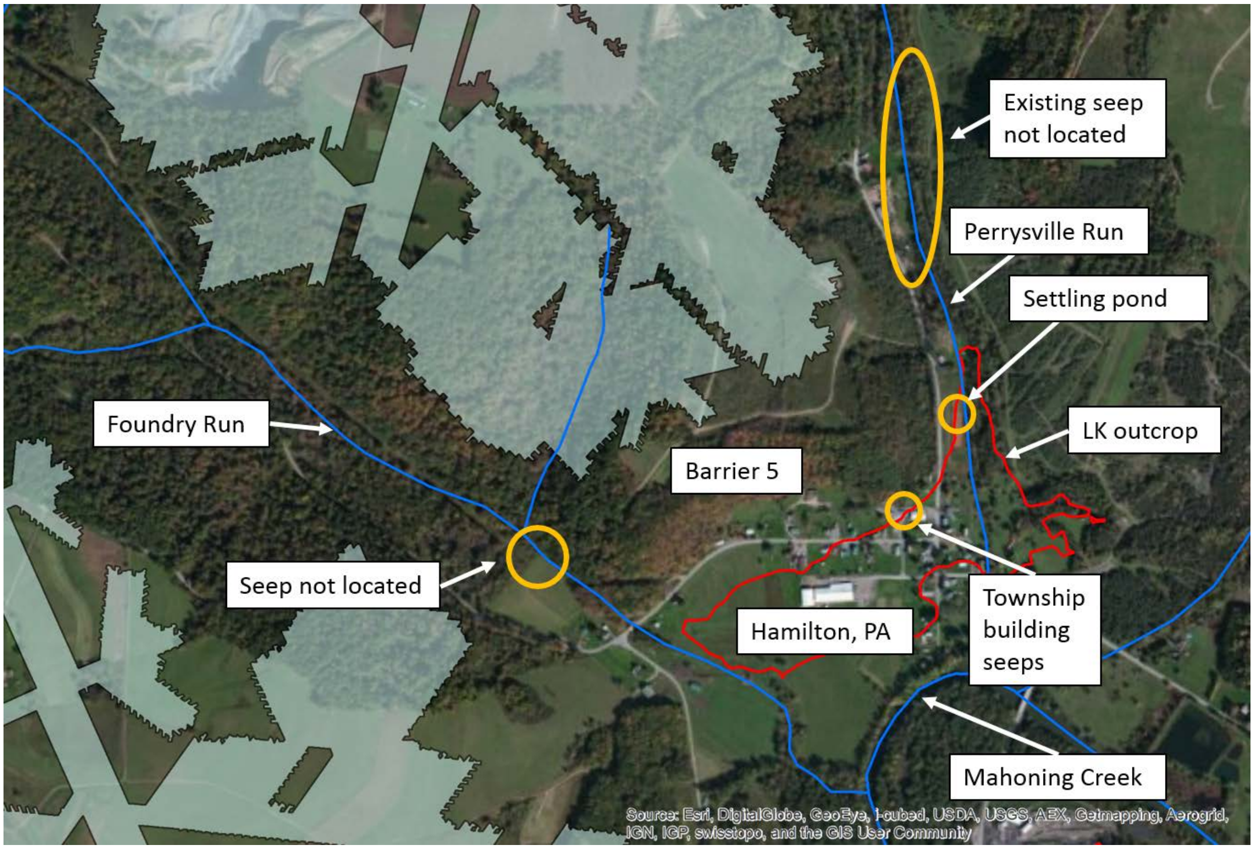


Figure 4.16 Aerial image of barrier 5 at the Dora 6 mine, including locations of seeps and the LK outcrop.

Table 4.8 Darcy calculations representing the possible hydrogeologic conditions of the township seep at barrier 5 at the Dora 6 mine.

Barrier Number	Barrier width (w_b), ft	Barrier length (L_b), ft	Hydraulic head (dh), ft	Flow Rate (Q), gpd	Flow Rate (Q), gpm	Hydraulic Conductivity K_h, ft/d
5	1200	100	32	1440	1	0.235

The groundwater movement from the mine workings at Dora 6 is an interesting case. In addition to surface discharges, several monitoring wells have been recorded to contain water with elevated levels of SO_4^{2-}, which is indicative of mine pool water from the Dora 6 mine. The town of Hamilton is surrounded by the LK outcrop. This is interesting because the majority of the wells that were affected do not pass through the LK coalbed. Mahoning Creek borders Hamilton to the south. It is a larger stream than that of Perryville Run and Foundry Run. Therefore, the alluvial deposits in this area are more extensive. The LK outcrop is mostly covered in the Mahoning Creek valley due to erosion and deposition. The majority of discharges are located in areas that are higher in elevation than the mapped outcrop, which was generated in ArcGIS from in-mine survey points and DEMs. If the coal seam were below these discharge areas, it would be highly unlikely that the groundwater would travel horizontally through the coalbed and subsequently vertical through alluvial material rather than exiting the coalbed through the outcrop and subsequently through the alluvial material. The preferential flow path of groundwater is strongly correlated to lower hydraulic head, which is found in paths of lesser resistance.

4.4 PENN VIEW

The Penn View mine is located in the Lower Kittanning (LK) coal seam of Indiana County, Pennsylvania. Mining operations began in the year 2000 by Penn View Mining Inc. and ended in 2009 (Figure 4.17).

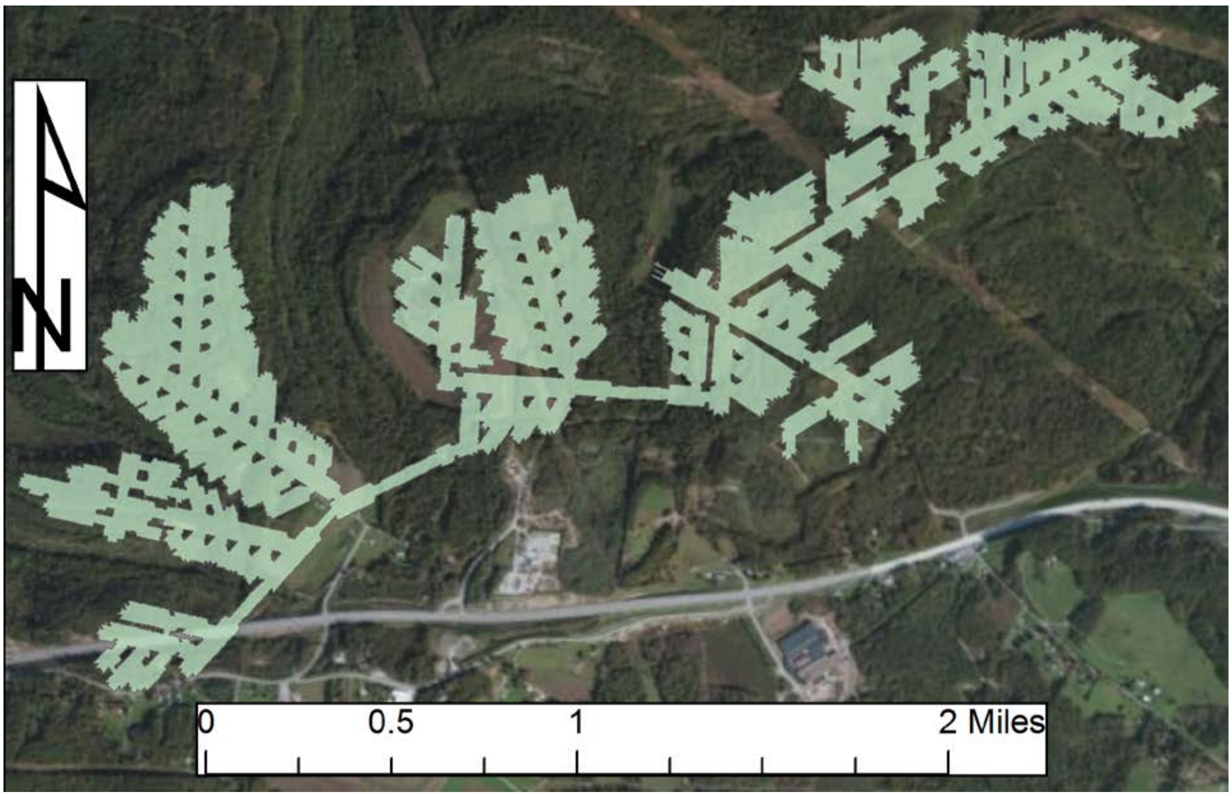


Figure 4.17 Aerial image of the Penn View mine.

There are several documents reporting on the geology and hydrogeology of the Penn View mine area. Surface mining of the Upper and Lower Freeport (UF, LF) seams have been the recipe for acidic discharges. The Freeport seams have been replaced by mine spoil, which create a perched aquifer flow system about the Penn View mine. The Upper Kittanning (UK) seam receives impaired water inflow from the overlying mine spoil. It lies at an elevation approximately 120 ft. above the LK seam. The Middle Kittanning (MK) lies at an elevation approximately 60 ft. above the LK coal seam. It is mostly unaffected by the Freeport mine spoil, with exception to one piezometer. The MK aquifer is more unconfined in nature. The LK horizon is a low-volume water-bearing zone. Water quality reports of the LK show near neutral pH readings, a net-alkaline condition, and elevated levels of Fe, Mn, and SO42-. Groundwater movement within the coalbed aquifers are highly influenced by topography, as determined by several seeps and discharges in low cover sections. Seeps in the LK coalbed were apparent before deep mining occurred, thus attributing the discharges to LK strip mining. The LK coalbed structure dips in two separate directions. To the east of the portal, the LK dips to the northeast (NE). To the west, the LK dips to the west-northwest (WNW). Exploratory cores have revealed that the primary roof material in the Penn View mine is shale. The thicknesses of the shale varies from approximately 20 to 40 feet on average, mixed with the occasional thin sandstone layer. Floor material consists primarily of shale and clayshales with the occasional fireclay layers. The average LK coal seam thickness at Penn View is 3.5 ft.. The maximum elevation of mined coal is 1715.3 ft. The hydraulic seal elevation was proposed to be at 1684.5 ft.. The Moody report found several characteristics of the geology in the Penn View deep mine area:

- Jointing was observed in the sandstone unit west of deep mining
- There is no evidence of lineaments in the area
- 100 feet or more of cover will keep fracture aperture size to a minimum and keep groundwater flow localized
- Fracture flow does not seem to have a major influence on groundwater movement in the area

- RQD analysis shows that the depth to which fractures do not affect stream valley groundwater movement is between 50 and 60 ft. on average

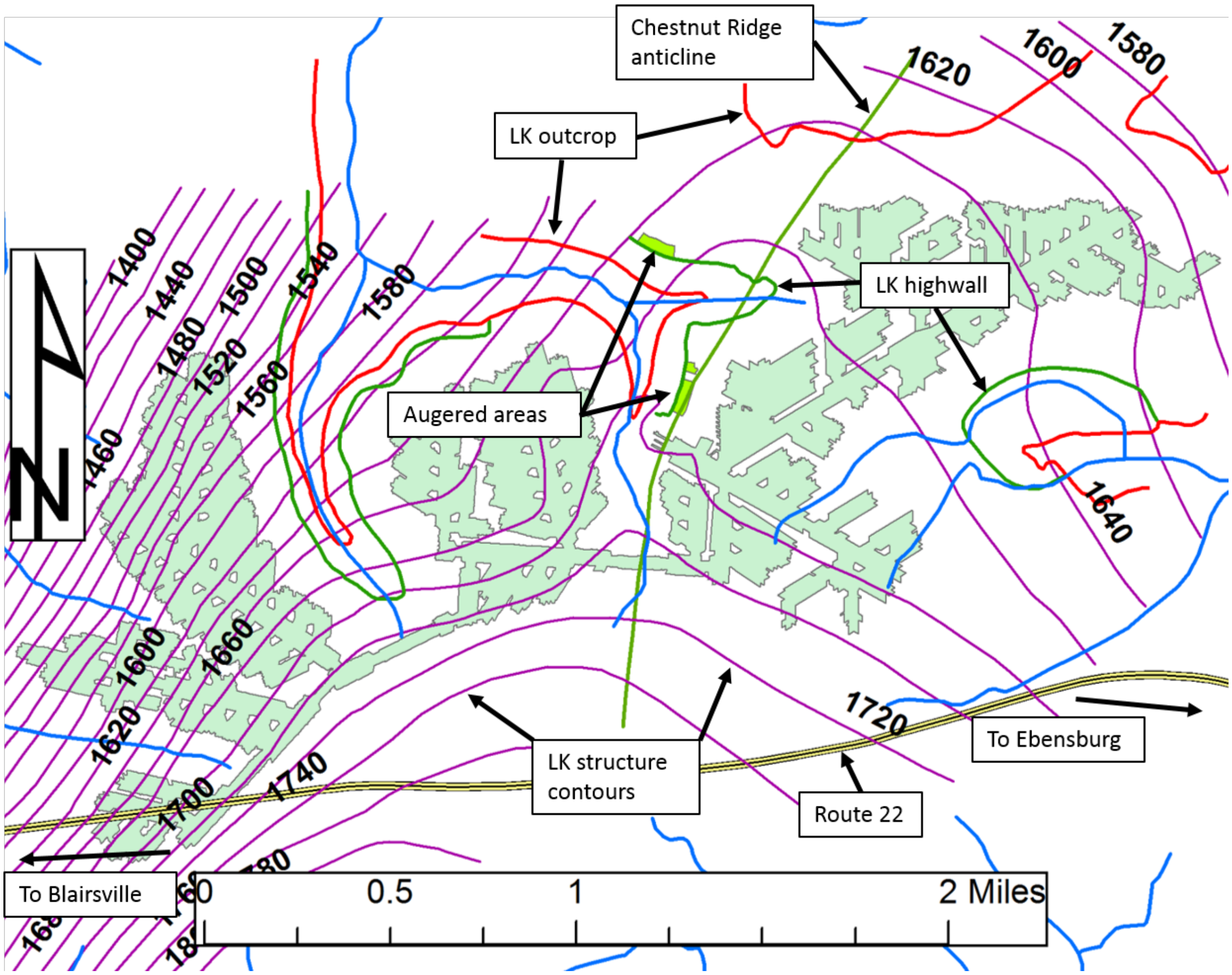


Figure 4.18 Penn View mine overlain by LK structure contours. Route 22 lies to the south of the deep mine. Barrier areas exist between the edges of mining and adjacent LK highwalls, LK outcrop, or augered areas. The Chestnut Ridge anticline stretches through the area.

To this date, no deep mine discharges have been recorded at the Penn View mine. Field visits with agents from industry have shown that the Penn View deep mine is not filling with groundwater. The mine receives an insignificant amount of recharge to fill the mine void. The mine is located on the Chestnut Ridge anticline, which may reduce the amount of recharge entering the mine. Barrier areas surrounding the mine are primarily above-drainage, due to the steep grades of the Chestnut Ridge anticline. Above-drainage barriers are located at elevations much higher than drainages, making gravity drainage from the mine pool more likely. Water buildup within the Penn View mine will not be significant due to the lower head levels within the barrier areas. Overburden depths in the area of the Penn View mine reach as high as 250 ft. in some locations. Permitted barriers do not extend into areas where overburden cover is less than 100 ft.. The mining methods at the Penn View mine have been traditional room-and-pillar techniques. The extraction ratio for the hydraulic barrier areas averages approximately 0.68.

A barrier evaluation was conducted for the Penn View mine by Moody & Associates in 1997. This analysis included a recharge and seepage rate estimation and barrier permitting. Aquifer tests were used in the estimation of K values for the barrier areas. Pump tests were conducted in open drill holes to estimate a K value for the combined LK coal and shales in the overburden material. A K value of 0.42 ft/d was calculated, however, the average linear velocity (0.53 ft/d) was used to estimate barrier seepage. The average linear velocity takes into account the effective porosity of the media, which was estimated to be 0.2. This value is slightly higher than the K value, since it is measuring the velocity of flow in a linear fashion. The following formula was used to calculate the period of time needed for the Penn View mine to fill with water:

$$\text{Mine flood time} = \text{Mine void volume} / \text{Recharge flow rate}$$

Based on this formula the amount of time needed for the Penn View deep mine to completely fill with water is 730 days, or 2 years from the time of mine closure in 2009. In

March of 2014, a piezometer measurement was taken that confirmed the mine pool is not filled with water (it was found to be dry at the piezometer location). Barrier outflow seepage rates were based on a flooded mine and a 1 ft. seepage face. For the barrier areas on the boundaries of the Penn View deep mine, the amount of flow seepage was estimated to be 12,390 ft3/d. This flow rate is equivalent to approximately 93,000 gpd, or approx. 64 gpm. Barriers widths were permitted to be as wide as 400 ft. at the Penn View mine. Barriers were measured from the edges of mining to the closest measured LK outcrop or the 100 ft. cover line (whichever applies first). Pre-mining geological investigations were used to discover that no linear structures were located in the Penn View mine region. Estimates of recharge and barrier seepage have both been found to be less than what was calculated. The seepage calculations were conservative based on the underestimation of recharge into the Penn View mine. No high-flow discharges have been observed as a result of deep mining.

5.0 INTERPRETATION

This chapter will synthesize the case studies and literature review. When engineers design coal barriers, the primary factors responsible for preventing a high-flow discharge are the basis for the design. Coal is not impermeable and will permit the flow of water through it. Further, coal is typically the most transmissive of unaltered materials in terms of horizontal hydraulic conductivity in western Pennsylvania. Therefore, given sufficient hydraulic head, a coal barrier will allow mine pool water to discharge at the surface. In the case study barriers, hydraulic gradients lower than 0.1 (hydraulic head as low as 21 ft.) were found to be enough to cause a discharge. The rate of discharge is the primary concern. A high flow rate discharge can impair surface waters (if mine water is impaired), usually by introducing acidic conditions, a low pH, and elevated metals and sulfates.

In the case of barrier 1 at the Solar 7 mine, factors responsible for the observed discharge are considered. The iron-rich discharge was observed during the period of maximum height in the Solar 7 mine pool. During this period the mine pool elevation was higher than the elevation of the calculated coal outcrop and the surface elevation of the relatively high-flow discharge. The narrow zone of iron-rich waters closely resembled the impaired waters recorded in the Solar 7 mine pool. Since a wetlands area to the west of the discharge location was unaffected by mine water, it is more likely that the discharge was related to fracture flow. The modeling of mine pool flow through an unaltered coalbed suggests geologic discontinuities in the LK. Previous studies on the determination of K values show that the K values calculated in the modeling of barrier 1 are outside of the range for bituminous coal.

The modeling of fracture flow through barrier 1 is more realistic when considering aperture size. The geology of the Solar 7 mine has shown that both sandstones and shales are present in roof rock. Even though geologic core data has not been found in barrier 1, it is still possible that barrier 1 contains sandstone in the roof rock. If shale was the primary material in the roof, fracturing would likely be more prominent. Moreover, the mining methods adjacent to barrier 1 could have been the cause of the fracturing. Full and partial pillar recovery methods were used in this area and have been found to alter geologic conditions (Iannacchione, 2013). Full recovery of pillars leaves subsidence profiles similar to longwall mining, creating induced fracture networks in surrounding strata during subsidence. In addition to the observed fault trend within the Solar 7 mine, a linear structure has been recorded in the area. Lineaments have often been correlated with intense fracturing of subsurface strata.

In addition, the width and depth of the barrier may be too small. Barrier 1 has an average width of approximately 456 ft., and the overburden thickness reaches as high as 120 ft. suggesting the relatively low barrier width contributed to barrier failure. The recognition of a linear structure overlying the Solar 7 mine should have raised awareness about the potential for a high-flow discharge. Evidence in the mine indicates a regional fault. Adjacent full and partial pillar recovery in this area may have contributed to the failure of barrier 1. Fracture networks, if present, will have a less likely chance of ‘sealing up’ under low vertical stresses over time. The combination of fracture networks, a low overburden thickness, and a sufficient hydraulic head pressure to push through open fissures, is a recipe for a high-flow discharge.

In the case of barrier 2 located between the Solar 7 and Solar 10 mines, similar conditions to barrier 1 exist. There is no indication that a high flow discharge has occurred at barrier 2 surrounding the Stoystown wells. The amount of hydraulic head on the northern side of the barrier adjacent to Solar 7 is approximately 10 ft., while the amount of hydraulic head on the southern portion adjacent to Solar 10 is approximately 120 ft.. The northern portion of the barrier does not seem to be failing as the Solar 7 mine pool is of poor water quality and the Stoystown well water quality is not impaired. The condition of the southern portion of the barrier is less clear. The Solar 10 mine pool is of a better quality and therefore contributions from mine water cannot be inferred from Stoystown water well chemistry. Even though barrier 2 is adjacently surrounded by partial and full pillar recovery techniques at the Solar 7 and 10 mines, barrier width is at a minimal 1800 ft.. In addition, overburden heights range from 200 ft. at the Stoystown wells to greater than 400 ft.. Even if fracture networks were present at barrier 2, the chances of them all being open (due to relatively higher overburden thicknesses than barrier 1) and connected (due to the relatively high barrier width) are reduced.

Two main coal barriers (3 & 4) were examined at the Little Toby mine. A high-flow discharge has not occurred in the Mead Run valley thus far. Hydraulic head levels on barriers 3 and 4 are 29 ft. and 41.5 ft., with average barrier widths of 914 ft. and 566 ft., respectively. These are not excessively wide barriers in comparison with barriers 1 and 2 at the Solar 7 and 10 mines. The difference is that the ends of the barriers are located beneath the Mead Run stream valley. This means that mine pool water would most likely need to travel in a general vertical direction from the coalbed to the stream valley to produce a high-flow discharge. Since there has been no high-flow discharge to this date, Darcy’s Law was utilized to solve for the amount of flow that could be reaching the Mead Run stream valley, given an appropriate K value. The rate of flow discharging into the Mead Run stream valley varies widely (0.120 to 3.56 x 10^4 gpm) depending on the K value chosen. However, since the barriers seem to be performing well the actual K value is most likely within the literature range. What factors contribute to the success of barriers 3 and 4? The geology and topography of the Little Toby region could play an important role. Shale is the primary overburden material in the barrier areas of the Mead Run stream valley. Overburden thicknesses for barriers 3 and 4 reach as high as 250 ft. at the edge of the mine workings. In addition, pillar extraction techniques were not used at Little Toby. These combined factors most likely contribute to the successes of barriers 3 and 4 to this date.

The coal barrier design at the Dora 6 mine is an interesting case. The town of Hamilton, PA has had several issues with mine water reaching locals water well sources. Several high-flow discharges have also been recorded in this barrier area. A major limitation to quantifying this data is gathering the cumulative flow of water coming through barrier 5 as discharge water. This makes analysis difficult because the rate of flow coming into Foundry Run and Perryville Run is needed for the sake of estimating a K value. Even though there has been difficulty in quantifying the amount of water exiting barrier 5, a field visit to the site has put the amount of seepage in perspective. A 1 gpm seep near the LK outcrop in the town of Hamilton has allowed the calculation of a K value representing barrier 5. The K value (estimated at 0.235 ft/d) is relatively low when comparing with K values estimated in previous studies. The K value calculation from Darcy's Law shows that fracture flow may not be prevalent at barrier 5 at this time.

The town of Hamilton, which borders barrier 5 to the south, is accompanied by a higher ordered stream (Mahoning Creek). Thick alluvial deposits have accumulated in the stream valley with core logs indicating depths of 39 ft. in some areas. The alluvial material deposited by Mahoning Creek in the past borders barrier 5 in addition to Foundry Run and Perrysville Run.

The stream valley material tends to be hold a greater number of groundwater flow paths than typical surface materials. Mine pool water that flows through barrier 5 most likely enters this material, indicated by the locals' water sources in the past. Another explanation for the contamination of local's water wells is the sandstone aquifer that has been observed in the floor of the Dora 6 mine. Since the location of this aquifer has not been determined it cannot be proven that it is a major factor of barrier flow.

Since the outcrop of the LK is not so apparent, it could mean that the flow rate exiting barrier 5 is much higher than what can be seen. It is known that mine water is flowing through the alluvium, and it is possible that this water does not reach the surface. It could either be exiting the barrier then continuing through the alluvium or it could be exiting the barrier and pushing into alluvial material in a more vertical direction, depending on the potential hydraulic head and path of least resistance.

Analysis of the Penn View mine has shown an important factor of hydraulic barrier performance. Low recharge into the Penn View mine workings is apparently due to the Chestnut Ridge anticline. Several barrier areas exist on the perimeter of the Penn View mine due to the steep slopes associated with the Chestnut Ridge anticline. The barriers are above-drainage and the potential for a high-flow discharge is of less concern due to the insignificant recharge into the mine. Limited mine pool data and piezometer placement (outside of the mine void) prevents the exact mine pool level from being known. The hydraulic barrier situation at Penn View is comparable to the Dora 6 mine, where recharge is significant enough to produce a hydraulic gradient capable of producing high-flow discharges in the above-drainage areas.

The K value chart containing hydraulic conductivity measurements from the Solar 7, Dora 6, and Grove 1 case are displayed along with the literature K values (Figure 5.1). The new K values help define trends in thinner overburdens.

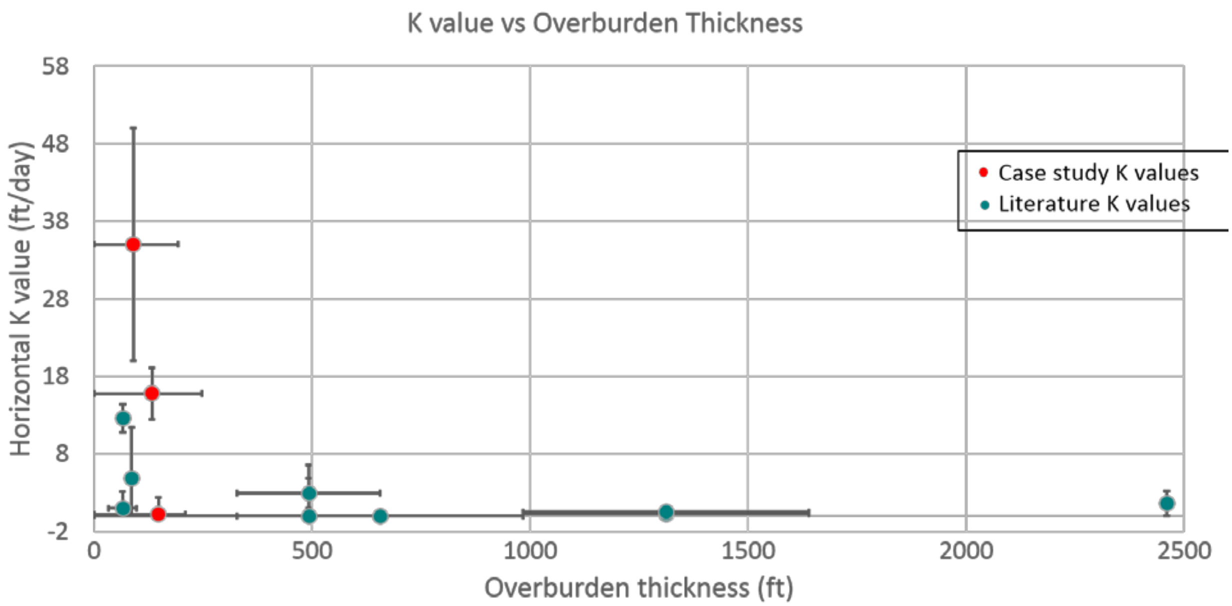


Figure 5.1 K values from the literature and case studies (red) versus overburden thickness at the investigation site.

6.0 SUMMARY AND CONCLUSIONS

The University of Pittsburgh's ARIES project goal was to investigate the factors responsible for the performance of engineered hydraulic coal barriers. Over the course of two years, data collection from various sources was gathered to conduct the research. Case studies were chosen based on data availability and relevance: Solar 7 & 10, Little Toby, Dora 6, and Penn View. At these mines a number of coal barriers were chosen for analysis including both successful and unsuccessful barriers. Barrier analysis and modeling was conducted based upon site specific conditions. The aim of this report is to understand the most important parameters controlling barrier performance and produce a set of general guidelines for barrier design. Examination of these cases indicates a number of factors are contributing to barrier performance (Table 6.1).

Table 6.1 Characteristics of barrier performance at the case study sites (*Iannacchione et al, 2013)

Name	High-flow Discharge/s	Max. Hydraulic Head (ft)	Hydraulic Gradient	Adjacent Extraction Ratio	Barrier Geology	Adjacent Overburden Depth (ft) [Avg; Range]	Average Barrier Width (ft)
Barrier 1	Yes	21	0.05	0.7 to > 0.9	Unknown; Shale/Sandstone in mine; presence of linear fault	Avg: 90; 0-193	456
Barrier 2	Unknown	120	0.07	0.67 to > 0.9	Primarily shale	Avg: 290; 207-466	1800
Barrier 3	No	29	0.03	0.67	Shale	Avg: 130; 17-242	914
Barrier 4	No	41.5	0.07			Avg: 136; 43-229	566
Barrier 5	Yes	60	0.14	0.72	Shale and sandstone	Avg: 148; 0-210	435
Grove 1 mine*	Yes	78	0.03	0.55 to > 0.9	Sandstone and shale	Avg: 133; 0-247	2750

The important factors can be separated into two categories:

Primary factors

- Extraction ratio **–** The extraction ratio of coal in underground mining influences several aspects of barrier performance. Higher extraction ratios will cause greater vertical strain on pillars, increasing potential for pillar failure. Full and partial pillar recovery mining can alter the hydraulic properties of coal and surrounding strata, by causing major ground movements, deformation, and sometimes subsidence. Barrier successes in these case studies are associated with adjacent extraction ratios lower than 0.67.

- Geology – The strata surrounding a coal barrier is important to barrier success. Groundwater movement will generally follow faulting and fracture networks, both a function of local geology. The strength of materials such as sandstone and shale are important in determining the extent of fracturing. Strong rock layers tend to be more brittle, resistant to closure, and will thus tend to stay open under greater depths of overburden than will softer, weaker rocks. Observations in the case studies have shown that rock composition plays an important role in barrier performance. High-flow discharges are a major indicator to groundwater seepage through a fracture.

- Hydraulic conductivity - K values of coal are an important feature when rock layers are homogenous and contain no major geologic discontinuities. K values of surrounding strata are generally lower, making coal the most transmissive of unaltered materials. From the literature it is seen that the K value of coal varies widely (1.12×10^{-4} to 14.4 ft/d). This is due to the site specifics of each literature study. Vertical K values are generally several orders of magnitude lower than horizontal K values for overburden strata. When simulating a fracture through a coalbed (Little Toby barrier modeling), it has been predicted that the vertical K value must be several orders of magnitude higher than horizontal K value to redirect coalbed flow.

- Overburden thickness – Overburden thickness influences barriers in a number of ways. Differing amounts of vertical strain on a barrier and surrounding strata will cause differing hydraulic conditions. Fractures are more likely to close with increasing overburden depth. Strata and alluvial material beneath stream valleys in western Pennsylvania is known to be highly fractured. This is known as stress-relief fracturing and is impelled by vertical strains of topography. The trend in the literature and the case studies shows that average overburden thicknesses less than 150 ft. lead to a higher probability for barrier failure.

<u>The following factors are also important</u>

- Hydraulic gradient – The hydraulic gradient acting on all barriers in this study were examined. A discharge potential is estimated based on the maximum mine pool elevation and surrounding minimum surface elevations. In some cases, the maximum mine pool elevation has risen higher than predicted. The hydraulic head divided by the width of the coal barrier is equal to the hydraulic gradient. Relationships between hydraulic gradient and barrier performance have shown that relatively low hydraulic gradients (as low as 0.03) can cause hydraulic barrier failure.

- Barrier thickness – The coal barrier thickness is the most controversial factor in hydraulic coal barrier permitting. Since many factors affect the performance of hydraulic coal barriers, the width of a barrier is crucial. When multiple factors are deemed to have an effect on a hydraulic coal barrier area, the width should be increased to account for the factors that create a higher probability for barrier failure.

By examining the appropriate factors and conditions, a properly designed coal barrier can be utilized to withstand a high-flow discharge capable of impairing surface waters. Hydraulic coal barriers cannot be fully characterized without taking all factors of performance into account. There is no single factor that can be used to explain the overall performance of hydraulic coal barriers. Barrier performance is due to a combination of the most important factors. Case study data suggests that hydraulic barrier conditions are site specific.

Analysis of case studies and peer-reviewed literature reveals several factors contributing to the performance of down-dip coal barriers. The case studies illustrate the primary factors responsible for down-dip coal barrier performance. This analysis indicates the coal extraction ratio may significantly impact coal barrier performance. The presence of a hydraulic gradient creates the need for a hydraulic coal barrier. Mine plans ultimately control the post-mining mine pool elevation, which influences the hydraulic gradient via hydrostatic pressures. Geological conditions of the strata surrounding the coalbed play a role in hydraulic performance of the barrier. The presence of a fault and/or interconnected fracture networks can cause coal barriers to fail in the prevention of high-flow discharges. The examination of K values of coal and surrounding strata is important for identifying fractured zones. The lack of vertical strain due to higher overburden depths can allow for increased fracture sizes and intensity. Steep changes in vertical strain has the same effect on adjacent stream valley aquifers as adjacent coal barriers. A general set of guidelines should be followed when engineering a coal barrier (Table 6.2).

Table 6.2 Recommended guidelines for hydraulic coal barrier design (Probability of failure is expressed by rating each site specific factor as a low or high probability)

Factor	Low probability	High probability
Coal extraction ratio	Barrier adjacent mining Re less than 0.67	Barrier adjacent mining with Re greater than 0.67
Geology	Pre-mining coring and geologic observations	No pre-mining investigations conducted
Overburden thickness	Greater than 150 ft. of cover	Less than 150 ft.
Above-drainage	No down-dip coal outcrop (or mine infiltration rate is lower than barrier outflow seepage rate)	Exposed down-dip coal outcrop (and mine infiltration rate is higher than barrier outflow seepage rate)
Barrier width	High quality surveying data	Inaccurate or no survey data

The guidelines in Table 6.2 should be used to address the probability for a site specific hydraulic coal barrier to fail. Permitting a hydraulic coal barrier under optimal conditions would represent low probabilities of failure for all factors in Table 6.2. Formulas used for barrier design in the past have been based on stress and the potential for coal blowouts. The formulas are inadequate for hydraulic coal barrier design because they do not take overburden thickness into account. All of the factors influencing hydraulic coal barrier performance are not represented by the use of the stress-based barrier design formulas.

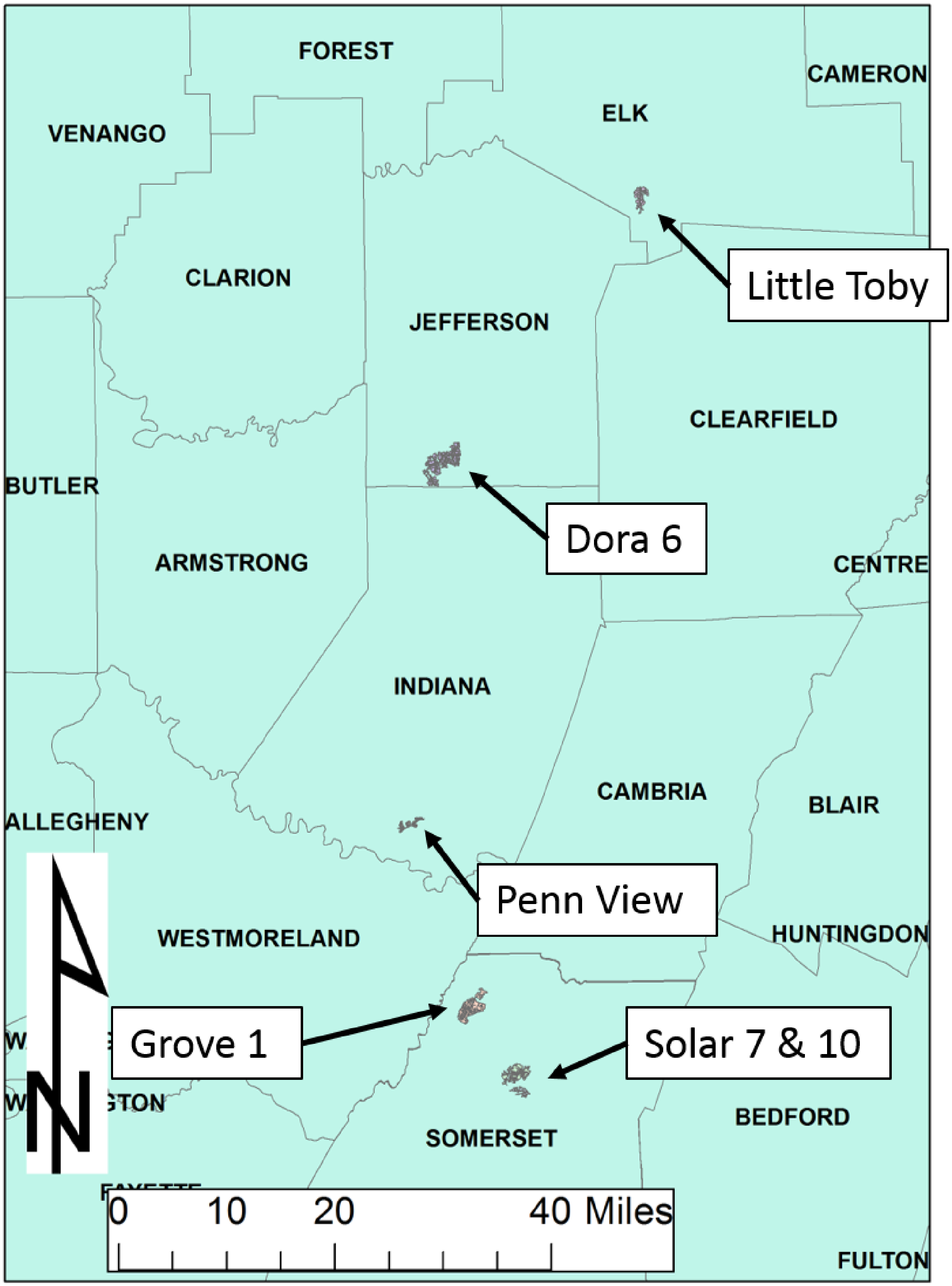
In addition to the quantitative factors (coal extraction ratio; overburden thickness) are the factors of geology, above-drainage setting, and barrier width. For geological conditions, pre-mining investigations need to be conducted to characterize the hydraulic barrier’s condition. This includes drilling and examining geologic cores, analyzing lineament structures, and other techniques. Permitting hydraulic coal barriers that haven’t been properly analyzed for geologic conditions are at a higher probability for failure. An exposed coal outcrop of a down-dip hydraulic coal barrier creates a condition where the probability of failure is higher, given that the mine infiltration rate is higher than the barrier outflow seepage rate. Coal outcroppings in the case studies of this thesis have been observed to allow high-flow discharges (these mines have a higher infiltration rate than barrier outflow seepage rate). Several factors influence hydraulic coal barrier conditions and performance. A combination of the primary factors should determine the width of the hydraulic barrier. Before a barrier is permitted, however, accuracy must lie in the maps and survey data to properly measure the critical hydraulic barrier. The extent of mining and the location of the coal outcrop must be known to accurately measure the critical hydraulic barrier width.

7.0 RECOMMENDATIONS

The most controversial component of an engineered coal barrier is its width. Environmental regulators and mining operations have a common interest in successful coal barrier design. Drawing on the primary factors, officials will be able to collect the pertinent data and design an engineering plan that utilizes best practices for implementing barrier conditions. Using site specific conditions, controls can be put in place to limit the unwanted mining impacts to an engineered coal barrier prior to mining. Natural conditions, such as geologic and topographic features must be accounted for in pre-mining investigations. Environments with faulting or fracture-intense zones must be treated differently in hydraulic barrier design than regions with less geologic discontinuities. Geologic coring and RQD studies should be used to fully characterize hydraulic barrier conditions, including determining actual coal outcrops and fracture-intense zones. Research into more efficient geologic characterization techniques should be highly regarded. By collecting the pertinent data, an accurate prediction of coal barrier performance can be utilized to size the barrier to a proper width, change mine plans, or setup additional controls.

APPENDIX A

A.1 MAP OF CASE STUDY MINES IN WESTERN PENNSYLVANIA


FOREST
CAMERON
ELK
VENANGO
Little Toby
CLARION
JEFFERSON
CLEARFIELD
BUTLER
Dora 6
ARMSTRONG
CENTRE
INDIANA
CAMBRIA
BLAIR
ALLEGHENY
Penn View
WESTMORELAND
HUNTINGDON
Grove 1
Solar 7 & 10
BEDFORD
SOMERSET
0 10 20 40 Miles
FULTON

A.2 HYDRAULIC CONDUCTIVITY TABLE FOR BITUMINOUS COAL

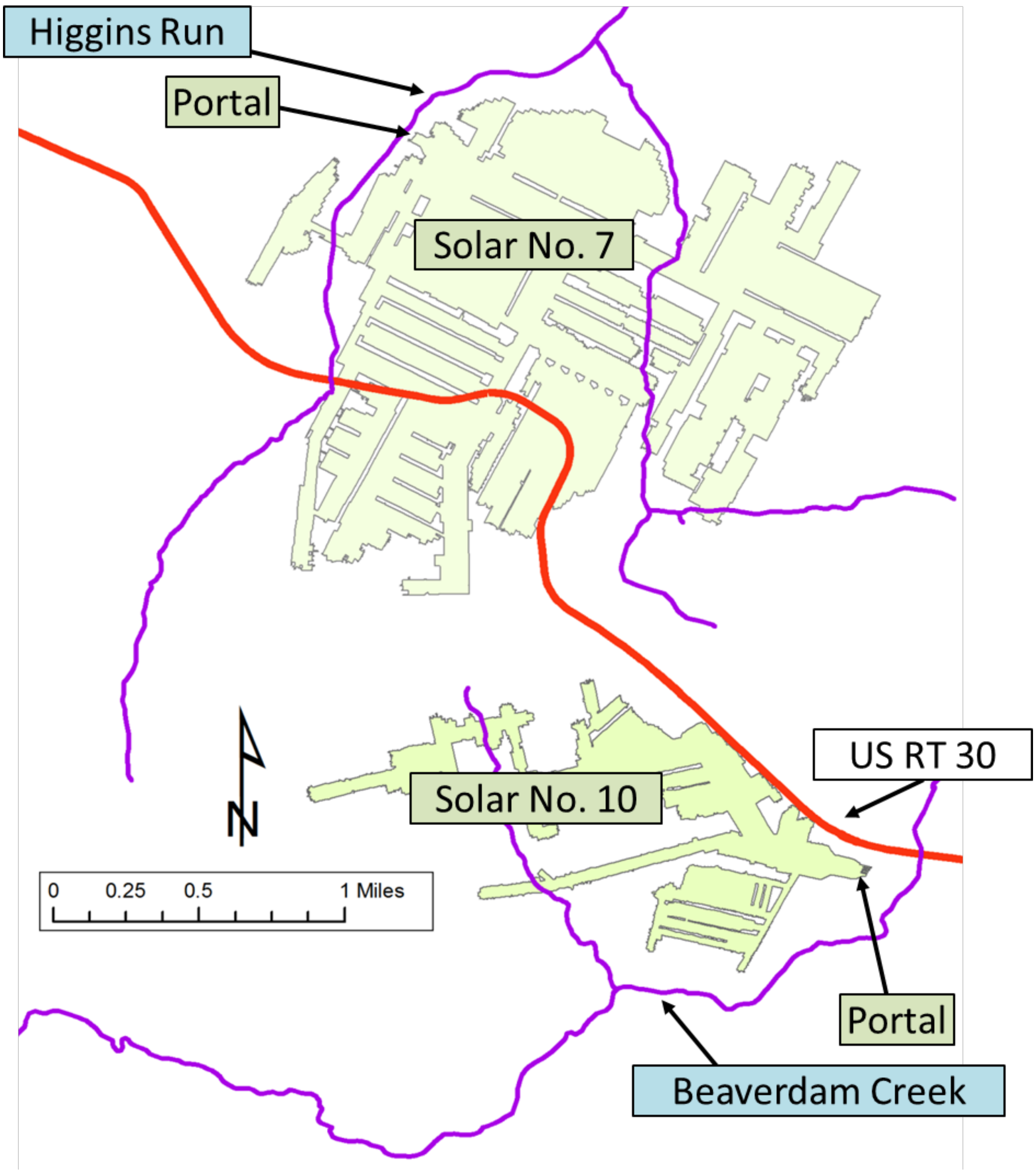
Source	Year	K-max (ft/d)	K-min (ft/d)	K-med (ft/d)	Overburden Low (ft)	Overburden Mid (ft)	Overburden High (ft)	Seam	Location	Notes
Dabbous	1974	0.033	2.85E-03	0.017				Pittsburgh	PA	Isotropic
Miller and Thompson	1974	3.15	0.722	0.984	33	65.5	98	Upper Freeport, Lower Kittanning	PA	Isotropic
Dames and Moore	1981	4.92	1.02	2.96	328	492	656		-	Isotropic
Hobba	1991	14.4	10.8	12.6	66	66	66	Upper Freeport	WV	Isotropic
Aljoe and Hawkins	1992			0.361					WV, PA	Isotropic
McCord	1992	3.28	0.033	1.65	2460	2460	2460		CO, NM	Isotropic
Harper and Olyphant	1993	11.5	0.197	4.92	75	86.5	98	Mariah Hill	IN	Isotropic
Harlow and Lecain	1993	6.56	1.12E-04	0.033	0	492	984		VA	Isotropic
Minns	1995	0.013	2.89E-04	8.63E-04	328	656	984	Fireclay	KY	Isotropic
Moody (Penn View)	1997	0.632	7.23E-04	0.181				Lower and Middle Kittanning	PA	Isotropic
Moody (Kaufman)	1997			0.103					PA	Isotropic
Luo	2001	0.230			1312	1312	1312		-	Isotropic
McCoy	2004	0.492	0.098	0.295	984	1312	1640	Pittsburgh	WV	Isotropic
McCoy	2004	0.984	0.066	0.524	984	1312	1640		WV	Anisotropic
OSM	2005			0.780					WV	
McCoy	2006	1.1	0.072	0.586					PA, WV	Anisotropic
Solar 7 (barrier 1)	2014	50	20	35	0	90	193	Upper Kittanning	PA	Isotropic
Dora 6 (barrier 5)	2014	2.41	0.041	0.235	0	148	210	Lower Kittanning	PA	Isotropic
Grove 1 mine discharge	2014	19.1	12.5	15.8	0	133	247	Upper Kittanning	PA	Isotropic

A.3 MAPS OF THE SOLAR 7 & 10 MINES, SOMERSET COUNTY, PENNSYLVANIA

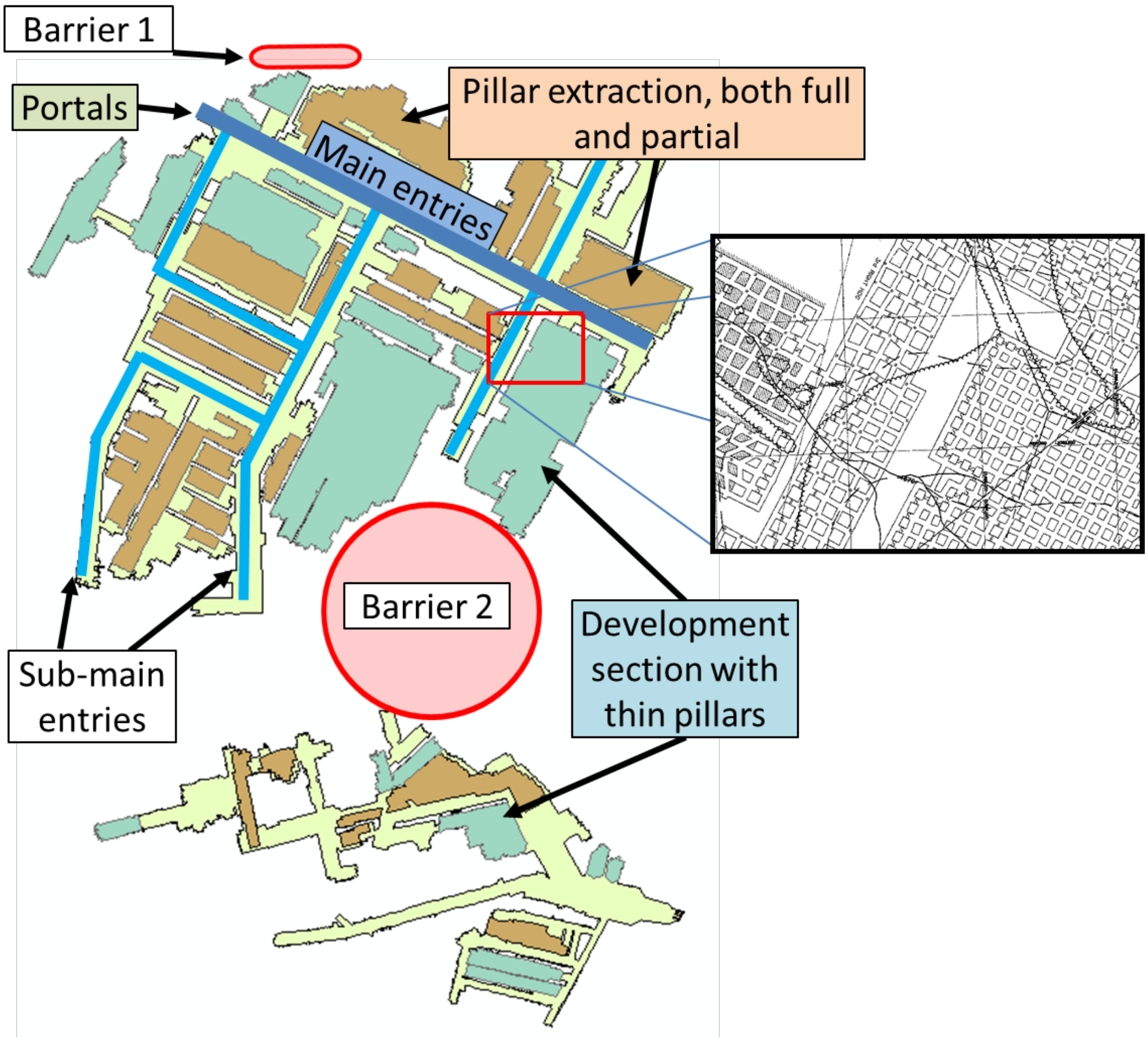
The following maps of the Solar 7 and Solar 10 mines show detailed characteristics of the mined region. Maps included are: Aerial image and mine outline, streams and roads, mining methods, surface topography, coal structure, overburden thickness, mine pool elevation, barrier 1 coal outcrop, barrier 1 line segments, barrier 1 profile transect, barrier 2 profile transect, barrier 1 profile, and barrier 2 profile.

A.3.1 AERIAL IMAGE OF THE SURFACE OVERLYING THE SOLAR 7 AND 10 MINES

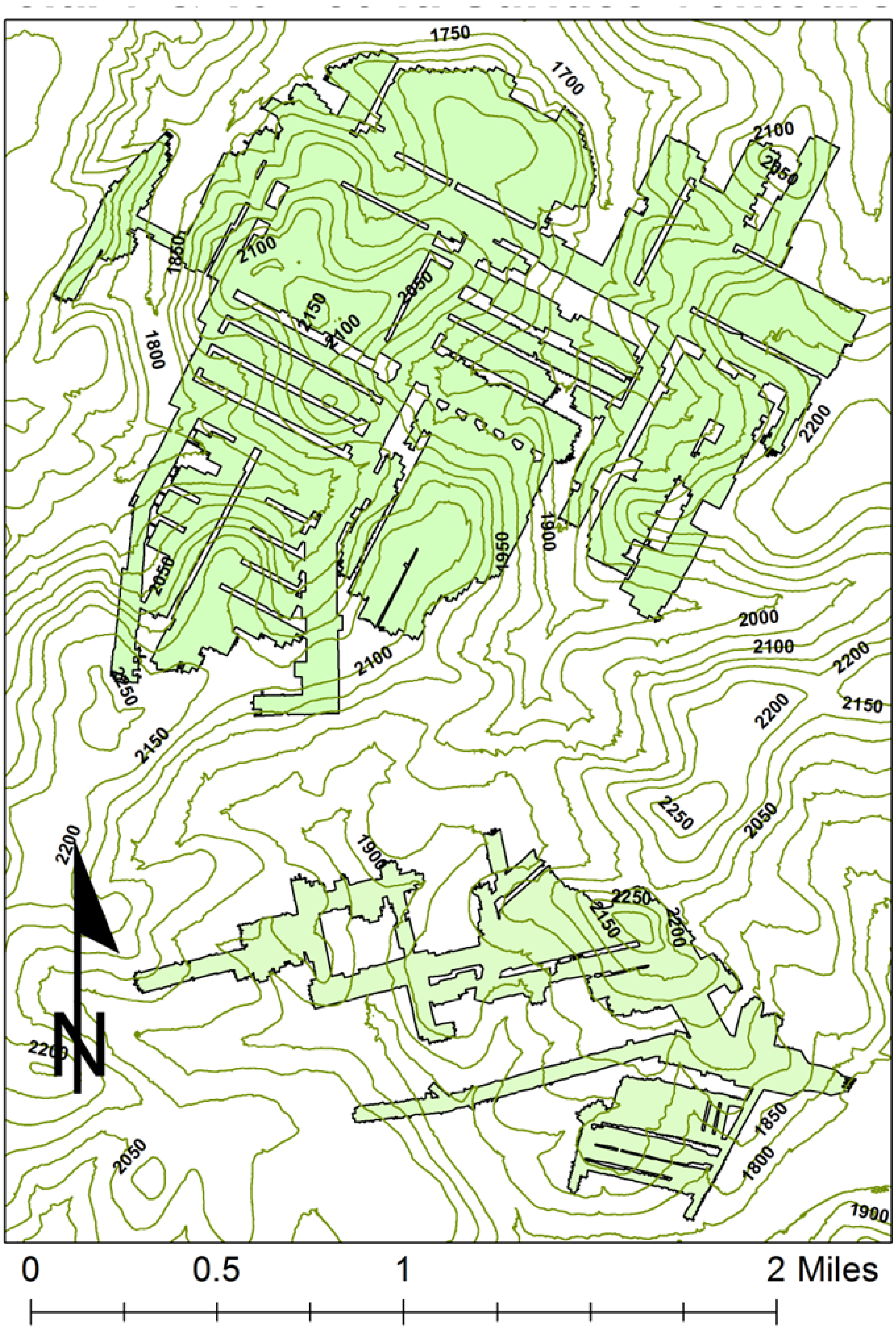
A.3.2 STREAMS AND ROADS AT THE SOLAR 7 & 10 MINES (Locations of Higgins Run, Beaverdam Creek, and U.S. route 30)



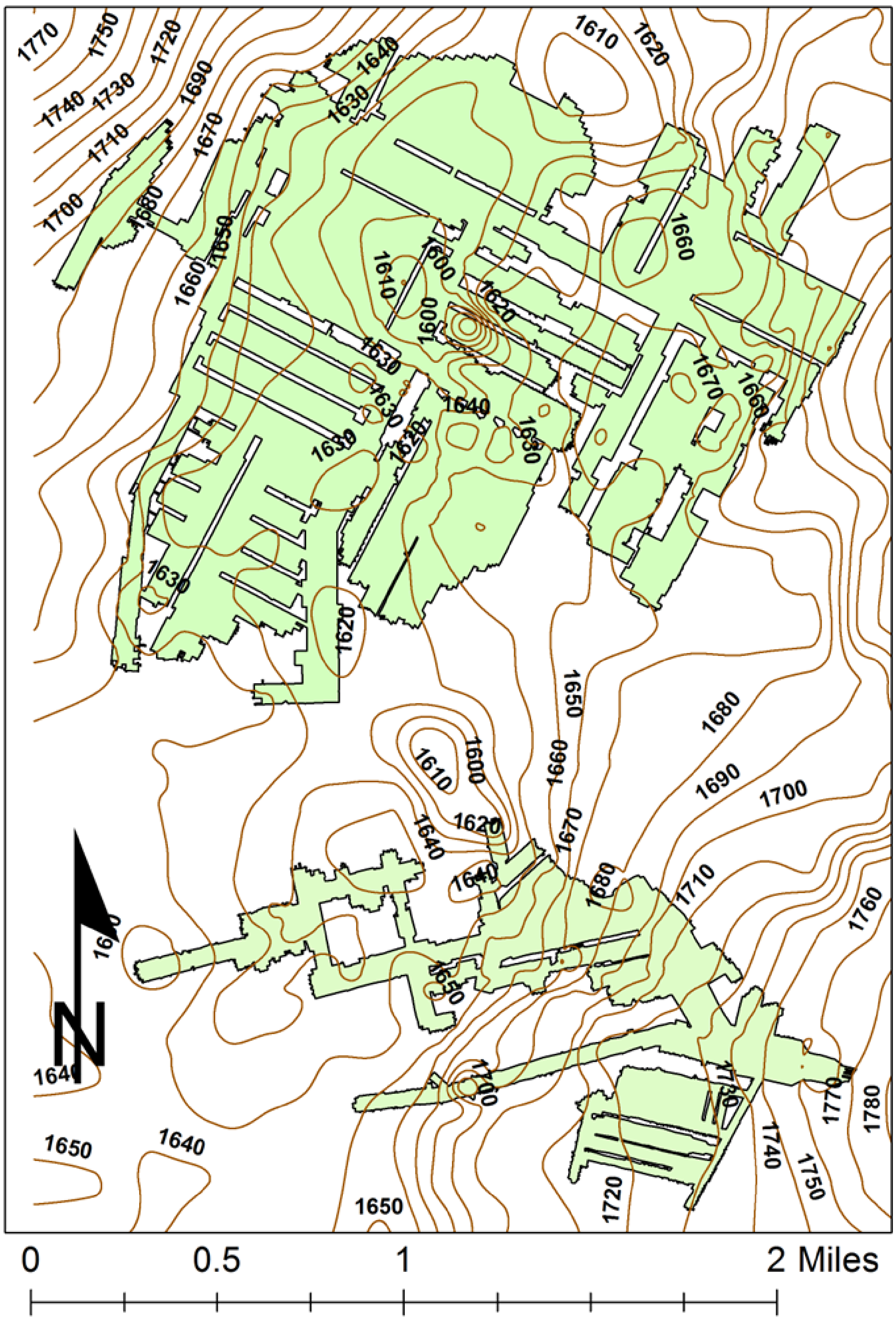
A.3.3 MINING METHODS AT THE SOLAR 7 & 10 MINES (multiple-entry room-and-pillar, pillar extraction sections (brown), and thin pillar development sections (green). A screen-capture of the 6-month mining map gives a visual representation of differently mined sections)



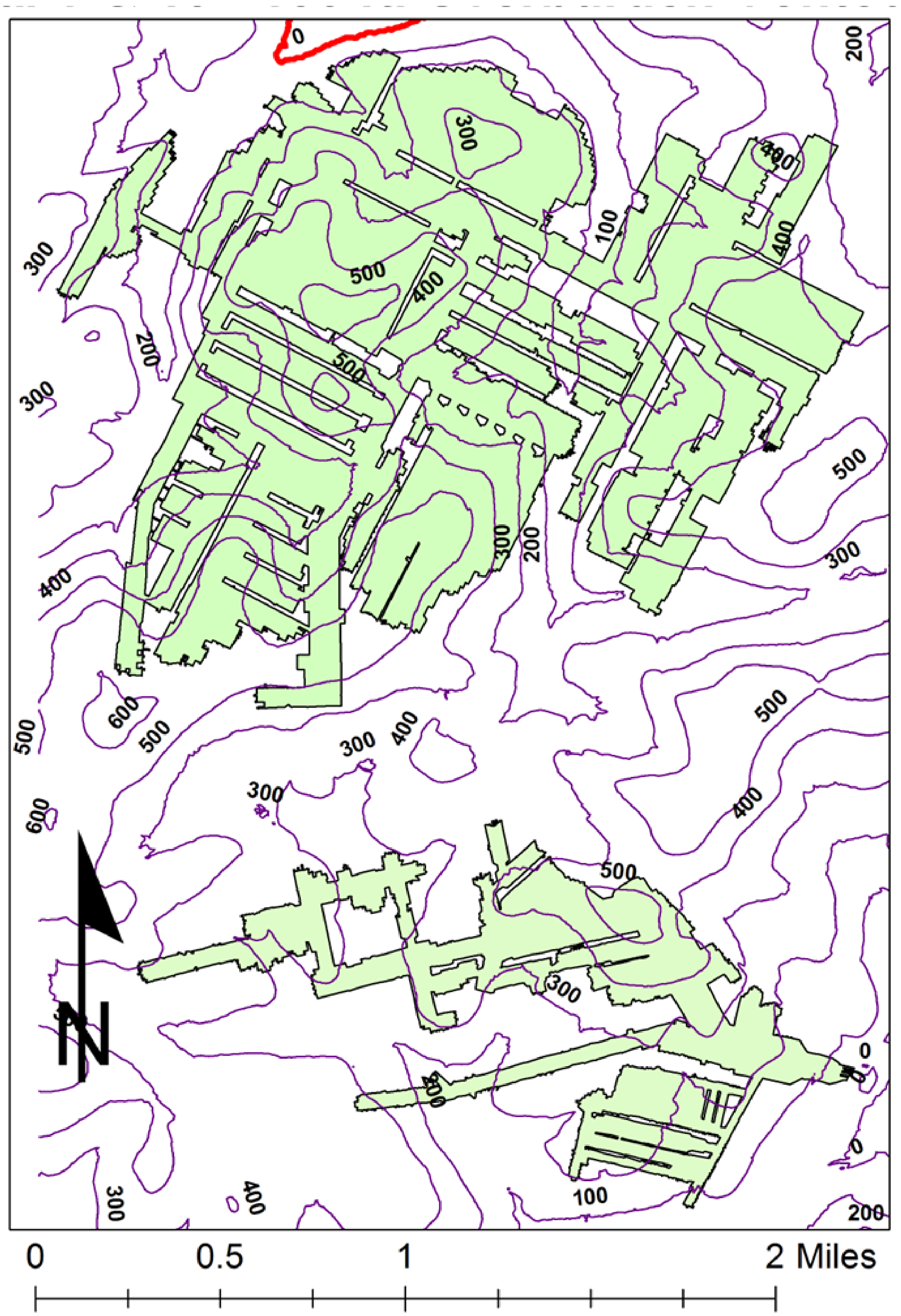
A.3.4 SURFACE TOPOGRAPHY AT THE SOLAR 7 & 10 MINES (50-ft contours)



A.3.5 COAL STRUCTURE CONTOURS AT THE SOLAR 7 & 10 MINES (10-ft contours)

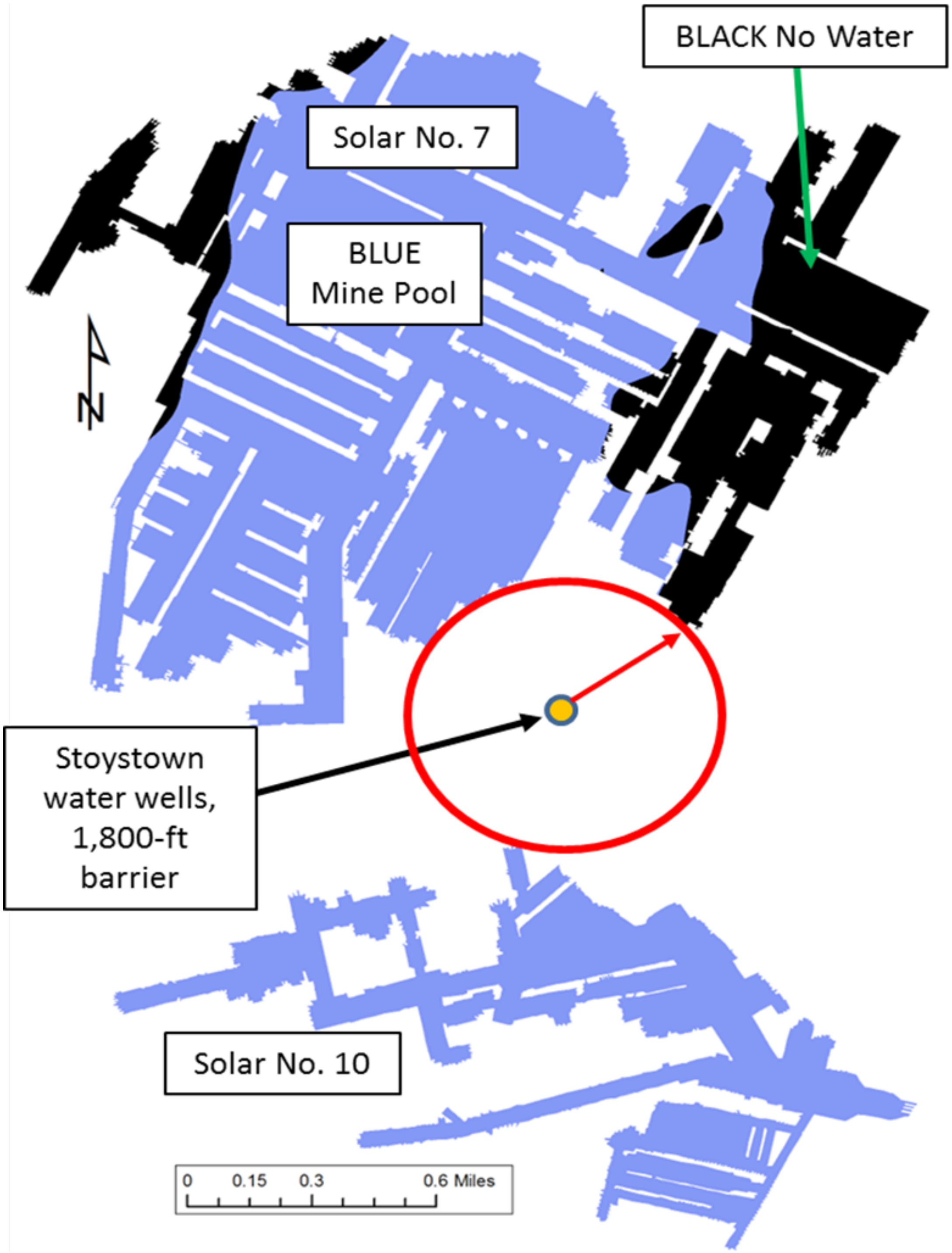


A.3.6 OVERBURDEN THICKNESS AT THE SOLAR 7 & 10 MINES (100-ft contours)

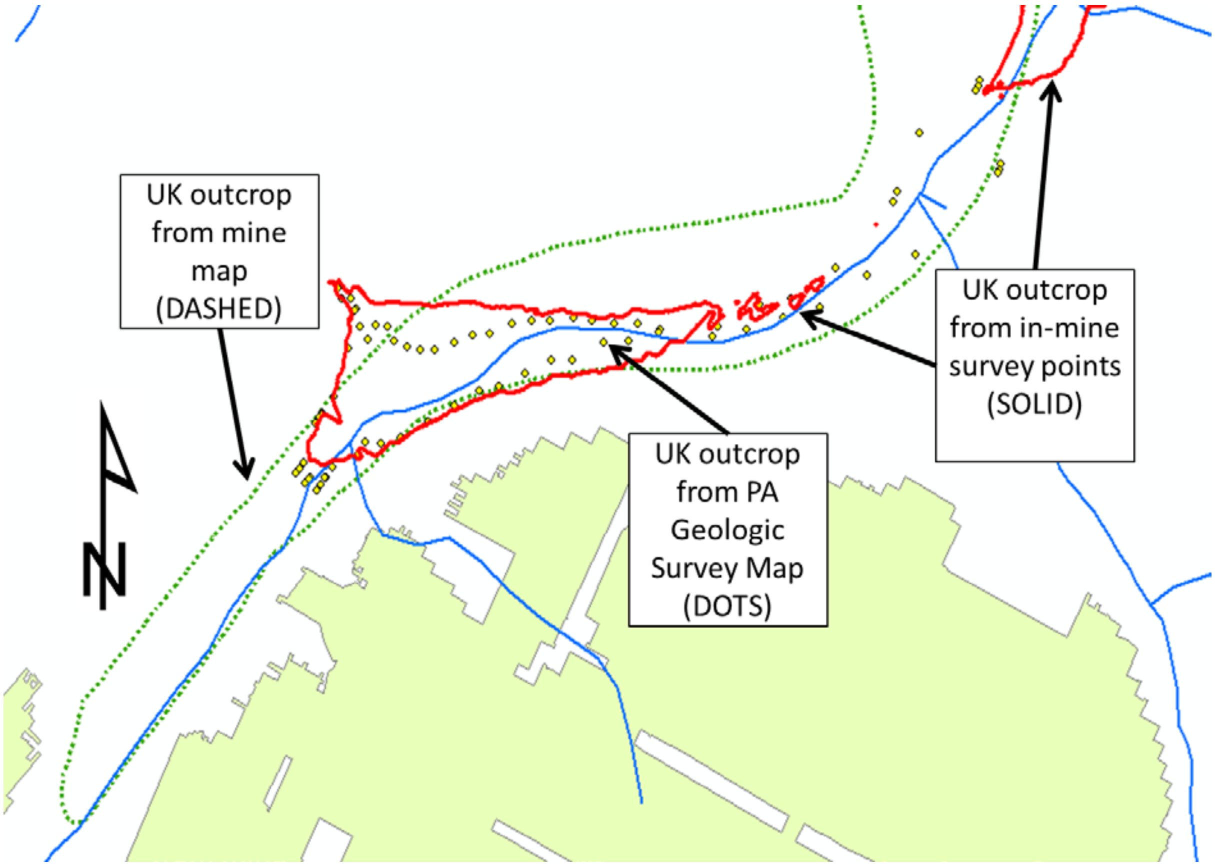


A.3.7 MINE POOL ELEVATIONS (FT. ABOVE MSL) AT THE SOLAR 7 & 10 MINES

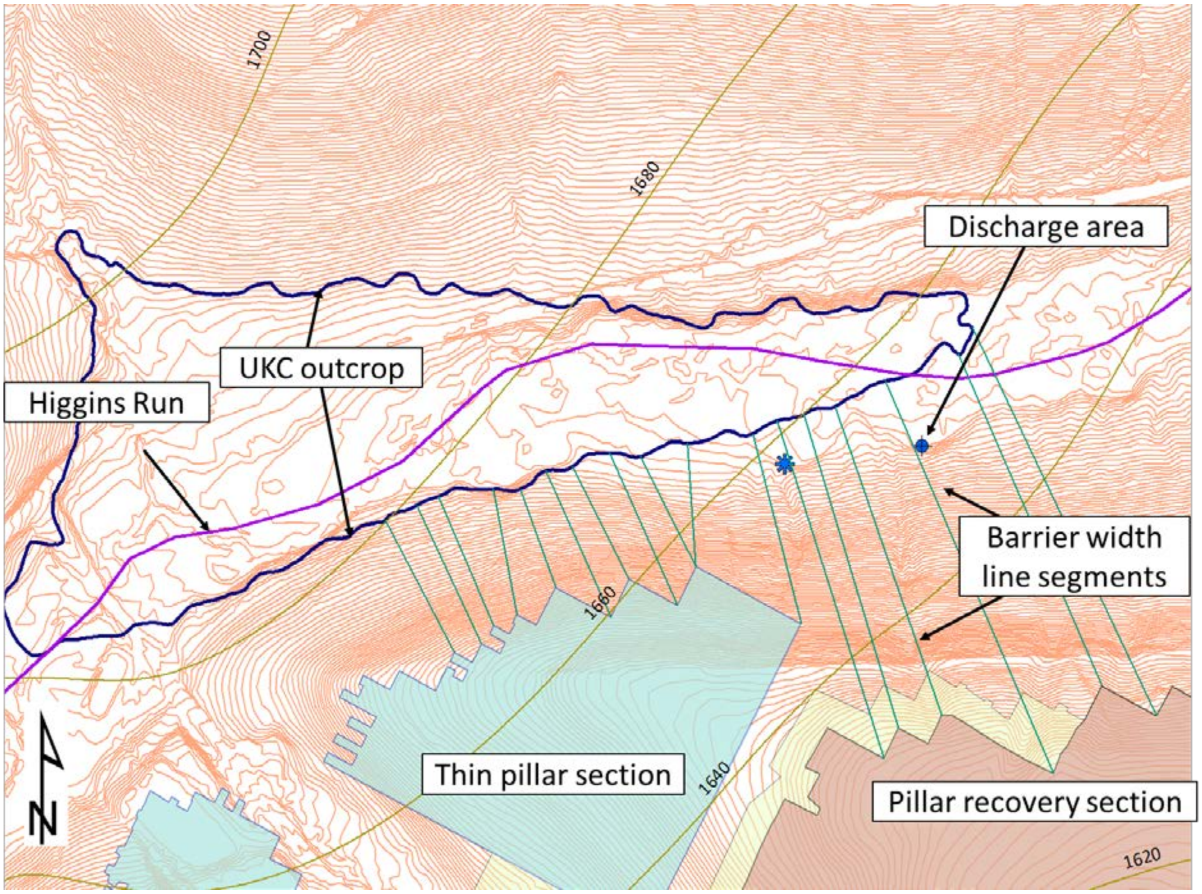
(the highest mine pool elevation for the Solar 7 (1655 ft.) and Solar 10 (1765 ft.) mine pools)



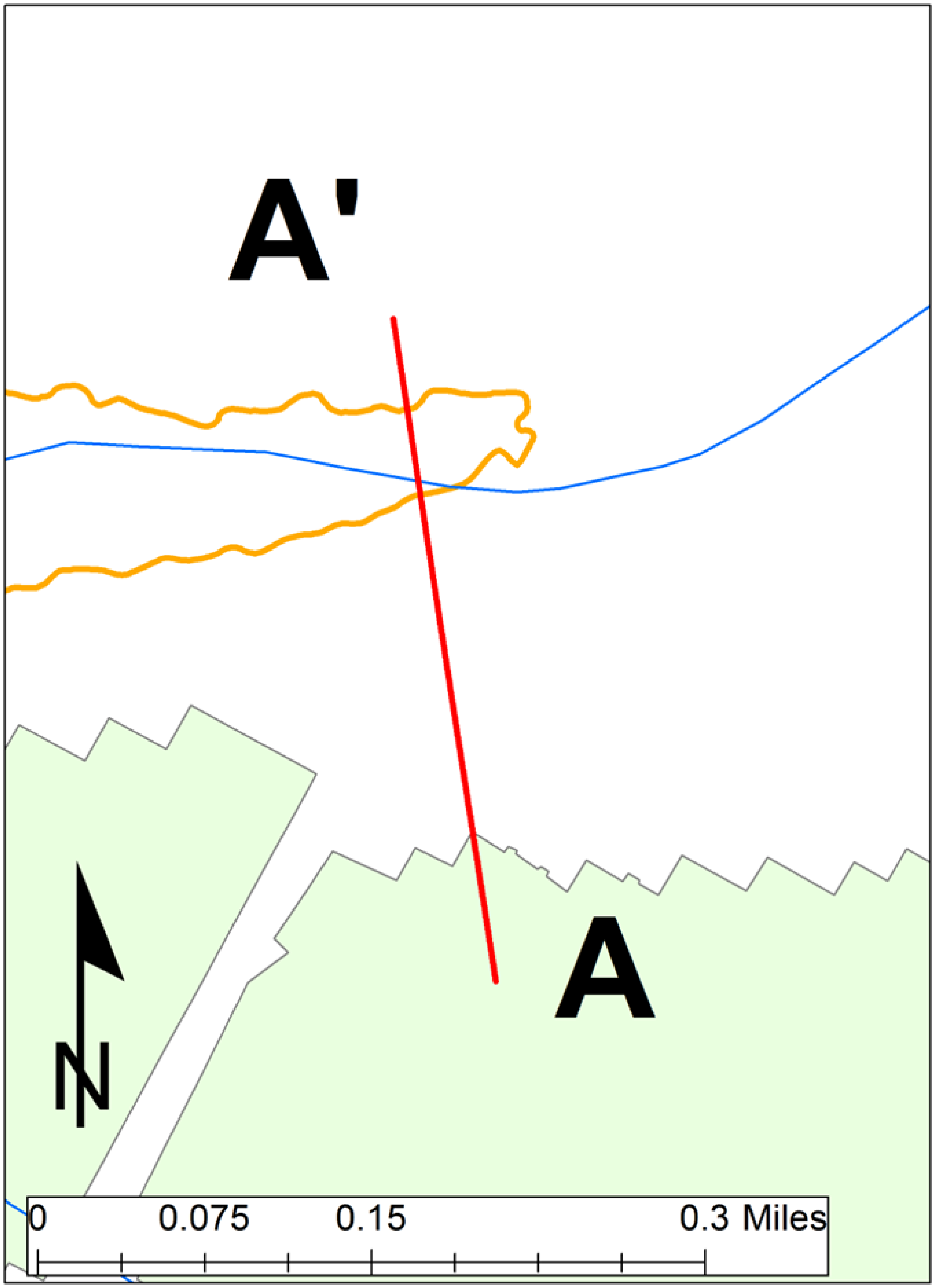
A.3.8 BARRIER 1 OUTCROP AT THE SOLAR 7 MINE (Upper Kittanning coalbed outcrop lines along Higgins Run)



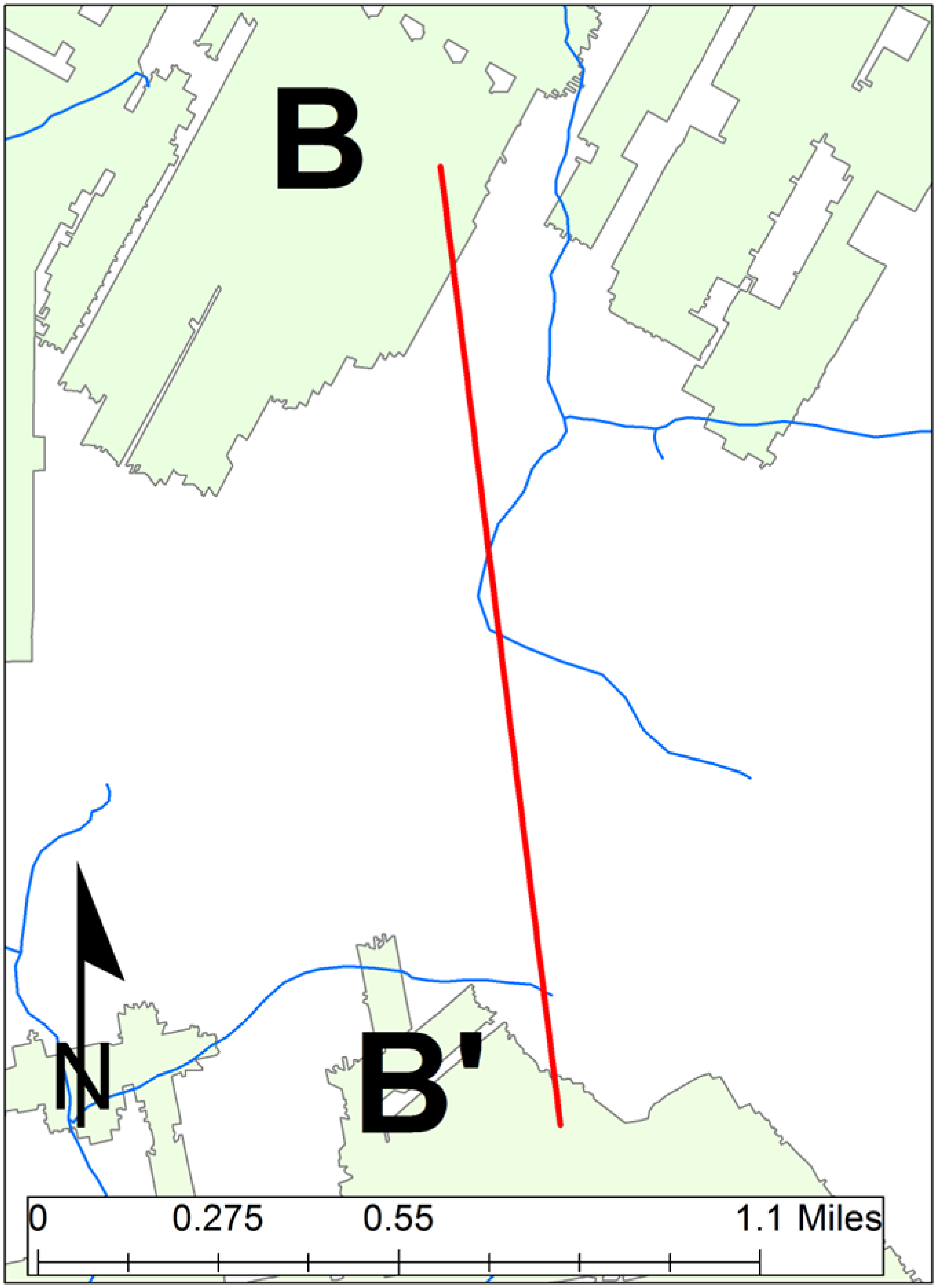
A.3.9 BARRIER 1 LINE SEGMENTS



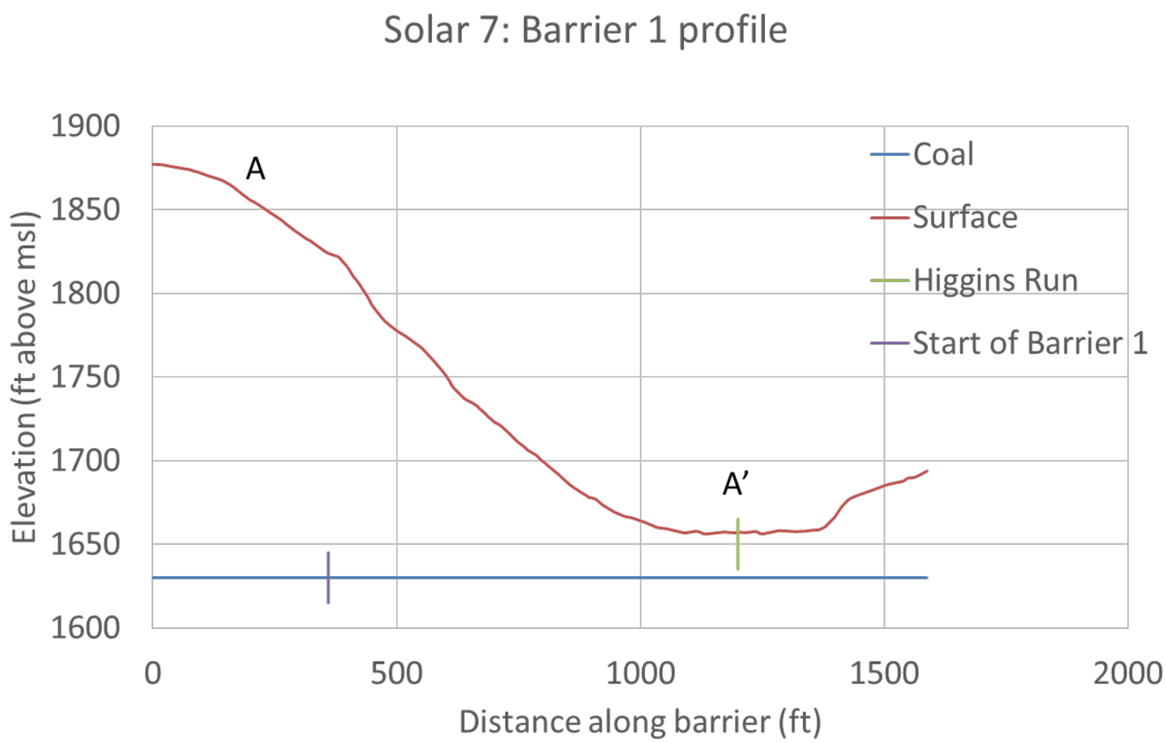
A.3.10 BARRIER 1 PROFILE TRANSECT



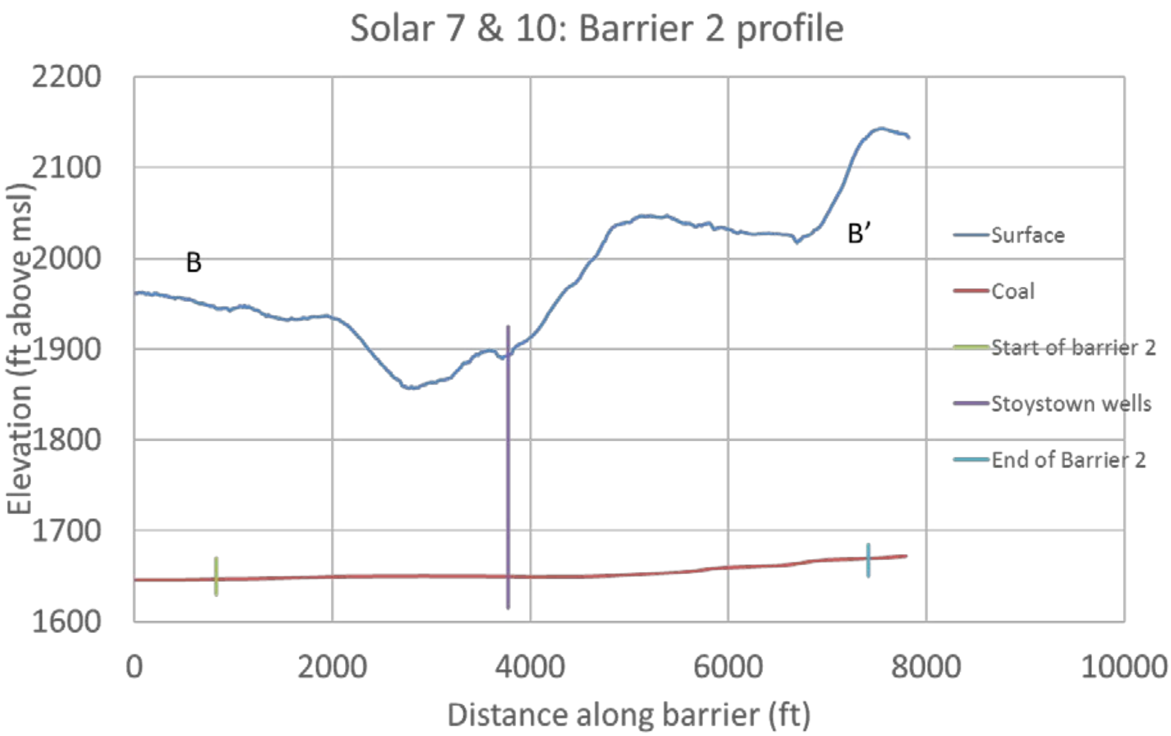
A.3.11 BARRIER 2 PROFILE TRANSECT



A.3.12 BARRIER 1 PROFILE



A.3.13 BARRIER 2 PROFILE

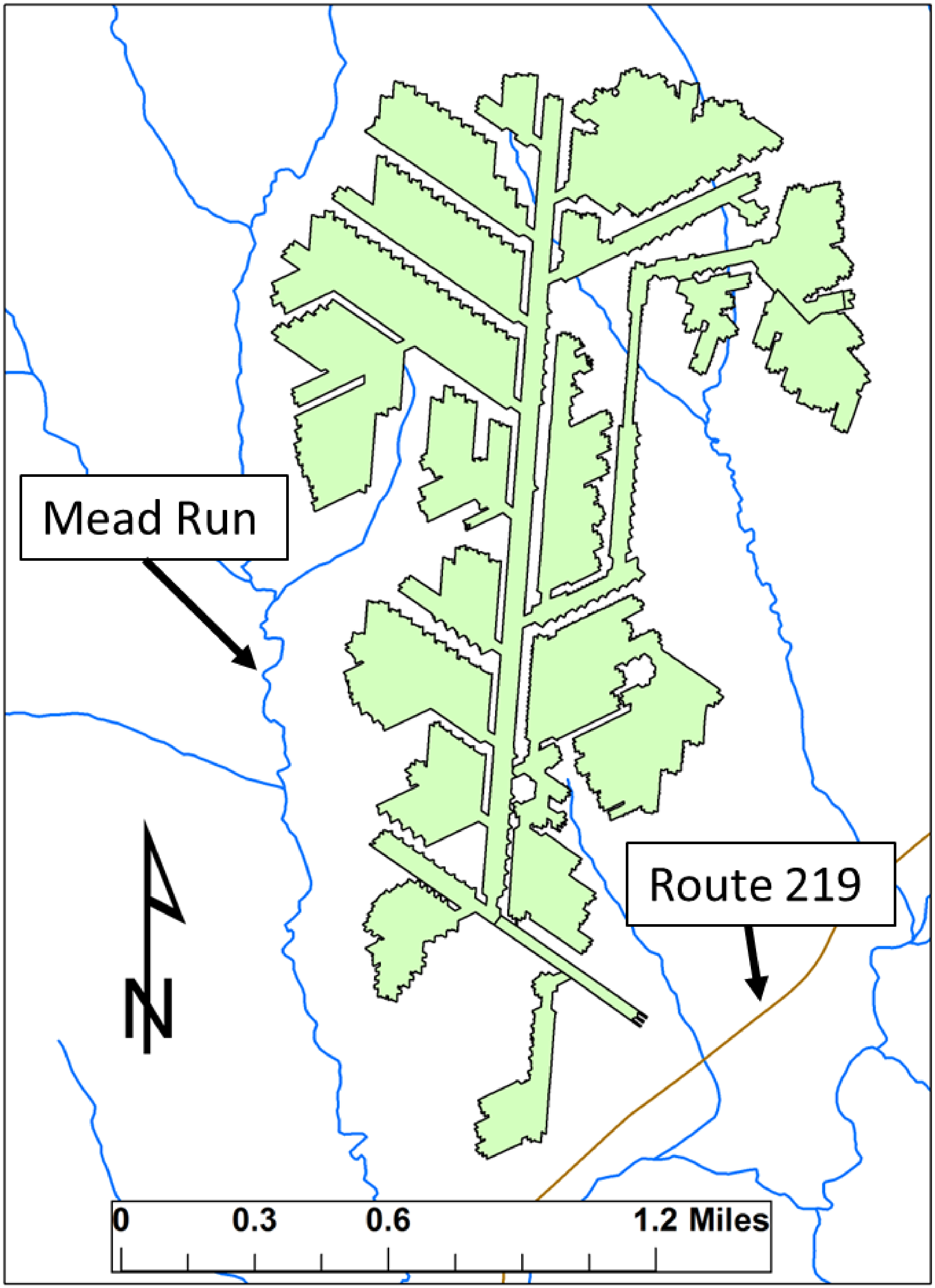


A.4 MAPS OF THE LITTLE TOBY MINE, ELK COUNTY, PENNSYLVANIA

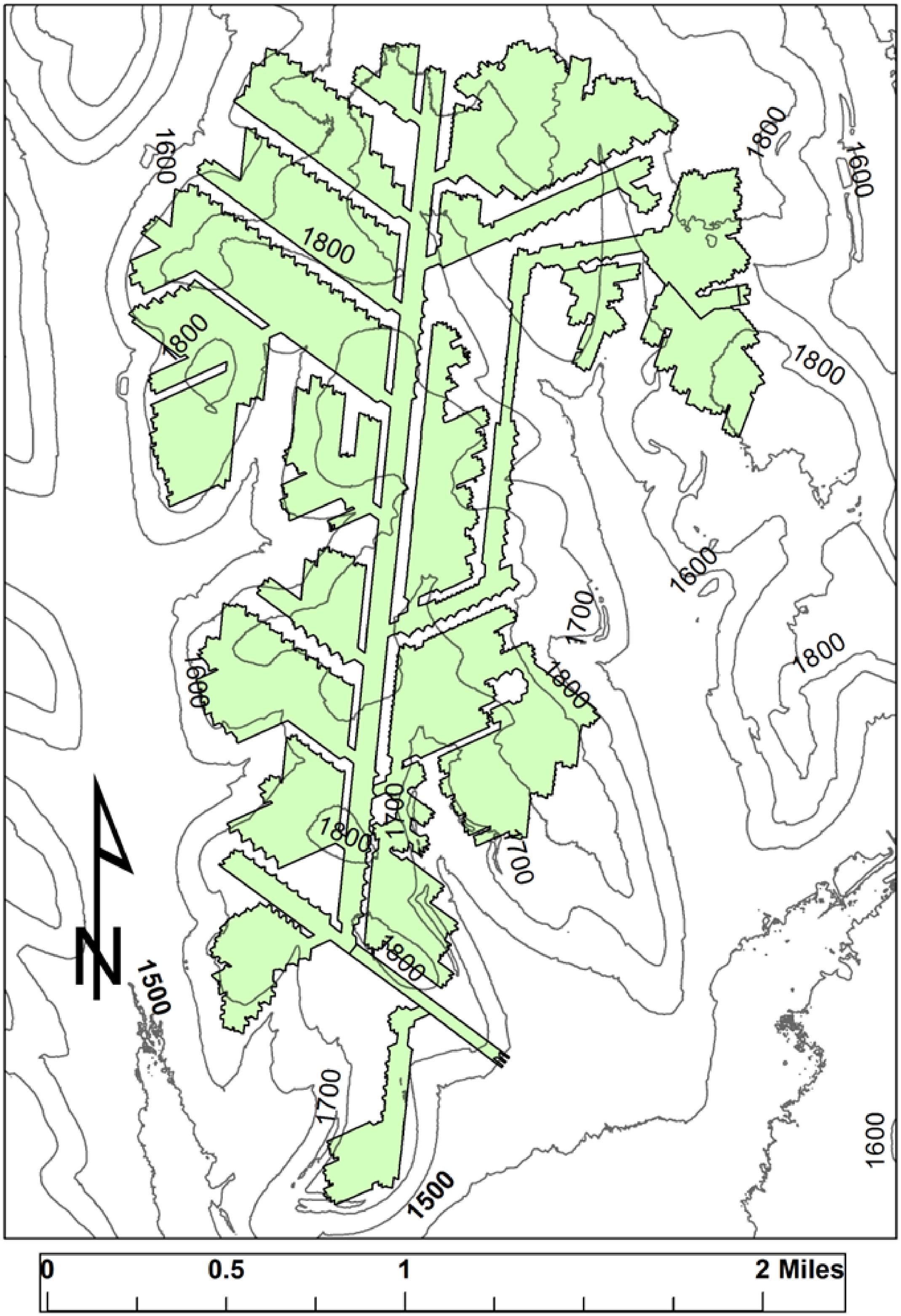
The following maps of the Little Toby mine show detailed characteristics of the mined region. Maps included are: Aerial image and mine outline, streams and roads, surface topography, coal structure, overburden thickness, mine pool elevation, barrier 1 coal outcrop, barrier 1 line segments, barrier 1 profile transect, barrier 2 profile transect, barrier 1 profile, and barrier 2 profile.

A.4.1 AERIAL IMAGE OF THE SURFACE OVERLYING THE LITTLE TOBY MINE

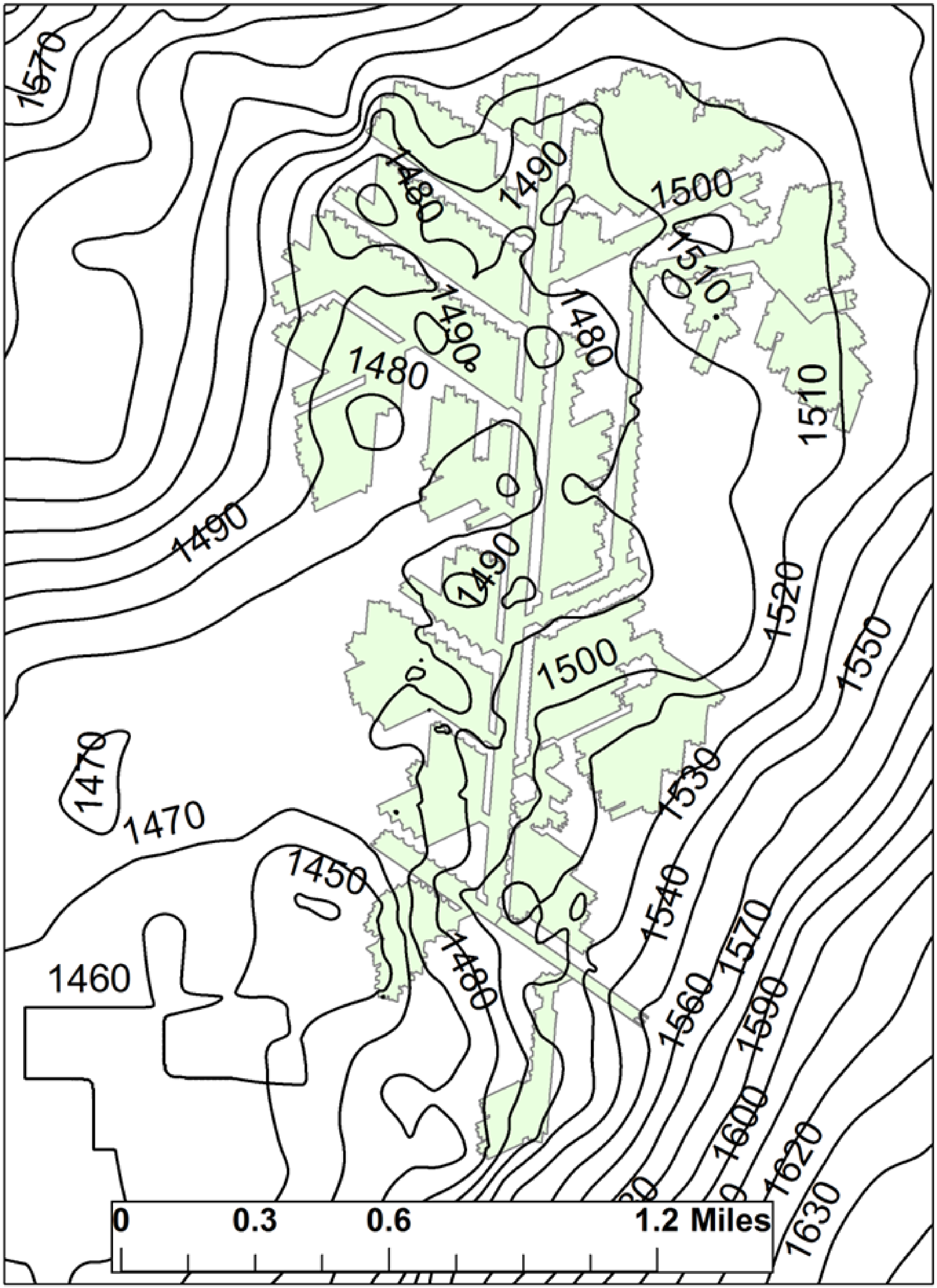
A.4.2 STREAMS AND ROADS AT THE LITTLE TOBY MINE (Location Mead Run and route 30)



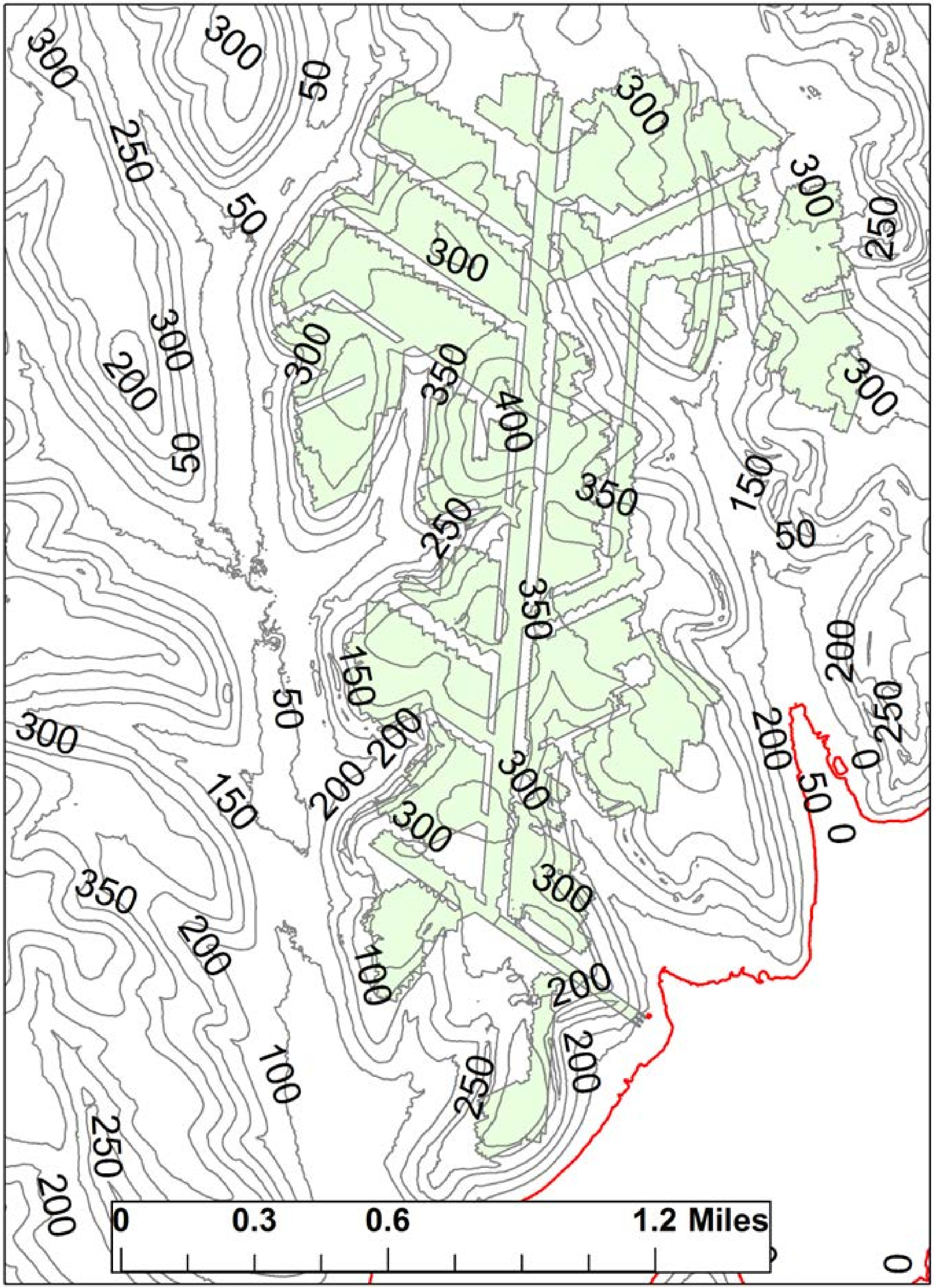
A.4.3 SURFACE TOPOGRAPHY AT THE LITTLE TOBY MINE (100-ft contours)



A.4.4 COAL STRUCTURE CONTOURS AT THE LITTLE TOBY MINE (10-ft contours)

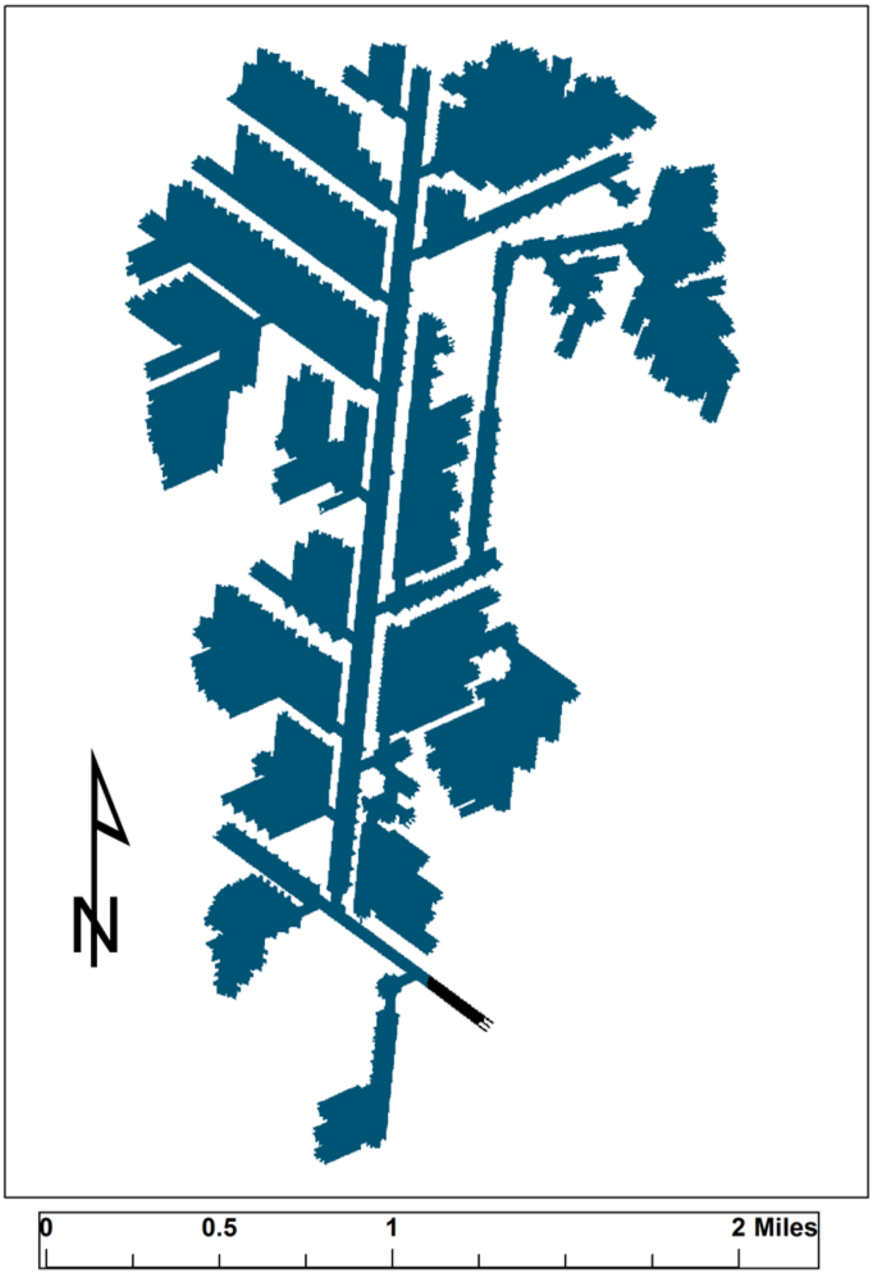


A.4.5 OVERBURDEN THICKNESS AT THE LITTLE TOBY MINE (50-ft contours)

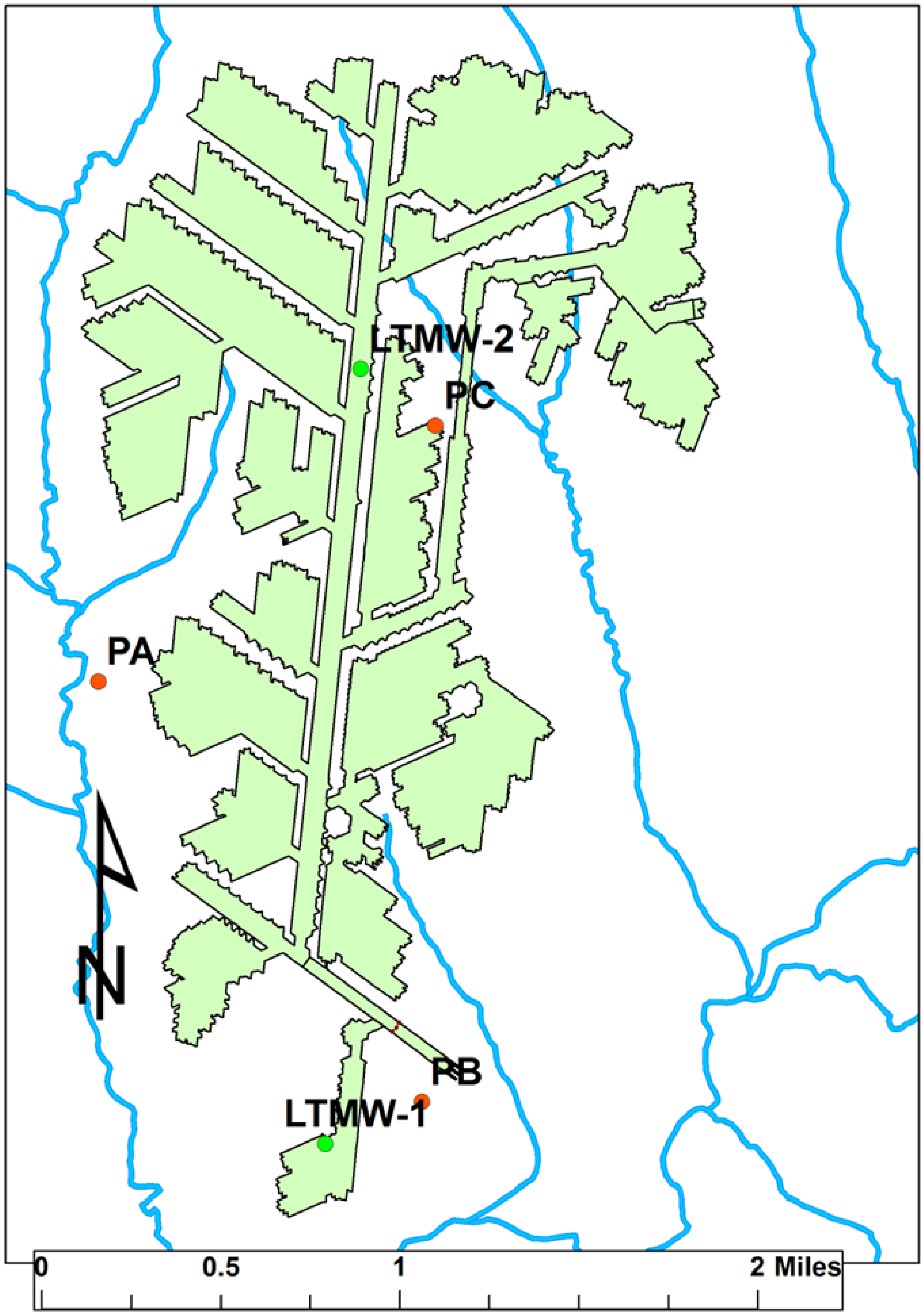


A.4.6 MINE POOL ELEVATION (FT. ABOVE MSL) AT THE LITTLE TOBY MINE

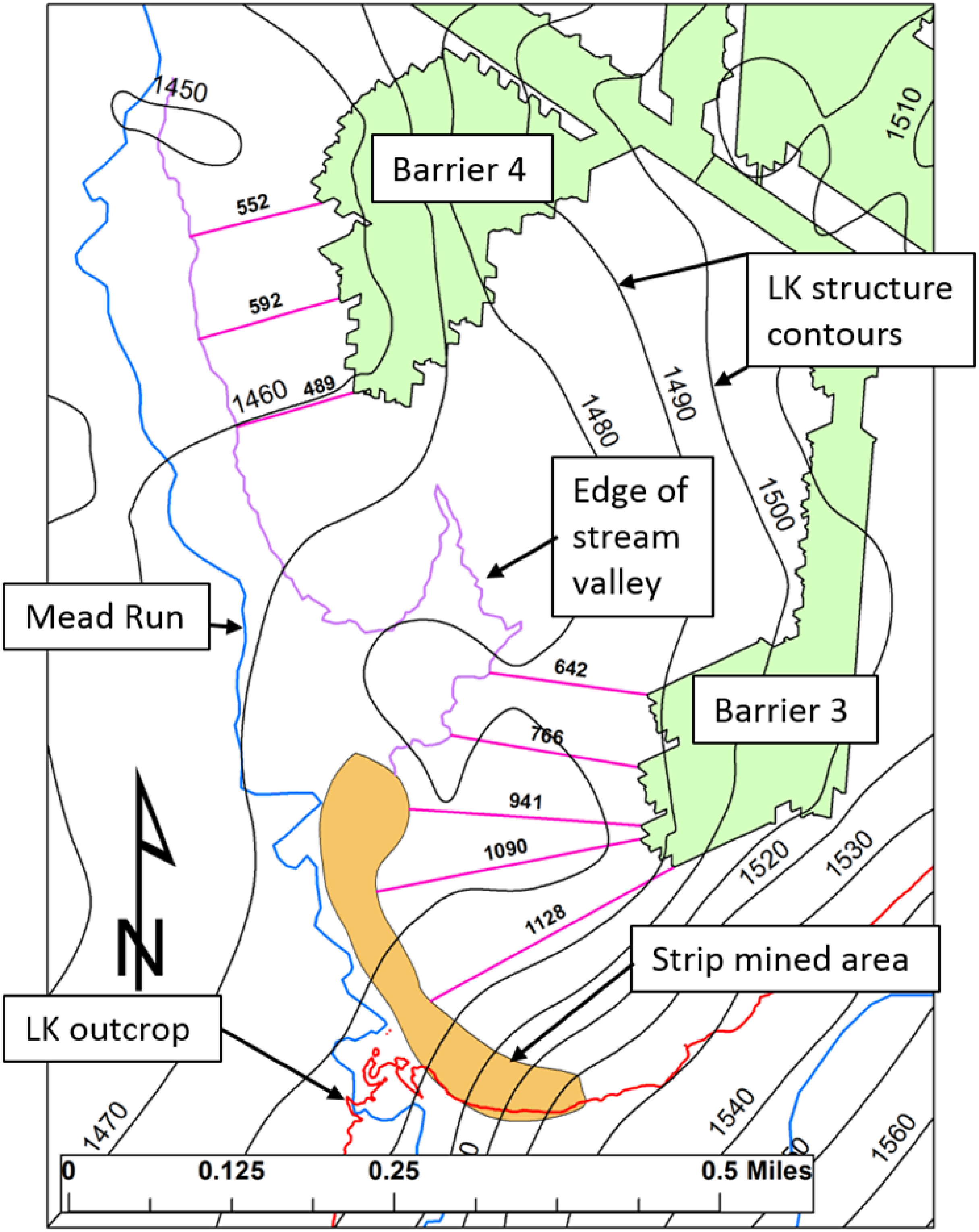
(the highest mine pool elevation for the Little Toby mine pool (1529 ft.))



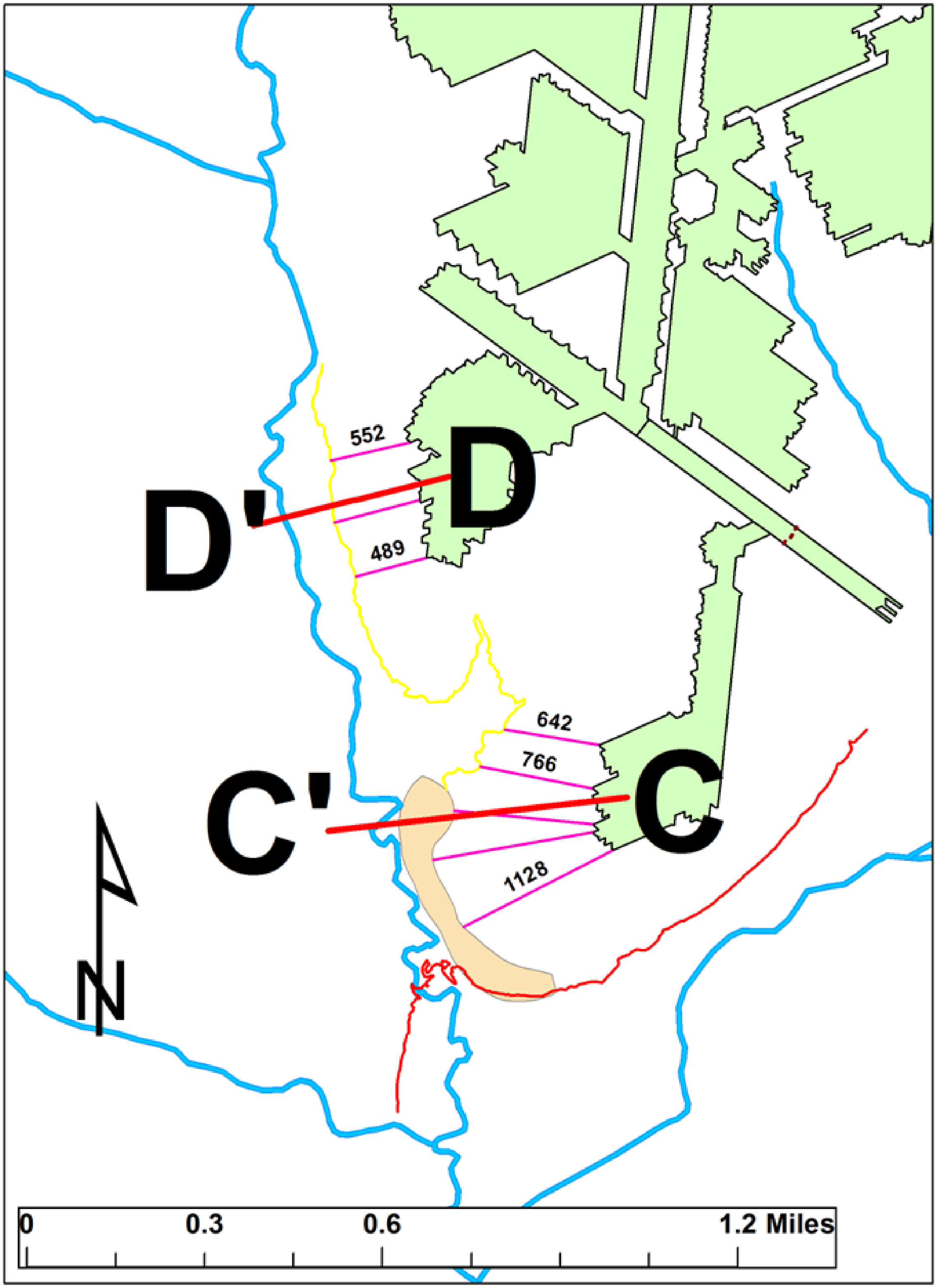
A.4.7 LITTLE TOBY MINE MONITORING POINTS (Piezometers and mine pool monitoring wells)



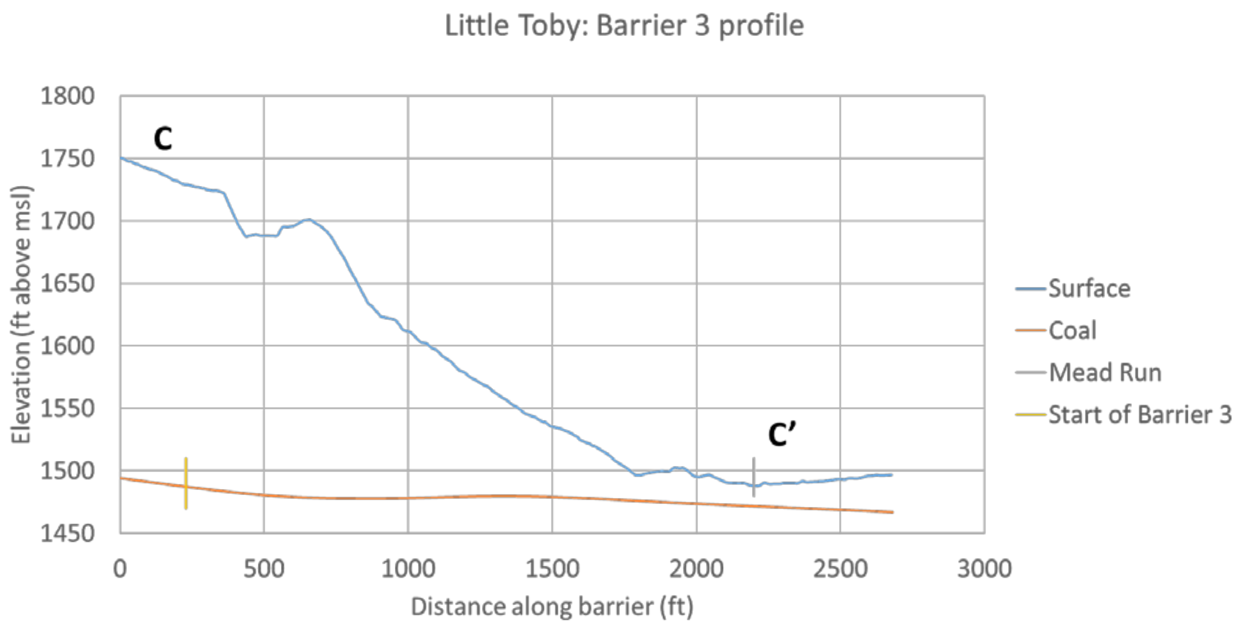
A.4.8 BARRIER 3 & 4 LINE SEGMENTS



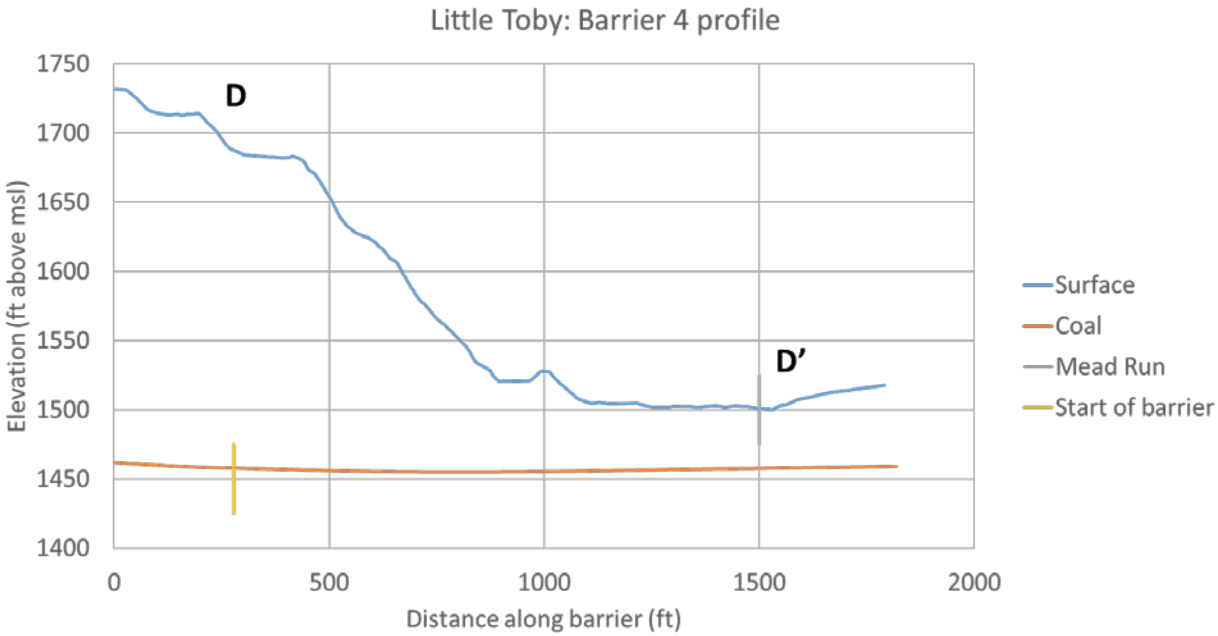
A.4.9 BARRIER 3 & 4 PROFILE TRANSECT



A.4.10 BARRIER 3 PROFILE



A.4.11 BARRIER 4 PROFILE

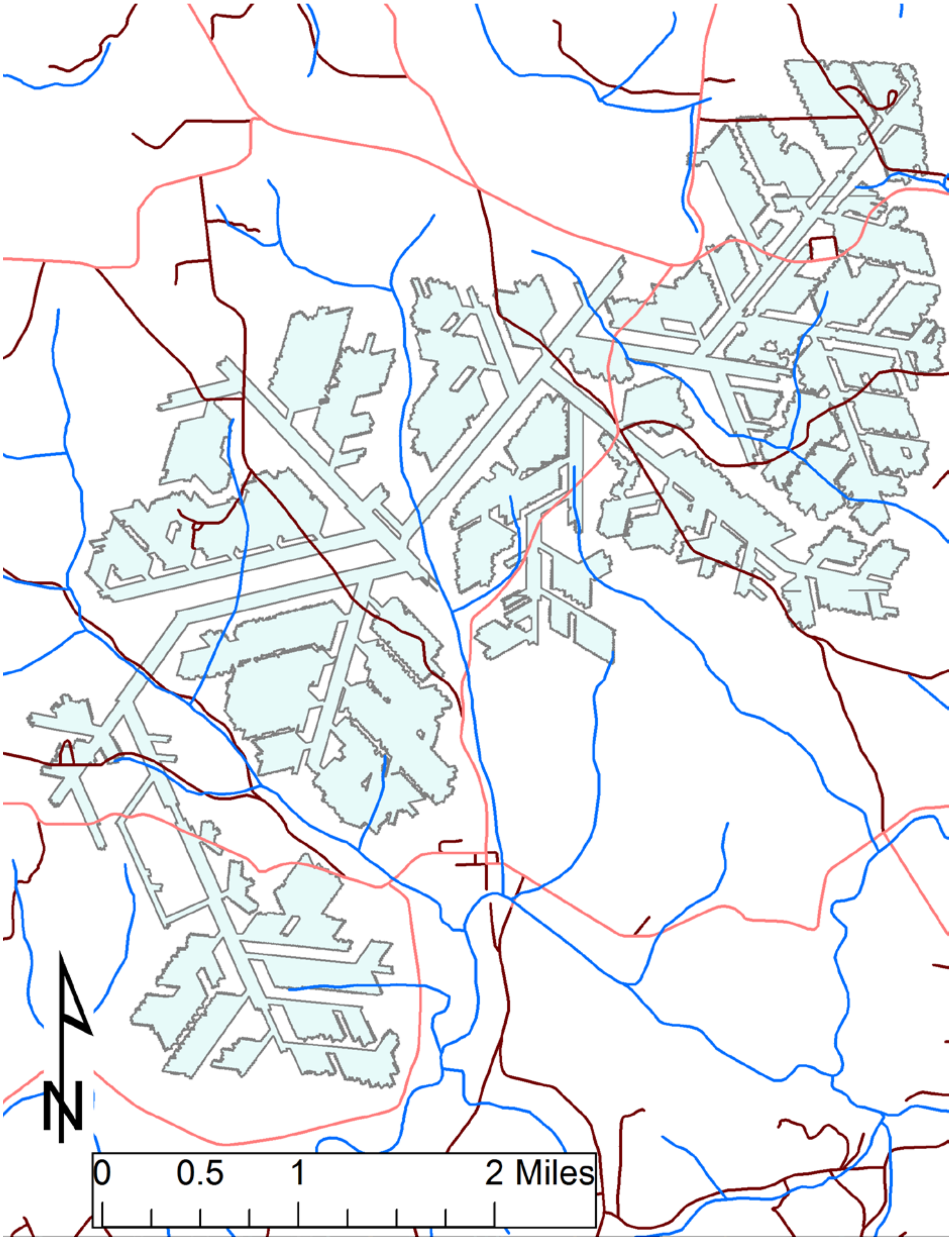


A.5 MAPS OF THE DORA 6 MINE, JEFFERSON COUNTY, PENNSYLVANIA

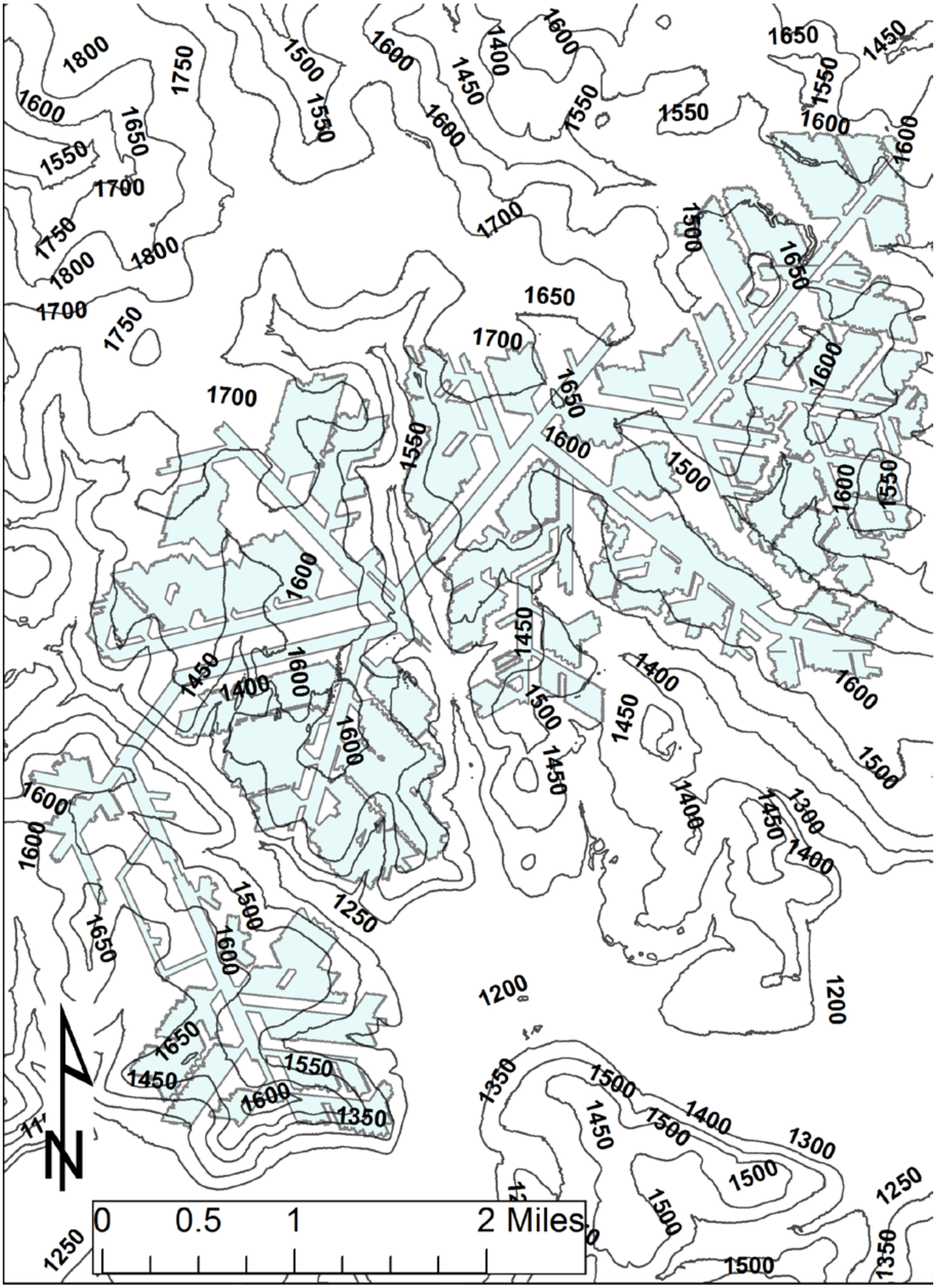
The following maps of the Dora 6 mine show detailed characteristics of the mined region. Maps included are: Aerial image and mine outline, streams and roads, surface topography, coal structure, overburden thickness, current mine pool elevation, barrier 5 line segments, barrier 5 profile transect, and barrier 5 profile.

A.5.1 AERIAL IMAGE OF THE SURFACE OVERLYING THE DORA 6 MINE

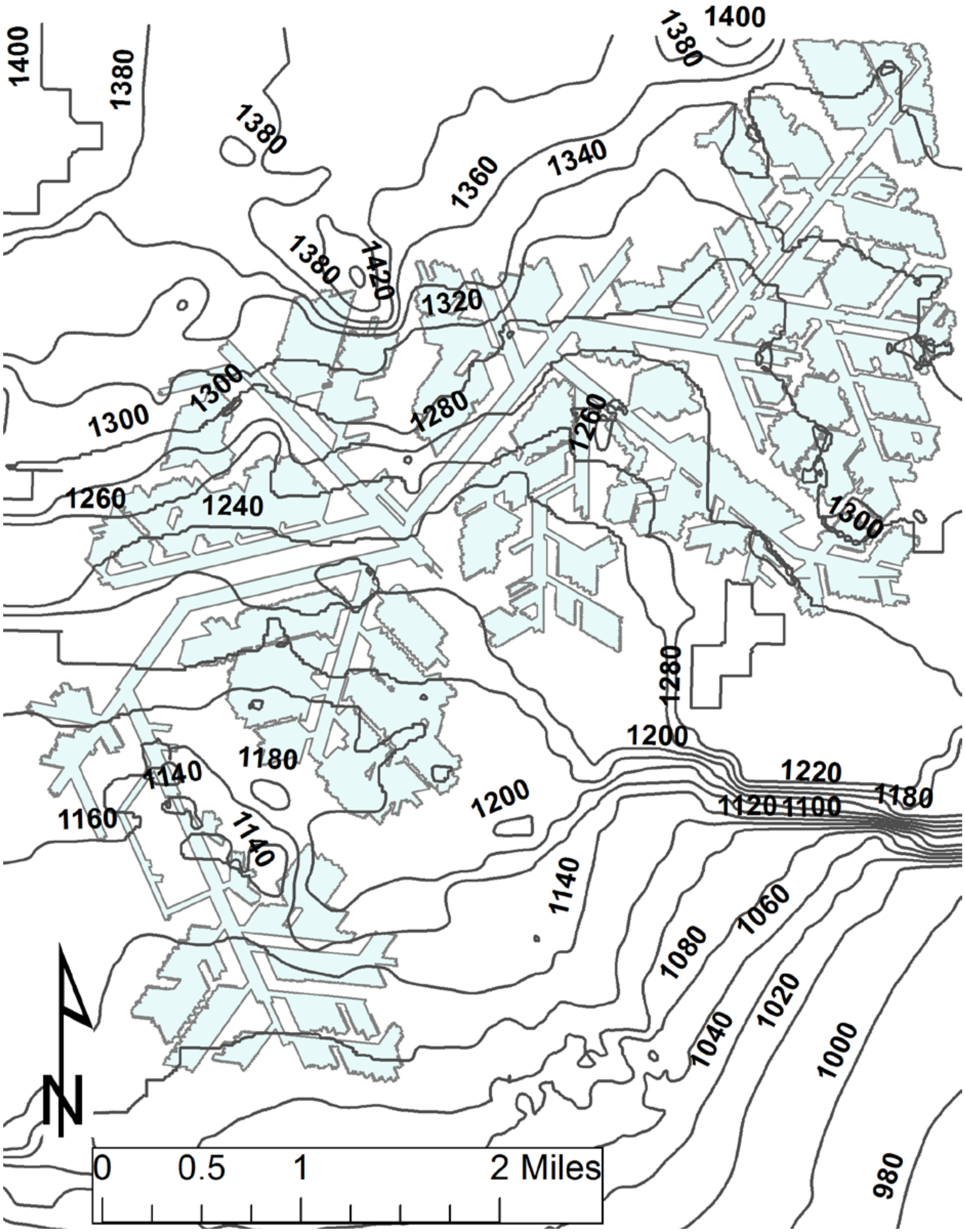
A.5.2 STREAMS AND ROADS AT THE DORA 6 MINE



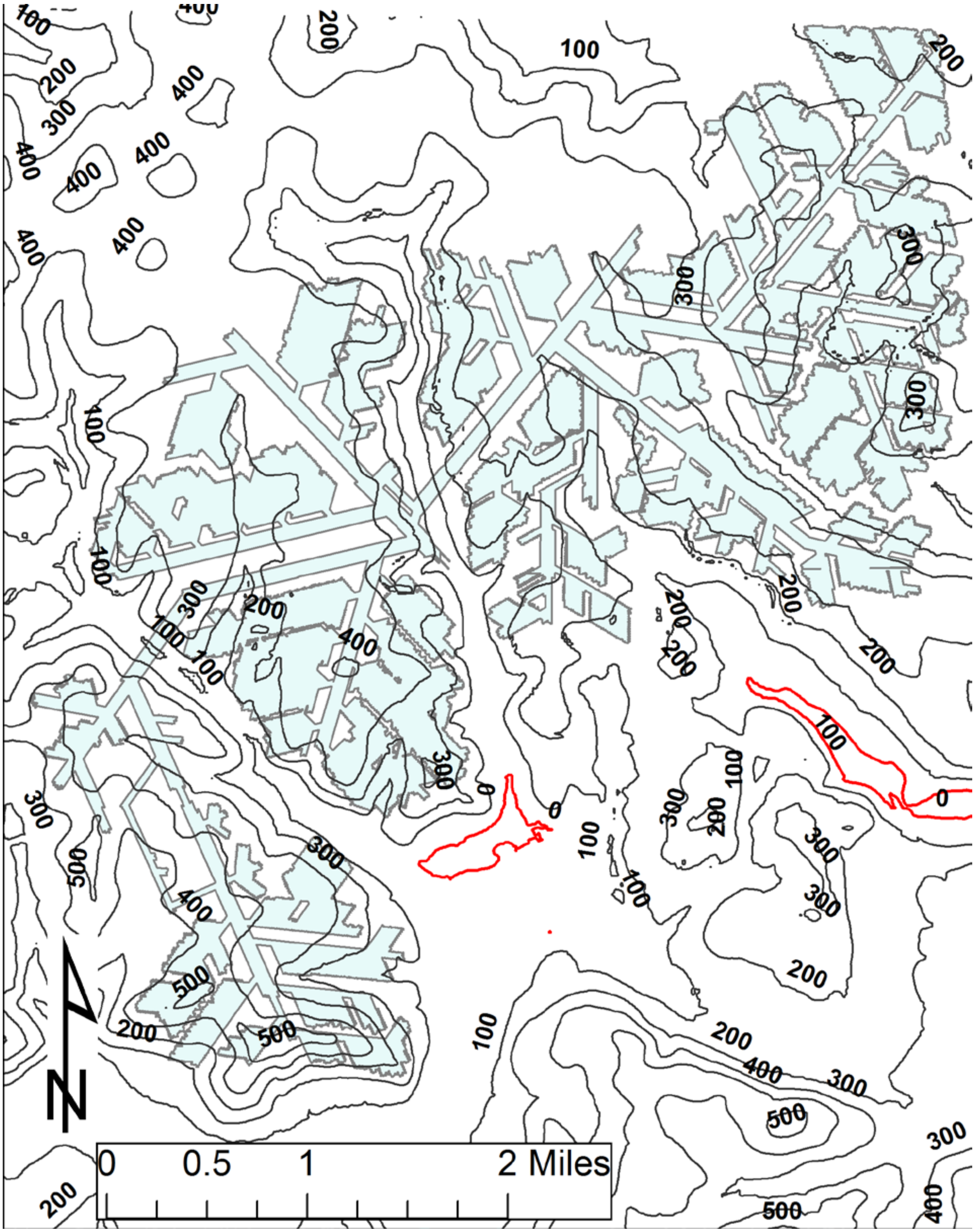
A.5.3 SURFACE TOPOGRAPHY AT THE DORA 6 MINE (50-ft contours)



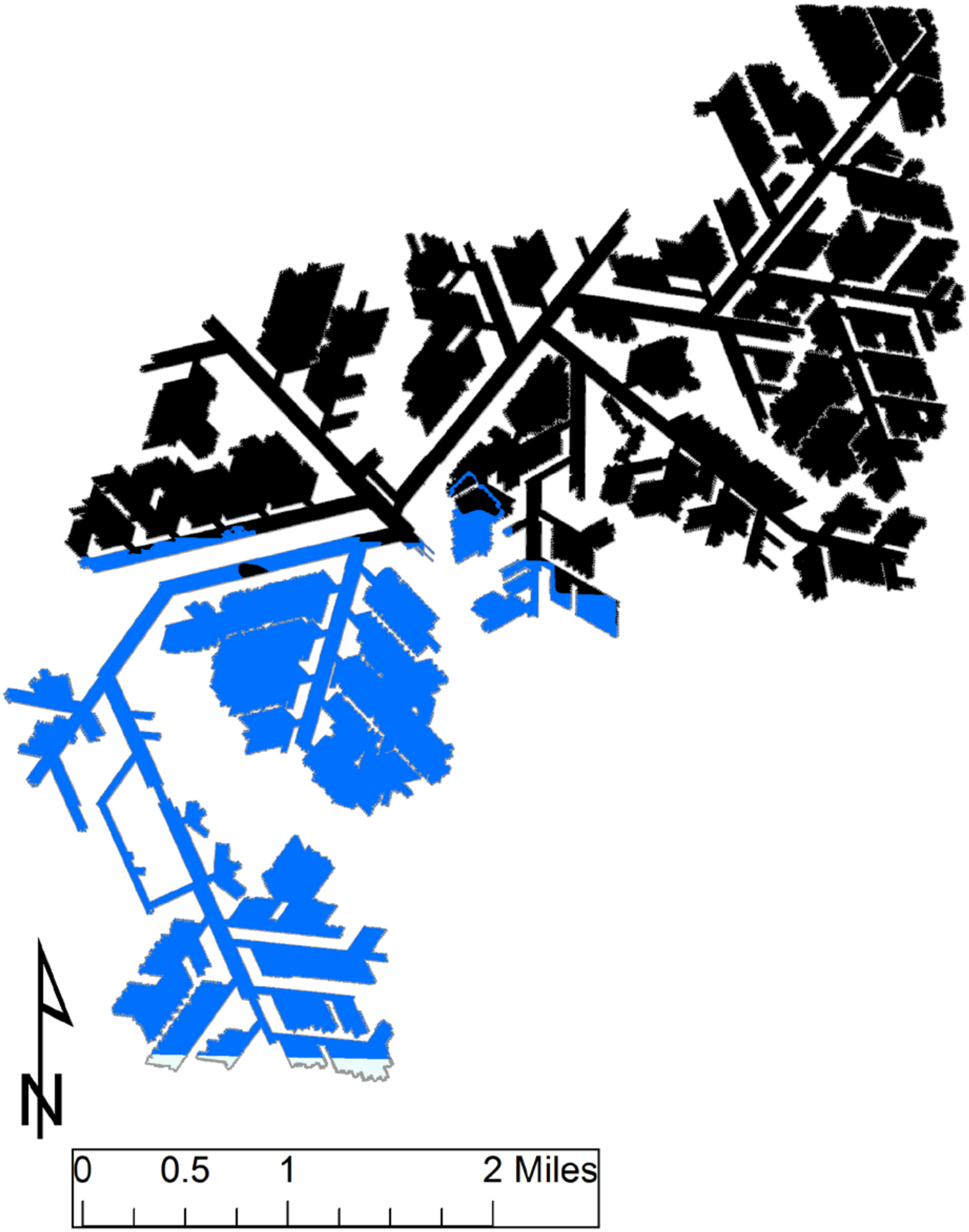
A.5.4 COAL STRUCTURE CONTOURS AT THE DORA 6 MINE (20-ft contours)



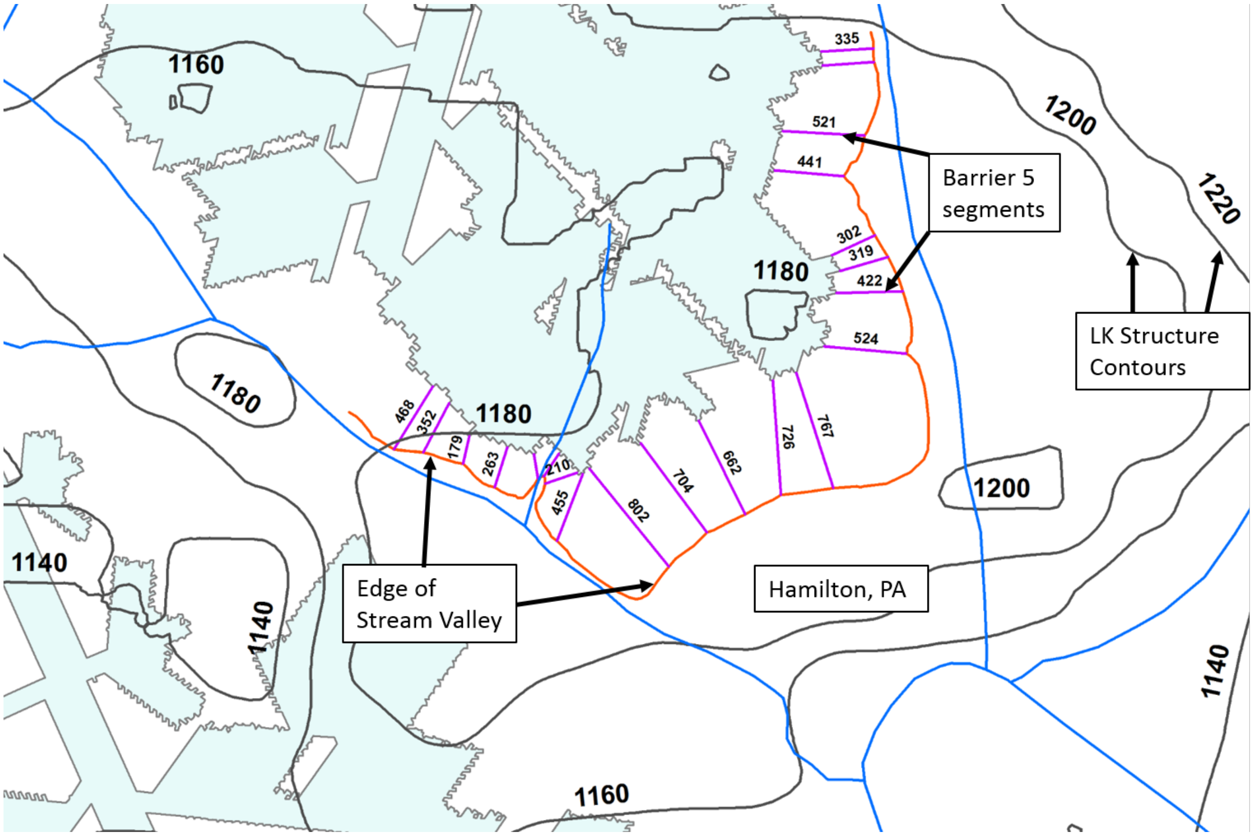
A.5.5 OVERBURDEN THICKNESS AT THE DORA 6 MINE (100-ft contours)



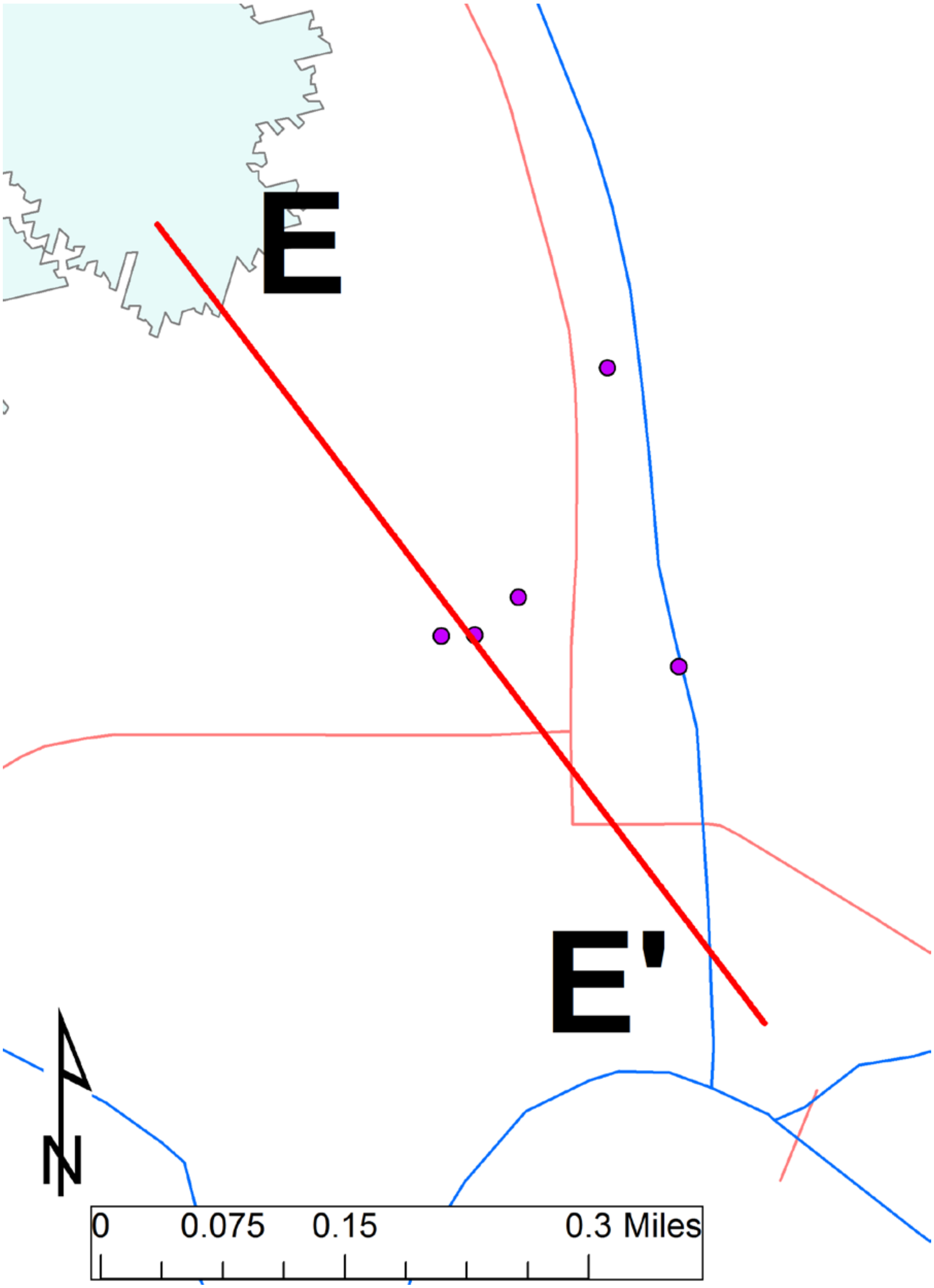
A.5.6 MINE POOL ELEVATION (FT. ABOVE MSL) AT THE DORA 6 MINE (the current mine pool elevation (1230 ft.))



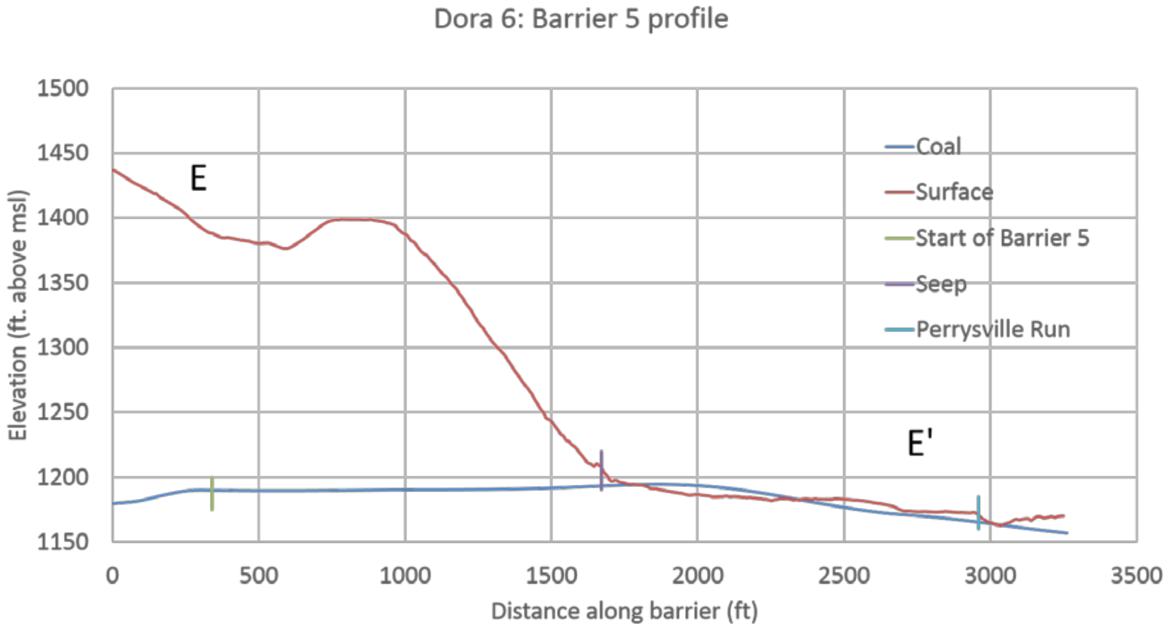
A.5.7 DORA 6 MINE BARRIER 5 SEGMENTS



A.5.8 BARRIER 5 PROFILE TRANSECT



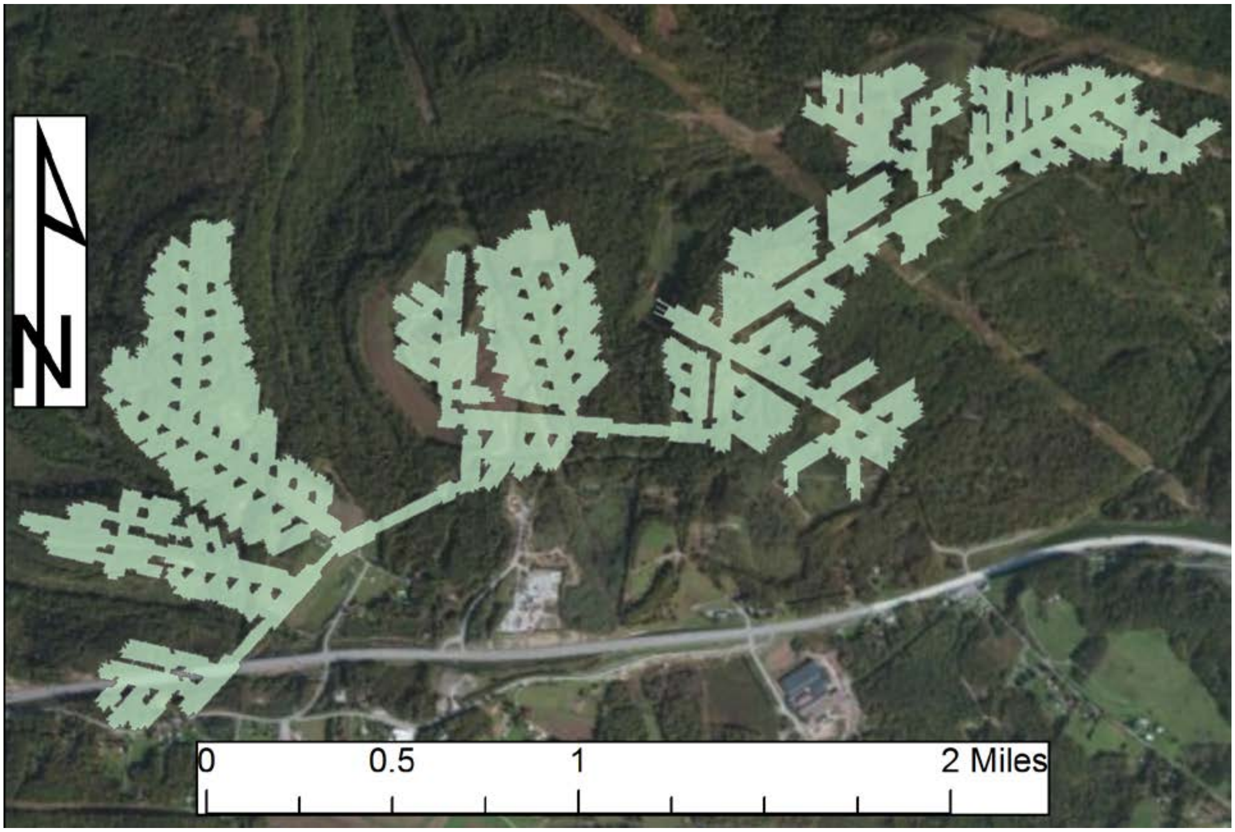
A.5.9 BARRIER 5 PROFILE



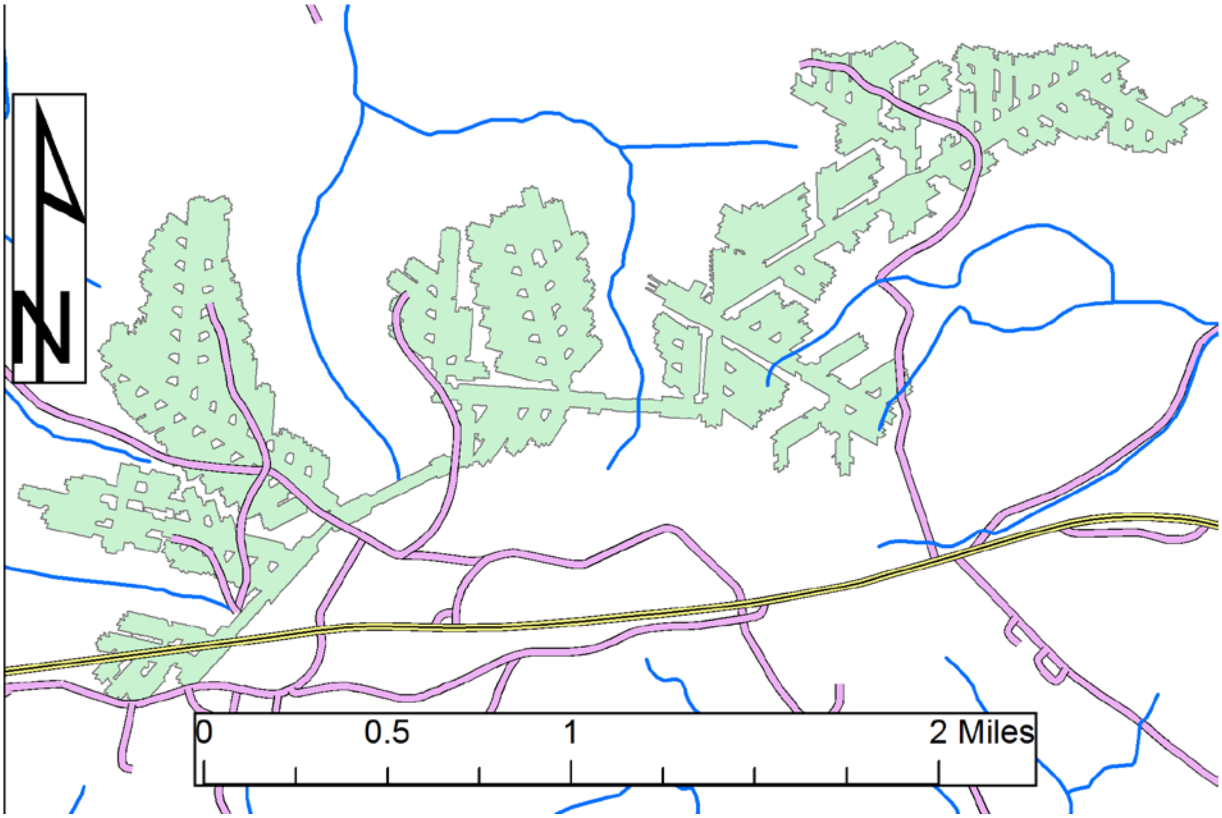
A.6 MAPS OF THE PENN VIEW MINE, INDIANA COUNTY, PENNSYLVANIA

The following maps of the Penn View mine show detailed characteristics of the mined region. Maps included are: Aerial image and mine outline, streams and roads, surface topography, and coal structure.

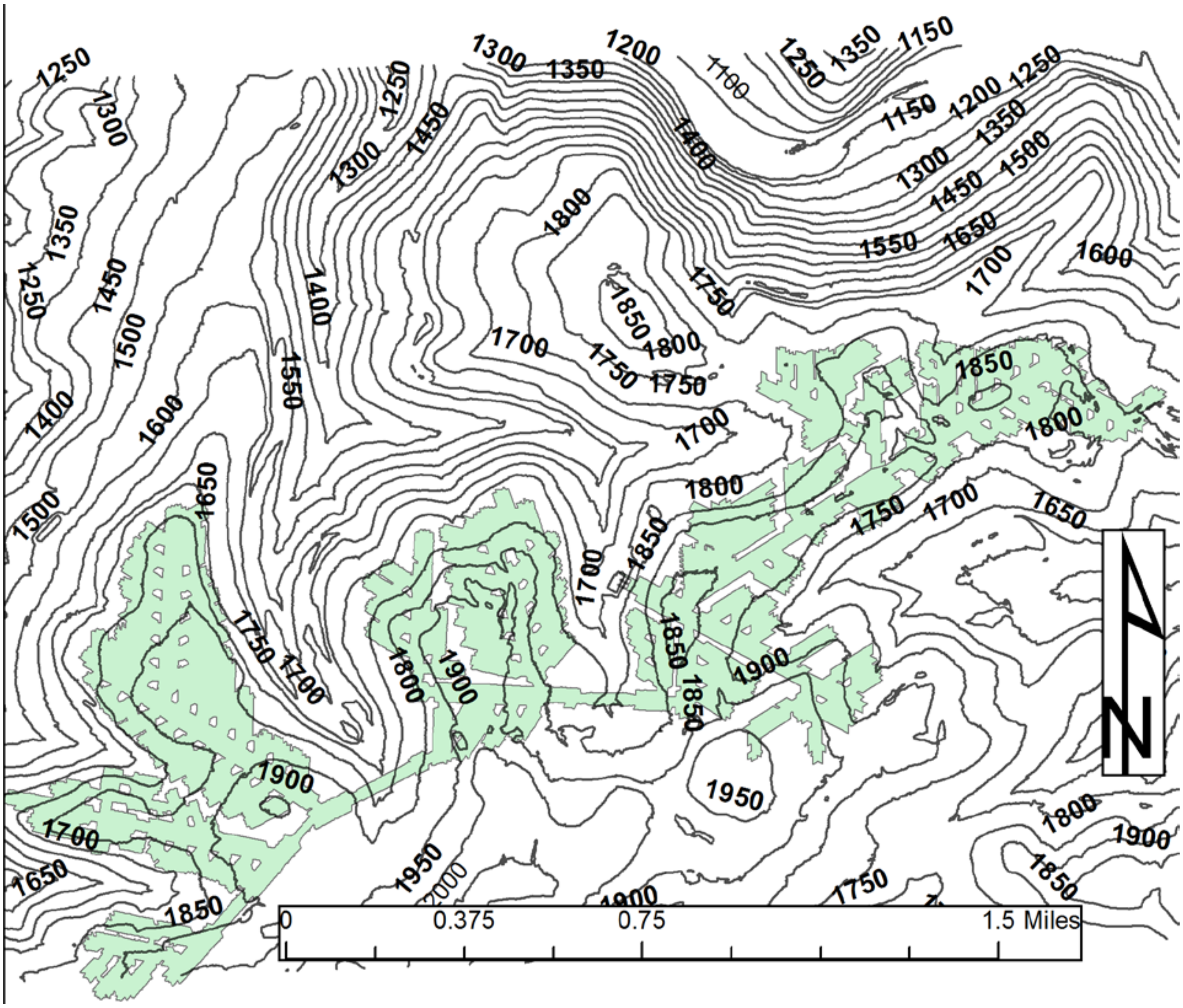
A.6.1 AERIAL IMAGE OF THE SURFACE OVERLYING THE PENN VIEW MINE



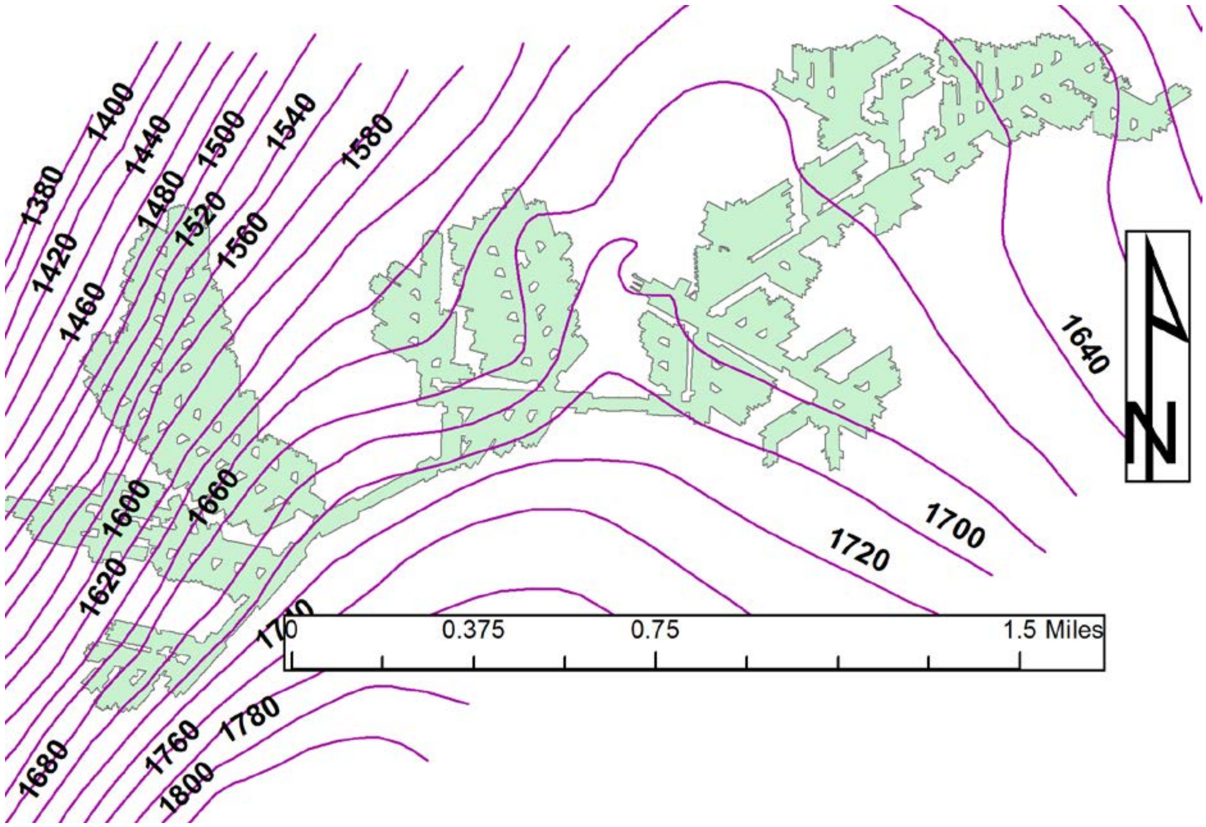
A.6.2 STREAMS AND ROADS AT THE PENN VIEW MINE



A.6.3 SURFACE TOPOGRAPHY AT THE PENN VIEW MINE (50-ft contours)



A.6.4 COAL STRUCTURE CONTOURS AT THE DORA 6 MINE (20-ft contours)



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